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EVALUATION OF CONCRETE AND AGGREGATE DURABILITY TEST

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16. Abstract

This study was to determine the test configuration of ASTM C 666, "Resistance of Concrete to Rapid Freezing and Thawing", that could best be used to identify aggregates having frost susceptible characteristics. A special piece of equipment was designed and constructed with specific emphasis on its capability to meet both procedures of ASTM C 666 and to be programmable to give flexibility in duration of freeze and thaw periods. To test the machine's capability and to determine the best test method to use, three types of coarse aggregate moisture treatment, three durations of concrete beam curing, and two durations of freezing-and-thawing cycle for both Procedure A, Rapid Freezing and Thawing in Water, and Procedure B, Rapid Freezing in Air and Thawing in Water, were evaluated.

ASTM C 666, Procedure B, with a five-hour nominal test cycle using 24-hour-soak moisture treatment of the coarse aggregate and 35-day cure of concrete beams was chosen to be Missouri's standard method for rapid freeze and thaw testing.

Previously, 100 cycles of manual freeze-thaw testing required 2 years and 800 man-hours to complete after beams were made. With the new equipment, results can be obtained in 90 days with only 160 man hours.

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EVALUATION OF CONCRETE AND AGGREGATE DURABILITY TEST

STUDY 86-1

Prepared By

MISSOURI HIGHWAY AND TRANSPORTATION DEPARTMENT

DIVISION OF MATERIALS AND RESEARCH

JANUARY 1993

In Cooperation With

U. S. DEPARTMENT OF TRANSPORTATION

FEDERAL HIGHWAY ADMINISTRATION

The opinions, findings, and conclusions expressed in this publication are not necessarily those of the Federal Highway Administration.

EVALUATION OF CONCRETE AND AGGREGATE DURABILITY TEST

EXECUTIVE SUMMARY

This study was to determine the test configuration of ASTM C 666, "Resistance of Concrete to Rapid Freezing and Thawing", that could best be used to identify aggregates having frost susceptible characteristics. A special piece of equipment was designed and constructed with specific emphasis on its capability to meet both procedures of ASTM C 666 and to be programmable to give flexibility in duration of freeze and thawing periods. To test the machine's capability and to determine the best test method to use, three types of coarse aggregate moisture treatment, three durations of concrete beam curing, and two durations of freezing-and-thawing cycle for both Procedure A, Rapid Freezing and Thawing in Water, and Procedure B, Rapid Freezing in Air and Thawing in Water, were evaluated.

Concrete freeze and thaw test beams and flexural strength beams were made from four types of coarse aggregates of varying durability and field performance histories. Beams were tested for weight change, length change, and relative dynamic modulus of elasticity each work day. Beams were subjected to freezing and thawing for 300 cycles or until a 40 percent loss in dynamic modulus of elasticity, whichever came first.

ASTM C 666, Procedure B, with a five-hour nominal test cycle using 24-hour-soak moisture treatment of the coarse aggregate and 35-day cure of concrete beams will be Missouri's standard method for rapid freeze and thaw testing.

Previously, 100 cycles of freeze-thaw testing required 2 years and 800 man-hours to complete after beams were made. With the new equipment, results can be obtained in 90 days with only 160 man hours. The new freezing and thawing equipment will provide results faster and more efficiently. It also allows flexibility if tests need to be performed with different cycle characteristics.

TABLE OF CONTENTS

List of Abbreviations ii

List of Tables iv

List of Figures v

Introduction 1

Experimental Design and Test Procedures 2

Equipment 7

Results and Discussion 8

General 8

Analysis of Variance, by Aggregates 11

Analysis of Variance, by Test Method Variables . . . 18

Regression of Results 21

Correlation Between Length Change and Durability Factor 25

Changes in Weight, Length, and Modulus of Elasticity During Cure 28

ASTM C 666 Versus AASHTO T 161 31

Cost Benefit 31

Conclusions 33

Implementation 34

References 35

Appendix A (Materials, Mix Design, Batch Characteristics, Batching Sequence, and Concrete Beam Identification). . . 36

Appendix B (A3 Series' Data) 45

Appendix C (A5 Series' Data) 50

Appendix D (B3 Series' Data) 55

Appendix E (B5 Series' Data) 60

LIST OF ABBREVIATIONS

Abbreviation	Name
ANOVA	Analysis of Variance
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
A3	Procedure A using a nominal 3-Hour Cycle
A5	Procedure A using a nominal 5-Hour Cycle
BF	Bethany Falls
B3	Procedure B using a nominal 3-Hour Cycle
B5	Procedure B using a nominal 5-Hour Cycle
Co.	Company
CV%	Coefficient of Variation, in percent
D	Day
DF	Durability Factor
Hr.	Hour(s)
$K_{0.05}$	Value of Minimum Significant Difference by Tukey's Statistical Test Method at a 5% Significance Level
Ls.	Limestone
Mo.	Missouri
Min.	Minute(s)
mm	Millimeter(s)
N.A.	Not Applicable
P	Relative Dynamic Modulus of Elasticity
psi	Pounds per square inch
R	Correlation Coefficient

LIST OF ABBREVIATIONS (continued)

R¬2	Coefficient of Determination (R^2)
Sat.	Saturation
Str.	Strength
$S_{y.x}$	Standard Error of Estimate
t	Total time
t_c	Freezing time from 0 to 40°F
temp.	Temperature
t_w	Thawing time from 40 to 0°F
Vac.	Vacuum
Vs.	Versus

LIST OF TABLES

Table 1	-	Example of Anova Results With Tukey's Test Calculated on Durability Factors . .	13
Table 2	-	Summary of Anova and Tukey's Test Results for Durability Factors	14
Table 3	-	Summary of Anova and Tukey's Test Results for Percent Length Change Per Cycle . . .	15
Table 4	-	Summary of Anova and Tukey's Test Results for Weight Change in Grams Per Cycle . . .	16
Table 5	-	Summary of Anova and Tukey's Test Results By Test-Method Variables	20
Table 6	-	Correlation Coefficients for Percent Length Change Per Cycle to Durability Factors	27
Table 7	-	Effects of Cure Duration Upon Weight, Length, and Relative Modulus	29
Table A1	-	Physical Properties of Coarse Aggregate	40
Table A2	-	Physical Properties and Gradation of Fine Aggregate	41
Table A3	-	Sources and Properties of Blended Cement	42
Table A4	-	Concrete Mix-Design Factors and Characteristics of Fresh Concrete	43
Table A5	-	Randomized Batching Sequence	44
Table B1	-	Cycle Characteristics (A3 Series)	47
Table B2	-	Summary of Test Results (A3 Series) . . .	48
Table C1	-	Cycle Characteristics (A5 Series)	52
Table C2	-	Summary of Test Results (A5 Series) . . .	53
Table D1	-	Cycle Characteristics (B3 Series)	57
Table D2	-	Summary of Test Results (B3 Series) . . .	58
Table E1	-	Cycle Characteristics (B5 Series)	62
Table E2	-	Summary of Test Results (B5 Series) . . .	63

LIST OF FIGURES

Figure 1 - Experimental Design for Freezing-and-Thawing Study 4

Figure 2 - Durability Factors by Series, Saturation, and Cure Duration 9

Figure 3 - Percent Length Changes Per Cycle by Series, Saturation, and Cure 10

Figure 4 - Relative Modulus Vs. Percent Flexural Strength Reduction For All Test Beams (At End of Test) 22

Figure 5 - Percent Length Change Vs. Percent Flexural Strength Reduction For All Test Beams 23

Figure 6 - Weight Change Vs. Percent Flexural Strength Reduction For All Test Beams . . 24

Figure 7 - Correlation Between Length Change and Durability For All Test Beams. 26

Figure 8 - Average Effects of Cure Duration Upon Weight, Length, and Dynamic Modulus of Elasticity 30

Figure B1 - Typical Freezing-and-Thawing Cycle (A3 Series) 46

Figure B2 - Relative Modulus Vs. Cycles of Freezing and Thawing (A3 Series) 49

Figure C1 - Typical Freezing-and-Thawing Cycle (A5 Series) 51

Figure C2 - Relative Modulus Vs. Cycles of Freezing and Thawing (A5 Series) 54

Figure D1 - Typical Freezing-and-Thawing Cycle (B3 Series) 56

Figure D2 - Relative Modulus Vs. Cycles of Freezing and Thawing (B3 Series) 59

Figure E1 - Typical Freezing-and-Thawing Cycle (B5 Series) 61

Figure E2 - Relative Modulus Vs. Cycles of Freezing and Thawing (B5 Series) 64

INTRODUCTION

Previously, durability and expansion of concrete have been determined by manually loading concrete beam specimens on racks in a walk-in freezer and then transferring them to a tank filled with 40°F water for thawing. The beams were subjected to two cycles per day in the "fast" method or to one cycle per week in the "slow" method. Both methods were labor-intensive and took one to two years to complete. Neither cycle met the cycling rate requirements of ASTM C 666, "Resistance of Concrete to Rapid Freezing and Thawing" [1].

A survey of different federal and state agencies showed that although many agencies used ASTM C 666, there was little concensus of specific test procedure[2]. ASTM C 666 allows for either freezing and thawing in water (Procedure A), or freezing in water and thawing in air (Procedure B). The specified cycle time can be from two to five hours. A cure duration other than 14 days is allowed. Neither ASTM C 666, nor other applicable ASTM Standards, prescribe the aggregate moisture content or conditioning except that it is to be definite and uniform.

Missouri acquired an automatic freezing-and-thawing unit for testing concrete beam specimens. This testing unit is capable of adjustments within the allowable limits of ASTM C 666 for either Procedure A or Procedure B.

This study was to determine, using this equipment, the preferred test method and cycle that complies with ASTM C 666, that would discriminated among beams made with different coarse aggregates and that would best evaluate field serviceability of coarse aggregates.

EXPERIMENTAL DESIGN AND TEST PROCEDURES

The test-method variables evaluated in this study were as follows:

Moisture treatment of the coarse aggregate (three levels)

1. Air drying, by raking till constant moisture content,
2. 24 hour soaking, in accordance with ASTM C 192, and
3. vacuum saturation, at 16 mm of mercury for 20 minutes, preceded by oven drying.

Duration of concrete beam cure (three levels)

Removed molds after one day of curing in moist room and placed in saturated lime water at about 73°F for an additional:

1. 13 days,
2. 34 days, and
3. 90 days.

Method of freezing and thawing, per ASTM C 666 (two levels)

1. Procedure A, freezing and thawing in water, and
2. Procedure B, freezing in water and thawing in air.

Nominal duration of the freezing-and-thawing cycle (two levels)

1. 3 hours, and
2. 5 hours.

The study was divided into four series, combining the variables of freezing-and-thawing method and nominal cycle duration. The series were identified and run in the following order: Procedure B with a nominal three-hour cycle time (B3), Procedure A with a nominal three-hour cycle time (A3), Procedure A with a nominal five-hour cycle time (A5), and Procedure B with a nominal five-hour cycle time (B5).

Four sources of crushed limestone were selected as coarse aggregate for making the concrete beams. Specifically, the aggregates chosen were one from Callaway, one from Plattin, and two from Bethany Falls formations. Although the purpose of this study was not to evaluate the coarse aggregates, the four were chosen, from experience, as aggregates with varying durability and field performance histories. The sources were:

1. Beck Materials Co. at Holts Summit, MO (Callaway ls.)
2. Missouri Rock Co., Inc. at Missouri City, MO (Bethany Falls limestone)
3. Southeast Mo. Stone Co. at Cape Girardeau, MO (Plattin limestone), and
4. Hunt Midwest Mining Co. at Randolph, MO (Bethany Falls limestone).

Except for the air-dry moisture "treatment", a complete factorial, with three replicate concrete beams per combination, was performed for each level of test variable and coarse aggregate. Beams made with air-dried coarse aggregate had only the fourteen day cure since it was believed the longer cures would have a saturating effect similar to the twenty-four hour soak; in addition, one of the Bethany Falls formations was excluded from air-dry moisture treatment due to lack of aggregate and freezing-and-thawing chamber space. This provided for a factorial of 324 test beams, as shown in Figure 1.

Replicate test beams were made from separate, randomized batches of concrete, as detailed in Appendix A, except for the beams made with air-dried coarse aggregate. As explained by

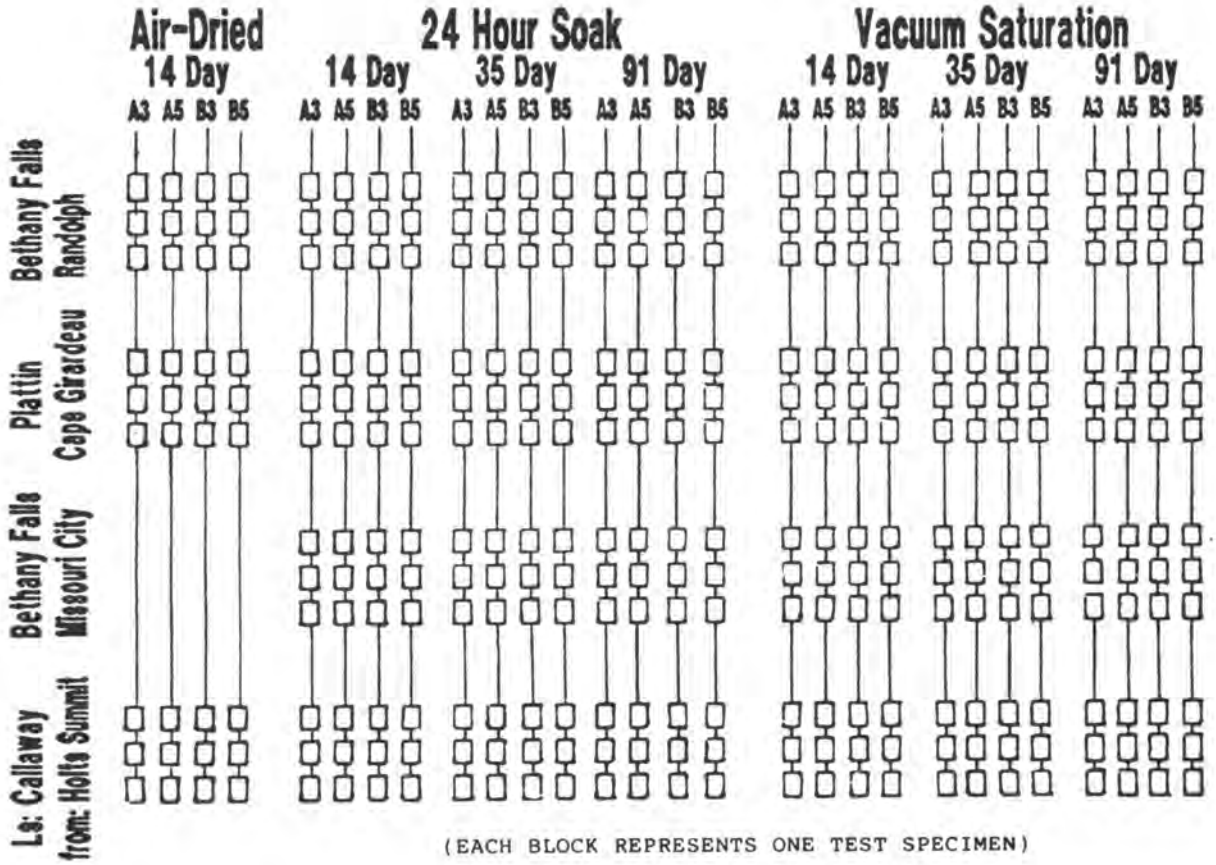


Figure 1. Experimental Design for Freeze-Thaw Study

Irick and Blackburn[3], randomization is necessary to validate probability statements which accompany an analysis of variance.

From each concrete batch, air content and slump were determined in accordance with ASTM C 231 and C 143, then three test beams and three flexural strength beams were made in accordance with ASTM C 192. Beam dimensions were 3½ by 4½ by 16 inches. Gage studs were cast in the ends of the test beams in accordance with ASTM C 490 giving an effective gage length of 14.0625 inches.

