TE
5092
.M8A3
no.
72-4

RI COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT 72-4

DEPARTMENT OF
TR...
JUN 1973

INVESTIGATION OF "D" CRACKING IN PCC PAVEMENTS

PHASE 2

MISSOURI STATE HIGHWAY DEPARTMENT
FEDERAL HIGHWAY ADMINISTRATION

TE
5072
.M8M3
no. 72-4

INVESTIGATION OF "D" CRACKING IN PCC PAVEMENTS
STUDY 68-3

DEPARTMENT OF
JUN 20 1973

LABORATORY PHASE 2

Prepared by

MISSOURI STATE HIGHWAY DEPARTMENT

Division of Materials and Research

March 1972

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.

ABSTRACT

This report investigates the durability of concrete beams fabricated with one aggregate and eleven different cements. The beams were subjected to a modified accelerated freeze and thaw test. The data indicates that cement source had a highly significant effect on the durability of the concrete.

Other variables considered in this phase of the laboratory test program were ultimate permanent dilation, ultimate weight gain, alkali content of the cement as manufactured, and storage conditions between freezing periods.

CONTENTS

Introduction 1

Conclusions 3

Implementation 4

Scope 5

Properties of Aggregates 8

Properties of Cements 9

Results of Freeze and Thaw Test 12

Discussion of Results 16

Part A - Correlation of Concrete Durability With Cement Properties 16

Part B - Correlation of Concrete Durability With Ultimate Permanent Dilation 21

Part C - Correlation of Concrete Durability With Ultimate Weight Gain 25

Part D - Correlation of Concrete Durability With Cement Alkali Content 28

Part E - Correlation of Concrete Durability With Storage Conditions Between Freeze Cycles 32

Appendix A: Properties of Fine Aggregate 36

Properties of Coarse Aggregate 37

Appendix B: Mix Design and Batching 40

Curing 41

Concrete Beam Identification 42

Results of Tests on Fresh Concretes and Control Beams 43

Appendix C: Freeze and Thaw Procedure 48

LIST OF TABLES

Table

1. Physical Properties of Cement 10

2. Chemical Properties of Cement 11

3. Ultimate Permanent Dilation of Concrete Beams Subjected to the Freeze and Thaw Test 13

4. Ultimate Change in Weight of Concrete Beams Subjected to the Freeze and Thaw Test 14

5. Ultimate Change in Sonic Frequency of Concrete Beams Subjected to the Freeze and Thaw Test 15

6. Analysis of Variance of Durability Factors 17

7. Summary of Data for Correlation of Alkali Content of Cements 31

8. Summary of Data for Correlation of Storage Conditions 33

9. Properties of Fine Aggregate 36

10. Bulk Specific Gravities of Coarse Aggregates Obtained from Standard Laboratory Procedures . . . 37

11. Gradation of Coarse Aggregate by Standard Laboratory Procedures 38

12. Two-Hour Absorption Properties of Coarse Aggregates 38

13. Characteristics of Fresh Concrete 44

14. Flexural Strengths of Control Beams and Beams Subjected to the Freeze and Thaw Test 45

LIST OF FIGURES

Figure

1. Location of Cement Sources 6

2. Rate of Deterioration of Nonair-Entrained Concretes as a Function of Sonic Modulus of Elasticity 18

3. Rate of Deterioration of Air-Entrained Concretes as a Function of Sonic Modulus of Elasticity 19

4. Durability Factor as a Function of Ultimate Permanent Dilation of Nonair-Entrained Concretes 22

5. Durability Factor as a Function of Ultimate Permanent Dilation of Air-Entrained Concretes 23

6. Durability Factor as a Function of Ultimate Weight Change of Nonair-Entrained and Air-Entrained Concretes 26

7. Durability Factor as a Function of the Total Alkali, Calculated as Na_2O Equivalent, of the Cements 29

INTRODUCTION

Throughout many areas of the United States a deterioration of concrete pavements known as "D" cracking exists. Both laboratory and field analyses have been attempted to discover the cause, rate of progression and a method of prevention. The coarse aggregate has generally been considered one of the major causes of "D" cracking. The Missouri Phase 1 Report, Investigation of "D" Cracking in PCC Pavements, produced a significant relationship between concrete durability, as subjected to laboratory freeze and thaw, and the basic specific gravity properties of various samples of Bethany Falls limestone quarried within the State of Missouri.

The Bethany Falls formation has been a major source for concrete aggregate within certain areas of the State for many years. However, the frequency of the occurrence of "D" cracking with serious deterioration of the pavement has increased in recent years. Since we did not believe the physical and chemical characteristics of the stone had changed drastically, the situation raised the question as to whether the cements manufactured today could be, in part, responsible for the increased concrete deterioration. Therefore, the primary purpose of this report, Laboratory Phase 2, was to determine the frost resistance of laboratory concrete specimens using one aggregate and cements from different sources.

Cements from eleven different sources were obtained and used in this phase. Type "F" was the cement used in Laboratory Phase 1 of this investigation.

The other variables included in this study were limited due to the freezing unit's capacity. These variables were air contents at two levels (entrained and nonair-entrained), total alkali content of cement (one with greater than 0.6 percent as Na_2O equivalent), and method of storage of concrete beams between cycles (completely or partially submerged).

The same modified accelerated laboratory freeze and thaw test as used in Laboratory Phase 1, was used as the basis for testing the relative effects of each of the variables.

This report presents the results of work completed under Laboratory Phase 2 and the conclusions which these results indicate. The properties of the materials used, the mix designs and batching data, and the test procedures are included in appendix form.

CONCLUSIONS

The laboratory tests completed under this phase of the "D" cracking investigation have provided results for analysis of the frost resistance of various cements obtained in and around the State of Missouri. Several other variables were included on an exploratory basis only and the results obtained, therefore, must necessarily be limited as must the corresponding conclusions.

Specifically, from the results of the laboratory tests thus performed under this phase of the "D" cracking investigation, the following conclusions seem justified:

1. The rate of deterioration of the concrete beams is significant between cements.

2. Storage of the concrete beams completely submerged resulted in more rapid deterioration than in the partially submerged storage.

3. Effect of air-entrainment on the durability of these concrete specimens was not significant.

4. Air-entrained concretes absorbed approximately 0.8 percent moisture and the nonair-entrained concretes generally absorbed 0.5 percent moisture gain by weight at failure. However, the nonair-entrained beams failed to respond to moisture gain after the first freeze cycle. The air-entrained beams continued to gain moisture during storage between cycles.

5. The ultimate permanent dilation of the beams is highly dependent upon the air content of the concrete. The nonair-entrained beams showed more uniform expansion than did the air-entrained beams.

6. Of the high and low alkali cements produced by the same manufacturer used in this phase, the concrete with the high alkali cement failed the freeze and thaw test at an earlier age in all cases regardless of air-entrainment.

IMPLEMENTATION

Based on the increasing occurrence and seriousness of "D" cracking in many of the concrete pavements located in the northwestern and west-central districts of the State of Missouri, major changes were made in the mix design of the concrete. In addition, placement of a 4 mil polyethylene sheeting moisture barrier was required between the aggregate base and the concrete pavement.

Laboratory Phase 1 of this study considered the major changes in mix design and indicated that the modifications that were made were warranted. As of this date, a sufficient number of pavements have not reached an age necessary to determine the effectiveness of the moisture barrier.

Laboratory Phase 2 of this study considered the effect of variation in cement on the durability of concrete. The conclusions from this phase indicate that variations in cement do affect the rate of deterioration in concrete. Based on this study, further research in this area is warranted. This has been undertaken in a pooled fund research project sponsored by the Highway Departments of Iowa, Kansas and Missouri and the Federal Highway Administration. This work is now in progress at the Battelle Memorial Institute.

SCOPE

Twelve cements, meeting AASHO M85, and representing normal Type I production from eleven cement plants were chosen for use in this Laboratory Phase 2 of the Investigation of "D" Cracking. Six of the cements were obtained from plants located within the Mississippi Valley Region of eastern Missouri and the remaining six cements were obtained from western Missouri and eastern Kansas, as shown in Figure 1, page 6. These cements are used extensively in Missouri highway construction. The factors used in the design of this investigation for the purpose of evaluating the freeze and thaw resistance of concrete with these cements were:

A. Only one stone from the Bethany Falls member of the Swope formation with a 2.64 saturated surface dry gravity was used with maximum size of one inch.

B. Each cement would be tested in nonair-entrained and air-entrained concretes.

C. The sand contents would be constant at 40.1% and 37.0% for the nonair-entrained and air-entrained concretes respectively.

D. Exploratory data to be obtained on a commercially produced high alkali cement (Cement Type "X").

E. Exploratory data to be obtained on a variation of storage conditions.

Figure 1 - Location of Cement Sources

Specific details of the physical characteristics of the aggregates used in this phase are shown in Appendix A.

A total of 100 3½x4½x16 inch beams were made and tested to establish the freeze and thaw resistance of the concretes with the characteristics described above.

The modified accelerated freeze and thaw test as described in the Phase 1 Report is reproduced as Appendix C of this report. The beams were terminated as their dynamic modulus of elasticity, "E", dropped below 70 percent of their 35-day value (30 percent loss) or at the end of 100 cycles.

PROPERTIES OF AGGREGATES

The fine aggregate used in this phase was that used in Phase 1 of this investigation. The moisture content of the fine aggregate was slightly higher than that for Phase 1. The physical properties of the fine aggregate are reproduced in Table 9, Appendix A, page 36.

The coarse aggregate was hand picked from the same geographic location as Stone Numbers 3, 4, and 6 of the previous phase. However, it was desired that the combined gravities of the two size fractions be similar to the Number 4 aggregate or 2.60 saturated surface dry rather than the 2.64 as shown in Table 10, page 37, which compares with Stone Number 3.

The gradation of the coarse aggregate as shown in Table 11, page 38, compared fairly well with the gradation of Stone Number 3 of Phase 1.

The absorption properties of the coarse aggregate at two hours soaking period compared fairly well with the absorption properties of Coarse Aggregate Number 3 of Phase 1 as shown in Table 12, page 38.

