REPORT **MR93-1**

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EVALUATION OF A REVISED FIVE-HOUR CYCLE USING ASTM C 666, PROCEDURE B

MISSOURI HIGHWAY AND TRANSPORTATION DEPARTMENT

EVALUATION OF A REVISED FIVE-HOUR CYCLE USING ASTM C 666, PROCEDURE B

RESEARCH INVESTIGATION 85-6A

Prepared By

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JANUARY 1993

EXECUTIVE SUMMARY

A previous investigation, reported under MCHRP 86-1 entitled Evaluation of Concrete and Aggregate Durability Test, studied the effects upon concrete durability of various coarse aggregate moisture treatments, durations of concrete specimen curing, and durations of the freezing-and-thawing cycle when performing ASTM C 666, Resistance of Concrete to Rapid Freezing and Thawing. However, in that investigation, the effect the freezing and thawing rate had upon concrete durability was not evaluated.

This previous investigation was divided into four series by ASTM procedure and total cycle time. It was concluded the series using Procedure B, Rapid Freezing In Air and Thawing in Water, and using a five-hour nominal cycle best discriminated among beams made with four different coarse aggregates. The cycle for this series, designated B5, had a 3-hour 27-minute freeze time and a 55-minute thaw time.

In this investigation, a parallel series to B5 was performed: Procedure B using a revised five-hour nominal cycle (RB5) with a 1-hour 41-minute freeze time and a 2-hour 46-minute thaw time. All other variables were the same as the previous study.

The following conclusions were made from the test results.

(1) Using statistical analysis of variance (ANOVA), the RB5 series generally resulted in less discrimination among beams made with the four coarse aggregates used in this investigation than did the B5 series.

(2) The cycle characteristics of the RB5 series caused concrete durability of the beams to decrease faster than the comparable beams tested in the B5 series.

(3) Results from this study do not change conclusions of the previous study from which it was decided to use the B5 cycle, 24-hour-soak moisture treatment and 35-day beam curing as Missouri's standard method for rapid freeze and thaw testing.

TABLE OF CONTENTS

List of Tables ii

List of Figures iii

List of Abbreviations iv

Introduction 1

Scope 6

Equipment 9

Results 10

Discussion 19

Conclusions 28

Implementation 29

Appendix A (Materials, Mix-Design and Batching Sequence and Specimen Identification)

Appendix B (Tabulated Summaries of Test Results for RB5, B5, and B3 Series)

Appendix C (Correlations Between Control and Test Beams)

LIST OF TABLES

Table No.	Description	Page
1	Cycle Characteristics	4
2	Example of ANOVA Results with Tukey's Test Calculated on Durability Factors . .	20
3	Summary of One-Way Anova and Tukey's Test Results	21
A1	Physical Properties of Coarse Aggregate	
A2	Physical Properties and Gradation of Fine Aggregate	
A3	Sources and Properties of Blended Cement	
A4	Concrete Mix Design Factors	
A5	Characteristics of Fresh Concrete	
A6	Randomized Batching Sequence	
B1	Summary of Test Results (RB5 Series)	
B2	Summary of Test Results (B5 Series)	
B3	Summary of Test Results (B3 Series)	

LIST OF FIGURES

Figure 1 - Typical Freeze-Thaw Cycles (ASTM C 666, Method B) 3

Figure 2 - Durability Factors by Cure and Saturation 11

Figure 3 - Relative Modulus vs. Cycles of Freeze and Thaw; Air-Dry Coarse Aggregate and 14 Day Cure of Beams 12

Figure 4 - Relative Modulus vs. Cycles of Freeze and Thaw; 24 Hour Soak of Coarse Aggregate and 14 Day Cure of Beams 13

Figure 5 - Relative Modulus vs. Cycles of Freeze and Thaw; 24 Hour Soak of Coarse Aggregate and 35 Day Cure of Beams 14

Figure 6 - Relative Modulus vs. Cycles of Freeze and Thaw; 24 Hour Soak of Coarse Aggregate and 91 Day Cure of Beams 15

Figure 7 - Relative Modulus vs. Cycles of Freeze and Thaw; Vacuum Saturation of Coarse Aggregate and 14 Day Cure of Beams 16

Figure 8 - Relative Modulus vs. Cycles of Freeze and Thaw; Vacuum Saturation of Coarse Aggregate and 35 Day Cure of Beams 17

Figure 9 - Relative Modulus vs. Cycles of Freeze and Thaw; Vacuum Saturation of Coarse Aggregate and 91 Day Cure of Beams 18

Figure 10 - Relative Modulus vs. Percent Flexural Strength Reduction 25

Figure 11 - Percent Length Change vs. Percent Flexural Strength Reduction 26

Figure 12 - Weight Change vs. Percent Flexural Strength Reduction 27

Figure C1 - Correlation of Densities Between Test and Control Beams

Figure C2 - Correlation of Dynamic Young's Modulus of Elasticity Between Test and Control Beams

LIST OF ABBREVIATIONS

Abbreviation	Name
Aggr.	Aggregate
ANOVA	Analysis of Variance
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BF	Bethany Falls
B3	Procedure B using a 3-Hour Nominal Cycle
B5	Procedure B using a 5-Hour Nominal Cycle
CA	Coarse Aggregate
Cu Yd	Cubic Yard
CV%	Coefficient of Variation, in percent
D	Day
DF	Durability Factor
F	Fahrenheit
Init.	Initial
Ls.	Limestone
N	Number of data points
P	Relative Modulus of Elasticity
psi	Pounds per square inch
R	Correlation Coefficient
R^2	Coefficient of Determination

LIST OF ABBREVIATIONS (Continued)

RB5	Procedure B using a Revised 5-Hour Nominal Cycle
Sat.	Saturation
SSD	Saturated Surface Dry
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
Wgt.	Weight

INTRODUCTION

A previous investigation, reported under MCHRP 86-1 (1), studied the effects upon concrete durability of various coarse aggregate moisture treatments, durations of concrete specimen curing, and durations of the freezing-and-thawing cycle when performing ASTM C 666, Resistance of Concrete to Rapid Freezing and Thawing (2). However, the effect the relation of freezing time to thawing time a given cycle had upon concrete durability was not evaluated.

The previous investigation incorporated four series of tests based on procedure (Procedure A being rapid freezing and thawing in water and Procedure B being rapid freezing in air and thawing in water) and total cycle time. The four series were: Procedure A using a three hour nominal cycle, Procedure A using a five-hour nominal cycle, Procedure B using a three-hour nominal cycle (B3), and Procedure B using a five-hour nominal cycle (B5). Of the four, it was concluded the B5 series best discriminated among the specimens made from different coarse aggregates of varying frost susceptibility.

In this investigation, a parallel series to B5, having the same scope as B5, was performed using a revised five-hour cycle. While the B5 cycle had a long freeze time (3 hours 27 minutes) and a short thaw time (55 minutes), this new series, designated as RB5, had a short freeze time (1 hour 41 minutes) and a long thaw time (2 hours 46 minutes). All other variables were held constant.

The first purpose of this investigation was to determine whether using this revised cycle configuration resulted in a better discrimination among the beams made with the different coarse aggregates. The second purpose was to determine the effects the shorter freezing time and longer thawing time of this revised cycle had upon concrete durability results.

In order to decide whether differences in the results between the B5 and RB5 series was due to the freezing rate or the thawing rate, the results from the B3 series was also reviewed. The B3 series had both a short freeze and thaw time. The cycles for the three series are shown in Figure 1, with cycle characteristics given in Table 1.

It has been thought that the more rapid the freezing rate, the more the concrete specimen suffers thermal shock. In T. C. Powers early papers, frost damage was attributed to hydraulic pressure in the pores with a faster rate of cooling equated to greater velocity in movement of unfrozen water, and greater stresses induced (3,4). This theory is still considered applicable for freezing in aggregate particles. However, many researchers now believe that most of the frost damage to the concrete paste is caused by stresses resulting from osmotic pressure (5).

Most literature addressing the effect of freezing rate and/or thawing rate correlate faster freezing rates with lower concrete durability results (6,7). The Highway Research Board Special Report 47 concluded that for the air-freeze method, a rapid cycle appeared to cause more damage per cycle than a slow

