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Durability of Portland Cement Concrete: Aggregates, Cements and Pozzolans

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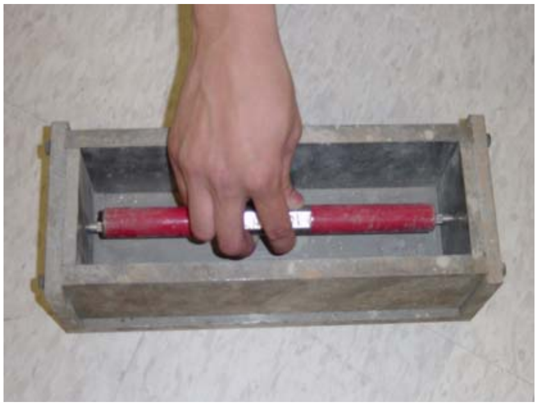
Nebraska Department of Roads

Project No. SPR-1(02) P547



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16. Abstract

The Nebraska Department of Roads in 2001 initiated an effort to improve the durability of concrete for state paving projects. The objectives were to evaluate the alkali-silica reactivity (ASR) potential of selected aggregates, and to identify the specific amounts of supplementary cementing materials, such as fly ash, slag and silica fume, to effectively mitigate ASR.

The testing included 4 sources of fine aggregates, 1 source of limestone, 5 sources of portland cement, 2 sources of Class C fly ash, 1 source of Class F fly ash, 1 source of slag, and 1 source of silica fume. ASTM C 1293 and performance tests, including compression strength, flexural strength, split-tensile strength, freeze-thaw resistance and chloride ion penetration, were conducted on the same concrete mixes.

Using 17 to 23.5% of F ash, 20 to 35% of slag, or 20% of C ash plus 3% silica fume effectively reduced the ASR expansion without compromising the concrete performance per Nebraska 47B Specifications.

17. Key Words Alkali-silica reactivity, fly ash, slag, silica fume, freeze-thaw resistance, strength, durability.	18. Distribution Statement		
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LIST OF FIGURES

LIST OF TABLES

TABLE OF CONTENTS

CHAPTER 5 DISCUSSION OF RESULTS

CHAPTER 6 SUMMARY AND RECOMMENDATIONS

CHAPTER 1

INTRODUCTION

1.1 ALKALI-SILICA REACTION

Alkali-Silica Reaction (ASR) was first documented by Stanton[1] in 1940, and is the most recognized cause of deterioration of highway concrete structures and pavements in the United States. ASR takes place between certain reactive siliceous aggregates (e.g., opal, chalcedony and volcanic glass) and hydroxyl ions (OH^-) associated with the alkalis (Na_2O and K_2O) from the portland cement paste and external sources. A reaction product gel forms that, in the presence of water, expands and may result in cracking of the mortar and concrete. Surface cracks are aggravated by winter deicing salts and freeze-thaw action, leading to shallow delaminations, rebar corrosion, potholes, and other serious problems including structural failure. Three conditions are required for the ASR reaction to take place: high alkali content primarily from the cement, reactive silica in the aggregate, and sufficient moisture content in the concrete. The mechanism governing ASR and the resulting expansion is complex. Several schools of thought on this phenomenon have been proposed[2]. In its simplest form, ASR can be visualized as a two-step process[3]:

Step 1: Silica + Hydroxyl Ions (OH^-) + Moisture → Silicate Gel (ASR Gel)

Step 2: ASR Gel + Additional Moisture → Expansion

Originally many jurisdictions specified the use of low-alkali cement ($< 0.6\%$ Na_2O_e) as a method for preventing concrete damage due to ASR. However, simply limiting the alkali content in the cement is not sufficient, since the amount of alkalis available for reaction in the concrete also depends upon the amount of cement used in the concrete. Tests[4,5] conducted using highly reactive aggregates showed that concrete expansions were directly related to the alkali content in concrete. Further, other sources such as aggregates, chemical and mineral admixtures and deicing salts may contribute significant quantities of alkalis to the concrete. As a result, many national and provincial specifications limit the alkali content of concrete to minimize the risk of ASR damage, with a typical maximum limit of 3.0 kg/m^3(5 lbs/yd^3).

Recent studies[6,7,8] have shown that using mineral admixtures (i.e., pozzolans and slag) and chemical admixtures (e.g., lithium nitrate) are effective measures for mitigating ASR damage. Blended hydraulic cements containing silica fume, Class F fly ash, calcined clay, and/or slag in addition to portland cement have recently become commercially available. It is expected that future performance-based concrete specifications will include blended hydraulic cements as options for ASR mitigation as well as for concrete durability improvement.

1.2 STATEMENT OF NEED

A consensus was reached among the material engineers of NDOR, aggregate suppliers, cement suppliers, suppliers of pozzolanic materials and concrete producers, that there was a need to quantify the reactivity levels of the aggregates from the various sources frequently used in Nebraska. Simple means were also sought to mitigate the unwanted deleterious expansion of concrete due to ASR. An Advisory Committee was formed to assist in the testing and evaluations of the aggregate reactivity and the effectiveness of various remedial measures for mitigating ASR. Members of this Committee are listed in Appendix I.

1.3 RESEARCH SIGNIFICANCE

A review of the major highway and interstate construction projects in Nebraska revealed that measures have been taken to mitigate ASR. For instance, F ash was used to control ASR for Highway 21 during the mid-1940’s, limestone was used to mitigate ASR for Highway 81 to the Kansas state border during the 1950’s, and the alkali content of cement was limited for the I-80 construction from early 1960’s to mid-1970’s. However, no definitive specifications have been developed for the production of durable concrete and effective ASR mitigation in Nebraska.

The objectives of this study were to evaluate the alkali-silica reactivity (ASR) potential of selected aggregates according to the ASTM C 1260 and C 1293 tests, and to identify the specific amounts of supplementary cementing materials (SCM), such as fly ashes (Class C and F), slag and silica fume, to effectively mitigate ASR. The concrete mixes developed were also subject to durability tests. It is anticipated that the use of SCM’s proposed in this study would help produce durable concrete for infrastructure construction projects in Nebraska.

1.4 ORGANIZATION OF THE REPORT

This report contains six chapters: Chapter 1 provides an introduction to the alkali-silica reaction and a brief summary of literature survey. Chapter 2 gives a detailed description of the laboratory tests conducted in this investigation. The laboratory tests consisted of the ASTM C 1260, the ASTM C1293 and durability tests. Chapter 3 presents the ASTM C1260 and the ASTM C1293 test data, and Chapter 4 presents the durability test data. Chapter 5 provides discussions of the results. Chapter 6 summarizes the findings and provides recommendations to address further research needs.

CHAPTER 2

TEST PROGRAM

2.1 INTRODUCTION

The two-and-a-half-year test program included 4 sources of potentially reactive fine aggregates, 1 source of limestone, 5 sources of cement (Type I, Type IP/F, low-alkali and high-alkali), 2 sources of Class C fly ash, 1 source of Class F fly ash, 1 source of slag, and 1 source of silica fume. The percentages used for cement replacement by mass included C ash at 17%, 25% and 35%, C ash at 20% plus silica fume at 3%, F ash at 17% and 25%, and slag at 20% and 35%. The low-alkali cement (0.45% alkali) was used to cast concrete with an alkali content of 1.78 kg/m^3 (3 lb/yd^3).

Both standard and accelerated ASTM C 1293 tests were conducted to determine the ASR-induced expansions. Durability tests including compression strength, flexural strength, split-tensile strength, freeze-thaw resistance, chloride ion penetration and Nebraska wet/dry tests were conducted on the same mixtures used in the C 1293 tests except with air-entrainment admixture added. The test matrix involving the selected aggregates with varying amounts of cements, fly ashes (Class C and F), ground granulated blast furnace slag (GGBFS) and silica fume is given in Appendix II. The procedures for preparing ASTM C1293 specimens are given in Appendix III.

For the first part of the test program, the NDOR's 47B-3500 Specification was used for the mix designs. Concrete mixes with 25% and 35% C ash, 20% C ash + 3% silica fume, 17% and 25% F ash, 20% ground slag, Type 1P/F cement, for cement substitution were batched to cast the ASTM C 1293 and durability test specimens.

2.2 SELECTION OF THE FINE AGGREGATES

Based on previous field performance records, NDOR conducted the ASTM C 1260 tests on potentially reactive fine aggregates (sand and gravel) from 10 sources in Nebraska. The top 4 sources that had higher 14-day expansions (shown in Fig. 2.1) were subject to further ASR potential and durability evaluations. The chemical compositions of the limestone and the fine aggregates used were analyzed using X-Ray Fluorescence (XRF) Spectrometry and Flame Photometry. The results are given in Table 2.1.

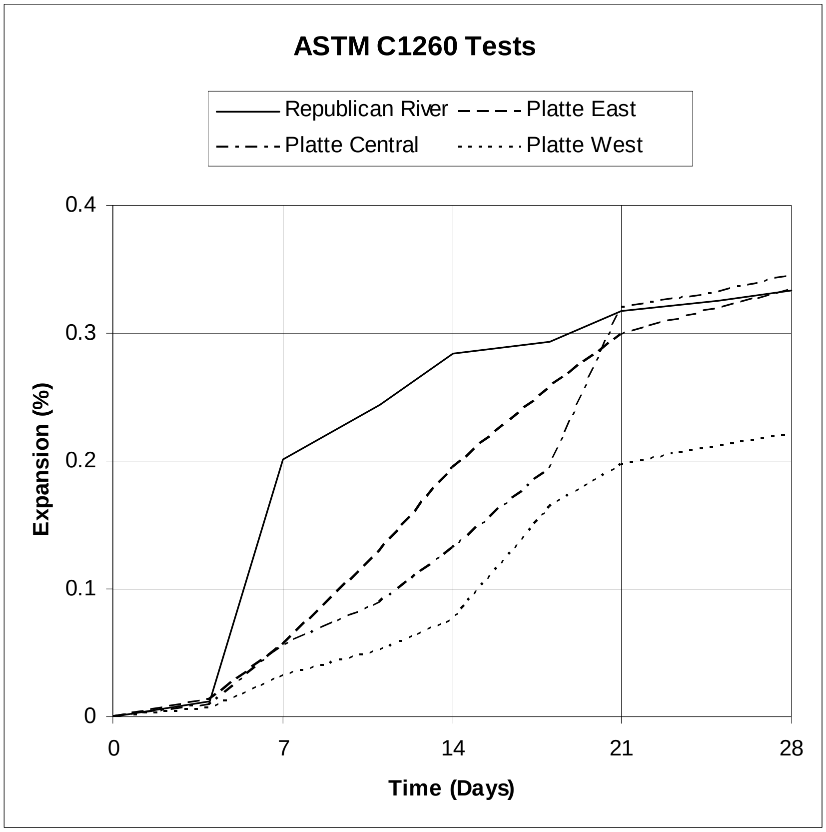

Figure 2.1 ASTM C 1260 Expansion Data

Table 2.1 Chemical Composition of Aggregates

Aggregate	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	LOI
Limestone	1.80	0.54	0.33	53.38	0.37	0.03	0.05	42.37
Platte River East	80.70	10.20	0.73	0.80	0.094	1.30	4.60	0.29
Platte River Central	83.50	8.00	0.72	1.60	0.11	1.20	3.40	0.64
Platte River West	76.10	12.10	1.40	1.90	0.23	1.70	4.90	0.70
Republican River	80.90	8.90	0.98	1.90	0.11	1.10	4.60	1.09

Note: LOI = Loss on ignition, percentage by weight (moisture-free basis).

2.3 CEMENTITIOUS MATERIALS

The chemical compositions of the portland cements, fly ashes, slag and silica fume were analyzed according to ASTM C 150, C 618 and C 989 Specifications. The results are presented in Table 2.2, 2.3 and 2.4, respectively.

Table 2.2 Chemical Composition of Cement

Cement	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	LOI
Type I/II	20.62	4.30	3.09	63.11	3.06	0.16	0.61	1.23
Type IP/F	27.75	8.36	3.16	52.92	1.05	0.19	0.80	1.27
High Alkali	20.59	4.78	3.28	63.93	1.27	0.15	0.76	0.84
High Alkali - II	20.70	4.79	3.42	63.72	1.21	0.19	0.74	1.21
Low Alkali	21.13	5.19	3.42	63.13	1.42	0.18	0.41	1.04
Lone Star	20.91	5.26	2.47	63.57	1.72	0.29	0.83	0.00

Cement	**Eq. Alkali**	**SO_3**	**C_3S**	**C_2S**	**C_3A**	**C_4AF**	**Blaine Fineness***
Type I/II	0.56	2.68	57	17	6.20	10.00	380
Type IP/F	0.71	2.80	---	---	16.80	9.62	396
Low Alkali	0.45	3.17	47.61	24.66	8.00	10.41	370
High Alkali	0.66	2.92	58.65	14.79	7.10	9.98	384
High Alkali - II	0.68	3.11	---	---	6.90	---	---
Lone Star	0.84	3.11	52.14	20.64	9.76	7.52	---

* Blaine Fineness is given in m^2/kg of cement.
Equivalent alkali in cement = $Na_2O + 0.658 \times K_2O$ in percentage by mass of cement.

Table 2.3 Chemical Composition of Fly Ash

Mineral Admixture	**SiO_2**	**Al_2O_3**	**Fe_2O_3**	**Sum of Oxides**	**CaO**	**MgO**	**Na_2O**	**K_2O**	**Eq. Alkali**	**SO_3**
Class C Fly Ash – A	38.53	17.63	5.55	61.71	24.15	4.96	1.23	0.52	1.57	1.86
Class C Fly Ash – B	30.84	16.21	6.09	53.14	27.70	4.85	1.38	0.30	1.58	2.13
Class F Fly Ash	54.24	14.20	6.55	74.99	13.67	3.55	1.66	2.05	3.01	0.74
Class F Fly Ash – II*	49.67	14.00	6.97	70.67	15.87	3.37	1.93	2.05	3.27	0.92

***** Second batch of Class F fly ash ordered.

Table 2.4 Chemical Composition of Silica Fume and Ground Slag

Mineral Admixture	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	Eq. Alkali	SO_3
Ground Slag	33.52	8.69	0.70	42.07	10.66	0.18	0.34	0.40	1.57
Ground Slag – II*	33.33	9.50	0.47	41.60	9.70	0.16	0.31	0.36	3.20
Silica Fume	93.20	0.26	0.23	0.62	0.18	0.08	0.64	0.50	0.24

***** Second batch of ground slag ordered.

2.4 THE ASTM C 1293 TESTS

Based on a 3-year study, Touma et al.[9] identified a testing environment to effectively accelerate the ASTM C1293 tests. As a result, two test methods (A and B) are allowable in the ASTM C 1293 specification. Method A uses a 60^{o}C (140^{O}F) with 100 percent relative humidity storage environment and a testing duration of three months, while Method B uses a 38^{o}C (100^{O}F) with 100 percent relative humidity storage environment and a testing duration of 52 weeks. However, if SCM are used in Method B, a testing period up to two years may be necessary for slowly reactive aggregates.

The length changes of 76mm×76mm×286mm (3”×3”×11.25”) concrete prisms cast with specified SCM were monitored. Four concrete prisms were cast for each mix design and stored in a 22-liter (5 gal) polyethylene pail with airtight lid, as shown in Figs. 2.2(a) and (b). The cement with 0.66% equivalent alkali (Na_2O_e) was used in making the prisms with a water-to-cementitious material ratio of 0.42 to 0.45. Sodium oxide was added in the mixing water to bring the total equivalent alkali content of the concrete to 1.25%.

Figure 2.2 (a) Four concrete prisms from the same mix in a container


APR 15 2003

Figure 2.2 (b) A plywood disk underneath the specimens

The ASTM C 1293 recommends a storage environment with temperature and humidity closely controlled. It is not practical to put all the storage containers in a big curing room, which is commonly shared by many projects. As a result, it is difficult to maintain a constant temperature and humidity environment throughout the long testing period. Instead, a heater and a fan were suspended from the lid of each container, as shown in Figs. 2.3(a) and (b). The fan kept the air circulated to maintain uniform temperature and humidity. In addition, a thermocouple was placed inside each container to monitor the temperature. As shown in Figs. 2.4(a) and (b), the storage containers were stacked on wood shelves and the heaters were controlled by a thermostat. The reference temperature reading was provided by a thermocouple installed inside the reference container. Consistent daily temperature and humidity readings (shown in Figs. 2.5(a) and (b)) proved that this alternative way for storage environment control has worked very well.

Figure 2.3 (a) A thermostat-controlled heater

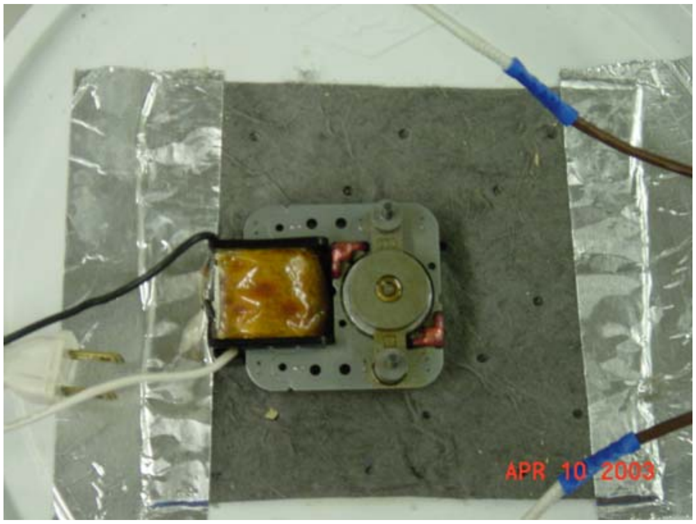

Figure 2.3 (b) A fan motor on the lid of container

Measurements of prism lengths were taken with a digital comparator at 7, 28, and 56 days, and 3, 6, 9, and 12 months. According to the ASTM C 1293, potentially deleterious ASR is indicated if the one-year expansion is greater than or equal to 0.04 percent. The duration of the accelerated test was three months with measurements taken at 7, 14 and 28 days, as well as 2 and 3 months.

(a) Storage containers layout

(b) Thermostat with power control

Figure 2.4 Alternative storage environment with temperature and humidity control

(a) Thermocouple reader

(b) Relative humidity meter

Figure 2.5 Taking temperature and relative humidity readings

In the first part of the test program, the aggregate gradation and cement quantity (i.e., 335 kg/m^3 or 564 lbs/yd^3 of concrete) followed the NDOR standard 47B concrete specifications. Some concrete mixes were subjected to both Methods A and B for comparison.

In the second part of the test program, the aggregate gradation and cement quantity (i.e., 420 kg/m^3 or 708 lbs/yd^3 of concrete) specified by the ASTM C 1293 were strictly followed along with using cement having 0.84% equivalent alkali content (see Table 2.2).

2.5 DURABILITY TESTS

A list of the acronyms for mix design identification is given in the Appendix IV. Only the C ash from source A with higher alkalinity and the fine aggregates from Platte River Central and Republican River sources were used for the durability test specimens. Concrete mixes for these tests were produced according to the NDOR standard 47B concrete specifications, with a maximum water-to-cementitious materials ratio **w/cm** = 0.48. Air entraining admixtures were added in accordance with the NDOR standard specifications to attain air content in the range of 5 to 7.5 percent. The durability test data collected included aggregate gradation, slump, workability, air content, compressive strength, flexural strength, freeze/thaw resistance, chloride ion penetrability, split tensile strength and the weight, modulus and length changes from wet/dry tests.

The compressive and flexural strength tests were conducted at 3, 7, 14, 28 and 56 days. Two cylinders for compressive strength and two beams for flexural strength were tested at each day specified. Split tensile strength tests were conducted at 28 and 56 days. Two cylinders were tested at each day specified.

The freeze/thaw tests were conducted in accordance with the ASTM C 666 – procedure A, but with only three beams for each mix design. The size of the beams was 3”×4”×16”

(76mm×102mm×406mm). The tests started after the specimens had been cured for 14 days and lasted about twelve weeks for 300 freeze-thaw cycles. A sonometer was used to measure the fundamental transverse frequencies of the specimens at the end of each week or after about 27 freeze-thaw cycles. Three 3”×4”×16” specimens from each mix design were fabricated for the Nebraska wet dry tests. The specimens had been moisture cured for 28 days before they were shipped to NDOR for the tests. The procedures of the wet and dry test are given in Appendix V.

