SCHOOL OF
CIVIL ENGINEERING

INDIANA
DEPARTMENT OF TRANSPORTATION

JOINT HIGHWAY RESEARCH PROJECT

FHWA/IN/JHRP-94/11
Final Report

STAY-IN-PLACE DECK PANELS - PART 1

Ariel Goldman
Menashi D. Cohen
Julio A. Ramirez

PURDUE UNIVERSITY

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Freezing-and-Thawing Durability of Concrete Bridge Deck Overlays with Corrugated Steel Deck Forms

by
Ariel Goldman
Menashi D. Cohen
Julio A. Ramirez

Joint Highway Research Project
Project No.: HPR-2062
File No.: 7-4-31

Prepared as Part of an Investigation
conducted by the
Joint Highway Research Project
Engineering Experiment Station
Purdue University

In Cooperation with the
Indiana Department of Transportation
and the
U.S. Department of Transportation
Federal Highway Administration

School of Civil Engineering
Purdue University
West Lafayette, Indiana 47907

September 1, 1995

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA/IN/JHRP 94/11		

4. Title and Subtitle STAY-IN-PLACE DECK PANELS. PART 1. FREEZING-AND-THAWING DURABILITY OF CONCRETE BRIDGE DECK OVERLAYS WITH CORRUGATED STEEL DECK FORMS	5. Report Date September 1, 1995 6. Performing Organization Code
7. Author(s) Ariel Goldman, Menashi D. Cohen, Julio A. Ramirez	8. Performing Organization Report No. JHRP 94/11
9. Performing Organization Name and Address Joint Highway Research Project Purdue University 1284 Civil Engineering Building West Lafayette, IN 47907	10. Work Unit No. 11. Contract or Grant No. Indiana HRP-2062
12. Sponsoring Agency Name and Address Indiana Department of Transportation State Office Building 100 North Senate Avenue Indianapolis, IN 46204	13. Type of Report and Period Covered Final Report Executive Summary Dec. 31, 1993-June 30, 1994 14. Sponsoring Agency Code

15. Supplementary Notes

Type B Study

16. Abstract

The objective of this study was the evaluation of frost resistance of concrete bridge decks with stay-in-place galvanized steel deck forms. The evaluation included specific aspects related to the potential for D-cracking in concrete bridge decks with these forms.

The experimental program has been set up so that the real parameters of the bridge deck overlays and the environmental conditions could have been modelled. The program included freezing-and-thawing testing of large concrete slab specimens (22¼"x17¼"x5¼") situated in a computer-controlled environmental chamber and of small specimens (3"x4"x12") immersed in water situated in a freezing-and-thawing machine. The following tests have been carried out: relative ultrasonic pulse velocity, expansion of small specimens, weight changes of small specimens. Relative humidity and moisture content have been measured for controlling the moisture state of concrete.

The results of this study suggest that corrugated steel deck forms may promote the damage of concrete made with D-cracking coarse aggregate due to freezing-and-thawing action. The coarse D-cracking aggregate may by itself cause cracking and scaling of concrete bridge decks with or without steel deck forms.

17. Key Words	18. Distribution Statement
steel deck, D-cracking, moisture, relative humidity, freezing-thawing, pulse velocity, scaling, popout	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	131	

Form DOT F 1700.7 (8-69)

ACKNOWLEDGEMENTS

Thanks are extended to the advisory committee members, especially Mr. R. Smutzer, Mr. D. Andrewski, and Mr. T. Zander for their suggestions and helpful comments in establishing and carrying out the experimental program; to Mr. D. Davis of Irving Materials Inc., who organized the delivery of ready-mixed concrete; to Mr. B. Eisan of Vaisala Inc. for his advice on the relative humidity measurements; and to Mrs. Linda Vail for typing and editing the report.

Financial support provided by the INDOT and the Federal Highway Administration through the Joint Highway Research Project, School of Civil Engineering, Purdue University, West Lafayette, Indiana, is thankfully acknowledged.

Freezing-and-Thawing Durability of Concrete Bridge Deck Overlays with Corrugated Steel Deck Forms

Implementation Report

The objective of this study was to evaluate the frost resistance of concrete bridge decks with stay-in-place galvanized steel deck forms. The evaluation included specific aspects related to the potential for D-cracking in concrete bridge decks with these forms.

The experimental approach was based on freezing-and-thawing test of concrete specimens with and without steel deck forms. The concrete contained coarse aggregate susceptible to D-cracking. Two kinds of specimens have been prepared: (a) large 22¼"x17¼"x5¼" slabs, and (b) small 3"x4"x12" beams. The specimens were conditioned to different moisture contents.

The results of this study suggest that corrugated steel deck forms may promote the damage of concrete made with D-cracking coarse aggregate due to freezing-and-thawing action. The coarse aggregate used in this study could by itself promote extensive cracking and consequent scaling of concrete cast either with or without steel deck forms.

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INTRODUCTION

1.1 Background

One of the most popular methods of bridge constructions consists of prestressed concrete or steel girders supporting a roadway deck. Although timber decks were used originally, reinforced concrete is the most popular material today because of its unique properties like workability, strength, and durability. During the past 12 years the construction cost of concrete bridge decks in the state of Indiana has been reduced by the use of stay-in-place galvanized steel deck forms. Their use results in considerable labor savings over that needed with timber formwork. Stay-in-place galvanized steel deck forms have rapidly emerged as a viable cost effective bridge construction system.

The galvanized steel deck forms are designed to carry the weight of the concrete slab, their own weight, and construction live load. After the deck has been completed, the galvanized steel deck is not considered to serve a useful structural function. These stay-in-place forms are very light (from 2 to 4.5 psf), and relatively easy to place on their hanger system attached to the beams. The corrosion problems which have been experienced in some instances with steel forms, and the fact that the bottom of the deck cannot be visually inspected are probably the principal reservations engineers have when considering the use of stay-in-place steel deck forms. In Indiana, additional concerns have been raised with the use of these forms in regard to the possibility of the concrete damage due to freeze-thaw action in the bridge deck. Improper drainage of the concrete slab due to the presence of the steel deck form could cause the problem with cracking in the slab propagating from the bottom up. The presence of water accumulated at the bottom of the slab could make the damage a critical one if the concrete was made with coarse aggregate susceptible to D-cracking.

1.2 Objective of the study

This research report contains only Phase 1 of the planned research study. Phase 2 of the study should follow successful completion of Phase 1, as has been suggested in the research proposal. The Phase 1 of the proposed research study has been focused on the following objective:

> Evaluation of frost resistance of concrete bridge decks with stay-in-place galvanized steel deck forms. The evaluation includes specific aspects related to the potential for D-cracking in concrete bridge decks with these forms.

1.3 Research approach

The proposed experimental program was aimed at assessing the frost resistance characteristics of concrete bridge decks cast on stay-in-place steel forms as a function of relative humidity (%RH) of concrete. The possibility of existence of a %RH threshold level above which laboratory panels would be susceptible to D-cracking was investigated. An extensive series of preliminary tests have been run for this purpose.

The experimental program has been set up so that the real parameters of the bridge deck overlays and the environmental conditions could have been modelled. This approach led to the production of large size specimens, actually slabs, where the concrete was cast onto large fragments of galvanized steel deck forms. The forms were the same as those used in the field. The concrete mix composition also was the same as used in the field, provided by INDOT (Table 2.2). The concrete mix was made with a crushed limestone coarse aggregate which might be susceptible to D-cracking.

1.4 Experimental problems

Two major problems have been resolved while carrying out this research project. The first one referred to the reliability of %RH measurements in concrete. The other problem was a long duration of freezing-and-thawing cycles required for adequate testing of large slab specimens.

As a result of an extensive search for possible means of %RH measurement, several techniques have been chosen. Preliminary tests done on these techniques have shown their relatively low accuracy at high levels of %RH (≈80% and higher). Thus, the moisture condition of the concrete was established by means of direct gravimetric determination of the moisture content, along with the measurements of %RH.

To resolve the problem of long freezing-and-thawing cycles (42 hours per cycle) required for large slab specimens, an alternative experimental program has been worked out. This program has been approved by INDOT. It has been completed in a relatively short time, while the freeze-thaw testing of large slab specimens was still in progress.

This report is divided into three parts containing the description and the results of three major experimental programs, as follows.

1. Methods of measuring %RH and moisture content in concrete (Section 2).
2. Freezing-and-thawing testing of large concrete slabs (Section 3).
3. Alternative freezing-and-thawing test of small specimens carried out according to the expansion- extension research program (Section 4).

SECTION 2

METHODS OF MEASURING %RH AND MOISTURE CONTENT IN CONCRETE

2.1 Introduction

Part of the experimental program related to frost resistance of concrete bridge decks with steel forms was aimed at indicating a %RH level in concrete, above which the bridge decks might be susceptible to D-cracking. Also, the experiments were intended to clarify the possibility of moisture accumulation in the bottom part of the decks cross section, close to the interface between concrete and steel form.

For these purposes, it was proposed to create a range of five %RH values in concrete specimens: two below, one similar and two above the %RH level that presumably might occur close to the concrete-form interface. The program included the preparation of concrete specimens cast in wooden molds with fragments of corrugated steel deck forms. The specimens were to be (a) conditioned for different levels of %RH, (b) sealed when desired levels of %RH were achieved. and (c) subjected to freezing-and-thawing cycles in a computer controlled chamber. To carry out this program, two major experimental questions had to be answered:

1. how to measure the %RH in concrete;
2. how to establish a range of certain levels of %RH in concrete.

Water or moisture content in a "young" hardened concrete is usually high (up to 5-8%), which implies that %RH in its pores is close to 100%. This level can be kept at least as long as the concrete specimens are moist cured for two or more weeks. However, the establishment of desired %RH levels lower than 100% by artificial means in a limited time can be a difficult task.

Numerous techniques have been developed elsewhere for the measurements of %RH, being however suitable for the applications in open air spaces, rather than in small pores within the concrete. The accuracy of such measurements is usually ±2-3% when relative humidity becomes higher than 70-80%RH.

These problems have been discussed during a joint meeting with INDOT on November 10, 1992. A survey of relevant literature and %RH measurement techniques was reported at the meeting. It was suggested to run a series of preliminary tests. The results of these tests are represented herein.

2.2 Preliminary testing procedure

The objectives of this part of the experimental program were:

1. to clarify the possibility of reaching certain desired %RH levels in concrete;
2. to determine the duration of time needed to reach each of the %RH levels;
3. to establish a proper method of %RH measurements.

It was suggested that relative humidity at levels lower than 100%RH could be controlled by accelerating the evaporation of moisture from the concrete. This could be done by means of moderate heat applied to a concrete specimen at its top and/or bottom surface. Suggesting that heating of a bottom surface might be more efficient and thus should not take a long time, a technique was developed and represented to INDOT. A plywood box with four light bulbs was situated under the specimen (Fig. 2.1). The other possibility, i.e. heating the concrete surface at the top of the specimen, was explored using the same box (Fig. 2.2).

The %RH of concrete should be measured before and during heating in order to evaluate the efficiency of heating for evaporating moisture out of concrete. The measurements could be taken in one of the following ways, as described in the literature:

- inside the mass of concrete, when a RH sensor is embedded directly (i.e. cast), or inserted into a small sealed cavity (1,2);
- outside the concrete specimen, when a portion of the material is collected in a sealed testing container where an RH sensor is situated (3).

Extensive survey of commercially available %RH measurement systems have been done. Several systems based on different concepts, are described in Table 2.1. A few other systems using the same concepts were available, but could not be applied in this project. Actually, the RH sensors offered by numerous manufacturers can be divided into three groups: (a) capacitance sensors, (b) resistance sensors, and (c) dew point sensors (Table 2.1). According to the technical information available, both capacitance and resistance sensors are more accurate at normal temperatures (60-80°F), and when the %RH is lower than 70-80%. At higher RH levels, their accuracy could be ±3%, i.e. quite low. Dew point sensors are more accurate, but can work only in relatively large, open spaces. Failure of resistance sensors could be expected at about 100%RH. The sensors and other devices listed below have been chosen for this program:

1. Relative Humidity & Temperature Piercing Probe, HMP-36, manufactured by Vaisala Inc. The probe is equipped with a capacitor type RH sensor (Humicap-) and a resistor type (RTD) temperature detector.
2. Survivor II, a combined Relative Humidity & Temperature sensor. The %RH is measured using a tiny capacitor.

3. Mini Cap-2, a capacitor type Relative Humidity sensor.

4. Hand made capacitor type sensor, assembled in Purdue CE labs.

Two 16"x16"x5" concrete specimens were cast as part of the testing procedure. The concrete mixes were prepared in accordance with the composition provided by INDOT (Table 2.2). The specimens contained fragments of corrugated galvanized steel deck forms at their bottom part. The depth of the corrugations was 2 inches.

The first specimen was cast with four "pre-fabricated" deep cavities, sealed by nuts (Fig. 2.3). The specimen was kept in the mold and cured by wet covering for 14 days. During this period, the %RH was registered using both techniques mentioned above, i.e. inside the cavities and outside the concrete specimens.

The %RH inside the concrete, at the bottom part of the specimen, was measured through the "prefabricated" cavities shown in Fig.2.3. Specially designed sleeves, supplied by the manufacturer (Vaisala, Inc.), were used for creating relatively small sealed spaces within the cavities (Fig. 2.3). In addition to "prefabricated" cavities, the %RH was measured in a few others, drilled by a 5/8" concrete drill bit (Fig. 2.4).

The concrete powder obtained while drilling was collected as shown in Fig. 2.4. The %RH was measured above the powder sample in a sealed container (Fig. 2.5). The container was designed and constructed at Purdue, as well as some other items shown in Figs. 2.4, 2.5. The powder was put into the container as quickly as possible, in about half a minute. The whole procedure of powder sampling and of the %RH measurements in a sealed container was developed at Purdue.

Table 2.1 Commercially available systems of %RH measurement

	1. RH & T Probe:			2. RH & T Meter:		3. RH sensor (or RH & T)		
	Type	L (mm)	D (mm)	Type	Oper. range	Type	Oper. range	Accuracy at 90-100% RH
I	Vaisala HMP-36 RH&T probe	325	12	a) HMI-31	+5- + 55℃	Humicap-H 0.062 HM Thinfilm capacitor (with RTD)	0-100% RH at -40+90℃	± 3% RH (at 20℃)
				b) HMI-32	+5- +55℃			
				c) HMI-36	0- + 50℃			
II	Protimeter-6900 Concrete probe	198 + 25	21	DP 989M	-10 to +60℃	Dewpoint measure using chilled mirror principle (with RTD)	20-100% RH at -10+50℃ (gold mirror)	± 1% RH (at +5 to 45℃) and 30-100% RH
III	---			---		HY-Cal Survivor II RH&T sensor IH-3602-C thin film capacitor	0-100% RH at 0 + 85℃ CMOS cirquit	± 2% RH (at 25℃) Total accuracy
IV	Panametrics MC-series probe (will work at 0 + 50℃)	?	?	MC-P MC series	0 + 50℃ and 0-100% RH	a) Panametric MinCap2 thin film polymer capacitor	5-95% RH at -40 +180℃	Linearity ± 1% RH (Typical)
						b) HybridCap (RH&T) with RTD	5-95% RH at -40 +180℃	Linearity ± 1% RH (Typical)

	1. RH & T Probe:			2. RH & T Meter:		3. RH sensor (or RH & T)		
	Type	L (mm)	D (mm)	Type	Oper. range	Type	Oper. range	Accuracy at 90-100% RH
V	Rotronic CP101 probe, works at -5 to 130℉ (-20.5 to 54.5℃) with 10" cable	250	10	a) DV2 indicator (RH&T)	-5 + 55℃	Hygromer C80 capacitive sensor, (contains RTD) with temp. compensation to maintain %RH accuracy	0-100% RH at -20 +55℃	± 2% RH (at 25℃)
				b) Recorder model 222 (RH&T	+5 +43℃			
VI	General Eastern no probes			Model 880 indicator		Bulk polymer resistance sensor - RH-8 (with RTD)	0-99% RH at -40 to +76℃	± 2% RH (at 25° C)) (at 20-95% RH)
VII	EG & G No probes available. All sensors use the NESS Nickel Electroplate mirror. Model 660 can be situated up to 75m. from the meter			a) Model 911 "Dew-All" Analyzer	-50 + 100℃	a) Model 660 Dew point measuring, with mirror (extended range) with PRT (RTD)	1-100% RH at -50 to 100℃	±0.5% RH
				b) Model 300 Microprocessor Analyzer for gases	-75 + 130℃ 0-100% RH	b) Model 911 Dew point meas., with mirror (standard range)	5-100% RH at -40 to 60℃	±0.5% RH
				c) Model 100 Dew Trak Portable Meter	appr. same as above	c) Model 300 Dew point meas., two mirrors, up to 150 extension cable. with RTD (PRT)	0-100% RH at -75 to +75 ℃	±0.5% RH

Table 2.2 Typical concrete mix composition for the use in bridge deck overlays (provided by INDOT)

IT 652
District Construction
District Testing
Project Engineer

YIELD, SLUMP, AND AIR CONTENT REPORT

92 - 0 - 79VV - 40237 (YEAR / FIELD/LAB / SUBMITTER / TEST NO) Contract R 19397

District GREENFIELD
Project No. IM-65-3(258)
Structure No

Plant 1 3VV PARIE KY. AVE (NAME & LOCATION) Type of Mix 1031 CLASS C

Spec 88 (85—1985 SP—SPEC PROV; 88—1988 SUPP SPEC; 86—W/TLY ASH) 10 01 92 (MO DAY YEAR) Purpose 72 (72—JOB CONTROL; 73—INFORMATION; 74—INDEPENDENT ASSURANCE) DESCRIPTION 5 9908

Today's Yardage 30 C (C—cu. yds. conc. Y—sq. yds. conc. L—Linear ft.) Report No

Remarks CLOSE Supplemental to 0

TVR

Material		Type		Source	Basis for Use Number from Approved List		Batch Wts. (lb./Cu. Yd.)
Pozzolan	29		30			11	
Cement	02	0111	03	0002 LONE STAR		14	658
Fine Agg.	04	2123	05	2310 OK SAND & GRAVEL	92 0 3318 17752	15	1251
Coarse Agg.	06	2538	07	2314 MARTIN MARIETTA	92 0 3318 11192	16	1750
Water				28		17	253
Admixture		Type		Product Name	Total Batch Weight (lb./Cu. Yd.)	18	3878
Air Entraining	08	8201 AEA	09	8265 MASTER BUILDERS	Admixtures must be from approved list / Oz. of admixture per 100 lbs. of cement	19	1.20
Chemical	10	8205 RAFARD	11	8266 W R GRACE, 2002		20	3.4
Other	12		13		01		

YIELD TEST		
Station Number		STR#9
Time of Test		0910
Gross Weight (Lb.)	J	
Weight of Container (Lb.)	K	
Net Weight of Concrete (lb.) = J − K =	U	35.75
Container Factor = 1/Vol =	F	4
Unit Weight (lb./Cu. Ft.) = U × F =	A 23	143.0
Relative Concrete Yield = 6/27A =	Y 24	1.008
Cement Content (lb./Cu. Yd.) = C/Y =	N	652

AIR CONTENT TEST	
Station Number	SAME
Time of Test	SAME
Air Meter Used	5047 30 REELS
Mixing Time (Minutes)	
Temp. of Concrete (°F) (1)*	
Percent of Air Gross	7.8
Agg. Correction (%)	0.3
Percent Air-Net 25	7.5

Comments: STR CONCRETE

SLUMP TEST		
Station Number		SAME
Slump (2)*	26	2.75

AGGREGATE PROPORTIONS	
Fine Aggregate %	41.7
Coarse Aggregate %	58.3

Water/Cement Ratio in lb./lb. (3)* 27 .

BASE 1 BASE 2 BASE 3 — K1Z8 RM AUTHORITY

Percent air content specified 3-Yes 4-No 71 4

Foot Notes:* (1) Disregard temperature if the Percent of Air-Net is within the Specified Range.
(2) Slump should be measured to the nearest 0.25 inch.
(3) If Water/Cement Ratio is reported attach Form IT 628

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Starting at the age of 14 days, the concrete was subjected to moderate heating for two days, while the specimen was mounted on top of a plywood box with four 90 watt light bulbs as the heat source. Then the heating was stopped, and the box was mounted on top of the specimen surface Thus, the heat was applied above the concrete. In eight days, the box was removed, and the specimen was cooled until the concrete temperature equilibrated with the ambient laboratory temperature. The %RH and temperature measurements have been taken periodically.

At this stage of the testing procedure, the %RH was measured by a HMP-36 probe with a Humicap capacitor type RH sensor. Temperature of the powder, and of the air inside cavities, was measured by the same probe.

The second concrete specimen was cast with different capacitance and resistance sensors embedded in its bottom part, close to the steel form (Fig. 2.6). Readings of %RH were taken using these sensors, and by HMP-36 probe following the concrete powder preparation procedure.

2.3 Results

2.3.1 Techniques of %RH measurements

situated in

The %RH values inside the concrete specimen, obtained by the Hy varied in a prefabricated cavities of the 1st specimen, were similar in all 4 cavit depend on the relatively narrow range between 95%RH and 98%RH. These vities were drilled orientations or on the depths of these cavities. However, when in the same specimen and the %RH of the concrete powder was measured outside in a sealed container, quite different results were obtained (Table 2.3).

Table 2.3 The %RH profile in concrete at the end of curing period

Depth (inches)	Relative Humidity, %	
	Powder out of the cavity (in sealed container)	Inside the cavity
1	81	---
2	87	---
3	47	---
4	79	94
5	77 78 82	96 98 98

At the depth of 4-5 inches, measurements were taken by drilling additional cavities; the results are also shown in Table 2.3. As a rule, the %RH above the powder was lower than the %RH measured in the cavity, which implies that significant loss of moisture occurred in a short time of about half a minute, before the powder was sealed in the container. This could take place if the powder temperature changed, inasmuch as the temperature factor strongly affects the relative humidity. Indeed, a fast temperature decrease was observed during the powder sampling tests, as shown below:

A	B	C	D	E
The drill bit, when drilling	The cavity, immediately after drilling	The cavity, 1-2 min after drilling	The powder in the container, 1-2 min after drilling	Ambient temperature in the lab
Above 212°F	162°F	95°F	79°F	72°F

The temperature in the cavity could become high during drilling, but could drop quickly after that. For the powder collected out of the cavity, the rate of cooling should be even higher. The increase of the surface area of solids, when the concrete was crushed into powder, also could cause loss of moisture. Therefore, the results shown in Table 2.3 for the powder taken out of the concrete might be incorrect.

On the other hand, the %RH values obtained by the HMP36 probe situated inside the cavities could be incorrect either. The nature of moisture is such that it tends to move through the concrete towards the surfaces. The temperature rise may accelerate this movement so that the %RH in the cavities can become significantly higher then in the mass of the concrete. This suggestion was proved by the %RH measurements taken when the specimen was heated.

Table 2.4 The %RH profile in concrete, obtained when the specimen was subjected to heating

Depth (inches)	Relative Humidity, %	
	Powder out of the cavity (in sealed container)	Inside the cavity
1	7	---
2	70	100
3-4	75	100
5	70	102 101 103

These results, as measured by the %RH sensor mounted on the HMP-36 which is situated in the cavity, indicate that the water vapor pressure in that cavity has reached the saturation level. This might not correlate with, i.e. could be higher than, the real moisture content or %RH in concrete. Similarly, the results obtained inside the cavity without heating the specimen ,shown previously in Table 2.3, also could be incorrect. That is, the %RH values measured inside cavities could be higher than they normally should be in the concrete mass.

The third possible way of taking RH measurements in concrete was by means of capacitance sensors embedded in the mass of concrete. Three of such sensors, representing the major types available in the market were tested, as shown in Fig. 2.6. The results obtained in the curing period indicated that the relative humidity was RH>100%, as it probably should be in a water saturated system. Some of the results could not be properly interpreted. The application of embedded capacitance sensors for air dry concrete may be more successful, however it requires considerable experimental work on establishing their suitable parameters, calibration and measuring procedures, etc. This task is, of course, out of the scope of the current research project.

2.3.2 Relative humidity versus moisture content

As shown in the previous section, the measurements of %RH in concrete meet considerable difficulties. The presence of water or moisture in the pore system implies that %RH in any small space (or in a void) should be high and should tend to reach values, higher than 70-80%RH. These values may be even close to 100%RH. The accuracy of %RH sensors available is relatively low (±2-3%) when the expected values of %RH are higher than 70-80%. The processes leading to the deterioration of concrete due to freezing and thawing require the presence of water, or moisture, in concrete. This can be true for several other processes affecting the durability of concrete, such as alkali-aggregate reaction, etc. Therefore the correlation between the actual moisture content and the results of %RH measurements can serve as a valuable parameter.

The following test has been carried out in order to clarify the character and the range of correlation between a given moisture content and a corresponding %RH. The technique used for this test was the same as in the case of taking %RH measurements above a powder sample situated in a sealed container (Fig. 2.5).

Eight powder samples, each prepared with a given water content, have been tested for %RH in the sealed container shown in Fig. 2.5. The percentages of water content were chosen so that their range (between 0% and 8% by weight) was covering the typical moisture content in hardened concrete. The results of this test are shown in Fig. 2.7. The correlation curve obtained here can be divided into two major sections:

- at the first section, a very wide range of %RH (20% to 85%) corresponds to a very low moisture content (up to 1%);
- in contrary to that, at the next sction, the %RH increased in a narrow range from 86% to only 90%, although corresponding to a very wide range of moisture contents (between 1% and 8%).