Test beams and their companion flexural strength beams were cured together in 73°F ± 3°F saturated lime water. Each week during the cure process, all beams were tested for weight, length, and fundamental transverse frequency. Immediately after the specified cure period, test beams were pre-conditioned to 40°F in water, tested as above, and placed in the freezing-and-thawing chamber. The companion flexural strength beams, still at about 73°F, were tested by center point loading.

The test beams were removed from the freeze and thaw chamber and tested once each work day. The beams were rotated in the chamber as they were replaced after testing. Weight change, length change and relative dynamic modulus of elasticity were calculated. The beams were subjected to freezing and thawing for three hundred cycles or until a 40 percent loss in dynamic modulus of elasticity, whichever came first. The beams were then removed from test and placed in saturated lime water until they reached 73°F ± 3°F and then were tested to determine their residual flexural strength by center point loading.

Center-point flexural tests were performed according to ASTM C 293 with the following exception. The beams were broken by laying the beams on their side whereby the 3 1/2 inch dimension becomes the depth of the beam over a span of 14 inches. Although this procedure does not exactly meet ASTM C 293, which states that the test span be three times the beam depth, it has been shown to correlate well with loss in dynamic modulus in past Missouri freezing-and-thawing studies.

Concrete for this study was designed with a cement factor of 6.1 sacks per cubic yard to correspond with mid-range for

portland cement concrete pavement under Missouri's Standard Specifications. Appendix A contains material, batching, and other mix-design information.

Detailed cycle characteristics and results of the tests made on the beams are given in Appendices B through E for the four series of freezing-and-thawing tests.

EQUIPMENT

The freezing-and-thawing unit used was a Cincinnati Sub-Zero Products top-loading model FT-37-705-S/AC, purchased in 1986. The machine's capacity is 48 beams when operating using ASTM C 666 Procedure A, Rapid Freezing and Thawing in Water, and 60 beams when operating using Procedure B, Freezing in Air and Thawing in Water, inclusive of a beam in which a Type T thermocouple for temperature measurement was embedded. All specimens were oriented vertically in the chamber. The unit is automated by a Micristar temperature programmer/controller system and a Honeywell multi-point strip chart recorder.

For Procedure A, the heat-transfer fluid used was a mixture of DOWTHERM SR-1®, manufactured by Dow Chemical Company, and deionized water. Containers which held the test beams submersed in one to three millimeters of tap water, were constructed from 20 gauge stainless steel with one inch flexible seams of rubber stripping on two sides and bottom. Rubber seams were designed to provide flexibility as required by ASTM C 666.

A horizontal length comparator and an invar reference bar were made to conform to ASTM C 490. The comparator was equipped with a dial micrometer graduated to read in 0.0001-inch units. The reference bar was used to standardize the comparator and correct for any fluctuation of room temperature.

Apparatus and procedure for measuring fundamental transverse frequencies and calculation of dynamic Young's modulus of elasticity were in accordance with ASTM C 215.

RESULTS AND DISCUSSION

General

This study was to choose (1) the coarse-aggregate moisture treatment, (2) duration of specimen curing, (3) duration of freezing-and-thawing cycle and (4) ASTM C 666 procedure that best discriminated among the beams made from the four coarse aggregates used in this study.

A durability factor, a percent length change per cycle and a weight change per cycle was calculated for each test beam after terminating it from freezing-and-thawing testing. Results of the three replicate beams per each combination of variables were averaged. Figures 2 and 3 graphically depict these average values for durability factors and percent length change per cycle.

As stated in ASTM C 666, durability factors are calculated by multiplying the relative dynamic modulus of elasticity by the number of cycles the beam was in test and dividing by the maximum allowed number of cycles of exposure (300 in this study). In Figure 2, the reference line at 60 percent indicates which test beams went below the 60 percent relative modulus within 300 cycles.

Although it might appear by looking at Figure 2, for example, which combinations of the test method variables produced a good range in durability factors between the aggregates, it does not take into account variability between the replicate beams. Therefore, analysis of variance was used to determine where the differences among the average test results were

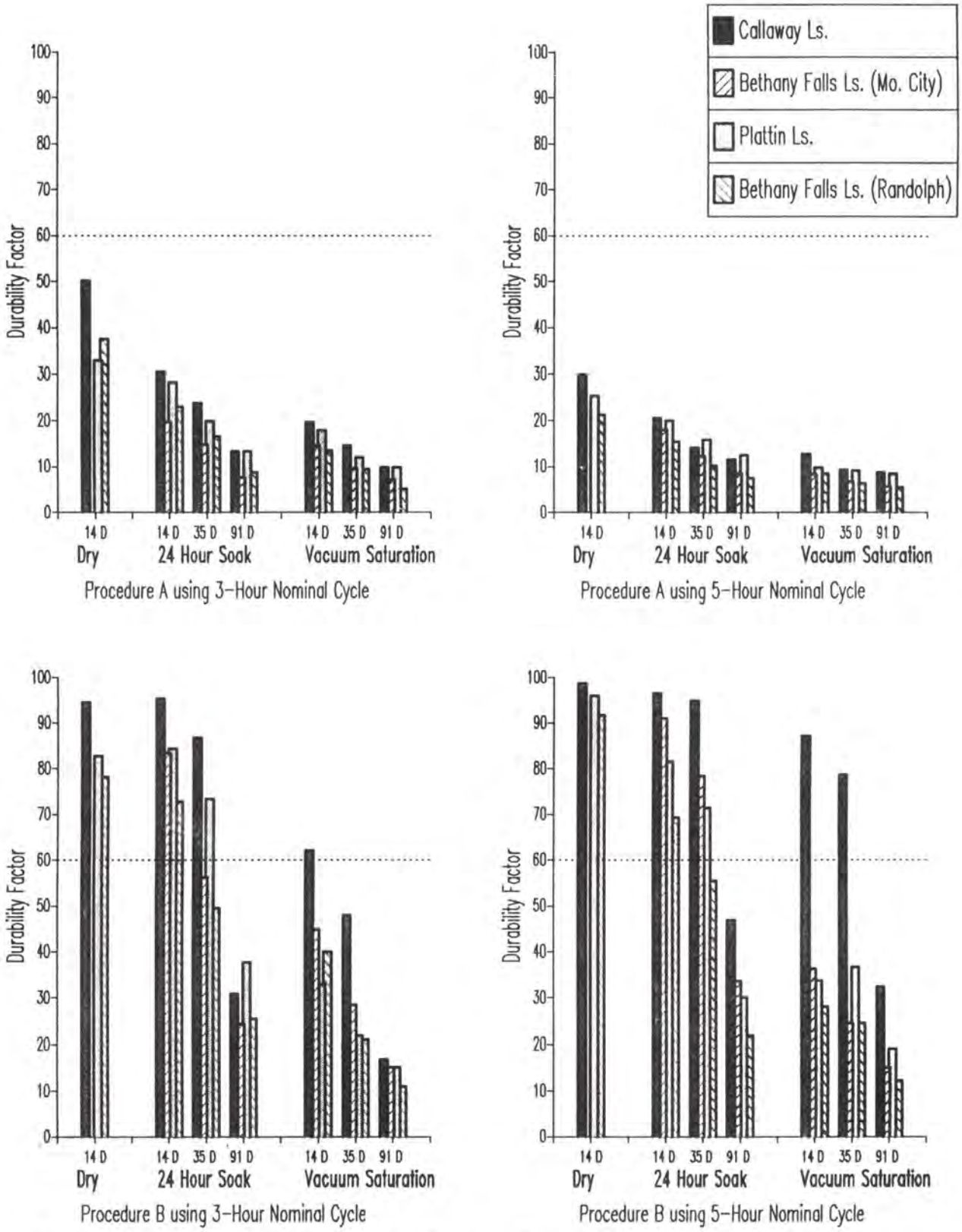


Figure 2. Durability Factors by Series, Saturation, and Cure Duration

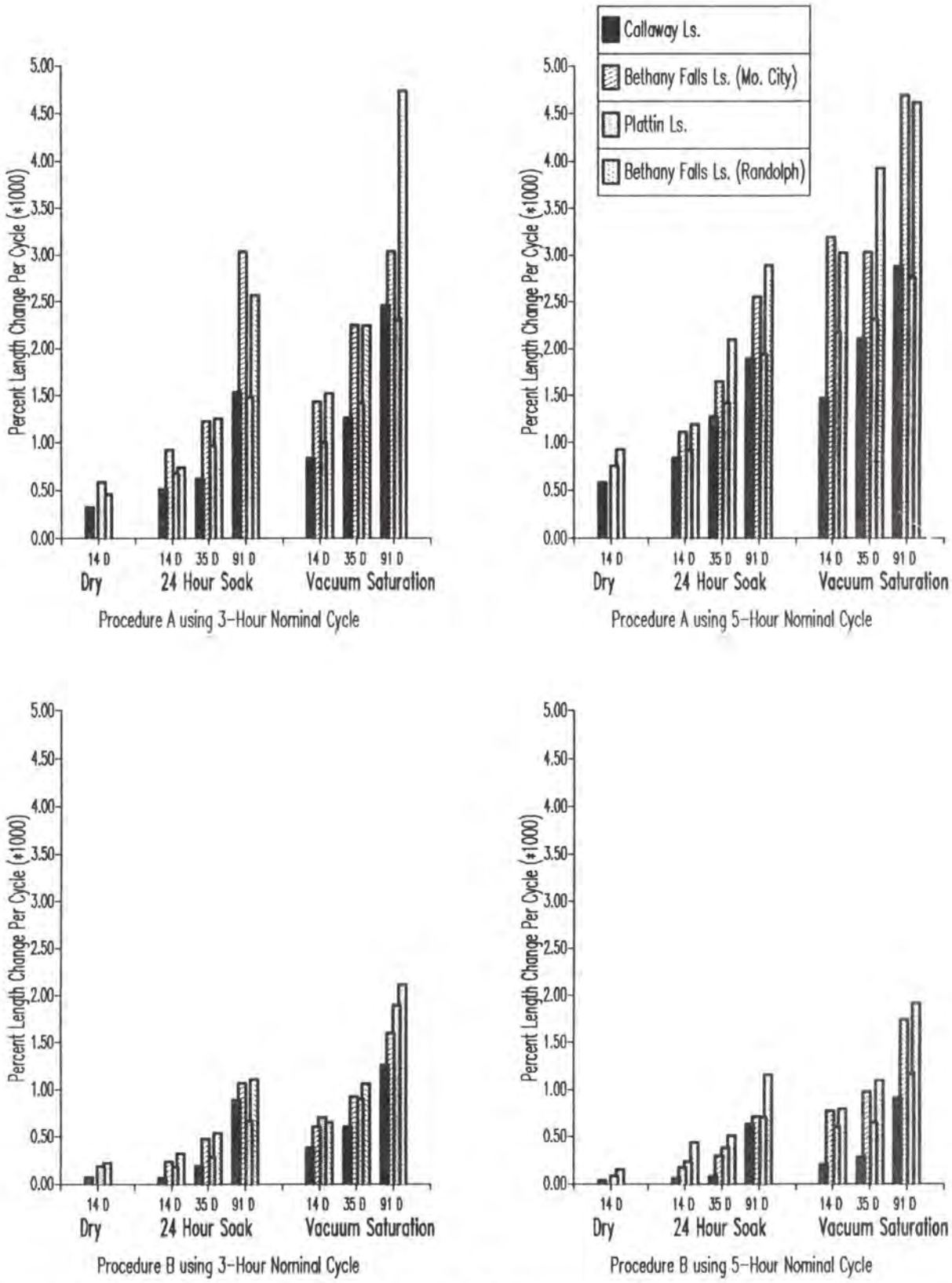


Figure 3. Percent Length Changes Per Cycle by Series, Saturation, and Cure

significant. Results for the test beams with the air-dry moisture treatment are excluded from this analysis of variance because of a lack of complete factorial. A 5 percent significance level was chosen for all analyses of variance. Other analyses performed were regression of durability test results and calculation in change in weight, length and modulus of elasticity during curing.

Analysis of Variance, by Aggregates

Analysis of variance was used to determine, for each combination of test-method variables, whether there was significant difference in average durability results among beams made from the different coarse aggregates.

Each analysis incorporated results from 12 beams since there was four levels of coarse aggregate with three replicate beams per level. Sample calculations on durability factor results are shown in Table 1 for the following test-method variables: 24-hour-soak moisture treatment of the coarse aggregate, 14-day cure duration and A3 series.

A five percent significance level, which is to say a 95 percent probability that the effects due to a variable will correctly be declared not significant, was chosen at the beginning of the study. Significant difference in result means due to the coarse aggregates was declared if an F-ratio was greater than 4.07, the cutoff point for the F distribution at a 5 percent significance level.

However, this procedure alone does not reveal which specific pairs of means differed significantly. For this, Tukey's test method, as outlined by Bowker and Lieberman [4] was used.

A value of significant difference, $K_{0.05}$, was calculated and compared to the differences between each pair of test means. Since the aggregates were initially chosen as those with varying field performance histories, it seemed reasonable that the least number of aggregate pairs with no significant difference in their test means could be used as a criteria in judging which coarse-aggregate moisture treatment, duration of concrete cure, and test procedure to use. Another criteria used was the range in the means. Statistical analysis results for the above procedures are shown in Tables 2, 3, and 4 for durability factors, percent length change per cycle, and weight change per cycle respectively with the data grouped by series.

TABLE 1

EXAMPLE OF ANOVA RESULTS WITH TUKEY'S TEST CALCULATED ON DURABILITY FACTORS
A3 SERIES - 24 HOUR SOAK - 14 DAY CURE
SOLVED ON 7-19-1990

DURABILITY FACTORS:
There are 4 coarse aggregates, 3 replicate beams per coarse aggregate

Aggregate No. 1= Callaway Ls.	1) 34.3	2) 28.7	3) 28.8
Aggregate No. 2= Mo. City BF Ls.	1) 18.6	2) 20.1	3) 20.7
Aggregate No. 3= Plattin Ls.	1) 25.7	2) 29.3	3) 29.9
Aggregate No. 4= Randolph BF Ls.	1) 24.6	2) 22.2	3) 22.3

MEANS FOR EACH AGGREGATE:
Aggregate No. 1= 30.6
Aggregate No. 2= 19.8
Aggregate No. 3= 28.3
Aggregate No. 4= 23.0
The range of mean durability factors = 10.8

ANOVA RESULTS:

Source	Degrees of Freedom	Sum of Squares	Mean of Squares	F-Ratio	5% Cutoff Point for the F Distribution
Between Aggregates	3	217.22	72.41	15.70	4.07
Within Aggregates	8	36.89	4.61		
Total	11	254.11	23.10		

TUKEY'S TEST FOR SIGNIFICANT DIFFERENCE IN MEANS:

Calculation OF $K_{0.05}$ (5% SIGNIFICANCE)
$K_{0.05} = k^* \times$ (Mean of Squares Within Aggregates ÷ Number of Beams per Aggregate)$^{\wedge}\frac{1}{2}$, where k^* is taken from a table.
$K_{0.05} = 4.53 \times (19.63 \div 3)^{\wedge}\frac{1}{2} = 5.60$

Three (out of six possible) pairs of durability factor means did not differ significantly in that their difference was less than the calculated $K_{0.05}$:

Aggregates #1 & #3 (Callaway Ls. and Plattin Ls.)	= 1.3
Aggregates #2 & #4 (Mo. City BF Ls. and Randolph BF Ls.)	= 3.2
Aggregates #3 & #4 (Plattin Ls. and Randolph BF Ls.)	= 5.3

TABLE 2

SUMMARY OF ANOVA AND TUKEY'S TEST RESULTS FOR DURABILITY FACTORS

Sat.	Cure	Range	F Ratio	$K_{0.05}$	Combinations without Significant Difference
A3 SERIES:					
24 Hour	14 Day	10.8	15.70	5.60	3
24 Hour	35 Day	9.0	5.05	8.03	5
24 Hour	91 Day	5.6	7.64	4.86	2
Vacuum	14 Day	6.3	2.45	N.A.	6
Vacuum	35 Day	5.1	6.74	4.18	4
Vacuum	91 Day	4.8	25.80	2.06	2
Average					3.7
A5 SERIES:					
24 Hour	14 Day	5.2	2.63	N.A.	6
24 Hour	35 Day	5.7	15.13	2.89	3
24 Hour	91 Day	5.0	33.92	1.87	2
Vacuum	14 Day	4.3	6.95	3.52	4
Vacuum	35 Day	2.9	4.12	3.38	6
Vacuum	91 Day	3.1	44.15	1.17	2
Average					3.8
B3 SERIES:					
24 Hour	14 Day	22.5	9.61	13.44	5
24 Hour	35 Day	37.2	12.37	21.68	3
24 Hour	91 Day	13.4	2.56	N.A.	6
Vacuum	14 Day	29.2	3.78	N.A.	6
Vacuum	35 Day	26.7	11.12	16.96	3
Vacuum	91 Day	5.8	7.93	4.38	4
Average					4.5
B5 SERIES:					
24 Hour	14 Day	27.2	7.87	19.28	4
24 Hour	35 Day	39.6	19.52	16.79	3
24 Hour	91 Day	34.1	52.56	9.11	2
Vacuum	14 Day	59.1	99.37	12.46	3
Vacuum	35 Day	54.2	28.78	21.68	3
Vacuum	91 Day	20.1	59.64	5.22	2
Average					2.7

Notes:

1) The "Range" is between the means, each an average of three replicate tests.
2) Calculation of a Tukey's test was not applicable (N.A.) for an F Ratio below 4.07.
3) Any difference between two means less than $K_{0.05}$ is insignificant at 95% probability. With four aggregates, there are six possible combinations of two means.