CHAPTER 3

ASTM C1260 and C1293 TEST RESULTS

3.1 ASTM C1260 TESTS

Fine aggregates obtained from 10 pit locations in Cass, Colfax, Dawson, Franklin, Hall, Keith, Lincoln, Platte, Red Willow and Scottsbluff Counties were subjected to the ASTM C1260 tests. The 14-day expansions of these fine aggregates ranged from 0.08 to 0.28%. The limestone used for coarse aggregate in the study was also subjected to the test, and the 14-day expansion was 0.02%. These tests were conducted by the Materials & Research Division of NDOR.

The top 4 sources that had higher 14-day expansions (see Fig. 2.1) were subject to further ASR potential and durability evaluations.

3.2 AGGREGATE GRADATIONS

Limestone is specified in the NDOR 47B-3500 to be used for coarse aggregate in the concrete. It is non-reactive according to the ASTM C1260 test data. The weight ratio of coarse aggregate to the total aggregate is 30 ± 3%. For each batch of concrete mix, coarse aggregate was sieved and aggregate of size greater than ¾-in. was removed. The sieved limestone was then placed on a tarp and homogenized with a shovel before placed in 5-gal buckets with lids. Fine aggregates were first dumped from 55-gal drums (about one-fourth of the quantity, depending on the batch size) and spread out on the tarp to reach SSD condition. The fine aggregate was then homogenized with a shovel before placed in 5-gal buckets with lids. The moisture contents of both coarse and fine aggregates were determined from the oven-dry weight of the aggregates prior to mixing, regardless of being stored in sealed buckets. Typical gradation curves obtained from sieve analyses of the limestone and the four sources of sand and gravel are presented in Fig. 3.1.

The ASTM C 1293 requires that the volume ratio of coarse aggregate to concrete to be 0.7 ± 0.3%. One third of the coarse aggregate should have diameter between 3/4 and 1/2 in., one third between 1/2 and 3/8 in., and one third between 3/8 in. and No.4 sieves. Since Nebraska 47B sand and gravel (not C33 sand) were used in the tests, these fine aggregates were sieved andused to replace part of the limestone to meet the grading requirements. The grading calculations for the mix designs are presented in Table 3.1, and the mix proportions are presented in Table 3.2.

3.3 SLUMP, WORKABILITY AND AIR CONTENT

Workability is controlled more by the unit water content than by the **w/cm**, consequently the **w/cm** ratio in some cases was adjusted to allow adequate workability. It was noted that adding fly ash or ground slag improved workability and that adding silica fume decreased workability. The slump, air content, aggregate moisture contents and workability of the ASTM C1293 test specimens are given in Table 3.3. Since air-entraining admixture was not added, the air content in the C1293 test specimens was typically about 2 to 4% due to the air trapped during batching.

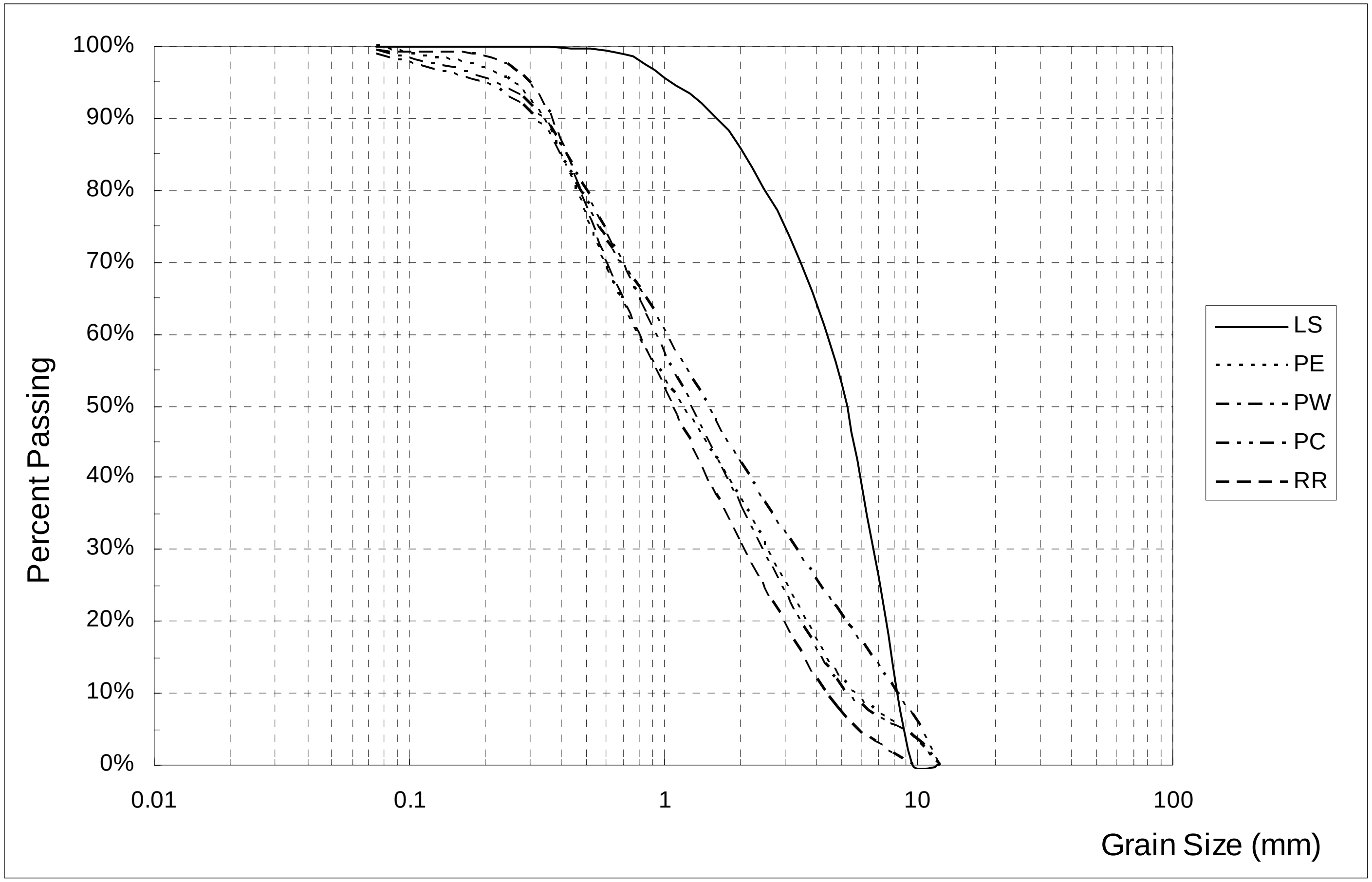

Figure 3.1 Gradation Curves for Limestone and PE, PW, PC, RR Fine Aggregates

Table 3.1 Grading of Aggregates used in ASTM C1293 Tests

	Sand & Gravel (lbs)					Limestone (lbs)			
	Total	3/4">ϕ>1/2"	1/2">ϕ>3/8"	3/8">ϕ>No.4	No.4 >ϕ	Total	3/4">ϕ>1/2"	1/2">ϕ>3/8"	3/8">ϕ>No.4
PE	1016.08	0.00	20.32	111.77	883.99	2102.16	700.65	680.33	588.88
	988.03	0.00	19.76	108.68	859.58	2044.12	681.30	661.54	572.62
	978.56	0.00	19.57	107.64	851.35	2024.53	674.78	655.21	567.13
	994.25	0.00	19.88	109.37	864.99	2056.98	685.59	665.71	576.23
	1006.68	0.00	20.13	110.73	875.81	2082.70	694.16	674.03	583.43
	1009.45	0.00	20.19	111.04	878.22	2088.43	696.07	675.89	585.04
PW	1005.92	10.16	20.32	91.45	883.99	2102.16	690.49	680.33	609.20
	997.07	10.07	20.14	90.64	876.21	2083.67	684.41	674.34	603.84
	987.70	9.98	19.95	89.79	867.98	2064.08	677.98	668.00	598.17
	984.30	9.94	19.88	89.48	864.99	2056.98	675.65	665.71	596.11
	996.61	10.07	20.13	90.60	875.81	2082.70	684.10	674.03	603.56
	999.35	10.09	20.19	90.85	878.22	2088.43	685.98	675.89	605.22
PC	1075.70	21.30	31.95	138.46	883.99	2102.16	679.35	668.70	562.19
	1066.24	21.11	31.67	137.24	876.21	2083.67	673.37	662.82	557.25
	1056.21	20.92	31.37	135.95	867.98	2064.08	667.04	656.59	552.01
	1052.58	20.84	31.26	135.48	864.99	2056.98	664.75	654.33	550.11
	1065.74	21.10	31.66	137.17	875.81	2082.70	673.06	662.51	556.99
	1068.68	21.16	31.74	137.55	878.22	2088.43	674.91	664.33	558.52
RR	964.54	0.00	9.65	67.52	887.38	2102.16	700.65	691.01	633.13
	952.41	0.00	9.52	66.67	876.21	2083.67	694.49	684.96	627.82
	943.45	0.00	9.43	66.04	867.98	2064.08	687.96	678.52	621.92
	940.21	0.00	9.40	65.81	864.99	2056.98	685.59	676.19	619.78
	951.96	0.00	9.52	66.64	875.81	2082.70	694.16	684.64	627.53
	954.59	0.00	9.55	66.82	878.22	2088.43	696.07	686.53	629.25

Table 3.2 Mix Proportions for the ASTM C1293 Tests

		Weight (lb/yd^3)							Volume (yd^3)								
		Cement	Ash	Water	Sand	Stone	Silica	Slag	Cement	Ash	Water	Air	Silica	Slag	Sand	Stone	Total
PE	I-BS	708.00	0.00	297.36	883.99	2102.16	0.00	0.00	0.133	0.000	0.176	2%	0.000	0.000	0.201	0.469	1.0
	I-17CA	587.64	120.36	318.60	859.58	2044.12	0.00	0.00	0.111	0.029	0.189	2%	0.000	0.000	0.195	0.456	1.0
	I-35CA	460.20	247.80	318.60	851.35	2024.53	0.00	0.00	0.087	0.059	0.189	2%	0.000	0.000	0.194	0.452	1.0
	I-25F	531.00	177.00	297.36	864.99	2056.98	0.00	0.00	0.100	0.048	0.176	2%	0.000	0.000	0.197	0.459	1.0
	IPF	708.00	0.00	297.36	875.81	2082.70	0.00	0.00	0.140	0.000	0.176	2%	0.000	0.000	0.199	0.465	1.0
	I-35BFS	460.20	0.00	297.36	878.22	2088.43	0.00	247.8	0.087	0.000	0.176	2%	0.000	0.051	0.200	0.466	1.0
PW	I-BS	708.00	0.00	297.36	883.99	2102.16	0.00	0.00	0.133	0.000	0.176	2%	0.000	0.000	0.201	0.469	1.0
	I-17CA	587.64	120.36	297.36	876.21	2083.67	0.00	0.00	0.111	0.029	0.176	2%	0.000	0.000	0.199	0.465	1.0
	I-35CA	460.20	247.80	297.36	867.98	2064.08	0.00	0.00	0.087	0.059	0.176	2%	0.000	0.000	0.197	0.461	1.0
	I-25F	531.00	177.00	297.36	864.99	2056.98	0.00	0.00	0.100	0.048	0.176	2%	0.000	0.000	0.197	0.459	1.0
	IPF	708.00	0.00	297.36	875.81	2082.70	0.00	0.00	0.140	0.000	0.176	2%	0.000	0.000	0.199	0.465	1.0
	I-35BFS	460.20	0.00	297.36	878.22	2088.43	0.00	247.8	0.087	0.000	0.176	2%	0.000	0.051	0.200	0.466	1.0
PC	I-BS	708.00	0.00	297.36	883.99	2102.16	0.00	0.00	0.133	0.000	0.176	2%	0.000	0.000	0.201	0.469	1.0
	I-17CA	587.64	120.36	297.36	876.21	2083.67	0.00	0.00	0.111	0.029	0.176	2%	0.000	0.000	0.199	0.465	1.0
	I-35CA	460.20	247.80	297.36	867.98	2064.08	0.00	0.00	0.087	0.059	0.176	2%	0.000	0.000	0.197	0.461	1.0
	I-25F	531.00	177.00	297.36	864.99	2056.98	0.00	0.00	0.100	0.048	0.176	2%	0.000	0.000	0.197	0.459	1.0
	IPF	708.00	0.00	297.36	875.81	2082.70	0.00	0.00	0.140	0.000	0.176	2%	0.000	0.000	0.199	0.465	1.0
	I-35BFS	460.20	0.00	297.36	878.22	2088.43	0.00	247.8	0.087	0.000	0.176	2%	0.000	0.051	0.200	0.466	1.0
RR	I-BS	708.00	0.00	297.36	887.38	2102.16	0.00	0.00	0.133	0.000	0.176	2%	0.000	0.000	0.201	0.469	1.0
	I-17CA	587.64	120.36	297.36	879.57	2083.67	0.00	0.00	0.111	0.029	0.176	2%	0.000	0.000	0.199	0.465	1.0
	I-35CA	460.20	247.80	297.36	871.30	2064.08	0.00	0.00	0.087	0.059	0.176	2%	0.000	0.000	0.197	0.461	1.0
	I-25F	531.00	177.00	297.36	868.31	2056.98	0.00	0.00	0.100	0.048	0.176	2%	0.000	0.000	0.197	0.459	1.0
	IPF	708.00	0.00	297.36	879.16	2082.70	0.00	0.00	0.140	0.000	0.176	2%	0.000	0.000	0.199	0.465	1.0
	I-35BFS	460.20	0.00	297.36	881.58	2088.43	0.00	247.8	0.087	0.000	0.176	2%	0.000	0.051	0.200	0.466	1.0

Table 3.3 Slump, Air Content and Moisture Content of the ASTM C1293 Test Specimens

					Moist Content (%)							Moist Content (%)	
	Mix Design	Slump (in.)	Air Content (%)	W/Cm	Fine Agg.	Coarse Agg.		Mix Design	Slump (in.)	Air Content (%)	W/Cm	Fine Agg.	Coarse Agg.
PE	I-BS	1.25	3.9	0.48	1.54	0.86	PW	I-BS	0.75	1.8	0.47	0.32	0.28
	I-25CA	2.75	3.0	0.48	1.54	0.86		I-25CA	1.00	2.1	0.47	0.32	0.28
	I-25CB	2.25	3.8	0.48	1.54	0.86		I-25CB	1.38	1.9	0.47	0.32	0.28
	I-35CA	2.00	1.9	0.48	1.54	0.86		I-35CA	1.00	2.2	0.45	1.44	0.34
	I-35CB	2.25	3.6	0.48	1.54	0.86		I-35CB	1.00	2.1	0.45	1.44	0.34
	I-20CA-3SF	1.25	2.3	0.48	1.54	0.86		I-20CA-3SF	0.50	2.3	0.47	0.39	0.33
	I-20CB-3SF	0.75	3.7	0.48	1.54	0.51		I-20CB-3SF	0.88	3.2	0.47	0.39	0.33
	I-17F	1.38	2.3	0.48	1.54	0.51		I-17F	1.13	3.4	0.47	0.39	0.33
	1PF	1.88	2.0	0.50	1.54	0.51		I-25F	1.25	3.4	0.47	0.39	0.24
	I-25F	4.50	3.1	0.48	0.11	0.12		1PF	1.38	2.8	0.47	0.39	0.24
	I-20BFS	2.00	2.6	0.48	0.11	0.12		I-20BFS	0.75	3.0	0.48	0.39	0.24

Table 3.3 Slump, Air Content and Moisture Content of the ASTM C1293 Test Specimens (Continued)

					Moist Content (%)							Moist Content (%)	
	Mix Design	Slump (in.)	Air Content (%)	W/Cm	Fine Agg.	Coarse Agg.		Mix Design	Slump (in.)	Air Content (%)	W/Cm	Fine Agg.	Coarse Agg.
PC	I-BS	1.13	2.6	0.47	1.72	1.54	RR	I-BS	0.68	3.0	0.47	1.39	2.57
	I-25CA	1.75	2.1	0.45	1.72	1.54		I-25CA	1.00	2.5	0.45	0.76	0.30
	I-25CB	2.00	1.9	0.45	1.72	1.54		I-25CB	1.25	2.4	0.45	0.76	0.30
	I-35CA	2.00	1.9	0.45	1.72	1.54		I-35CA	1.00	2.8	0.45	1.39	2.57
	I-35CB	2.07	2.0	0.45	1.72	1.54		I-35CB	1.13	2.7	0.45	0.76	0.30
	I-17F	1.25	2.5	0.45	1.12	0.56		I-17F	1.00	2.7	0.45	0.73	0.10
	I-25F	1.25	2.5	0.45	1.12	0.56		I-25F	1.38	2.1	0.45	1.76	0.57
	I-20BFS	1.25	2.3	0.45	1.12	0.56		I-20BFS	0.75	2.8	0.45	1.76	0.57
	1PF	1.00	2.6	0.45	1.12	0.56		1PF	1.00	2.5	0.45	1.76	0.57
	I-20CA-3SF	1.00	2.5	0.45	1.17	2.57		I-20CA-3SF	1.00	2.4	0.45	0.73	0.10
	I-20CB-3SF	1.13	2.3	0.45	1.17	2.57		I-20CB-3SF	1.00	2.5	0.45	0.73	0.10

3.4 ASTM C 1293 TEST DATA

During the first few weeks of accelerated ASTM C1293 testing, all the specimens consistently exhibited about 0.01 to 0.03% of length shrinkage regardless if they were moisture cured. The prisms showed recovery and started expanding usually between the 6th and 8th week. Concrete with silica fume, fly ash and/or slag commonly shrinks at early age. It was noted in another study that Spratt could reach 0.013% shrinkage with fly ash or slag, while shrinkage could reach 0.012% for Placitas with slag. To assess the effect of having a fan on the lid with possible moisture escape, the initial shrinkages of duplicate specimens of the same mix at 7 days are compared in Fig. 3.2. The initial weights of some specimens with different mix proportions are also compared against those at 7 days in Fig. 3.3. The shrinkage appeared to be related to hydration process and not to moisture loss.

3.4.1 Using 564 Pounds of Cementitious Materials per Cubic Yard of Concrete

The ASTM C1293 states that "The basic intent of this test method is to develop information on a particular aggregate at a specific alkali level of 8.85 lb/yd^3. This high alkali level is required to identify certain deleteriously reactive aggregates." It further states that "The value of 1.25% Na_2O equivalent by mass of cement has been chosen to accelerate the process of expansion rather than to reproduce field conditions." The equivalent alkali contents of the test specimens prepared according to Nebraska 47B specifications are presented in Table 3.4. All the specimens under the regular C1293 tests (Method B) did not show noticeable expansion after a period of 52 weeks. Due to the lower than required alkali content, these tests were discontinued after 52 weeks. However, most specimens under the accelerated C1293 (Method A) showed about 0.01 to 0.015% of expansion after a period of 12 weeks, as shown in Table 3.5.