Taking into account that the moisture contents in air dry concrete, as well as in water saturated concrete, usually are more than 1-2%, one could conclude that the correlation between %RH and moisture content for these concretes might be not quite satisfactory. The difference obtained between the lowest (86%) and the highest (90%) values of %RH is 4%. Actually, it is similar to the range of accuracy (±3%) of an RH sensor at high %RH levels. These findings imply that %RH measurements taken alone, without a justification of results by means of alternative techniques, might not represent a real mousture condition of concrete. Thus, it can be suggested that a direct measurement of the moisture content in concrete, taken along with the measurement of %RH, can serve as a valuable tool. These results have been reported at the ACI Fall 1993 Convention in Minneapolis (4).

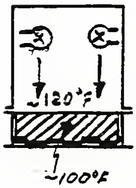
2.3.3 Conditioning the concrete to different moisture contents

Prior to the conditioning, the concrete was wet cured and so it was moisture saturated. The purpose of conditioning was to reduce the moisture content to a required level by means of drying. Two possible ways of conditioning the concrete to a required moisture content have been developed and compared, using a plywood box with four 90 watt light bulbs as a heater(Fig. 2.2). At first, the box was situated on top of the specimen, thus imitating a natural in-situ situation where the bridge decks are heated by the sun radiation (Fig. 2.2). Then the specimen was put on top of the box, so that the moderate heat affected the bottom surface of the specimen. In both cases, the measurements of %RH were taken periodically, indicating changes in the moisture state of the concrete. The results are shown in Table 2.5 and in Table 2.6. Each value of %RH was obtained by drilling the concrete and taking a measurement above the powder situated in a sealed container, as shown in Figs. 2.4, 2.5.

Apparently, the evaporation of moisture took a very long time when the concrete was heated at the top surface of the specimen (Table 2.5). This technique was considerably less efficient, in comparison with the results of heating the bottom surface of the specimen situated on top of the box 2.6). On the other hand, heating the bottom surface did not represent the in-sity situation.

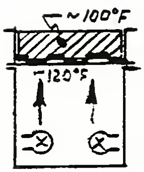
The optimum way of conditioning the concrete could be, therefore, by heating both top and bottom surfaces simultaneously. That's how the conditioning has been done in this project (see the description in the next chapter).

Table 2.5 Conditioning (drying) the concrete by heating its top surface



Depth (in)	%RH (powder sampling)		
	Before heating	In 2 weeks	In 6 weeks
1-2	94	73	86
2-3½	94	91	85
3½-5	94	97	91

Table 2.6 Conditioning (drying) the concrete by heating its bottom surface



Depth (in)	%RH (powder sampling)	
	Before heating	In 2 days
1-2	84	74
2-3½	83	72
3½-5	82	73

2.4 Summary

A. The moisture content of concrete can be controlled as the moisture evaporation out of concrete can be accelerated by moderate heating of the specimen. When a constant heat is applied, the duration of heating (until certain reduction of %RH is achieved) depends upon the following factors:

a. specimen volume and geometry;

b. concrete porosity, or its initial water-cement ratio.

Regarding a relatively large size of the specimens used in this project and a low water-cement ratio of concrete (w/c=0.4), the reduction of moisture content, forced by heating, can take a long time. From this point of view, heating the concrete bottom surface can be more effective than heating its top surface. However, the latter way, i.e. heating the top, can better represent the real situation of the bridge decks. Both ways can be applied simultaneously.

B. None of %RH measurement techniques available for the use in this project can provide sufficient accuracy needed for controlling the heating procedure. Thus, it is not possible to reach and maintain different levels of %RH in different concrete specimens. Also, the interaction between the temperature distribution and moisture profiles in concrete can make this task difficult.

C. Although each of the %RH measurement techniques has its own disadvantages, some of them can be used for indicating the extreme conditions of the concrete specimens, such as "wet" and "dry". This can be done by taking %RH measurements using a Vaisala HMP-36 probe situated above the concrete powder in a sealed container, along with direct moisture content measurement. This technique may be more efficient when applied for the field evaluation of the wetness of real concrete bridge decks.

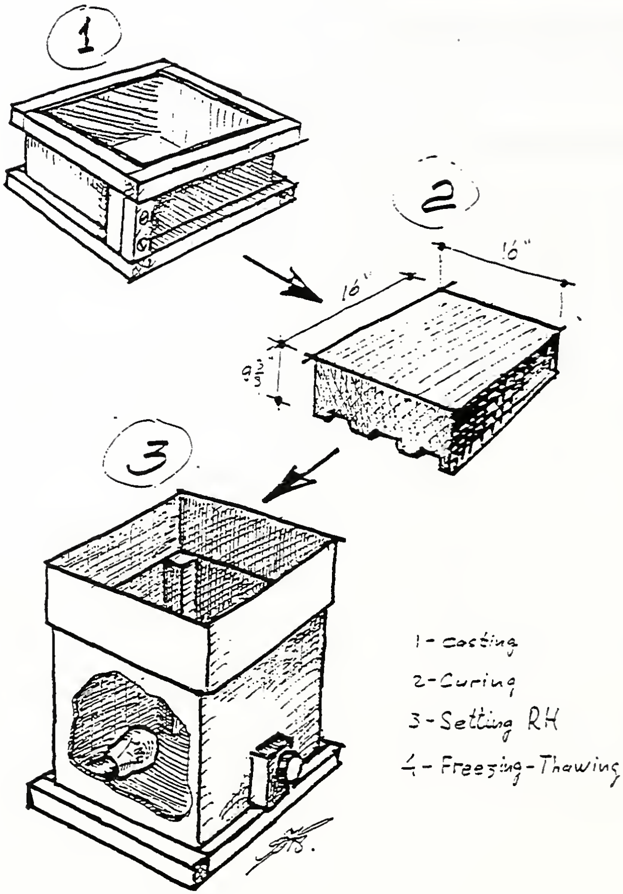


Fig. 2.1 Suggested specimen size for preliminary tests, and concrete heating technique

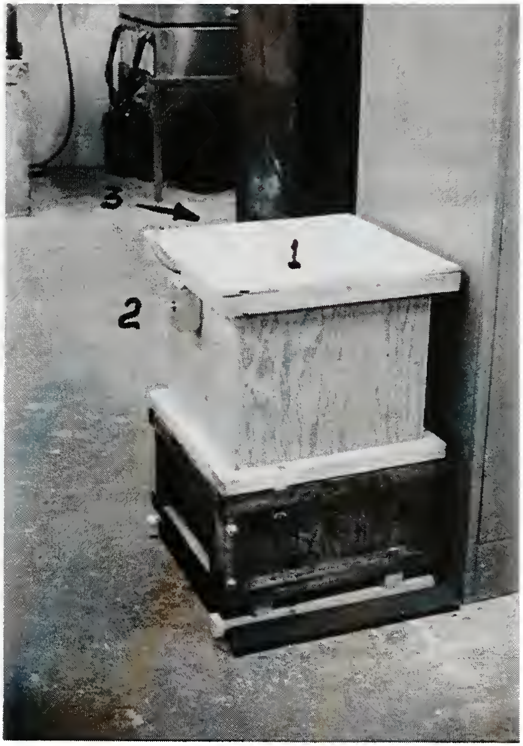


Fig. 2.2 A concrete slab specimen heated at the top surface:

1 - "heater", a plywood box with four 90w light bulbs mounted inside;

2 - dimmer used for controlling the temperature inside the box;

3 - thermometer (not visible).

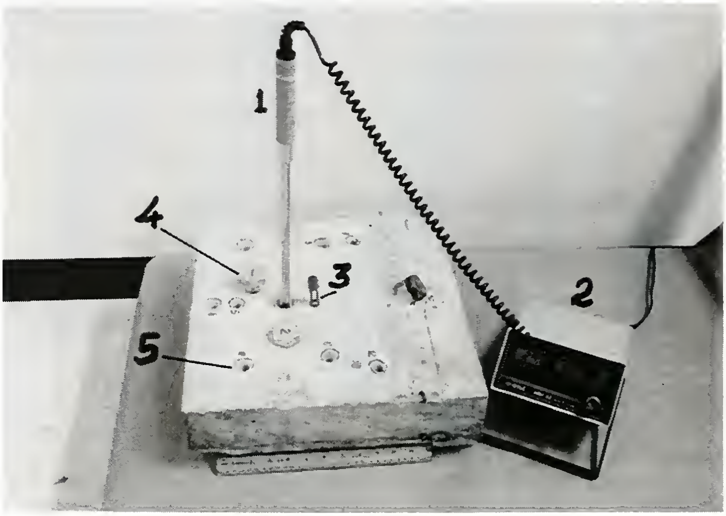


Fig. 2.3 Measurement of %RH in a prefabricated cavity, within the concrete:

1 - relative humidity and temperature probe HMP-36;

2 - relative humidity and temperature indicator (shows 89.2%RH at 24.1°C);

3 - standard sealing sleeve used to create a sealed space when inserted into a cavity;

4 - nuts used for sealing the prefabricated cavities;

5 - drilled cavities.

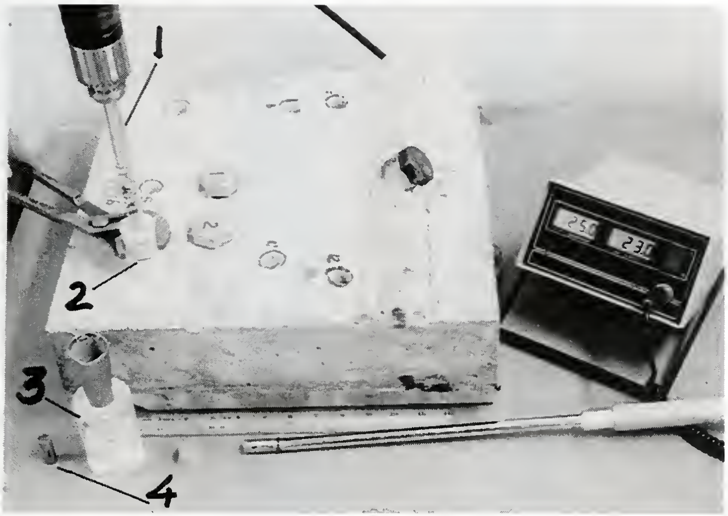


Fig. 2.4 Collection of the powder while drilling a cavity in the concrete:

1 - 5/8" concrete drill bit;

2 - vessel where certain portion of the powder is collected;

3 - container where the powder is sealed;

4 - protective cap designed to fit the relative humidity and the temperature probe; the cap provides efficient sealing of %RH and T° sensors in the container, above the powder sample.

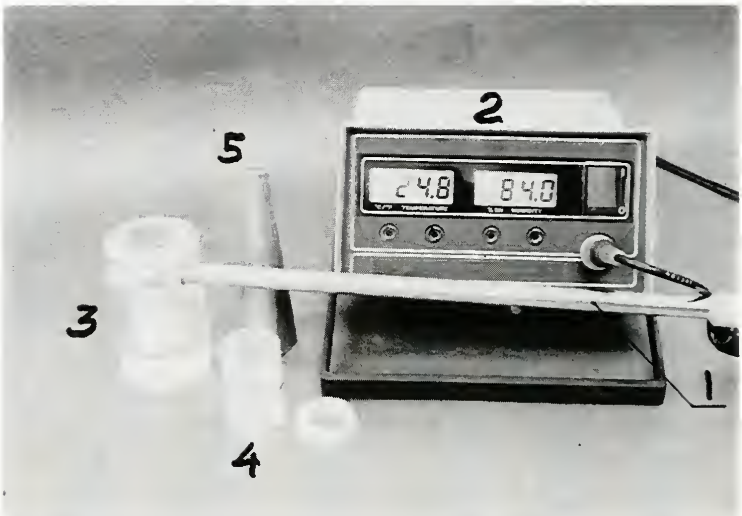


Fig. 2.5 Measurement of %RH above a sample of the concrete powder in a sealed container:

1 - relative humidity and temperature probe HMP-36;

2 - relative humidity and temperature indicator;

3 - sealed container with the powder sample;

4 - vessel where the powder was collected;

5 - paper cone used for transferring the powder into the container

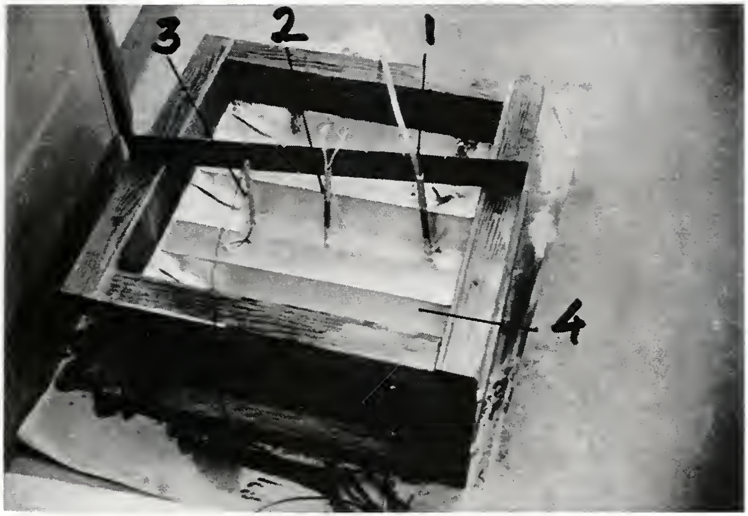


Fig. 2.6 Situation of capacitance type %RH sensors in the mold prior to casting the concrete specimen:

1 - Survivor II® %RH & T sensor;

2 - MiniCap-2® %RH sensor;

3 - %RH sensor made at Purdue;

4 - fragment of a corrugated galvanized steel deck form.

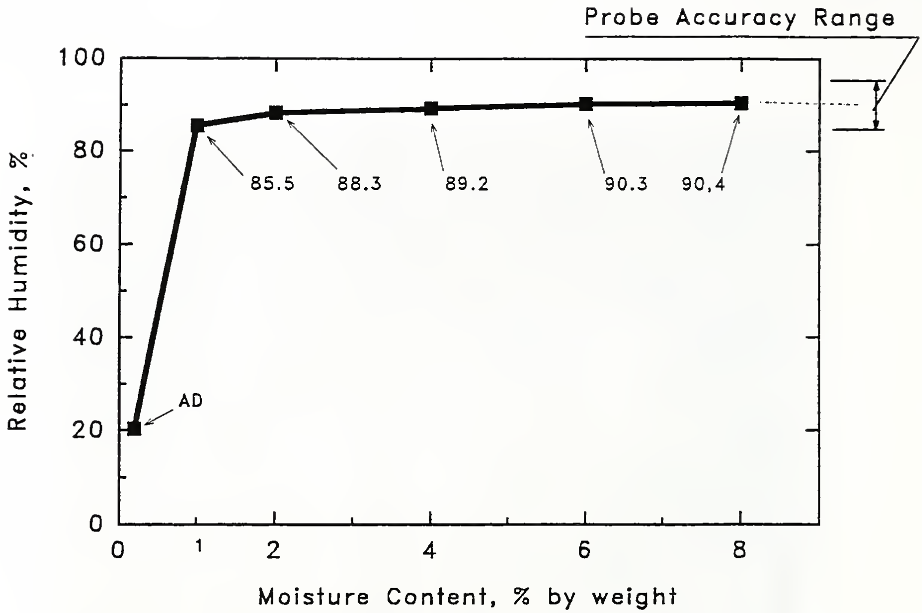


Fig. 2.7 Correlation between %RH and typical moisture contents of concrete

SECTION 3

FREEZING-AND-THAWING TESTING OF LARGE CONCRETE SLABS

3.1 Introduction

The experimental program described in this section has been worked out based on extensive preliminary testing (Section 2). The results of the preliminary tests have been reported to INDOT, and the general purpose of the experimental program was established during the advisory committee meeting held on March 15, 1993.

Several experimental problems reported at that meeting have been resolved during the preliminary testing. However, additional problems appeared when the freezing-and-thawing test was started. These problems referred mainly to the duration of the freezing-and-thawing cycles, which was extremely long: one cycle took 42 hours, i.e. approximately half a cycle per day in contrast to 3-4 cycles per day required by the conventional ASTM C666 Procedure "A".

This program was activated on April 29, 1993. The freezing-and-thawing test started on September 2, 1993, after the desired conditioning of the specimens for the moisture content was achieved. By December, 1994, 221 cycles have been performed. Only a few signs of minor damage have been observed, taking place only in the water saturated slabs. It should be mentioned, however, that despite the duration of this program was very long (about a year and a half), the program posesses a considerable advantage, that is modelling the real situation.

3.2 Experimental program

Twenty 22¼" x 17¼" x 5¼" concrete specimens, actually slabs, have been cast at Purdue University on April 29, 1993. The concrete was supplied by the IMI batching plant in West Lafayette, IN. The mix design was provided by INDOT. The coarse aggregate was supposed to be susceptible to D-cracking. The concrete mix composition is given in Table 2.2 (section 2). The concrete delivery ticket is attached (Appendix A).

One day after casting, ten slabs were demolded, and the steel deck forms used as the bottom part of the molds were removed. All the slabs, i.e. ten with and another ten without steel deck forms, were then subjected to wet curing for three weeks. After curing, the slabs were divided into three groups, to be conditioned to different moisture contents in accordance with the experimental program (Fig. 3.1):

Group 1 - WET (water saturated) slabs;

Group 2 - DRY (dried by moderate heating) slabs;

Group 3 - AIR DRY (air cured) slabs.

Six slabs were demolded and immersed in water saturated with lime at 70-72°F to form Group 1. Three of these slabs were without steel deck forms. Another six slabs were kept in the molds, while their top and bottom surfaces were subjected to a moderate heating, as shown in Fig. 3.2, to form Group 2. The heating procedure, developed as result of preliminary testing described in Section 2, was applied for this purpose. The air temperature near the top and the bottom surface of the specimens was maintained at 140-150°F and 165-175°F, respectively. Air flow was provided near the top surface of the specimens (Fig. 3.3). Three of these specimens were with steel deck forms, and three others were without steel deck forms.

Eight slab specimens of Group 3 were subjected to ambient conditions in the concrete lab, as shown in Fig. 3.2. Four of these specimens were with steel deck forms, and four others were without the forms.

Along with large slab specimens, eighteen 3" x 6" concrete cylinders were prepared and conditioned, forming the same three groups, i.e. wet, dry (heated) and air-dry. Part of the cylinders have been tested for the compressive strength prior to the freezing-and-thawing test. The following results have been obtained:

Group 1 (wet) - 5930 psi.

Group 2 (dry) - 4060 psi.

Group 3 (air dry) - 5820 psi.

The duration of conditioning, prior to the freezing-and-thawing test, was subject to the requirement of achieving the lowest possible moisture content in concrete by means of heating. The conditioning period lasted seven weeks, probably due to the large volume and thickness of the specimens. At the completion of heating, the lowest moisture content in the concrete (Group 2) was approximately 0.9%. The average moisture contents in the wet (Group 1) and in the air-dry concrete specimens (Group 3) were 7.0% and 3.1%, respectively. The moisture content was determined by oven drying the fragments of fractured concrete cylinders at 105°C during 7 days.

The conditioning of all the slab specimens was stopped when the moisture content of the heated slabs reached the level of 0.9%. By the same time, the preparations of the freezing-and-thawing chamber for conducting the test had been completed. These included the installation of 12 thermocouples, their connection to the temperature indicator, and the temperature calibration. The chamber is computer operated (Fig. 3.4). A group of devices, including the temperature indicator, was mounted outside the chamber for this project.

Prior to the freezing-and-thawing test, the reference pulse velocity measurement was taken for all the slabs. For each slab, five measurements of pulse velocity were taken (Fig. 3.5). The results of these measurements, as well as the results of the measurements taken later on during the freeze-thaw tests, are collected in Appendix B.

3.2.1 Freezing-and-thawing Cycles

The moisture conditions achieved for the three groups of slab specimens have been considerably different (0.9%, 3.1% and 7.0% for dry, air-dry and wet specimens, respectively). This implied different durations of freezing-and-thawing cycles, which also might be very long. However all the slabs were situated in the same chamber, each group had to be isolated. After a few unsuccessful attempts to seal the wet and the dry slabs, an epoxy based coat (HorseySet WDE) was applied. This coat has provided sufficient protection of the dry slabs from wetting and of the wet slabs from drying, resulting in considerable shortening of freezing-and-thawing times. However, these times were still significantly longer than the time required for freezing-and-thawing of normally used 3"x3"x12" specimens. The situation of the slab specimens in the freeze-thaw chamber is shown in Fig. 3.6.

Amongst the three groups of specimens (i.e. dry, air-dry and wet), the wet specimens required the longest freezing-and-thawing cycles. The shortest freezing time established for these specimens was 18 hours, and the shortest thawing time was 24 hours. Consequently, the shortest possible freezing-and-thawing cycle was 18+24=42 hours, because all three groups of slab specimens were treated in the same chamber. Under these circumstances, the rate of the test was 4 cycles a week. The weekly freeze-thaw chart is shown in Fig. 3.7.

3.3 Results

The measurements of pulse velocity were taken in the freeze-thaw chamber approximately every 30 cycles, that is once in 7½ weeks. Any visible signs of deterioration such as cracks, have not been observed on any of the slab specimens at 131 cycles, except for a single aggregate grain popout. This popout has occurred in November, 1993, on the top surface of a water saturated slab marked 5W.

Only a minor damage was indicated at 131 cycles in dry slabs (Group 2) and in air dry slabs (Group 3), with or without steel deck forms. This was true also for most of the wet (moisture saturated) slabs of Group 1. Considerable damage has been indicated, however, in wet slabs with steel deck forms. At 221 cycles, the average reduction of square relative pulse velocity in these slabs (3W, 4W, 6W) was 37.6%. The most severe damage occured in the slab marked 3W. In this slab, the reduction of square pulse velocity was 43.8%.

The percentages of square relative pulse velocity reduction in all three groups of slabs after 221 freezing-and-thawing cycles are shown hereby.

Group 1: WET (water-saturated) slabs

- with steel deck forms: 37.6%;
- without steel deck forms: 16.2%.

Group 2: DRY (dried by moderate heating) slabs

- with steel deck forms: 6.5%;
- without steel deck forms: 3.3%.

Group 3: AIR-DRY (air-cured) slabs

- with steel deck forms: 5.9%;
- without steel deck forms: 7.9%.

The square relative pulse velocity curves for the Groups 1, 2 and 3 are given in Figures 3.8, 3.9 and 3.10, respectively. The relevant measurements, taken at 0, 5, 31, 51, 71, 101, 131, 161, 191 and 221 freeze-thaw cycles, are collected in Appendix B.

The saturated condition of wet slabs was maintained by wetting their top surface periodically. These slabs were covered by wet burlap sacks sealed with plastic sheets and silicon rubber. The moisture condition of dry slabs was measured periodically by a %RH probe inserted into a cavity drilled in the slab marked 1H. The relative humidity measured in that slab at 5 cycles was very low (26.1%). At 131 cycles it was very low as well (32%RH), although showing a tendency to increase slowly. At 211 cycles, the %RH registered in the same slab was 52.5%. However relatively high, this level should still correspond to a very low (less than 2%) moisture content in concrete.

3.4 Summary

Freezing-and-thawing test of large slab specimens is a long term procedure. The rate of cooling, as well as the rate of thawing, is very low mainly because of the large specimen size, but it could be affected also by other factors, such as the large volume of the chamber. The completion of this test requires another 79 freeze-thaw cycles to be carried out, however the results obtained so far are clear enough.

Considerable damage of concrete is indicated, in terms of square relative pulse velocity, in the water saturated slabs (Group 1, WET). The average percentage of the square relative pulse velocity reduction in these slabs was significantly higher than in two other groups of slabs (Group 2, DRY, and Group 3, AIR DRY).

As is noticed, the largest drop of square relative pulse velocity has occurred in water saturated slabs with steel deck forms. This supports the suggestion that more water can be accumulated in the bottom part of the slabs with steel deck forms, than in the slabs without the forms, thus indicating the negative role of the forms.

The changes of square relative pulse velocity indicated the damage of the slab specimens, i.e. certain reduction of the relative dynamic modulus of elasticity E_d has occurred. Although, no visible signs of damage has been observed.

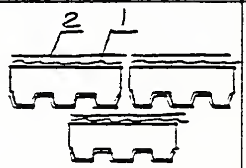
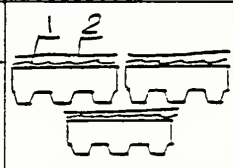
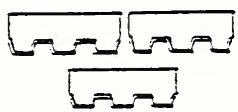
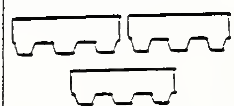
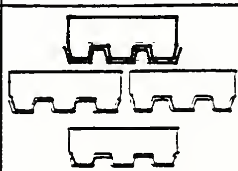
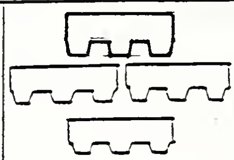
Specimens subjected to freezing-and-thawing:	with steel deck forms	without steel deck forms	Compressive strength (3" x 6" cylinders)
1. Water Saturated			6
2. Dried by Heating			6
3. Air Dried			6
Total	10	10	18

Fig. 3.1 Three groups of 22¼ x 17¼ x 5¼ in. concrete slab specimens: 1 - burlap sacks, 2 - plastic covers. Moisture saturated large specimens are sealed at their bottom and side surfaces. Their top surfaces are covered with wet burlap sacks and plastic sheets. The sacks are wettened periodically.

The specimens dried by heating (group 2) are complete sealed at all their surfaces.

The air dry specimens (group 3) are sealed only at their side surfaces.

All the specimens are positioned on the wood bars, so that there is no direct contact between them and the floor of the freezing-and-thawing chamber.