PROPERTIES OF CEMENTS

The source of cement being the primary variable in this phase of the "D" cracking investigation, a discussion of the physical and chemical properties of each cement as shown in Tables 1 and 2, pages 10 and 11 follows.

The chemical properties of the eleven primary cements (Type "A" through "T") show no outstanding differences in the oxides except for the potassium and sodium which shows up in the calculation of "Total Alkali", which is expressed as percent sodium oxide equivalent. The range in alkali content is shown to be 0.28 percent. To provide a greater range in alkali equivalent, Cement "X" with alkali equivalent of 0.84 percent was also included.

Table 1 - Physical Properties of Cement

Cement (Item)	Specific Surface Blaine (cm^2/g) (1)	Normal Consistency (Percent) (2)	Time of Set Initial (Hrs & Min) (3)	Time of Set Final (Hrs & Min) (4)	Specific Gravity (5)	Soundness Autoclave (Percent) (6)	Tensile Strength (psi) 3 Days (7)	Tensile Strength (psi) 7 Days (8)	False Set % Water (9)	False Set Initial Penetration (mm) (10)	False Set Final Penetration (mm) (11)	False Set Percent Final Penetration (12)
A	3415	23.8	2:55	4:45	3.164	0.05	337	420	24.6	32	26	81
B	3625	25.0	2:45	4:35	3.164	0.08	328	433	26.4	28	24	86
F	3390	24.0	3:15	5:20	3.168	0.02	353	460	25.9	30	26	87
G	3485	24.6	3:00	5:00	3.164	0.11	377	455	25.4	31	25	81
H	3370	24.0	2:40	4:55	3.122	0.08	395	452	25.5	30	24	80
L	3300	23.6	3:35	5:25	3.163	0.01	377	432	25.0	32	25	78
M	3375	24.4	3:35	5:25	3.168	0.04	397	457	25.6	30	22	73
N	3515	23.4	2:45	4:20	3.164	0.00	345	428	25.6	34	30	88
O	3980	24.4	2:20	4:05	3.176	0.16	380	477	25.6	28	23	82
Q	3565	22.4	2:45	4:20	3.172	0.05	372	458	24.0	28	19	68
T	3620	24.4	2:55	4:45	3.129	0.06	335	443	26.2	31	27	87
X	3105	23.6	3:25	5:15	3.164	0.04	367	427	25.1	28	17	61
Y	Same as Cement Type "F" shown above.											

Table 2 - Chemical Properties of Cement

Cement	Compounds Present (Percent)														
	Silica (SiO_2)	Aluminum Oxide (Al_2O_3)	Ferric Oxide (Fe_2O_3)	Calcium Oxide (CaO)	Magnesium Oxide (MgO)	Sulfur Trioxide (SO_3)	Loss on Ignition	Insoluble Residue	Tricalcium Silicate (C_3S)	Dicalcium Silicate (C_2S)	Tricalcium Aluminate (C_3A)	Potassium Oxide (K_2O)	Sodium Oxide (Na_2O)	Total Alkali	Total Alkali (Na_2OEq)
(Item)	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
A	22.0	5.1	2.2	63.7	2.7	2.4	0.64	0.19	47.9	27.0	9.8	0.55	0.26	0.81	0.62
B	21.7	5.1	2.4	63.9	2.6	2.5	0.90	0.12	50.4	24.3	9.4	0.38	0.11	0.49	0.36
F	22.1	4.9	3.2	64.5	1.8	1.8	1.05	0.20	51.9	24.3	7.6	0.40	0.23	0.63	0.49
G	21.8	4.3	2.8	63.9	2.1	2.0	0.87	0.17	55.7	20.6	6.7	0.41	0.33	0.74	0.60
H	20.6	4.2	2.8	63.2	2.1	2.5	1.68	0.14	61.3	12.9	6.4	0.55	0.25	0.80	0.61
L	21.4	5.3	2.1	64.3	2.4	2.6	0.80	0.25	53.1	21.4	10.5	0.60	0.25	0.85	0.64
M	21.0	5.1	3.1	63.7	3.2	2.2	0.86	0.08	54.7	19.1	8.3	0.42	0.23	0.65	0.51
N	22.1	5.2	2.3	64.2	2.3	2.4	0.82	0.10	48.3	27.0	9.9	0.60	0.13	0.73	0.52
O	20.6	5.4	3.7	62.8	3.0	2.6	0.88	0.16	50.0	21.4	8.0	0.33	0.18	0.51	0.40
Q	20.8	5.6	2.3	64.5	3.0	2.7	0.46	0.16	55.8	17.6	10.9	0.63	0.09	0.72	0.50
T	21.5	4.8	2.0	64.2	2.7	2.7	1.14	0.26	55.0	20.2	9.3	0.65	0.15	0.80	0.58
X	21.7	5.2	2.2	64.4	2.0	2.3	0.72	0.14	52.2	22.9	10.1	0.84	0.29	1.13	0.84
Y	Same cement as cement type "F" shown above.														

RESULTS OF FREEZE AND THAW TEST

The concrete beams subjected to the freeze and thaw test were tested once each week for their changes in length, weight and sonic frequency. Tables 3, 4, and 5, pages 13, 14, and 15, summarize the average results of the measurements taken on each of the four replicate specimens for each mix design. The mix designs are explained in Appendix B of this report. The results shown in these tables will be used extensively throughout the following discussions. Conversion of the sonic data to durability factors, shown in Table 5, is based on the percent residual sonic frequency at termination. These values will be used in establishing the correlations contained in this report.

Table 3 - Ultimate Permanent Dilation of Concrete Beams Subjected to the Freeze and Thaw Test

Concrete Mix Design	Cycles to Complete	Gain in Length(1) (Percent) Top	Bottom	Concrete Mix Design	Cycles to Complete	Gain in Length(1) (Percent) Top	Bottom
a. Nonair-Entrained Concrete Beams							
AOA	86	0.162	0.112	MOA	96	0.153	0.068
B	99	0.122	0.116	B	90	0.159	0.073
C	82	0.140	0.085	C	93	0.184	0.090
D	90	0.147	0.120	D	97	0.127	0.089
BOA	100	0.095	0.056	NOA	99	0.112	0.101
B	100	0.092	0.030	B	99	0.119	0.114
C	100	0.148	0.037	C	100	0.088	0.142
D	100	0.127	0.050	D	93	0.104	0.133
FOA	100	0.036	0.105	OOA	100	0.033	0.030
B	(2)	- -	- -	B	100	0.045	0.041
C	(2)	- -	- -	C	100	0.080	0.063
D	100	0.082	0.043	D	100	0.063	0.060
GOA	100	0.126	0.080	QOA	91	0.138	0.119
B	100	0.076	0.063	B	(2)	- -	- -
C	100	0.072	0.086	C	92	0.182	0.094
D	100	0.093	0.087	D	91	0.135	0.093
HOA	100	0.104	0.083	TOA	95	0.151	0.101
B	100	0.060	0.119	B	96	0.118	0.148
C	100	0.106	0.087	C	97	0.171	0.090
D	100	0.114	0.076	D	99	0.127	0.129
LOA	91	0.109	0.126	XOA(3)	79	0.183	0.103
B	92	0.130	0.123	B	80	0.152	0.127
C	89	0.151	0.107	C	55	0.110	0.077
D	92	0.183	0.068	D	49	0.063	0.062
b. Air-Entrained Concrete Beams							
A6A	90	0.094	0.156	M6A	89	0.082	0.111
B	84	0.086	0.137	B	100	0.083	0.110
C	96	0.095	0.128	C	100	0.060	0.103
D	96	0.108	0.126	D	100	0.080	0.116
B6A	100	0.040	0.101	N6A	84	0.083	0.130
B	100	0.050	0.078	B	95	0.066	0.129
C	100	0.052	0.075	C	97	0.068	0.132
D	100	0.058	0.056	D	89	0.068	0.170
F6A	100	0.084	0.097	O6A	100	0.077	0.033
B	100	0.049	0.094	B	100	0.051	0.042
C	100	0.022	0.087	C	100	0.032	0.035
D	100	0.026	0.107	D	100	0.031	0.047
G6A	100	0.068	0.094	Q6A	90	0.088	0.152
B	100	0.070	0.136	B	84	0.097	0.110
C	100	0.061	0.083	C	90	0.086	0.116
D	100	0.053	0.085	D	90	0.063	0.128
H6A	100	0.067	0.178	T6A	95	0.059	0.159
B	100	0.102	0.116	B	93	0.060	0.169
C	100	0.061	0.125	C	94	0.073	0.122
D	(2)	- -	- -	D	99	0.086	0.090
L6A	91	0.070	0.158	X6A(3)	83	0.101	0.119
B	95	0.103	0.108	B	81	0.133	0.122
C	99	0.108	0.111	C	87	0.084	0.120
D	94	0.093	0.102	D	82	0.114	0.124

(1) Gain in length based on the length after 35 days curing.
(2) Beam accidentally broken - no data available.
(3) The high alkali cement was omitted in computations of function with durability factors.