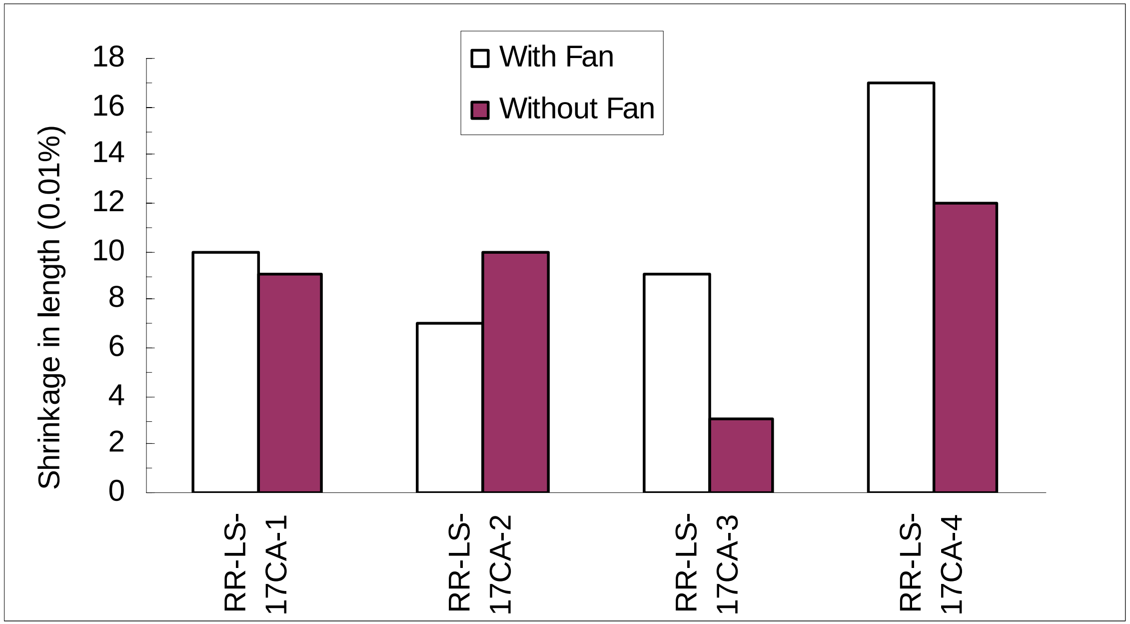

Figure 3.2 The Effect of Fan on the Initial Length Shrinkage in ASTM C1293 Tests

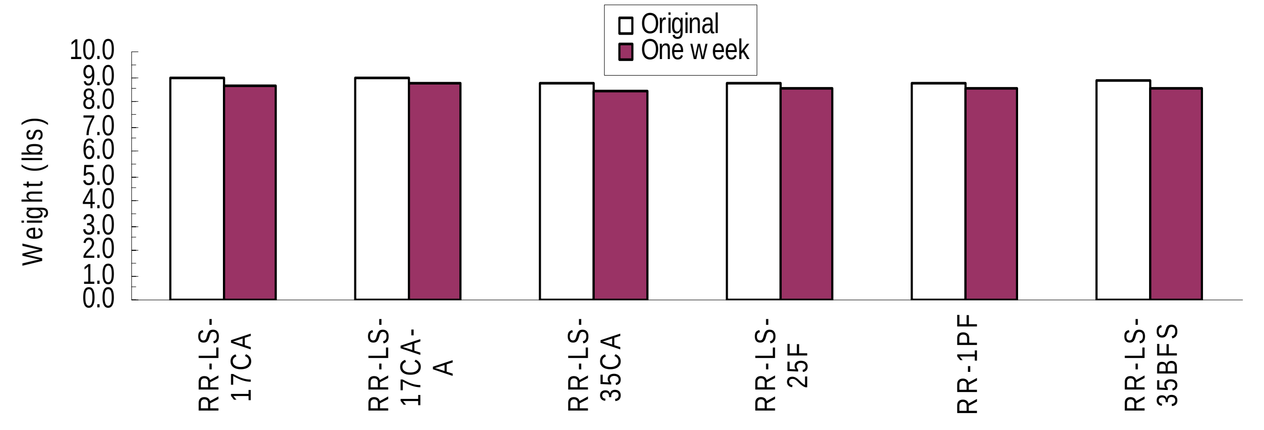

Figure 3.3 One-week Weight Changes of ASTM C1293 Specimens

Table 3.4 Total Alkali, Lime and Silica Contents of Cementitious Materials

(using 564 pounds of cementitious materials)

Unit: Pounds per cubic yard of concrete

Cementitious Materials	Total Alkali	Lime	Silica	[alkali + lime]/silica
	Na_2O_{eq}	CaO	SiO_2	
I-BS	7.05	355.94	116.30	3.12
I-25CA	7.50	301.01	141.55	2.18
I-25CB	7.52	306.01	130.71	2.40
I-35CA	7.68	279.03	151.65	1.89
I-35CB	7.70	286.04	136.47	2.15
I-20CA-3SF	7.71	301.42	148.78	2.08
I-20CB-3SF	7.72	305.42	140.11	2.24
I-17F	8.74	308.54	148.53	2.14
I-25F	9.53	286.23	163.70	1.81
I-20BFS	6.09	332.21	130.85	2.58

Table 3.5 Expansion Data under Accelerated ASTM C1293 Tests (using 564 pounds of cementitious materials)

Mix Designation	**Week**							
	0	1	2	4	6	8	10	12
PE-I-BS	0.0000%	-0.0013%	0.0005%	-0.0030%	0.0012%	0.0085%	0.0198%	0.0277%
PE-I-25CA	0.0000%	-0.0085%	-0.0058%	-0.0073%	-0.0038%	0.0000%	0.0098%	0.0188%
PE-I-35CA	0.0000%	-0.0070%	-0.0082%	-0.0045%	-0.0042%	-0.0035%	0.0080%	0.0147%
PE-I-20CA-3SF	0.0000%	-0.0050%	-0.0070%	-0.0025%	-0.0022%	-0.0005%	0.0078%	0.0160%
PE-I-17F	0.0000%	-0.0125%	-0.0072%	-0.0075%	-0.0072%	-0.0035%	-0.0032%	0.0038%
PE-I-25F	0.0000%	-0.0062%	-0.0065%	-0.0067%	-0.0078%	-0.0060%	-0.0012%	0.0080%
PE-I-20BFS	0.0000%	-0.0062%	-0.0060%	-0.0077%	-0.0100%	-0.0067%	0.0025%	0.0120%
PW-I-BS	0.0000%	-0.0043%	-0.0027%	-0.0023%	0.0005%	0.0107%	0.0175%	0.0228%
PW-I-25CB	0.0000%	-0.0098%	-0.0105%	-0.0098%	-0.0037%	0.0055%	0.0115%	0.0165%
PW-I-35CB	0.0000%	-0.0183%	-0.0155%	-0.0185%	-0.0150%	-0.0103%	-0.0055%	0.0005%
PW-I-20CB-3SF	0.0000%	-0.0110%	-0.0102%	-0.0135%	-0.0127%	-0.0072%	-0.0005%	0.0093%
PW-I-17F	0.0000%	-0.0175%	-0.0147%	-0.0212%	-0.0272%	-0.0205%	-0.0125%	-0.0032%
PW-I-25F	0.0000%	-0.0073%	-0.0073%	-0.0087%	-0.0092%	-0.0040%	0.0040%	0.0117%
PW-I-20BFS	0.0000%	-0.0030%	-0.0052%	-0.0093%	-0.0145%	-0.0128%	-0.0073%	0.0057%
RR-I-BS	0.0000%	-0.0042%	-0.0020%	-0.0060%	-0.0072%	-0.0017%	0.0045%	0.0120%
RR-25CA	0.0000%	-0.0143%	-0.0175%	-0.0195%	-0.0183%	-0.0065%	0.0015%	0.0065%
RR-1PF	0.0000%	-0.0103%	-0.0095%	-0.0098%	-0.0080%	-0.0130%	-0.0083%	-0.0110%
PE-I-BS-708*	0.0000%	-0.0090%	-0.0130%	-0.0170%	-0.0093%	0.0060%	0.0265%	0.0340%
PW-I-BS-708*	0.0000%	-0.0050%	-0.0043%	-0.0003%	0.0085%	0.0175%	0.0285%	0.0382%
RR-I-BS-708*	0.0000%	-0.0063%	-0.0030%	-0.0025%	0.0110%	0.0363%	0.0438%	0.0547%

* 708 pounds of cement (0.56% Na_2O_e) per cubic yard of concrete.

3.4.2 Using 708 Pounds of Cementitious Materials per Cubic Yard of Concrete

The test results from using 564 lb/yd^3 of cementitious materials did not show ASR expansions indicative of deleterious reactive aggregates. The procedures of ASTM C1293 (Method A) were strictly followed during further testing of the 4 sources of fine aggregates. The equivalent alkali content of the Type I cement used was 0.84%. The equivalent alkali contents of the test specimens are presented in Table 3.6. The expansion data of these tests are presented in Table 3.7. The average expansions of the baseline specimens made from all 4 sources of fine aggregates were more than 0.04% at 12 weeks. These results would lend support to the C 1260 data presented in Fig. 2.1, indicating that all 4 sources of the fine aggregates are potentially deleteriously reactive.

3.4.3 Additional Regular ASTM C1293 Parallel Tests

Additional regular ASTM C1293 (Method B) tests were conducted using the Platte River Central fine aggregate and the high alkali cement (0.66% Na_2O_e). Three mixes: the baseline (PC-HC-BS-R), mix with 25% C ash from source A, and mix with 25% F ash were tested. The tests were conducted in parallel by both University of Nebraska-Lincoln (UNL) and the University of New Brunswick (UNB) for comparisons. The procedures of the ASTM C1293 were strictly followed, using 708 pounds of cement at 1.25% Na_2O_e per cubic yard. The test data from UNB is presented in Fig. 3.4. The baseline mix showed a 0.059% expansion at the end of a two-year period. However, the tests conducted by UNL did not show any expansion at all at the end of one year, and were discontinued afterwards. The plots of the regular and accelerated C1293 test data conducted at UNL are given in Appendix VI.

Table 3.6 Total Alkali, Lime and Silica Contents of Cementitious Materials

(using 708 pounds of cementitious materials)

Unit: Pounds per cubic yard of concrete

Cementitious Materials	Total Alkali	Lime	Silica	[alkali + lime]/silica
	Na_2O_{eq}	CaO	SiO_2	
LS-BS	8.85	450.08	148.04	3.10
LS-17CA	9.24	402.63	169.25	2.43
LS-35CA	9.64	352.39	191.71	1.89
LS-25F	11.97	361.75	198.95	1.88
1PF	8.85	374.67	196.47	1.95
LS-35BFS	6.74	396.80	179.29	2.25

Table 3.7 Expansion Data under Accelerated ASTM C1293 Tests
(using 708 pounds of cementitious materials)

Mix Design	**Week**							
	0	1	2	4	6	8	10	12
PE-LS-17CA	0.0000%	-0.0255%	-0.0105%	0.0050%	0.0158%	0.0263%	0.0363%	0.0430%
PE-LS-35CA	0.0000%	-0.0238%	-0.0125%	0.0058%	0.0170%	0.0248%	0.0338%	0.0422%
PE-LS-25F	0.0000%	-0.0232%	-0.0137%	0.0110%	0.0170%	0.0305%	0.0405%	0.0483%
PE-IPF	0.0000%	-0.0235%	-0.0128%	0.0122%	0.0218%	0.0318%	0.0418%	0.0490%
PE-LS-35BFS	0.0000%	-0.0210%	-0.0097%	0.0103%	0.0178%	0.0308%	0.0370%	0.0453%
PE-LS	0.0000%	-0.0257%	-0.0130%	0.0060%	0.0153%	0.0268%	0.0320%	0.0400%
PW-LS-17CA	0.0000%	-0.0130%	0.0010%	0.0150%	0.0260%	0.0377%	0.0422%	0.0447%
PW-LS-35CA	0.0000%	-0.0163%	0.0027%	0.0120%	0.0227%	0.0335%	0.0395%	0.0432%
PW-LS-25F	0.0000%	-0.0135%	0.0008%	0.0103%	0.0230%	0.0273%	0.0332%	0.0373%
PW-IPF	0.0000%	-0.0143%	0.0002%	0.0135%	0.0230%	0.0302%	0.0345%	0.0380%
PW-LS-35BFS	0.0000%	-0.0145%	0.0012%	0.0145%	0.0248%	0.0340%	0.0380%	0.0408%
PW-LS	0.0000%	-0.0143%	0.0027%	0.0125%	0.0225%	0.0355%	0.0420%	0.0465%
PC-LS-17CA	0.0000%	-0.0310%	-0.0052%	0.0045%	0.0205%	0.0273%	0.0338%	0.0405%
PC-LS-35CA	0.0000%	-0.0242%	-0.0042%	0.0075%	0.0193%	0.0263%	0.0315%	0.0370%
PC-LS-25F	0.0000%	-0.0225%	-0.0032%	0.0045%	0.0172%	0.0223%	0.0260%	0.0310%
PC-IPF	0.0000%	-0.0285%	-0.0047%	0.0048%	0.0180%	0.0232%	0.0265%	0.0313%
PC-LS-35BFS	0.0000%	-0.0283%	-0.0065%	0.0055%	0.0197%	0.0240%	0.0293%	0.0338%
PC-LS	0.0000%	-0.0215%	-0.0022%	0.0070%	0.0227%	0.0285%	0.0357%	0.0422%
RR-LS-17CA	0.0000%	-0.0187%	-0.0062%	0.0063%	0.0180%	0.0260%	0.0340%	0.0418%
RR-LS-35CA	0.0000%	-0.0215%	-0.0090%	0.0042%	0.0175%	0.0255%	0.0327%	0.0390%
RR-LS-25F	0.0000%	-0.0202%	-0.0075%	0.0073%	0.0148%	0.0225%	0.0270%	0.0310%
RR-IPF	0.0000%	-0.0190%	-0.0087%	0.0073%	0.0125%	0.0223%	0.0272%	0.0322%
RR-LS-35BFS	0.0000%	-0.0205%	-0.0033%	0.0063%	0.0143%	0.0240%	0.0305%	0.0355%
RR-LS	0.0000%	-0.0197%	-0.0055%	0.0093%	0.0198%	0.0278%	0.0365%	0.0435%

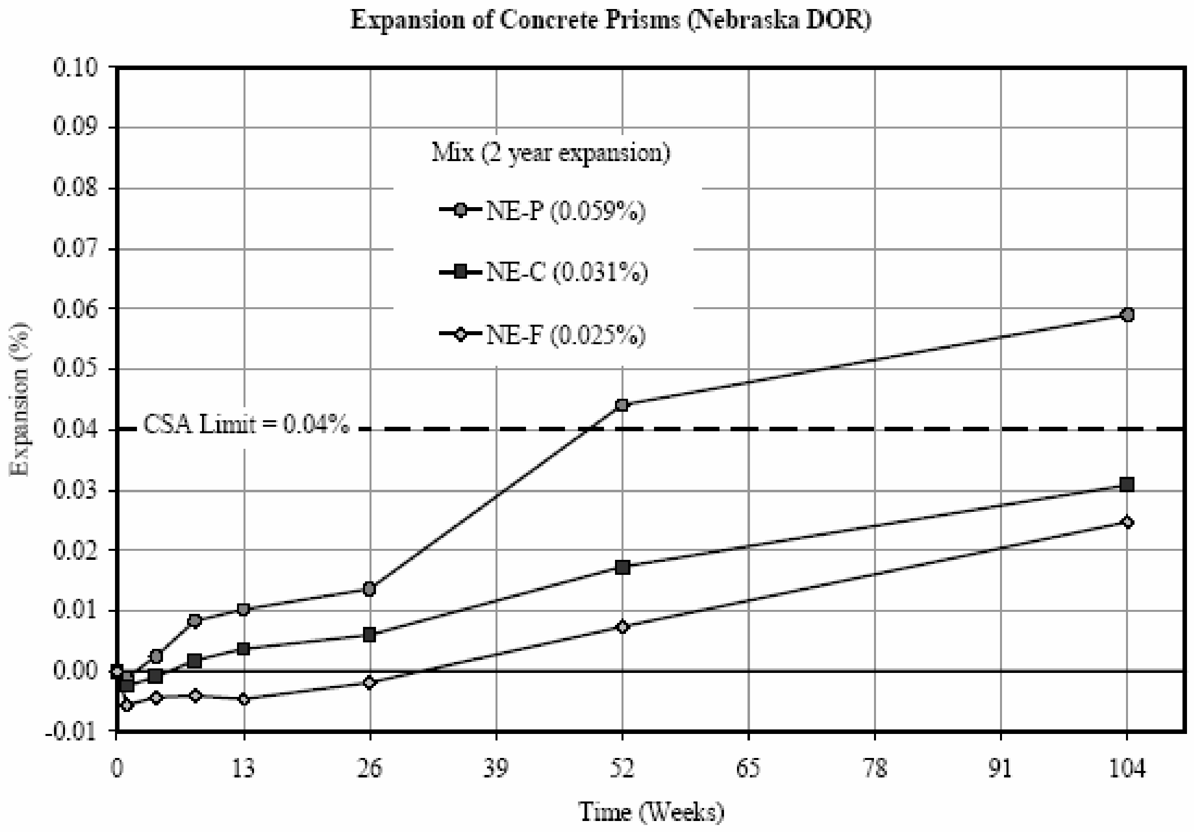

Figure 3.4 Regular ASTM C1293 Test Results

(Conducted by the University of New Brunswick)

CHAPTER 4

DURABILITY TEST RESULTS

4.1 SLUMP, WORKABILITY AND AIR CONTENT

The aggregate gradation and the mix designs for durability tests followed the NDOR standard 47B concrete specifications, with a maximum water-to-cementitious materials ratio **w/cm** = 0.48. Air entraining admixtures were added in accordance with the NDOR standard specifications to attain air content in the range of 5 to 7.5 percent. The test data collected included aggregate gradation, slump, workability, air content, compressive strength, flexural strength, freeze/thaw resistance, chloride ion penetrability, split tensile strength and the weight, modulus and length changes from wet/dry tests. The slump, air content, aggregate moisture contents and workability of the durability test specimens are given in Table 4.1.

4.2 MECHANICAL STRENGTHS

The compressive strengths, flexural strengths and split tensile strengths of the various mix proportions are presented in Tables 4.2, 4.3 and 4.4, respectively.

4.3 CHLORIDE ION PENETRATION TESTS

The chloride ion penetration tests were conducted by the Portland Cement Concrete Testing Laboratory of NDOR per ASTM C1202. The total amounts of electric current passing through 2-in. thick slices of 4-in. diameter cylinders under 60-V potential difference during a 6-hour period were recorded. The specimen samples were tested at the age of about 60 days. The resistance of the specimens to chloride ion penetration is directly related to the total electric charges passed, in coulombs, which are presented in Table 4.5. Most specimens had chloride ion penetrability in the low to moderate range.

Table 4.1 Slump, Air Content and Moisture Content of Durability Test Specimens

				Moist Content (%)				
	Mix Design	Slump (in.)	W/Cm	Fine Aggrg.	Coarse Aggrg.	Air Entrainment (oz/yd^3)	Air Content (%)	Workability
PC	HC-17F	5.00	0.48	0.23	0.09	3.0	3.0	Good
	HC-BS	5.75	0.48	0.18	0.18	5.0	6.0	Good
	HC-35CA	6.75	0.48	0.61	0.58	5.0	3.3	Good
	HC-25F	7.00	0.48	0.24	0.20	5.5	9.0	Good
	HC-20BFS	3.00	0.48	0.23	0.09	3.5	3.0	Good
	HC-20CA-3SF	5.00	0.48	0.29	0.18	4.5	4.2	Good
	HC-25CA	6.50	0.48	0.29	0.18	5.4	4.8	Good
	I-BS	4.50	0.48	0.61	0.30	5.0	8.0	Good
	I-25CA	5.00	0.45	0.28	0.18	4.0	8.0	Good
	I-35CA	4.00	0.47	0.44	0.10	3.5	2.1	Good
	20BFS	3.00	0.48	0.23	0.09	3.5	3.0	Good
	20CA-3SF	5.00	0.48	0.29	0.18	4.5	4.2	Good
	25CA	6.50	0.48	0.29	0.18	5.4	4.8	Good
	IPF	4.25	0.46	1.81	0.15	4.0	3.3	Good
	3AL	4.25	0.46	1.36	0.09	4.0	6.5	Good
RR	I-20BFS	3.50	0.48	0.20	0.09	5.0	6.5	Good
	3AL	3.25	0.48	0.20	0.09	5.0	6.5	Good
	I-20CA-3SF	4.00	0.48	0.90	0.63	6.0	6.0	Good
	I-25CA	5.50	0.48	0.90	0.63	6.0	6.0	Good
	I-35CA	6.50	0.48	0.90	0.63	6.0	5.1	Good
	I-17F	5.50	0.48	0.69	0.28	6.0	7.8	Good
	I-25F	7.00	0.48	0.69	0.28	6.0	8.5	Good
	I-BS	5.00	0.48	0.38	0.11	3.5	6.0	Good
	IPF	3.75	0.49	0.56	0.11	3.5	3.2	Good

Table 4.2 Compressive Strength Data

Mix Designation		Compressive Strength (psi)				
		3 days	7 days	14 days	28 days	56 days
PC-HC-BS	Sample 1	3640	3980	4290	5080	5360
	Sample 2	3400	3760	4210	4410	5330
	Average	3520	3870	4250	4745	5345
PC-HC-35CA	Sample 1	3440	3990	4290	3840	4770
	Sample 2	3390	3890	3960	4880	5270
	Average	3415	3940	4125	4360	5020
PC-HC-25F	Sample 1	2190	2250	2300	2890	3810
	Sample 2	2350	2510	2270	3030	3100
	Average	2270	2380	2285	2960	3455
PC-I-BS	Sample 1	2770	2960	3260	3810	4270
	Sample 2	2500	2770	3290	3880	4220
	Average	2635	2865	3275	3845	4245
PC-I-25CA	Sample 1	2460	2260	2890	3730	4420
	Sample 2	2520	2350	3250	3250	3750
	Average	2490	2305	3070	3490	4085
RR-I-BS	Sample 1	2770	2990	4420	4290	4070
	Sample 2	2720	3360	4530	3860	4650
	Average	2745	3175	4475	4075	4360
RR-1PF	Sample 1	3200	3710	4150	4620	5020
	Sample 2	2860	3540	4020	5060	5810
	Average	3030	3625	4085	4840	5415
PC-I-35CA	Sample 1	3670	4300	4740	5590	5850
	Sample 2	3600	4190	4010	5440	5630
	Average	3635	4245	4375	5515	5740

PC-I-20CA-3SF	Sample 1	3840	4530	4840	5940	6150
	Sample 2	3480	4740	5120	6330	6880
	Average	3660	4635	4980	6135	6515
PC-I -25F	Sample 1	1710	2070	2950	3110	3580
	Sample 2	1930	2180	2770	2650	3310
	Average	1820	2125	2860	2880	3445
PC-I -17F	Sample 1	2840	3210	3340	3570	4620
	Sample 2	2740	3280	3220	3500	4240
	Average	2790	3245	3280	3535	4430
PC-I-20BFS	Sample 1	3120	4200	4340	4460	5630
	Sample 2	2820	4100	4200	4450	5630
	Average	2970	4150	4270	4455	5630
PC-1PF	Sample 1	3210	4160	4340	5270	5750
	Sample 2	3950	3980	4840	4620	5470
	Average	3580	4070	4590	4945	5610
PC-3AL	Sample 1	2750	3280	3940	3730	4780
	Sample 2	2810	3310	3240	4670	4600
	Average	2780	3295	3590	4200	4690

The nominal 28-day compressive strength f_c' = 3500 psi according to NDOR 47B-3500.