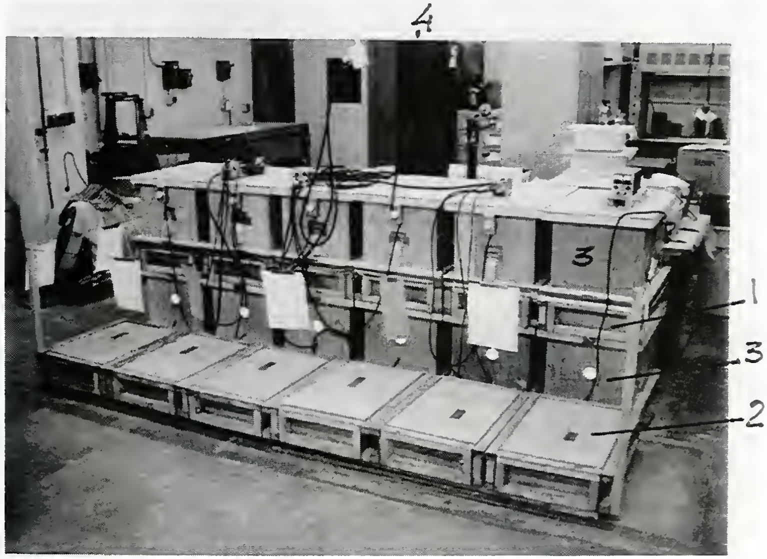


Fig. 3.2 Conditioning of concrete slab specimens in the concrete lab (Purdue Civil Engineering Building):

1 - heated slabs (Group 2);
2 - air-dry slabs (Group 3);
3 - plywood boxes, each containing four 90 watt light bulbs;
4 - dimmers;
5 - thermometers (not shown).

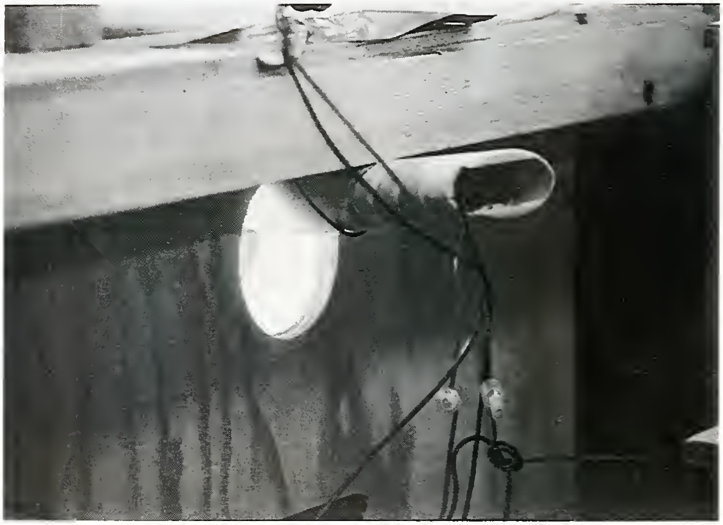


Fig. 3.3 A small fan fixed on the heating box for increasing the air flow above the slab specimen surface.

Each of the six heating boxes mounted on top of the slabs was equipped with a fan. The fans were switched on periodically, by a timer.

Fig. 3.4 Freezing-and-thawing chamber operating post:
1 - computer;
2 - commutator box with temperature indicator connected to the 12 thermocouples.

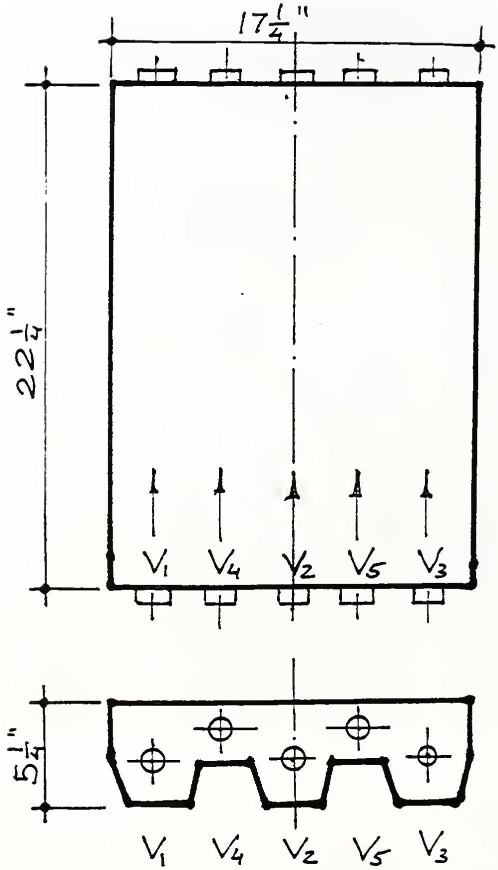


Fig. 3.5 Point of pulse velocity measurements (V_1 through V_5) along a large slab specimen. Indices (1, 2, 3, 4, 5) show the sequence of the measurements.

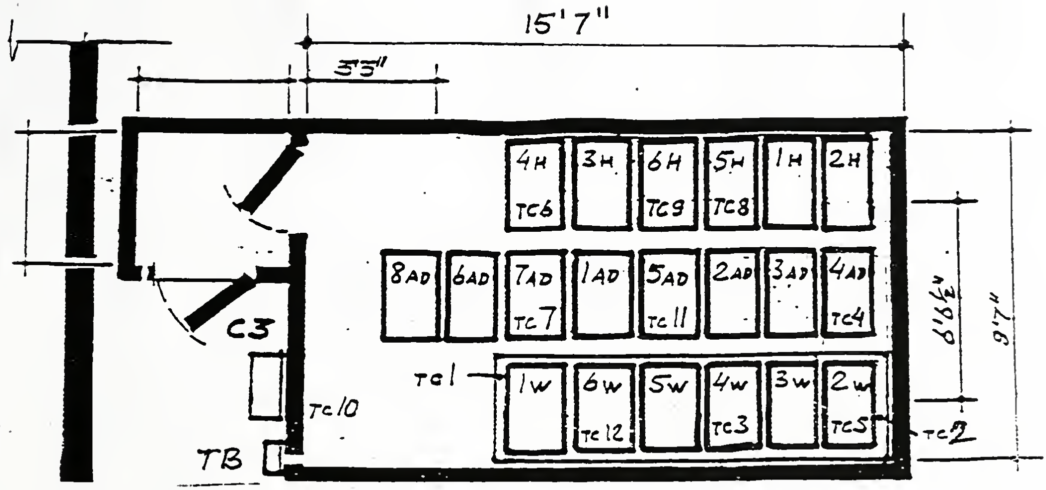


Fig. 3.6 The situation of large slab specimens in the freezing-and-thawing chamber:

1H-6H - heated (dry) slabs;
1AD-8AD - air-dry slabs;
1W-6W - wet (water saturated) slabs;
TC - thermocouples.

For each group, the thermocouples have been embedded in three slabs, as shown. Three thermocouples (TC1, and TC2 and TC10) have been situated in different areas of the chamber. Also shown in Fig. 3.6, are the computer (C3) and the temperature indicator box (TB).

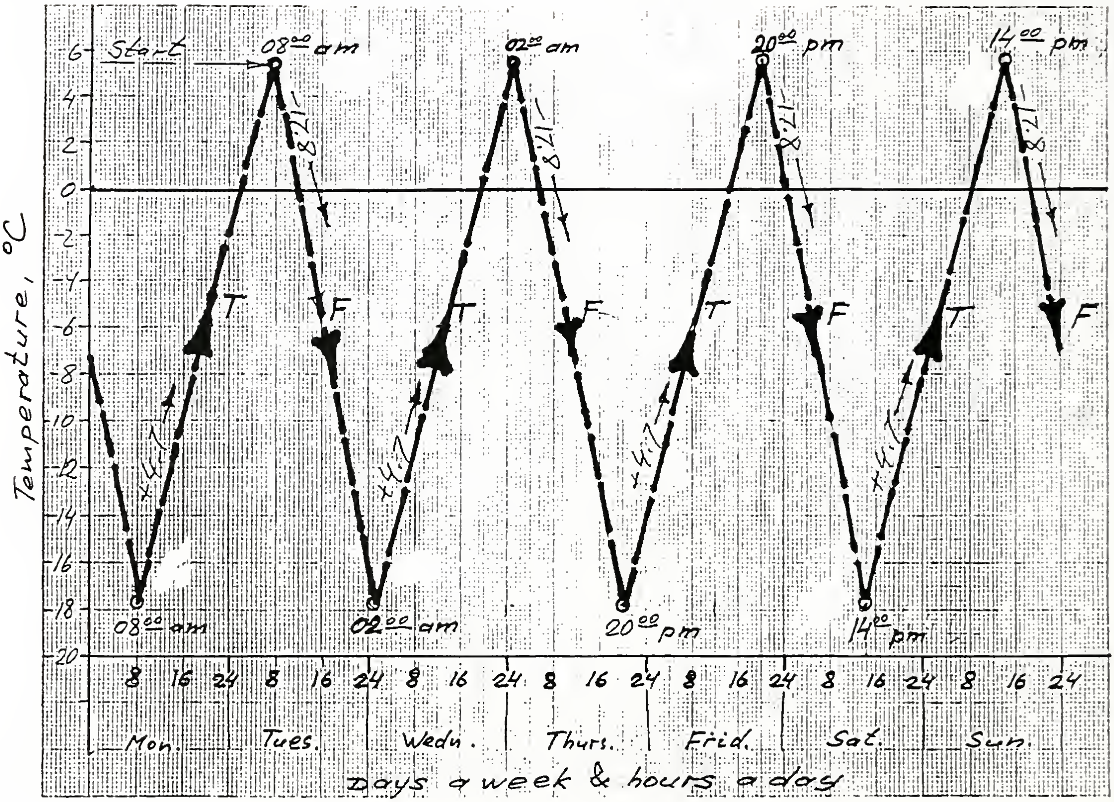


Fig. 3.7 Weekly freeze-thaw chart for the large slab specimens situated in the freeze-thaw chamber:

F - freezing from +4.7°C to -17.8°C;
T - thawing from -17.8°C to +4.7°C.

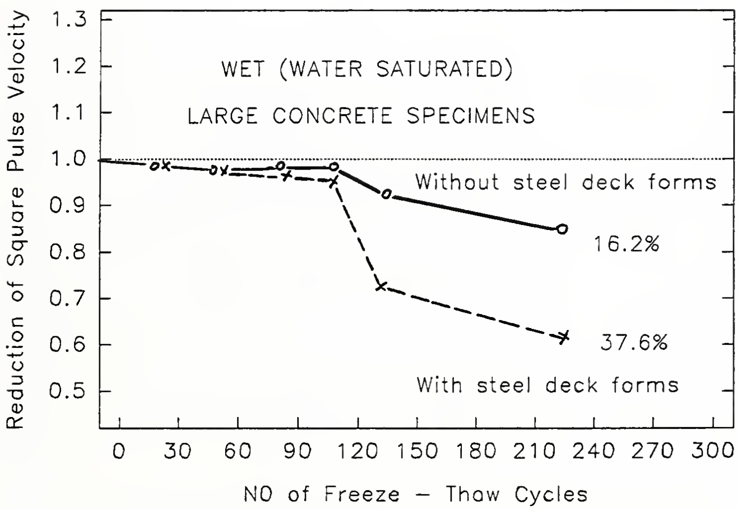


Fig. 3.8 The reduction of relative square pulse velocity in wet (water saturated) large concrete slab specimens after 221 freeze-thaw cycles.

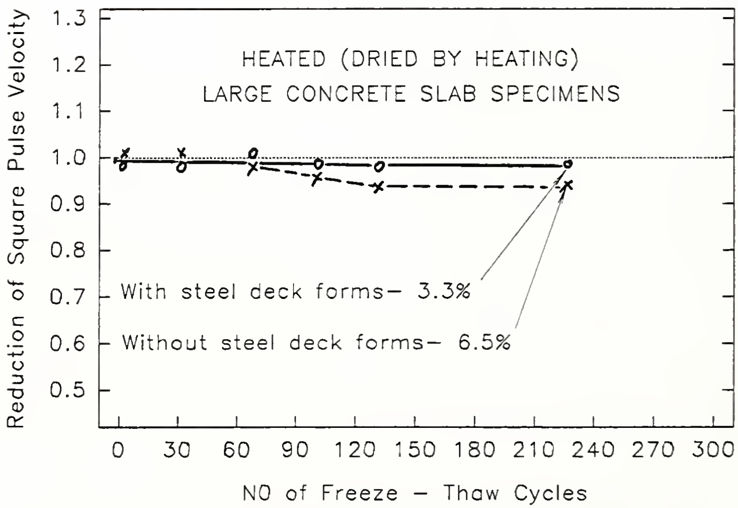


Fig. 3.9 The reduction of relative square pulse velocity in heated (dried by heating) large concrete slab specimens after 221 freeze-thaw cycles.

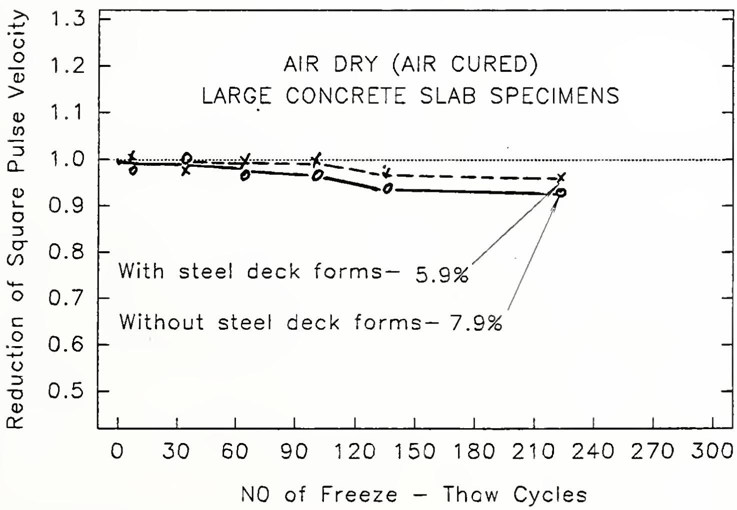


Fig. 3.10 The reduction of relative square pulse velocity in air dry (air cured) large concrete slab specimens after 221 freeze-thaw cycles.

SECTION 4

FREEZING-AND-THAWING TEST

OF 3″×4″×12″ CONCRETE SPECIMENS (EXPANSION-EXTENSION RESEARCH PROGRAM)

4.1 Introduction

This program has been described in the Expansion-Extension Research Proposal submitted to INDOT on September 1993. The proposal was aimed at shortening the duration of the freeze-thaw testing, so that the Task 2 of this project could be completed in a more reasonable time than that estimated for the testing of large slab specimens. For this purpose, the alternative experimental program has been worked out, where small concrete beams should be tested in accordance with the standard ASTM-C 666 procedure.

The alternative program has been completed by the end of May, 1994. The following was done while carrying out that program: (a) designing and making plywood molds; (b) casting 3x4x12 inch concrete beams; (c) preparation of the freezing-and-thawing machine for testing; (d) curing and conditioning of the beams; (e) running 301 freeze-thaw cycles; and (f) periodical testing of the beams each 30 cycles.

4.2 Experimental program

The experimental program included the preparation of sixteen 3"x4"x12" concrete beams, so that the following four groups were formed (see also Fig. 4.1):

1 - four air dry specimens with steel deck forms,

2 - four air dry specimens without steel deck forms,

3 - four water saturated specimens with steel deck forms,

4 - four water saturated specimens without steel deck forms.

All these specimens were of the same shape and size (Fig. 4.1). Wooden molds were constructed so that a fragment of a steel deck form served as the bottom part of the mold (Fig. 4.2). Such fragments were made of the forms used previously for casting large slab specimens, but removed according to the procedure described in Section 3. The molds were designed and built carefully, so that the exact size and shape of the specimens was achieved. Stainless steel pins were used for the concrete expansion measurements. These pins have been precisely situated in the molds and, later on, in the concrete.

The concrete mix was prepared at Purdue. The mix design was same as that used for casting large concrete slab specimens (Section 3), i.e. that provided by INDOT (see Table 2.2, Section 2).

The aggregate for concrete was a limestone, same as the one used previously (Section 3). The susceptibility of the aggregate to D-cracking has been tested by a method developed at Purdue (5),prior to the preparation of specimens. The method is based on the correlation between the aggregate pore size distribution and the freeze-thaw durability of concrete batched with that aggregate. The pore size distribution of four aggregate samples has been determined by MIP (mercury intrusion porosimetry). The Expected Durability Factor (EDF, see ref. 5) has been calculated for each of the samples. The results indicate that the aggregate may promote the damage of concrete and the D-cracking due to freezing and thawing (Fig. 4.3). Total porosity of that aggregate was high (2%), determined by oven drying at +105°C.

The specimens were cast and wet cured in the molds for one day. On the next day, the specimens were demolded, and six steel deck forms were removed. At this step, all the specimens, i.e. with and without steel deck forms, were subjected to moisture curing for one week.

In a week, eight specimens, five of them with steel deck forms and three without, were subjected to moderately accelerated drying (Fig. 4.4) in a small chamber equipped with four 90 watt light bulbs and with a fan (Fig. 4.5). Plywood boxes used for heating of the large slab specimens (Section 3) were taken for assembling the chamber. The drying procedure took another 8 days. The moisture content of the concrete, obtained by that procedure, was 3.9%, determined by oven drying at 105°C. The dried specimens were marked "AD", for "air dry". Another 8 specimens were cured in the moisture room during 15 days. These specimens were marked "W", for "wet". The final arrangement of the specimens is shown in Fig. 4.6.

The freezing-and-thawing machine have been recalibrated. Three additional thermocouples have been installed in the specimens AD-4, W-4 and W5 to provide the efficient control of the freeze-thaw cycles.

When the curing and conditioning procedures were completed, the AD specimens were sealed by HorseySet WDE sealer, applied in 3 layers. The W specimens have been sealed by one layer of that material (Fig. 4.7). In the freezing-and-thawing machine, all but two trays were filled with water. Two specimens (AD-1 and W-8) have been situated in the air, in tray No. 1 and No. 18 (Fig. 4.8). The positioning of the specimens in the freezing-and-thawing machine is shown in Fig. 4.9 and Fig. 4.10.

The number of freezing-and-thawing cycles performed was 301. The following parameters were measured periodically (mostly every 30 cycles):

- specimen weight change (Fig. 4.11);

- specimen expansion , i.e. length change (Fig. 4.12);

- ultrasonic pulse velocity (fig. 4.13).

The weight measurement was aimed at assessing possible weight loss due to scaling of the concrete. It was helpful also in controlling the moisture content of air dry (AD) specimens. Periodically (at 42, 126 and 250 cycles), the AD specimens were removed, dried in the air, and resealed.

The positions of the specimens in the freezing-and-thawing machine were changed periodically, along with the measurements listed above. This was done in order to provide uniformity of freezing and thawing for each specimen (see Appendix C).

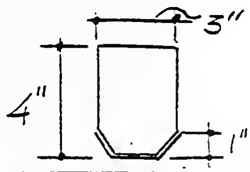
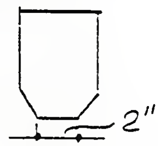
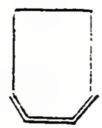
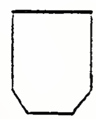
Groups of specimens	Amount	Sketch
1. Air dried, with steel deck forms	5	
2. Air dried, without steel deck forms	3	
3. Wet cured, with steel deck forms	5	
4. Wet cured, without steel deck forms	3	
Total	16	

Fig. 4.1 Experimental program

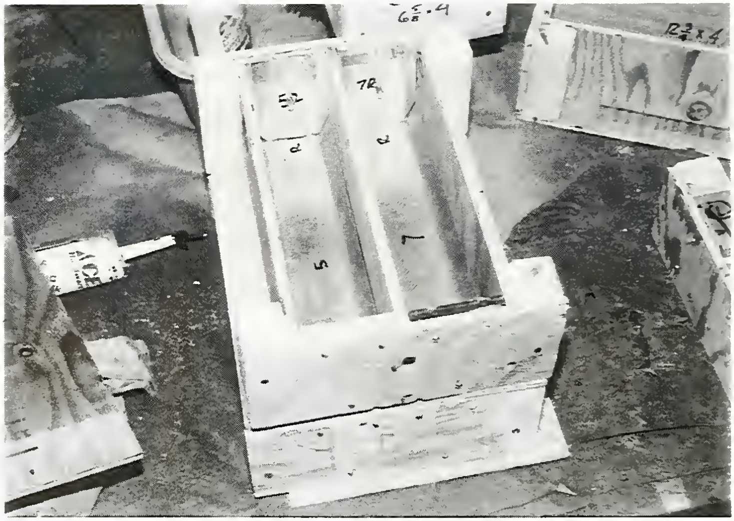
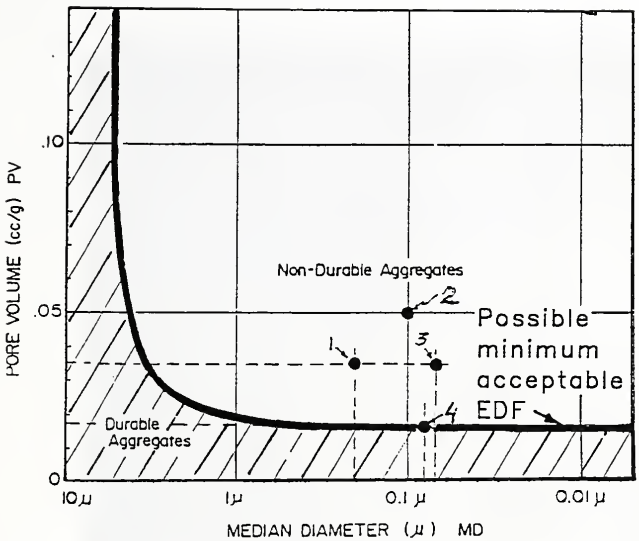


Fig. 4.2 Assembled plywood molds, used for casting 3"x4"x12" concrete specimens.

The fragments of steel deck forms (5,7) have been sealed at the bottom of the mold.



Sample	EDF
1	20.8
2	35.7
3	20.0
4	14.0

Total Porosity:

P=2%

Fig. 4.3 Expected Durability Factor (EDF) of Peru limestone aggregate, according to the method developed by Kaneuji, Winslow and Dolch (4)

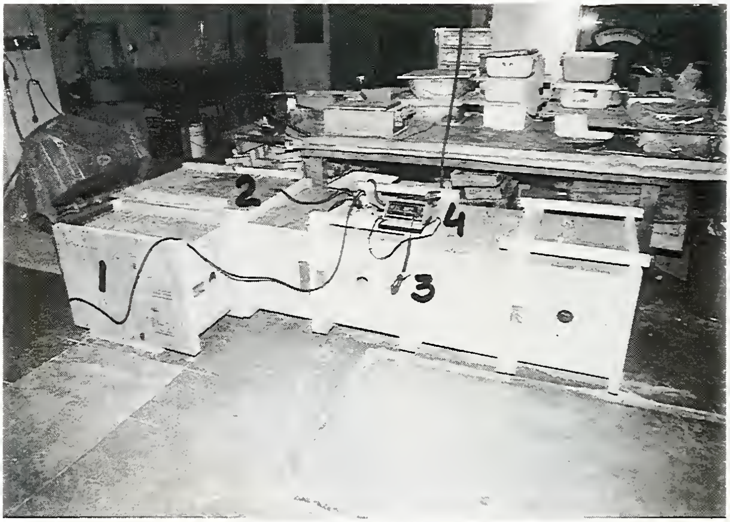


Fig. 4.4 The tunnel assembled for drying out the 3"x4"x12" concrete specimens:
1 - lightbulb box;
2 - position of the fan;
3 - relative humidity and temperature probe;
4 - relative humidity and temperature indicator.

The air temperature in the tunnel was up to 85°F. The relative humidity varied between 8-15%.

Fig. 4.5 The situation of the fan (1) and of the light bulbs (2) inside the drying tunnel. Four concrete specimens (3) can be seen.

Specimen:			Status:			
			in water	open deck	closed deck	no deck
1.		AD-1	X	X		
2.		AD-2	X	X		
3.		AD-3	X	X		
4.	T	AD-4	X		X	
5.		AD-5	X		X	
6.		AD-6	X			X
7.		AD-7	X			X
8.		AD-8				X
9.		W-1	X			
10.		W-2	X			
11.		W-3	X			
12.	T	W-4	X			
13.	T	W-5	X			
14.		W-6	X			
15.		W-7	X			
16.		W-8				

Fig. 4.6 Groups of 3"x4"x12" specimens prepared for the freeze-thaw test: AD - air dried specimens; W - water saturated specimens; T - specimens with thermocouples.

Specimens AD-8 and W-8 have not been immersed in water.