Table 4 - Ultimate Change in Weight of Concrete Beams Subjected to the Freeze and Thaw Test

Concrete Mix Design	Cycles to Complete	Gain in[1] Weight (%x10^{-3})	Concrete Mix Design	Cycles to Complete	Gain in[1] Weight (%x10^{-3})
a. NonAir-Entrained Concrete Beams					
AOA	86	-9.7	MOA	96	-136.6
B	99	108.2	B	90	-380.5
C	82	144.9	C	93	117.2
D	90	97.2	D	97	57.4
BOA	100	19.4	NOA	99	39.2
B	100	-9.7	B	99	68.2
C	100	49.2	C	100	59.3
D	100	-58.7	D	93	39.3
FOA	100	-49.6	OOA	100	-97.0
B	(2)	- -	B	100	-88.3
C	(2)	- -	C	100	-87.7
D	100	-48.6	D	100	-137.2
GOA	100	-19.4	QOA	91	105.9
B	100	-67.8	B	(2)	- -
C	100	48.3	C	92	114.4
D	100	19.6	D	91	77.0
HOA	100	-79.0	TOA	95	19.7
B	100	0	B	96	-137.1
C	100	9.8	C	97	0
D	100	0	D	99	59.1
LOA	91	99.0	XOA (3)	79	-39.0
B	92	79.2	B	80	29.2
C	89	166.0	C	55	78.2
D	92	-19.3	D	49	68.3
b. Air-Entrained Concrete Beams					
A6A	90	365.2	M6A	89	309.8
B	84	338.2	B	100	296.6
C	96	351.1	C	100	335.1
D	96	272.0	D	100	303.5
B6A	100	225.0	N6A	84	-20.4
B	100	190.3	B	95	362.8
C	100	194.1	C	97	430.6
D	100	234.4	D	89	271.6
F6A	100	219.0	O6A	100	50.4
B	100	207.4	B	100	70.6
C	100	293.6	C	100	-50.4
D	100	283.3	D	100	-159.8
G6A	100	214.9	Q6A	90	294.8
B	100	109.7	B	84	258.0
C	100	149.2	C	90	423.5
D	100	209.2	D	90	372.9
H6A	100	363.5	T6A	95	283.7
B	100	118.5	B	93	280.5
C	100	364.5	C	94	241.4
D	(2)	- -	D	99	335.0
L6A	91	258.3	X6A (3)	83	274.8
B	95	243.7	B	81	142.5
C	99	272.4	C	87	162.0
D	94	221.9	D	82	302.5

(1) Gain in weight based on the weight after 35 days curing.
(2) Beam accidentally broken - no data available.
(3) The high alkali cement was omitted in computations of function with durability factors.

Table 5 - Ultimate Change in Sonic Frequency of Concrete Beams Subjected to the Freeze and Thaw Test

Concrete Mix Design	Cycles to Complete	Sonic Frequency (Cycles/Sec. at 40°F) 35Days	Sonic Frequency (Cycles/Sec. at 40°F) End(1)	Residual Sonic Frequency (%) (2)	Durability Factor (DF)	Concrete Mix Design	Cycles to Complete	Sonic Frequency (Cycles/Sec. at 40°F) 35Days	Sonic Frequency (Cycles/Sec. at 40°F) End(1)	Residual Sonic Frequency (%) (2)	Durability Factor (DF)
a. Nonair-Entrained Concrete Beams											
AOA	86	2080	1740	69.98	60.2	MOA	96	2070	1710	68.24	65.5
B	99	2090	1740	69.31	68.6	B	90	2055	1720	70.05	63.0
C	82	2100	1760	70.24	57.6	C	93	2080	1710	67.59	62.9
D	90	2095	1750	69.78	62.8	D	97	2100	1740	68.65	66.6
BOA	100	2075	1945	87.86	87.9	NOA	99	2055	1720	70.05	69.3
B	100	2095	2010	92.05	92.0	B	99	2065	1730	70.19	69.5
C	100	2085	1880	81.30	81.3	C	100	2075	1800	75.25	75.2
D	100	2095	1935	85.31	85.3	D	93	2055	1715	69.65	64.8
FOA	100	2045	1900	86.32	86.3	OOA	100	2035	2020	98.53	98.5
B	(3)	- -	- -	- -	- -	B	100	2035	2010	97.56	97.6
C	(3)	- -	- -	- -	- -	C	100	2035	1960	92.76	92.8
D	100	2085	1855	79.15	79.2	D	100	2035	1955	92.29	92.3
GOA	100	2060	1850	80.65	80.6	QOA	91	2085	1750	70.45	64.1
B	100	2060	1925	87.32	87.3	B	(3)	- -	- -	- -	- -
C	100	2075	1850	79.49	79.5	C	92	2115	1755	68.85	63.3
D	100	2070	1850	79.87	79.9	D	91	2105	1750	69.11	62.9
HOA	100	2055	1860	81.92	81.9	TOA	95	2065	1740	71.00	67.4
B	100	2065	1840	79.40	79.4	B	96	2070	1720	69.04	66.3
C	100	2035	1800	78.24	78.2	C	97	2085	1730	68.85	66.8
D	100	2050	1840	80.56	80.6	D	99	2100	1730	67.87	67.2
LOA	91	2060	1695	67.70	61.6	XOA	79	2055	1720	70.05	55.3
B	92	2030	1700	70.13	64.5	B	80	2040	1635	64.25	51.4
C	89	2090	1740	69.31	61.7	C	55	2085	1750	70.45	38.7
D	92	2105	1740	68.33	62.9	D	49	2075	1905	84.29	41.3
b. Air-Entrained Concrete Beams											
A6A	90	2050	1710	69.58	62.6	M6A	89	2025	1680	68.83	61.2
B	85	2055	1710	69.24	58.9	B	100	2020	1740	74.20	74.2
C	96	2015	1675	69.10	66.3	C	100	1985	1865	88.27	88.3
C	96	2040	1710	70.26	67.4	D	100	2015	1775	76.83	76.8
B6A	100	2045	1900	86.32	86.3	N6A	84	2015	1670	68.69	57.7
B	100	2015	1850	84.29	84.3	B	95	2015	1665	68.28	64.9
C	100	1995	1925	93.11	93.1	C	97	2025	1680	68.83	66.8
D	100	1980	1920	94.03	94.0	D	89	2020	1680	69.17	61.6
F6A	100	2025	1740	73.83	73.8	O6A	100	2020	1890	87.54	87.5
B	100	2020	1850	83.88	83.9	B	100	1995	1945	95.05	95.1
C	100	1995	1905	91.18	91.2	C	100	2005	2030	102.51	102.5
D	100	2015	1915	90.32	90.3	D	100	2005	2005	100.00	100.0
G6A	100	2010	1700	71.53	71.5	Q6A	90	2055	1705	68.84	62.0
B	100	2015	1790	78.91	78.9	B	84	2055	1715	69.65	58.5
C	100	2010	1865	86.09	86.1	C	90	2005	1660	68.55	61.7
D	100	1995	1875	88.33	88.3	D	90	2020	1670	68.35	61.5
H6A	100	1975	1670	71.50	71.5	T6A	95	2015	1660	67.87	64.5
B	100	1995	1740	76.07	76.1	B	93	2025	1680	68.83	64.0
C	100	1995	1760	77.83	77.8	C	94	2015	1655	67.46	63.4
D	(3)	- -	- -	- -	- -	D	99	1990	1645	68.33	67.6
L6A	91	2010	1670	69.03	62.8	X6A	83	1965	1630	68.81	57.1
B	95	2005	1660	68.55	65.1	B	81	1980	1640	68.61	55.6
C	99	2005	1650	67.62	67.0	C	87	1985	1650	69.10	60.1
D	94	1990	1655	69.17	65.0	D	82	1970	1645	69.73	57.2

(1) "End" signifies the sonic frequency remaining in the beam at the date of termination from the freeze and thaw test.
(2) Calculated as percent difference in the squares of the frequencies at termination and the 35-day frequency.
(3) Beam accidentally broken - no data available.

DISCUSSION OF RESULTS

PART A - CORRELATION OF CONCRETE DURABILITY WITH CEMENT PROPERTIES

To establish that there does exist a significant difference in the results obtained for this test, an analysis of variance was made using the durability factors shown in Table 5. This analysis, shown in Table 6, demonstrated the significance of the source of the cement and negligible significance of air-entrainment. The fact that the source of the cement was a major influence and the air-entrainment, which also carried the overtone of sand and water contents, was not a factor, indicates the durability of these concretes must be influenced by the cement used. The rate of deterioration of each cement is shown in Figures 2 and 3, pages 18 and 19, by using the computed modulus of elasticity based on the sonic modulus of elasticity test (ASTM C 215) for determining the fundamental transverse frequency, for the nonair-entrained and air-entrained concretes.

This data establishes that there is definitely a large variation in the resistance of various cements to the freeze and thaw test used in this study.

The physical and chemical properties of the cements, shown in Tables 1 and 2, were subjected to a step-wise multiple regression analysis using the resultant durability factors of the nonair-entrained and air-entrained concretes. The results of these analyses based on the eleven Type I

Table 6 - Analysis of Variance of Durability Factors

a. Complete Analysis

Source[1]	df	SS	MS	F	α	S
A	1	30.984	31.0	.58	--	NS
M	11	13424.681	1220.4	36.65	.001	HS
AM	11	589.160	53.6	1.61	--	NS
R	68	2266.852	33.3			
Total	91	16311.677	179.2			

b. Nonair-Entrained Concrete Beams

Source	df	SS	MS	F	α	S
M	11	7753.723	704.9	47.31	.001	HS
R	33	492.037	14.9			
Total	44	8245.760	187.4			

c. Air-Entrained Concrete Beams

Source	df	SS	MS	F	α	S
M	11	6928.338	629.8	20.19	.001	HS
R	35	1091.142	31.2			
Total	46	8091.480	174.3			

(1) Source abbreviations are:
A = Air-entrainment
M = Cement Manufacturer
R = Residual or pooled effects

Figure 2 - Rate of Deterioration of Nonair-Entrained Concretes as a Function of Sonic Modulus of Elasticity