TABLE 3

SUMMARY OF ANOVA AND TUKEY'S TEST RESULTS FOR PERCENT LENGTH CHANGE PER CYCLE (* 1000)

Sat.	Cure	Range	F Ratio	$K_{0.05}$	Combinations without Significant Difference
A3 SERIES:					
24 Hour	14 Day	0.41	6.17	0.31	5
24 Hour	35 Day	0.63	15.45	0.34	3
24 Hour	91 Day	1.56	12.71	0.99	2
Vacuum	14 Day	0.68	2.59	N.A.	6
Vacuum	35 Day	0.99	2.67	N.A.	6
Vacuum	91 Day	2.44	21.51	1.09	3
Average					4.2
A5 SERIES:					
24 Hour	14 Day	0.35	1.31	N.A.	6
24 Hour	35 Day	0.83	23.32	0.34	2
24 Hour	91 Day	1.00	5.72	0.92	4
Vacuum	14 Day	1.47	8.77	1.22	4
Vacuum	35 Day	1.82	5.47	1.59	4
Vacuum	91 Day	1.93	4.55	2.26	6
Average					4.3
B3 SERIES:					
24 Hour	14 Day	0.25	7.77	0.17	5
24 Hour	35 Day	0.34	5.76	0.30	5
24 Hour	91 Day	0.45	3.21	N.A.	6
Vacuum	14 Day	0.32	3.45	N.A.	6
Vacuum	35 Day	0.46	7.33	0.32	4
Vacuum	91 Day	0.86	13.34	0.46	3
Average					4.8
B5 SERIES:					
24 Hour	14 Day	0.38	15.18	0.19	2
24 Hour	35 Day	0.43	19.37	0.19	2
24 Hour	91 Day	0.52	9.17	0.36	3
Vacuum	14 Day	0.59	19.71	0.28	3
Vacuum	35 Day	0.81	25.52	0.33	2
Vacuum	91 Day	1.01	26.99	0.42	2
Average					2.3

Notes:

1) The "Range" is between the means, each an average of three replicate.
2) Calculation of a Tukey's test was not applicable (N.A.) for an F Ratio below 4.07.
3) Any difference between two means less than $K_{0.05}$ is insignificant at 95% probability. With four aggregates, there are six possible combinations of two means.

TABLE 4

SUMMARY OF ANOVA AND TUKEY'S TEST FOR WEIGHT CHANGE IN GRAMS PER CYCLE

Sat.	Cure	Range	F Ratio	$K_{0.05}$	Combinations without Significant Difference
A3 SERIES:					
24 Hour	14 Day	0.32	2.20	N.A.	6
24 Hour	35 Day	0.32	1.53	N.A.	6
24 Hour	91 Day	0.95	2.30	N.A.	6
Vacuum	14 Day	0.61	1.20	N.A.	6
Vacuum	35 Day	0.58	3.67	N.A.	6
Vacuum	91 Day	0.64	0.20	N.A.	6
Average					6.0
A5 SERIES:					
24 Hour	14 Day	0.64	0.52	N.A.	6
24 Hour	35 Day	1.17	2.16	N.A.	6
24 Hour	91 Day	0.41	0.59	N.A.	6
Vacuum	14 Day	0.50	0.16	N.A.	6
Vacuum	35 Day	1.13	1.16	N.A.	6
Vacuum	91 Day	0.43	0.51	N.A.	6
Average					6.0
B3 SERIES:					
24 Hour	14 Day	0.10	25.58	0.04	3
24 Hour	35 Day	0.09	7.46	0.06	4
24 Hour	91 Day	0.04	1.66	N.A.	6
Vacuum	14 Day	0.15	4.40	0.16	5
Vacuum	35 Day	0.20	9.21	0.13	3
Vacuum	91 Day	0.26	6.26	0.20	5
Average					4.3
B5 SERIES:					
24 Hour	14 Day	0.14	8.11	0.07	4
24 Hour	35 Day	0.15	36.06	0.05	3
24 Hour	91 Day	0.07	0.97	N.A.	6
Vacuum	14 Day	0.24	24.88	0.09	3
Vacuum	35 Day	0.25	28.76	0.09	2
Vacuum	91 Day	0.48	1.02	N.A.	6
Average					4.0

Notes:
1) The "Range" is between the means, each an average of three replicate tests.
2) Calculation of a Tukey's test was not applicable (N.A.) for an F Ratio below 4.07.
3) Any difference between two means less than $K_{0.05}$ is insignificant at 95% probability. With four aggregates, there are six possible combinations of two means.

As shown on these tables, the B5 series consistently averaged the least number of insignificant differences. If the data presented in these tables had been grouped by coarse aggregate moisture treatment or duration of specimen curing, the average number of combinations without significant difference would be as follows. These averages indicate that using 14-day curing resulted in less discrimination among beams.

	Durability Factors Data	% Length Change Per Cycle Data	Weight Change Data
24-Hour Soak	3.7	3.8	5.2
Vacuum Saturation	3.8	4.1	5.0
14 Day Cure	4.6	4.6	4.9
35 Day Cure	3.8	3.5	4.5
91 Day Cure	2.8	3.6	5.9

By test series, the following statements may be made:

A3 Series: (Procedure A with a nominal 3-hour cycle time)

Except for the beams cured for 91 days, there was little significant difference in results. With the vacuum-saturation moisture treatment of the coarse aggregate and 91-day curing, the durability factor means were all significantly different except for the beams made from the two Bethany Falls limestones. The 91-day-cure beams generally expanded more and went out of test sooner than those with the other cure durations.

Due to random scaling, spalling, and chipping of corners and edges of the test beams, weight measurements were without significance. This was also true for the A5 series and could be assumed whenever Procedure A is used.

A5 Series: (Procedure A with a nominal 5-hour cycle time)

This series had the harshest effect of the four series on the test beams. A possible reason this series was more severe than the A3 series is the freezing rate was greater for the A5 series (51°F/hour compared to 42°F/hour for the A3 Series, as given in Appendices B and C).

As with the A5 series and as shown visually in Figure 2, the durability factors were all closely spaced.

B3 Series: (Procedure B with a nominal 3-hour cycle time)

For any combination of moisture treatment and cure duration, at least three pairs of durability test means had no significant difference.

B5 Series: (Procedure B with a nominal 5-hour cycle time)

This series best discriminated among the beams made with the different coarse aggregates. It also resulted in the largest ranges in values of average durability factors.

Analysis of Variance, by Test-Method Variables

Analyses on durability test data were also performed to determine whether the results were significantly different between the different moisture treatments, among the different cure durations, and among the different series. For example, the results for the two levels of moisture treatment were analyzed for the 48 combinations of cure duration, series, and aggregates. A summary of results is shown in Table 5.

Moisture treatment, whether the coarse aggregates were soaked for 24 hours or vacuum saturated, usually caused

significant differences in the test-beam results. As expected, vacuum saturation had the more severe effect on concrete durability.

The longer the cure duration, the more severe the effect upon concrete durability results. However, the differences in results were often not statistically significant. For the B5 series with 24-hour-soak moisture treatment for all four coarse aggregates, there was no significant differences in results between the 14-day and the 35-day cure durations while there was between the 35-day and the 91-day.

Procedure A of ASTM C 666 was always significantly more severe on concrete durability than Procedure B.

TABLE 5

SUMMARY OF ANOVA AND TUKEY'S TEST RESULTS BY TEST-METHOD VARIABLES

	Number of Analyses	Number of Analyses Resulting in No Significant Difference in Means of Durability Factors	Number of Analyses Resulting in No Significant Difference in Means of Percent Length Change Per Cycle
By Moisture Treatment			
Between 24 Hour Soak and Vacuum Saturation	48	7	13
By Cure Duration			
Between 14 & 35 Day	32	16	27
Between 35 & 91 Day	32	11	5
Between 14 & 91 Day	32	2	2
By Series			
Between A3 & A5	24	21	13
Between A3 & B3	24	0	6
Between A3 & B5	24	0	2
Between B3 & A5	24	0	0
Between B3 & B5	24	13	24
Between B5 & A5	24	0	0
By ASTM C 666 Procedure			
Between A & B	48	0	6
By Nominal Cycle Duration			
Between 3 Hour & 5 Hour	48	30	37

Regression of Results

Linear regression was used to determine which of the following methods or monitoring concrete deterioration was best related to percent reduction in flexural strength: relative dynamic modulus of elasticity, percent length change, and weight change in grams. Using all 324 test data, results of linear regressions are shown in Figures 4, 5, and 6. The coefficients of determination were 0.87 for relative dynamic modulus of elasticity, Figure 4, and 0.54 for percent length change, Figure 5, when regressed against percent flexural strength reduction. Data was broken down further into series and into different combinations of test-method variables. Almost always, relative modulus versus percent flexural-strength reduction had the highest coefficient of determination and lowest coefficient of variance.

Weight change versus percent flexural-strength reduction, Figure 6, had a coefficient of determination of only 0.08. This was due to including the A3 and A5 series' data, which was affected by random scaling and spalling of the test beams. Still, the coefficients of determination using only the B3 and B5 series data were also low, 0.19 and 0.24 respectively. Overall, weight change was an unreliable indicator of reduction in flexural strength. A report by the Michigan Department of Transportation also concluded that weight change was an unreliable indicator of concrete durability[2].

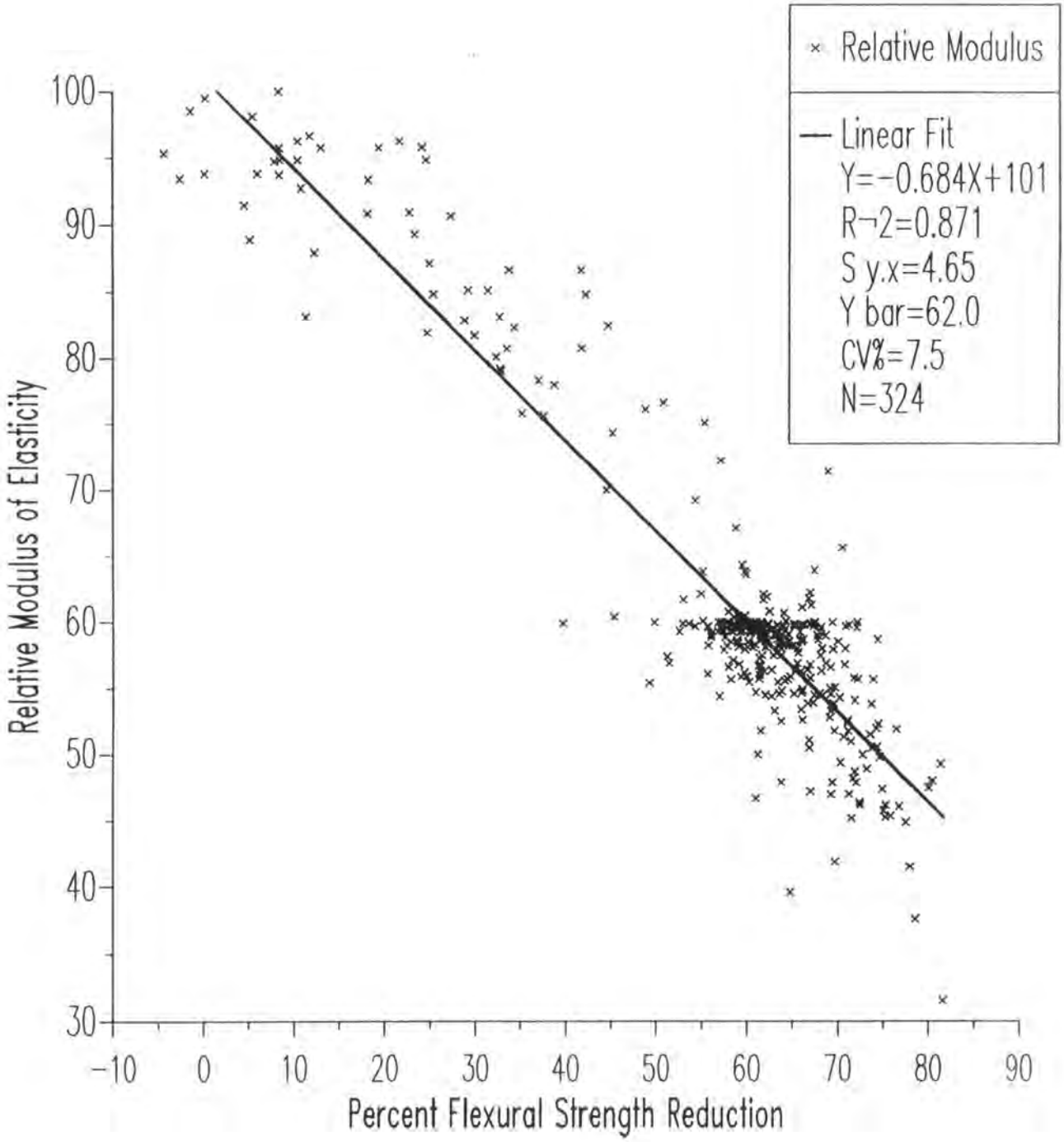


Figure 4. Relative Modulus of Elasticity Vs. Percent Flexural Strength Reduction For All Test Beams (At End of Test)