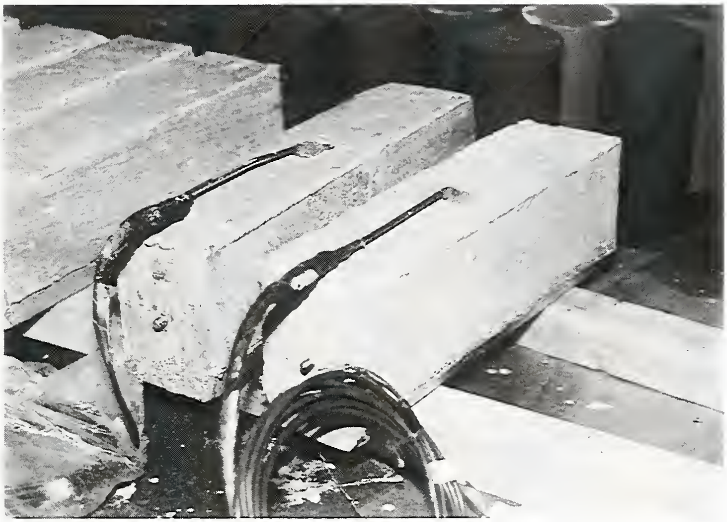
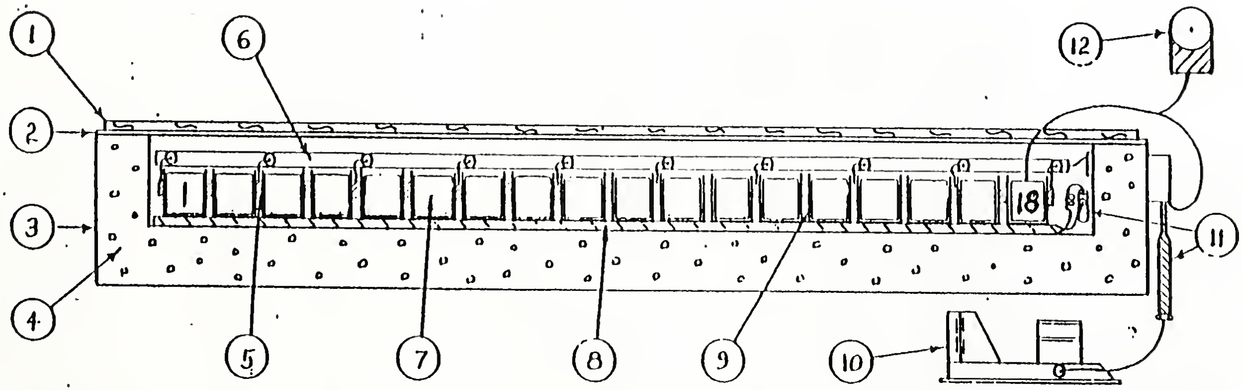


Fig. 4.7 Sealed 3"x4"x12" concrete specimens, ready for positioning in the freezing-and-thawing machine:

1 - steel deck form;
2 - pin for the elongation measurement;
3,4 - thermocouples.



1. Rubber Seal
2. Masonite
3. Sheet Metal
4. Insulation Material
5. Heating Units
6. Electrical Outlet Bar
7. Trays
8. Cooling Plate
9. Specimen Container
10. Compressor
11. Cooling System
12. Temperature Recording Device

Fig. 4.8 Sectional view of the automatic freezing and thawing equipment

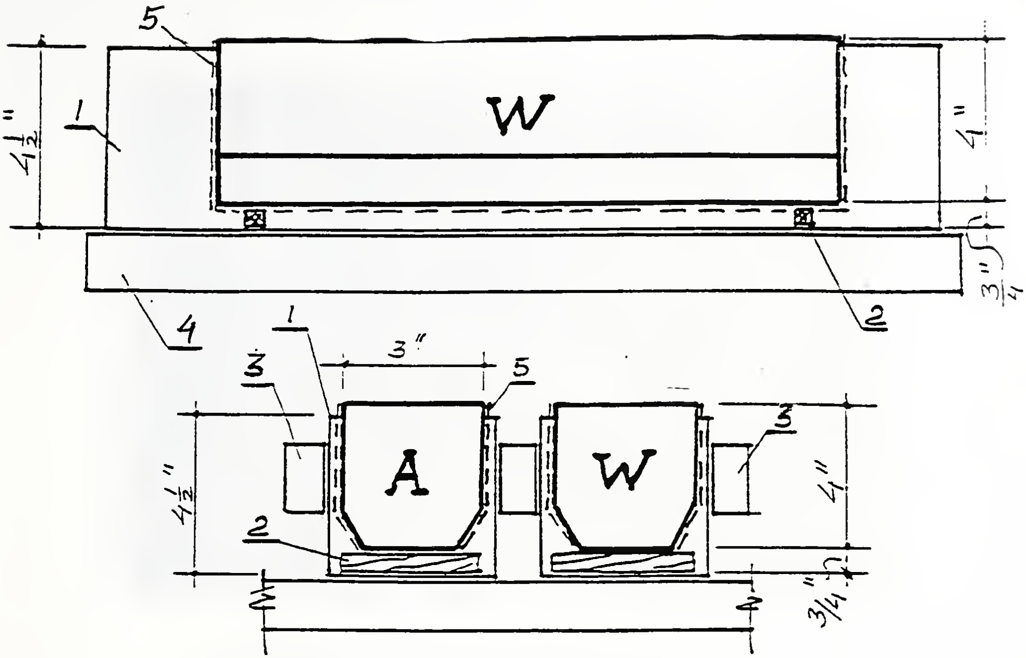


Fig. 4.9 Positioning of 3"x4"x12" specimens in the trays:

A - air dry specimen,
W - water saturated specimen,

1 - tray,
2 - supports,
3 - heating units,
4 - cooling plate,
5 - sealed surfaces (with HorseySet WDE)

Fig. 4.10 Positioning of 3"x4"x12" specimens in the freezing-and-thawing machine

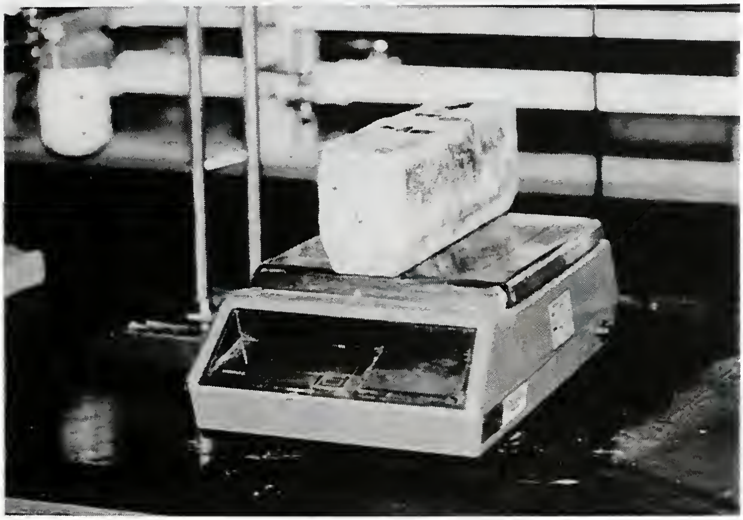


Fig. 4.11 Measurement of the specimen weight

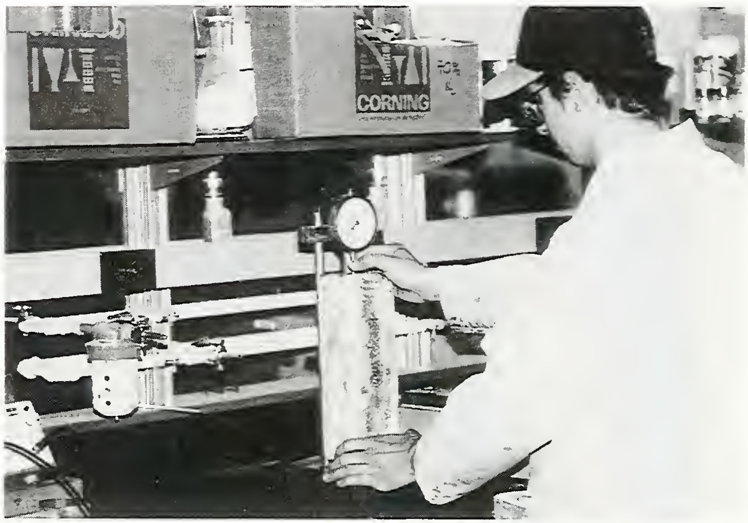


Fig. 4.12 Measurement of the specimen expansion

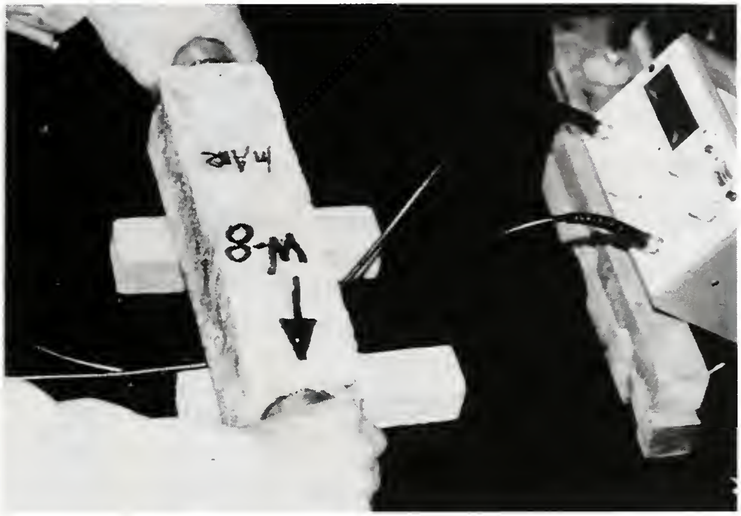


Fig. 4.13 Measurement of ultrasonic pulse velocity

4.3 Results

The results of the measurements listed above are collected in Appendix D. The measurements have been taken from 13 out of 16 specimens, except for those holding thermocouples (AD-4, W-4 and W-5), marked T.

4.3.1 Ultrasonic pulse velocity

Relative square pulse velocity of the ultrasonic wave run along the solid matter is proportional to the dynamic modulus of elasticity E_d of that matter (5). The values of relative square pulse velocity in the concrete specimens have been calculated using the measured pulse time (Appendix D) and knowing the initial length of the specimens. The pulse time has been taken as shown in Fig. 4.13. The following results were obtained.

A. wet (water saturated) specimens:

- the most extensive drop of squared pulse velocity up to 55% (Fig. 4.14);
- more extensive drop of relative square pulse velocity in specimen with steel deck forms (curve D in Fig. 4.14) than in specimens without the forms (curve E in Fig. 4.14).

B. air dry specimens:

- more intensive drop of squared pulse velocity in specimens with steel deck forms (curve A in Fig. 4.15) than in specimens without the forms (curve B in Fig. 4.15).

C. specimens without steel deck forms:

- more severe damage in water saturated concrete (curve E in Fig. 4.16) than in air dried concrete (curve B in Fig. 4.16).

D. specimens with steel deck forms:

- more severe damage in water saturated concrete (curve D in Fig. 4.17) than in air dry concrete (curve A in Fig. 4.17).

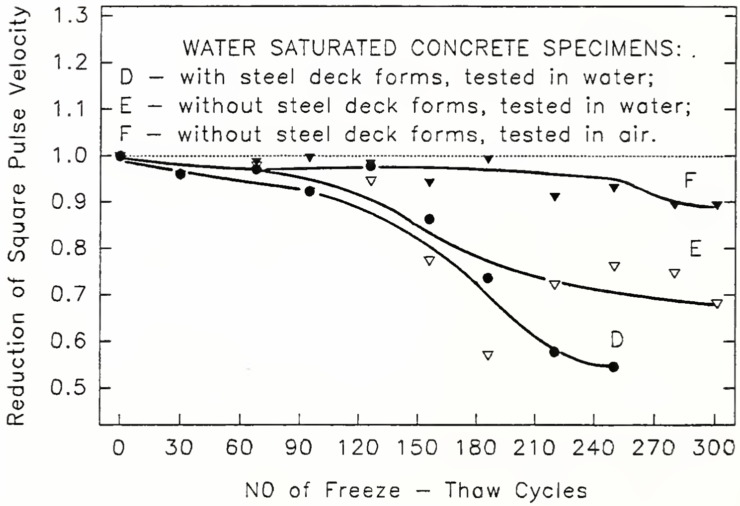


Fig. 4.14 Reduction of relative squared pulse velocity $\left(\frac{V}{V_o}\right)^2$ in water saturated 3"x4"x12" concrete specimens

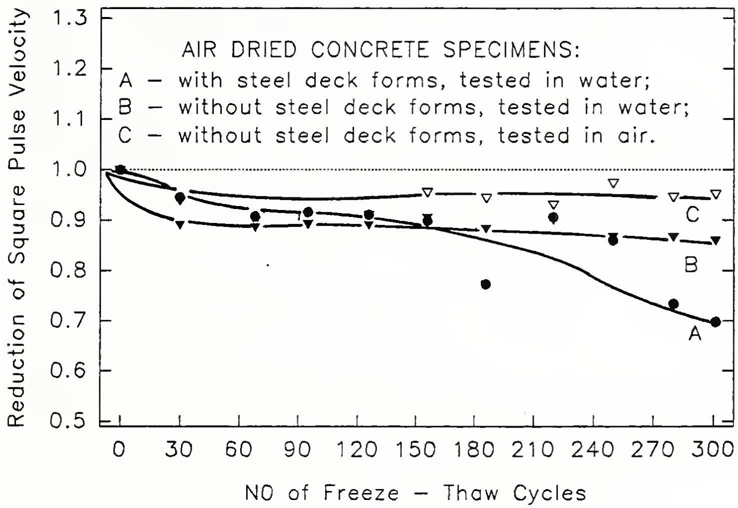


Fig. 4.15 Reduction of relative square pulse velocity $\left(\frac{V}{V_o}\right)^2$

in air dried 3"x4"x12" concrete specimens

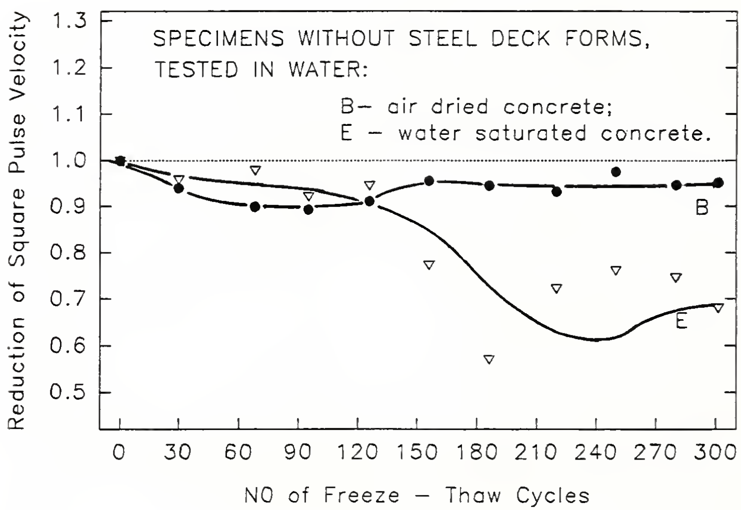


Fig. 4.16 Reduction of relative square pulse velocity $\left(\frac{V}{V_o}\right)^2$

in 3"x4"x12"concrete specimens

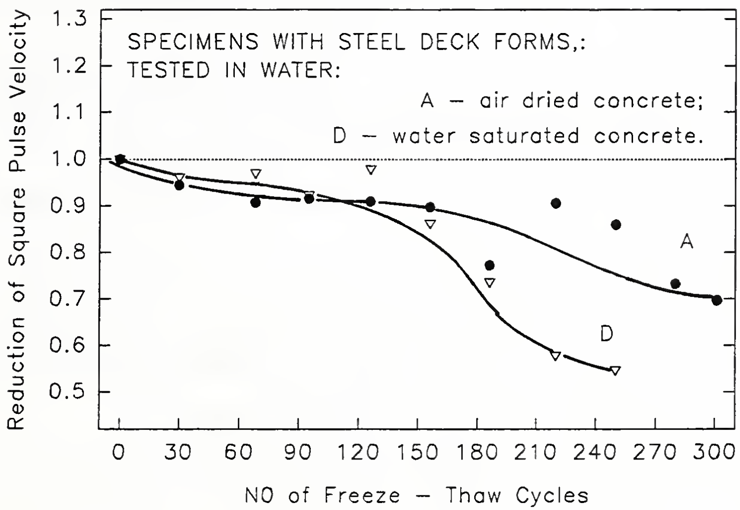


Fig. 4.17 Reduction of relative square pulse velocity $\left(\frac{V}{V_o}\right)^2$ in 3"x4"x12" concrete specimens

4.3.2 Expansion

The measurements of the concrete expansion (the elongation of the specimens) have been taken as shown in Fig. 4.12. The following results have been obtained.

- Air dried specimens with steel forms have been considerably expanded (0.22%). Probably, these specimens have absorbed more water than air dried specimens without the forms (0.02%, see Fig. 4.18).
- Water saturated specimens with steel forms, in which the measurements could be taken as long as the freeze-thaw test run, have expanded to at least 0.25% (Fig. 4.19).
- Severe deterioration was observed in other water saturated specimens with steel forms, and thus the expansion measurements were interrupted at 180-210 cycles (Fig. 4.19).
- The highest values of expansion have been recorded in water saturated specimens without steel forms (0.44% and 0.34%, see Fig. 4.20). However the most severe deterioration took place in these specimens, the expansion measurements still could have been done.
- Destruction of water saturated specimens with the forms occurred mainly at the edges. This explains the reason why the expansion measurements have been interrupted. In contrary, the destruction of water saturated specimens without the forms was spreading along their bottom part (see Section 4.3.3).

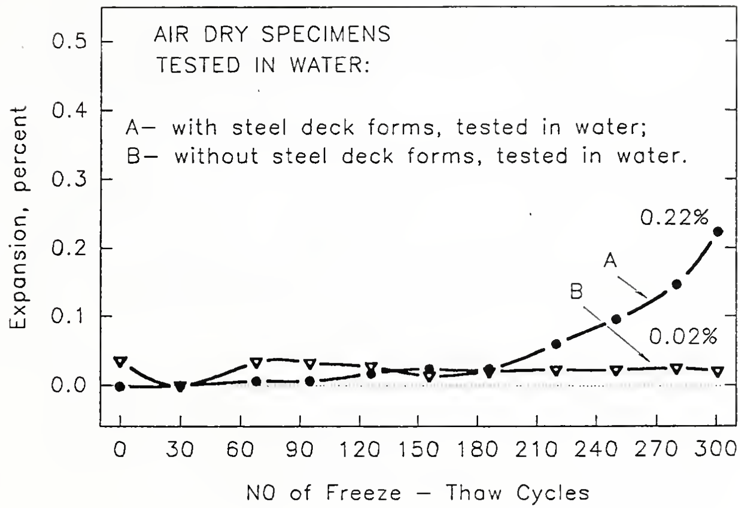


Fig. 4.18 Expansion of air dry 3"x4"x12" concrete specimens, measured during the standard (ASTM C-666) freeze-thaw test

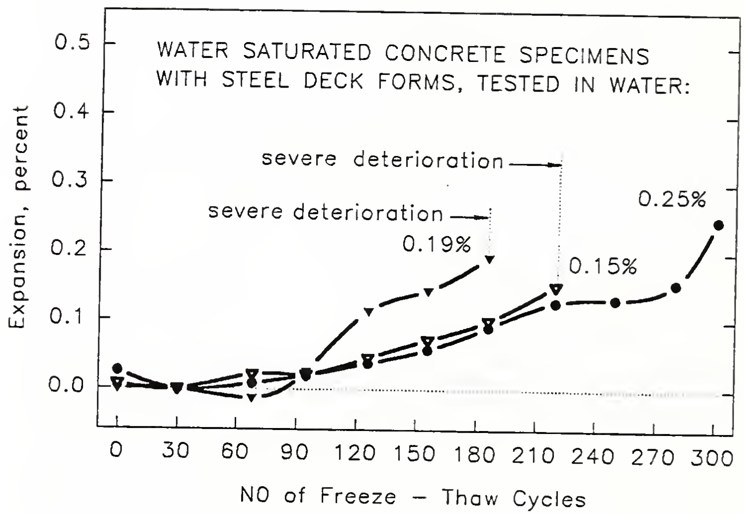


Fig. 4.19 Expansion of water saturated 3"x4"x12" concrete specimens with steel deck forms, measured during the standard (ASTM C-666) freeze-thaw test

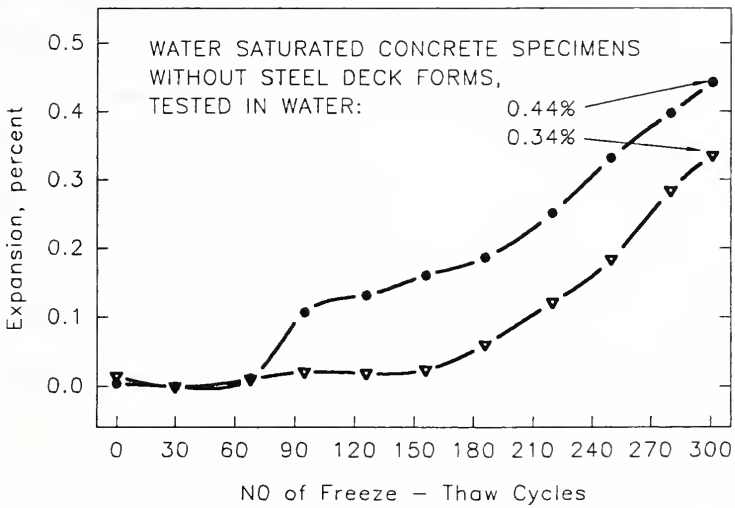


Fig. 4.20 Expansion of water saturated 3"x4"x12" concrete specimens without steel deck forms, measured during the standard (ASTM C-666) freeze-thaw test

4.3.3 Weight changes

Air dried specimens were absorbing water continuously during the freeze-thaw test, despite the precautions that were taken (see Section 4.2). The water absorption in air dried specimens without steel deck forms was low (up to 0.3%, Fig. 4.21). But air dried specimens with the forms could have absorbed more water (up to 5.3%, Fig. 4.21). The possibility of the moisture accumulation at the bottom part of the specimen seems unlikely, because the concrete was initially dry. Probably, water could penetrate into the specimen through the interface between the concrete and the form.

Water saturated specimens suffered severe damage and scaling as a result of freeze-thaw action. However, the specimens with steel deck forms have lost less than the specimens without the forms (Fig. 4.22, 4.23). Taking into account the observation given previously, that the destruction of the specimens with the forms occurred mainly at their edges (Section 4.3.2), one might suggest that the steel forms could play even a positive role in this particular situation. The total weight loss in specimens without forms was up to 19%, but in specimens with forms it was lower (up to 10.3%, Fig. 4.2.3). A minor weight loss observed on one of these specimens (1.8%), could be explained by a better adhesion between the concrete and the form. The scaled fragments of concrete could also remain stuck, supported by the deck.

The most important observation refers, however, to the moisture state of the concrete. Water saturated concrete disintegrated, while dry concrete did not.

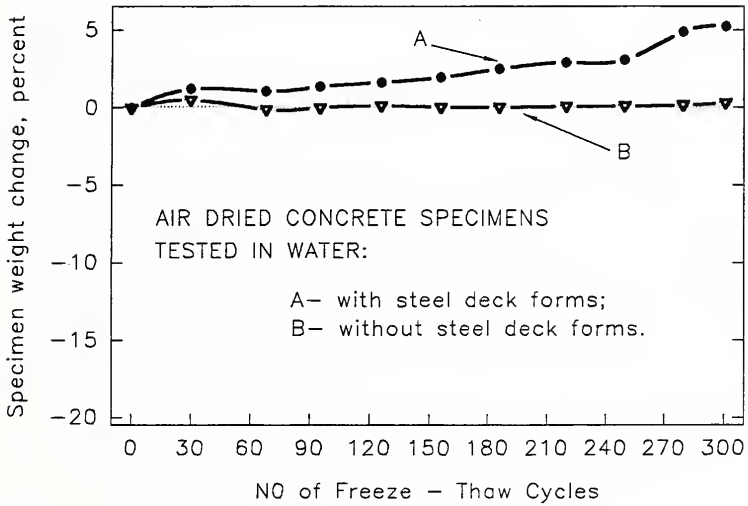


Fig. 4.21 Continuous absorption of water in air dried 3"x4"x12" concrete specimens

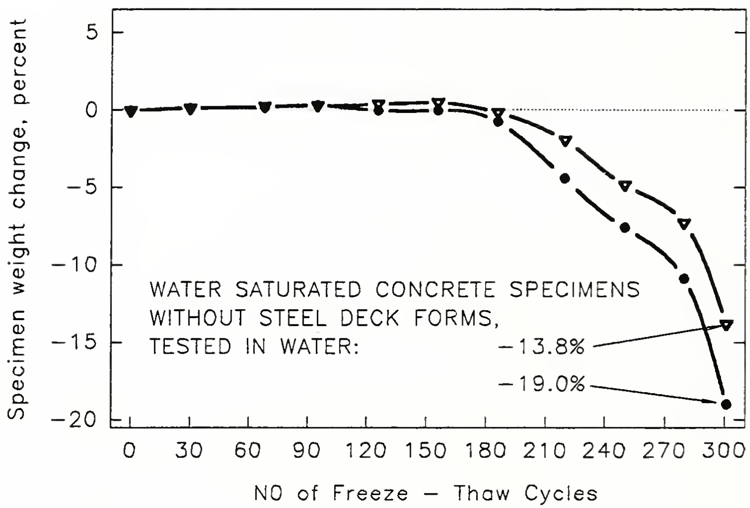


Fig. 4.22 Weight loss in water saturated 3"x4"x12" concrete specimens, without steel deck forms

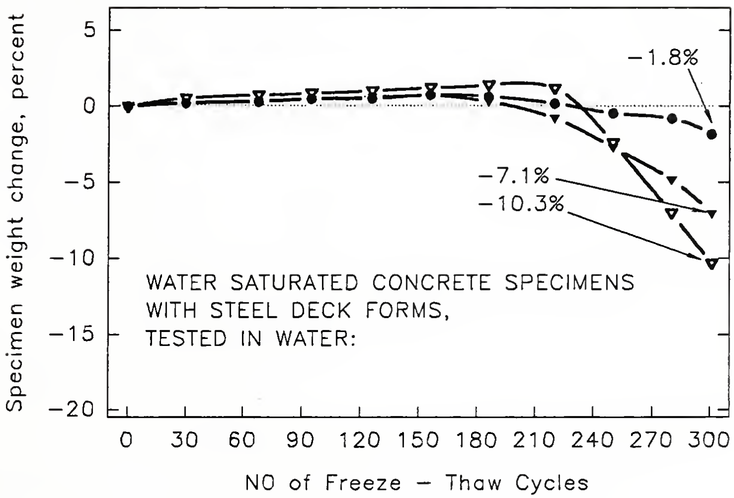


Fig. 4.23 Weight changes in water saturated 3"x4"x12" concrete specimens with steel deck forms

SECTION 5

SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

5.1 Summary

This research investigation was aimed at assessing the freezing-and-thawing durability of concrete bridge decks with stay-in-place steel deck forms. In particular, it was intended to clarify the possibility of D-cracking due to the increased moisture content, mainly in the bottom part of the deck.