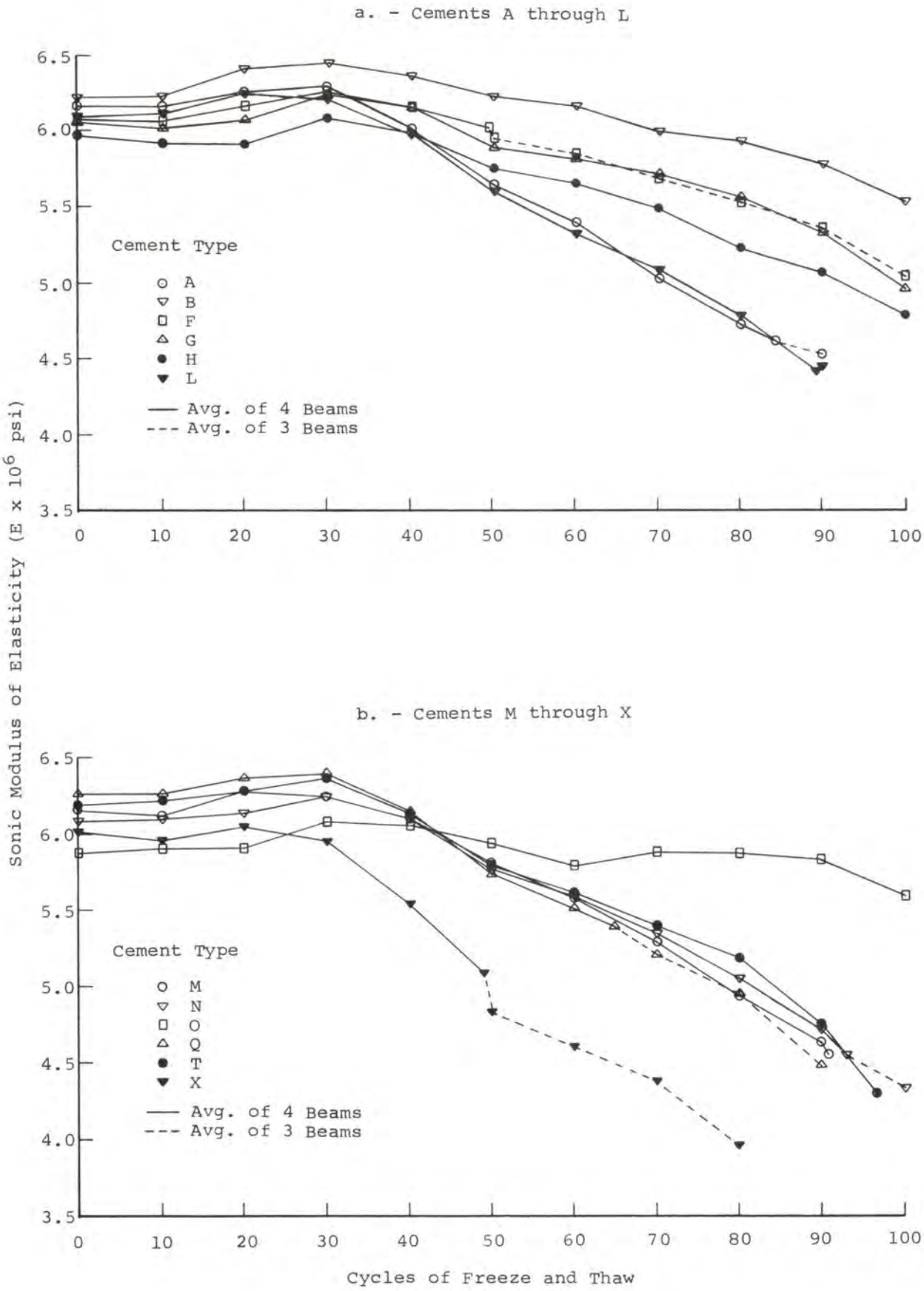
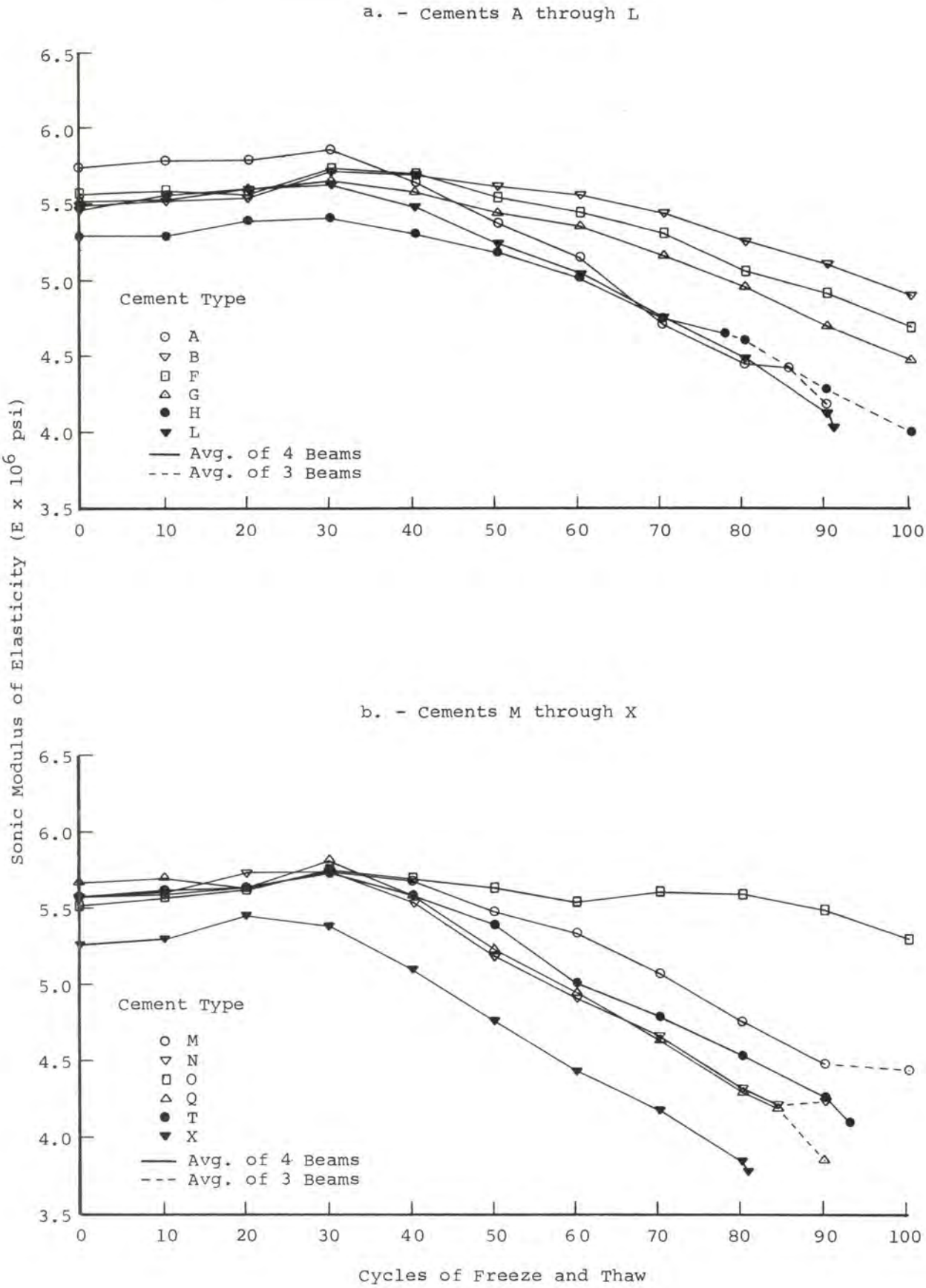


Figure 3 - Rate of Deterioration of Air-Entrained Concretes as a Function of Sonic Modulus of Elasticity



cements (A through T), are mentioned briefly for information only. The three most significant physical and chemical properties of the cements in the nonair-entrained concretes were the difference in initial and final false set penetrations, soundness by autoclave and tensile strength at seven days, and the tricalcium aluminate, sulfur trioxide, and total alkali as sodium oxide equivalent respectively. Likewise, the three most significant properties of the cement in the air-entrained concretes were initial time of set, final time of set, and consistency for the physical properties, and potassium oxide, sulfur trioxide, and magnesium oxide for the chemical properties. Apparently, the nonair-entrained and air-entrained concretes will cause different properties of the cements to be significant; however, only by further research on many more samples will any such analysis be well founded and prove meaningful.

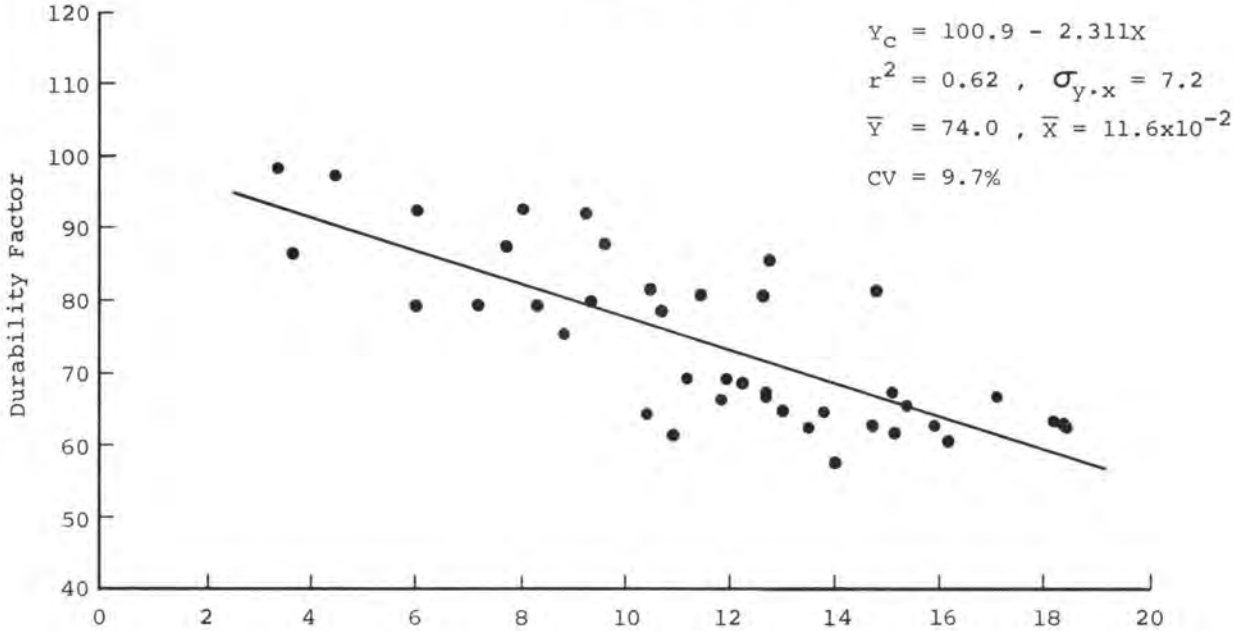
PART B - CORRELATION OF CONCRETE DURABILITY WITH ULTIMATE PERMANENT DILATION

Each time the beams were tested for change in sonic modulus of elasticity, the length of the top and bottom of each beam, determined by gage points set at approximately eight inch centers, were also recorded. The resultant ultimate change in length for each beam in the freeze and thaw test is shown in Table 3. There is a noticeable difference in the ultimate values obtained for the top and bottom of many of the beams. This data was converted to graphical form by showing the durability factor of each beam as a function of the ultimate change in length of the top and bottom separately.