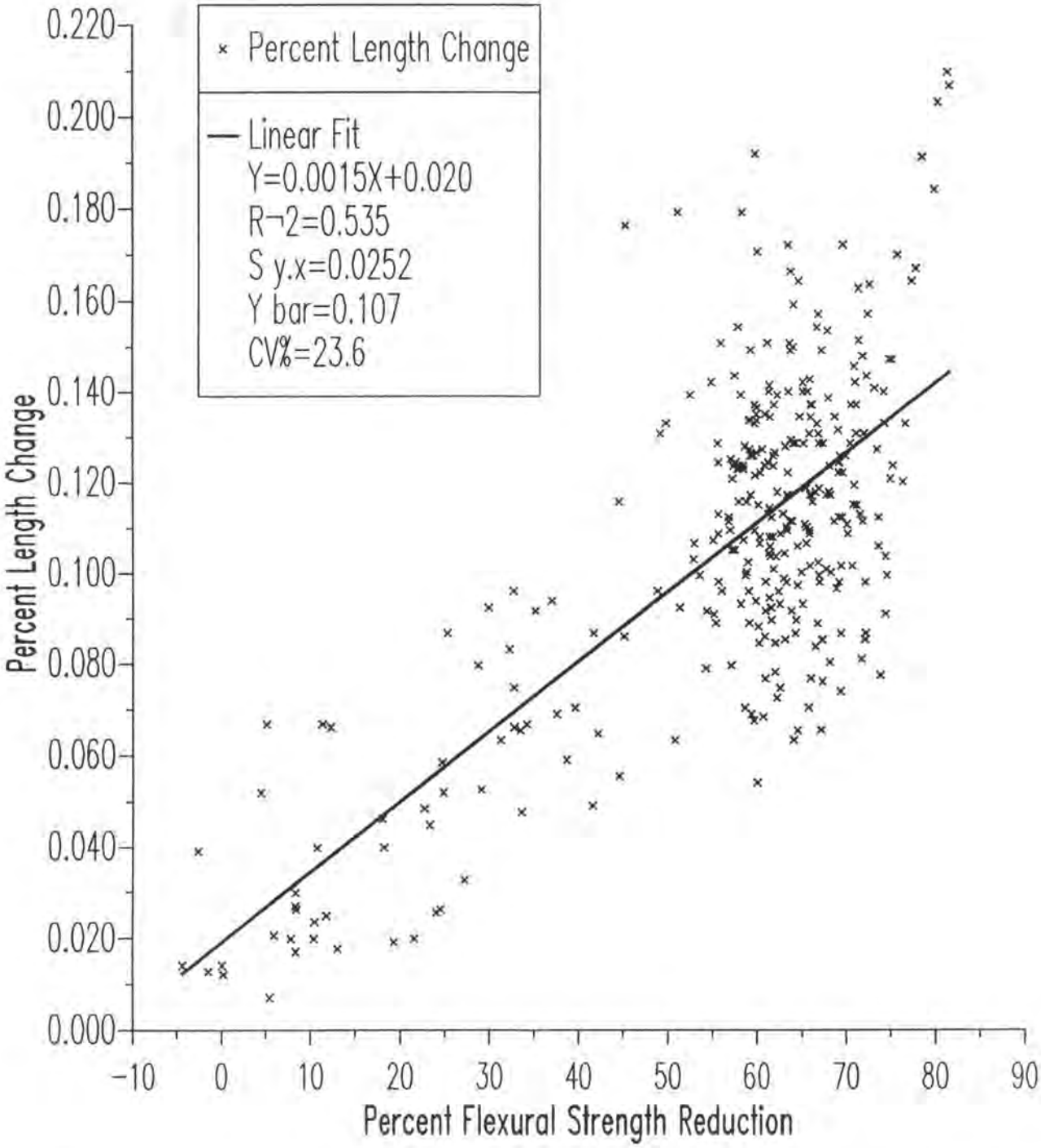


Figure 5. Percent Length Change Vs. Percent Flexural Strength Reduction For All Test Beams

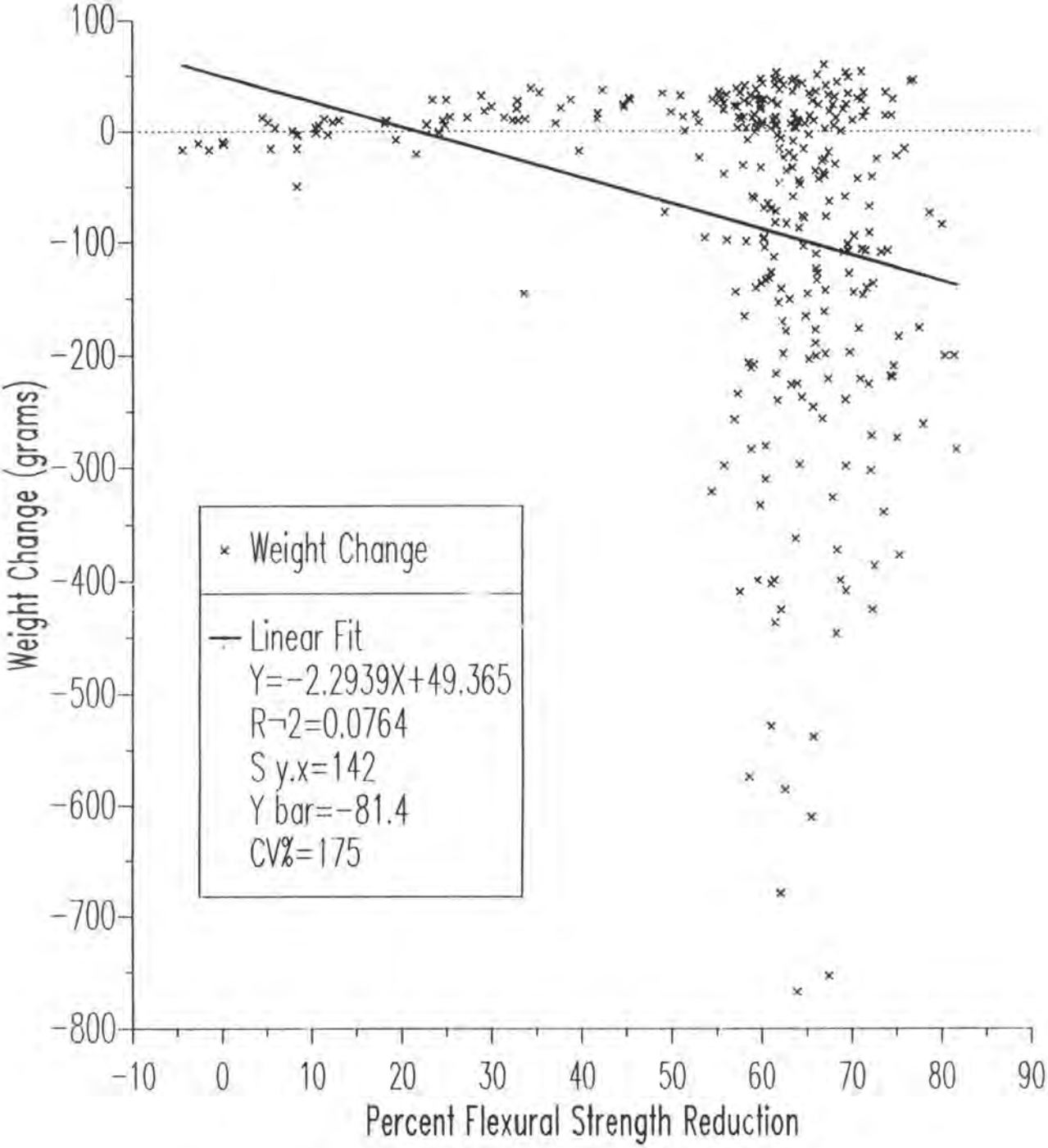


Figure 6. Weight Change Vs. Percent Flexural Strength Reduction For All Test Beams

CORRELATION BETWEEN LENGTH CHANGE AND DURABILITY FACTOR

Both linear and non-linear correlations were determined between percent length change per cycle and durability factor which are the per cycle equivalent of percent length change and relative modulus. The highest correlation between these two methods of expressing concrete deterioration for all 324 beams was -0.942 with a power curve (Figure 7).

Correlations were also performed for each series and for each combination of test variables and correlation coefficients are given in Table 6. The B5 series using the 24-hour-soak moisture treatment and 35-day cure duration had one of the highest correlation coefficient (-0.984) between durability factor and percent length change per cycle. The formula of that fitted line is:

Percent length change per cycle = (1.13-0.0108 DF)/1000,

where DF is the durability factor of the specimen.

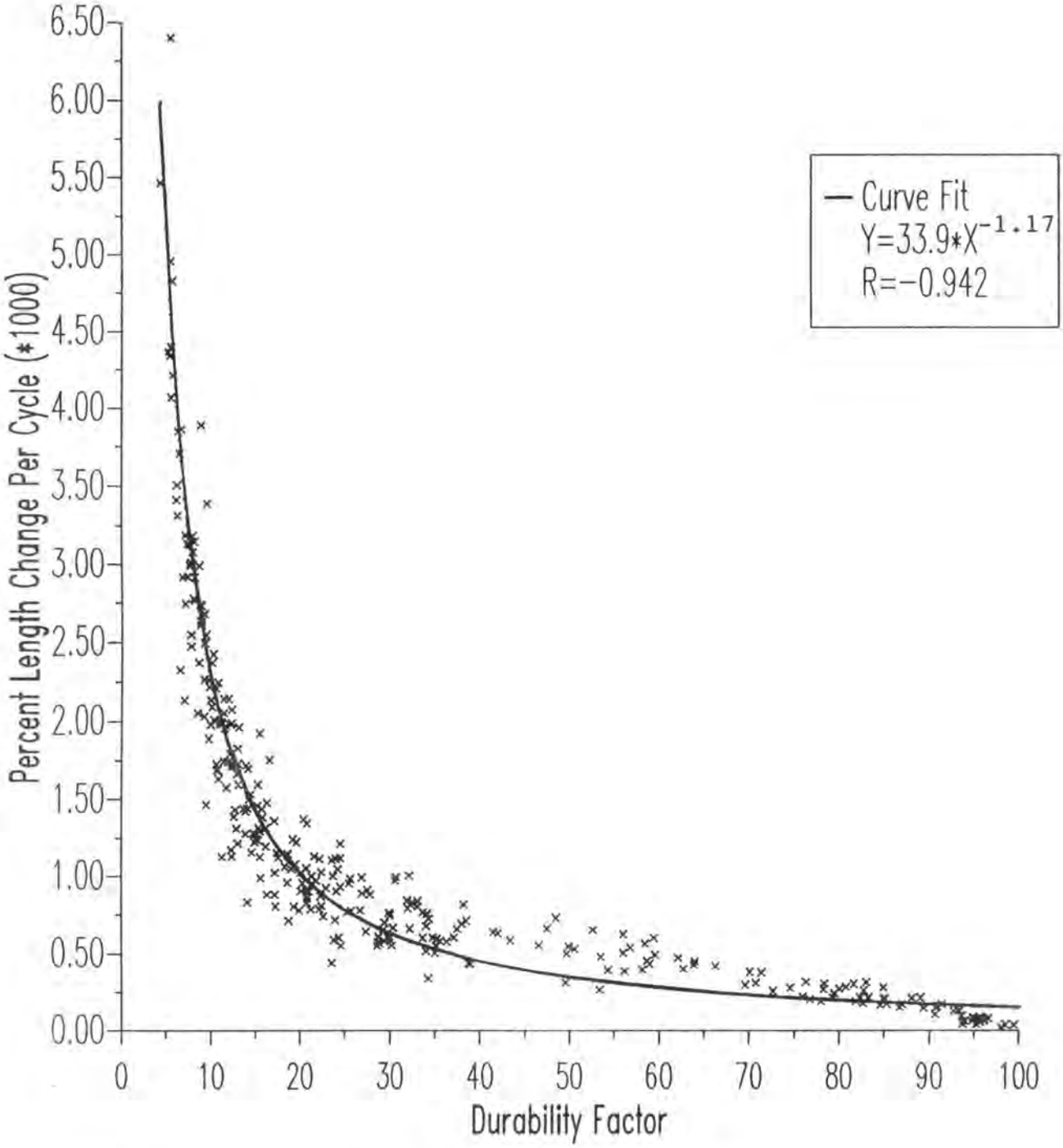


Figure 7. Correlation Between Durability Factor and Length Change For All Test Beams

TABLE 6

CORRELATION COEFFICIENTS FOR PERCENT LENGTH CHANGE PER CYCLE TO DURABILITY FACTORS

Moisture Treatment	Cure Duration	Series	Type of Curve Fit: Linear	Exponential	Log	Power
Air-dry	14 Day	A3	-0.59	-0.66	-0.57	-0.64
24 hr soak	14 Day	A3	-0.92	-0.90	-0.91	-0.88
24 hr soak	35 Day	A3	-0.87	-0.89	-0.89	-0.89
24 hr soak	91 Day	A3	-0.98	-0.97	-0.98	-0.96
Vacuum sat.	14 Day	A3	-0.76	-0.80	-0.75	-0.78
Vacuum sat.	35 Day	A3	-0.79	-0.80	-0.84	-0.83
Vacuum sat.	91 Day	A3	-0.93	-0.96	-0.96	-0.97
All	All	A3	-0.74	-0.89	-0.87	-0.96
Air-dry	14 Day	A5	-0.91	-0.92	-0.91	-0.91
24 hr soak	14 Day	A5	-0.87	-0.87	-0.88	-0.87
24 hr soak	35 Day	A5	-0.83	-0.83	-0.84	-0.84
24 hr soak	91 Day	A5	-0.86	-0.87	-0.88	-0.89
Vacuum sat.	14 Day	A5	-0.75	-0.80	-0.75	-0.78
Vacuum sat.	35 Day	A5	-0.76	-0.77	-0.78	-0.78
Vacuum sat.	91 Day	A5	-0.84	-0.89	-0.84	-0.89
All	All	A5	-0.81	-0.93	-0.89	-0.96
Air-dry	14 Day	B3	-0.99	-0.95	-0.98	-0.94
24 hr soak	14 Day	B3	-0.94	-0.91	-0.94	-0.89
24 hr soak	35 Day	B3	-0.96	-0.93	-0.97	-0.89
24 hr soak	91 Day	B3	-0.94	-0.95	-0.95	-0.96
Vacuum sat.	14 Day	B3	-0.95	-0.97	-0.96	-0.96
Vacuum sat.	35 Day	B3	-0.79	-0.82	-0.80	-0.82
Vacuum sat.	91 Day	B3	-0.94	-0.94	-0.94	-0.94
All	All	B3	-0.89	-0.97	-0.96	-0.93
Air-dry	14 Day	B5	-0.97	-0.90	-0.97	-0.89
24 hr soak	14 Day	B5	-0.95	-0.86	-0.95	-0.84
24 hr soak	35 Day	B5	-0.98	-0.80	-0.97	-0.87
24 hr soak	91 Day	B5	-0.67	-0.67	-0.75	-0.75
Vacuum sat.	14 Day	B5	-0.92	-0.93	-0.91	-0.90
Vacuum sat.	35 Day	B5	-0.93	-0.96	-0.95	-0.94
Vacuum sat.	91 Day	B5	-0.86	-0.90	-0.89	-0.91
All	All	B5	-0.90	-0.93	-0.95	-0.89
All	All	All	-0.71	-0.94	-0.87	-0.94

Changes in Weight, Length, and Modulus of Elasticity During Cure

Weight change, percent length change, and percent increase in the dynamic modulus of elasticity were calculated for each beam between the seventh day of cure and the final cure duration. The only exception was for percent length change of the flexural strength beams since they were made without gage studs. Results are shown in Table 7 by coarse aggregate and moisture treatment. The entries are averages of not only the three replicate beams but also the four series. Since the changes were very similar regardless of the coarse aggregate or moisture treatment of the coarse aggregate, it is assumed that the changes were mainly due to water absorption and hydration in the concrete matrix.

Figure 8 graphically shows the overall average effects of the cure duration. Beam weights and modulus of elasticity increased throughout curing, although the rate lessened with cure duration.

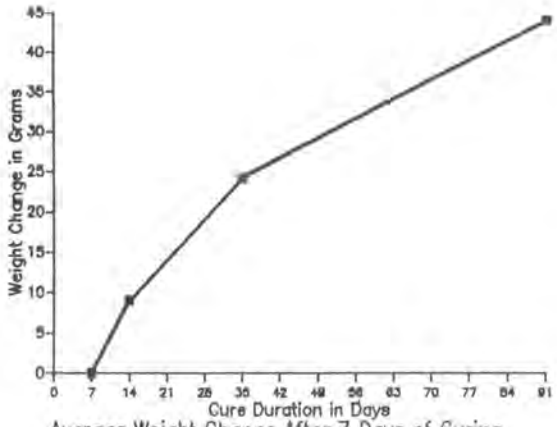
Results for percent length change tended to have a large range in values during cure. Some beams measured shorter at ninety-one days than at seven. Overall, the average beam length decreased from the seventh day to the fourteenth day and then increased thereafter.