The experimental approach was based on conditioning the concrete to several levels of wetness, and on establishing the moisture content by means of relative humidity measured above samples of concrete powder. The samples were obtained by drilling the concrete.

The specimens made for the project were large concrete slabs with and without steel deck forms. The choice of the large specimen size was intended to make the situation in the lab more similar to that in the real bridge decks.

The experimental problems described in this report have been related to the techniques of relative humidity measurements and to the use of large size concrete slabs. To resolve these problems and to reach the objects of the project, an extensive experimental program has been carried out. Following are its major results, conclusions and recommendations.

Apparently, several techniques of relative humidity measurement ,applied in this project, were inefficient due to the limitations described in Section 2. Probably, the relative humidity measurement was not a suitable tool for determining the internal moisture state of wet and/or air dry concrete. In this project, the direct measurement of moisture content has been applied as an alternative, along with the relative humidity measurement.

The measurement of the freezing-and-thawing test of the large 22¼"x17¼"x5¼" concrete slabs was described in Section 3. The results obtained after 221 cycles indicated the reduction of relative square pulse velocity in the range of 3.3%-7.9% (dry and air-dry concrete slabs). Considerable drop of relative square pulse velocity was observed in moisture saturated concrete slabs with steel deck forms (37.6%), indicating a reduction of the relative dynamic modulus of elasticity (E_d).

5.2 Role of steel deck forms

Steel deck forms might have promoted the accumulation of water at the bottom of 3"x4"x12" concrete specimens (and probably of the large slab specimens) where the concrete meets the steel deck. This assumption is supported by the results given in Section 4 above and in Section 3 for large water-saturated concrete slabs with the decks. They tend to deteriorate to a higher extent that water-saturated slabs without the decks.

The deterioration of some of the 3"x4"x12" specimens, as measured by relative pulse velocity, was more extensive in the presence of steel deck forms. This was found in air dry concrete (Fig. 4.15) as well as in water saturated concrete (Fig. 4.14).

The expansion measurements gave results in support of the negative role of the steel decks for air dry concrete (Fig. 4.18). However, the expansion measured in this case could be caused by excessive absorption of water from the freeze-thaw cells in the air dry concrete (Fig. 4.21, curve A). As to the water saturated concrete, these specimens (with decks) deteriorated at their edges after 180-210 cycles (Fig. 4.19). The stainless steel pins used for the expansion measurements popped out of the concrete, which interrupted the measurements.

5.3 Role of aggregate

The water absorption capacity of the coarse aggregate used in this project was 2%. The Expected Durability Factor (EDF) was determined by a method described in Section 4. The EDF values indicated that the aggregate could be considered a Non-Durable, susceptible for D-cracking.

Observations of deteriorating specimens have shown numerous cracked or broken coarse aggregate grains in the fracture planes (Fig. 5.1). Popouts of whole grains as well as of grain fragments have occurred frequently (Fig. 5.2). There was no significant deterioration of the hardened paste-matrix. There was no deterioration in air dry concrete (when it did not absorb considerable amounts of water). These observations indicate that generally, water-saturated coarse aggregate grains could play a major role in the deterioration process, and specifically, that coarse aggregates which are non-durable and susceptible to D-cracking under freezing-and-thawing conditions should not be used in concrete decks that are cast on stay-in-place metal forms.

The deterioration has occurred only in water saturated concrete specimens, along with the extensive drop in relative pulse velocity and expansion. These imply that considerable deterioration is likely to occur when the moisture content in concrete is high, i.e. is up to 4-8%, and when the absorption capacity of the coarse aggregate is also high.

Fig. 5.1 Typical view of a deteriorated water saturated 3"x4"x12 concrete specimen:

1 - failure of aggregate grains

Fig. 5.2 Popouts at the surface of a deteriorated water saturated 3"x4"x12" concrete specimen

5.4 Conclusions

1. The majority of experimental results obtained in this study suggest that corrugated steel deck forms may promote the damage of concrete made with D-cracking coarse aggregate caused by freezing-and-thawing action.
2. The coarse aggregate used in this study could by itself promote extensive cracking and consequent scaling of water-saturated 3"x4"x12" concrete specimens cast either with or without steel deck forms.

5.5 Recommendations

It is known that corrugated steel deck forms have been widely used in bridge construction. These forms provide considerable technological and economical benefits. The recommendations for future applications of these forms can be given as follows:

1. The corrugations of the steel deck forms can be perforated. This may provide the drainage of excessive water out of the interfacial gap between the concrete and the form. However, the perforation may not be very efficient, for example, because the holes can be easily plugged by the fresh concrete.
2. The forms may be anchored into the concrete. This may help to minimize the interfacial gap between the concrete and the form, and thus to reduce the accumulation of water in that gap.
3. Chemical admixtures can be incorporated into the concrete mix and/or applied onto the steel form surface prior to casting. Hence, the bond between the concrete and the steel form should be improved, so that the interfacial gap would be minimized.

4. Good quality concrete, designed for a low water permeability and for a low internal bleeding, shall be applied. The aggregates for the concrete shall be of a sufficient quality, i.e. non-D-cracking.

5. The application of coarse aggregate like that used in this project is questionable. However, the reduction of the maximum aggregate size may lower the probability for the D-cracking to occur.

6. The freeze-thaw testing of large slab specimens is in progress. Some interesting observations have been made recently (Section 3). Additional results can therefore be obtained by the completion of this test, describing the performance of air dry and water saturated concrete slabs with steel deck forms.

7. It is desirable to compare the results obtained under laboratory conditions with observations done on actual bridge decks. Measurements of moisture content in the bridge concrete done in different seasons, as well as the observations of the actual interfacial gap between the concrete and the steel deck forms, can provide valuable information on their performance.

References

1. L. J. Parrott, "Factors influencing relative humidity in concrete", Magazine of Concrete Research, No. 154, Vol. 43, March 1991, pp. 45-52.

2. L. J. Parrott, "Moisture Profiles in Drying Concrete", Advances in Cement Research, Vol. 1, No. 3, July 1988, pp. 406-415.

3. D. Stark, "The moisture condition of field concrete exhibiting alkali-silica reactivity", Proceedings of the International Workshop on Alkali-Aggregate Reactions in Concrete, Halifax, Nova Scotia, May 1990, paper 2.

4. A. Goldman, M. D. Cohen and J. A. Ramirez, "Measurement of relative humidity and moisture content of concrete", presentation at Fall 1993 ACI Convention, Minneapolis, MN, November 1993.

5. M. Kaneuji, D. N. Winslow and W. L. Dolch, "The relationship between an aggregate's pore size distribution and its freeze-thaw durability in concrete", Cement and Concrete Research, Vol. 10, 1980, pp. 433-441.

APPENDIX A. The concrete delivery ticket

CONCRETE 634-5802 AGGREGATE 335-2421 imi IRVING MATERIALS INC. REMIT TO: 8032 N. ST. RD. 9 GREENFIELD, IN. 46140-9097 317/326-3101

DELIVERY TICKET

PLANT	TICKET NUMBER	TRUCK	LOAD SIZE	MIX	SLUMP	USE	DATE	CUSTOMER NO.
16	260	302	3.0	231	4.0	SPECIAL	04/29/93	4282

SOLD TO	TX CD	DRIVER	NOTES
PURDUE UNIVERSITY	EX	1020 SPITZ	INDUT MIX

DELIVERY ADDRESS	P.O. NUMBER
STRUCTURES LAB	ARIEL GOLDM

LOAD QUANTITY	TOTAL YARDS	ORDERED QTY.	PRODUCT CODE	PRODUCT DESCRIPTION	UNIT PRICE	AMOUNT
~~3.00~~ 2.06	~~3.00~~ 2.00	~~3.00~~ 2.00	231	7 BAG STONE AIR		

WATER ADDED AT CUSTOMER'S REQUEST ________ No. Gal. SIGNATURE ________

SUBTOTAL	
TAX	
TOTAL	

09:56
1465

"WE'RE PROUD OF OUR WORK"

CUSTOMER COPY

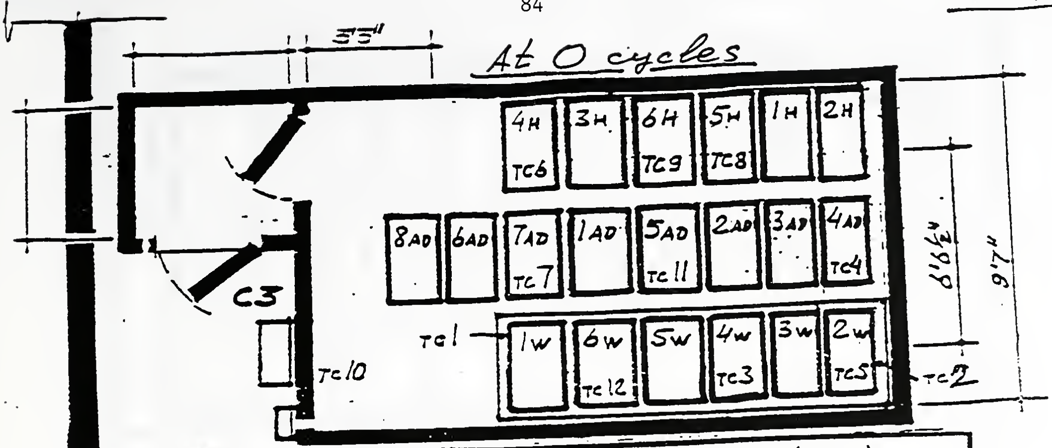
APPENDIX B.

Freezing-and-Thawing Test of Large Slab Specimens

Measurements of Relative Square Pulse Velocity

%RH in slab 1H: 10.5% at 22.0°C

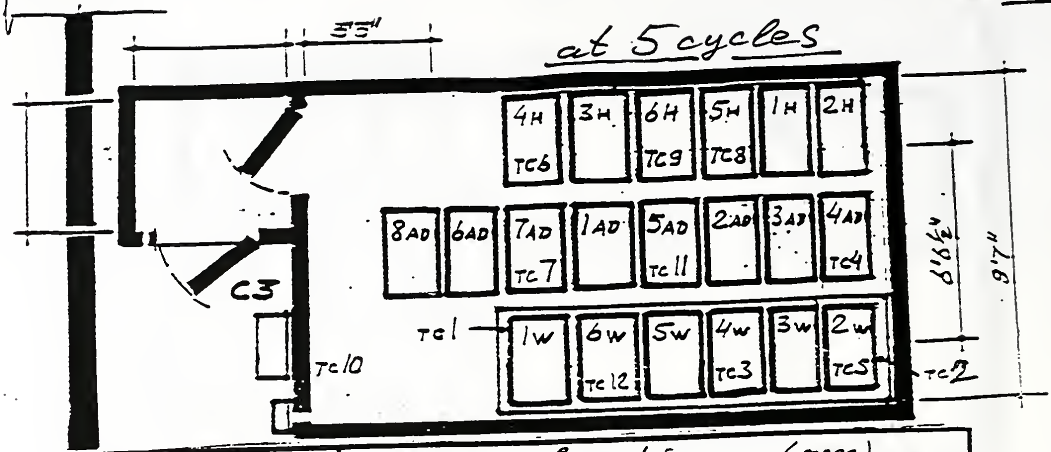
At 0 cycles



Date	Specimens: with deck	Specimens: without deck	Pulse time (msec) V_1	V_2	V_3	V_4	V_5
July 19-23, 1993	1AD		143.6	142.8	143.8	140.7	141.0
	2AD		143.8	144.4	144.6	141.6	142.8
	3AD		144.6	146.6	147.4	142.3	143.3
	4AD		141.8	142.2	141.3	141.6	140.7
		5AD	144.4	145.2	145.8	145.3	144.7
		6AD	144.0	145.4	143.8	143.1	143.0
		7AD	143.2	146.7	144.2	144.3	143.6
		8AD	143.3	142.5	143.6	142.4	143.0
		1W	144.3	144.1	144.6	144.4	144.4
		2W	141.6	142.4	142.3	143.3	141.4
	3W		141.6	142.2	141.0	140.0	140.1
	4W		142.4	142.8	142.3	141.6	143.4
		5W	141.0	140.8	141.5	140.6	141.3
	6W		142.6	141.3	141.1	141.4	140.4
	1H		150.7	154.3	152.8	153.2	153.0
	2H		157.7	156.5	156.4	157.1	156.6
	3H		157.8	157.3	156.4	157.6	155.4
		4H	158.6	159.4	159.3	159.3	159.4
		5H	157.4	160.0	159.8	158.4	160.7
		6H	155.4	157.5	156.7	156.0	157.1

%RH in 1H deck: 26.1% at 21.2°C

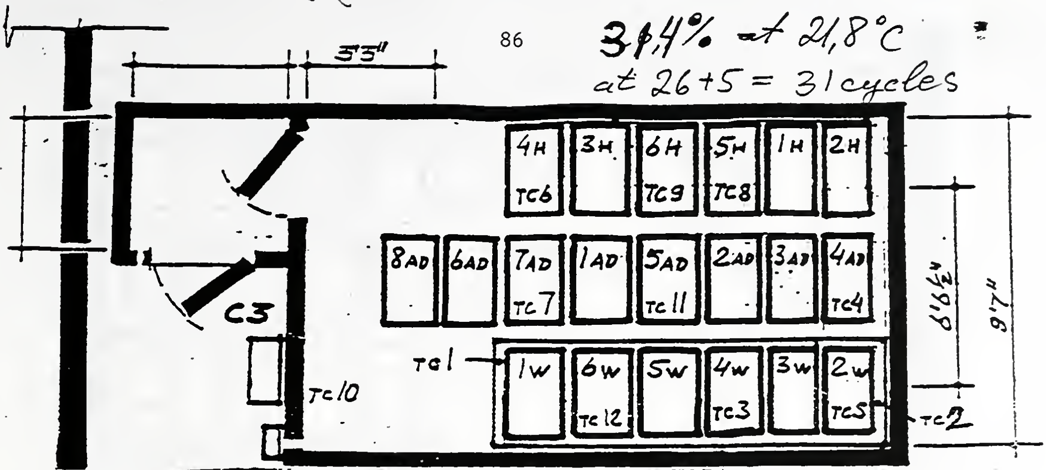
at 5 cycles



Date	Specimens: with deck	Specimens: without deck	pulse time (msec) V_1	V_2	V_3	V_4	V_5	
09.11.93	1AD							
	2AD		144.3	145.7	144.9			
	3AD							
	4AD							
		5AD						
		6AD						
		7AD						
		8AD	148.0	148.6	148.5	144.6	146.5	
		1W						
		2W	145.3	147.2	146.2	146.7	144.5	
	3W							
	4W		147.4	146.7	144.8	144.6	143.7	
		5W						
	6W		144.4	145.0	145.6	144.4	145.9	
	1H		157.4	159.6	158.4	158.8	159.5	
	2H		160.7	163.6	160.0	163.7	162.0	
	3H		163.3	164.3	162.5	163.2	162.4	
		4H	162.6	165.1	163.6	162.7	163.6	
		5H	162.0	163.7	164.2	163.8	162.6	
		6H	159.4	161.7	160.4	160.0	159.6	

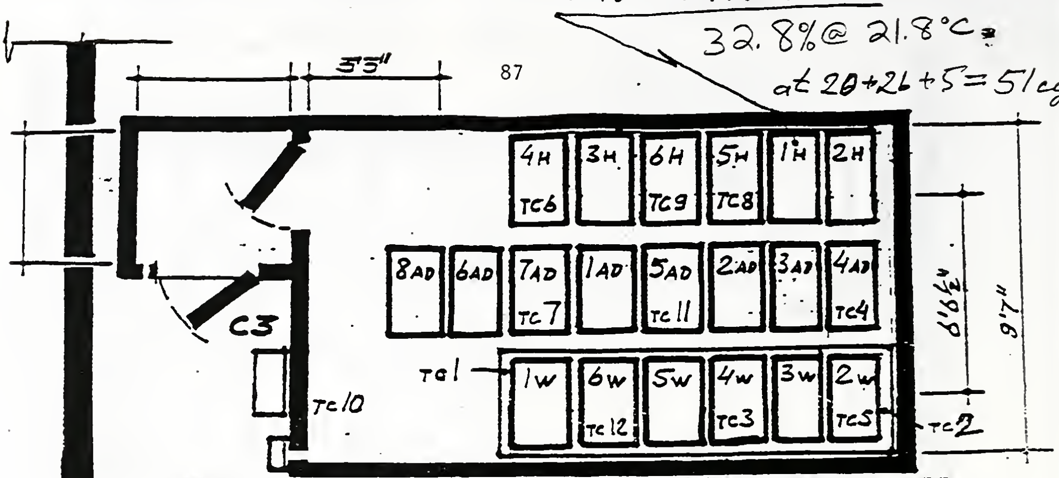
31.4% @ 21.8°C

%RH in 1H deck:
31.4% at 21.8°C
at 26+5 = 31 cycles



Date	Specimens: with deck	Specimens: without deck	Pulse time (msec) V1		V2		V3		V4		V5			
10.27.93	1AD		143	2	144	0	145	0	143	0	142	4		
"	2AD		146	3	144	8	145	6	142	0	143	3		
"	3AD		147	3	147	6	146	3	145	0	146	6		
"	4AD		144	2	143	4	145	2	142	7	142	3		
"		5AD	148	0	147	0	147	3	148	7	143	7		
"		6AD	149	6	147	0	147	0	147	8	146	3		
"		7AD	146	7	147	5	146	9	146	1	147	3		
"		8AD	146	5	147	1	147	1	144	1	146	3		
"		1W	149	1	146	8	152	5	146	6	151	1		
"		2W	138	7	142	0	142	3	144	7	143	6		
"	3W		144	3	144	4	147	6	144	0	144	6		
"	4W		145	2	144	3	145	3	140	8	144	3		
"		5W	146	5	144	7	147	3	147	2	145	2		
"	6W		144	2	143	7	144	2	144	8	146	6		
"	1H		156	3	161	7	151	3	161	0	159	7		
"	2H		157	4	162	6	156	8	162	0	162	6		
"	3H		162	5	163	1	160	5	164	7	162	2		
"		4H	161	8	163	4	161	8	162	8	162	8		
"		5H	162	0	164	1	161	5	162	4	161	6		
"		6H	160	0	161	0	159	0	160	2	160	3		

%RH in 1H deck:
32.8% @ 21.8°C
at 20+26+5=51 cyc



Date	Specimens: with deck	Specimens: without deck	Pulse time (msec) V1		V2		V3		V4		V5			
11,29-30	1AD		144	2	143	6	143	5	143	7	142	8		
"	2AD		144	6	[illegible]	4	145	6	143	7	141	7		
"	3AD		147	9	146	0	145	4	144	4	[illegible]	8		
"	4AD		145	1	142	8	142	0	142	4	141	6		
"		5AD	147	8	147	5	148	1	148	6	147	3		
"		6AD	148	4	148	4	147	4	148	4	148	3		
"		7AD	146	3	149	2	146	6	147	6	147	0		
"		8AD	145	8	145	2	146	4	145	3	146	6		
"		1W	148	6	149	4	153	6	148	5	151	4		
"		2W	144	1	148	8	144	6	144	8	143	4		
"	3W		145	4	146	6	152	4	144	4	152	5		
"	4W		148	8	146	4	149	5	144	8	144	4		
"		5W	146	0	145	3	146	2	147	0	147	0		
"	6W		141	5	143	8	143	4	143	3	142	6		
"	1H		154	6	158	9	158	8	[illegible]	0	159	4		
"	2H		158	8	162	1	159	0	162	3	160	8		
"	3H		163	2	163	8	160	6	163	8	162	4		
"		4H	162	4	163	5	160	4	162	1	162	4		
"		5H	163	0	160	[illegible]	161	7	[illegible]	[illegible]	161	4		
"		6H	157	6	159	6	153	3	160	2.	158	4		

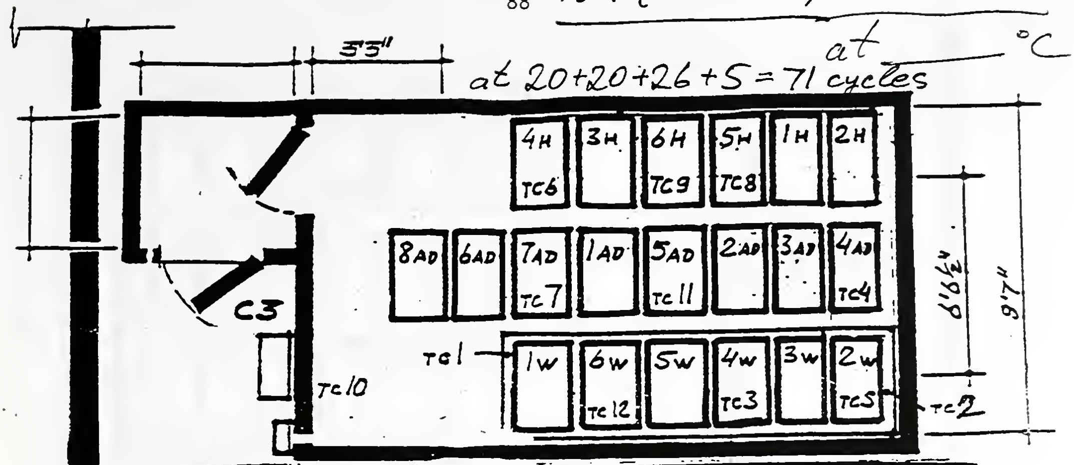
note: off since [illegible]

a popout has been observed.