Figures 4a and 4b, page 22, were constructed from the data given for the nonair-entrained concretes. The permanent dilation of the top of the beams seem to correlate slightly better with the durability factors than does the permanent dilation of the bottoms. The permanent dilations of the tops of the beams show slightly lower standard error of estimates and coefficient of variation. Both analyses, however, show fairly close approximations of the durability factors. The average permanent dilation being 0.116 and 0.089 percent for the top and bottom respectively does indicate the top part of the beams may be receiving a harsher freeze condition than the bottom part of the beams. The beams are frozen with the tops, as molded, facing up. However, the rack assembly and the

Figure 4 - Durability Factor as a Function of Ultimate Permanent Dilation of Nonair-Entrained Concretes

a. - Top of Beam



b. - Bottom of Beam

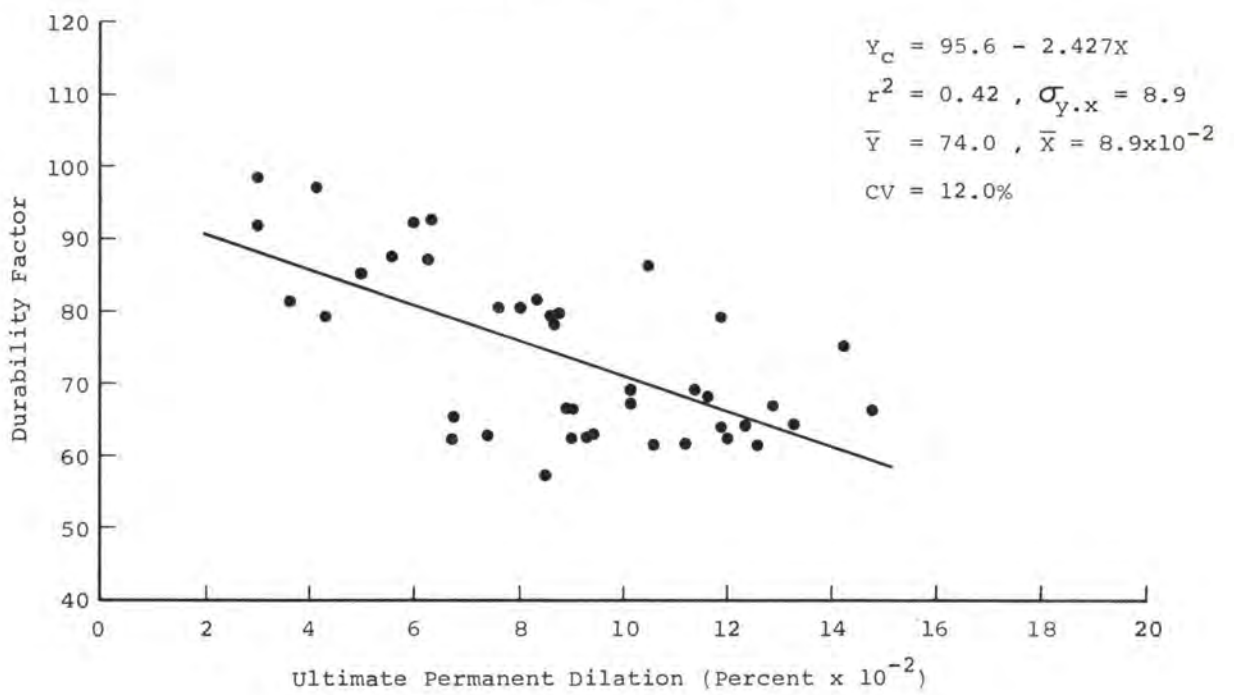
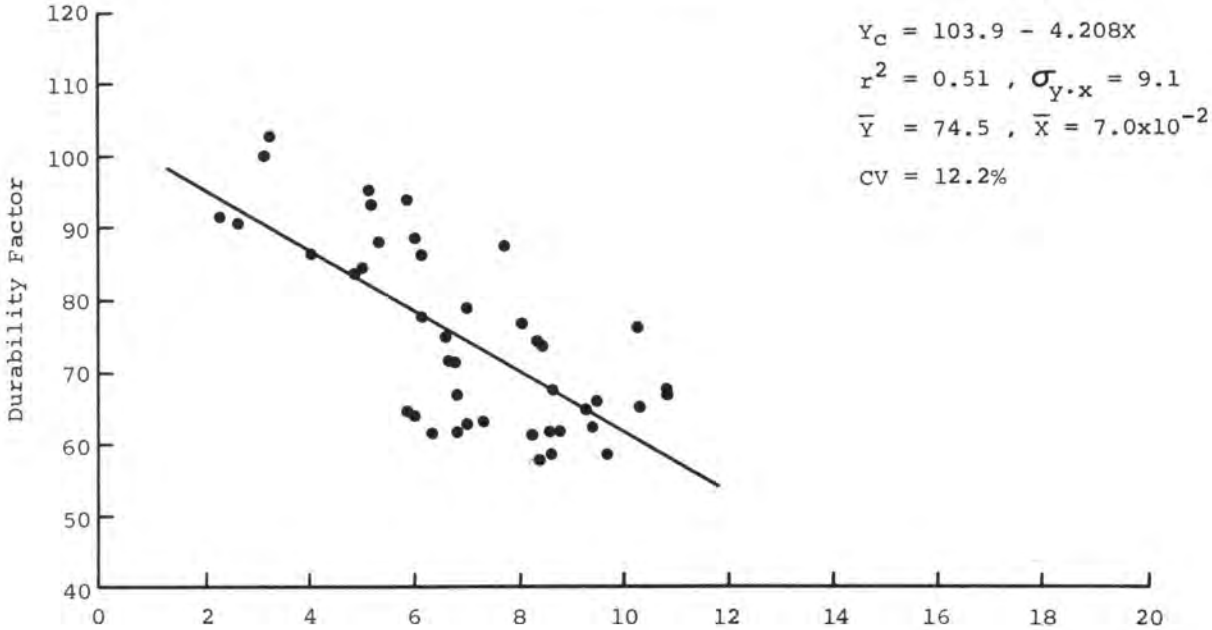
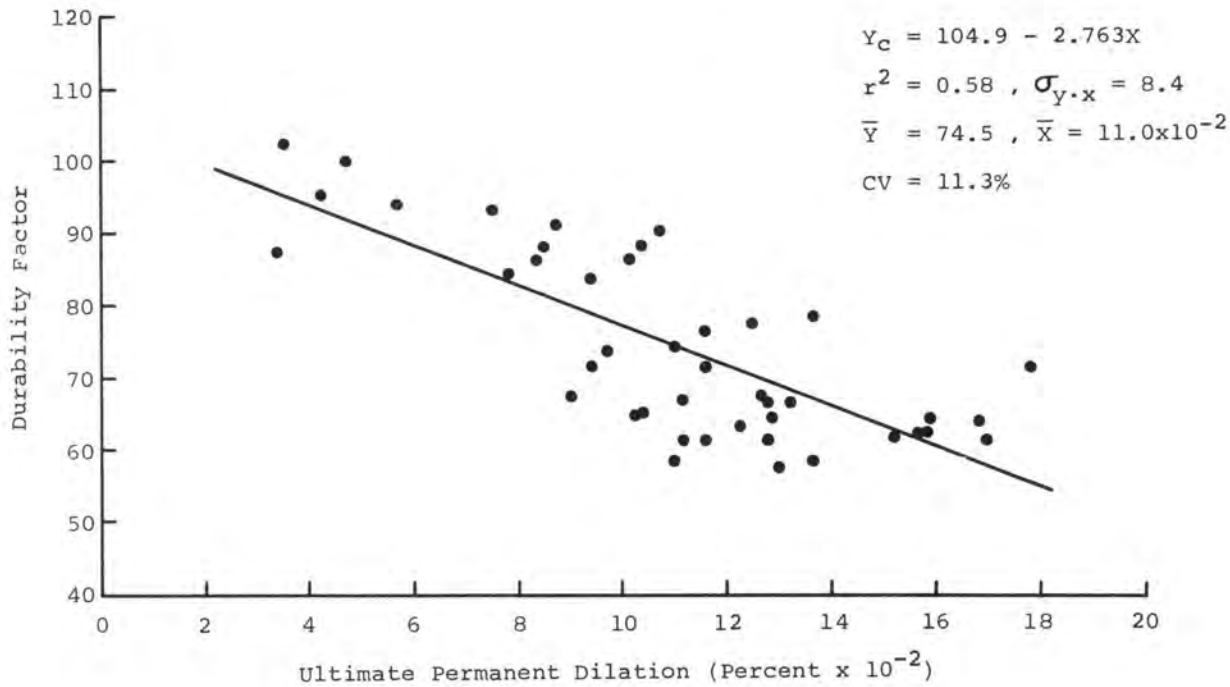


Figure 5 - Durability Factor as a Function of Ultimate Permanent Dilation of Air-Entrained Concretes

a. - Top of Beam



b. - Bottom of Beam



size of the facility are such that equal exposure with regard to the temperature at the beam surface is assumed.

Figures 5a and 5b, page 23, were constructed from the data given for the air-entrained concretes shown in Table 3. The permanent dilation results of the beams seem to indicate that much less expansion occurs in the top, as molded, than in the bottom of these beams. Even though the standard error of estimates and the coefficients of variation are similar, the required slopes of the regression equations are quite different.