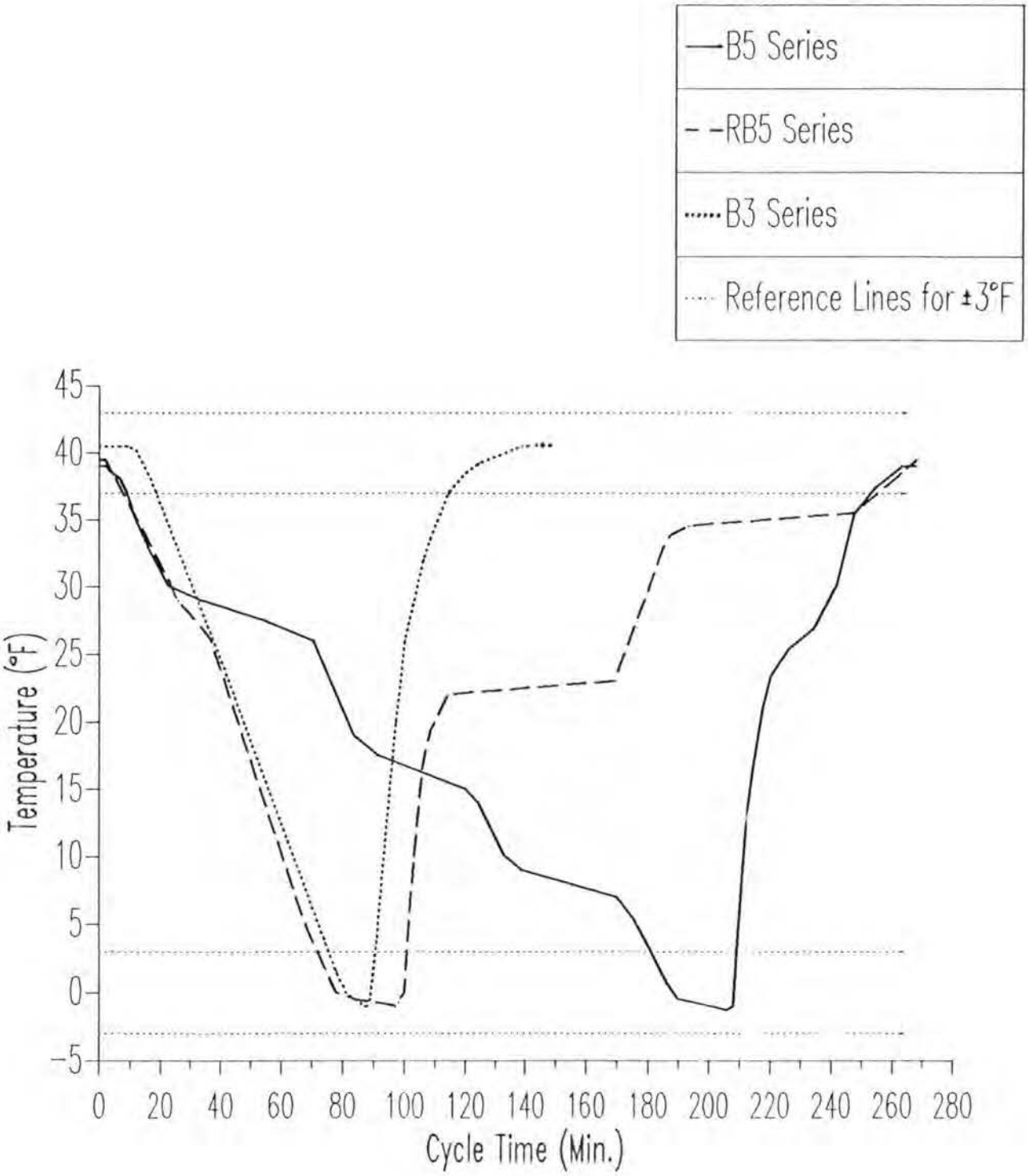


Figure 1. Typical Freeze-Thaw Cycles ASTM C 666 Method B

TABLE 1

CYCLE CHARACTERISTICS

For Each Cycle	Typical RB5 Series Cycle	Typical B5 Series Cycle	Typical B3 Series Cycle
Total time (t)	267 min.	262 min.	139 min.
Freezing time (t_c)	101 min.	207 min.	90 min.
Thawing time (t_w)	166 min. (62%)	55 min. (21%)	49 min. (35%)
Freezing time, 37-3°F	62 min. (61%)	172 min. (62%)	61 min. (68%)
Thawing time, 3-37°F	153 min. (92%)	42 min. (69%)	25 min. (51%)
Low beam temp.	-1°F	-1°F	-1°F
High beam temp.	39.5°F	39°F	41°F
Average Freezing Rate	33°F/hr.	12°F/hr.	33°F/hr.
Average Thawing Rate	13°F/hr.	44°F/hr.	82°F/hr.
Freezing time, 35-10°F	50 min.	121 min.	51 min.
Thawing time, 10-35°F	145 min.	34 min.	19 min.
Variation Between Cycles			
Freezing time, 35-10°F	24 min. (14%)	15 min. (7%)	13 min. (14%)
Thawing time, 10-35°F	10 min. (6%)	8 min. (15%)	4 min. (8%)

NOTE: The percentages in parentheses are in reference to ASTM C 666 cycle requirements for Procedure B as follows:

1. Not less than 20% of the total time shall be used for thawing.
2. The time required for the temperature of the center of any specimen to be reduced from 37 to 3°F shall be no less than one-half of the length of the cooling period and likewise from 3° to 37°F shall not be less than one-half of the length of the heating period.
3. For specimens to be compared with each other, the time required to change the temperature at the centers of any specimens from 35 to 10°F shall not differ by more than one-sixth of the length of the cooling period and likewise from 10° to 35°F shall not differ by more than one-third of the length of the heating period.

cycle (8). However, a report by Lin, Walker, and Payne (9) concluded "for concretes made with soaked or air-dried aggregates, the faster rate of freezing tends to result in greater concrete durability." Their study was conducted using rapid freezing and thaw in water (ASTM C 666, Procedure A).

One interesting note: A main criticism of rapid freezing and thawing tests has been that the acceleration itself may cause the test conditions to differ dramatically from actual service conditions (10). T. F. Willis stated the following (11):

> "The fastest rate of cooling to which pavements in this country are subjected under service conditions is 6 F per hour. If rate of cooling is a factor in the deterioration of concrete exposed to frost action, the acceleration achieved by these test procedures is somewhat analogous to accelerating a test of a glass shelf, intended as a support for a light flower pot, by hitting it with a sledge hammer."

SCOPE

Twenty-seven groups of concrete specimens were made from the following variables.

Moisture treatment of the coarse aggregate (three levels)

1) air drying, by racking till constant moisture content,

2) 24-hour soaking, in accordance with ASTM C 192, and

3) vacuum saturation, at 16 millimeters of mercury for 20 minutes, preceded by oven drying.

Duration of concrete specimen curing (three levels)

Specimens were removed from molds after one day of curing in a moist room and placed in saturated lime water at about 73°F, as required by ASTM C 666, for an additional:

1) 13 days,

2) 34 days, and

3) 90 days.

Source of crushed limestone (four levels)

1) Beck Materials Co. at Holts Summit, MO (Callaway Ls.)

2) Missouri Rock Co., Inc. at Missouri City, MO (Bethany Falls)

3) Southeast Mo. Stone Co. at Cape Girardeau, MO (Plattin), and

4) Hunt Midwest Mining Co. at Randolph, MO (Bethany Falls).

The data matrix was incomplete because freezer space would only allow so many specimens. Beams made with air-dried coarse aggregate had only the fourteen-day cure and only three coarse aggregates were used. Three replicate beams were made per group for a total of 81 beams in the RB5 series, same as in each of the previous series.

From each concrete batch, air content and slump were determined, then three test beams and three flexural strength beams were made in accordance with ASTM C 192, "Method of Making and Curing Concrete Test Specimens in the Laboratbry". 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, "Apparatus For Use in Measurement of Length Change of Hardened Cement Paste, Mortar, and Concrete", giving an effective gage length of 14.0625 inches.

Test beams and their companion flexural strength beams were cured together in about 73°F saturated lime water after one day in the molds in a 73°F moist room. 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. 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 and then were tested to determine their residual flexural strength by center point loading.

The flexural tests were performed generally according to ASTM C 293, "Flexural Strength of Concrete (Simple Beam With Center-Point Loading)" with the following exception. The beams were broken by laying the beams on their side whereby the 3½-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 close to mid-range for portland cement concrete pavement under Missouri's Standard Specifications. Appendix A contains material, batching, and other mix-design information.

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. 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. A 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, "Fundamental Transverse, Longitudinal, and Torsional Frequencies of Concrete Specimens".

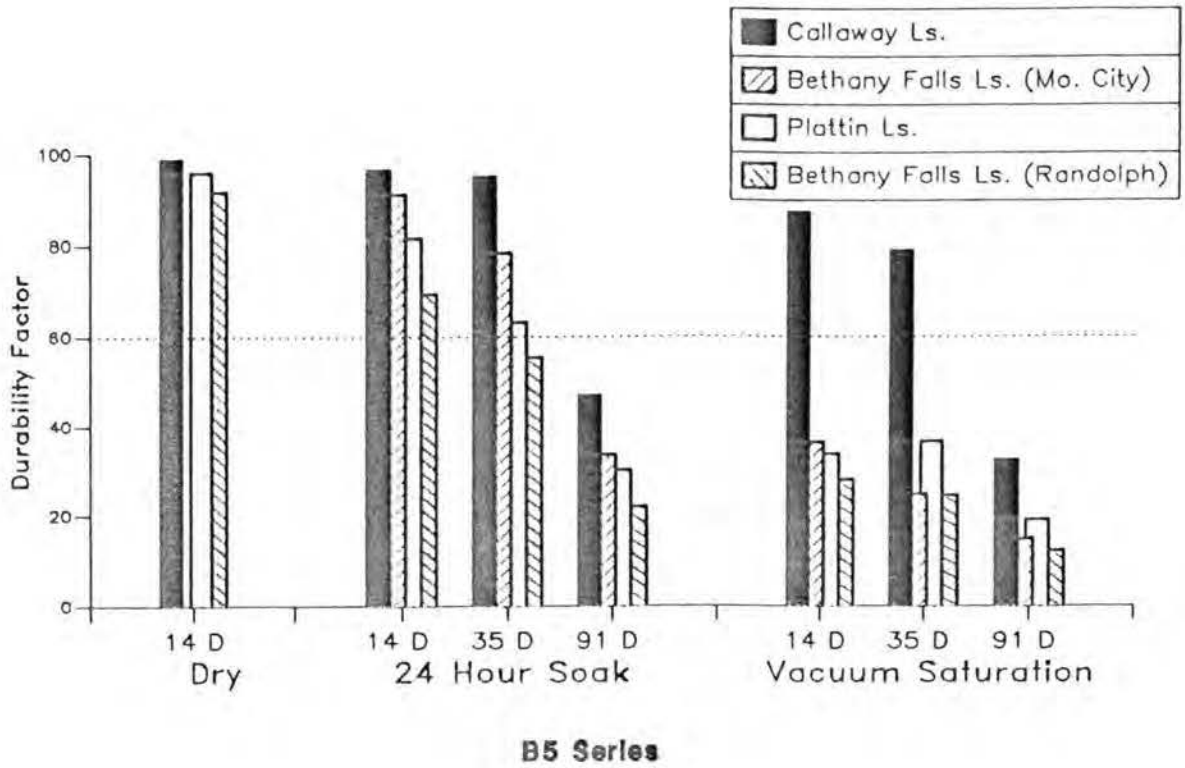
RESULTS

Average durability factors are shown in Figure 2 for the 27 groups of specimens for both the RB5 and B5 series. The reference line at 60 percent indicates those groups, each with three replicate beams, which went below the 60 percent relative modulus within 300 cycles.