%R (1H deck) ?

at °C

at 20+20+26+5 = 71 cycles

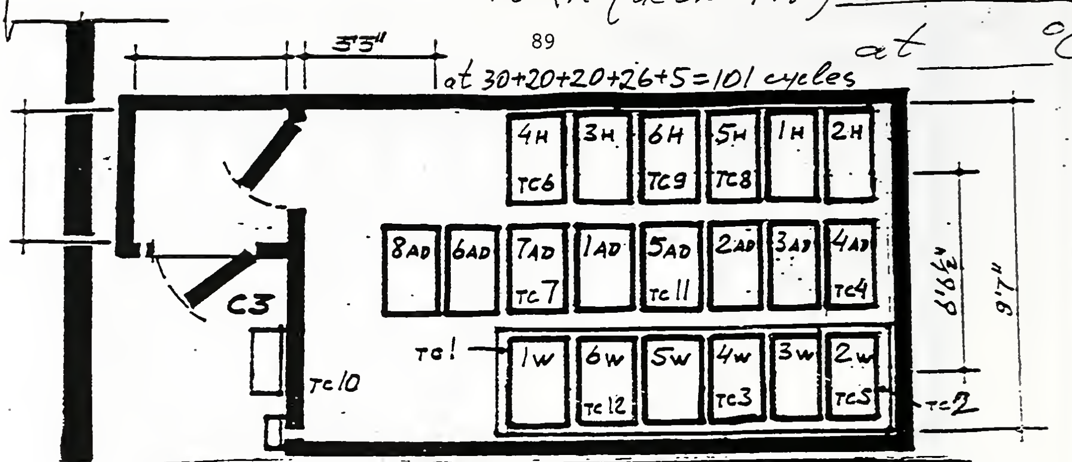


Indicate some minor) expansion (noted beside rows 1W–6W)

Date	Specimens: with deck	Specimens: without deck	Pulse time (msec) V1		~~V2~~ E3		~~V3~~ E2		V4		V5			
01.18.94	1AD		144	5	144	6	144	6	143	4	143	4		
	2AD		144	2	144	6	145	4	142	7	143	7		
	3AD		149	8	146	6	146	6	145	4	145	4		
	4AD		152	2	152	2	145	3	143	8	142	4		
		5AD	148	7	148	6	148	6	148	6	149	0		
		6AD	148	4	147	0	146	8	148	3	147	3		
		7AD	146	4	148	1	146	4	147	3	148	0		
		8AD	147	3	146	1	146	5	145	6	147	4		
		1W	149	0	150	5	155	4	150	2	155	3		
		2W	143	6	145	6	145	2	143	6	144	6		
	3W		147	3	150	7	168	6	146	4	160	2		
	4W		158	8	146	4	153	3	149	2	149	2		
		5W	145	4	146	1	148	7	147	0	148	3		
	6W		149	3	144	1	145	6	144	8	147	3		
	1H		157	4	160	8	156	2	160	7	159	6		
	2H		159	7	162	0	162	2	152	6	160	6		
	3H		163	4	163	3	160	0	163	0	161	4		
		4H	159	6	162	8	160	1	161	3	161	4		
		5H	160	6	162	7	160	6	162	0	160	8		
		6H	157	7	160	4	158	0	158	6	158	6		

%RH (deck 1H) ________ at ______ °C

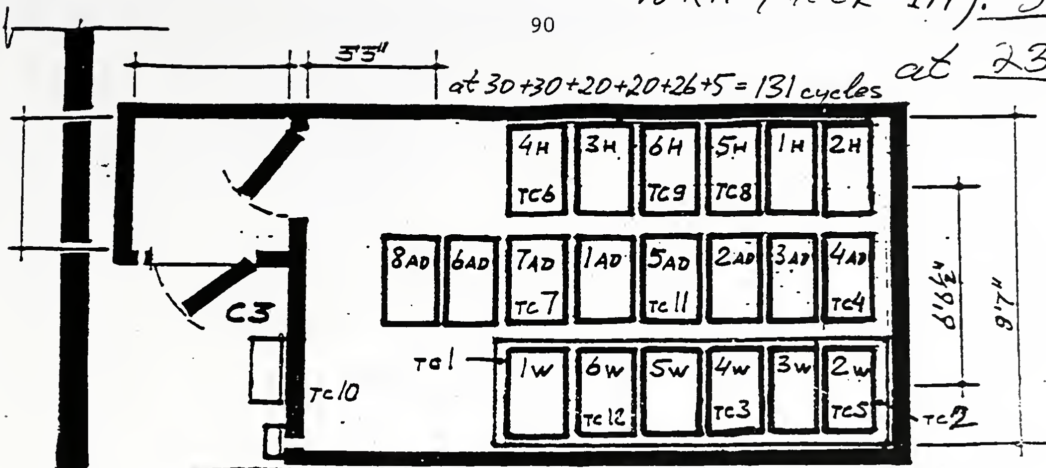
at 30+20+20+26+5=101 cycles



Date	Specimens: with deck	Specimens: without deck	pulse time (msec) V1		V2		V3		V4		V5		
3/13/94	1AD		144	7	144	0	145	0	143	6	142	4	
	2AD		144	6	145	3	145	6	144	3	146	2	
	3AD		145	4	146	6	144	5	145	4	146	9	
	4AD		144	8	144	8	144	8	143	4	143	4	
		5AD	149	8	147	6	150	4	148	3	148	7	
		6AD	148	3	149	6	149	7	149	1	149	4	
		7AD	151	2	150	0	149	4	150	8	149	6	
		8AD	148	8	148	8	150	7	147	4	150	1	
		1W	152	7	154	2	156	6	149	2	150	8	
		2W	150	6	151	7	147	4	150	7	150	8	
	3W		149	7	148	7	154	8	152	6	153	6	
	4W		150	3	151	4	147	4	147	4	148	5	
		5W	163	7	156	7	150	6	167	5	153	3	
	6W		146	3	144	3	144	4	148	8	145	0	
	1H		157	1	160	5	156	0	160	6	160	8	
	2H		161	0	162	8	161	2	161	3	160	8	
	3H		162	6	162	4	160	5	164	2	161	0	
		4H	159	3	160	8	160	5	160	6	160	6	
		5H	159	6	162	6	160	4	162	2	160	8	
		6H	157	8	160	4	159	1	158	9	158	7	

%RH (deck 1H): 32% at 23 °C

at 30+30+20+20+26+5 = 131 cycles



Date	Specimens: with deck	Specimens: without deck	Pulse time (msec) V1		V2		V3		V4		V5	
07.05.94	1AD		151	3	147	0	147	6	145	7	144	8
	2AD		144	0	143	8	146	4	145	1	144	8
	3AD		148	2	150	5	152	4	149	2	150	3
	4AD		147	4	148	8	146	6	146	4	148	4
		5AD	149	8	148	4	149	2	148	7	148	2
		6AD	152	4	151	8	149	4	151	4	149	4
		7AD	150	2	152	4	150	6	148	7	148	3
		8AD	151	3	150	6	152	4	149	8	147	2
		1W	155	2	147	5	148	4	150	2	148	2
		2W	145	1	145	4	144	4	144	7	144	8
	3W		184	5	178	8	160	7	188	4	170	4
	4W		152	6	148	2	151	8	151	7	148	8
		5W	153	2	146	8	145	7	150	1	148	4
	6W		145	6	143	5	145	5	146	6	145	6
	1H		156	7	161	6	157	4	161	0	161	3
	2H		160	7	161	3	161	7	162	7	161	5
	3H		162	3	163	8	162	8	164	7	162	5
		4H	160	2	161	5	161	3	162	0	161	0
		5H	162	6	162	6	161	6	162	6	161	6
		6H	157	3	160	4	158	0	158	6	158	0

APPENDIX C.

Positioning of the 3"x4"x12" specimens in the freezing-and-thawing machine

Freezing-and-thawing cycle counter charts.*

* The freezing and thawing temperatures have been controlled by three thermocouples fixed in the specimens (see Section 4).

Positions of specimens in the freezing-and-thawing machine.

controls	
1	W-8
2	(T) W-5
3	AD-2
4	AD-6
5	W-6
6	— none
7	AD-1
8	W-4
9	reference
10	W-3
11	AD-7
12	W-7
13	AD-3
14	W-2
15	AD-5
16	(T) AD-4
17	AD-8
18	W-1

Started on Thursday, Jan. 27 1994
at 0 cycles

Changed on Wednesday, February 2 1994
at 25 cycles

Remarks:

- 18 (~5 hours) cycles, probably at slightly below the freezing point of water.
- 7 adjusted cycles, between ≈ 8°F and ≈ 47°F.
- the duration of one adjusted cycle was ≈ 5½ hours.
- the lowest temperature (≈ 8°F) was probably achieved in 4-5 cells, and could be much higher in all other cells.
- water leaked from the cell # 18.

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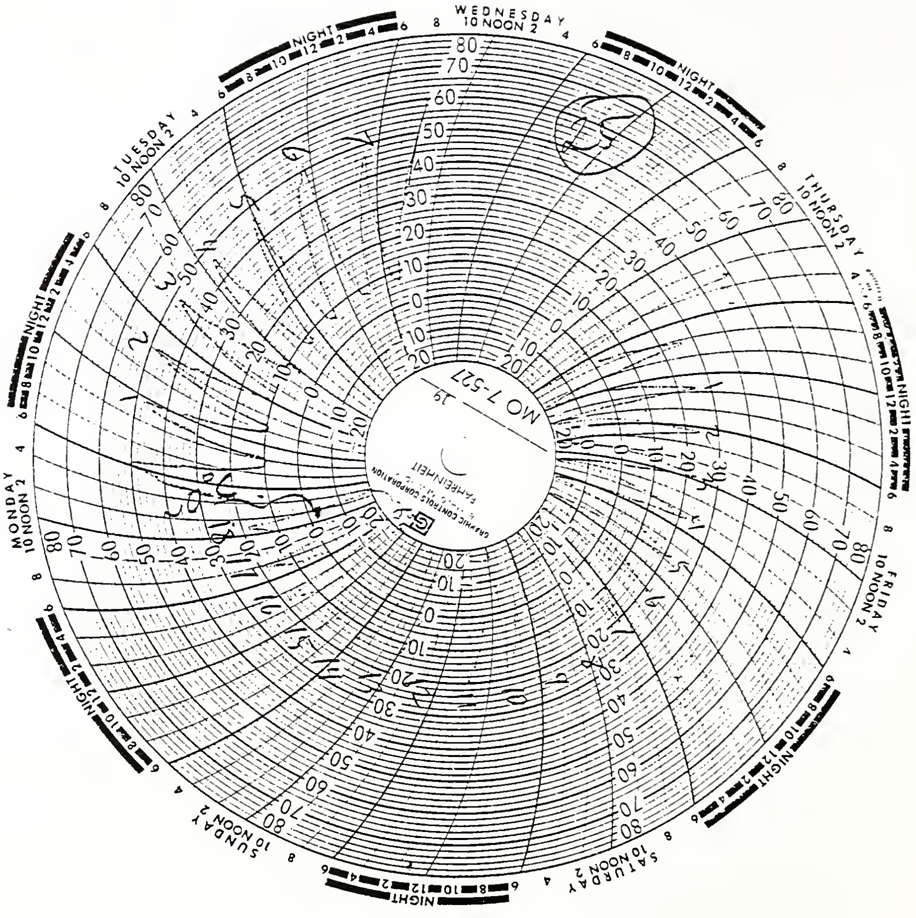
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Positions of specimens in the freezing-and-thawing machine.

controls

Cell	Specimen
1	W-8 (in the air)
2	(TC-2) W-5
3	AD-2
4	AD-6
5	W-6
6	none
7	AD-1
8	W-4
9	(TC-3 in water) Ref
10	W-3
11	AD-7
12	W-7
13	AD-3
14	W-2
15	AD-5
16	(TC-1) AD-4
17	W-1
18	AD-8 (in the air)

Started on Thursday, February 3rd 1994 at 25 cycles

Changed on Friday February 4th 1994 at 30 cycles

Remarks:

- 3 thermocouples have been activated:
  - TC-1 in specimen
  - TC-2 " "
  - TC-3 in water above the ref. (cell 9)
- AD-4 reached 0°F at 08:14pm
  W-5 reached -16.9°C at that time, and showed 0°C at 08:23pm
- cutoff at 08:28 pm:
  - TC-3 in water -16.4°C
  - TC-1 in AD-4 -19.9°C
  - TC-2 in W-5 -18.7°C
- Feb. 4 cutoff at 09:56 am: water -17.1; AD-4 -18.8; W-5 -16.8
- further on:

		water	AD-4	W-5	
	11:02 am	-0.5°C	8.3°C	1.7°C	
4 hours	11:22 am	5.5	15.3	5.8	cutin
	3:28 p.m.	-17.9	-21.3	-19.0	cutoff
1.5 hours	5:07 pm	≈ 11.0	± ≈6.5	± ≈17.8	shut off

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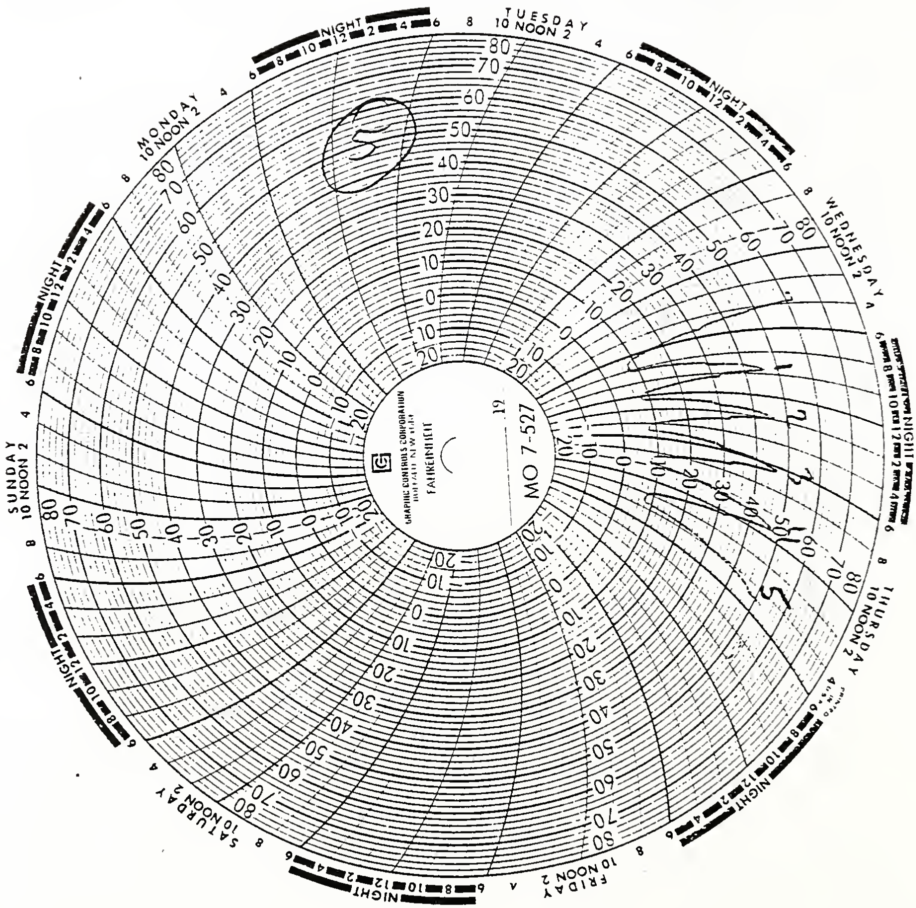
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Positions of specimens in the freezing-and-thawing machine.

Controls

Cell	Specimen
1	W-8 (in the air)
2	AD-6
3	AD-2
4	TC-2 W-5
5	W-6
6	none
7	AD-1
8	TC-3 W-4
9	Reference
10	W-3
11	AD-7
12	W-7
13	AD-3
14	TC-1 AD-4
15	AD-5
16	W-2
17	W-1
18	AD-8 (in the air)

Started on FEB 7 [5:30PM] 1994 at 30 cycles

Changed on FEB 10 [11:00AM] 1994 at 42 cycles

Remarks:

- TC-1 and TC-2 moved to cells 14 and 4 respectively. ✓
- TC-3 put into W-4. ✓

TIME	TC1	TC2	TC3	ALL TEMPS IN °C
2/7 9:45PM	-18.4	-17.6	-17.4	
2/7 10:50PM	-24.4	-23.7	-22.9	CUT-OFF
2/8 9:00am	+2.1	+4.0	+2.7	freezing
2/8 5:10pm	-19.6	-17.9	-19.4	cut-off
2/9 6:20pm	-22.6	-23.4	-24.6	cutoff adjusted

- WATER LEVEL IN CHAMBER 8 [W-4(TC-3)] WAS INITIALLY ... TOP OF SPECIMEN, NOT OVER; DUE TO WET SILICON.
- NOTICED FREEZING SETTING WAS AT ABOUT -5°F (SO -22°C). RAISED -4°F FOR NOW.
- 02.08 9.00am added water in some cells. Tried to adjust the freezing point.
- 02.09. 08.30am - recorder problem?

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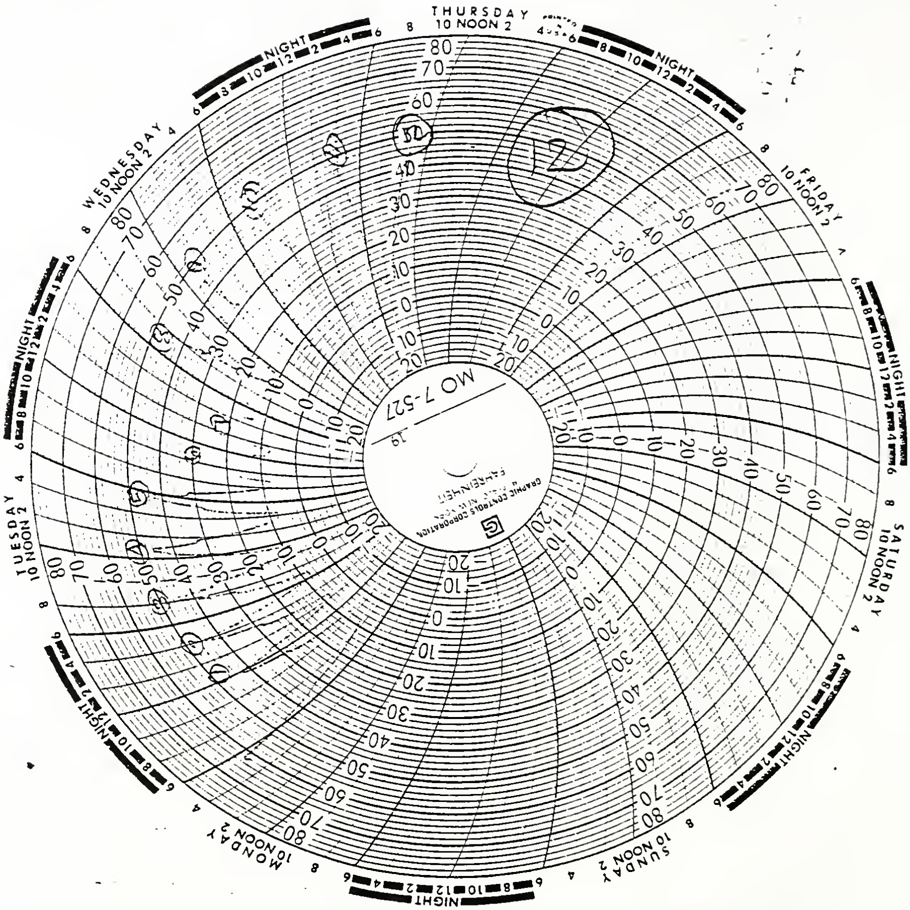
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Controls

1	W-8 (in the air)
2	AD-6
3	AD-2
4	W-6
5	TC-2 W-5
6	none
7	AD-1
8	W-3
9	Reference
10	TC-3 W-4
11	AD-7
12	W-7
13	AD-3
14	TC-1 AD-4
15	W-2
16	AD-5
17	W-1
18	AD-8 (in the air)

Positions of specimens in the freezing-and-thawing machine.

Started on FEB 14, [3:00PM] 1994 at 42 cycles

Changed on FEB 19 [1:00 PM] 1994 at 68 cycles

Remarks:

- first 3 cycles graphed incompletely due to loose recorder door. secured door.
- last 2 cycles incomplete due to recorder door.
- excessive ice on cells: 8, 10, 12, 13, 14, 15
- moderate ice on remaining cells.
- specimen / cell changes: AD-2 → 2, AD-6 → 3, AD-5 → 16; W-2 → 15

STRIPPED CAULKING, LET DRY 24hrs
APPLIED CLEAR DOW CORNING DAP SILICONE (SPEC TT-S-001543A, CLASS A) LET DRY FOR 24hrs.
SEE ATTACHED FOR NEW WEIGHTS.

TIME	TC1	TC2	TC3
2/15 2:20PM	-19.0	-16.4	-20.0

CUT-OFF

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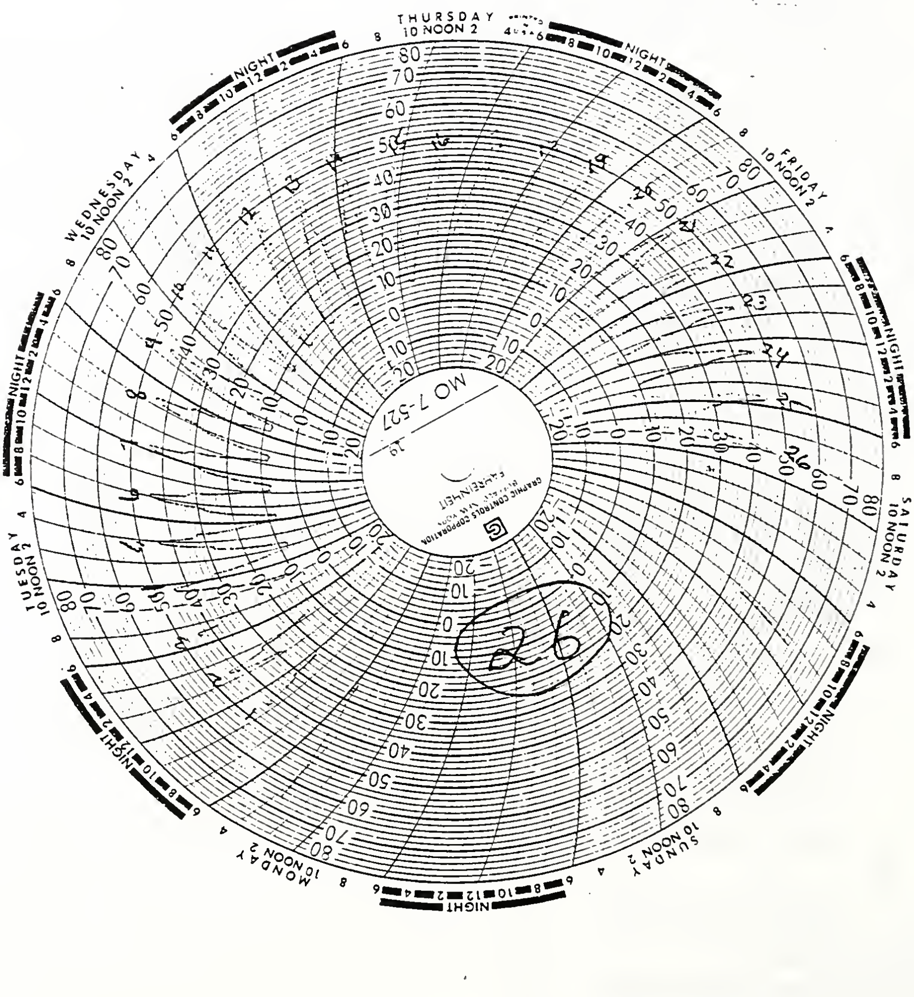

Positions of specimens in the freezing-and-thawing machine.

Started on Feb 21, 1994 [1:45am] 1994 at 68 cycles

Changed on Mar. 1 1994 [10:30am] 1994 at 95 cycles

Controls

1	W-8 in the air
2	W-7
3	TC-2 W-5
4	W-3
5	AD-2
6	NONE
7	AD-3
8	AD-7
9	Reference
10	AD-6
11	TC-3 W-4
12	AD-1
13	W-6
14	TC-1 AD-4
15	W-1
16	AD-5
17	W-2
18	AD-8 in the air

Remarks:

- TC-2 and TC-3 moved to cells 3, 11 respectively.
- TC-1 remained 14.
- W-1, reapplied small amount of silicon where deck meets concrete.

TIME	TC 1	TC 2	TC 3	
2/21 1:45am	18.6	19.2	18.9	START
2/22 12:20PM	-20.6	-19.9	-22.6	CUT-OFF
2/25 10:25PM	14.4	14.8	16.6	CUT-OFF

W3 → SURFACE CRACK & POP-OFF ON TOP

W6 → MAJOR CRACK ON BOTTOM LOWER CORNER 5683.9 g AFTER CHUNK FALLS OFF

2/23 → CHANGE CONTROL TO +50° & ±0°F ACHIEVED TOTAL THAW & TOTAL FREEZE

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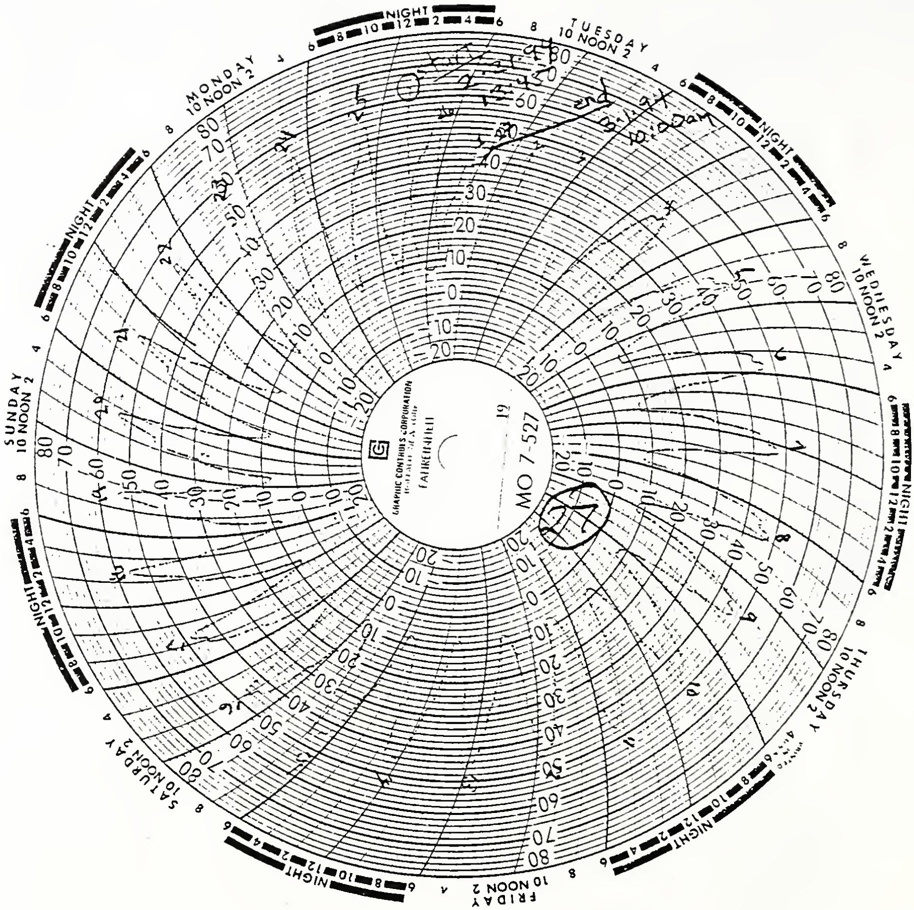
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Positions of specimens in the freezing-and-thawing machine.

Started on MARCH 4 [6:00pm] 1994 at 95 cycles

Changed on MARCH 12 [5:10pm] 1994 at 126 cycles

controls

1	W-8 (AIR)
2	AD-7
3	TC-2 W-5
4	AD-6
5	AD-1
6	NONE
7	W-3
8	AD-5
9	REFERCS
10	W-1
11	TC-3 W-4
12	W-6
13	AD-3
14	TC-1 AD-4
15	AD-2
16	W-2
17	W-7
18	AD-8 (AIR)

Remarks:

TIME	TC1	TC2	TC3	
3/1 10 40	-18.4	-17.3	-18.4	CUT OFF

NOTE: MOSTLY FROZEN NOT TOTAL.

3/5 12:35pm FTM was in a cut-out stage. reset button out. Reset button in FTM resumed cycles.

03.10 16:00pm - much water missing in all the cells. Refilled.

03.12	TC-1	TC-2	TC-3	Time
Cutoff	-18.0	-14.6	-16.4	03.11 - 11.00 am
Cutoff at 3:17pm	-18.6	-14.6	-17.4	03.12 - 3:23 pm
	the temperature still dropped for six minutes after the cutoff.			

Significant water absorption in "AD" specimens was observed by 03.13.94.