Table 7

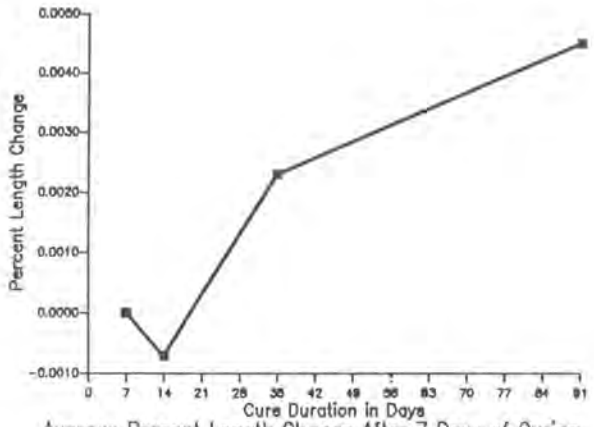
Effects Of Cure Duration Upon Weight, Length, and Relative Modulus

Coarse Aggregate	Moisture Treatment	14 Day Cure			35 Day Cure			91 Day Cure		
		Weight Change	% Length Change	% Mod Change	Weight Change	% Length Change	% Mod Change	Weight Change	% Length Change	% Mod Change
Callaway	Air Dry	8.8	.0008	2.98	--	--	--	--	--	--
Callaway	24 Hr. Soak	9.2	-.0004	2.91	24.8	.0018	6.87	45.4	.0028	8.37
Callaway	Vac. Sat.	9.4	-.0024	2.71	24.6	-.0009	6.11	47.0	.0021	7.80
BF-Mo. City	24 Hr. Soak	9.0	.0047	3.44	24.8	-.0002	6.88	45.5	.0027	10.05
BF-Mo. City	Vac. Sat.	8.6	.0008	2.68	24.5	.0006	6.40	45.5	.0036	8.81
Plattin	Air Dry	8.9	-.0007	3.29	--	--	--	--	--	--
Plattin	24 Hr. Soak	8.5	-.0011	2.96	23.2	.0043	6.14	39.9	.0102	8.31
Plattin	Vac. Sat.	9.8	-.0043	2.77	22.7	.0056	6.02	40.8	.0048	7.88
BF-Randolph	Air Dry	8.9	-.0042	3.02	--	--	--	--	--	--
BF-Randolph	24 Hr. Soak	8.0	-.0028	3.14	24.5	.0026	7.13	44.6	.0076	9.63
BF-Randolph	Vac. Sat.	9.4	.0010	3.51	24.1	.0046	6.48	44.4	.0019	8.79
Average		9.0	-.0007	3.04	24.2	.0023	6.50	44.1	.0045	8.71

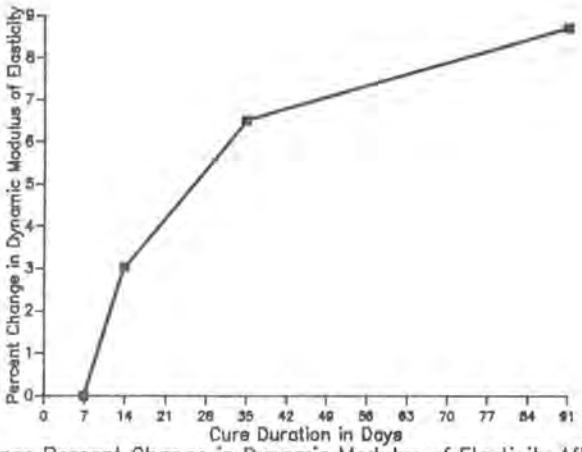
Notes: Weight change is in grams.
Seven-day values were used as the basis for calculations.



Average Weight Change After 7 Days of Curing



Average Percent Length Change After 7 Days of Curing



Average Percent Change in Dynamic Modulus of Elasticity After After 7 Days of Curing

Figure 8. Average Effects of Cure Duration Upon Weight, Length, and Dynamic Modulus of Elasticity

ASTM C 666 Vs. AASHTO T 161

The only significant difference between these two testing specifications, both titled, "Resistance of Concrete to Rapid Freezing and Thawing", is AASHTO T 161[5] requires the total cycle time to be maximum of 4 hours rather than the 5 hours allowed by ASTM C 666. The typical cycle time used for the B5 series was 4 hours, 22 minutes.

Although the B5 series discriminated among the beams in this study better than the B3 series, this may have been due to cycle characteristics other than total cycle time. It may be possible to reduce the cycle time used in the B5 series to meet AASHTO T 161 without significantly affecting results.

Cost Benefit

Freezing and thawing tests performed by Missouri prior to this study and the purchase of the Cincinnati Sub-Zero Products Unit were performed by manually transferring beams between a walk-in freezer and tanks filled with 40°F water. Ice was used to maintain the temperature of the thaw water. Each series of tests were restricted to 60 beams due to shelf and freezer space. Beams were cured for 35 days prior to testing.

The "slow" method, in which beams were subjected to one freeze-and-thawing cycle per week, was typically used since the "fast" method was found to cause beams to dehydrate. A series of tests using the "slow" method required slightly over 2 years and approximately 800 man-hours to complete 100 cycles at a salary cost of $10,240. This cost was for both transferring beams and

monitoring their durability. Using the automatic freezing and thawing unit and recommended test procedures, curing and 300 cycles of freezing and thawing can be performed in 90 days with only 160 man-hours and a salary cost of $2,040. Most of this cost would be in monitoring the durability of beams.

In addition to having results much quicker and at a lower cost per series of tests, the new equipment also provides the following advantages over the previous test method. First, it allows Missouri to meet all ASTM testing specifications. Second, the cycles of freezing and thawing are probably more consistent since programmed. Third, the new equipment allows for flexibility to use either rapid freezing in water (Procedure A) or rapid freezing in air (Procedure B), and to change other cycle characteristics, if needed in the future.

CONCLUSIONS

The following conclusions were made from the test results:

(1) ASTM C 666, Procedure B, with a five-hour nominal cycle duration best discriminated among the beams made from the four different coarse aggregates used in this study.

(2) The 24-hour soak discriminated among the beams made from the four different coarse aggregates as well as or slightly better than vacuum saturation.

(3) The 14-day curing on the average resulted in less discrimination among beams made from the four different coarse aggregates compared to the 35-day and 91-day curing.

(4) Percent loss in flexural strength between test and control concrete beams generally correlated with the relative dynamic modulus of elasticity better than with values of percent length change or much better than values of weight change.

(5) Concrete beams continued to increase in weight and dynamic modulus of elasticity throughout the cure period. The rates of increase lessened with longer cure duration.

(6) On the average, the beams shrank from the seventh day to the fourteenth day of cure, and thereafter they expanded.

(7) Using the new automatic equipment, freeze-thaw durability results can be obtained much quicker and at less cost than with the previous manual methods.

IMPLEMENTATION

Based on results of this study and experience gained using the automatic equipment, ASTM C 666, Procedure B, with a nominal five-hour freeze thaw cycle and 35-day curing of concrete specimens will be Missouri's Standard freezing-and-thawing configuration for general aggregate durability testing.

REFERENCES

(1) American Society of Testing and Materials, *1987 Annual Book of ASTM Standards*, Section 4, Construction, Volume 4.02 Concrete and Aggregates

(2) Vogler, R. H. and Grove, G. H., Freezing-and-thawing Testing of Coarse Aggregate in Concrete: Procedures used by Michigan Department of Transportation and Other Agencies, ASTM Committee C9, 1987

(3) Irick, P. E. and Blackburn, J. B., Application of Statistical Methods to Laboratory Concrete Freezing-and-thawing Data, Highway Research Board, *1955 Annual Proceedings*

(4) Albert, H. B. and Lieberman, G, J., *Engineering Statistics*, Prentice-Hall Inc., 1972

(5) American Association of State Highway and Transportation Officials, *Standard Specifications for Transportation Materials and Methods of Sampling and Testing*, Fifteenth Edition. 1990, Part II, Tests

APPENDIX A

Materials, Mix Design, Batch Characteristics, Batching Sequence, and Concrete Beam Identification

Materials

The coarse aggregates from each source were obtained from one lot and were batched by individual sieve, as follows, to produce a consistent gradation. Physical characteristics are listed in Table A1.

1" - 3/4"	7%
3/4" - 1/2"	37%
1/2" - 3/8"	28%
3/8" - #4	25%
#4 - #10	3%

The fine aggregate used for this study was a Class A Missouri River sand from Capital Sand Company at Jefferson City, Missouri. Physical characteristics and gradation are listed in Table A2.

A blend of six Type 1 cements was used to minimize any adverse effects with the coarse aggregates. The sources and the properties of the blend are listed in Table A3. Ad-Aire, manufactured by Carter-Waters Corporation, was the air-entraining admixture used.

Mix Design, Batch Characteristics, and Batching Sequence

The concrete mix design and the range of fresh concrete characteristics are shown in Table A4. The water/cement ratio was allowed to vary in order to keep slump relatively constant. Twenty-seven concrete mix batches were made for each series, 108 in total, each 1.3 cubic feet. As shown in Table A5, batching was randomized for each series and, except for the beams made

with air dried aggregate, the three sets of test and control beams per variable combination were made from different batches.

Concrete Beam Identification

A six-character code identified each test beam. Its companion control beam had the same code, but was distinguished by not having any length studs.

The first character denoted the source of crushed coarse aggregate:

C - Callaway Ls., Beck Materials Co., Holts Summit, MO

M - Bethany Falls Ls., Mo. Rock Co. Inc., Missouri City, MO

P - Plattin Ls., Southeast Mo. Stone Co., Cape Girardeau, MO

R - Bethany Falls Ls., Hunt Midwest Mining Co., Randolph, MO

The second character denoted the type of moisture treatment for the coarse aggregates retained on the #4 sieve and above. Aggregates passing the #4 but retained on the #10 sieve were batched air-dried.

D - air drying

S - 24 hour soaking

V - vacuum saturation

The third character denoted the length of beam cure. The beams were cured in saturated lime water in accordance with ASTM C 666.

B - 14 Days

E - 35 Days

M - 91 Days

The fourth character denotes whether the beam was from the first, second or third batch made for each variable combination.

The fifth character denoted whether the beam was tested using Procedure A or B.

The sixth character denotes the nominal cycle length. ASTM C 666 states the nominal freezing-and-thawing cycle shall not be less than two nor more than five hours. For both Procedure A and B, three and five hours were used in this study.

For example, beam CSB1B3 was first of three made with Callaway limestone course aggregate soaked for twenty-four hours before batching, in which the beam was cured for fourteen days and then tested using Procedure B with a three hour nominal freezing-and-thawing cycle.

TABLE A1

PHYSICAL PROPERTIES OF COARSE AGGREGATE

BULK SPECIFIC GRAVITY, DRY

Aggregate	1-3/4	3/4-1/2	1/2-3/8	3/8-4	4-10
Callaway	2.64	2.62	2.62	2.63	2.59
BF from Mo. City	2.63	2.62	2.61	2.61	2.59
Plattin	2.69	2.70	2.68	2.67	2.65
BF from Randolph	2.61	2.61	2.60	2.58	2.57

BULK SPECIFIC GRAVITY, Saturated Surface Dry

Aggregate	Saturation	1-3/4	3/4-1/2	1/2-3/8	3/8-4	4-10	Combined Total
Callaway	24 Hr. Soak	2.67	2.65	2.65	2.66	-	2.65
	Vac. Sat.	2.66	2.66	2.65	2.65	-	2.65
BF from Mo. City	24 Hr. Soak	2.66	2.65	2.65	2.65	-	2.65
	Vac. Sat.	2.66	2.66	2.65	2.65	-	2.65
Plattin	24 Hr. Soak	2.72	2.72	2.71	2.70	-	2.71
	Vac. Sat.	2.72	2.71	2.70	2.69	-	2.70
BF from Randolph	24 Hr. Soak	2.65	2.64	2.64	2.63	-	2.64
	Vac. Sat.	2.65	2.65	2.64	2.64	-	2.64

ABSORPTION, Percent

Aggregate	Saturation	1-3/4	3/4-1/2	1/2-3/8	3/8-4	4-10
Callaway	24 Hr. Soak	1.0	1.1	1.3	1.2	1.6
	Vac. Sat.	1.0	1.2	1.3	1.3	-
BF from Mo. City	24 Hr. Soak	1.0	1.2	1.4	1.4	2.5
	Vac. Sat.	1.3	1.3	1.5	1.7	-
Plattin	24 Hr. Soak	1.0	0.9	1.2	1.2	1.5
	Vac. Sat.	1.1	1.1	1.2	1.4	-
BF from Randolph	24 Hr. Soak	1.4	1.4	1.5	1.9	2.2
	Vac. Sat.	1.6	1.6	1.6	1.8	-

UNIT WEIGHT, Pounds per Cubic Foot

Callaway	97
Bethany Falls from Mo. City	94
Plattin	96
Bethany Falls from Randolph	94

TABLE A2

PHYSICAL PROPERTIES AND GRADATION OF FINE AGGREGATE

BULK SPECIFIC GRAVITY, DRY	2.63
ABSORPTION, Percent	0.4
UNIT WEIGHT, Pounds per Cubic Foot	111
GRADATION, Passing	
3/8" sieve	100
No. 4 sieve	99
No. 20 sieve	60
No. 50 sieve	17
No. 100 sieve	1
No. 200 sieve	0

TABLE A3

SOURCES AND PROPERTIES OF BLENDED CEMENT

SOURCES

Ash Grove Cement Co. at Chanute, Kansas
Continental Cement Co. at Hannibal, Missouri
Dundee Cement Co. at Clarksville, Missouri
Lone Star Cement Co. at Cape Girardeau, Missouri
Missouri Portland Cement Co. at Sugar Creek, Missouri
River Cement Co. at Festus, Missouri

PHYSICAL PROPERTIES

Normal Consistency, percent	24.2
Soundness, Autoclave	0.01
Initial Set (Hr. and Min.) ASTM C 266	3:25
Final Set (Hr. and Min.) ASTM C 266	5:10
Compressive Strength, Average, psi	
3-Days	2830
7-Days	3610
Specific Surface, Blaine	3520
Specific Gravity	...