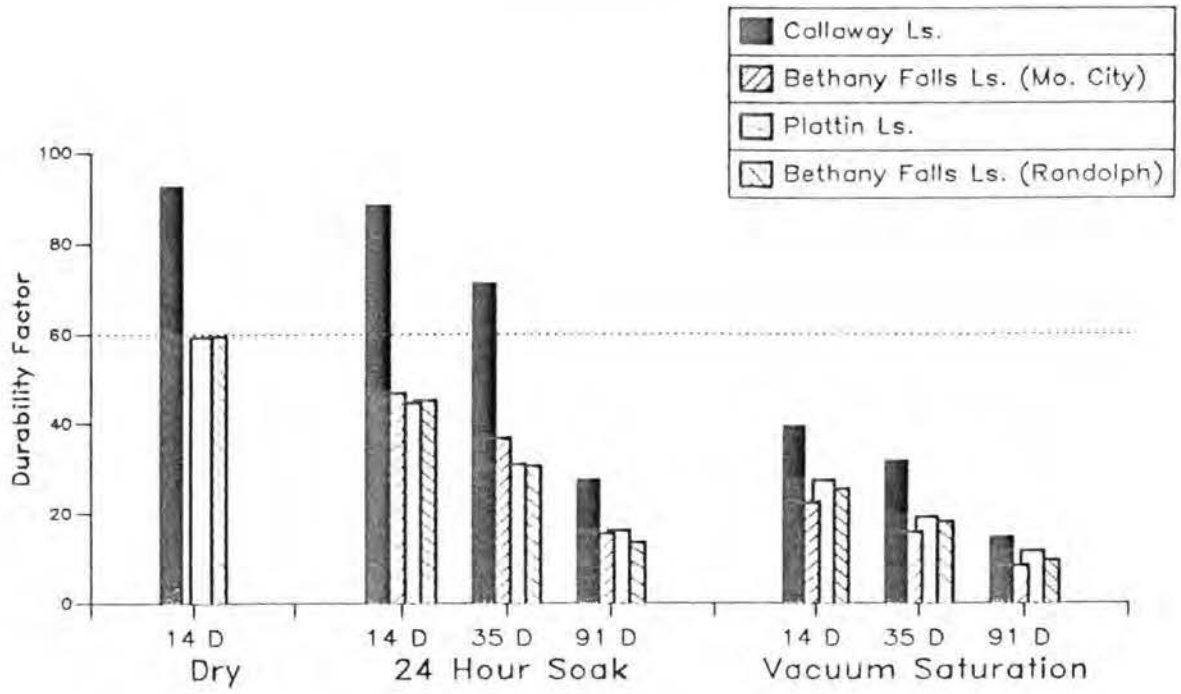
As recommended in ASTM C 666, the average values for relative modulus of elasticity on each group of replicate specimens are plotted against time, expressed as the number of cycles of freezing and thawing. These graphs are given in Figures 3 through 8. These figures show the concrete durability for every group decreased faster in the RB5 series compared to the B5 series.

Expansion, weight change, and flexural strength results for the RB5, B5, and B3 series are given in Appendix B.

Graphs showing correlation between test and control beams are given in Appendix C.



B5 Series



RB5 Series

Figure 2. Durability Factors by Cure and Saturation

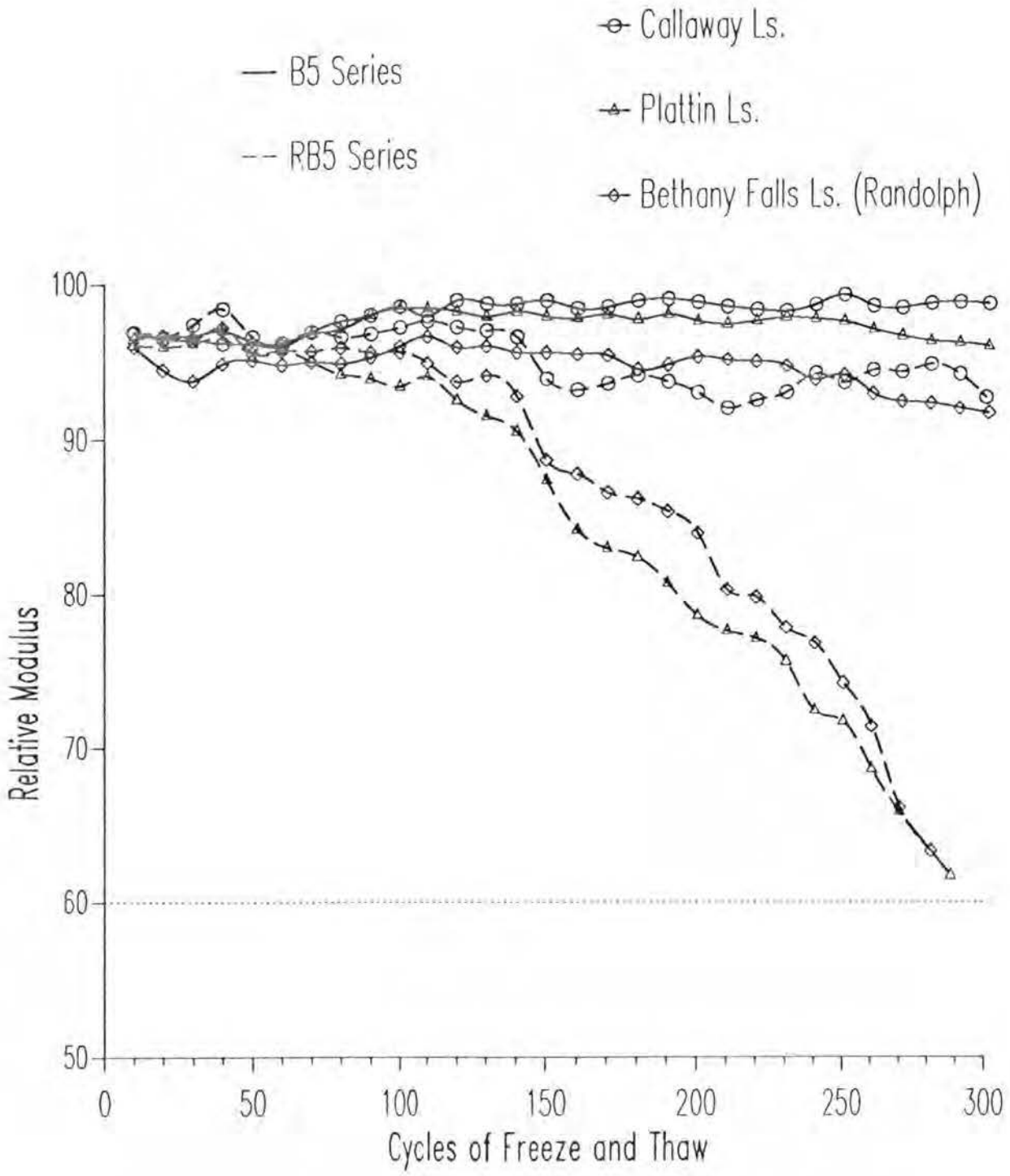


Figure 3. Relative Modulus vs. Cycles of Freeze and Thaw Air-Dry Coarse Aggregate and 14 Day Cure of Beams

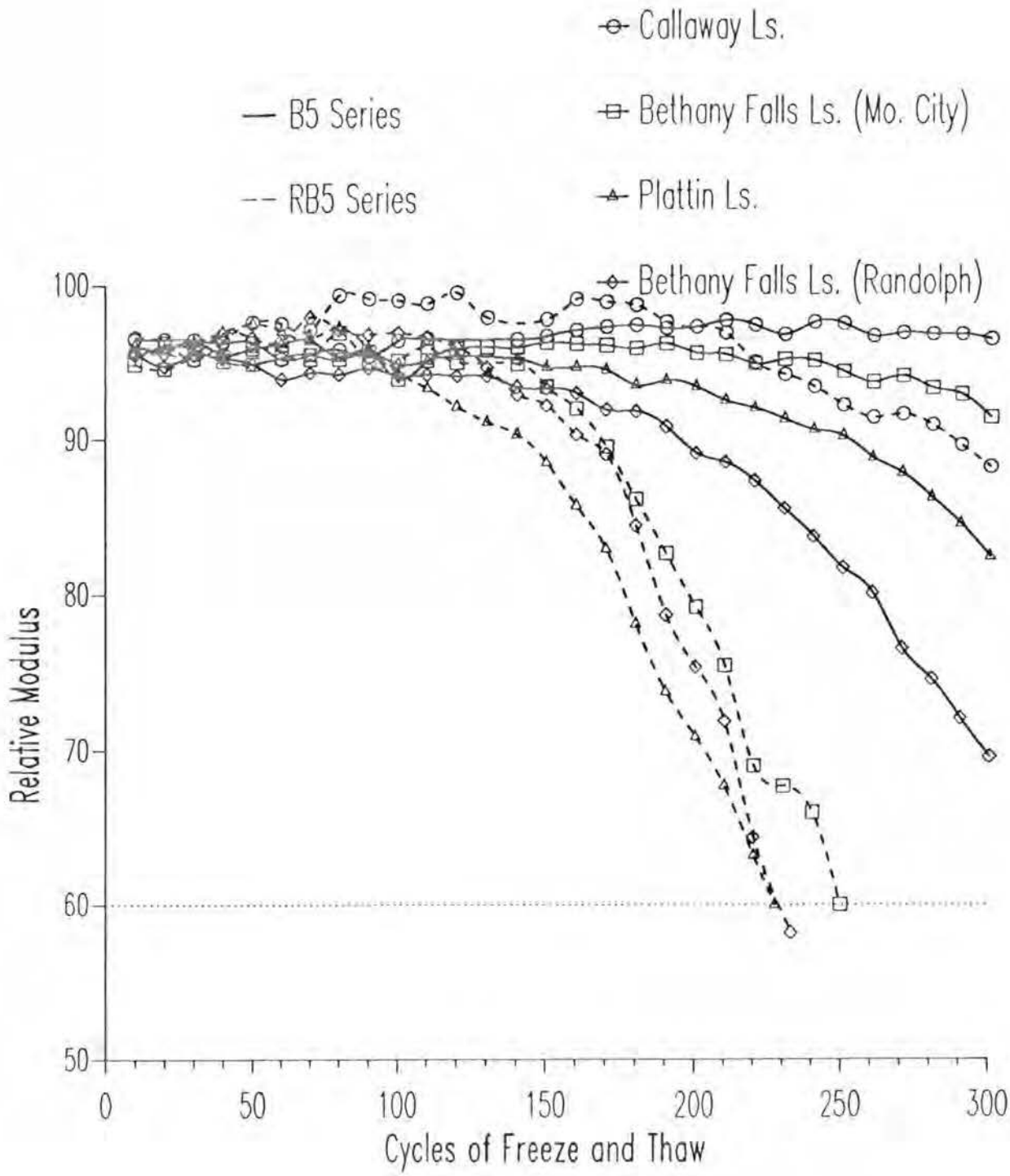


Figure 4. Relative Modulus Vs. Cycles of Freeze and Thaw 24 Hour Soak of CA and 14 Day Cure of Beams