The mix designations are explained in the Appendix IV.

Table 4.3 Flexural Strength Data

Mix Designation		Flexural Strength (psi)				
		3 days	7 days	14 days	28 days	56 days
PC-HC-BS	Sample 1	410	560	640	690	690
	Sample 2	520	660	620	640	660
	Average	465	610	630	665	675
PC-HC-35CA	Sample 1	460	450	630	660	650
	Sample 2	520	470	580	660	680
	Average	490	460	605	660	665
PC-HC-25F	Sample 1	350	310	420	470	500
	Sample 2	370	400	400	460	600
	Average	360	355	410	465	550
PC-I-BS	Sample 1	420	490	620	650	640
	Sample 2	400	430	540	550	650
	Average	410	460	580	600	645
PC-I-25CA	Sample 1	330	370	400	420	660
	Sample 2	380	450	490	480	570
	Average	355	410	445	450	615
RR-I-BS	Sample 1	430	520	530	530	580
	Sample 2	490	560	570	530	600
	Average	460	540	550	530	590
RR-1PF	Sample 1	520	530	640	600	690
	Sample 2	530	560	620	650	710
	Average	525	545	630	625	700
PC-I-35CA	Sample 1	450	530	670	800	810
	Sample 2	460	570	750	690	740
	Average	455	550	710	745	775

PC-I-20CA-3SF	Sample 1	460	630	810	860	880
	Sample 2	450	600	720	780	840
	Average	455	615	765	820	860
PC-I -25F	Sample 1	410	400	430	580	600
	Sample 2	410	440	410	510	560
	Average	410	420	420	545	580
PC-I -17F	Sample 1	500	590	610	690	770
	Sample 2	450	590	580	730	730
	Average	475	590	595	710	750
PC-I-20BFS	Sample 1	430	560	650	700	790
	Sample 2	540	600	630	710	760
	Average	485	580	640	705	775
PC-1PF	Sample 1	570	730	690	740	840
	Sample 2	510	720	710	760	700
	Average	540	725	700	750	770
PC-3AL	Sample 1	550	610	680	750	740
	Sample 2	620	590	720	670	750
	Average	585	600	700	710	745

The nominal flexural strength is calculated to be $7.5\sqrt{f_c^{'}} = 443$ psi

Table 4.4 Split Tensile Strength Data

Mix Designation		Split Tensile Strength (psi)		Mix Designation		Split Tensile Strength (psi)	
		28 days	56 days			28 days	56 days
PC-HC-BS	Sample 1	380	460	**PC-I-35CA**	Sample 1	470	560
	Sample 2	330	470		Sample 2	470	580
	Average	355	465		Average	470	570
PC-HC-35CA	Sample 1	470	520	**PC-I-20CA-3SF**	Sample 1	510	580
	Sample 2	420	510		Sample 2	590	670
	Average	445	515		Average	550	625
PC-HC-25F	Sample 1	290	380	**PC-I -25F**	Sample 1	420	430
	Sample 2	340	340		Sample 2	390	410
	Average	315	360		Average	405	420
PC-I-BS	Sample 1	400	470	**PC-I -17F**	Sample 1	430	480
	Sample 2	360	390		Sample 2	560	560
	Average	380	430		Average	495	520
PC-I-25CA	Sample 1	420	420	**PC-I-20BFS**	Sample 1	480	550
	Sample 2	380	440		Sample 2	390	500
	Average	400	430		Average	435	525
RR-I-BS	Sample 1	380	430	**PC-1PF**	Sample 1	540	470
	Sample 2	390	440		Sample 2	440	570
	Average	385	435		Average	490	520
RR-1PF	Sample 1	510	530	**PC-3AL**	Sample 1	500	480
	Sample 2	460	540		Sample 2	450	500
	Average	485	535		Average	475	490

Table 4.5 Chloride Ion Penetration Test Data

Mix Designation		Total Charge (Coulombs)	Mix Designation		Total Charge (Coulombs)
RR-I-BS	Sample 1	3148	**PC-HC-BS**	Sample 1	3484
	Sample 2	2423		Sample 2	2890
	Sample 3	2909		Sample 3	4012
	Average	2827		Average	3462
RR-1PF	Sample 1	984	**PC-HC-20CA-3SF**	Sample 1	994
	Sample 2	1064		Sample 2	---
	Sample3	953		Sample 3	949
	Average	1000		Average	972
RR-I-25CA	Sample 1	3108	**PC-HC-25CA**	Sample 1	1256
	Sample 2	2543		Sample 2	1464
	Sample 3	3291		Sample 3	1343
	Average	2981		Average	1354
RR-I-35CA	Sample 1	1523	**PC-HC-35CA**	Sample 1	1567
	Sample 2	1528		Sample 2	1687
	Sample 3	1652		Sample 3	1420
	Average	1568		Average	1558
RR-I-17F	Sample 1	---	**PC-HC-25F**	Sample 1	1402
	Sample 2	2638		Sample 2	1410
	Sample 3	3456		Sample 3	1125
	Average	3044		Average	1312
RR-I-25F	Sample 1	1569	**PC-I-25CA**	Sample 1	3358
	Sample 2	1378		Sample 2	2530
	Sample 3	1253		Sample 3	2700
	Average	1400		Average	2863
RR-I-20CA-3SF	Sample 1	1345	**PC-I-35CA**	Sample 1	976
	Sample 2	1445		Sample 2	1006
	Sample 3	1407		Sample 3	1055
	Average	1399		Average	1012

Mix Designation		Total Charge (Coulombs)	Mix Designation		Total Charge (Coulombs)
RR-I-20BFS	Sample 1	1344	**PC-I-20CA-3SF**	Sample 1	1090
	Sample 2	1352		Sample 2	1105
	Sample 3	1254		Sample 3	944
	Average	1317		Average	1046
RR-3AL	Sample 1	2262	**PC-I-17F**	Sample 1	1898
	Sample 2	2465		Sample 2	1901
	Sample3	2645		Sample 3	2017
	Average	2457		Average	1939
PC-1PF	Sample 1	873	**PC-I-25F**	Sample 1	1356
	Sample 2	784		Sample 2	1362
	Sample 3	736		Sample 3	1287
	Average	798		Average	1335
PC-3AL	Sample 1	2054	**PC-I-20BFS**	Sample 1	2200
	Sample 2	2030		Sample 2	2667
	Sample 3	2136		Sample 3	2054
	Average	2073		Average	2307

4.4 FREEZE-THAW RESISTANCE

The procedures specified in ASTM C666 were followed to evaluate the resistance of concrete to rapid freezing and thawing. Each test usually lasted about 12 weeks (i.e., about 25 freeze-thaw cycles/week). The dynamic modulus of elasticity of a test specimen is known to be proportional to the square of its fundamental transverse frequency, which is measured with a sonometer. The decays of the relative dynamic modulus of elasticity with time of some specimens are presented in Fig. 4.1. In addition, the weight losses or gains of the test specimens with time are presented in Fig. 4.2.

Some specimens showed low freeze-thaw resistance. The appearances of the PC-HC-35CA and the PC-HC-BS specimens after 120 cycles are compared in Fig. 4.3. Fig. 4.4 shows that one PC-HC-35CA specimen completely disintegrated before the 300 freeze-thaw cycles were attained.

4.5 WET AND DRY TESTS

The wet and dry tests were conducted by NDOR during the period from March 2004 to August 2005. These tests were intended to provide data for comparisons with the freeze-thaw tests conducted at UNL. Three specimens from each mix design, except PC-HC-17F and PC-HC-20BFS only with two specimens, were tested. The weight loss, relative modulus and length changes of the specimens with respect to the wet and dry cycles are presented in Figs. 4.5, 4.6 and 4.7, respectively. These data represent the average of the three (or two) specimens from each mix.

Among the mix designs, PC-HC-25CA, PC-HC-35CA, RR-I-17F, RR-I-20CA-3SF, RR-I-25CA, and RR-I-35CA showed about 15 to 25% decrease in modulus along with significant length increases after 420 wet and dry cycles.