This data indicates the effects of air-entrainment may significantly reduce the expansions in the surface of concretes subjected to freezing and thawing. However, air-entrained concretes becoming highly saturated will fail by incurring expansions on the bottom of the slab of nearly the same magnitude as shown for the nonair-entrained concretes.

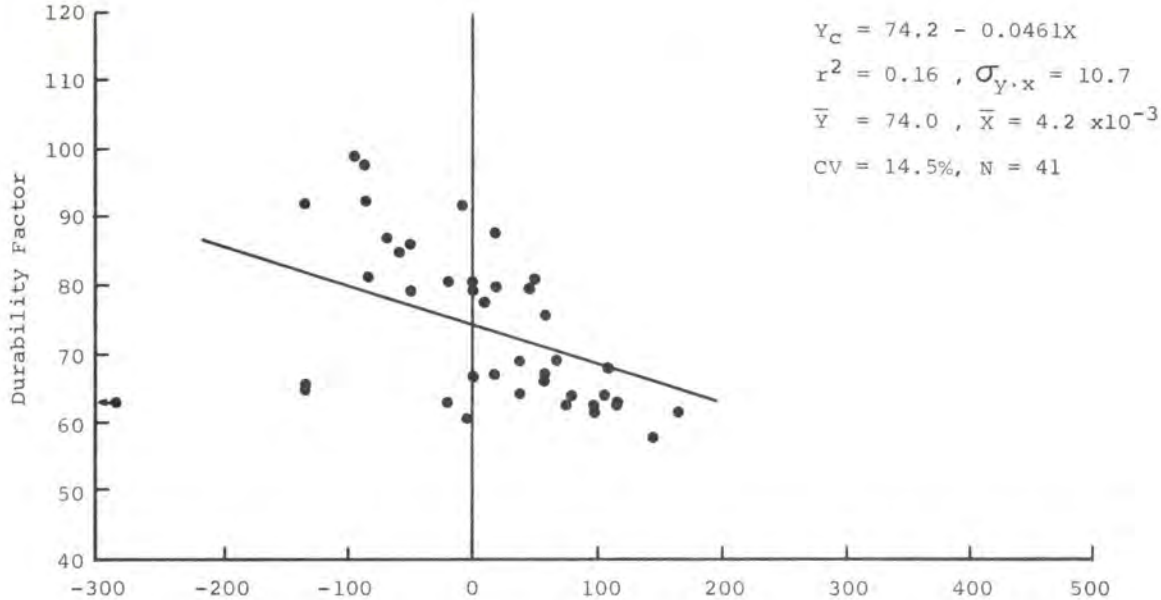
PART C - CORRELATION OF CONCRETE DURABILITY WITH ULTIMATE WEIGHT GAIN

Each time the beams were tested for change in sonic modulus of elasticity, the weight (saturated surface dry) of each beam was recorded to the nearest gram. The resultant ultimate change in weight for each beam in the freeze and thaw test is shown in Table 4. There is a noticeable difference in the ultimate values obtained for the nonair-entrained and air-entrained beams. The average weight gain during the freeze and thaw test was 4.2×10^{-3} and 241.6×10^{-3} percent for the nonair-entrained and air-entrained beams respectively. These values are based on the weight gain after the initial 35-day curing period; however, by calculating the average weight gain during the curing period only, the beams gained 546.3×10^{-3} and 579.1×10^{-3} percent for the nonair-entrained and air-entrained beams respectively.

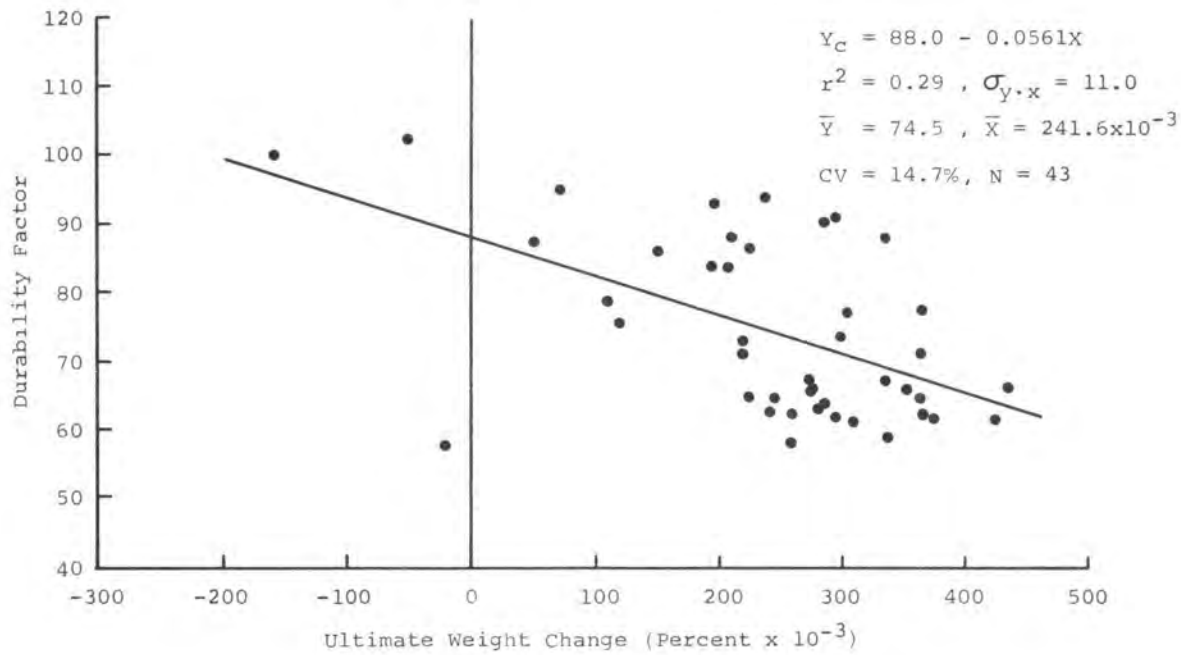
This data indicate the absorption characteristics for the beams are similar during the initial curing period. However, by subjecting these beams to the freeze and thaw test, the absorption characteristics of the nonair-entrained concretes change drastically and will generally accept very little additional water or will tend to lose moisture due to the freeze which will not be regained by soaking. Converting this data to graphical form as shown in Figures 6a and 6b, page 26, the ability of weight measurements of the nonair-entrained beams to predict durability is slightly less significant than that shown for the

Figure 6 - Durability Factor as a Function of Ultimate Weight Change of Nonair-Entrained and Air-Entrained Concretes

a. - Nonair-Entrained Concretes



b. - Air-Entrained Concretes



air-entrained beams. The properties of these correlations are all similar in magnitude and low in significance, thereby, indicating no real difference in their ability to predict a concrete's durability due to freeze and thaw.

The weight change of the beams was initially considered as being a simple indicator of the gain or loss of moisture content of the concretes. These results indicate the air-entrained concretes must, on the average, absorb approximately 0.8 percent moisture, whereas, the nonair-entrained concretes generally need only 0.5 percent moisture gain by weight to fail by freeze and thaw. The fact that the nonair-entrained concretes generally did not gain moisture during the freeze and thaw test may indicate that resaturation may require longer periods of soak than one week. This means that the air-entrained concretes may tend to resaturate or continue to gain moisture after thawing.

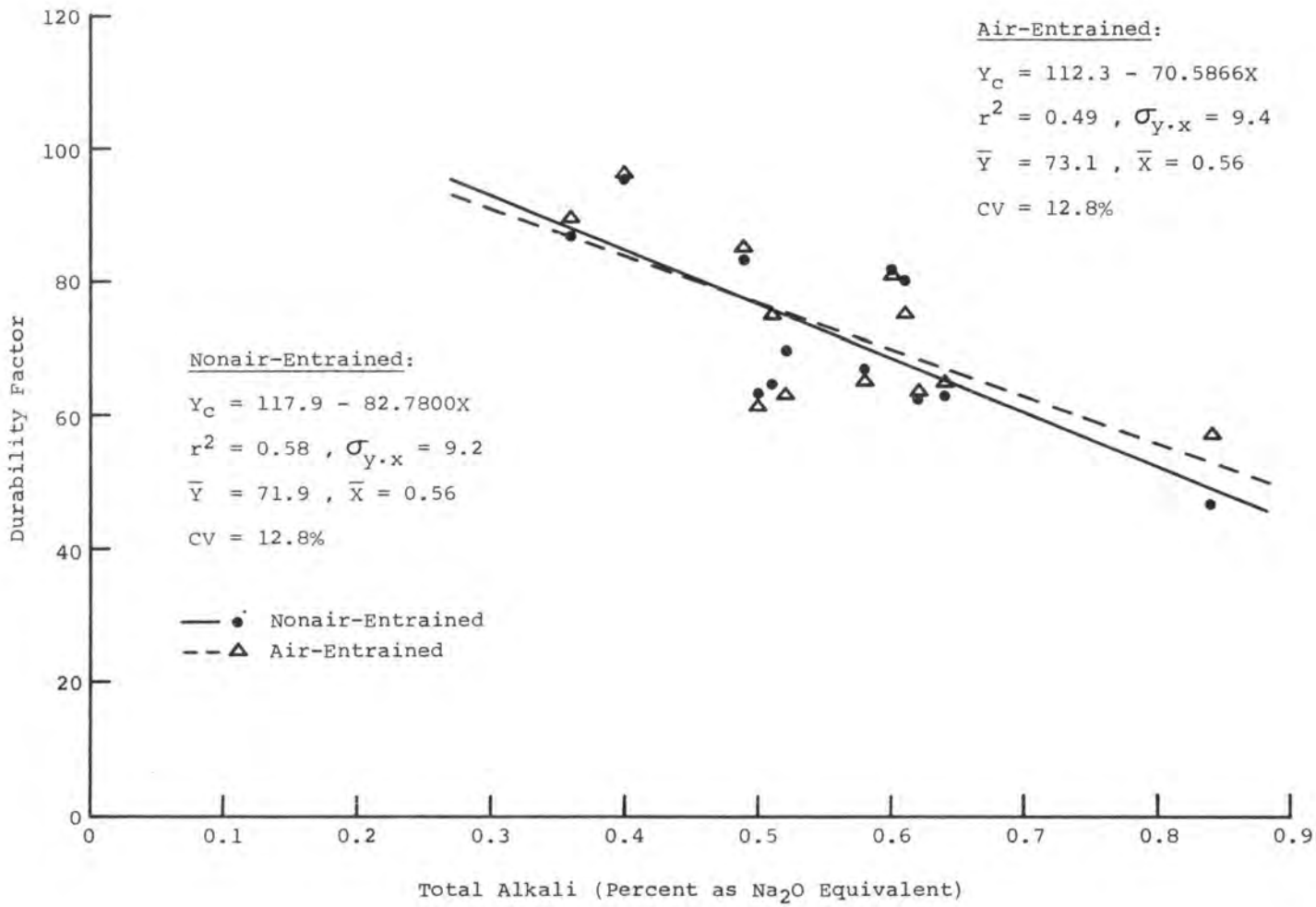
PART D - CORRELATION OF CONCRETE DURABILITY WITH CEMENT ALKALI CONTENT

The alkali content of the cement has long been a topic of discussion when considering the durability of concretes. Cement Type "X" was included as an exploratory item because of its relatively high total alkali content as shown in Table 2. Therefore, this section will examine only the correlation existing between the total alkali content and the average durability factor for each group of beams tested as nonair-entrained and air-entrained.