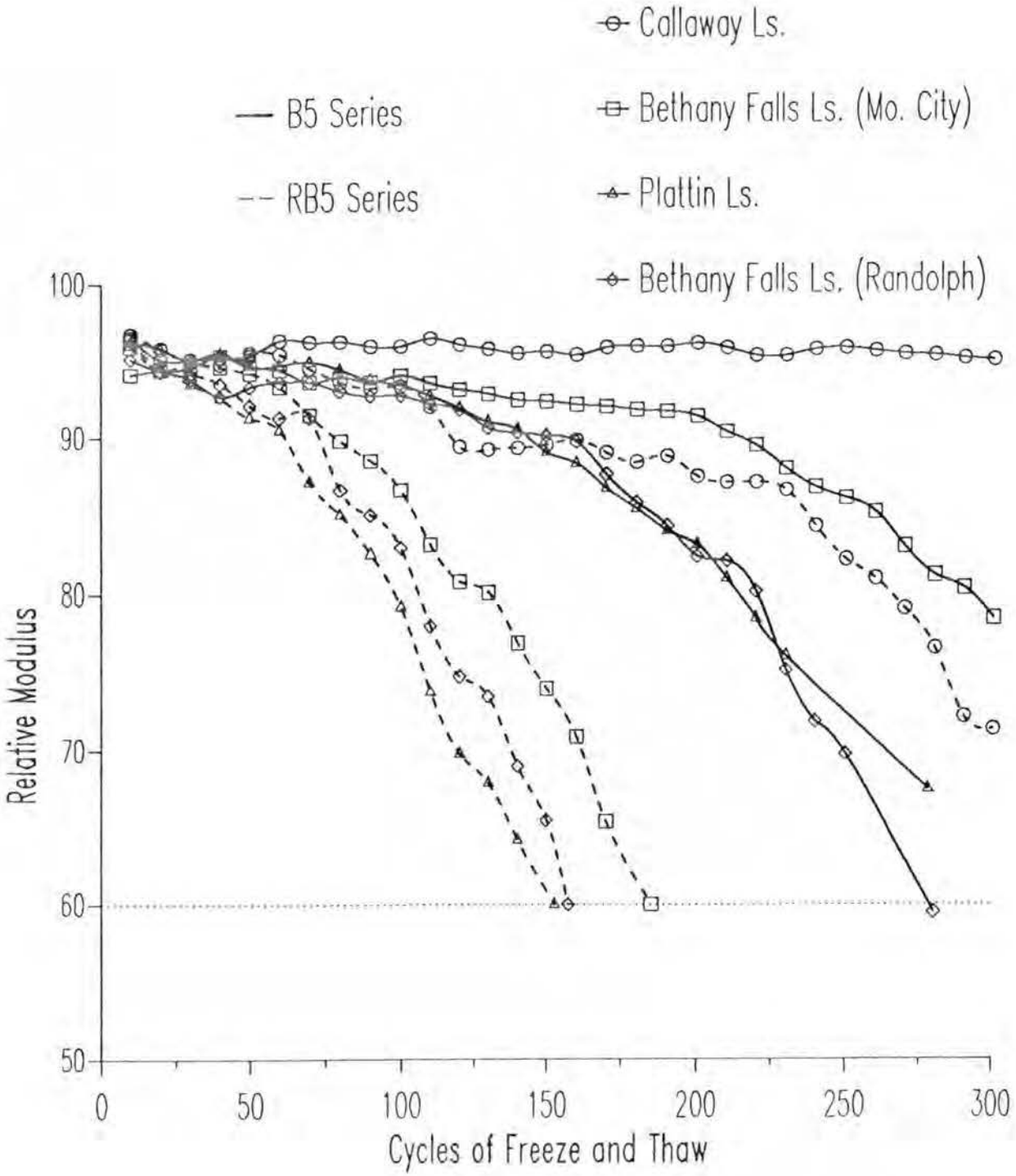


Figure 5. Relative Modulus Vs. Cycles of Freeze and Thaw 24 Hour Soak of CA and 35 Day Cure of Beams

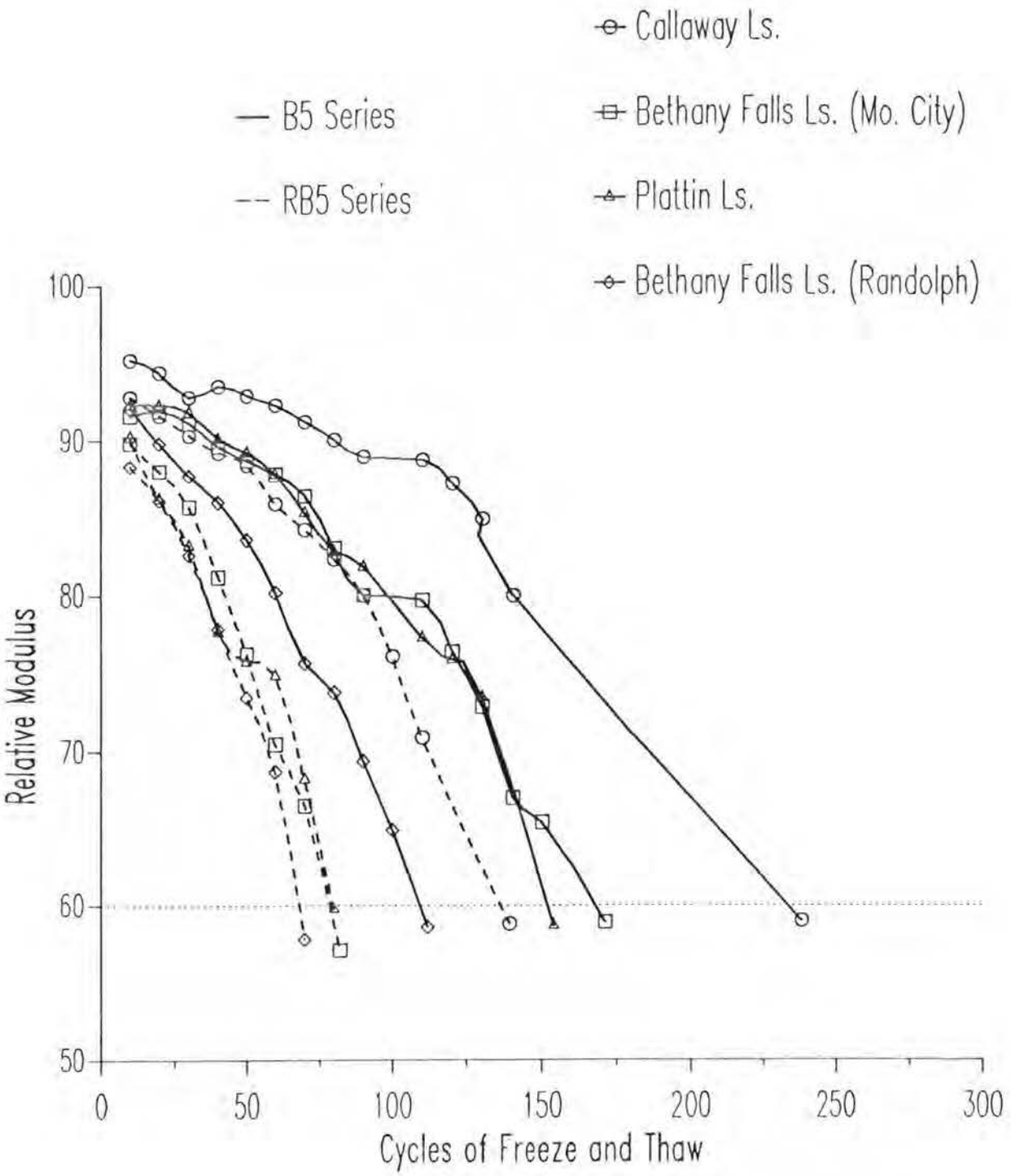


Figure 6. Relative Modulus Vs. Cycles of Freeze and Thaw 24 Hour Soak of CA and 91 Day Cure of Beams