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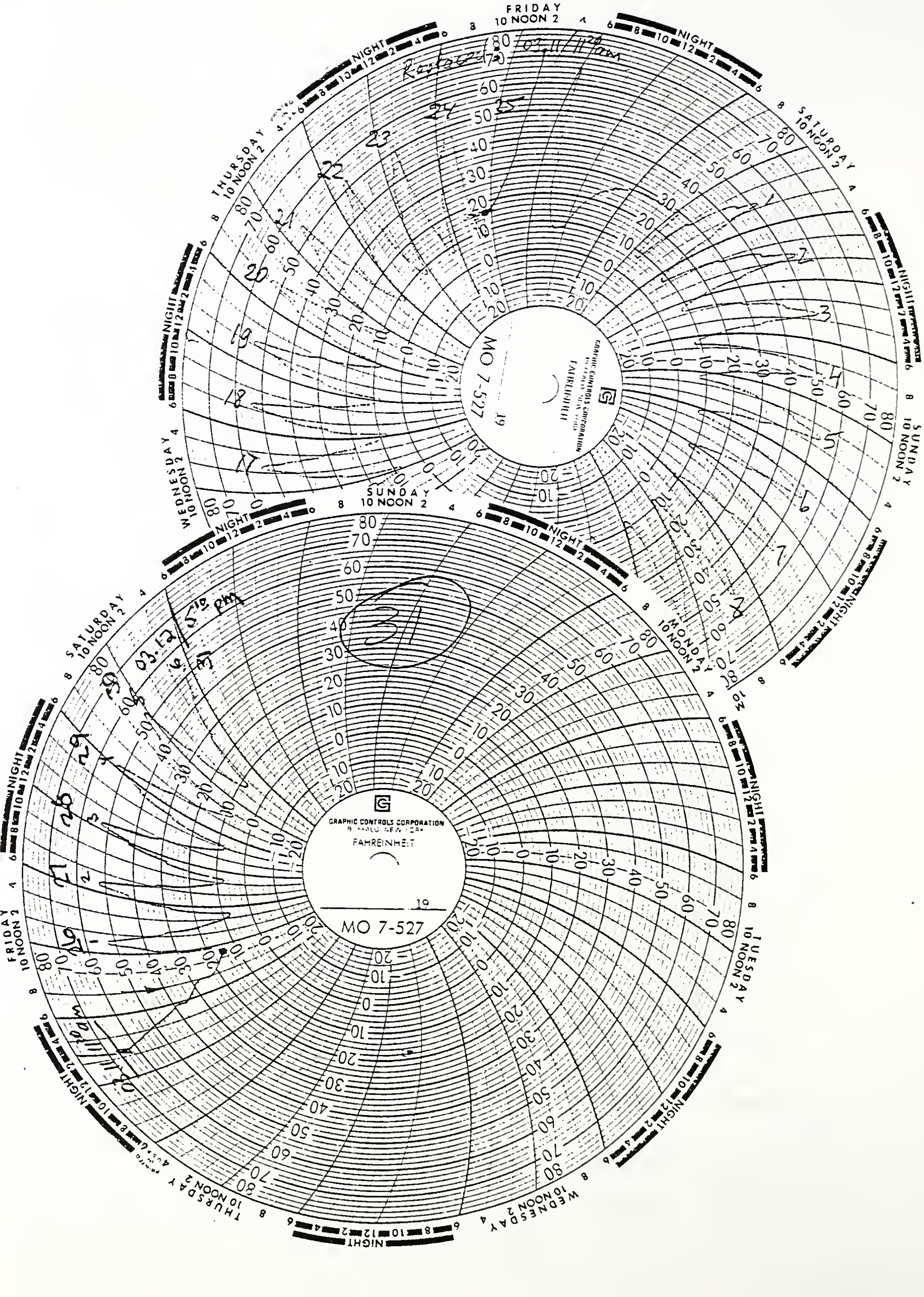
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Positions of specimens in the freezing-and-thawing machine.

controls	
1	W-8 (Air)
2	W-3
3	W-5 (T)
4	AD-5 ✓
5	AD-2 ✓
6	NONE
7	W-6 ✓
8	W-7 ✓
9	REFERENCE
10	AD-3
11	W-4 (T)
12	AD-7 ✓
13	AD-6 ✓
14	AD-4 (T) ✓
15	AD-1 ✓
16	W-1 ✓
17	W-2 ✓
18	AD-8 (Air)

Started on March 13 5:30PM 1994
at 126 cycles
Interrupted 03.14, restarted 03.21
Changed on ______ 1994
at 156 cycles

Remarks: /af

03.14.94	TC-1	TC-2	TC-3	
cut on at 6:44 pm	13.6°C	14.9°C	14.8°C	very high values

The temperature still raised after the cut on for additional $\Delta T \cong 5°C$.
At this point the machine was shut off for the specimen testing.
-All the "AD" specimens taken out of the machine. Their drying was started in the concrete lab at 10:00 p.m., 03.14.94.
- Restarted at 3:00pm, 03.21.94

03.22.94	TC-1	TC-2	TC-3
cut off at 4:10pm	-22.3	-20.1	-21.9
4:15pm	-22.5	-20.3	-22.0

03.28.94 - The rec. chart replaced at 29 cyd
- low water in the cells.

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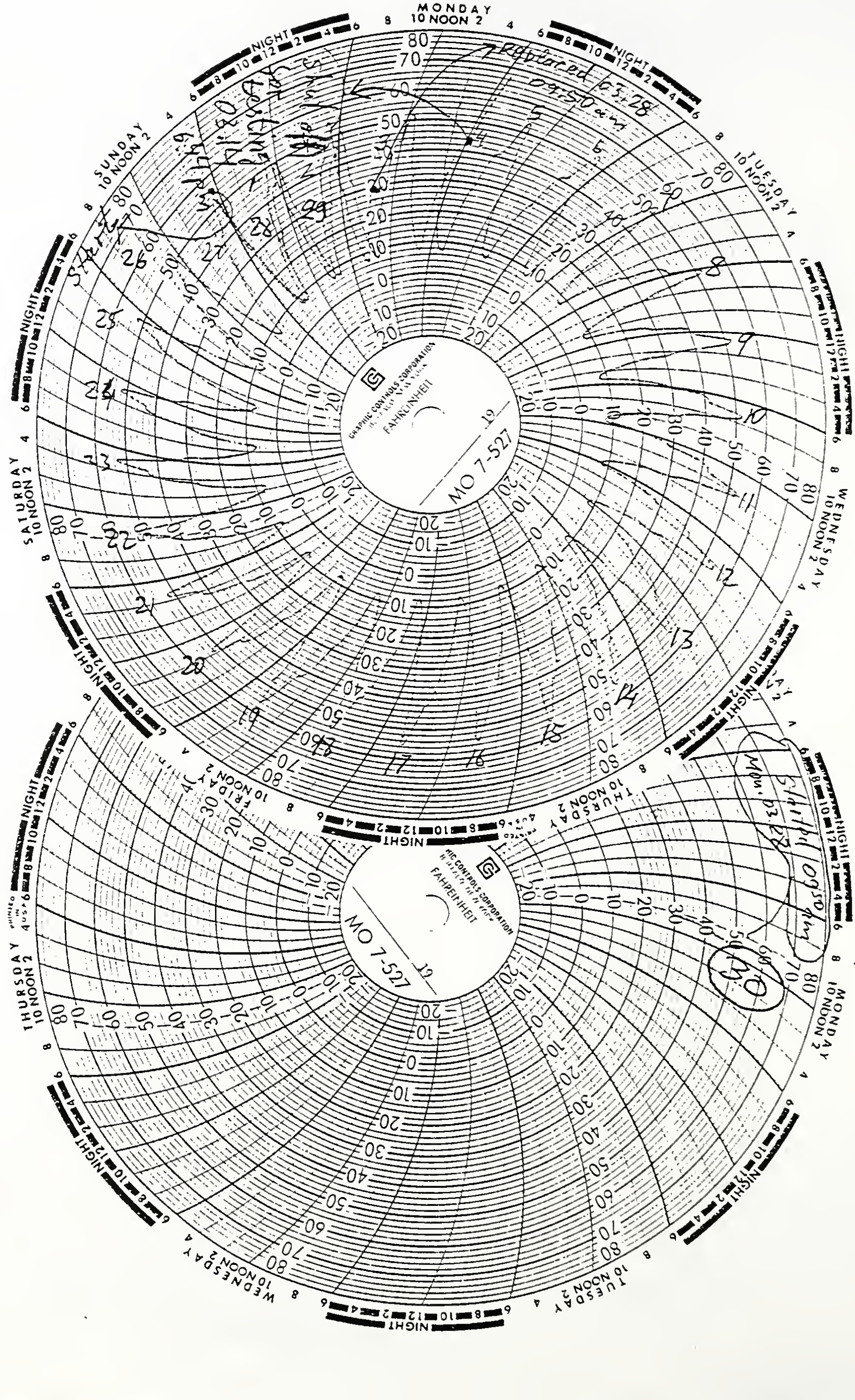
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SATURDAY
SUNDAY
NIGHT
NOON

Controls	
1	AD-8 (AR)
2	W-2
3	W-5 Ⓣ
4	AD-7
5	AD-6
6	NONE
7	W-1
8	AD-1
9	REFERENCE
10	W-7
11	W-4 Ⓣ
12	AD-5
13	W-3
14	AD-4 Ⓣ
15	AD-3
16	AD-2
17	W-6
18	W-8 (AIR)

Positions of specimens in the freezing-and-thawing machine.

Started on March 28 [3:55 pm] 1994 at 156 cycles

Changed on April 5 [9: ~~a.m.~~] ~~1994~~ at 186 cycles

Remarks: (at 156 cycles)

W-6: CONSIDERABLE DAMAGE TO BOTTOM

W-7: SOME DAMAGE TO BOTTOM

W-2: STILL COATED, CORNERS SHOWING DAMAGE

W-4: POP-OFF & CRACKS ALONG FACES

W-3: CRACKS (HEAVY) ON TOP FACE

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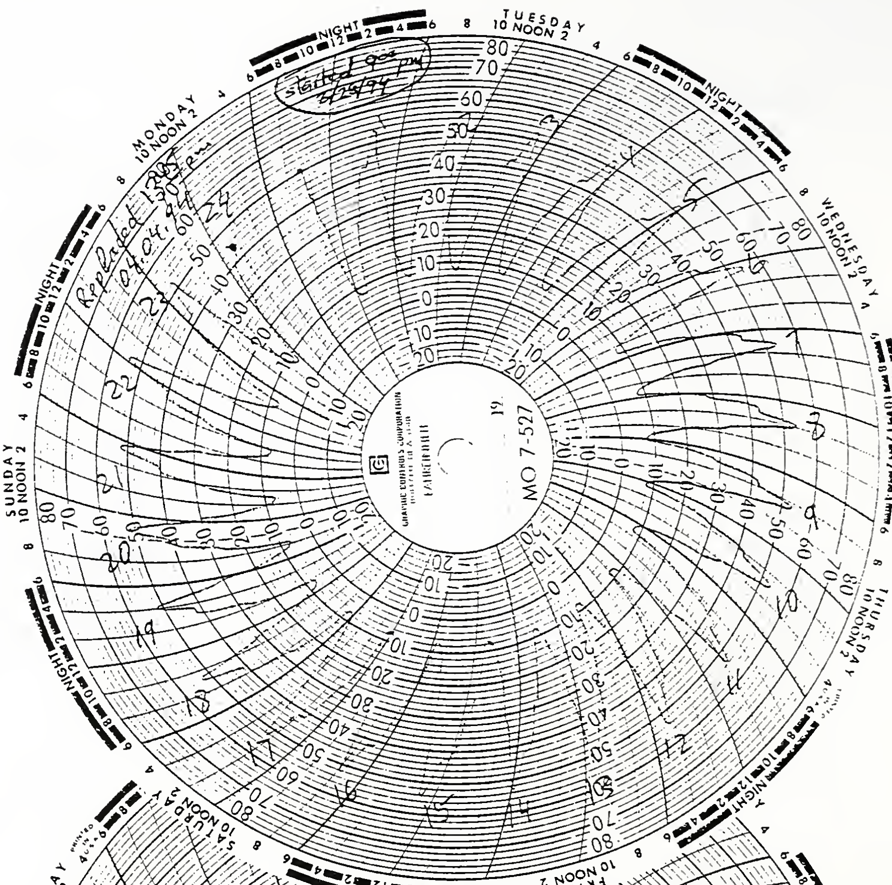
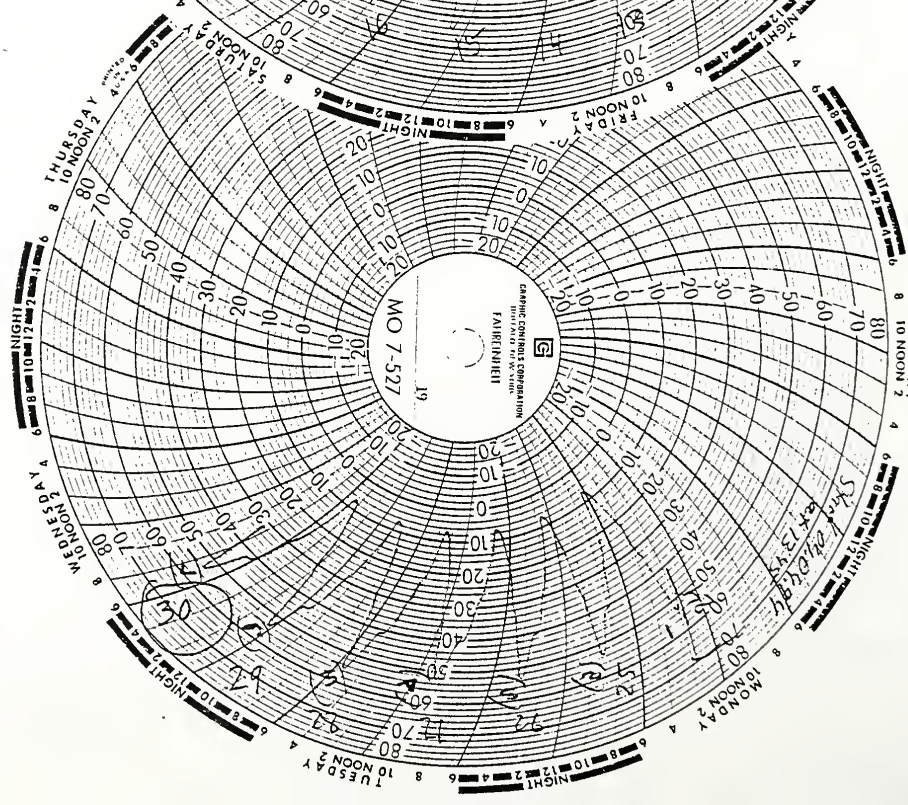
801-752-5120


GRAPHIC CONTROLS CORPORATION
FAHRENHEIT
MO 7-527


GRAPHIC CONTROLS CORPORATION
FAHRENHEIT
MO 7-527

Positions of specimens in the freezing-and-thawing machine.

Controls	
1	W-8
2	W-1
3	W-5 (T)
4	AD-3
5	AD-5
6	NONE
7	W-7
8	AD-2
9	RSF
10	AD-1
11	W-4 (T)
12	W-3
13	AD-7
14	AD-4 (T)
15	W-2
16	AD-6
17	W-6
18	AD-8

Started on April 5 (10:05) 1994 at 186 cycles

Changed on April 16 [1:30pm] 1994 at 220 cycles

Remarks: (at 186 cycles)

MOST 'A's HAVE DAMAGE.

W-1 : HVY DAMAGE

W-2: BULGING SIDES

W-3 = HALF OF TOP FLAT [illegible] [illegible] OFF.

04.13, 08 a.m. About 30% water missing!

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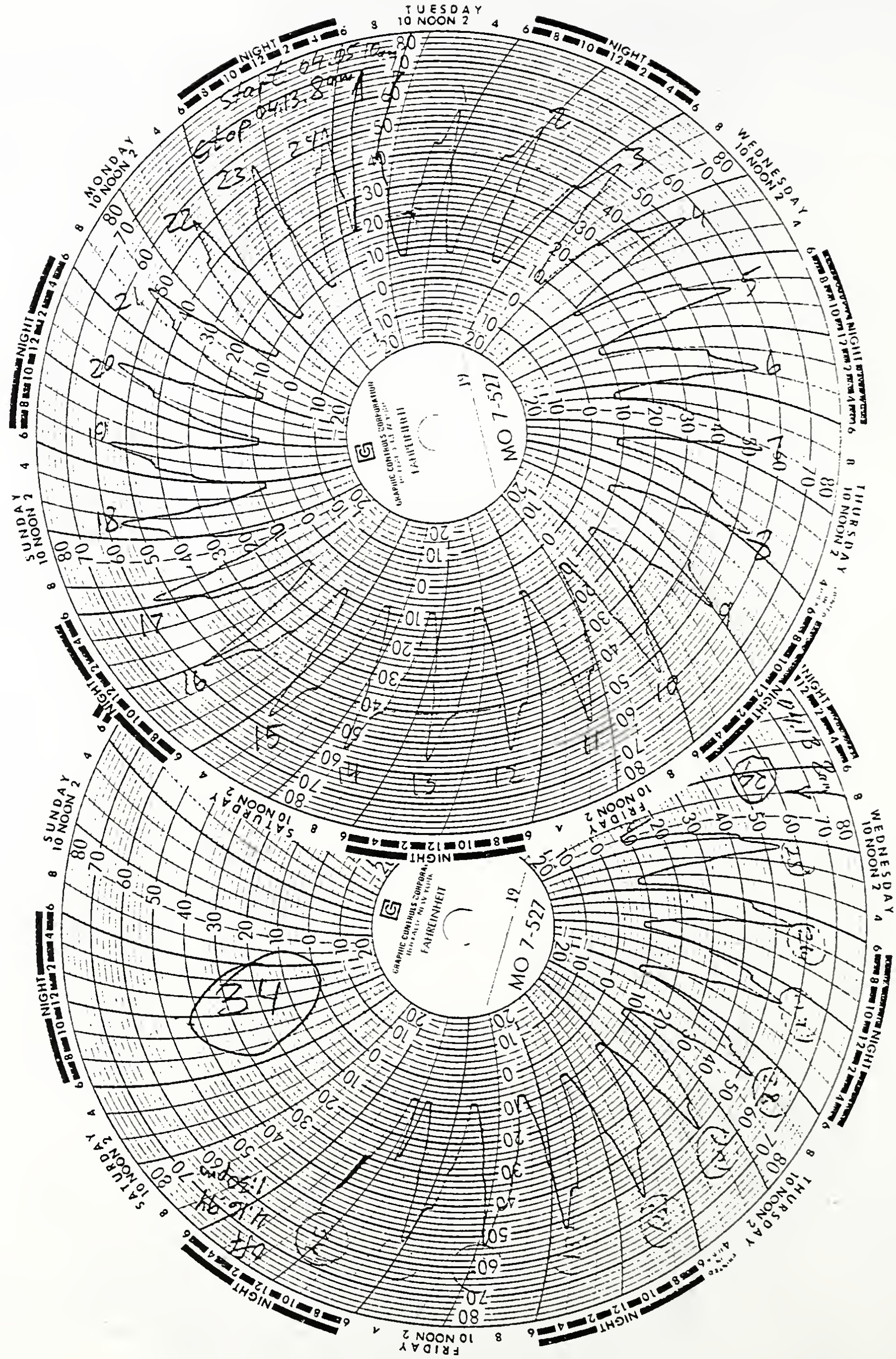
GRAPHIC CONTROLS CORPORATION
BUFFALO NEW YORK
FAHRENHEIT
MO 7-527
19
TUESDAY
WEDNESDAY
THURSDAY
FRIDAY
SATURDAY
SUNDAY
MONDAY
NOON
NIGHT
34

Controls

1	W-8 in air
2	AD-5
3	W-5 (T)
4	W-6
5	AD-1
6	NONE
7	W-7
8	AD-3
9	Reference
10	AD-7
11	W-4 (T)
12	W-1
13	W-2
14	AD-4 (T)
15	AD-2
16	W-3
17	AD-6
18	AD-6 in air

Positions of specimens in the freezing-and-thawing machine.

Started on April 17th 11:15am 1994
at 220 cycles

Changed on April 26, 1:00 p.m. 1994
at 250 cycles

Remarks: (at 220 cycles)

AD-2 - cracks visible on end of specimen
AD-3 - " " on both ends.

deck seperation on W-1, W-2, W-3

deterioration making V_2 unreadable
on W-3, W-6, W-7

W-3 pin removed during cycling

04.26.94 (at 250 cycles)

For next 30 cycles:

- relocate the specimens containing thermocouples:
  1. move W-5 from (3) to (5)
  2. move W-4 from (11) to (7)
  3. move AD-4 from (14) to (17)

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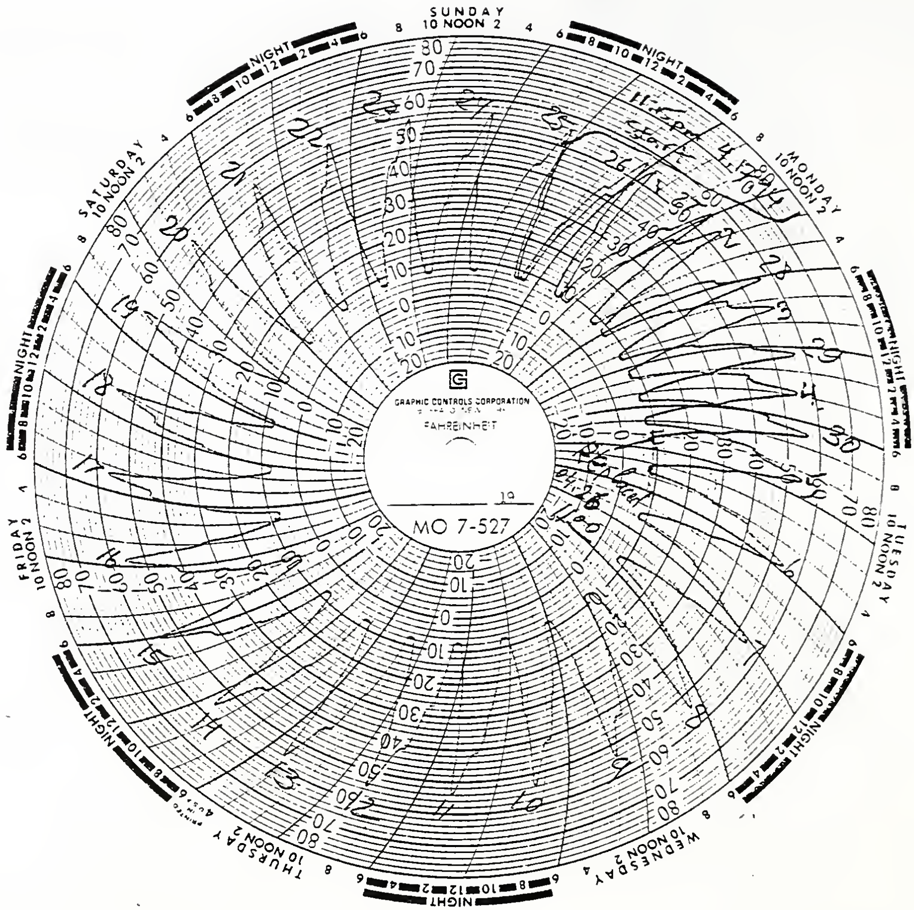

SUNDAY
MONDAY
TUESDAY
WEDNESDAY
THURSDAY
FRIDAY
SATURDAY
NIGHT
10 NOON 2
GRAPHIC CONTROLS CORPORATION
FAHRENHEIT
MO 7-527

Positions of specimens in the freezing-and-thawing machine.

Started on MAY 1, 1994 [1:00 PM] 1994
at 250 cycles

Changed on MAY 9, 1994 1994
at 280 cycles

	controls
1	W8 (AIR)
2	AD6
3	AD5
4	W2 CURED
5	W-5 (T)
6	NONE
7	W4 (T)
8	AD3
9	REF
10	W7
11	W1
12	AD1
13	AD7
14	W6
15	W3
16	AD2
17	AD4 (T)
18	AD 8 (AIR)

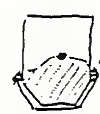
Remarks: 04.27.94

WET CURED SHOWING HEAVY DETERIATION. AIR DRIED SHOWING SMALL CRACKS.

04.28.94

All AD specimens taken out of the machine to allow some air drying.

- Significant amounts of water absorbed
- Cracks, mostly in the lowest third of the cross-section
- Swelling of protective silicon layer along deck edges (AD-1-5). Water accumulated mostly there.
- No cracks and minor water absorption in AD-6 & AD-7 (without deck).