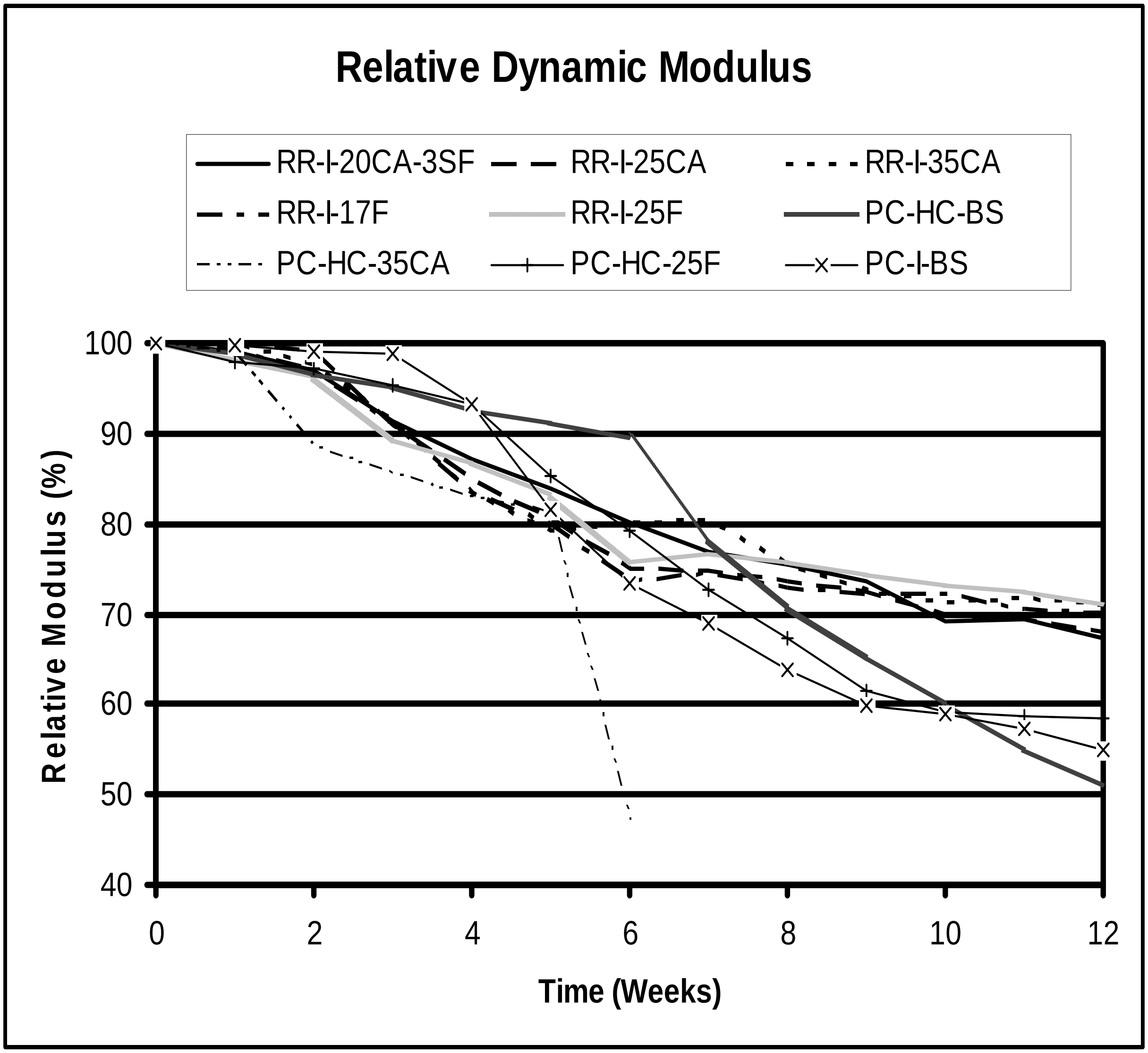

Figure 4.1 Relative Dynamic Modulus due to Freeze-Thaw Cycles

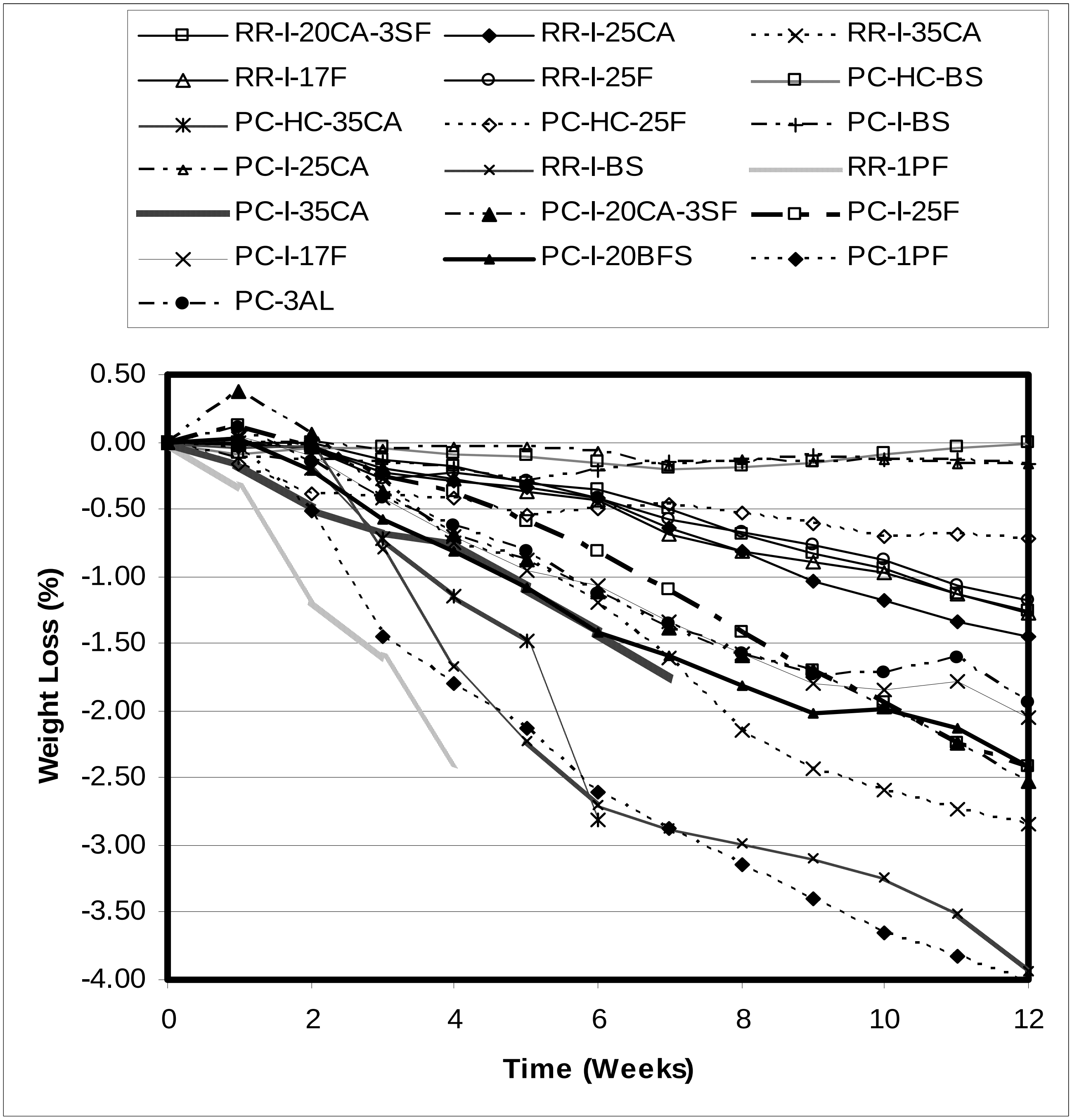

Figure 4.2 Weight Loss of Freeze-Thaw Test Specimens

Figure 4.3 Comparison between PC-HC-35CA and PC-HC-BS Specimens after 120 cycles

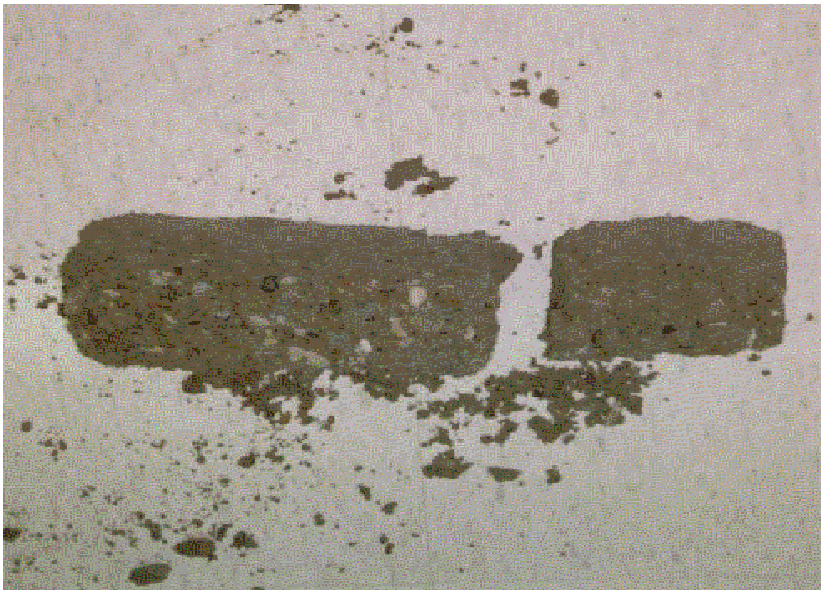

Figure 4.4 Failed PC-HC-35CA specimen after 150 cycles

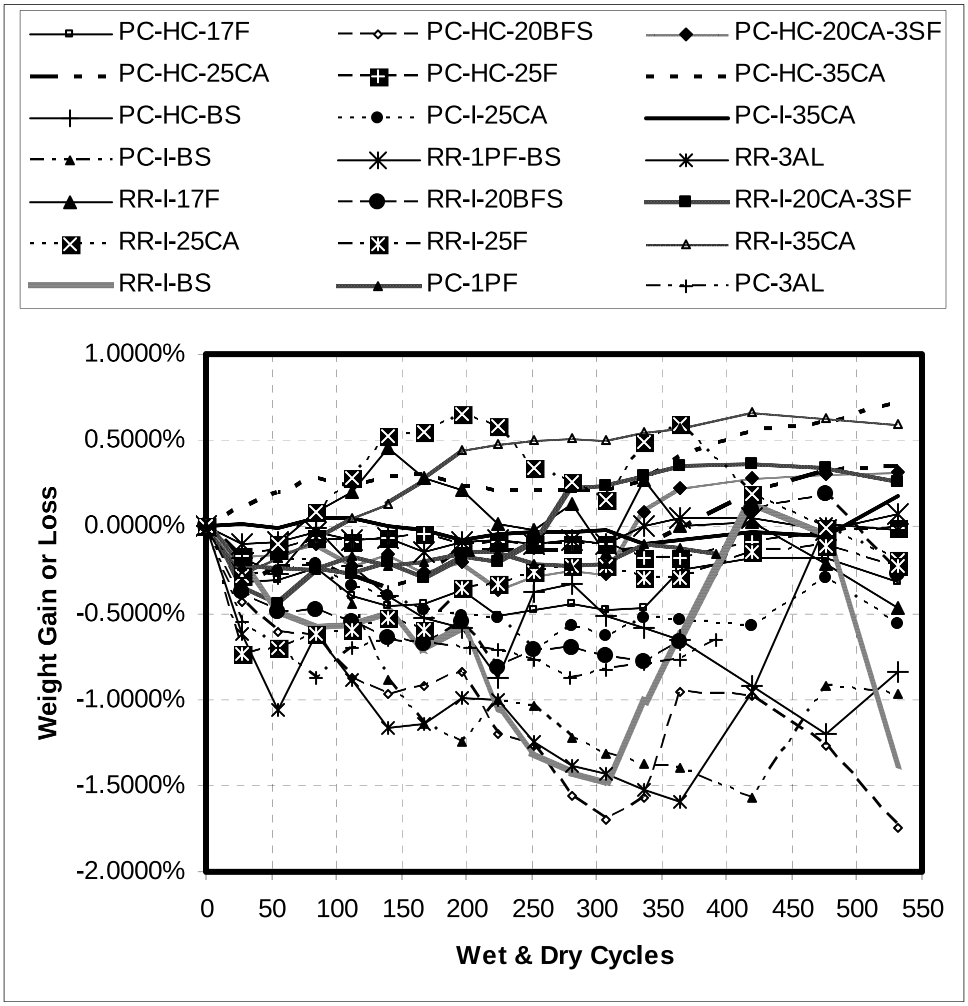

Figure 4.5 Weight Gains or Losses in Wet & Dry Tests

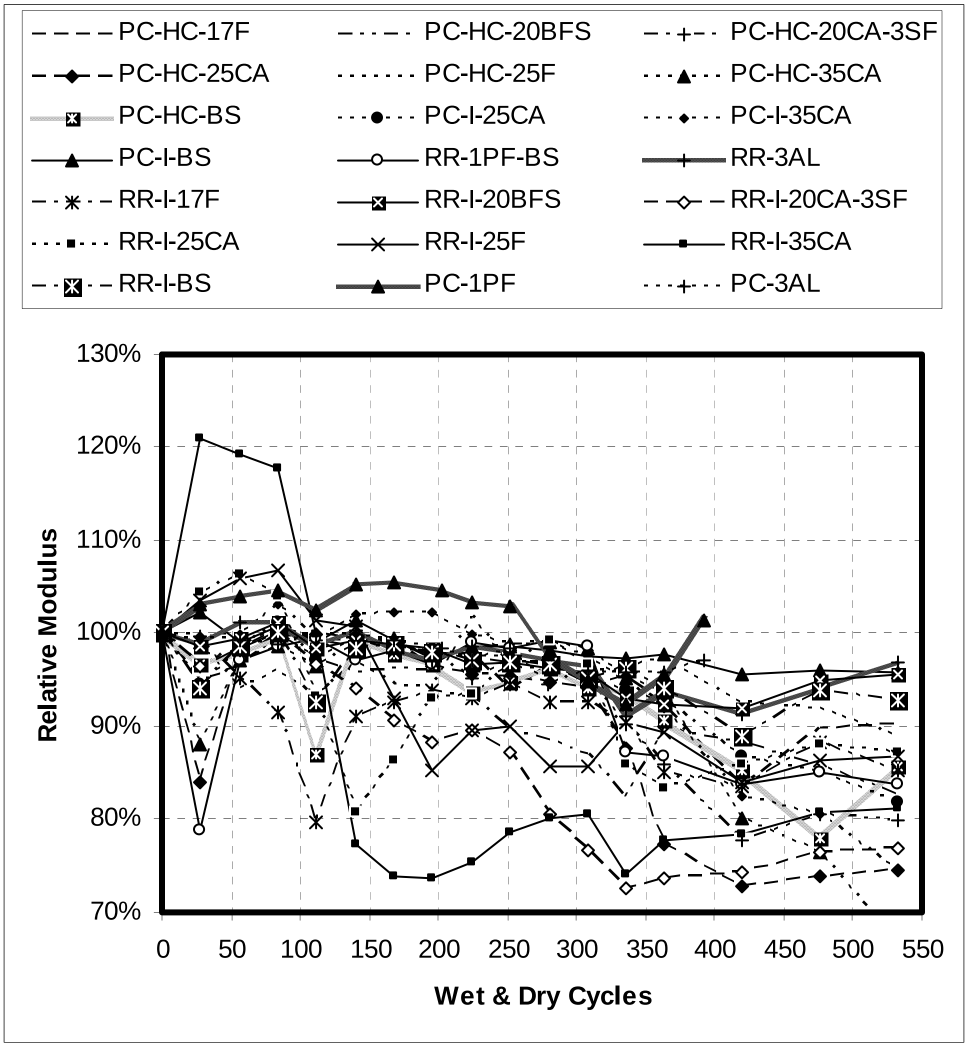

Figure 4.6 Relative Modulus Variations in the Wet & Dry Tests

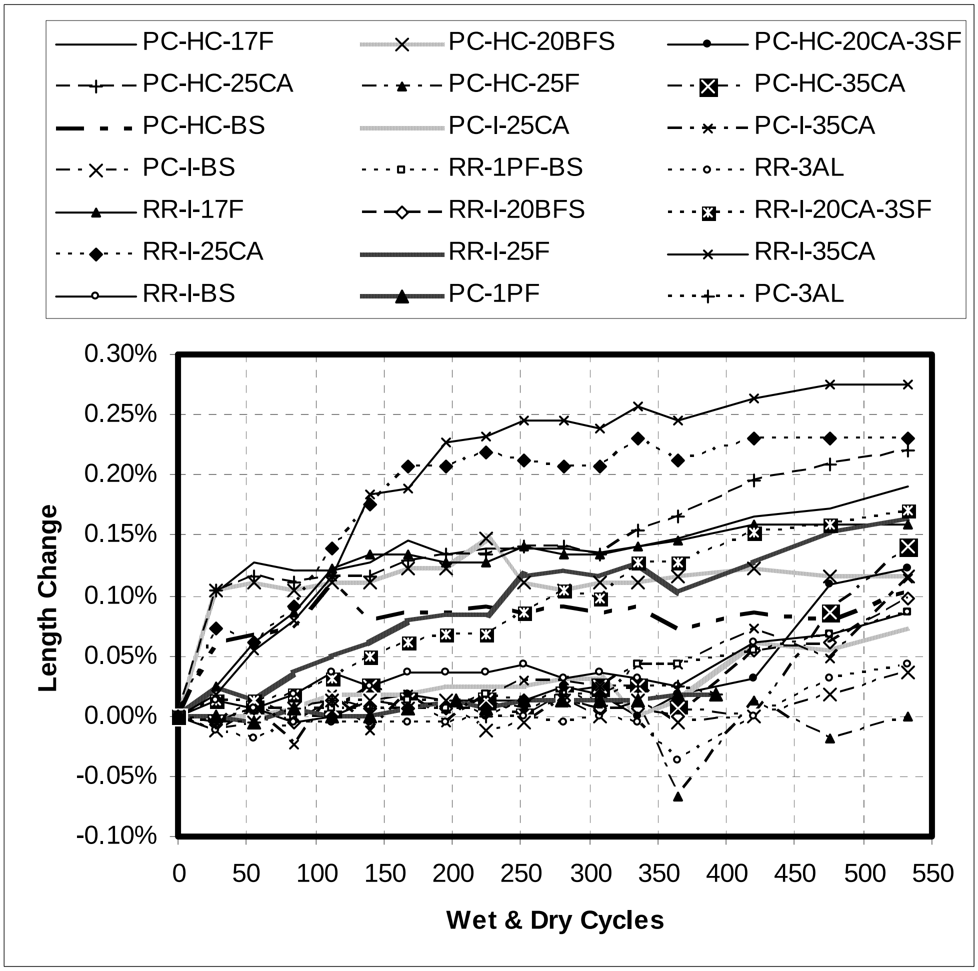

Figure 4.7 Length Changes of the Test Specimens in Wet & Dry Tests

CHAPTER 5

DISCUSSION OF RESULTS

5.1 LIMITATIONS

The ASTM C1293 data were closely reviewed first in order to identify the SCM percentages to effectively mitigate the potential expansion due to ASR. The performance data were then reviewed to identify any adverse effects of those SCM percentages on the durability of the concrete.

A recent report by Folliard et al. [10] has disputed the validity of the accelerated ASTM C1293 tests (Method A). Their research found that the expansions at 140^{o}F were significantly less than (or about 60%) the long-term expansions obtained at 100^{o}F. The reduction was mainly due to the increased specimens drying, increased alkali leaching at 140^{o}F as well as the accelerated cement hydration. These test results are preliminary from an on-going research. Nevertheless, the findings of the current study hinge on the validity of the accelerated version of the ASTM C1293 tests.

5.2 EFFECTIVE PERCENTAGES OF SCM's TO MITIGATE ASR EXPANSION

The expansion data given in Table 3.7 suggests that using 17 to 35% of Class C fly ash would reduce the expansion by about 4 to 10%, using 35% of ground slag would reduce the expansion by about 17%, and using 1PF and 25% of Class F fly ash would reduce the expansion by about 23 to 25%. These data are consistent for the PW, PC and RR aggregates with the exception of PE. It is peculiar that using SCM did not seem to reduce the expansions associated with the PE aggregate. The expansion data given in Table 3.5 further suggests that using 17 to 25% of Class F fly ash, 1PF or 20% of Class C fly ash plus 3% of silica fume, were all effective in controlling the expansion, even though these tests were not conducted strictly following the ASTM C1293. The 1PF cement contained 23.5% of Class F fly ash.

As shown in Table 3.7, the 12-week expansions of PC-LS-BS, PC-LS-17CA and PC-LS-25F from the accelerated ASTM 1293 tests were 0.042%, 0.041% and 0.031%, respectively. These readings showed similar trend as the two-year expansions of PC-HC-BS, PC-HC-25CA and PC-HC-25F from the regular ASTM C1293 tests conducted by the University of New Brunswick, namely, 0.059%, 0.031% and 0.025%, respectively. It should be noted that the expansion readings from the accelerated ASTM C1293 tests were not necessarily less than those from the regular tests, as claimed by Folliard et al. [10]

5.3 IMPACT OF USING SCM's ON THE MECHANICAL STRENGTHS

It is known that adding Class C fly ash or silica fume will significantly improve concrete early strength, while adding Class F fly ash or slag would produce low early strength. However, fly ash or slag would improve the long-term concrete strength.

5.3.1 Compressive strength – These effects are evident in the compressive strengths shown in Table 4.2, the 28-day compressive strengths being deficient for the cases where 25% of fly ash was used.

5.3.2 Flexural strength – The data presented in Table 4.3 indicate that all the mix designs had adequate flexural strengths. Most concrete specimens reached the peak strengths in 14 days, except those containing fly ash or slag. The specimens showing the lowest strengths (i.e., PC-I-25CA and PC-HC-25F) had an air content of 8% and 9%, respectively.

5.3.3 Split tensile strength – The split tensile strengths of the PC and RR baseline specimens were 380 psi and 430 psi at 28 and 56 days, respectively. The two mix designs containing 25% F ash had the lowest strengths.

The concretes containing 20% C ash plus 3% silica fume had the highest compressive, flexural and split tensile strengths and the lowest chloride ion penetrability among all the specimens.

5.4 IMPACT OF USING SCM's ON THE CHLORIDE ION PENETRABILITY

The test data in Table 4.5 shows that all the mix designs had low (1000-2000 Coulombs) to moderate (2000-4000 Coulombs) chloride ion penetrability. As shown in Fig. 5.1, for those specimens with moderate chloride ion penetrability, there is a strong correlation between the total electric charges recorded and the total equivalent alkali levels (given in Table 3.4) in the specimens.

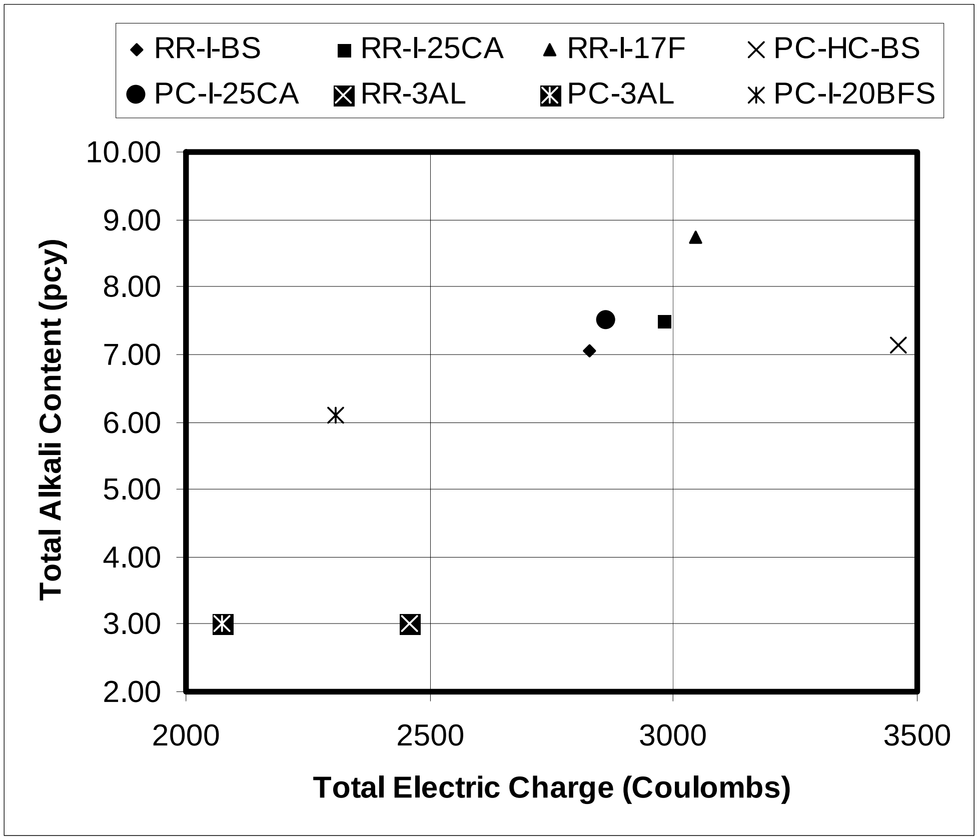

Figure 5.1 Correlation between Chloride Penetrability and Alkali Contents

5.5 IMPACT OF USING SCM's ON THE FREEZE-THAW RESISTANCE

The freeze-thaw resistance of concrete depends mainly upon the amount of air-entrainment in the concrete. Fig. 4.1 shows that PC-HC-BS, PC-I-BS, PC-HC-25F and PC-HC-35CA, experienced significant relative dynamic modulus deteriorations (e.g., 70% after 300 freezing and thawing cycles). The weight loss time-histories shown in Fig. 4.2 further indicate PC-I-35CA, PC-1PF, RR-I-BS, RR-1PF, RR-I-35CA also failed the tests. Most failed specimens had air contents either too low (2 to 3.5%) or too high (8 to 9%). The specimens that disintegrated after only 7 to 8 weeks of testing contained 35% C ash or 25% F ash.

The NDOR wet and dry tests were intended for evaluating the behavior of a mix under heating and cooling environment to predict the amount of expansion that would occur in the field due to the reactivity of the aggregate. The freeze-thaw tests were intended for evaluating the behavior of a mix under freezing and thawing condition, especially the resistance to the hydraulic pressure caused by water upon freezing. The PC-HC-25CA, PC-HC-35CA, and RR-I-35CA mixes failed both freeze-thaw and wet & dry tests. Further, the RR-I-17F, PC-HC-25F, PC-1PF and RR-1PF mixes contained 17 to 25% F ash and showed low resistance to freeze-thaw action. However, these findings should be considered preliminary as the number of the specimens tested was small.

CHAPTER 6

SUMMARY AND RECOMMENDATIONS

6.1 SUMMARY

A review of the major highway and interstate construction projects in Nebraska revealed that measures have been taken by NDOR to mitigate ASR. However, no definitive specifications have been developed for the production of durable concrete and effective ASR mitigation in Nebraska. The objectives of this study were to evaluate the alkali-silica reactivity (ASR) potential of selected aggregates according to the ASTM C 1260 and C 1293 tests, and to identify the specific amounts of supplementary cementing materials (SCM), such as fly ashes (Class C and F), slag and silica fume, to effectively mitigate ASR. The test program included 4 sources of potentially reactive fine aggregates, 1 source of limestone, 5 sources of cement (Type I, Type IP/F, low-alkali and high-alkali), 2 sources of Class C fly ash, 1 source of Class F fly ash, 1 source of slag, and 1 source of silica fume. The percentages used for cement replacement by mass included C ash at 17%, 25% and 35%, C ash at 20% plus silica fume at 3%, F ash at 17% and 25%, and slag at 20% and 35%.

A synthesis of the data analysis indicates that using 17 to 23.5% of Class F fly ash, or 20 to 35% of ground slag, would effectively control the ASR expansion without compromising the mechanical strength and durability of concrete per Nebraska 47B Specifications. It was necessary to use high volume of Class C fly ash (> 35%) to mitigate ASR expansion which inadvertently would compromise the concrete strength and durability. However, a combination of 20% of Class C fly ash and 3% silica fume proved to be very effective in controlling the ASR expansion as well as enhancing the concrete strength and durability.

The ASTM C1293 test data showed that the PE and RR aggregates are fast reactive, while the PC and PW aggregates are slowly reactive. It is anticipated that if the above recommended SCM percentages are used in concrete production according to the Nebraska 47B Specifications, the ASR expansion potential would be effectively mitigated while providing adequate mechanical strength and concrete durability.

6.2 RECOMMENDATIONS

A recent report by Folliard et al. [10] has disputed the validity of the accelerated ASTM C1293 tests (Method A). Their findings indicated that the expansions at 140^{O}F were significantly less than (or about 60%) the long-term expansions obtained at 100^{O}F. The reduction was mainly due to the increased specimens drying, increased alkali leaching at 140^{O}F as well as the accelerated cement hydration. These test results are preliminary from an on-going research. Nevertheless, the findings of the current study hinge on the validity of the accelerated version of the ASTM C1293 tests.

One objective of this study was to develop guidelines and specifications for durable concrete production in Nebraska. However, the regular ASTM C1293 tests conducted did not produce significant ASR expansions due to insufficient amount of total alkali contents (i.e., 564 pounds of cement at 1.25% Na_2O_e per cubic yard of concrete). Further, the validity of the accelerated version of the ASTM C1293 is questionable at this point of time. Therefore, it is recommended that the regular ASTM C1293 tests specified in the test matrix be re-conducted, using 708 pounds of cement at 1.25% Na_2O_e per cubic yard of concrete, to confirm the findings from this study.