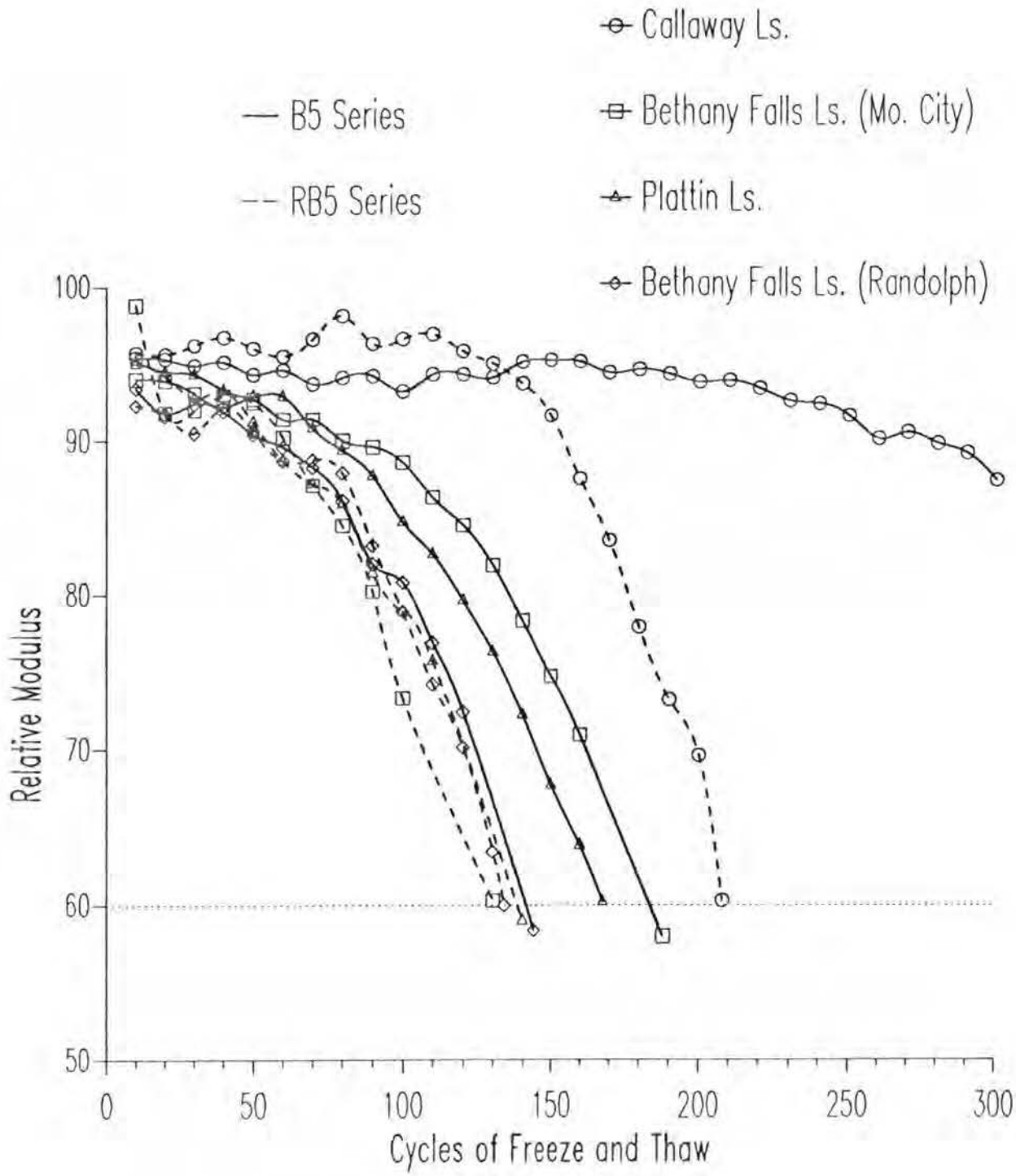


Figure 7. Relative Modulus Vs. Cycles of Freeze and Thaw Vacuum Saturation of CA and 14 Day Cure of Beams

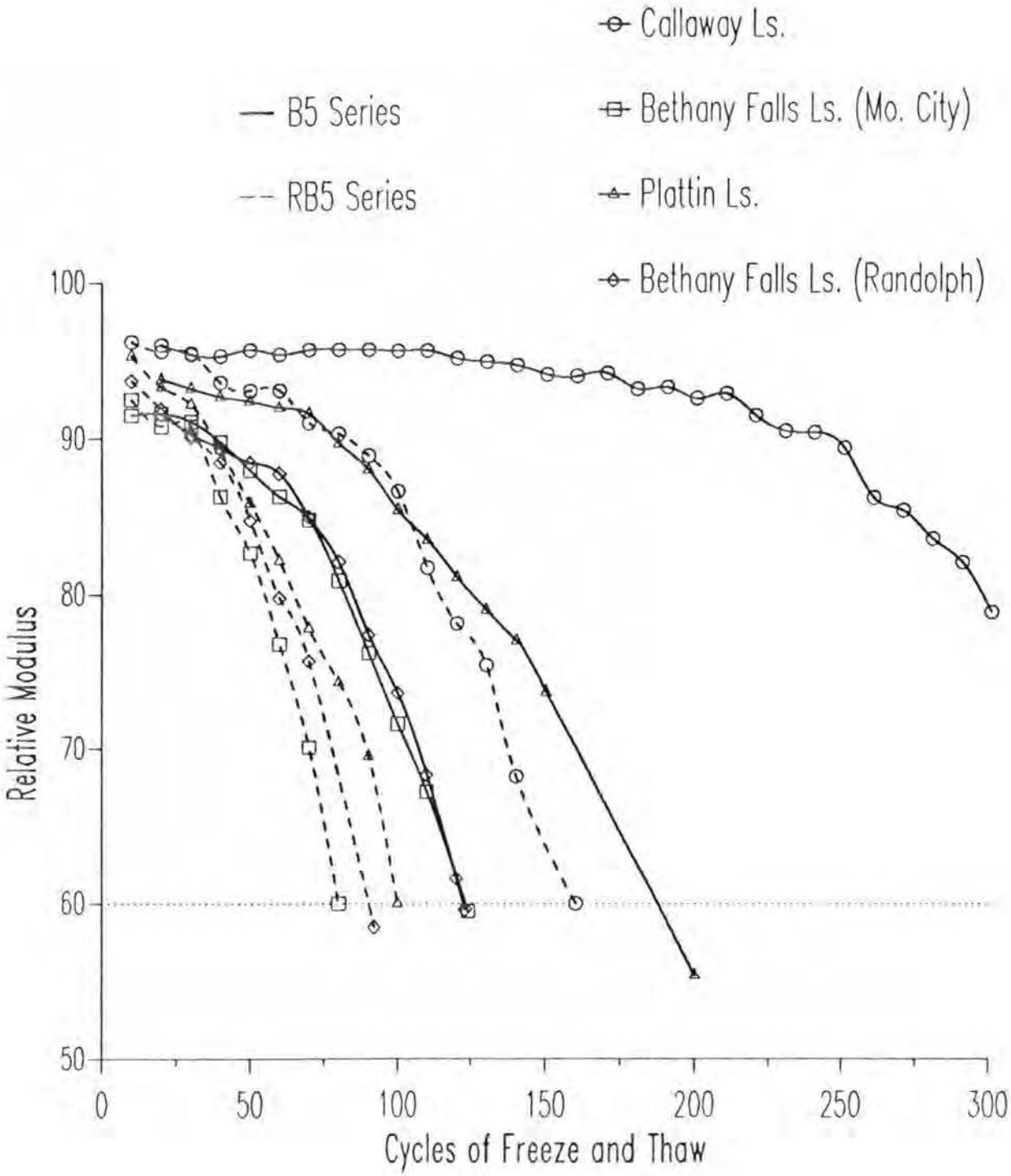


Figure 8. Relative Modulus Vs. Cycles of Freeze and Thaw Vacuum Saturation of CA and 35 Day Cure of Beams

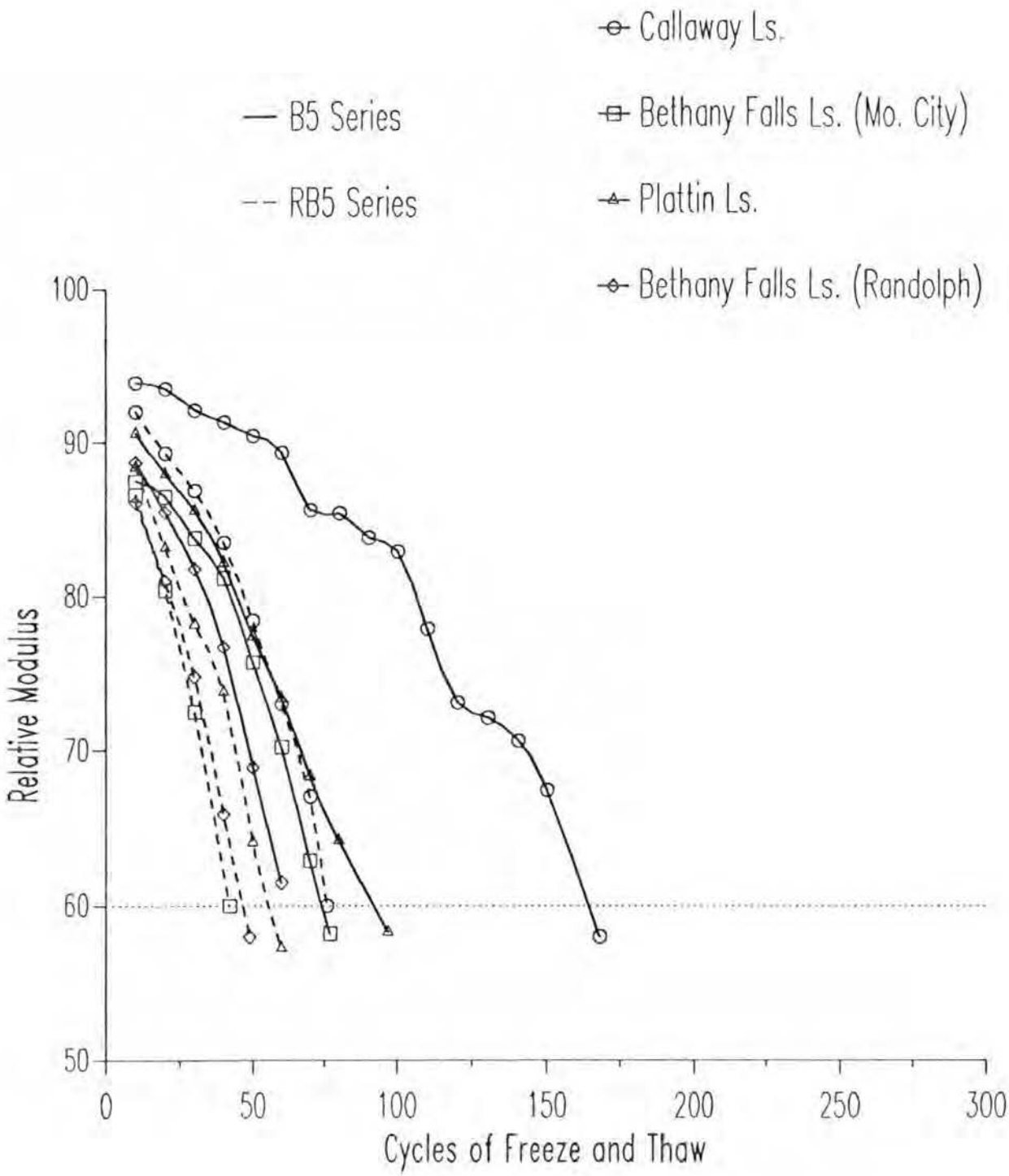


Figure 9. Relative Modulus Vs. Cycles of Freeze and Thaw Vacuum Saturation of CA and 91 Day Cure of Beams

DISCUSSION

Analysis of variance (ANOVA) with Tukey's statistical test for significant difference in means (12) was performed to determine whether the revised cycle configuration of the RB5 series resulted in a better discrimination among beams made with the different coarse aggregates, as compared to the B5 series. An example of such calculations is shown in Table 2 with a summary of results shown in Table 3. The results for the specimens made with air-dry aggregate was excluded from the analysis since they lacked a complete matrix with the other variables.

As shown in Table 3, the B5 series generally resulted in less, or the same number of, insignificant differences among the specimens due to the coarse aggregates, than did the RB5 series. Durability and length change are the two main ways for measuring concrete deterioration and the average number of insignificant differences was lower for both types of results with the B5 series. Therefore, it could be concluded that the B5 series resulted in a better discrimination among the coarse aggregates. Since the four aggregates used in this investigation were initially chosen from experience as those with varying field performance histories, it seems reasonable the series with results showing more significant differences among the aggregates could be chosen as the better of the two.