CHEMICAL PROPERTIES

Percent SiO_2 (Silica)	21.89
Percent Al_2O_3 (Aluminum Oxide)	4.72
Percent Fe_2O_3 (Iron Oxide)	2.66
Percent CaO (Calcium Oxide)	64.32
Percent MgO (Magnesium Oxide)	2.74
Percent Na_2O (Sodium Oxide)	0.15
Percent SO_3 (Sulfur Trioxide)	2.53
Percent K_2O (Potassium Oxide)	0.57
Percent Insoluble Residue	0.14
Percent Total Alkali Oxides	0.72
Percent Total Alkali as Na_2O Equiv.	0.53
Percent Loss on Ignition	0.92
Percent C_3S (Tricalcium Silicate)	52.7
Percent C_2S (Dicalcium Silicate)	23.2
Percent C_3Al (Tricalcium Aluminate)	7.9

TABLE A4

CONCRETE MIX DESIGN FACTORS

Cement Factor (sacks/cubic yard)	6.10
Slump (Inches)	3.0 Maximum
Air Content (Percent)	
(Using a Type A Air Meter, ASTM C 231)	5.5 ± 1.5
Fine Aggregate (Percent of aggregate fraction)	45
Coarse Aggregate (Percent of aggregate fraction)	55

CHARACTERISTICS OF FRESH CONCRETE

ALL SERIES

	Range	Average
Cement Factor (sack/cubic yard)	6.02 - 6.17	6.09
Water/Cement Ratio (gal/sack)	4.60 - 5.24	4.84
Slump (inches)	1.00 - 2.50	2.29
Air Content (percent) By Meter	4.2 - 6.7	5.63

A3 SERIES

	Range	Average
Cement Factor (sacks/cubic yard)	6.05 - 6.15	6.08
Water/Cement Ratio (gal/sack)	4.65 - 4.95	4.85
Slump (inches)	1.50 - 2.50	2.19
Air Content (percent) By Meter	4.8 - 6.3	5.80

A5 SERIES

	Range	Average
Cement Factor (sacks/cubic yard)	6.02 - 6.13	6.09
Water/Cement Ratio (gal/sack)	4.60 - 4.90	4.80
Slump (inches)	1.80 - 2.50	2.15
Air Content (percent) By Meter	5.1 - 6.7	5.65

B3 SERIES

	Range	Average
Cement Factor (sacks/cubic yard)	6.03 - 6.13	6.09
Water/Cement Ratio (gal/sack)	4.68 - 5.24	4.87
Slump (inches)	1.00 - 2.50	1.88
Air Content (percent) By Meter	5.0 - 6.4	5.66

B5 SERIES

	Range	Average
Cement Factor (sacks/cubic yard)	6.03 - 6.17	6.10
Water/Cement Ratio (gal/sack)	4.60 - 4.98	4.85
Slump (inches)	1.50 - 2.50	2.00
Air Content (percent) By Meter	4.2 - 6.3	5.40

TABLE A5

RANDOMIZED BATCHING SEQUENCE

Day of Week	Batch Order	Description	Cure of Beams 14 D	35 D	91 D
			Beam Ident.*		
Tues	1	Callaway Ls., 24 Hour Soak	CSB1	CSE1	CSM1
	2	Randolph Ls., 24 Hour Soak	RSB1	RSE1	RSM1
	3	Plattin Ls., Vacuum Saturated	PVB1	PVE1	PVM1
	4	Randolph Ls., Vacuum Saturated	RVB1	RVE1	RVM1
Wed	5	Mo. City Ls., Vacuum Saturated	MVB1	MVE1	MVM1
	6	Callaway Ls., Vacuum Saturated	CVB1	CVE1	CVM1
	7	Plattin Ls., 24 Hour Soak	PSB1	PSE1	PSM1
	8	Mo. City Ls., 24 Hour Soak	MSB1	MSE1	MSM1
Thurs	9	Plattin Ls., Vacuum Saturated	PVB2	PVE2	PVM2
	10	Callaway Ls., 24 Hour Soak	CSB2	CSE2	CSM2
	11	Randolph Ls., Vacuum Saturated	RVB2	RVE2	RVM2
	12	Callaway Ls., Vacuum Saturated	CVB2	CVE2	CVM2
Tues	13	Mo. City Ls., Vacuum Saturated	MVB2	MVE2	MVM2
	14	Randolph Ls., 24 Hour Soak	RSB2	RSE2	RSM2
	15	Mo. City Ls., 24 Hour Soak	MSB2	MSE2	MSM2
	16	Plattin Ls., 24 Hour Soak	PSB2	PSE2	PSM2
Wed	17	Randolph Ls., Vacuum Saturated	RVB3	RVE3	RVM3
	18	Callaway Ls., 24 Hour Soak	CSB3	CSE3	CSM3
	19	Plattin Ls., Vacuum Saturated	PVB3	PVE3	PVM3
	20	Randolph Ls., 24 Hour Soak	RSB3	RSE3	RSM3
Thurs	21	Mo. City Ls., Vacuum Saturated	MVB3	MVE3	MVM3
	22	Callaway Ls., Vacuum Saturated	CVB3	CVE3	CVM3
	23	Mo. City Ls., 24 Hour Soak	MSB3	MSE3	MSM3
	24	Plattin Ls., 24 Hour Soak	PSB3	PSE3	PSM3
			(All cured 14 Days)		
Tues	25	Randolph Ls., Dry	RDB1	RDB2	RDB3
	26	Callaway Ls., Dry	CDB1	CDB2	CDB3
	27	Plattin Ls., Dry	PDB1	PDB2	PDB3

*Both Test and Control Beams

APPENDIX B

ASTM C 666 Procedure A using 3-Hour Nominal Cycle Time

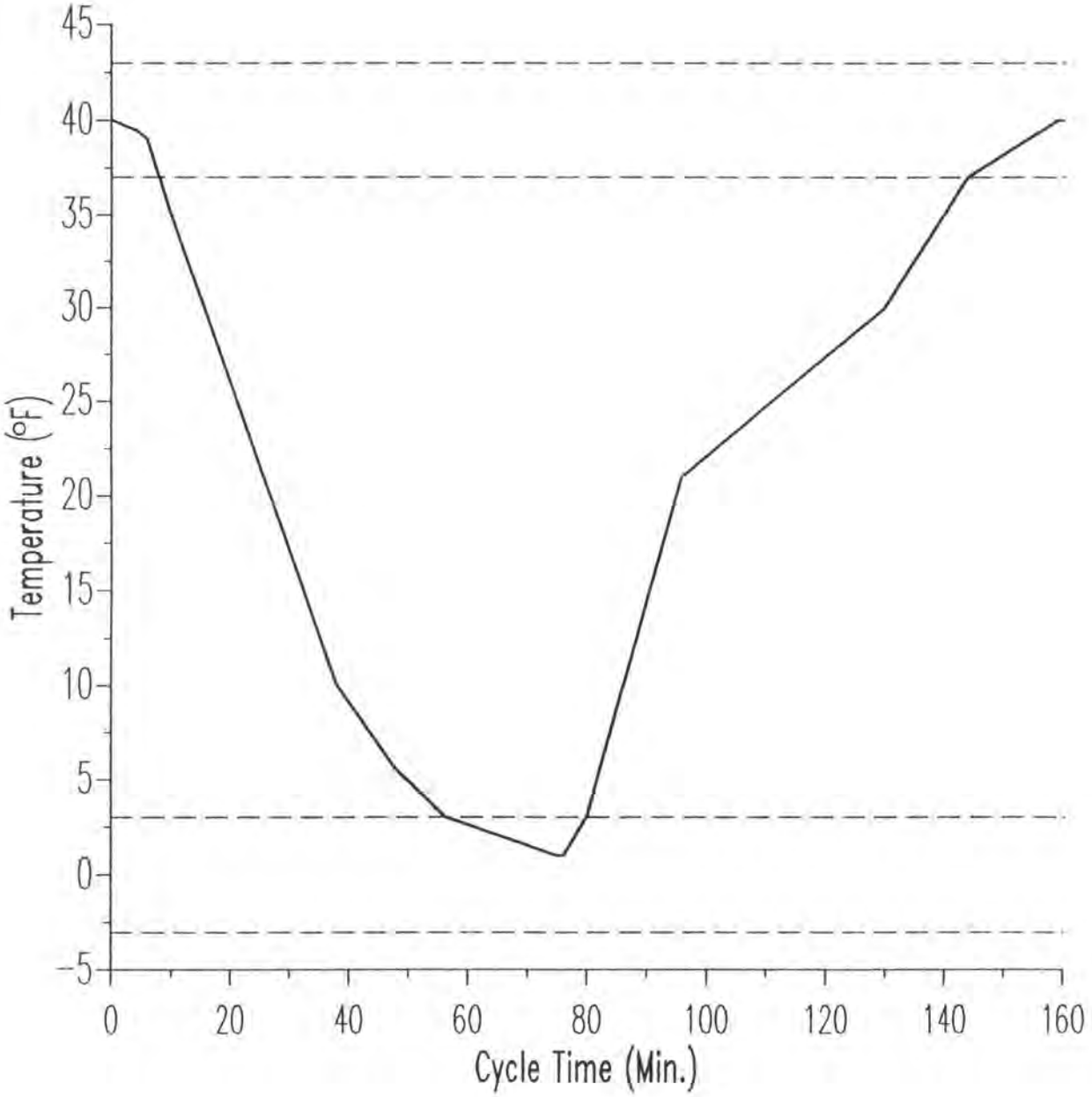


Figure B1. Typical Freezing-and-Thawing Cycle
ASTM C 666 Procedure A using 3-Hour Nominal Cycle

TABLE B1

Cycle Characteristics
ASTM C 666 Procedure A using 3-Hour Nominal Cycle Time

Typical Cycle	ASTM C 666 Cycle Requirements	Actual Cycle Conditions
Total time (t)	2-5 Hours	2 hr. 39 min.
Freezing time (t_c)	None	1 hr. 16 min.
Thawing time (t_w)	≥ 25% of t	1 hr. 23 min. (52%)
Freezing time from 37-3°F	≥ 50% t_c	48 min. (63%)
Thawing time from 3-37°F	≥ 50% t_w	1 hr. 3 min. (76%)
Beam temp. at end of freeze	0 ± 3°F	1°F
Beam temp. at end of thaw	40 ± 3°F	40°F
Freezing Rate from 37°F to 3°F	None	42°F/hr.
Thawing Rate from 3°F to 37°F	None	32°F/hr.
Freezing time from 35-10°F	None	27 min.
Thawing time from 10-35°F	None	55 min.
Transition, freeze to thaw	≤ 10 min.	5 min.
Transition, thaw to freeze	≤ 10 min.	8 min.
Variation Between Cycles		
Freezing time from 35-10°F	≤ 16.7% t_c	10 min. (13%)
Thawing time from 10-35°F	≤ 33.3% t_w	23 min. (30%)

TABLE B2

SUMMARY OF TEST RESULTS*
ASTM C 666 Procedure A using 3-Hour Nominal Cycle Time

Aggregate Formation	Saturation	Cure	DF	P	Percent Length Change	Weight Loss	Flexural Str. Initial	Flexural Str. Final
Callaway	Dry	14	50.2	61.0	.1019	317	935	379
	24-Hr. Soak	14	30.6	50.2	.0925	223	929	275
		35	23.8	55.6	.0785	123	969	330
		91	13.3	56.0	.1066	168	982	339
	Vacuum	14	19.6	51.1	.0927	113	997	245
		35	14.5	57.0	.0948	81	934	328
		91	9.9	56.4	.1296	144	1009	349
BF at Mo. City	24-Hr. Soak	14	19.8	52.2	.1060	111	916	308
		35	14.8	59.4	.0922	96	969	367
		91	7.7	53.9	.1304	120	1034	313
	Vacuum	14	14.5	53.5	.1202	51	922	269
		35	9.6	52.4	.1214	39	966	315
		91	7.1	57.2	.1119	99	1039	323
Plattin	Dry	14	32.9	57.2	.1010	244	983	353
	24-Hr. Soak	14	28.3	59.0	.0977	182	964	333
		35	19.9	59.8	.0960	101	1003	396
		91	13.3	65.4	.0931	202	921	421
	Vacuum	14	17.9	56.8	.0938	55	1006	349
		35	12.0	57.6	.0891	75	982	367
		91	9.8	57.2	.1181	107	941	374
BF at Randolph	Dry	14	37.5	59.2	.0872	234	926	342
	24-Hr. Soak	14	23.0	57.2	.0891	142	903	335
		35	16.5	56.8	.1072	87	945	353
		91	8.7	53.4	.1228	165	1004	332
	Vacuum	14	13.5	60.1	.1012	34	946	397
		35	9.4	53.5	.1164	33	1056	363
		91	5.1	46.4	.1600	76	1061	311

*Average of 3 tests

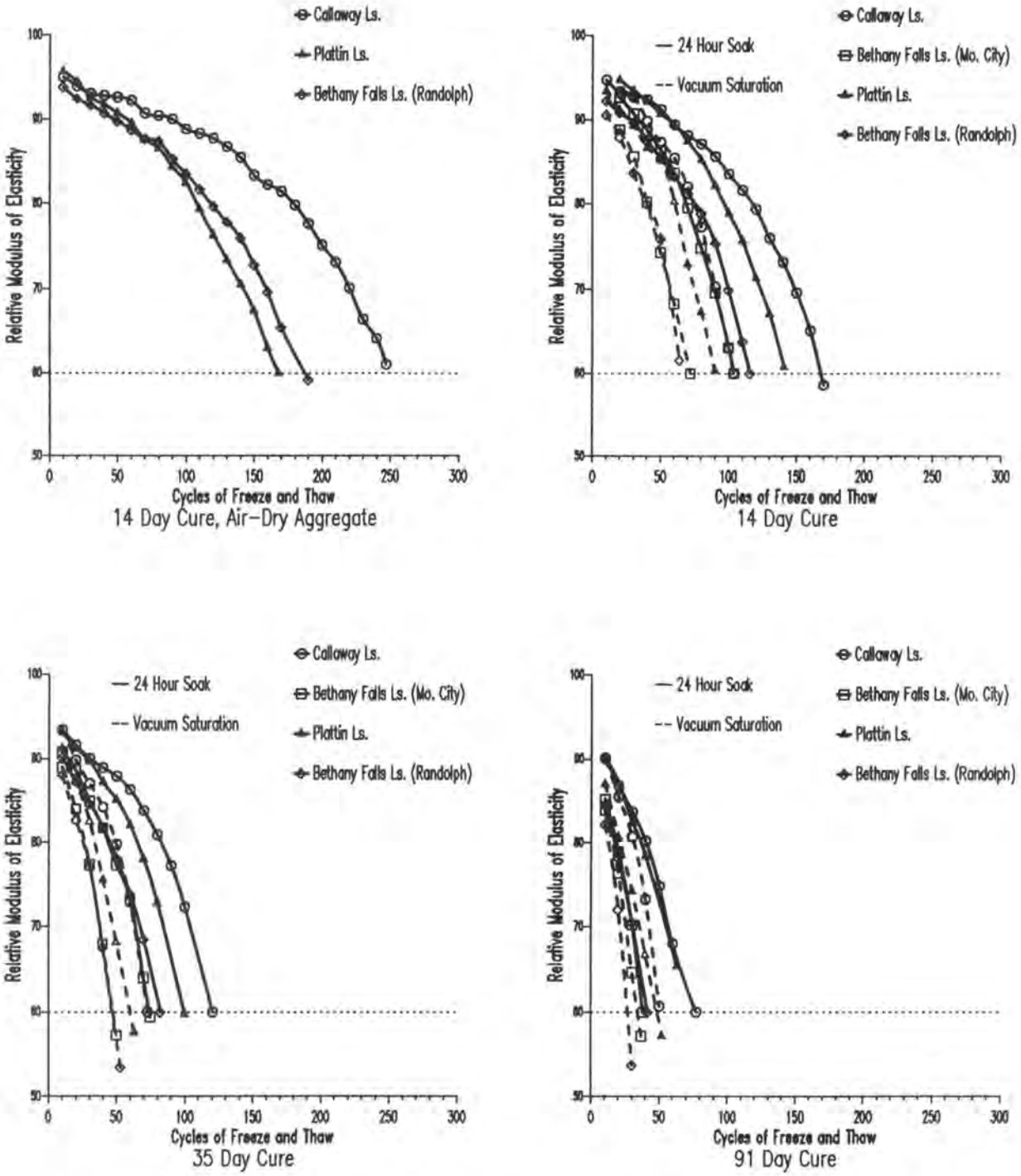


Figure B2. Relative Modulus of Elasticity vs. Cycles of Freeze and Thaw
ASTM C 666 Procedure A using 3-Hour Nominal Cycle