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APPENDIX I: Advisory Committee on Nebraska Aggregates Reactivity

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APPENDIX II

The Test Matrix:

ASTM C 1293 and Durability Tests

	Regular ASTM C 1293	Accelerated ASTM C 1293	Aggregate Gradation	Slump	Workability	Air Content	Compressive Strength	Flexural Strength	Freeze/Thaw	Split Tensile	Wet/Dry - NDOR
Total number of tests – all four aggregate sources	**47**	**44**	**19**	**80**	**25**	**80**	**14**	**14**	**21**	**14**	**25**
Number of specimens per test	**4**	**4**	**N/A**	**N/A**	**N/A**	**N/A**	**10**	**10**	**3**	**4**	**3**
Total number of specimens for all tests	**188**	**176**					**140**	**140**	**63**	**56**	**75**

		Regular ASTM C 1293	Accelerated ASTM C 1293	Aggregate Gradation	Slump	Workability	Air Content	Compressive Strength	Flexural Strength	Freeze/Thaw	Split Tensile	Wet/Dry - NDOR
Aggregate Platte East	**Baseline, no additives**	✓	✓		✓		✓					
	25% C ash - A	✓	✓		✓		✓					
	25% C ash - B	✓			✓		✓					
	35% C ash - A	✓	✓		✓		✓					
	35% C ash - B	✓			✓		✓					
	20% C ash - A plus 3% silica fume	✓	✓		✓		✓					
	20% C ash - B plus 3% silica fume	✓			✓		✓					
	17% F ash	✓	✓		✓		✓					
	25% F ash	✓	✓		✓		✓					
	20% blast furnace slag	✓	✓		✓		✓					
	Type 1P/F cement	✓			✓		✓					
	Type I cement (708 lb)		✓		✓		✓					
	Lone Star cement Baseline		✓		✓		✓					
	Lone Star cement plus 17% C ash - A		✓		✓		✓					
	Lone Star cement plus 35% C ash - A		✓		✓		✓					
	Lone Star cement plus 25% F ash		✓		✓		✓					
	Type 1P/F cement		✓		✓		✓					
	Lone Star cement plus 35% ground slag		✓		✓		✓					

		Regular ASTM C 1293	Accelerated ASTM C 1293	Aggregate Gradation	Slump	Workability	Air Content	Compressive Strength	Flexural Strength	Freeze/Thaw	Split Tensile	Wet/Dry - NDOR
Aggregate Platte Central	**Baseline, no additives**	✓			✓		✓					
	25% C ash - A	✓			✓		✓					
	25% C ash - B	✓			✓		✓					
	35% C ash - A	✓			✓		✓					
	35% C ash - B	✓			✓		✓					
	20% C ash - A plus 3% silica fume	✓			✓		✓					
	20% C ash - B plus 3% silica fume	✓			✓		✓					
	17% F ash	✓			✓		✓					
	25% F ash	✓			✓		✓					
	20% blast furnace slag	✓			✓		✓					
	Type 1P/F cement	✓			✓		✓					
	Lone Star cement Baseline		✓		✓		✓					
	Lone Star cement plus 17% C ash - A		✓		✓		✓					
	Lone Star cement plus 35% C ash - A		✓		✓		✓					
	Lone Star cement plus 25% F ash		✓		✓		✓					
	Type 1P/F cement		✓		✓		✓					
	Lone Star cement plus 35% ground slag		✓		✓		✓					

		Regular ASTM C 1293	Accelerated ASTM C 1293	Aggregate Gradation	Slump	Workability	Air Content	Compressive Strength	Flexural Strength	Freeze/Thaw	Split Tensile	Wet/Dry - NDOR
Aggregate Platte West	**Baseline, no additives**	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	25% C ash - A	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
	25% C ash - B	✓	✓		✓		✓					
	35% C ash - A	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
	35% C ash - B	✓	✓		✓		✓					
	20% C ash - A plus 3% silica fume	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
	20% C ash - B plus 3% silica fume	✓	✓		✓		✓					
	17% F ash	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	25% F ash	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	20% blast furnace slag	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Type 1P/F cement	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
	Type I cement (708 lb)		✓		✓		✓					
	Lone Star cement Baseline		✓		✓		✓					
	Lone Star cement plus 17% C ash - A		✓		✓		✓					
	Lone Star cement plus 35% C ash - A		✓		✓		✓					
	Lone Star cement plus 25% F ash		✓		✓		✓					
	Type 1P/F cement		✓		✓		✓					
	Lone Star cement plus 35% ground slag		✓		✓		✓					
	3 #/cu yd alkali loading			✓	✓	✓	✓	✓	✓	✓	✓	✓

		Regular ASTM C 1293	Accelerated ASTM C 1293	Aggregate Gradation	Slump	Workability	Air Content	Compressive Strength	Flexural Strength	Freeze/Thaw	Split Tensile	Wet/Dry - NDOR
Aggregate Republican River	**Baseline, no additives**	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	25% C ash - A	✓	✓	✓	✓	✓	✓			✓		✓
	25% C ash - B	✓			✓		✓					
	35% C ash - A	✓		✓	✓	✓	✓			✓		✓
	35% C ash - B	✓			✓		✓					
	20% C ash - A plus 3% silica fume	✓		✓	✓	✓	✓			✓		✓
	20% C ash - B plus 3% silica fume	✓			✓		✓					
	17% F ash	✓		✓	✓	✓	✓			✓		✓
	25% F ash	✓		✓	✓	✓	✓			✓		✓
	20% blast furnace slag	✓		✓	✓	✓	✓			✓		✓
	Type 1P/F cement	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
	Type I cement (708 lb)		✓		✓		✓					
	Lone Star cement Baseline		✓		✓		✓					
	Lone Star cement plus 17% C ash - A		✓		✓		✓					
	Lone Star cement plus 35% C ash - A		✓		✓		✓					
	Lone Star cement plus 25% F ash		✓		✓		✓					
	Type 1P/F cement		✓		✓		✓					
	Lone Star cement plus 35% ground slag		✓		✓		✓					
	3 #/cu yd alkali loading			✓	✓	✓	✓			✓		✓

		Regular ASTM C 1293	Accelerated ASTM C 1293	Aggregate Gradation	Slump	Workability	Air Content	Compressive Strength	Flexural Strength	Freeze/Thaw	Split Tensile	Wet/Dry - NDOR
High Alkali Cement – Platte Central Aggregate	**Baseline, no additives**	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
	25% C ash - A	✓			✓	✓	✓					✓
	25% C ash - B											
	35% C ash - A			✓	✓	✓	✓	✓	✓	✓	✓	✓
	35% C ash - B											
	20% C ash - A plus 3% silica fume				✓	✓	✓					✓
	20% C ash - B plus 3% silica fume											
	17% F ash				✓	✓	✓					✓
	25% F ash	✓		✓	✓	✓	✓	✓	✓	✓	✓	✓
	20% blast furnace slag				✓	✓	✓					✓

APPENDIX III – PROCEDURES FOR PREPARING ASTM C1293 TEST SPECIMENS

Preparing the materials

(1) Bring all materials to the environment with the temperature between 68°F and 86°F (ASTM C192).
(2) Sieve limestone to remove those diameter is greater than 3/4'' (ASTM C1293). (Conduct sieve analysis according to Table 1, ASTM C 1293)
(3) Determine the moisture content for both fine aggregate and limestone.
(4) Measure the weight of all the materials and seal them in buckets to prevent moisture loss.
(5) Dissolve NaOH in the mixing water in sufficient time and keep the temperature of the mixing water between 73.5 ± 3.5°F. (ASTM C490)

Preparing the molds

(1) Check the outside joints of the mold and the contact lines of the mold and base plate shall be sealed to prevent loss of water in fresh concrete. (ASTM C490)
(2) Thinly cover the interior surfaces of the mold with mineral oil. (ASTM C490)
(3) Measure the gage length to make sure it's 10 ±0.1 in (using a 10 in. gage length rod made by the lab). (ASTM C490)

Mixing concrete

(1) Prior to starting rotation of the mixer add the coarse aggregate and some of the mixing water. Start the mixer, and then add the fine aggregate, cement and water.(ASTM C192)
(2) Mix the concrete after all ingredients is in the mixer, for 3 min followed by a 3-min rest, followed by a 2-min final mixing. Cover the open end or top of the mixer to prevent evaporation during the rest period. (ASTM C192)
(3) Determine slump and air content according to ASTM C143 and C231.
(4) Using rodding, tamping and vibration to consolidating specimens depending on the slump and workability of the concrete. (ASTM C192)
(5) Loosen the middle studs outside a little bit to prevent the shrinkage after striking off the surface of the specimens. (ASTM C157). Pay attention to the loosened studs to prevent the cement paste coming out.
(6) After making concrete, move the specimens to the curing room as soon as possible. Cover the specimens immediately after finishing with plastic sheet. (ASTM C192)

Curing, demolding and reading

(1) All specimens are required to be preserved in the curing room with 73.0±3.0°F and a relative humidity of not less than 95%. (ASTM C511)
(2) If the humidity could not be greater than 95%, wet burlap could be used to prevent evaporation of water. (ASTM C192)

(3) Remove the specimens from the molds at an age of 23 1/2± 1/2 h after the addition of water to the cement during the mixing operation. (ASTM C157)

(4) Immediately take the initial comparator reading at an age of 24±1/2 h after the addition of water to the cement during the mixing operation. (ASTM C157)

(5) Using the demolding device remove specimens without striking or jarring and with particular care not to exert pressure directly against the gage studs. The gage stud holder shall remain attached to the stud during the operation. (ASTM C 157M)

(6) Keep the specimens at 38°C or 60°C in the storage environment according to ASTM C1293. Stand the specimens on end and they cannot be in contact with water in the bucket. (ASTM C1293)

(7) For subsequent readings, remove the containers holding the prisms and place them in the curing room in compliance with ASTM C511 (Temp.: 23.0±2.0 °C; Humidity: 95%.) for a period 16 ± 4 h before reading. (ASTM C1293)

(8) Identify the specimens so as to place the specimens in the comparator with the same end uppermost. After reading, replace the specimens in the storage container but invert the uppermost end as compared with the previous storage period. (ASTM C1293)

(9) All the readings are taken in the curing room, and the specimens are handled with latex gloves on.

APPENDIX IV – ACRONYMS FOR THE CONCRETE MIX DESIGNS

Type of ASTM C-1293 test:

R = Regular test environment

A = Accelerated test environment

Coarse aggregate: limestone

Nebraska 47B fine aggregates:

PE = Platte River East

PW = Platte River West

PC = Platte River Central

RR = Republican River

Portland cement:

I = Type 1

IPF = Type 1PF (contains 23.5% Class F fly ash)

HC = high-alkali cement (0.66%)

AL = Alkali loading in pounds per cubic yard of concrete

LS = high-alkali cement (0.84%)

Supplementary cementing materials (SCM):

CA = Class C fly ash from source A

CB = Class C fly ash from source B

F = Class F fly ash

SF = Silica Fume

BFS = Blast Furnace Slag

Concrete mix designations:

BS = Baseline mix design according to Nebraska 47B-3500

Numerical percentage = Percentage of cement replaced by SCM by weight

Example:

PE-I-20CA-3SF-R = Regular ASTM C-1293 test using Platte River East fine aggregate, Type 1 cement with 20% replacement of Class C fly ash from source A, and 3% replacement of silica fume in the mix design.

APPENDIX V

NEBRASKA WET AND DRY TEST

WET & DRY TEST

1. Moist room storage until 28 day age.
2. At 28 day age perform the following tests:
   - A. Length
   - B. Sonic Modulus
   - C. Weight in air (Nearest gram)
   - D. Weight in water (Nearest gram)
3. Place beams in Wetting and Drying Tank. All beam racks must be full at all times. If no space is available for test, the beams will be stored In the moist room until space is available.
4. Beams are only to be tested after 10 o'clock on any day.
5. After each 28 days in the W & D tank perform the following tests:
   - A. Length
   - B. Sonic Modulus
   - C. Weight in air (Nearest gram)
6. After 365 days in the W & D tank perform the following tests on a 56 day interval:
   - A. Length
   - B. Sonic Modulus
   - C. Weight in air (Nearest gram)
7. After 548 days in the W & D tank perform the following tests:
   - A. Length
   - B. Sonic Modulus
   - C. Weight in air (Nearest gram)
   - D. Weight in water (Nearest gram)
8. The 3x4x16 inch beams shall be measured for length change in the 16 inch horizontal comparator. The room temperature should be maintained at

approximately 70°F, The standard bar shall be placed in the comparator in the same relative position each time the device is zeroed, with both ends of the bar centered on the measuring studs of the comparator. The dial shall be positioned on the operator's left. To zero the dial needle, the ends of the bar shall be moved forward and backward until the longest reading possible is obtained.

The specimen shall be placed in the comparator in the same relative position each time. Care must be exercised so that the beam will rest in contact with the supports on the movable plate, instead of being elevated by sand particles or other foreign material. The beam shall be placed with the right end in contact with the stop on the supporting plate. The beam and support is then moved to the right into contact with the fixed comparator stud. The two plugs in the beam shall be lined up with the comparator stud and the dial plunger.

The dial plunger shall be brought into contact gently with the left beam plug. Then the beam shall be moved very slightly backward and forward until the longest measurement possible is obtained. Using a slight pressure against the beam toward the right to insure that the beam firmly contacts the fixed comparator post, read the dial to the nearest 0.001 Inch. Any unexplained shrinkage or an abnormal growth from a previous measurement shall be checked.

9. WEIGHING

The beams shall be cleaned of all loose material and wiped free of surface water before being weighed. Specimens shall be weighed in air and in water (when required) to the nearest gram. Loose material and scrapings from the specimens shall not be allowed to accumulate on the scale platform. The weighing equipment shall be zeroed before each set of measurements. An abnormal change in weight of a specimen from a previous weight shall be checked. If an explanation is apparent, it shall be recorded.

10. VOLUME

Prior to placing the beams in the W & D tank and at the time of their final removal from the W & D tank, the volume of the beams shall be determined. The beams shall be weighed in water, wiped free of surface water and weighed in air. These weights shall be used to determine the volume of the beams instead of measuring for length, width and depth.

$$\text{Volume of beam in cu. ft.} = \frac{\text{Wt. in air-Wt. in water}}{62.4}$$

11. MODULUS OF RUPTURE (FLEXURAL STRENGTH)

If it should become necessary to know the modulus of rupture of the specimens, the engineer in charge will designate at what age this will be determined prior to the fabrication of the beams. It is necessary to know how many beams will be used for modulus of rupture in order to finish the W & D treatment with these beams.

The modulus of rupture is determined by using a 12 inch span with center point loading. The load is applied at an increasing uniform rate of 15 pounds per second. The modulus of rupture is computed in accordance with ASTM C-293.

OPERATION OF THE WETTING AND DRYTING APPARATUS

CONTROLS

1. TOGGLE SWITCHES

The control panel contains six toggle switches. From left to right they are numbered 1 through 6. The first one on the left is mounted in a horizontal position and the two positions of the switch are labeled No. 1 and No. 2 on the panel. This switch connects the thermostats in the tank ducts to the large burner solenoid valve. When the switch is in the No. 1 position, the thermostat in Duct No. 1 (blue pen on the recorder) is in control of the large burner. When the switch is in the No. 2 position, the thermostat in Duct No. 2 (red pen on the recorder) controls the large burner.

The other switches control the following:

SWITCH NO.	FUNCTION	NORMAL POSITION
2	Water Filling Operation	On
3	Heating Operations	On
4	Drain Valve	On
5	Time Clock No. 1	On
6	Time Clock No. 2	On

2. PILOT LIGHTS

There are five pilot lights on the control panel. The first two on the left are in a separate location. The first is labeled 1 and it is lighted when the large burner is on. The second is labeled 2 and operates when the small burner is on. The three pilot lights on the right are grouped together and are numbered 1 through 3. They indicate the following:

PILOT LIGHT NO.	INDICATION
1	On --- Water in tank and filling valve operating
2	On --- Large filling valve operating
3	On --- Drain valve open

3. TIME CLOCKS

There are two time clocks which control the operation of the apparatus. They are numbered from right to left. No. 1 operates the filling valve. It turns on the valve at seven o'clock in the morning. The specimen tank then fills with water. The filling valve is turned off at three forty-five P.M. Clock No. 2 operates the drain valve and the furnace. Both are made operative at four-fifteen P.M. and are turned off at six forty-five A.M.

	POSITION OF SWITCHES INSIDE CLOCK.
Clock No. 1	On at 7:00 A.M. Off at 3:45 P.M.
Clock No. 2	On at 4:15 P.M. Off at 6:45 A.M.

A recorder on the control panel produces a record each day of the temperatures at the tank end of the two ducts which carry air to and from the furnace. The paper is changed every other day. The record of each day shall be dated by a notation written on the recorder chart. A pilot light on the upper left hand corner of the panel is illuminated when the recorder is operative.

4. AUTOMATIC CONTROLS

(a) A float valve turns off water at the proper level. This is located in the back at the furnace end. (b) A thermostat in the lid turns on cold water when the temperature rises above 700F, (c) A thermostat in the lid turns off the small burner when the temperature rises above 120°F.

DAILY OPERATING PROCEDURE

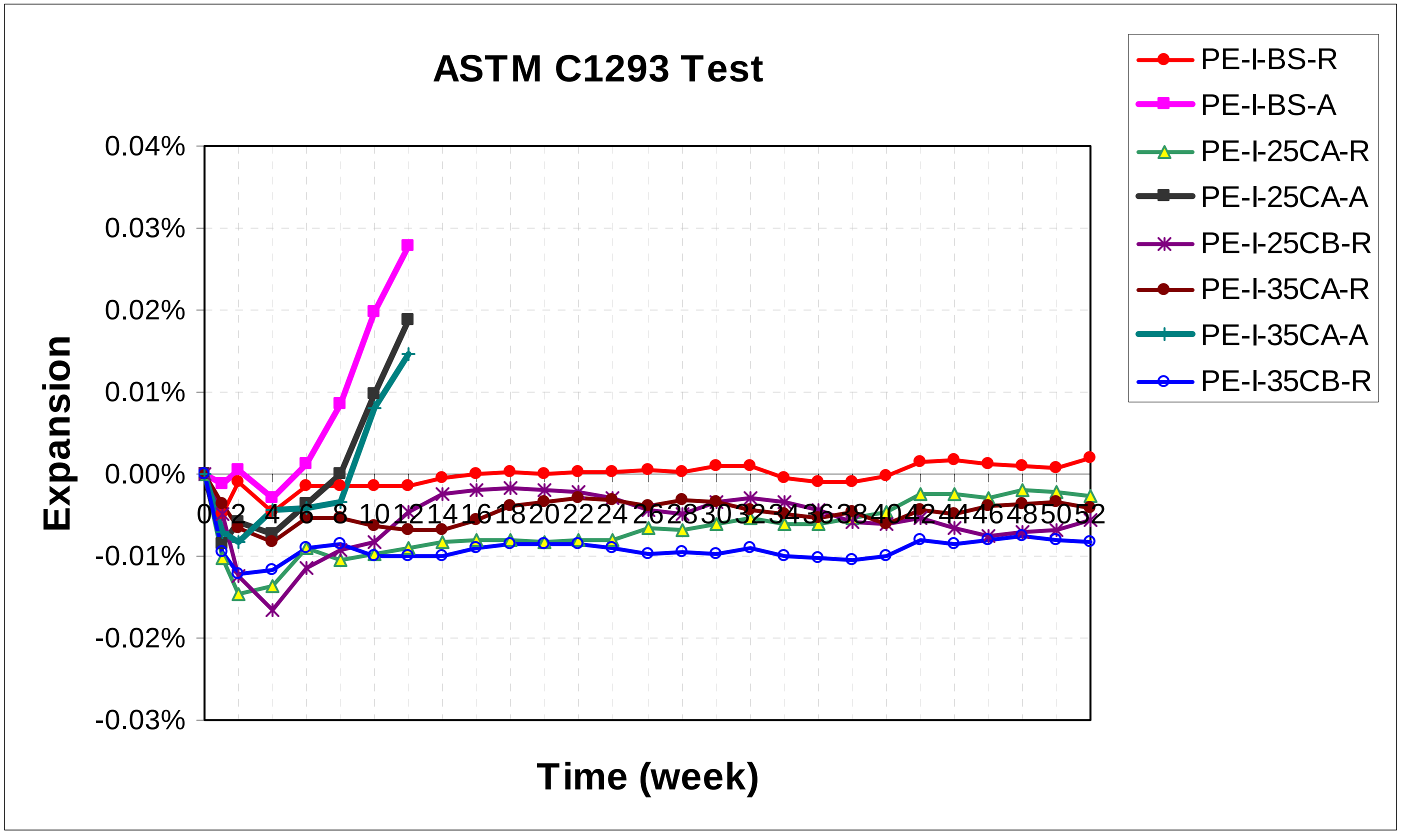
Every day the direction of flow of heated air is changed by adjusting the dampers in the ducts above the furnace plenum. It is also necessary to check the toggle switch on the panel, connecting the duct thermostats to the large furnace burner, so that it corresponds with the duct setting. When the No. 1 duct is open, the toggle switch must be in the No. 1 position. If this is not done, the air enters the tank through the No. 1 duct but the large burner is controlled by the thermostat in No. 2 duct, so it is controlled by the temperature of the air leaving the tank, not entering. This allows the temperature of incoming air to rise above the specified level of 120°F before the large burner is turned off. Also, the toggle switch must be in the number 2 position when duct No. 2 is open.