Within the RB5 series, Table 3 shows that the 24-hour soak moisture treatment usually resulted in less, or the same number of, insignificant differences among the beams compared to vacuum saturation. This agrees with the conclusion of the previous

TABLE 2

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

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

TABLE 3

SUMMARY OF ONE-WAY ANOVA AND TUKEY'S TEST RESULTS

Sat.	Cure	F-Ratio B5 Series	F-Ratio RB5 Series	Combinations of Means Without Significant Difference B5 Series	Combinations of Means Without Significant Difference RB5 Series
FOR DURABILITY FACTORS					
24 Hour	14 Day	7.87	120.85	4	3
24 Hour	35 Day	19.52	86.98	3	3
24 Hour	91 Day	8.13	13.85	2	3
Vacuum	14 Day	99.37	13.29	3	3
Vacuum	35 Day	28.78	20.96	3	3
Vacuum	91 Day	59.64	7.08	2	4
Average				2.8	3.2
FOR PERCENT LENGTH CHANGE PER CYCLE					
24 Hour	14 Day	15.18	8.51	2	3
24 Hour	35 Day	19.37	11.57	2	3
24 Hour	91 Day	9.17	4.87	3	5
Vacuum	14 Day	19.71	1.50	3	6
Vacuum	35 Day	25.52	1.81	2	6
Vacuum	91 Day	26.99	7.19	2	4
Average				2.3	4.5
FOR WEIGHT CHANGE PER CYCLE					
24 Hour	14 Day	8.11	18.04	4	3
24 Hour	35 Day	36.06	14.46	3	3
24 Hour	91 Day	0.97	1.58	6	6
Vacuum	14 Day	24.88	13.34	3	3
Vacuum	35 Day	28.76	18.86	2	2
Vacuum	91 Day	1.02	3.50	6	6
Average				4.0	3.8

NOTE: An F Ratio below 4.07 shows no statistical difference among the beams due to the coarse aggregates.

study (1) that the 24-hour soak discriminated among beams made from the four different course aggregates as well as or slightly better than vacuum saturation.

It was also decided from the previous study to use a 35-day curing period. The results from the RB5 series does not conflict with this decision in that little difference was found among 14-day, 35-day, and 91-day curing in regard to the number of insignificant differences.

The results should also reflect the pavement performance histories for these aggregates. The RB5 series tended to show no significant differences among the Plattin and two Bethany Falls limestones. The B5 series tended to show the Bethany Falls limestone from Missouri Rock Company as less frost susceptible than the Plattin limestone, although not significantly at a 5 percent significance level. Bethany Falls limestone is generally considered prone to D-cracking.

Test results for B5 and RB5 series were regressed against percent flexural strength reduction as shown in Figure 10, 11, and 12. Coefficients of determination (R^2) were consistently higher for the B5 series than the RB5 series. This would imply there was more variability in results in the RB5 series. The lower coefficients could also be due to the relative modulus of elasticity of more of the RB5 specimens reaching 60 percent before 300 cycles, and therefore more clustering of data points.

As stated in the Results section of this report, the average durability factor in every group of specimens was lower in the RB5 series compared to those in the B5 series. Whether this was

due to a faster freeze rate or slower thaw rate of the RB5 series, or both, is not determinable from the results of these two series alone. Therefore, the results of the B3 series were reviewed.

The cycle characteristics of the B3 series had both a fast freeze rate and fast thaw rate. Results from that series are given in Appendix B. The average durability factors for the B3 specimens were between those of the B5 and RB5 series, except for eight groups where the B3 series resulted in higher durability factors than both the B5 and RB5 series. For these eight groups, this indicates that the B3 series was less severe based on durability factors than the B5 or RB5 series.

One possible reason why the specimens in the B3 series performed as well as they did was because of the longer period of time in the thaw mode above 37°F even though the total cycle time was shorter. ASTM requires that the time required to change the beam temperature from 3°F to 37°F shall not be less than one-half of the total thawing time. For the B3 series, the time for this temperature change was about 51 percent of the total thawing time (see Figure 1 and Table 1). This could have resulted in some autogenous healing in dynamic modulus of elasticity, as noted by several researchers (6,13).

It is assumed that the previously stated ASTM specification on temperature change between 3°F and 37°F, and also the ASTM specifications that beams are to be stored in a frozen condition if the sequence of freezing-and-thawing cycles is interrupted, were written at least in part to prevent autogenous healing.

However, literature was not found concerning specifically at what thawing temperature this autogenous healing starts to occur. While the specimens in the B3 series cycles were above 37°F significantly more than those in the other two Procedure B series (27 percent of total cycle time versus 8 percent for the B5 and RB5 series), the B3 and RB5 series were comparably equal in the time above 32°F. Specimens in both cycles had 38 percent of the total cycle time above 32°F.

Another possible reason for the differences in concrete durability between specimens in the B3 and RB5 series, although both were subjected to a similar freeze cycle, may be found in the differences in the thaw cycle. Generally, it is considered that the rate of thawing is less likely to be significant than the rate of cooling. A reason given for this is that during thawing, the concrete will be expanding and the water contracting, thus eliminating some of the stress that is encountered during freezing (9). However, there was no literature found directly concerning research on the effect of a long thaw time compared to a short thaw time. It is possible that a long thaw time of the RB5 series may have significantly affected concrete saturation or some other factor.

Additional research needs to be performed to document how the thaw-cycle characteristics affect concrete durability.