APPENDIX C

ASTM C 666 Procedure A using 5-Hour Nominal Cycle Time

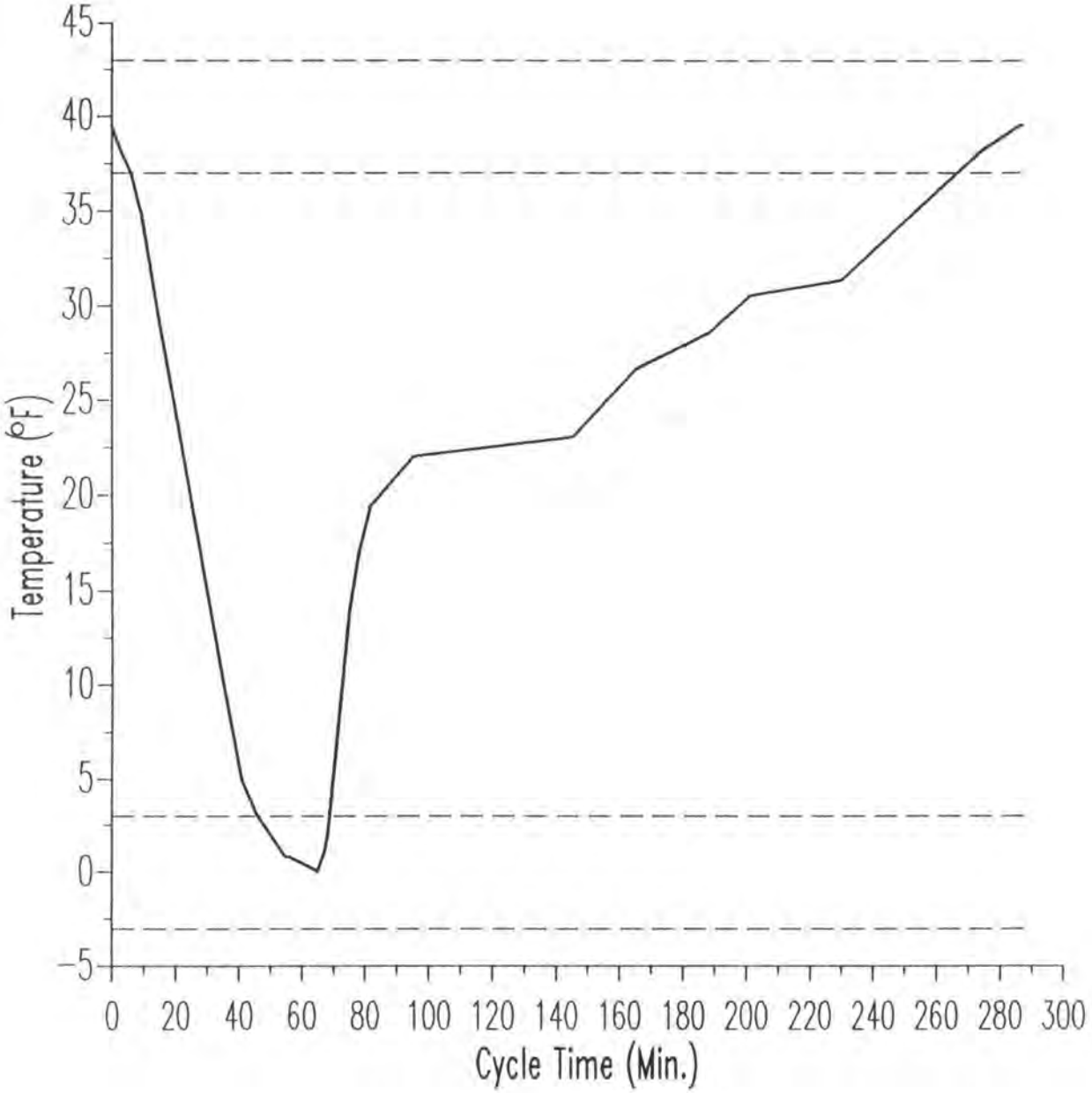


Figure C1. Typical Freezing-and-Thawing Cycle
ASTM C 666 Procedure A using 5-Hour Nominal Cycle

TABLE C1

CYCLE CHARACTERISTICS
ASTM C 666 Procedure A using 5-Hour Nominal Cycle Time

For A Typical Cycle	ASTM C 666 Cycle Requirements	Actual Cycle Conditions
Total time (t)	2-5 Hours	4 hr. 46 min.
Freezing time (t_c)	None	1 hr. 5 min.
Thawing time (t_w)	≥ 25% of t	3 hr. 41 min. (77%)
Freezing time from 37-3°F	≥ 50% t_c	40 min. (62%)
Thawing time from 3-37°F	≥ 50% t_w	3 hr. 15 min. (88%)
Beam temp. at end of freeze	0 ± 3°F	0°F
Beam temp. at end of thaw	40 ± 3°F	27°F
Freezing Rate from 37°F to 3°F	None	51°F/hr.
Thawing Rate from 3°F to 37°F	None	10°F/hr.
Freezing time from 35-10°F	None	26 min.
Thawing time from 10-35°F	None	2 hr. 58 min.
Transition, freeze to thaw	≤ 10 min.	3 min.
Transition, thaw to freeze	≤ 10 min.	3 min.
Variation Between Cycles		
Freezing time from 35-10°F	≤ 16.7% t_c	7 min. (11%)
Thawing time from 10-35°F	≤ 33.3% t_w	38 min. (17%)

TABLE C2

SUMMARY OF TEST RESULTS*
ASTM C 666 Procedure A, 5 Hour Cycle

Aggregate Formation	Saturation	Cure	DF	P	Percent Length Change	Weight Loss	Flexural Str. Initial	Flexural Str. Final
Callaway	Dry	14	29.8	59.3	.0872	733	974	346
	24-Hr. Soak	14	20.6	58.0	.0880	427	957	352
		35	14.2	53.4	.1031	340	1009	282
		91	11.6	56.3	.1171	58	1084	345
	Vacuum	14	12.8	56.3	.0991	258	930	289
		35	9.3	52.4	.1138	230	1034	294
		91	8.7	51.2	.1486	28	1075	303
BF at Mo. City	24-Hr. Soak	14	18.0	54.5	.1095	368	950	359
		35	12.3	56.8	.1067	243	1009	353
		91	8.5	56.2	.1152	30	1056	355
	Vacuum	14	8.4	44.1	.1842	196	983	220
		35	6.8	58.6	.1052	152	1041	386
		91	5.7	56.5.	.1415	19	1030	389
Plattin	Dry	14	25.3	59.0	.0976	574	1007	373
	24-Hr. Soak	14	20.1	58.7	.0938	409	983	354
		35	15.9	55.5	.1238	310	1020	406
		91	12.6	58.0	.1266	66	1031	437
	Vacuum	14	9.9	47.7	.1361	225	995	251
		35	9.1	53.5	.1216	173	1002	349
		91	8.5	59.5	.1183	8	1091	436
BF at Randolph	Dry	14	21.3	59.1	.1003	512	969	335
	24-Hr. Soak	14	15.5	58.8	.0922	339	959	367
		35	10.2	50.3	.1292	295	998	296
		91	7.6	57.3	.1147	23	1074	388
	Vacuum	14	8.5	53.6	.1477	183	987	335
		35	6.3	50.7	.1481	139	1036	311
		91	5.6	55.4	.1406	17	1089	347

*Average of 3 tests

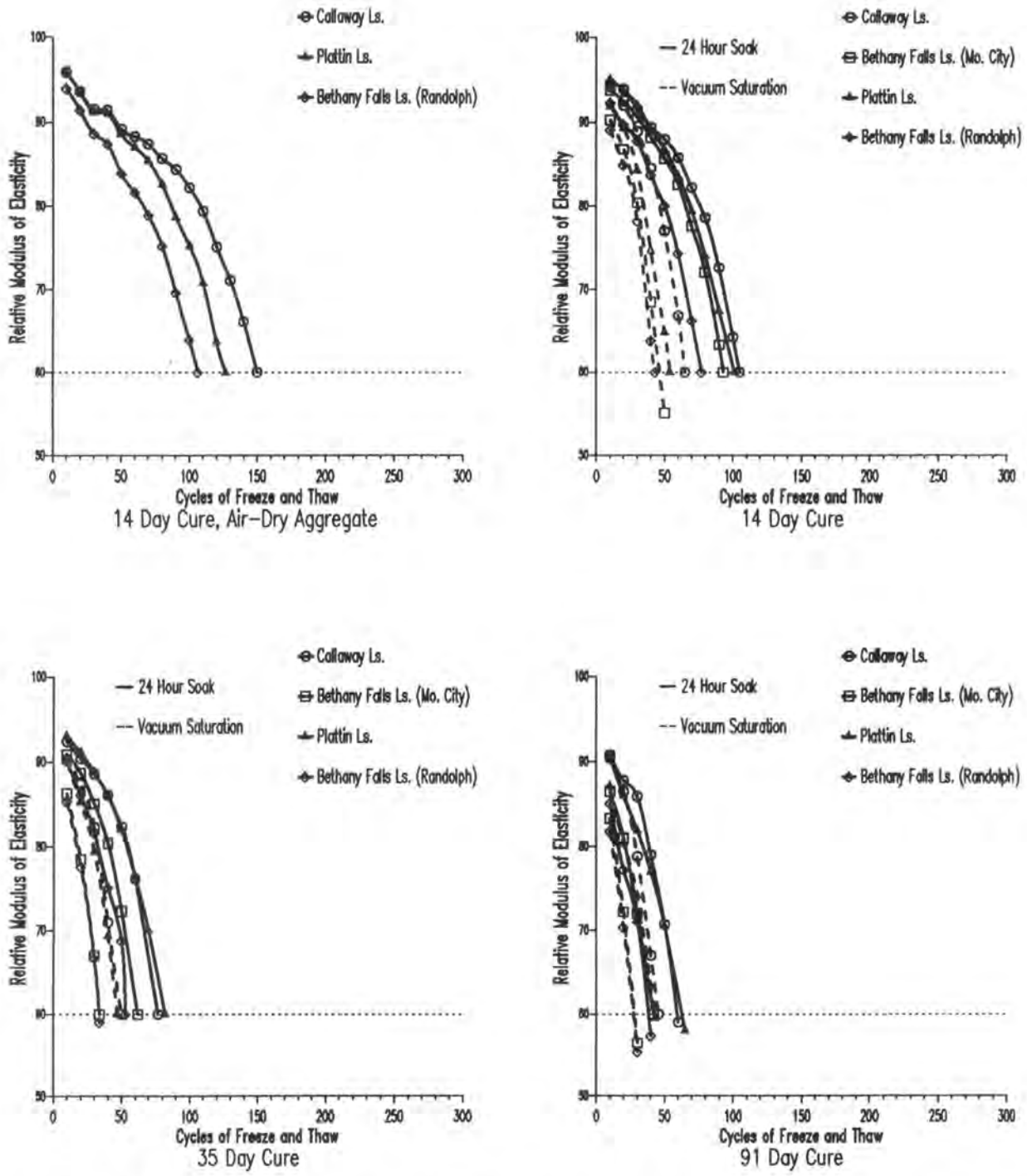


Figure C2. Relative Modulus of Elasticity vs. Cycles of Freeze and Thaw
ASTM C 666 Procedure A using 5-Hour Nominal Cycle

APPENDIX D

ASTM C 666 Procedure B using 3-Hour Nominal Cycle Time

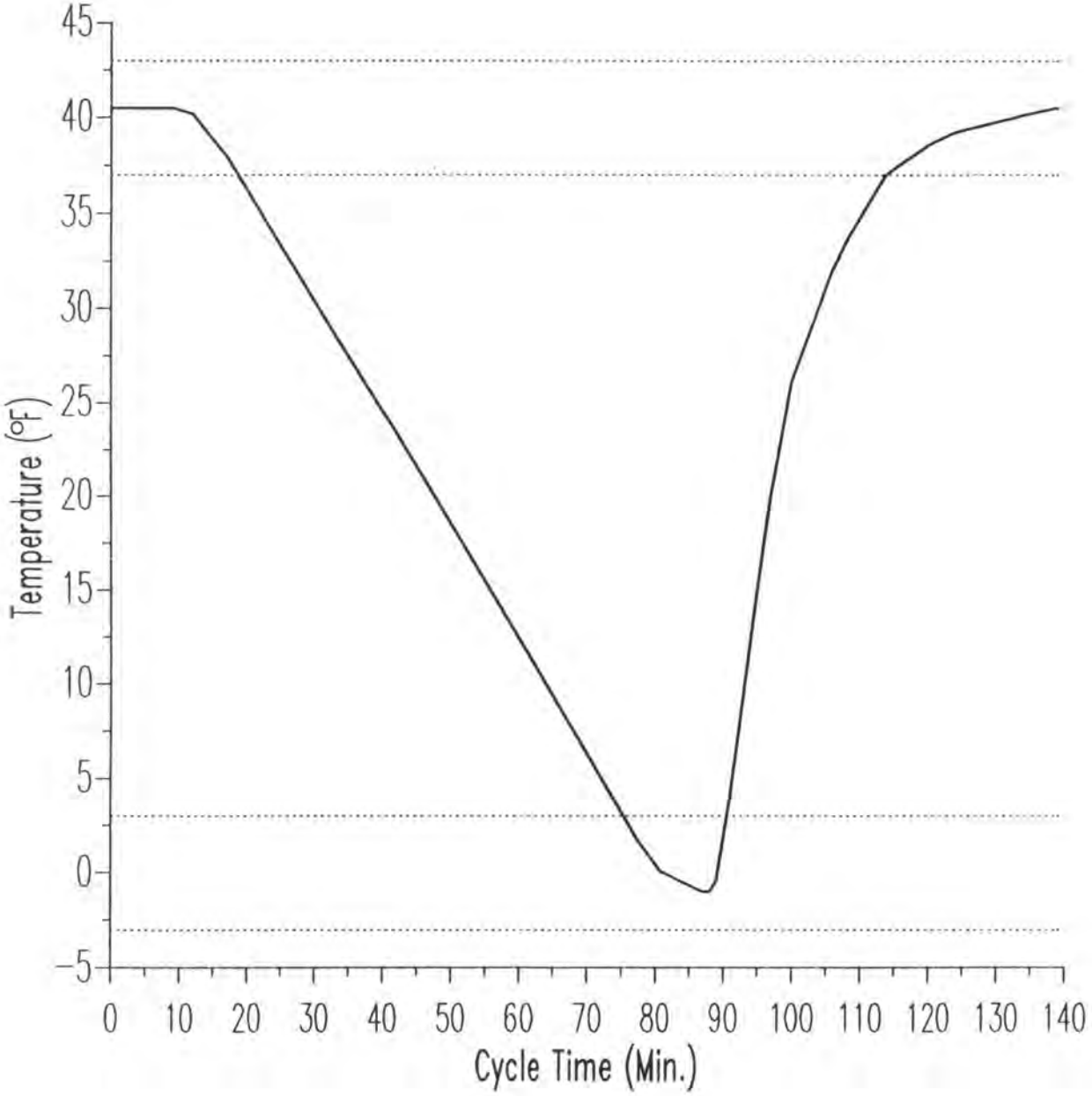


Figure D1. Typical Freezing-and-Thawing Cycle
ASTM C 666 Procedure B using 3-Hour Nominal Cycle

TABLE D1

CYCLE CHARACTERISTICS
ASTM C 666 Procedure B using 3-Hour Nominal Cycle Time

For A Typical Cycle	ASTM C 666 Cycle Requirements	Actual Cycle Conditions
Total time (t)	2-5 Hours	2 hr. 19 min.
Freezing time (t_c)	None	1 hr. 30 min.
Thawing time (t_w)	≥ 20% of t	49 min. (35%)
Freezing time from 37-3°F	≥ 50% t_c	61 min. (68%)
Thawing time from 0-37°F	≥ 50% t_w	25 min. (51%)
Beam temp. at end of freeze	0 ± 3°F	-1°F
Beam temp. at end of thaw	40 ± 3°F	41°F
Freezing Rate from 37°F to 3°F	None	33°F/hr.
Thawing Rate from 3°F to 37°F	None	82°F/hr.
Freezing time from 35-10°F	None	51 min.
Thawing time from 10-35°F	None	19 min.
Transition, freeze to thaw	≤ 10 min.	3 min.
Transition, thaw to freeze	≤ 10 min.	5 min.
Variation Between Cycles		
Freezing time from 35-10°F	≤ 16.7% t_c	13 min. (14%)
Thawing time from 10-35°F	≤ 33.3% t_w	4 min. (8%)

TABLE D2

SUMMARY OF TEST RESULTS*
ASTM C 666 Procedure B, 3-Hour Cycle

Aggregate Formation	Saturation	Cure	DF	P	Percent Length Change	Weight Gain	Flexural Str. Initial	Flexural Str. Final
Callaway	Dry	14	94.5	94.4	.0223	0	889	823
	24-Hr. Soak	14	95.3	95.1	.0213	8	987	828
		35	86.8	87.3	.0562	12	1053	722
		91	30.9	52.9	.1472	6	985	373
	Vacuum	14	62.0	65.3	.1093	37	946	448
		35	47.9	57.1	.1491	35	984	398
		91	16.8	53.6	.1171	13	973	304
BF at Mo. City	24-Hr. Soak	14	83.4	83.3	.0704	36	934	605
		35	56.1	60.3	.1311	34	965	389
		91	24.4	58.2	.1299	7	1024	352
	Vacuum	14	44.8	56.9	.1410	55	966	341
		35	28.5	58.8	.1337	45	1013	390
		91	15.1	58.9	.1214	20	976	347
Plattin	Dry	14	82.7	82.4	.0563	17	926	615
	24-Hr. Soak	14	84.4	84.3	.0533	29	943	624
		35	73.3	74.5	.0851	28	972	505
		91	37.7	61.7	.1223	15	941	413
	Vacuum	14	32.8	58.6	.1183	46	1025	358
		35	21.8	54.2	.1098	39	1043	305
		91	11.9	57.4	.1171	20	990	425
BF at Randolph	Dry	14	78.2	77.9	.0671	18	870	474
	24-Hr. Soak	14	72.8	72.5	.0972	35	923	467
		35	49.6	58.2	.1263	30	955	385
		91	25.5	56.5	.1474	8	1001	365
	Vacuum	14	40.0	44.7	.1292	50	931	284
		35	21.1	57.1	.1171	38	989	340
		91	11.0	56.5	.1244	23	993	378