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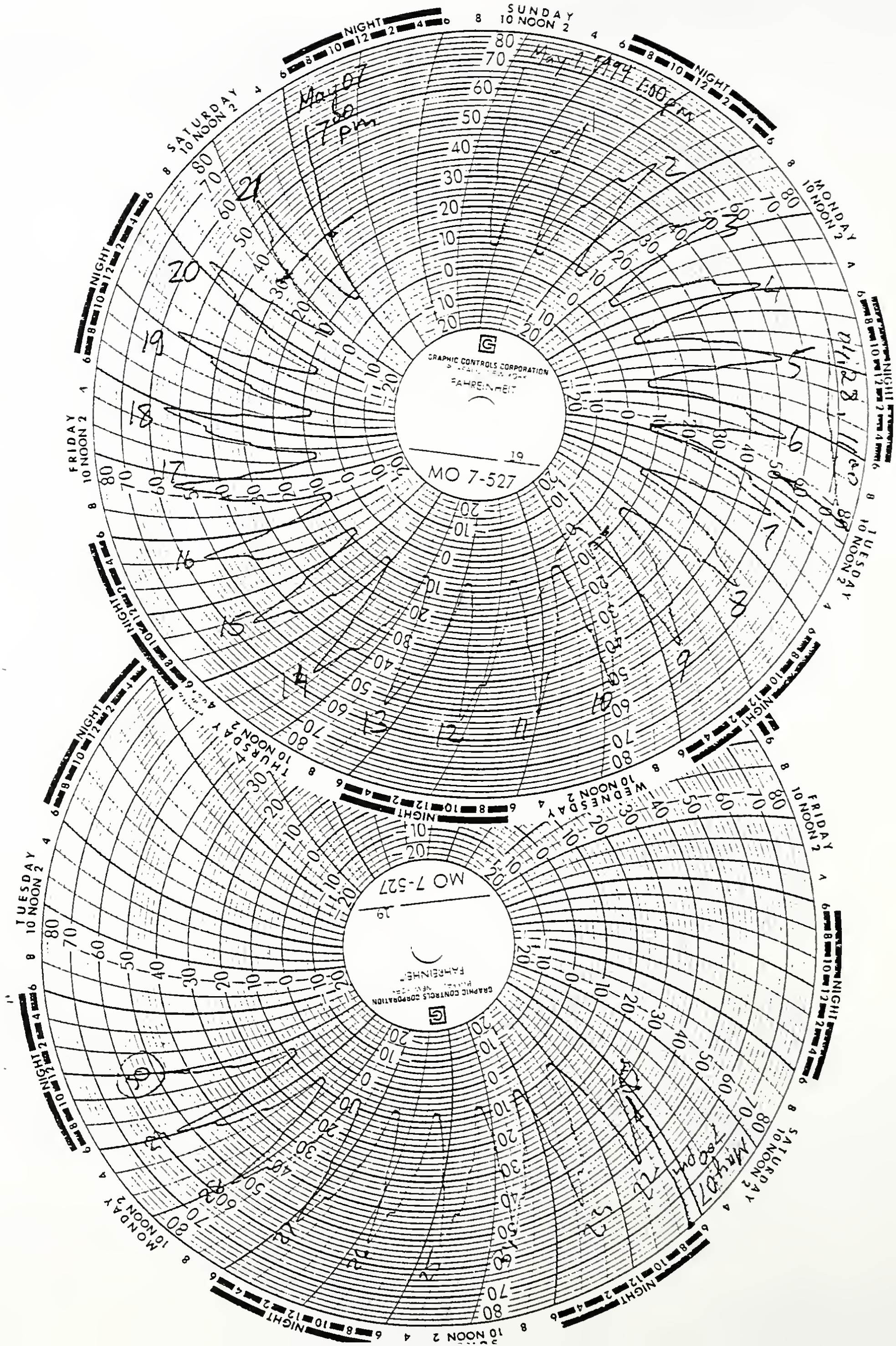
GRAPHIC CONTROLS CORPORATION
FAHRENHEIT
MO 7-527
May 1, 1994 1:00 pm
May 07 7 pm

Controls

1	W8 (AIR)
2	AD 6
3	AD 5
4	W 2 COATED
5	W-5 (T)
6	NONE
7	W-4 (T)
8	AD 3
9	REFERENCE
10	W-7
11	W-1
12	AD 1
13	AD 7
14	W 6
15	W 3
16	AD 2
17	AD 4 (T)
18	AD 8 (AIR)

Positions of specimens in the freezing-and-thawing machine.

Started on may 10, 1994 [7:00pm] 1994 at 280 cycles

Stopped ~~Changed~~ on may 16, 8:30am 1994 at 301 cycles

Remarks:

- pin breakout on AD-3, added silicon to missing pin area!
- severe crack  on AD-1.

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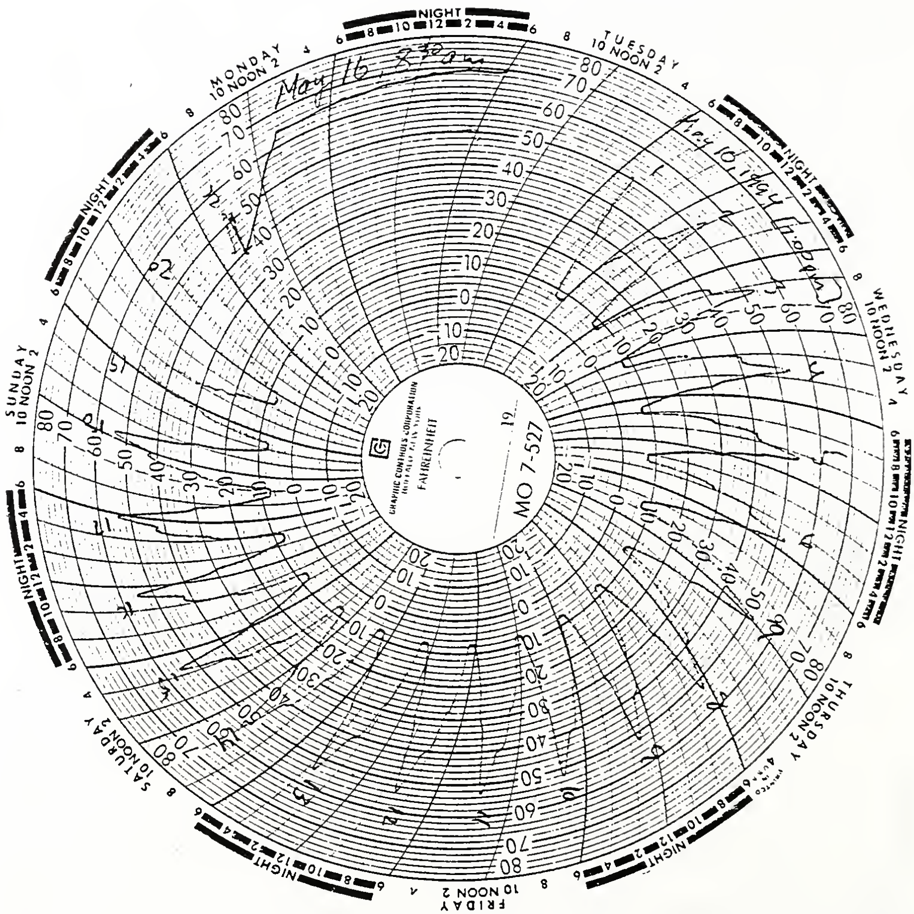
MONDAY
TUESDAY
WEDNESDAY
THURSDAY
FRIDAY
SATURDAY
SUNDAY
NIGHT
10 NOON 2
GRAPHIC CONTROLS CORPORATION
FAHRENHEIT
MO 7-527

APPENDIX D.

Measurements of weight, expansion and relative square pulse velocity
in 3"x4"x12" concrete specimens during freeze-thaw testing

before
25.1

Date: Jan 26, 94 Time: 7 p.m. Cycles: 0

Specimen:		Status: in water	open deck	closed deck	no deck	Pulse time, μS V_1	V_2	Length gage	Weight (g)
1.	AD-1	✓	✓			63.4	68.2	0.0492	5890.0
2.	AD-2	✓	✓			63.6	68.2	0.1423	5889.8
3.	AD-3	✓	✓			67.9	68.4	.0799	5827.4
4. Ⓣ	AD-4	✓		✓		68.0	68.6	—	—
5.	AD-5	✓		✓		68.0	67.8	—	5913.9
6.	AD-6	✓			✓	68.5	68.7	.0964	5623.4
7.	AD-7	✓			✓	68.7	68.8	0.0901	5724.8
8.	AD-8	no			✓	68.7	69.0	.1303	5507.6
						Length calibration: 0.0644			
9.	W-1	✓	✓			67.2	68.5	0.0968	5932.7
10.	W-2	✓	✓			68.5	65.6	0.0898	5943.0
11.	W-3	✓	✓			67.8	65.3	0.0833	5935.3
12. Ⓣ	W-4	✓		✓		68.5	68.2	—	—
13. Ⓣ	W-5	✓		✓		67.6	66.8	—	—
14.	W-6	✓			✓	66.8	67.3	0.1013	5684.4
15.	W-7	✓			✓	67.2	67.4	0.0077	5529.6
16.	W-8	no			✓	66.5	67.5	.0521	5668.1

A

Date: Feb.10,94 Time: 2 p.m. Cycles: 30

Specimen:		Status: in water	open deck	closed deck	no deck	Pulse time μS V_1	V_2	Length gage	Weight (g)
1.	AD-1	✓	✓			71.4	70.2	0.0467	5957.6
2.	AD-2	✓	✓	—	—	70.2	69.8	.1352	5767.5
3.	AD-3	✓	✓			70.4	69.6	0.0805	5895.5
4. Ⓣ	AD-4	✓		✓		Ⓣ	Ⓣ	—	—
5.	AD-5	✓		✓		70.5	70.6	—	5982.5
6.	AD-6	✓	—	—	✓	69.6	70.3	.0969	5651.9
7.	AD-7	✓	—	—	✓	71.7	71.8	0.0858	5755.7
8.	AD-8	NO	-		✓	72.8	71.0	.1067	5507.0
						Length calibration:	0.0842		
9.	W-1	✓	✓	—		69.3	69.5	0.0937	5946.0
10.	W-2	✓	✓	—		68.4	67.8	0.0889	5975.9
11.	W-3	✓	✓	—		67.8	68.2	0.0735	5951.3
12. Ⓣ	W-4			✓		Ⓣ	Ⓣ	—	—
13. Ⓣ	W-5	—	—	✓	—	Ⓣ	Ⓣ	—	—
14.	W-6	✓	—	—	✓	68.5	68.2	0.1008	5694.1
15.	W-7	✓	—	—	✓	68.4	69.3	0.0059	5537.7
16.	W-8	NO	—	—	✓	67.4	69.3	.0420	5613.8

Date: Feb 14 | Time: 3:00 | Cycles: 42

WEIGHT OF AIR DRIED AFTER SEALING ON FEB 13

Specimen:		Status: in water	open deck	closed deck	no deck	Pulse time µs V_1	V_2	Length gage	Weight g
1.	AD-1	✓	✓						5911.4
2.	AD-2	✓	✓						5732.6
3.	AD-3	✓	✓						5867.0
4. (T)	AD-4								—
5.	AD-5	✓		✓					5965.4
6.	AD-6	✓			✓				5282.6
7.	AD-7	✓			✓				5699.1
8.	AD-8	NO			✓				5490.8
						Length calibration:			
9.	W-1								
10.	W-2								
11.	W-3								
12.	W-4								
13.	W-5								
14.	W-6								
15.	W-7								
16.	W-8								

Date: FEB. 21, 1994 Time: 10:00 pm Cycles: 68

Specimen:		Status: in water	open deck	closed deck	no deck	Pulse time μS V_1	V_2	Length gage	Weight
1.	AD-1	✓	✓			72.0	70.7	0.0477	5962.4
2.	AD-2	✓	✓			71.8	70.8	0.1358	5749.6
3.	AD-3	✓	✓			73.3	71.5	0.0821	5886.9
4. (T)	AD-4	✓		✓		(T)	(T)	—	—
5.	AD-5	✓		✓		71.1	68.0	—	5978.6
6.	AD-6	✓			✓	71.5	71.8	0.0969	5631.3
7.	AD-7	✓			✓	72.6	73.6	0.0899	5706.7
8.	AD-8	NO			✓	72.4	73.8	0.1048	5499.5
						Length calibration: 0.0644 ⇒ ± 0.0000			
9.	W-1	✓	✓			67.4	68.4	0.0947	5951.9
10.	W-2	✓	✓			68.2	68.6	0.0915	5987.1
11.	W-3	✓	✓			67.6	68.8	0.0719	5957.0
12. (T)	W-4	✓		✓		(T)	(T)	—	—
13. (T)	W-5	✓		✓		(T)	(T)	—	—
14.	W-6	✓			✓	68.2	67.4	0.1022	5696.1
15.	W-7	✓			✓	68.4	67.5	0.0072	5543.7
16.	W-8	NO			✓	67.0	67.8	0.0500	5604.0

Date: Mar. 4, 1994 | Time: 4:15 pm | Cycles: 95

Specimen:		Status: in water	open deck	closed deck	no deck	Pulse time μs V_1	V_2	Length gage	Weight g
1.	AD-1	✓	✓			71.4	70.4	0.0480	5977.1
2.	AD-2	✓	✓			71.6	71.5	0.1354	5765.3
3.	AD-3	✓	✓			71.8	71.6	0.0830	5904.3
4. (T)	AD-4	✓		✓		(T)	(T)	—	—
5.	AD-5	✓		✓		71.5	70.3	—	5989.7
6.	AD-6	✓			✓	72.0	73.0	0.0965	5635.8
7.	AD-7	✓			✓	73.2	72.4	0.0897	5715.1
8.	AD-8	NO			✓	72.1	73.5	0.1061	5497.6
						Length calibration: 0.0642 = 7 + 0.0002			
9.	W-1	✓	✓			69.7	69.4	0.0961	5961.5
10.	W-2	✓	✓			69.1	71.0	0.0817	5994.2
11. *	W-3	✓	✓			69.0	71.1	0.0766	5966.4
12. (T)	W-4	✓		✓		(T)	(T)	—	—
13. (T)	W-5	✓		✓		(T)	(T)	—	—
14.	W-6	✓			✓	69.4	71.8	0.1137	5704.3
15.	W-7	✓			✓	68.3	70.3 ?	0.0084	5546.8
16.	W-8	NO			✓	67.4	66.8	0.0483	5536.2

A

Form K Approved for use in Purdue University

Date: 3/13/94 Time: 4:30 PM Cycles: 126

Specimen:		Status: in water	open deck	closed deck	no deck	Pulse time μS V_1	V_2	Length gage (NA)	Weight
1.	AD-1	✓	✓			70.9	71.2	.0388	5993.7
2.	AD-2	✓	✓			70.7	74.7	.1362	5786.3
3.	AD-3	✓	✓			70.7	72.0	.0729	5924.6
4. Ⓣ	AD-4	✓		✓		Ⓣ	Ⓣ	—	—
5.	AD-5	✓		✓		70.3	69.3	—	6001.9
6.	AD-6	✓			✓	71.8	71.8	.0972	5638.9
7.	AD-7	✓			✓	72.6	71.6	.1128	5720.1
8.	AD-8	NO			✓	72.8	73.0	.1056	5497.4
						Length calibration:		.0636	
9.	W-1	✓	✓			69.0	74.4	.0979	5967.5
10.	W-2	✓	✓			68.6	78.9?	.0841	6008.9
11.	W-3	✓	✓			67.6	64.7	.0786	5975.5
12. Ⓣ	W-4	✓		✓		Ⓣ	Ⓣ	—	—
13. Ⓣ	W-5	✓		✓		Ⓣ	Ⓣ	—	—
14.	W-6	✓			✓	67.2	71.0	.1158	5685.3
15.	W-7	✓			✓	70.6	74.8	.0038	5555.5
16.	W-8	NO			✓	67.8	67.3	.0426	5577.1

Date: 3/14/94 | Time: 8:30pm | Cycles: 126

Specimen:		Status: in water	open deck	closed deck	no deck	Pulse time μs V_1	V_2	Length gage	Weight
1.	AD-1	✓	✓			~~70.8~~	—	~~.0489~~	~~5993.7~~
2.	AD-2	✓	✓			74.3	80.5	.1372	5786.5
3.	AD-3	✓	✓			76.3	78.1	.0735	5924.5
4. (T)	AD-4	✓		✓		(T)	(T)	—	—
5.	AD-5	✓		✓		70.7	77.9	—	6001.5
6.	AD-6	✓			✓	71.7	70.8	.0967	5638.2
7.	AD-7	✓			✓	74.3	74.0	.0891	5721.2
8.	AD-8	NO			✓	72.5	74.6	.1055	5496.4
						Length calibration: .0642 ?			
9.	W-1	✓	✓			69.8	—	.0983	5963.5
10.	W-2	✓	✓			69.5	—	.0944	6003.9
11.	W-3	✓	✓			68.5	81.8	0.0872	5972.0
12. (T)	W-4	✓		✓		(T)	(T)	—	—
13. (T)	W-5	✓		✓		(T)	(T)	—	—
14.	W-6	✓			✓	70.7	79.7	.1167	5679.3
15.	W-7	✓			✓	71.0	78.5	.0082	5551.7
16.	W-8	NO			✓	68.7	68.8	.0490	5576.0

Date: 3/15/94 Time: 3:15 pm Cycles: 126

Specimen:		Status: in water	open deck	closed deck	no deck		Weight 03.21.94 2:45pm	Weight 03.17.94 08:45 a.m.	Weight 03.15.94
1.	AD-1						5976.6	5984.1	5988.6
2.	AD-2						5768.1	5777.1	5782.3
3.	AD-3						5905.4	5914.8	5920.1
4. (T)	AD-4								—
5.	AD-5						5988.1	5994.6	5998.4
6.	AD-6						5629.1	5634.0	5636.9
7.	AD-7						5709.3	5715.1	5718.5
8.	AD-8						5493.6	5495.6	5496.7
						Length calibration:			
9.	W-1								
10.	W-2								
11.	W-3								
12.	W-4								
13.	W-5								
14.	W-6								
15.	W-7								
16.	W-8								

Date: 3/28/94 Time: 7:40 Cycles: 156

Specimen:		Status: in water	open deck	closed deck	no deck	Pulse time μS V_1	V_2	Length gage	Weight
1.	AD-1	✓	✓			69.9	—	0.0495	6006.4
2.	AD-2	✓	✓			69.3	76.6	.1382	5803.4
3.	AD-3	✓	✓			69.6	77.4	.0740	5941.3
4. (T)	AD-4	✓		✓		(T)	(T)	—	—
5.	AD-5	✓		✓		68.5	69.4	—	6007.3
6.	AD-6	✓			✓	71.4	69.3	0.0957	5632.4
7.	AD-7	✓			✓	70.2	70.0	0.0875	5715.4
8.	AD-8	NO			✓	71.3	73.3	0.1050	5485.3
						Length calibration: .0642			
9.	W-1	✓	✓			70.4	—	0.1007	5979.6
10.	W-2	✓	✓			73.3	—	0.0976	6017.2
11.	W-3	✓	✓			66.8	79.8	0.0909	5978.9
12. (T)	W-4	✓		✓		(T)	(T)	—	—
13. (T)	W-5	✓		✓		(T)	(T)	—	—
14.	W-6	✓			✓	67.7	84.4	0.1202	5685.4
15.	W-7	✓			✓	70.0	83.3	0.0088	5558.4
16.	W-8	NO			✓	68.4	69.6	0.0470	5571.7

Date: 4/06/94 Time: 8:30AM Cycles: 186

Specimen:		Status: in water	open deck	closed deck	no deck	Pulse time µS V₁	V₂	Length gage	Weight
1.	AD-1	✓	✓			~~68.5~~	—	~~.0405~~	~~6028.7~~
2.	AD-2	✓	✓	—	—	68.7	88.8	.1320	5536.8
3.	AD-3	✓	✓	—	—	69.4	91.7	.2762	5979.0
4. (T)	AD-4	✓		✓		(T)	(T)	—	—
5.	AD-5	✓	—	✓	—	68.5	69.7	—	6024.6
6.	AD-6	✓	—	—	✓	69.8	69.6	0.0950	5636.1
7.	AD-7	✓	—	—	✓	71.6	71.6	.0882	5720.0
8.	AD-8	NO		-	✓	73.7	72.7	0.1055	5488.5
						Length calibration: .0640			
9.	W-1	✓	✓	—		72.6	—	0.1047	5971.3
10.	W-2	✓	✓	—		77.6	—	0.1010	6027.2
11.	W-3	✓	✓	—		67.8	105.5	.0968	5954.3
12. (T)	W-4	✓		✓		(T)	(T)	—	—
13. (T)	W-5	✓	—	✓	—	(T)	(T)	—	—
14.	W-6	✓	—	—	✓	70.3	106.6	0.1232	5644.3
15.	W-7	✓	-	—	✓	73.7	104.8	.0132	5522.7
16.	W-8	NO	—	—	✓	67.3	67.1	0.0455	5566.8

Date: 4/17/94 Time: 6:30 pm Cycles: 220

Specimen:		Status: in water	open deck	closed deck	no deck	Pulse time µS V_1	V_2	Length gage	Weight
1.	AD-1	✓	✓			69.0	—	.0490	6049.6
2.	AD-2	✓	✓			70.0	77.8	.1472	5860.7
3.	AD-3	✓	✓			72.7	—	.0820	6007.0
4. (T)	AD-4	✓		✓		(T)	(T)	—	—
5.	AD-5	✓		✓		69.2	73.2	—	6047.9
6.	AD-6	✓			✓	70.5	70.4	.0958	5637.9
7.	AD-7	✓			✓	72.3	71.4	.0885	5723.0
8.	AD-8	NO			✓	72.5	73.5	.1048	5487.1
						Length calibration:			
9.	W-1	✓	✓			96.4	deteriorated	.1090	5944.3
10.	W-2	✓	✓			105.6	deteriorated	.1072	6013.5
11.	W-3	✓	✓			72.7	deteriorated	deteriorated	5889.7
12. (T)	W-4	✓		✓		(T)	(T)	—	—
13. (T)	W-5	✓		✓		(T)	(T)	—	—
14.	W-6	✓			✓	74.2	deteriorated	.1310	5433.2
15.	W-7	✓			✓	84.8	deteriorated	.0205	5423.5
16.	W-8	NO			✓	70.5	69.8	.0460	5562.2

Date: April 27 | Time: 4:00 PM | Cycles: 250

Specimen:		Status: in water	open deck	closed deck	no deck	Pulse time μS V_1	V_2	Length gage	Weight
1.	AD-1	✓	✓			70.8	—	.0481	6060.8
2.	AD-2	✓	✓			74.4	79.8	.1557	5876.4
3.	AD-3	✓	✓			73.4	—	.0903	6029.4
4. (T)	AD-4	✓		✓		(T)	(T)	—	—
5.	AD-5	✓		✓		68.3	74.3	—	6064.2
6.	AD-6	✓			✓	68.3	69.3	.0967	5629.4
7.	AD-7	✓			✓	70.7	70.0	.0885	5727.7
8.	AD-8	NO			✓	72.7	75.1	.1052	5487.2
						Length calibration: .640			
9.	W-1	✓	✓			91.8	D	.1087	5906.1
10.	W-2	✓	✓			D	D	D	5802.2
11.	W-3	✓	✓			71.4	D	D	5775.9
12. (T)	W-4	✓		✓		(T)	(T)	—	—
13. (T)	W-5	✓		✓		(T)	(T)	—	—
14.	W-6	✓			✓	72.9	D	.1407	5253.9
15.	W-7	✓			✓	81.7	D	.0280	5262.0
16.	W-8	NO			✓	69.0	69.8	.0366	5555.9

D = DETERIORATED

Date: MAY 1, 1994 Time: 12:30 pm Cycles: 250

Weight after drying AD and resealing specimens.

Specimen:		Status: in water	open deck	closed deck	no deck	Pulse time μs V_1	V_2	Length gage	Weight
1.	AD-1								6109.2
2.	AD-2								5883.0
3.	AD-3								6008.4
4. (T)	AD-4								—
5.	AD-5								6105.9
6.	AD-6								5634.2
7.	AD-7								5723.0
8.	AD-8								5488.3
9.	W-1								
10.	W-2								
11.	W-3								
12.	W-4								
13.	W-5								
14.	W-6								
15.	W-7								
16.	W-8								

Date: 05/10/94 Time: 4:45 PM Cycles: 280

Specimen:		Status:				Pulse time μS		Length gage	Weight
		in water	open deck	closed deck	no deck	V_1	V_2		
1.	AD-1	✓	✓			[illegible]	—	.0512	6173.2
2.	AD-2	✓	✓	—		79.6	110.4	.1659	5963.2
3.	AD-3	✓	✓			80.0	—	deteriorated D	6123.3
4. (T)	AD-4	✓		✓		(T)	(T)	—	—
5.	AD-5	✓	—	✓		76.4	85.5	—	6142.0
6.	AD-6	✓		—	✓	70.0	69.9	.0962	5638.1
7.	AD-7	✓			✓	71.0	71.3	.0888	5732.2
8.	AD-8	NO			✓	72.8	75.0	.1049	5486.2
						Length calibration: .638			
9.	W-1	✓	✓			D	D	.1124	5885.6
10.	W-2	✓	✓			D	D	D	5524.4
11.	W-3	✓	✓			72.7	D	D	5647.2
12. (T)	W-4	✓		✓		(T)	(T)	—	—
13. (T)	W-5	✓		✓		(T)	(T)	—	—
14.	W-6	✓	—		✓	73.7	D	.1486	5065.9
15.	W-7	✓			✓	82.4	D	.0400	5126.8
16.	W-8	NO			✓	70.2	70.7	.0360	5554.5

Date: 5-16-94 Time: 8:41 pm Cycles: 301

Specimen:		Status: in water	open deck	closed deck	no deck	Pulse time μs V_1	V_2	Length gage	Weight
1.	AD-1	✓	✓			~~82.8~~	—	.0600	6190.0
2.	AD-2	✓	✓			82.6	155.4	.1755	5984.0
3.	AD-3	✓	✓			80.0	—	D	6150.7
4. (T)	AD-4	✓		✓		(T)	(T)	—	—
5.	AD-5	✓		✓		80.8	108.8	—	6154.3
6.	AD-6	✓			✓	69.6	69.6	.0967	5642.1
7.	AD-7	✓			✓	71.0	71.4	.0882	5740.7
8.	AD-8	NO			✓	73.6	74.8	.1050	5484.1
						Length calibration: 0.0640			
9.	W-1	✓	✓			D	D	.1235	5824.9
10.	W-2	✓	✓			D	D	D	5329.8
11.	W-3	✓	✓			76.8	D	D	5515.9
12. (T)	W-4	✓		✓		(T)	(T)	—	—
13. (T)	W-5	✓		✓		(T)	(T)	—	—
14.	W-6	✓			✓	75.5	D	.1540	4605.7
15.	W-7	✓			✓	88.8	D	.0462	4765.2
16.	W-8	NO			✓	70.4	71.3	.0360	5553.0

COVER DESIGN BY ALDO GIORGINI