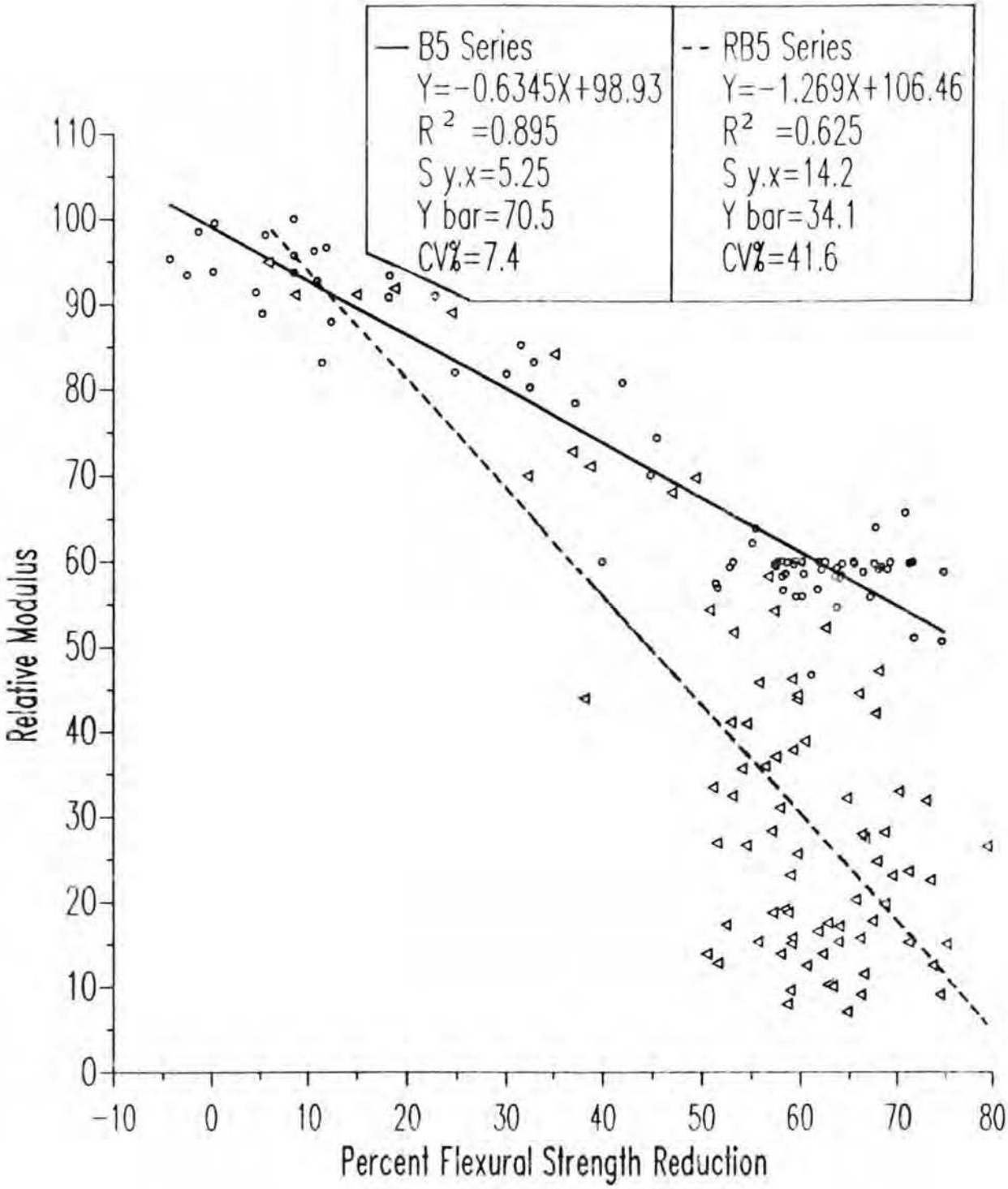


Figure 10. Relative Modulus Vs. Percent Flexural Strength Reduction

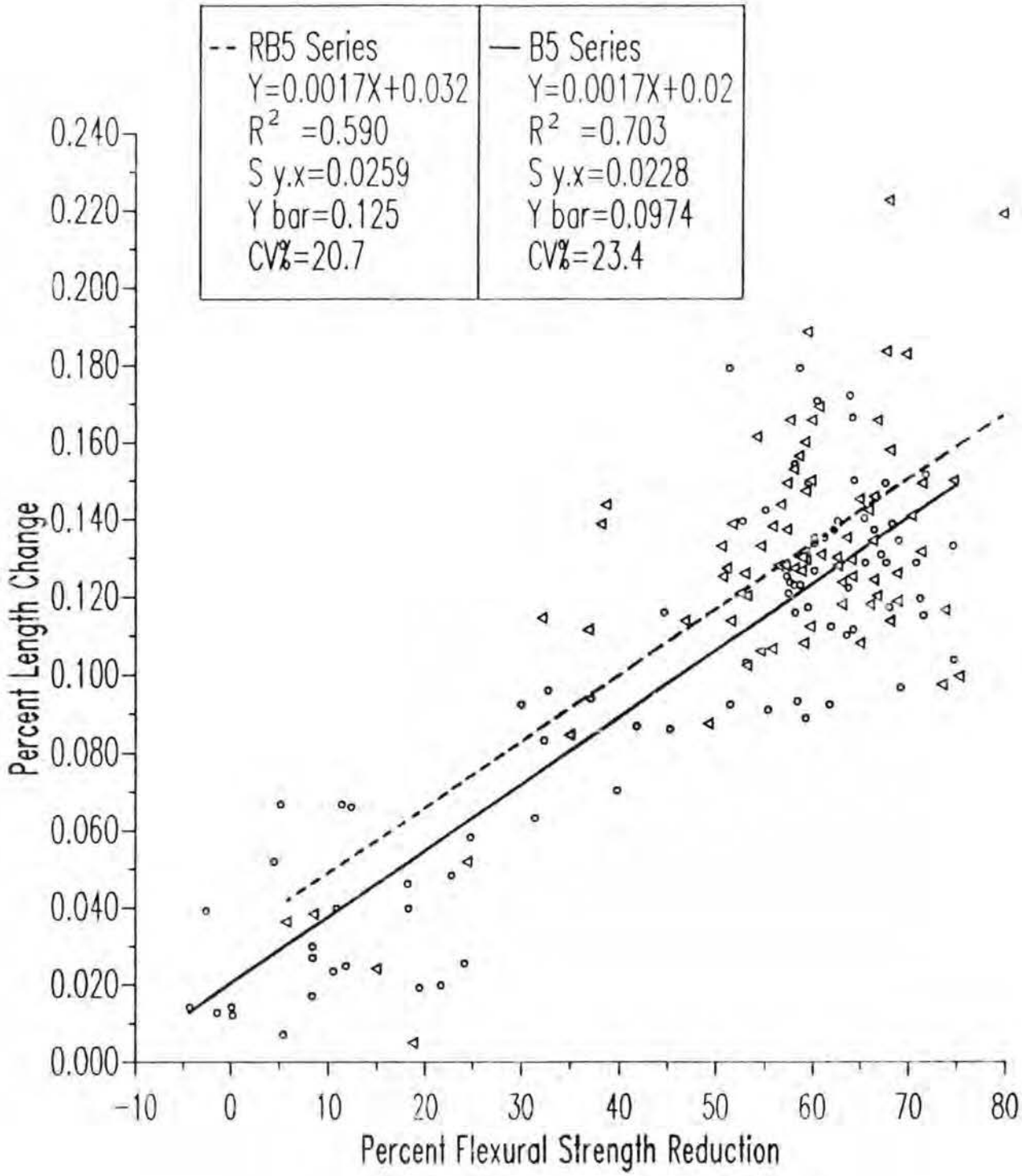


Figure 11. Percent Length Change Vs. Percent Flexural Strength Reduction

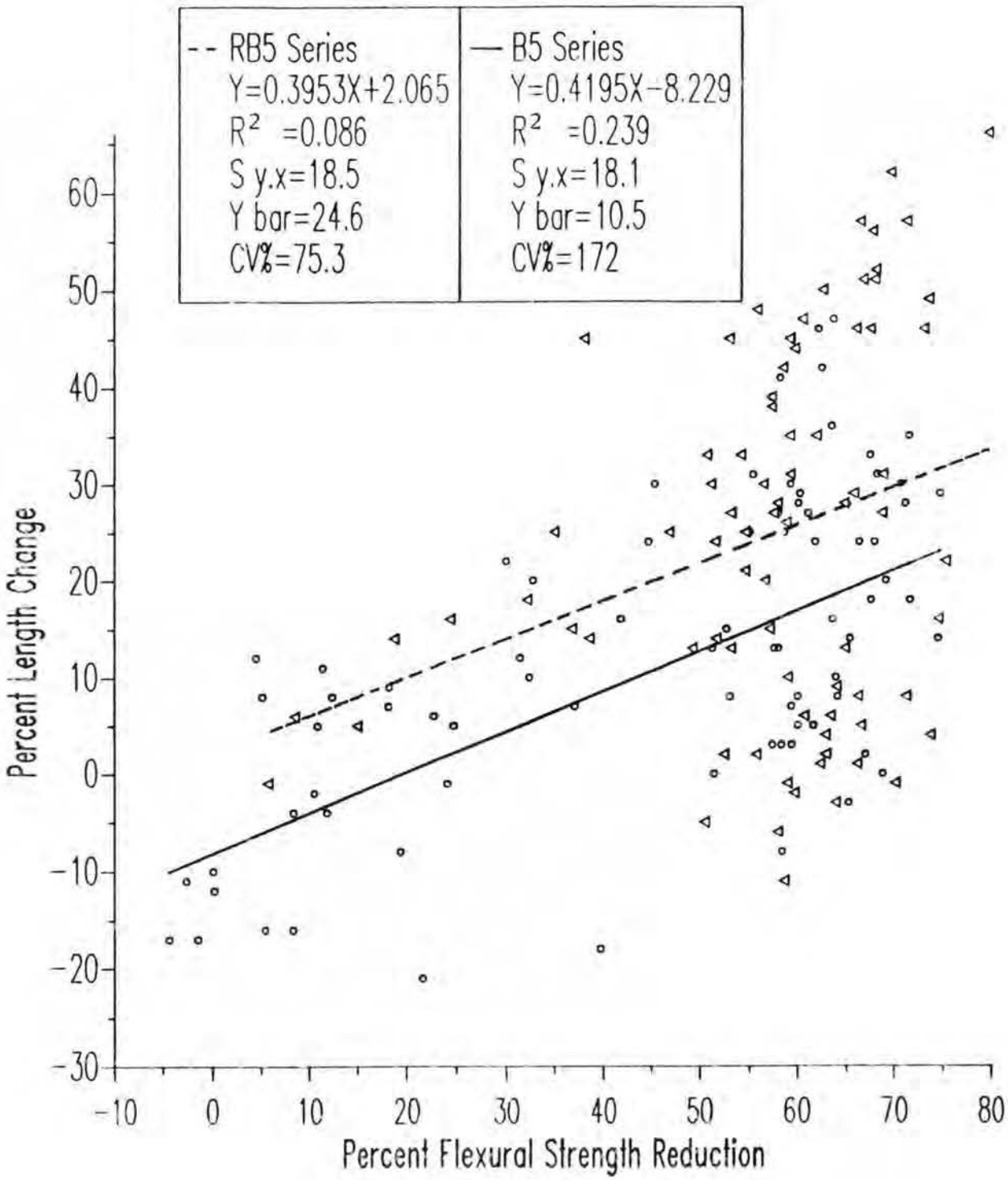


Figure 12. Weight Change Vs. Percent Flexural Strength Reduction

CONCLUSIONS

The following conclusions were made from the test results of the RB5 series:

1. The revised five-hour cycle (RB5) characteristics of this series of ASTM C 666 Procedure B tests generally resulted in less discrimination among beams made with the four coarse aggregates used in this investigation, as compared to the original five-hour cycle (B5).

2. The revised five-hour cycle (RB5) caused durability of the beams to decrease faster than comparable beams tested using the original five-hour cycle (B5).

3. Results of this study do not change the conclusions of Study 85-6, "Evaluation of Concrete and Aggregate Durability Test" from which 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 as Missouri's standard method for rapid freeze and thaw testing.

IMPLEMENTATION

The freezing and thawing cycle used for the B5 series will be used for routine testing of coarse aggregates by the Missouri Highway and Transportation Department.

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APPENDIX A

Material, Mix-Design and Batching Sequence and Specimen Identification

Materials

The coarse aggregates from each source 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 Callaway County 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 and Batching

The concrete mix design and the range of fresh concrete characteristic are shown in Table A4 and Table A5, respectively. Twenty-seven concrete mix batches were made for the RB5 series, each 1.3 cubic feet. As shown in Table A6, 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 four-character code identified each test beam within a series. 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 retained on the #10 sieve were batched air-dried.

D - Air Dried, by raking till constant moisture content

S - 24-Hour Soaking, in accordance with ASTM C 192

V - Vacuum Saturation, at 16 millimeters of mercury

The third character denoted the curing duration. The beams were cured in their molds for one day and then placed in hydrated lime, in accordance with ASTM C 666, for a total curing time of:

B - 14 Day

E - 35 Day

M - 91 Day

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

For example, beam CSB1 was first of three beams made with Callaway limestone coarse aggregate that was soaked for twenty-four hours before batching, and cured for fourteen days.

In addition, each beam was marked with "RB5" to distinguish the series.

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
Mo. City	2.63	2.62	2.61	2.61	2.59
Plattin	2.69	2.70	2.68	2.67	2.65
Randolph	2.61	2.61	2.60	2.58	2.57

BULK SPECIFIC GRAVITY, SSD

Aggregate	Saturation	1-3/4	3/4-1/2	1/2-3/8	3/8-4	4-10	Combined Total
Callaway	24 Hr. Sk.	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. Sk.	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. Sk.	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. Sk.	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. Sk.	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. Sk.	1.0	1.2	1.4	1.4	2.5
	Vac. Sat.	1.3	1.3	1.5	1.7	-
Plattin	24 Hr. Sk.	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. Sk.	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
BF from Mo. City	94
Plattin	96
BF 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 (Hours:Minutes)	3:25
Final Set (Hours: Minutes)	5:10
Compressive Strength, Avg., psi	
3-Days	2830
7-Days	3610
Specific Surface, Blaine	3520
Specific Gravity	3.15

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/cu yd)	6.10
Slump (Inches)	3.0 Maximum
Air Content (Percent) By Meter	5.5 ± 1.5
Fine Aggregate (Percent)	45
Coarse Aggregate (Percent)	55

TABLE A5

CHARACTERISTICS OF FRESH CONCRETE

B5 SERIES:

	Range	Average
Cement Factor (sacks/cu yd)	6.03 - 6.17	6.10
Water/Cement Ratio	4.60 - 4.98	4.85
Slump (inches)	1.50 - 2.50	2.00
Air Content (percent) By Meter	4.2 - 6.3	5.4

RB5 SERIES

	Range	Average
Cement Factor (sacks/cu yd)	6.05 - 6.11	6.09
Water/Cement Ratio	4.60 - 4.95	4.86
Slump (inches)	1.50 - 2.50	2.00
Air Content (percent) By Meter	5.4 - 6.3	5.70