Figure 7 shows the relative closeness of the results of the nonair-entrained and air-entrained beams. As each cement used maintained the same total alkali content whether the concrete was air-entrained or not, the points lying on the same vertical alignment represent the same cement. This demonstrates what was previously stated in Part A of this discussion, that air-entrainment caused no significant difference in the results.

The data in Figure 7 does show that the correlations are significant at the one percent level. However, it was pointed out in Part A that alkali was only a partial function of a more complete analysis of prediction for the durability factors. Therefore, it is not surprising to find relatively high standard error values, thus limiting the usefulness of this data until more testing can be conducted.

Figure 7 - Durability Factor as a Function of the Total Alkali, Calculated as Na_2O Equivalent, of the Cements



Another aspect of alkali content which may be studied within this analysis is the results obtained from the concrete beams having two cements manufactured from within the same plant (Cement Type "L" and "X") having two different alkali contents. For ease of comparison, the data shown in Tables 3, 4, and 5 for these beams, will be retabulated in Table 7.

The results show the high alkali cement (Type "X") does accelerate the rate of failure regardless of air-entrainment. The higher alkali content without air-entrainment causes failure of the beams to occur within 74.5 percent of the time required for the lower alkali cement. The differences in durability factors show an actual increase in the rate of failure of 16.41 and 10.28 percent for the nonair-entrained and air-entrained beams having high alkali cement.

The only other noticeable difference between these beams is the gain in weight of the nonair-entrained beams. Apparently, the moisture gain of the nonair-entrained concrete containing the high alkali cement does not have to be as great as that required for the normal cement, however, with air-entrainment the moisture gain appears to be nearly the same. All the other recorded measurements do not show appreciable differences.

Table 7 - Summary of Data for Correlation of Alkali Content of Cements

Concrete Mix Design	Cycles to Complete	Gain in Length (Percent) Top	Gain in Length (Percent) Bottom	Gain in Weight ($\%x10^{-3}$)	Residual Sonic Frequency	Durability Factor (DF)
Cement Type "L" - Total Alkali as Na_2O = 0.64 (Nonair-Entrained)						
LOA	91	0.109	0.126	99.0	67.70	61.6
B	92	0.130	0.123	79.2	70.13	64.5
C	89	0.151	0.107	166.0	69.31	61.7
D	92	0.183	0.068	-19.3	68.33	62.9
Average	91	0.143	0.106	81.2	68.87	62.7
(Air-Entrained)						
L6A	91	0.070	0.158	258.3	69.03	62.8
B	95	0.103	0.108	243.7	68.55	65.1
C	99	0.108	0.111	272.4	67.72	67.0
D	94	0.093	0.102	221.9	69.17	65.0
Average	95	0.094	0.120	249.1	68.62	65.0
Cement Type "X" - Total Alkali as Na_2O = 0.84 (Nonair-Entrained)						
XOA	79	0.183	0.103	-39.0	70.05	55.3
B	80	0.152	0.127	29.2	64.25	51.4
C	55	0.110	0.077	78.2	70.45	38.7
D	49	0.063	0.062	68.3	84.29	41.3
Average	66	0.127	0.092	34.2	72.26	46.7
(Air-Entrained)						
X6A	83	0.101	0.119	274.8	68.81	57.1
B	81	0.133	0.122	142.5	68.61	55.6
C	87	0.084	0.120	162.0	69.10	60.1
D	82	0.114	0.124	302.5	69.73	57.2
Average	83	0.108	0.121	220.4	69.06	57.5

PART E - CORRELATION OF CONCRETE DURABILITY WITH STORAGE CONDITIONS BETWEEN FREEZE CYCLES

During the planning stages of this phase of the investigation, some discussion was generated with respect to the storage procedures used in the previous phase. Some concern was expressed for the complete submergence of the beams as opposed to leaving one surface, the top as molded, exposed to air. It was decided that one group of four beams, being a replicate of one group of the test beams, would be placed in storage with 1/4 inch of the top of the beam exposed.

Cement Type "F" was chosen for this exploratory test with air-entrainment only. The results obtained for the different storage conditions are shown in Table 8. In both the length change and gain in weight, the submerged concretes show the greatest increases. Therefore, it is not surprising that the submerged concretes should show the greatest decrease in durability factors. From this data no direct clear decision can be made as to which storage method should be used that best coincides with actual field conditions. Perhaps some information will be gained from the field phase of this investigation that will shed light on the subject.

On the basis of present knowledge derived through the results of a previous report titled Comparison of Results Obtained by Subjecting Concretes to Accelerated Laboratory Freeze-Thaw and Long-Time Outdoor Exposure Tests, by the Missouri State Highway Department, and the limited knowledge of the rate of deterioration of comparable concretes in the

Table 8 - Summary of Data for Correlation of Storage Conditions

Concrete Mix Design	Cycles to Complete	Gain in Length (Percent) Top	Gain in Length (Percent) Bottom	Gain in Weight ($\%x10^{-3}$)	Residual Sonic Frequency	Durability Factor (DF)
Cement Type "F" - Storage by Complete Submersion						
(Air-Entrained)						
F6A	100	0.084	0.097	219.0	73.83	73.8
B	100	0.049	0.094	207.4	83.88	83.9
C	100	0.022	0.087	293.6	91.18	91.2
D	100	0.026	0.107	283.3	90.32	90.3
Average	100	0.045	0.096	250.8	84.80	84.8
Cement Type "F" Storage by Partial Submersion						
(Air-Entrained)						
Y6A	100	-0.005	0.035	69.6	98.02	98.0
B	100	0.006	0.028	49.7	100.00	100.0
C	100	-0.006	0.014	212.4	106.66	106.7
D	100	0.002	0.021	175.3	103.02	103.0
Average	100	-0.001	0.024	126.8	101.92	101.9

field, the submerged beams tend to indicate the best positive test in which to attempt correlation. By using a prolonged soak period between cycles, the concept of an accelerated test is lost. However, it appears this method will be more reasonable for the time required to resaturate the concretes as well as provide the best base for correlation with field observations of deteriorated portland cement concrete pavements which have been or may now be in service.

APPENDIX A

Properties of Fine Aggregate

Properties of Coarse Aggregate

Table 9 - Properties of Fine Aggregate

Gradation:	
Percentages retained on:	
3/8" sieve	0
No. 4 sieve	2.46
No. 20 sieve	37.08
No. 50 sieve	88.96
No. 100 sieve	98.76
Bulk Specific Gravity (Dry)	2.60
Bulk Specific Gravity (SSD)	2.61
Apparent Specific Gravity	2.63
Absorption, percent (24 hours)	0.4
Absorption, percent (30 min.)	0.4

Note: Generally the moisture content of the sand as used was 0.19 percent.

Table 10 - Bulk Specific Gravities of Coarse Aggregates Obtained from Standard Laboratory Procedures

Bulk Specific Gravity (Dry)			Bulk Specific Gravity (SSD)(1)		
Sample No.	+½" Fraction	-½" Fraction	Sample No.	+½" Fraction	-½" Fraction
A	2.6075	2.5686	A	2.6453	2.6197
B	2.6115	2.5766	B	2.6472	2.6276
C	2.6185	2.5696	C	2.6509	2.6206
Mean.	2.6125	2.5716	Mean.	2.6478	2.6226

Bulk Gravities for 52-48 Blend:

Bulk Specific Gravity (Dry)	2.5927
Bulk Specific Gravity (SSD)	2.6357

(1) Aggregate soaked for 2 hours.

Table 11 - Gradation of Coarse Aggregate by Standard Laboratory Procedures

Laboratory Analysis:	+½"Fraction (Percent)	-½"Fraction (Percent)
Retained on 1" Sieve	0	0
Retained on 3/4" Sieve	5.54	0
Retained on 1/2" Sieve	92.87	0
Retained on 3/8" Sieve	1.30	46.79
Retained on #4 Sieve	0.23	47.95
Retained on -#4 Sieve	0.06	5.26
	100.00	100.00

Therefore, for a 52-48 Blend, the Combined Gradation is:

Passing 1" Sieve	100.00%
Passing 3/4" Sieve	97.12%
Passing 3/8" Sieve	25.69%
Passing #4 Sieve	2.55%

Comparative Gradation for Stone Number 3, Phase 1 was:

Passing 1" Sieve	100.00%
Passing 3/4" Sieve	90.20%
Passing 3/8" Sieve	25.60%
Passing #4 Sieve	2.40%

Table 12 - Two-Hour Absorption Properties of Coarse Aggregate

Sample No.	2 Hour Absorption (% by Weight)			2 Hour Absorption (% by Volume)		
	½" to 1"	#4 to ½"	Combined (52:48)	½" to 1"	#4 to ½"	Combined (52:48)
A	1.45	1.99	1.71	3.77	5.10	4.41
B	1.37	1.98	1.66	3.57	5.10	4.30
C	1.24	1.99	1.60	3.24	5.10	4.13
		Mean	1.66%		Mean	4.28%

Comparative Absorption Properties of Coarse Aggregate Number 3, Phase 1 were:

2 Hour Absorption	1.80% by Weight
	4.64% by Volume

APPENDIX B

Mix Design and Batching

Curing

Concrete Beam Identification

Results of Tests on Fresh Concretes and Control Beams

Mix Design and Batching

Eight concrete specimens 3½x4½x16 inches were molded in two separate batches of four each for each mix design. Four of the specimens, two from each batch, were designated for control beams which were broken in flexure after 35 days curing. The remaining four specimens were designated for durability testing by the freeze in air and thaw in water method.