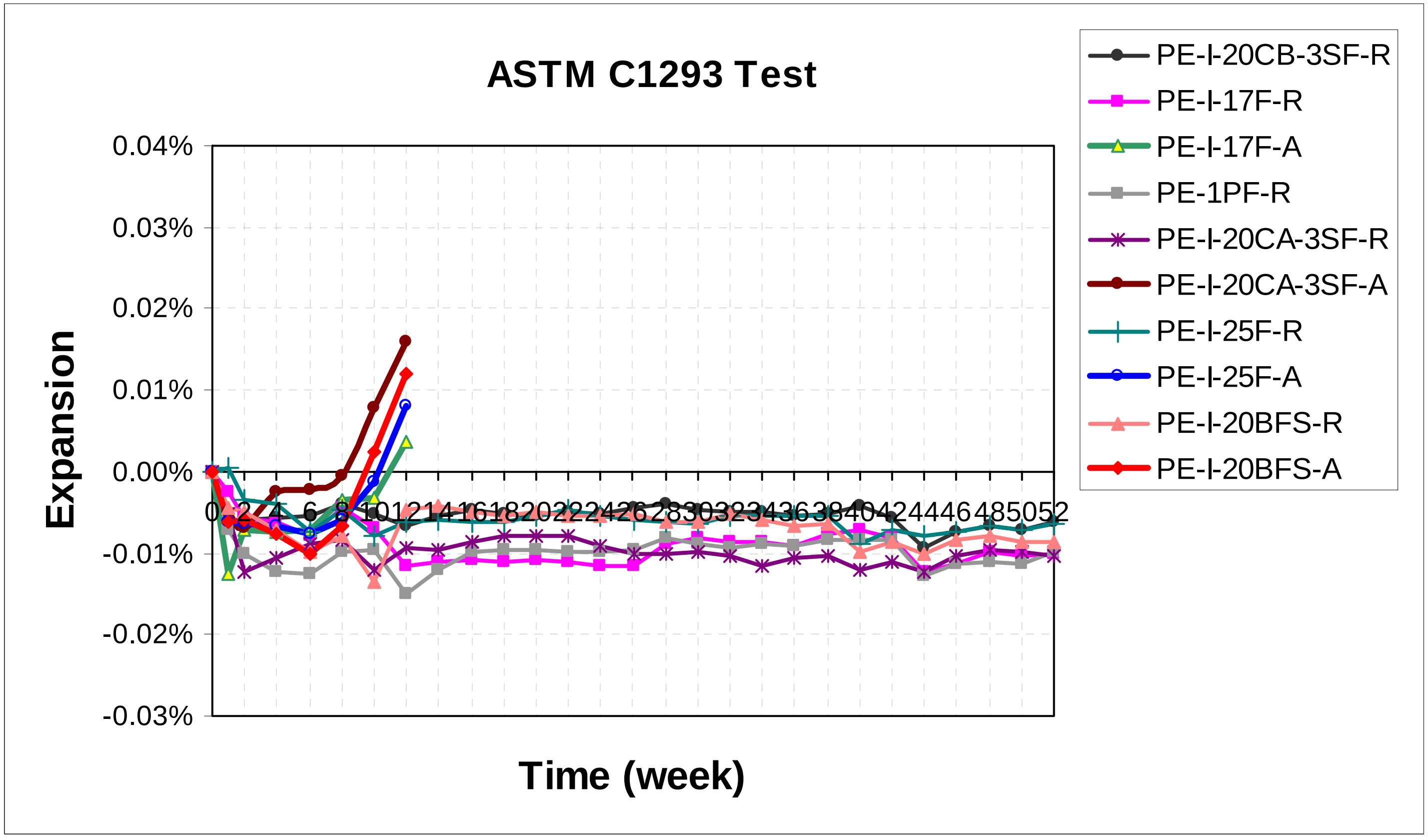
BEAM ROTATION

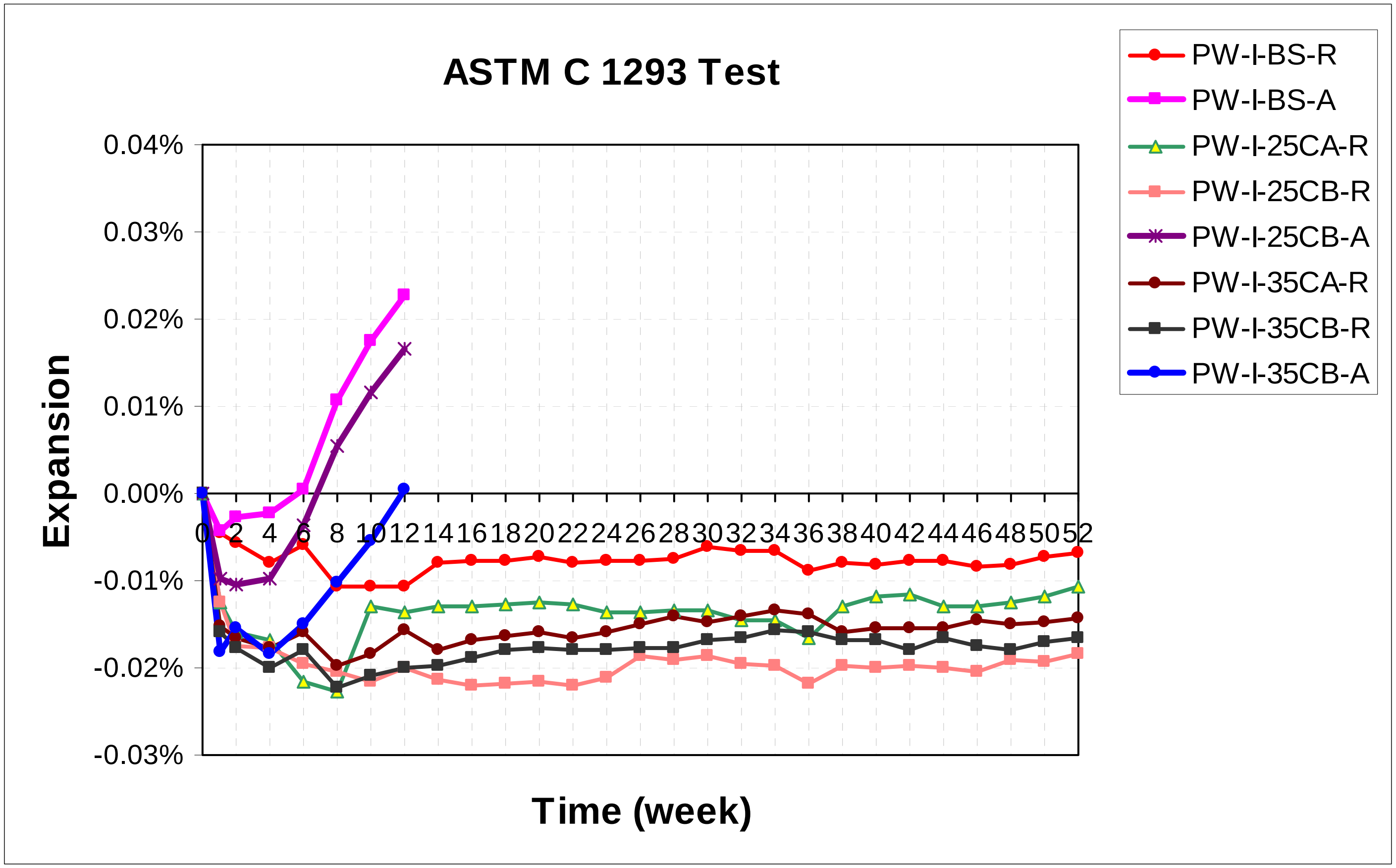
On the first working day of each month the beams and their racks will be rotated. The bottom beam on each rack will be moved to the top position on the rack and each of the remaining beams will be moved down one position. Also, each of the beam racks will be moved over one position in the tank. By doing this each rack will have been in each rack location once and each beam will have been at each level of the rack at least two times during a twelve month period.

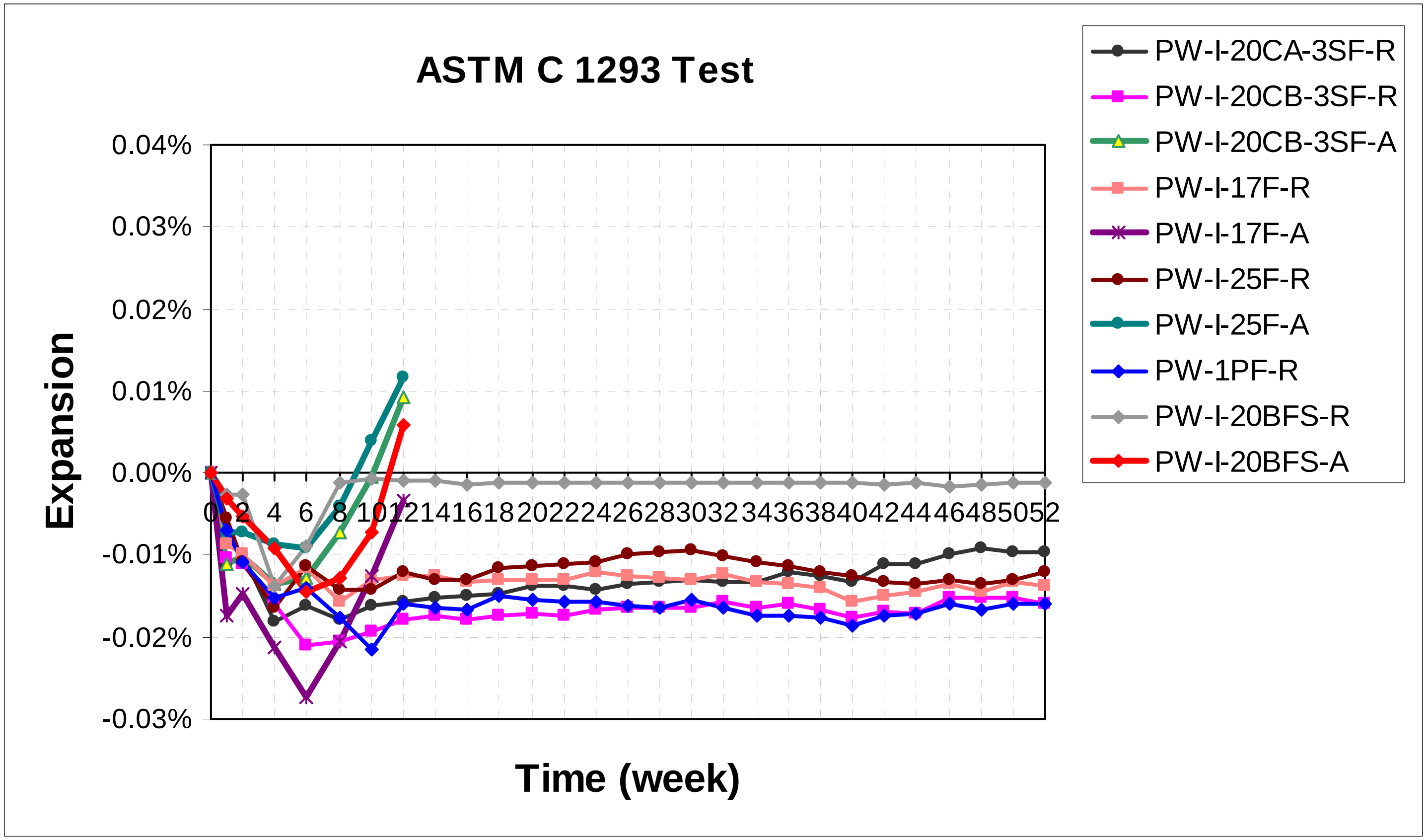
APPENDIX VI

DATA PLOTS OF THE ASTM C1293 TESTS




ASTM C1293 Test
Expansion
0.04%
0.03%
0.02%
0.01%
0.00%
-0.01%
-0.02%
-0.03%
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52
Time (week)
PE-I-20CB-3SF-R
PE-I-17F-R
PE-I-17F-A
PE-1PF-R
PE-I-20CA-3SF-R
PE-I-20CA-3SF-A
PE-I-25F-R
PE-I-25F-A
PE-I-20BFS-R
PE-I-20BFS-A


ASTM C 1293 Test
Expansion
0.04%
0.03%
0.02%
0.01%
0.00%
-0.01%
-0.02%
-0.03%
0
2
4
6
8
10
12
14
16
18
20
22
24
26
28
30
32
34
36
38
40
42
44
46
48
50
52
Time (week)
PW-I-BS-R
PW-I-BS-A
PW-I-25CA-R
PW-I-25CB-R
PW-I-25CB-A
PW-I-35CA-R
PW-I-35CB-R
PW-I-35CB-A


ASTM C 1293 Test
Expansion
0.04%
0.03%
0.02%
0.01%
0.00%
-0.01%
-0.02%
-0.03%
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52
Time (week)
PW-I-20CA-3SF-R
PW-I-20CB-3SF-R
PW-I-20CB-3SF-A
PW-I-17F-R
PW-I-17F-A
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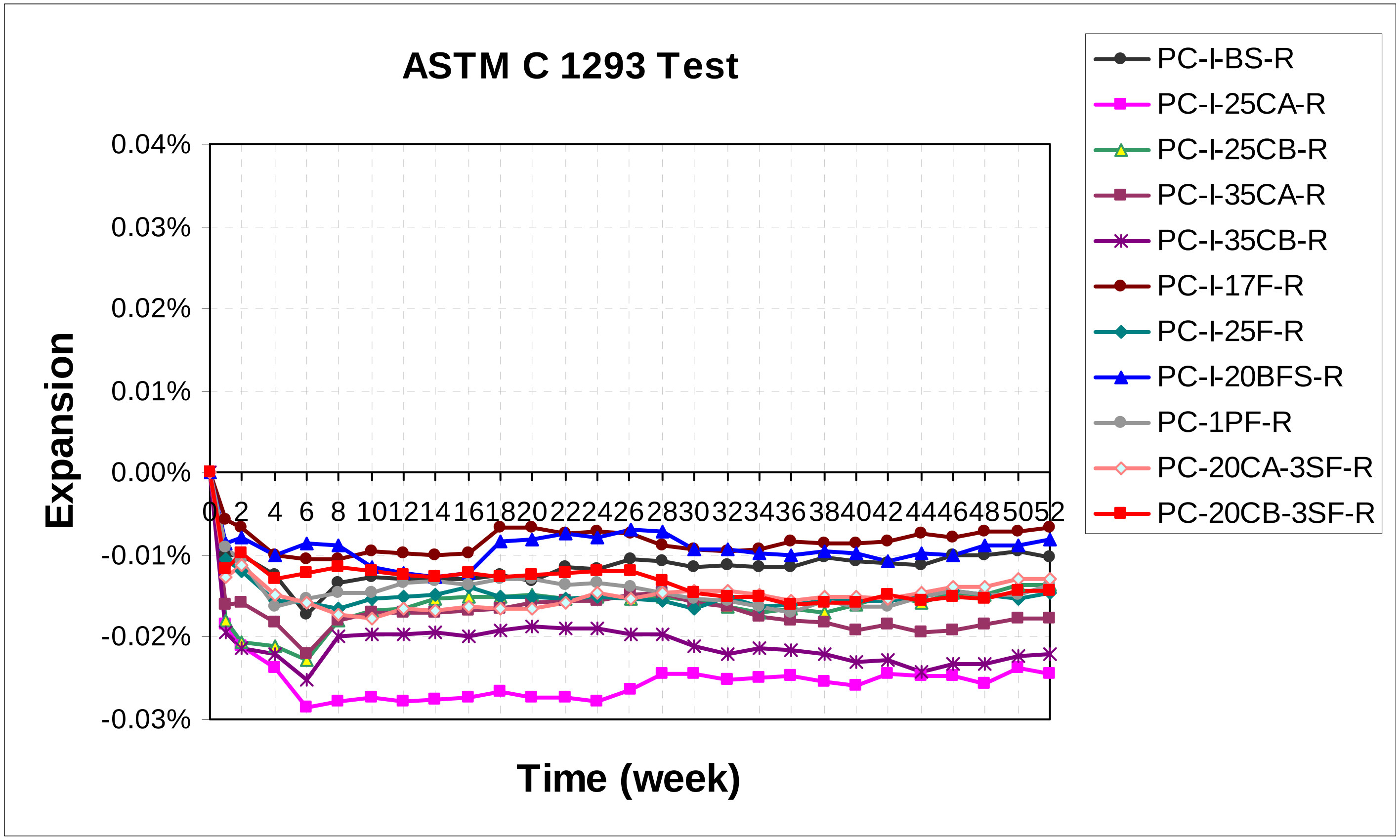
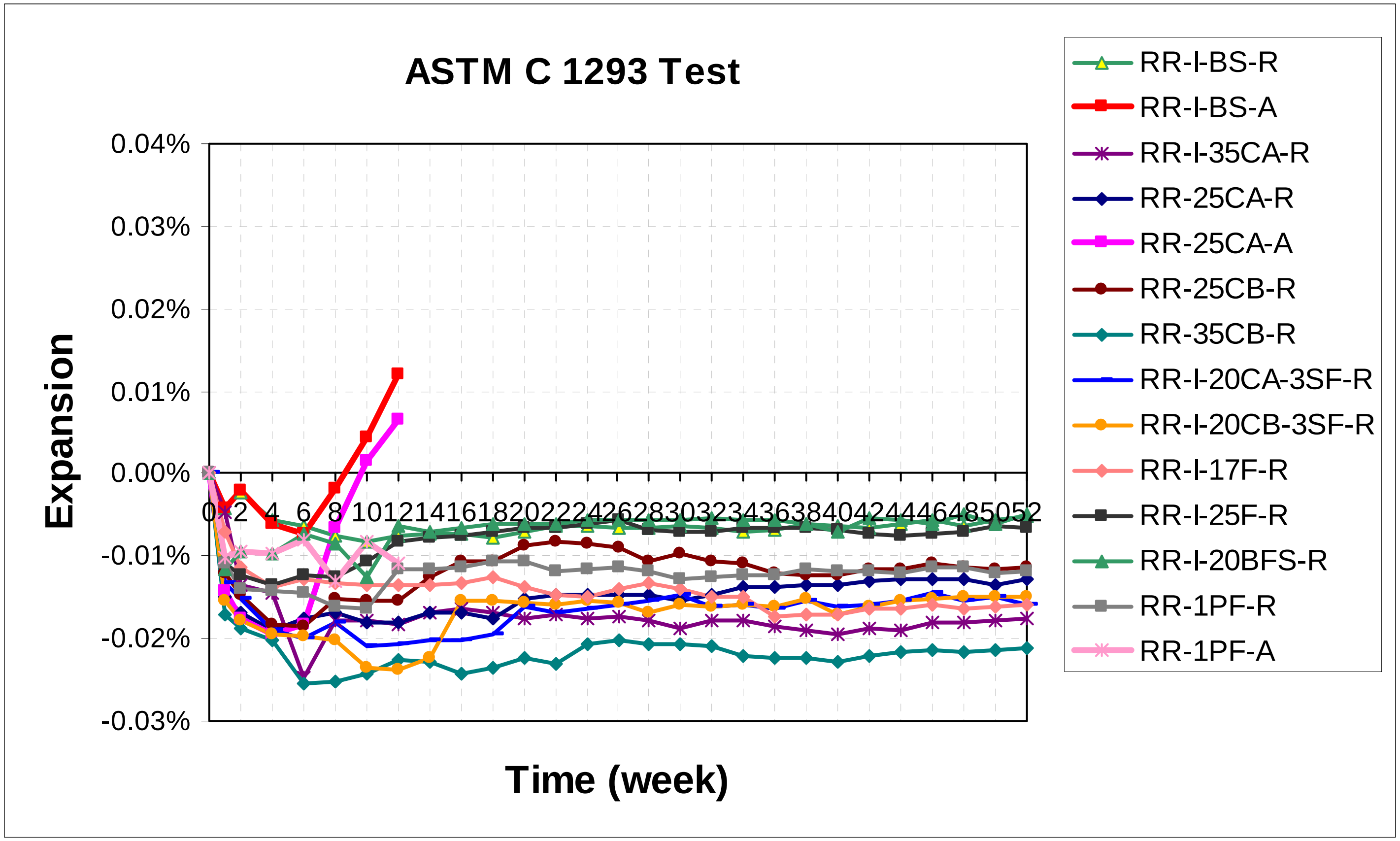
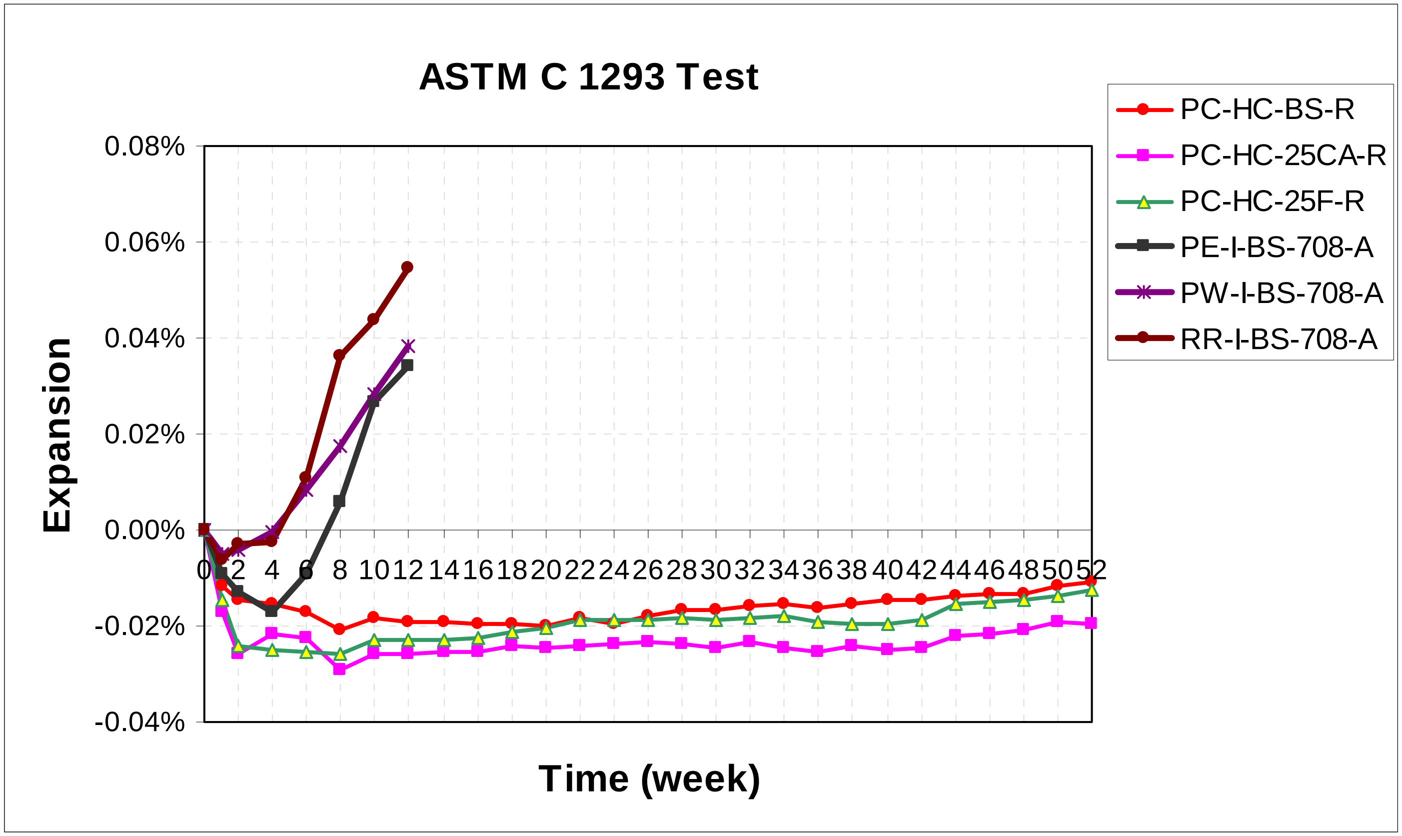
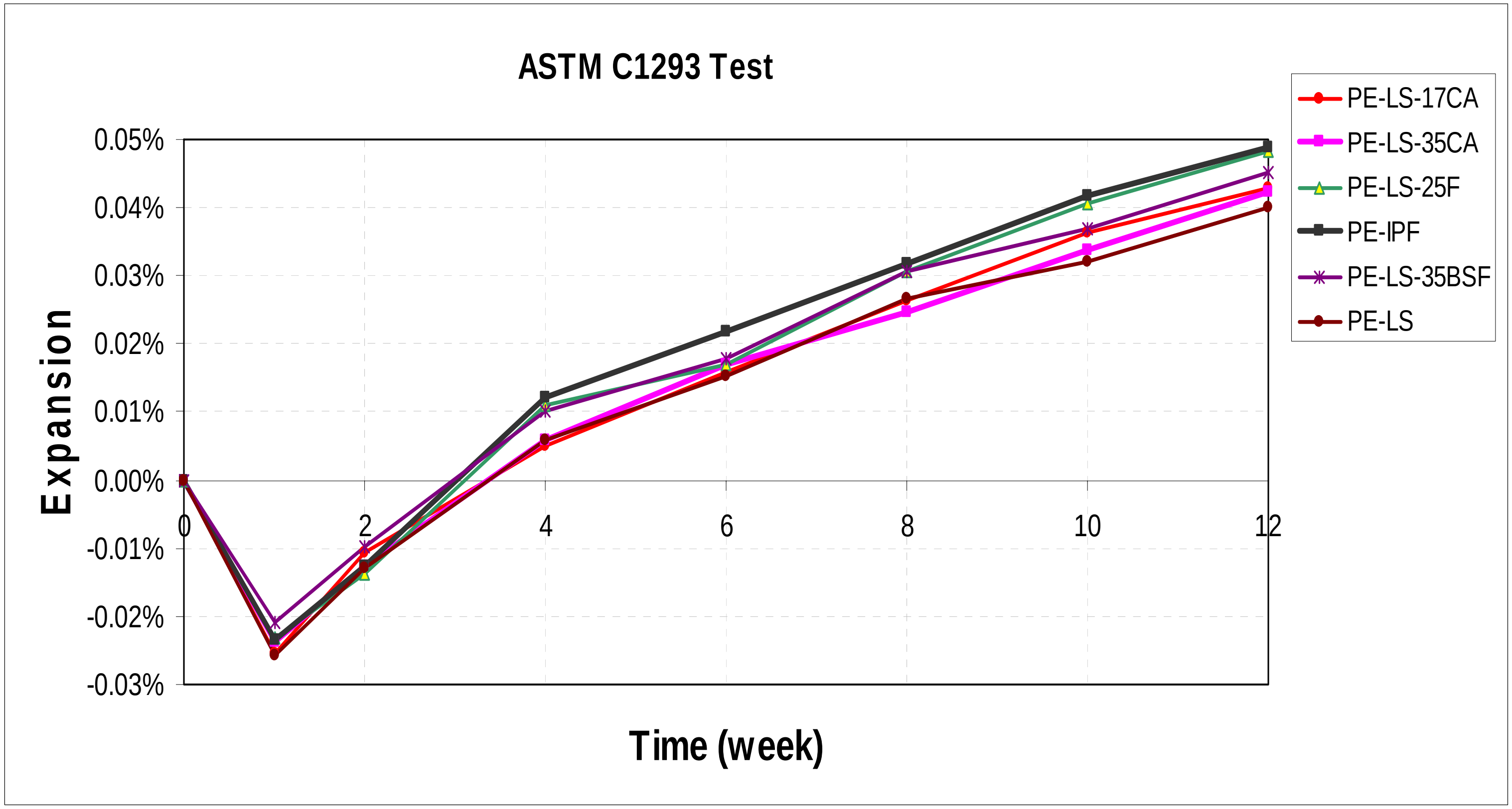
PW-1PF-R
PW-I-20BFS-R
PW-I-20BFS-A