TABLE A6

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

Tabulated Summaries of Test Results for RB5, B5, and B3 Series

TABLE B1

SUMMARY OF TEST RESULTS*
RB5 Series

Aggregate Formation	Saturation	Cure	DF	P	Exp.	Wgt. Gain	Flexural Strength Init.	Flexural Strength Final
Callaway	Dry	14	92.4	92.7	.0330	3	907	817
	24 Hr Soak	14	88.2	88.2	.0472	18	949	702
		35	71.1	71.2	.1142	14	1053	617
		91	27.2	58.8	.1382	-11	1028	380
	Vacuum	14	39.2	54.5	.1612	46	957	407
		35	31.5	56.3	.1292	27	1007	464
		91	14.6	53.5	.1292	2	1013	422
BF at Mo. City	24 Hr Soak	14	46.8	54.2	.1607	50	944	248
		35	36.7	56.7	.1479	27	965	397
		91	15.4	57.1	.1282	2	1037	379
	Vacuum	14	22.4	49.0	.1951	58	938	261
		35	15.8	57.4	.3307	34	957	382
		91	8.4	53.3	.1346	12	1008	317
Plattin	Dry	14	59.3	61.7	.1199	19	936	448
	24 Hr Soak	14	44.6	57.6	.1335	45	977	406
		35	30.8	58.0	.1273	24	1053	412
		91	16.1	58.0	.1207	2	957	397
	Vacuum	14	27.2	57.9	.2088	49	989	288
		35	19.2	54.2	.1415	37	991	379
		91	11.6	51.8	.1384	9	999	382
BF at Randolph	Dry	14	59.5	63.3	.1256	30	902	481
	24 Hr Soak	14	45.2	58.2	.1235	48	910	385
		35	30.4	55.7	.1313	27	936	436
		91	13.5	52.2	.1474	2	1028	356
	Vacuum	14	25.4	54.6	.1380	55	896	282
		35	18.0	58.5	.1240	26	1005	335
		91	9.5	58.0	.1266	-1	973	373

*Average of 3 tests

TABLE B2

SUMMARY OF TEST RESULTS*
B5 Series

Aggregate Formation	Saturation	Cure	DF	P	Exp.	Wgt. Loss	Flexural Strength Init.	Flexural Strength 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	46.8	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	63.1	67.5	.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

TABLE B3

SUMMARY OF TEST RESULTS*
B3 Series

Aggregate Formation	Saturation	Cure	DF	P	Exp.	Wgt. Gain	Flexural Strength Init.	Flexural Strength 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	15.0	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

APPENDIX C

Correlations Between Control and Test Beams

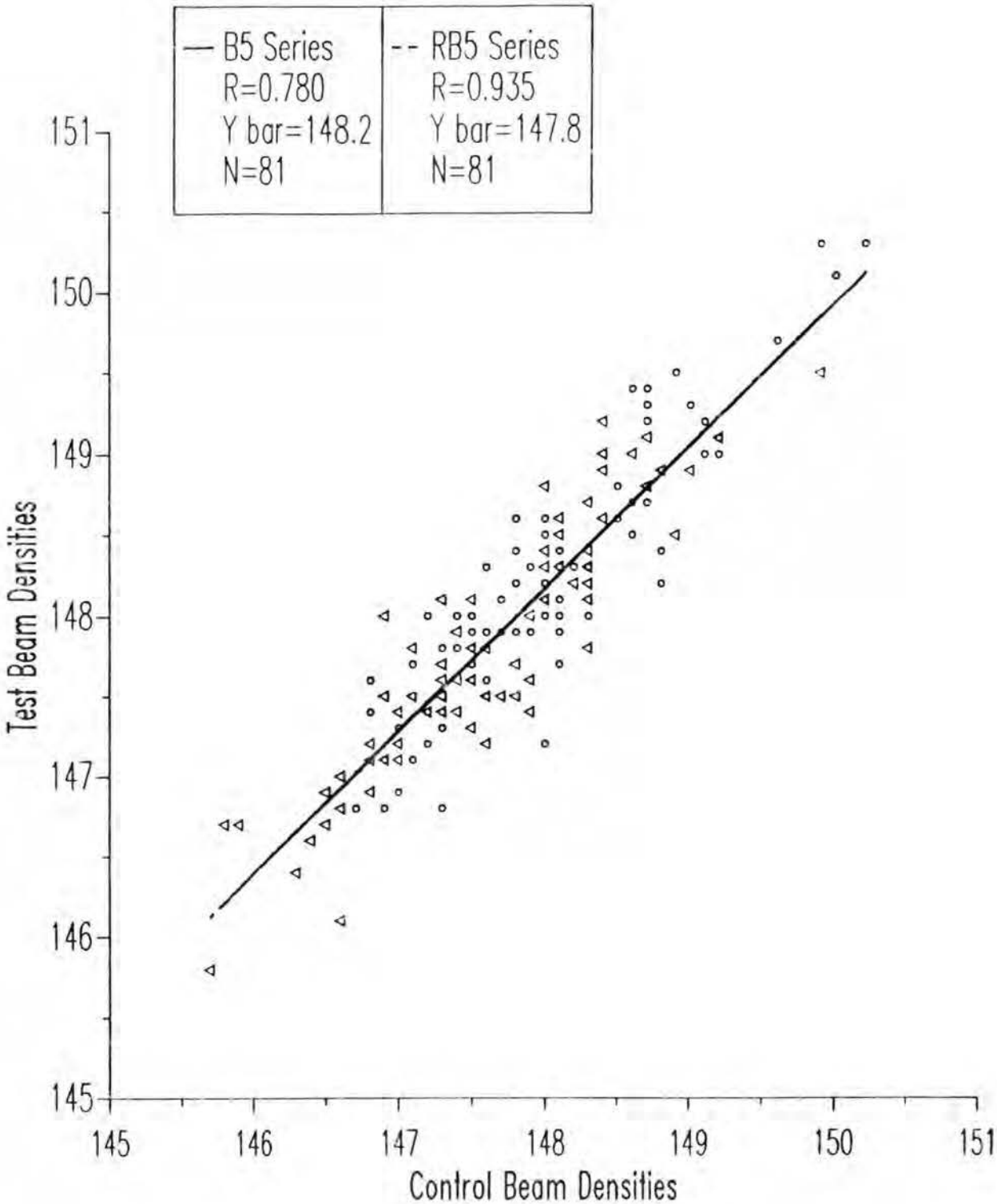

Figure C1. Correlation of Densities Between Test and Control Beams

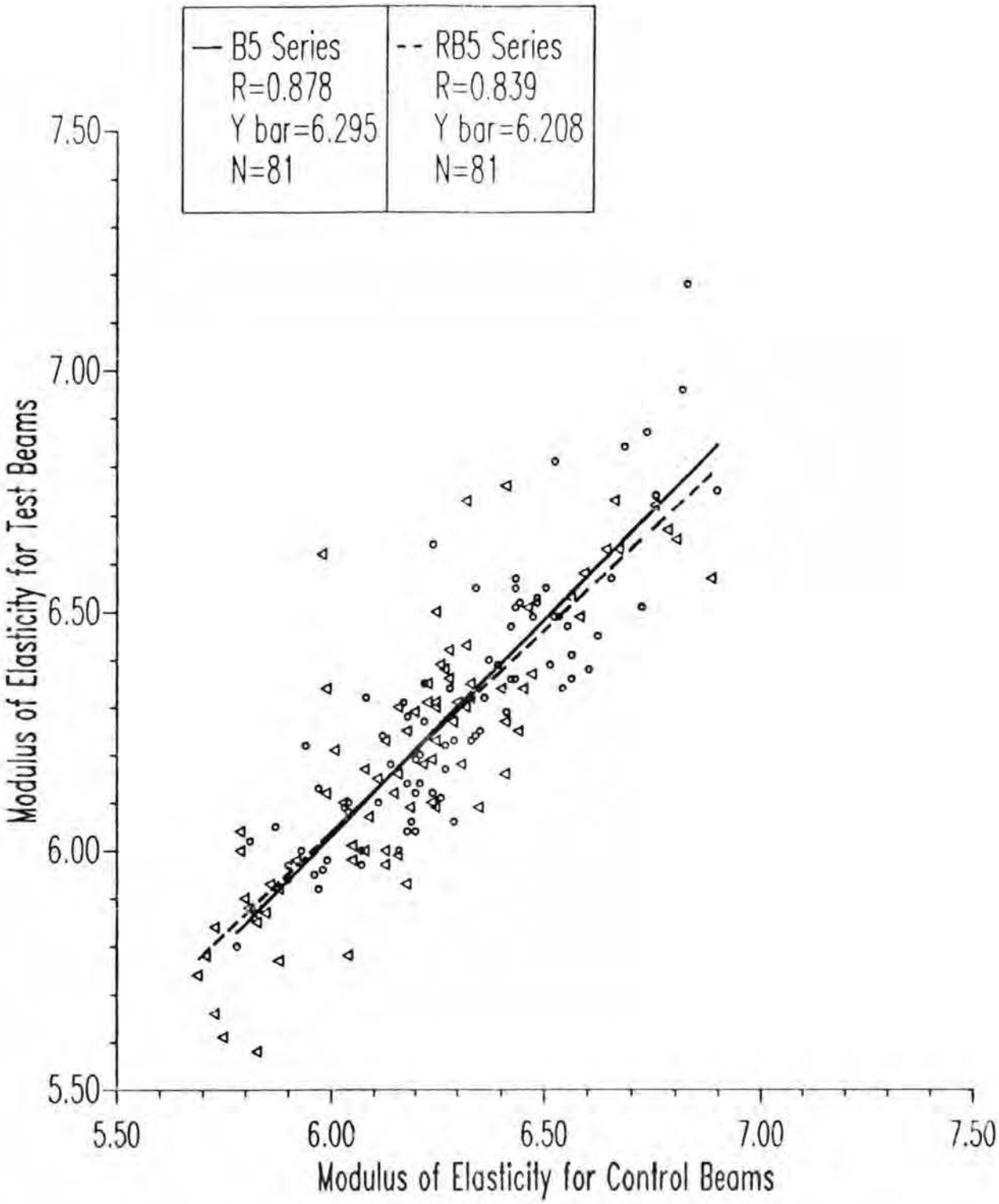

Figure C2. Correlation of Dynamic Young's Modulus of Elasticity Between Test and Control Beams