The mix designs consisted of nonair-entrained and air-entrained concretes with eleven different cements. The coarse aggregate quantities, based on absolute volume, were constant for all batches. The design water-cement ratio was constant at 0.67 for the air-entrained concretes and 0.73 for the nonair-entrained concretes. The cement quantities, based on absolute volume, were constant for all batches. The sand quantities were constant at 37.0 percent and 40.1 percent of the total aggregate fraction for the air-entrained and nonair-entrained concretes respectively.

Batching was completed within a two week period whereby one-half of the specimens for each mix design were molded the first week and the remaining one-half molded the second week. Two days of each week were required for batching with one day designated for all nonair-entrained specimens and the other day designated for all air-entrained specimens. Random ordering of the batches for any one day was used to prevent possible effects of mix order or time of day batching occurred or temperature variations during mixing.

CURING

Immediately after fabrication, the concrete beams were placed in a moist room controlled at approximately 73°F and 95 percent relative humidity. The following day, the molds were removed and the concrete beams were weighed in air and water and initial length measurements taken. Thereafter, the beams were handled as follows:

Control Beams: The 100 control beams to be broken in flexure were kept in the moist room on shelves until seven days old, then were stored in limewater at room temperature until they were broken in flexure at 35 days.

Freeze and Thaw Beams: The 100 freeze and thaw beams were kept in the moist room on shelves until seven days old, then were stored permanently in limewater solution at room temperature until the beginning of the freeze and thaw test at 35 days. The beams were removed from the limewater storage once each week for approximately 20 hours of freeze and thaw testing and then returned.

CONCRETE BEAM IDENTIFICATION

To properly identify each individual concrete beam the following abbreviated identification was used:

Column 1 - Indicates the brand of cement used, A, B, F,..., etc., with exception of "Y" which was used to identify a different storage condition for one mix design only.

Column 2 - Indicates air-entrained (6) or nonair-entrained (0) mix design.

Column 3 - Indicates the identity of the eight replicate specimens per mix design with A, B, C, and D indicating the freeze and thaw specimens and E, F, G, and H indicating the companion control specimens.

A typical identification code, such as F6C would be identified as a concrete beam designed with the cement designated as Type F, incorporating the use of air-entrainment, and is third of a set of four subjected to the freeze and thaw test. This code proved sufficient for collection of data in this test.

RESULTS OF TESTS ON FRESH CONCRETE AND CONTROL BEAMS

The cement factor, water-cement ratio, slump, and air content of the fresh concrete immediately after batching are shown in Table 13, page 44. As expected, the water-cement ratio for the nonair-entrained concretes was higher than the water-cement ratios for the air-entrained concretes. The slump and air contents remained well within our specifications for this test.

The flexural strengths of the control and freeze and thaw specimens are shown in Table 14, page 45. The control specimens were tested at the age of 35 days simultaneously with the beginning cycle of the companion freeze and thaw specimens. The freeze and thaw specimens were broken as they reached individual losses of 30% or more in sonic modulus of elasticity. The flexural strengths computed as the modulus of rupture and expressed as pounds per square inch are shown for both the 14 and 7 inch spans.

The strengths of the air-entrained concretes are noticeably below the strengths of the nonair-entrained concretes by approximately 9 percent. The difference between the 14 and 7 inch spans for the freeze and thaw beams were approximately 18 and 20 percent for the nonair-entrained and air-entrained concretes respectively.

These data show the flexural strengths of the air-entrained specimens to be approximately 9 percent below that shown for the nonair-entrained specimens. This difference increases to approximately 11 percent at termination.

Table 13 - Characteristics of Fresh Concretes (1)

Concrete Mix Design	Sand Content (%) (2)	Cement Factor (Actual)	W/C Ratio (Actual)	Slump (inches)	Air Content (%) Fresh Conc.
		Nonair-Entrained Concretes			
A0	40.1	1.55	0.66	1.81	0.88
B0	40.1	1.55	0.68	2.50	0.57
F0	40.1	1.55	0.68	2.81	0.44
G0	40.1	1.53	0.71	1.94	0.65
H0	40.1	1.54	0.68	2.06	1.12
L0	40.1	1.54	0.69	2.38	0.88
M0	40.1	1.55	0.68	2.00	0.59
N0	40.1	1.54	0.67	2.44	1.18
O0	40.1	1.53	0.71	2.56	1.10
Q0	40.1	1.55	0.66	2.00	0.97
T0	40.1	1.55	0.68	2.38	0.68
X0	40.1	1.54	0.68	2.12	0.76
		Air-Entrained Concretes			
A6	37.0	1.57	0.59	2.50	4.96
B6	37.0	1.56	0.61	2.31	4.90
F6	37.0	1.57	0.60	2.50	4.88
G6	37.0	1.56	0.62	2.44	4.58
H6	37.0	1.55	0.61	2.62	5.42
L6	37.0	1.55	0.61	2.06	5.29
M6	37.0	1.56	0.60	2.12	4.95
N6	37.0	1.57	0.59	2.44	4.97
O6	37.0	1.56	0.63	2.19	4.33
Q6	37.0	1.57	0.57	2.12	5.39
T6	37.0	1.56	0.61	2.69	5.12
X6	37.0	1.55	0.60	2.69	5.94

(1) All values shown are averages of two determinations.
(2) Percent sand content of total aggregate fraction.

Table 14 - Flexural strengths of Control Beams and Beams Subjected to the Freeze and Thaw Test (1)

Concrete Mix Design	Control Beams Average 35 Day Flexural Strengths		Freeze-Thaw Beams Avg. Strength at Termination		Percent Loss in Flexural Strength	
	14" Span	7" Span	14" Span	7" Span	14" Span	7" Span
Nonair-Entrained Concretes						
A0	1101	1186	483	518	56.13	56.32
B0	1111	1125	624	735	43.83	34.66
F0	1029	1172	510(3)	751	50.43	35.92
G0	1066	1206	579	631	45.68	47.67
H0	996	1124	489	521	50.90	53.64
L0	1049	1157	474	552	54.81	52.29
M0	1069	1194	512	538	52.10	54.94
N0	1153	1200	410	572	64.44	52.33
O0	978	1114	732	881	25.15	20.91
Q0	1087	1122	454(2)	574	58.23	48.84
T0	1089	1196	493	464	54.72	61.20
X0	1051	1169	404(2)	576	61.56	50.72
Average(4)	1066	1163	524	612	50.58	47.16
Air-Entrained Concretes						
A6	993	1070	436	476	56.09	55.51
B6	989	1086	585	688	40.84	36.64
F6	954	1029	469	635	50.83	38.28
G6	927	1064	468	524	49.51	50.75
H6	910	992	372	473	59.12	52.31
L6	989	1068	469	476	52.57	55.43
M6	966	1065	455	552	52.89	48.16
N6	1011	1108	386	463	61.81	58.21
O6	963	1014	636	768	33.95	24.26
Q6	995	1097	410	504	58.79	54.05
T6	968	1077	394	516	59.29	52.08
X6	933	1020	396	496	57.55	51.37
Average(4)	970	1061	462	552	52.34	47.79

(1) The values shown in this table are flexural strengths expressed as pounds per square inch (PSI). Each value shown is the average of four determinations unless otherwise noted.
(2) Average of three beams.
(3) Average of two beams.
(4) Average of Mix Designs A through T only.

The average percent loss in flexural strength of the concrete beams that failed by 30 percent loss in modulus of elasticity prior to the 100 cycle termination point was 64.9 and 57.7 percent respectively for the nonair-entrained and air-entrained beams, which still left some 11 percent difference between the concretes. Therefore, the actual percent loss in flexural strength to the point of failure as specified appears to be consistent regardless of the initial strength properties of the concretes.

APPENDIX C

Freeze and Thaw Test Procedure

FREEZING AND THAWING TEST PROCEDURE

The Missouri accelerated laboratory freezing and thawing test is a modification of the method described by T. C. Powers in his paper "Basic Considerations Pertaining to Freeze and Thaw Tests", ASTM Proceedings, Volume 55, 1955. Under the Missouri procedure the concrete beams are cooled to 40°F in a water bath prior to being placed in the freezer. The concrete beams are frozen in air, the temperature of which is maintained at 0°F. A typical freeze and thaw cycle consisted of approximately 16½ hours of freeze (overnight) and 2 hours of thaw. With this procedure only one freeze and thaw cycle was obtained per week per specimen. Storage of the specimens between cycles was at room temperature completely submerged in a saturated limewater solution.

The results of the freezing and thawing test were recorded by the change in length, weight, and fundamental sonic frequency when measuring the dynamic modulus of elasticity for each individual concrete beam before and after each freeze and thaw cycle. The change in length was measured by a Whittemore strain gauge (10" span) to the nearest 0.001 inch on both the top and bottom of each concrete beam. The change in weight was measured to the nearest gram on a laboratory Toledo balance. Due to handling the concrete beams over a period of 100 weeks, some chipping of the corners and edges was inevitable. Where possible, proper notation was made when large chips and excessive

changes in weight occurred. The change in dynamic modulus was measured electronically by the use of a frequency probe and pickup system.

The data obtained for the change in length, weight, and sonic frequency of each beam are shown in Tables 3, 4, and 5 respectively.

DOT LIBRARY
00354051