*Average of 3 tests

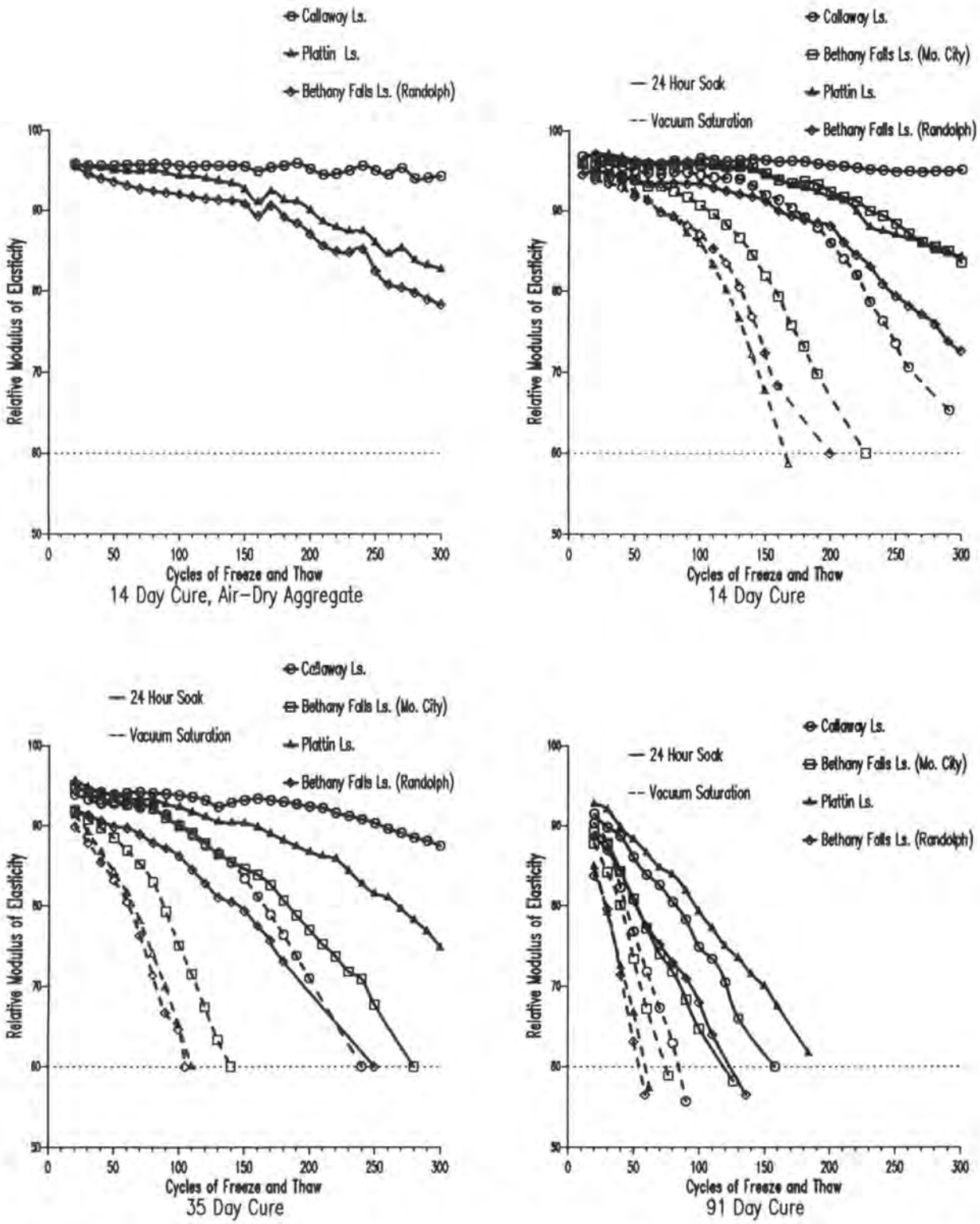


Figure D2. Relative Modulus of Elasticity vs. Cycles of Freeze and Thaw
ASTM C 666 Procedure B using 3-Hour Nominal Cycle

APPENDIX E

ASTM C 666 Procedure B using 5-Hour Nominal Cycle Time

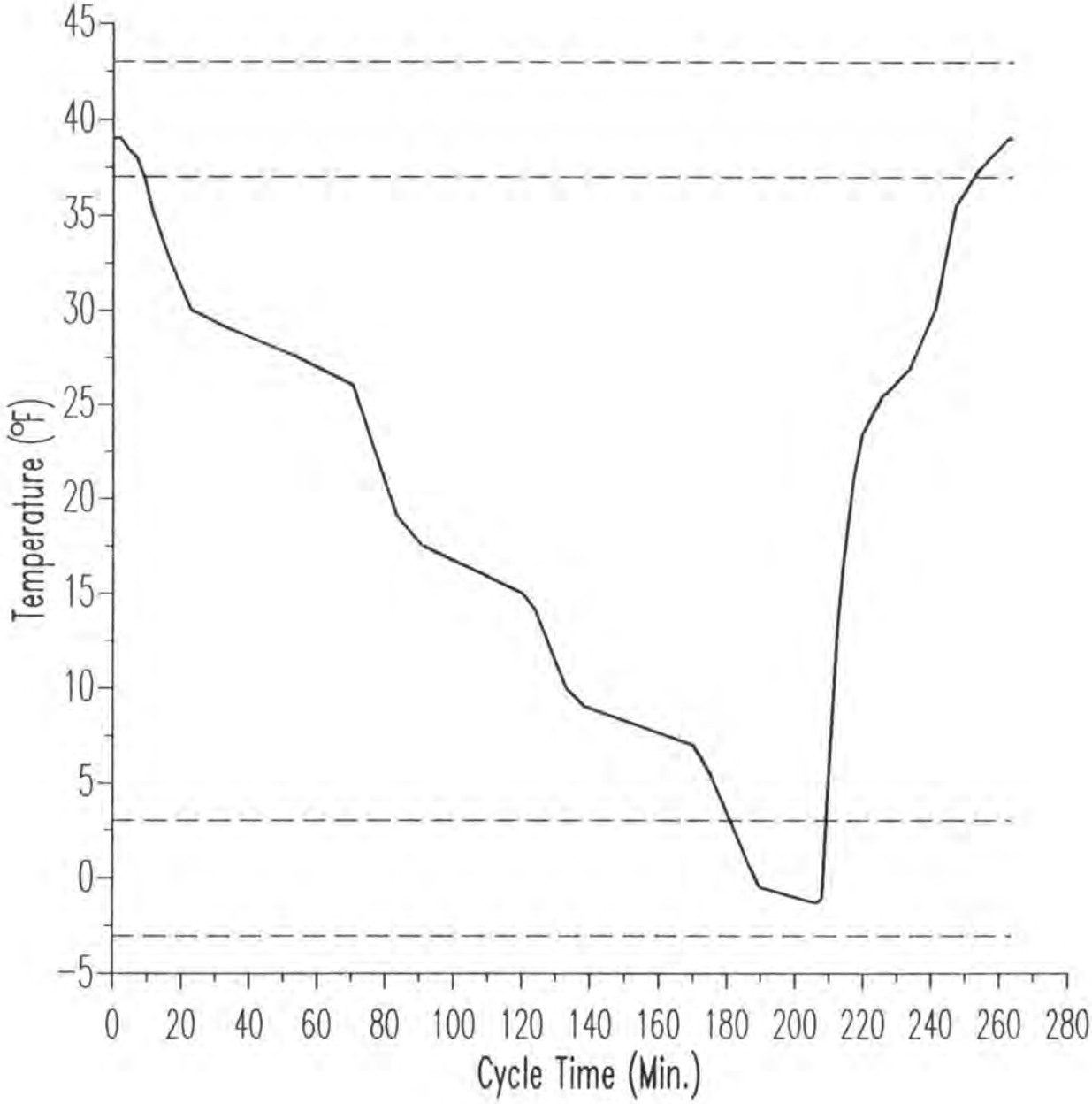


Figure E1. Typical Freezing-and-Thawing Cycle
ASTM C 666 Procedure B using 5-Hour Nominal Cycle

TABLE E1

Cycle Characteristics
ASTM C 666 Procedure B using 5-Hour Nominal Cycle Time

For Each Cycle	ASTM C 666 Cycle Requirements	Actual Cycle Conditions
Total time (t)	2-5 Hours	4 hr. 22 min.
Freezing time (t_c)	None	3 hr. 27 min.
Thawing time (t_w)	≥ 20% of t	55 min. (21%)
Freezing time from 37-3°F	≥ 50% t_c	3 hr. 12 min. (93%)
Thawing time from 3-37°F	≥ 50% t_w	42 min. (76%)
Beam temp. at end of freeze	0 ± 3°F	-1°
Beam temp. at end of thaw	40 ± 3°F	39°F
Freezing Rate from 37°F to 3°F	None	11°F/hr.
Thawing Rate from 3°F to 37°F	None	49°F/hr.
Freezing time from 35-10°F	None	2 hr. 1 min.
Thawing time from 10-35°F	None	34 min.
Transition, freeze to thaw	≤ 10 min.	2 min.
Transition, thaw to freeze	≤ 10 min.	7 min.
Variation Between Cycles		
Freezing time from 35-10°F	≤ 16.7% t_c	15 min. (7%)
Thawing time from 10-35°F	≤ 33.3% t_w	8 min. (15%)

TABLE E2

SUMMARY OF TEST RESULTS*
ASTM C 666 Procedure B, 5-Hour Cycle

Aggregate Formation	Saturation	Cure	DF	P	Percent Length Change	Weight Loss	Flexural Str. Initial	Flexural Str. Final
Callaway	Dry	14	98.7	98.7	.0107	15	953	939
	24-Hr. Soak	14	96.5	96.5	.0168	11	943	855
		35	95.0	95.0	.0244	16	997	947
		91	56.0	59.0	.1429	4	993	502
	Vacuum	14	87.1	87.0	.0609	10	985	816
		35	78.7	78.6	.0842	7	1007	617
		91	32.3	58.0	.1498	7	1005	392
BF at Mo. City	24-Hr. Soak	14	91.1	91.0	.0528	8	875	815
		35	78.4	78.4	.0875	15	945	605
		91	33.5	58.9	.1223	6	1000	399
	Vacuum	14	36.3	58.0	.1456	43	907	352
		35	24.6	59.5	.1199	26	985	336
		91	15.0	58.2	.1344	23	1046	368
Plattin	Dry	14	96.0	96.0	.0258	18	947	808
	24-Hr. Soak	14	81.5	81.4	.0701	14	923	668
		35	71.4	71.4	.1086	20	1017	452
		91	30.1	58.7	.1055	4	1028	473
	Vacuum	14	33.7	60.2	.1017	32	999	354
		35	36.6	55.4	.1254	22	1010	377
		91	19.0	58.3	.1130	10	993	407
BF at Randolph	Dry	14	91.7	91.7	.0448	7	934	750
	24-Hr. Soak	14	69.3	69.1	.1318	26	964	438
		35	55.4	59.5	.1422	26	1063	411
		91	21.9	58.6	.1280	3	1080	415
	Vacuum	14	28.0	58.4	.1140	39	897	361
		35	24.5	59.6	.1344	33	1029	320
		91	12.2	53.3	.1320	13	1017	305

*Average of 3 tests

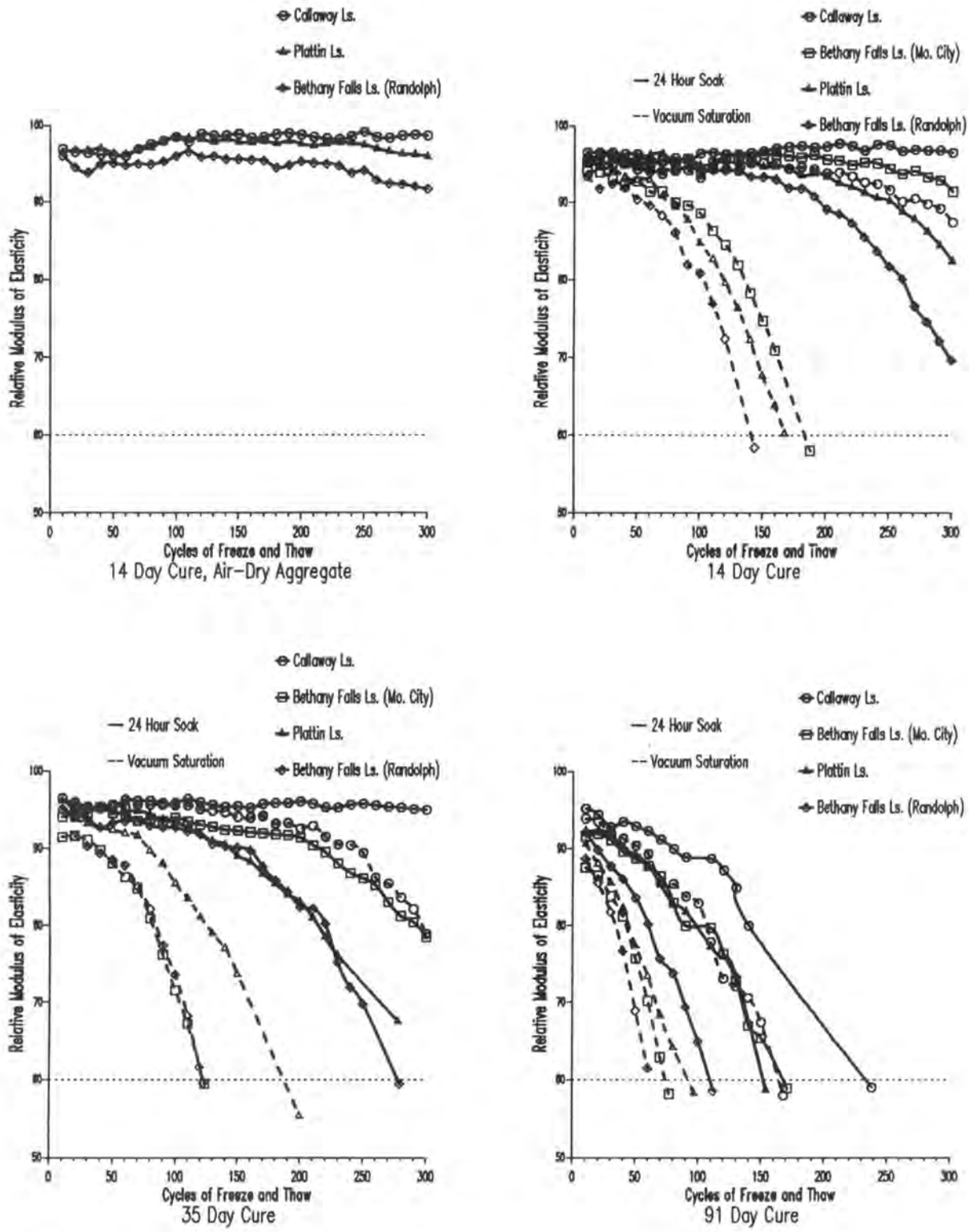


Figure E2. Relative Modulus of Elasticity vs. Cycles of Freeze and Thaw
ASTM C 666 Procedure B using 5-Hour Nominal Cycle

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