ASTM C 1293 Test
Expansion
0.04%
0.03%
0.02%
0.01%
0.00%
-0.01%
-0.02%
-0.03%
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52
Time (week)
PC-I-BS-R
PC-I-25CA-R
PC-I-25CB-R
PC-I-35CA-R
PC-I-35CB-R
PC-I-17F-R
PC-I-25F-R
PC-I-20BFS-R
PC-1PF-R
PC-20CA-3SF-R
PC-20CB-3SF-R


ASTM C 1293 Test
Expansion
0.04%
0.03%
0.02%
0.01%
0.00%
-0.01%
-0.02%
-0.03%
0 1 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52
Time (week)
RR-I-BS-R
RR-I-BS-A
RR-I-35CA-R
RR-25CA-R
RR-25CA-A
RR-25CB-R
RR-35CB-R
RR-I-20CA-3SF-R
RR-I-20CB-3SF-R
RR-I-17F-R
RR-I-25F-R
RR-I-20BFS-R
RR-1PF-R
RR-1PF-A


ASTM C 1293 Test
Expansion
0.08%
0.06%
0.04%
0.02%
0.00%
-0.02%
-0.04%
0 2 4 6 8 10 12 14 16 18 20 22 24 26 28 30 32 34 36 38 40 42 44 46 48 50 52
Time (week)
PC-HC-BS-R
PC-HC-25CA-R
PC-HC-25F-R
PE-I-BS-708-A
PW-I-BS-708-A
RR-I-BS-708-A


ASTM C1293 Test
Expansion
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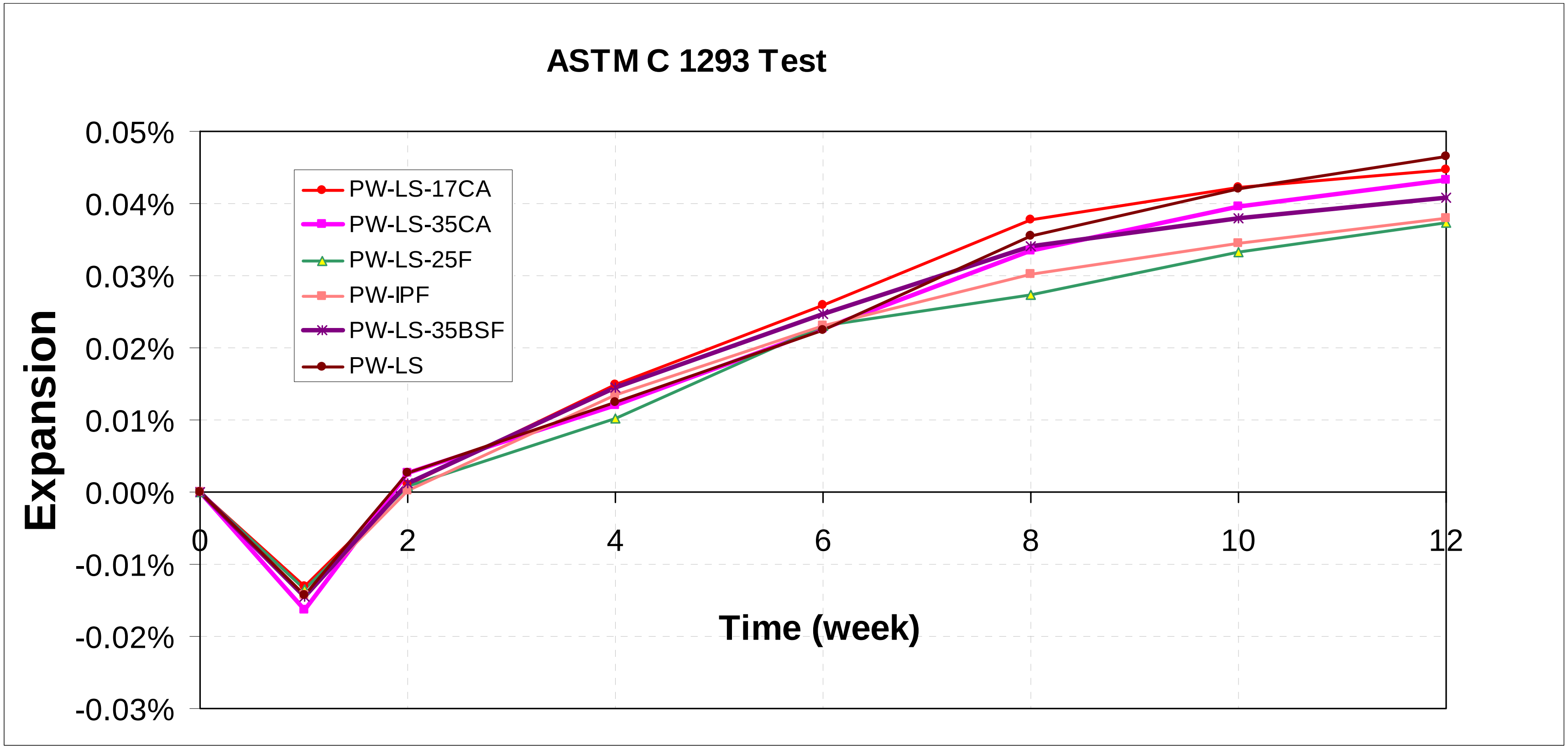
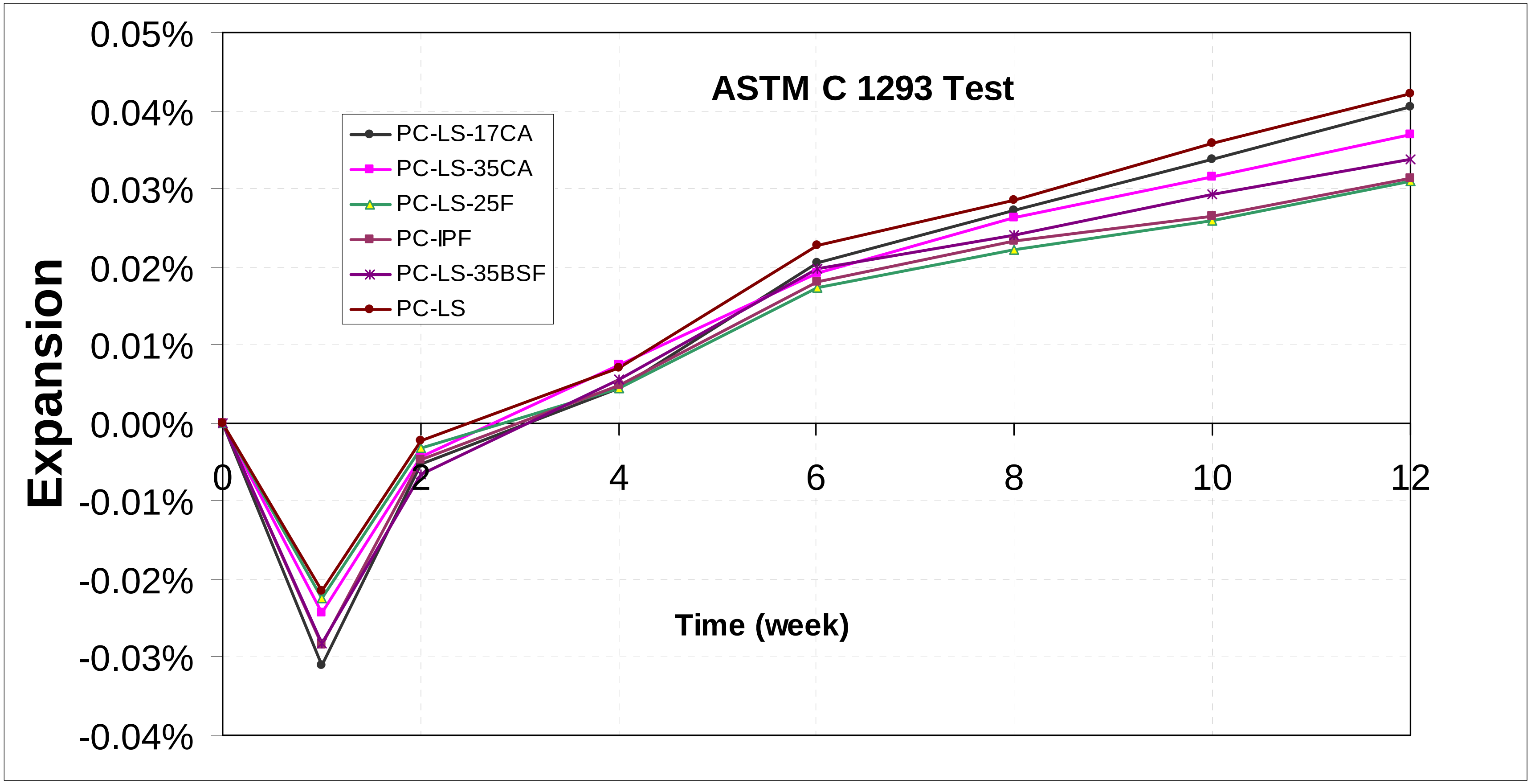
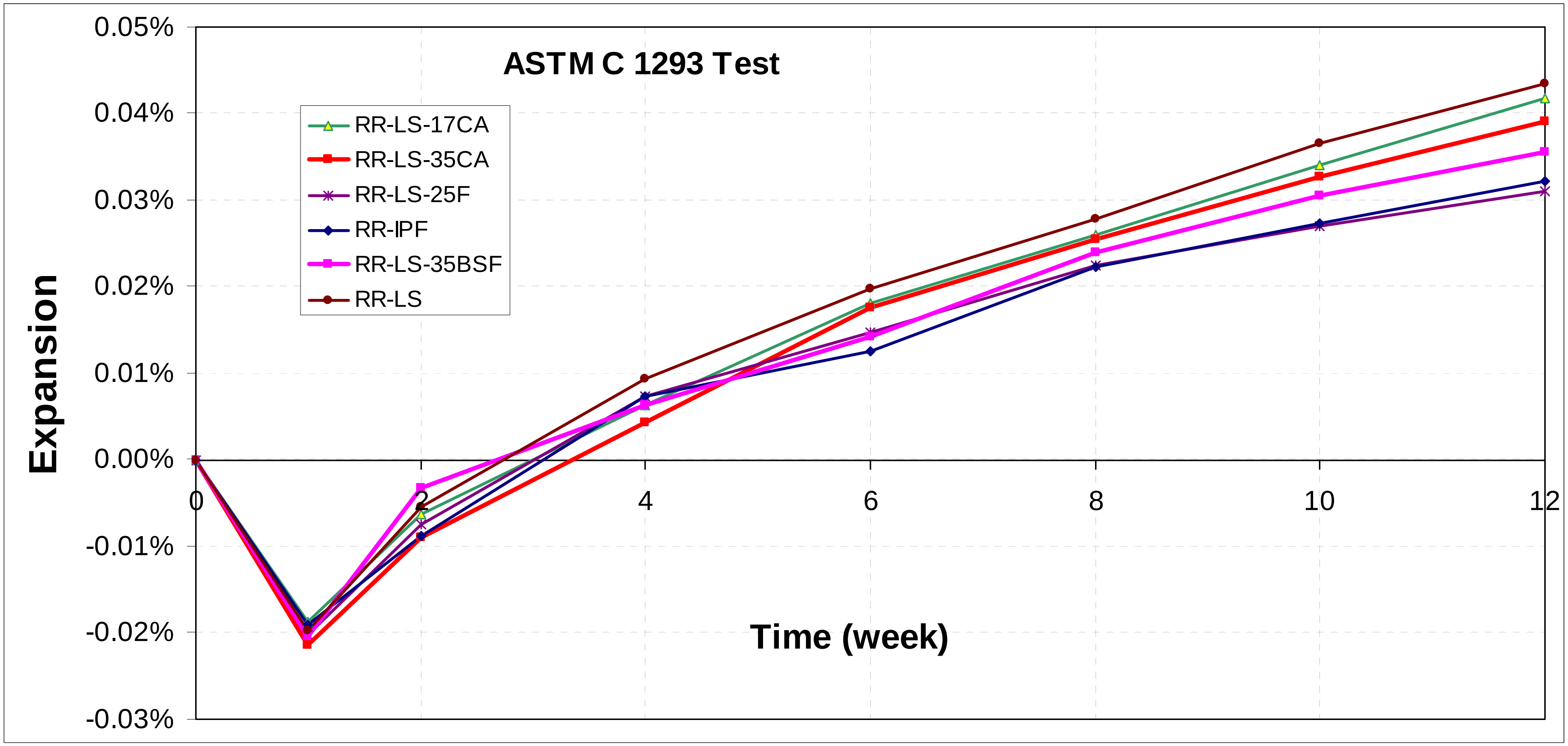
0.04%
0.03%
0.02%
0.01%
0.00%
-0.01%
-0.02%
-0.03%
0
2
4
6
8
10
12
Time (week)
PE-LS-17CA
PE-LS-35CA
PE-LS-25F
PE-IPF
PE-LS-35BSF
PE-LS


ASTM C 1293 Test
Expansion
Time (week)
0.05%
0.04%
0.03%
0.02%
0.01%
0.00%
-0.01%
-0.02%
-0.03%
0
2
4
6
8
10
12
PW-LS-17CA
PW-LS-35CA
PW-LS-25F
PW-IPF
PW-LS-35BSF
PW-LS


ASTM C 1293 Test
Expansion
Time (week)
0.05%
0.04%
0.03%
0.02%
0.01%
0.00%
-0.01%
-0.02%
-0.03%
-0.04%
0
2
4
6
8
10
12
PC-LS-17CA
PC-LS-35CA
PC-LS-25F
PC-IPF
PC-LS-35BSF
PC-LS


ASTM C 1293 Test
RR-LS-17CA
RR-LS-35CA
RR-LS-25F
RR-IPF
RR-LS-35BSF
RR-LS
Expansion
0.05%
0.04%
0.03%
0.02%
0.01%
0.00%
-0.01%
-0.02%
-0.03%
0
2
4
6
8
10
12
Time (week)