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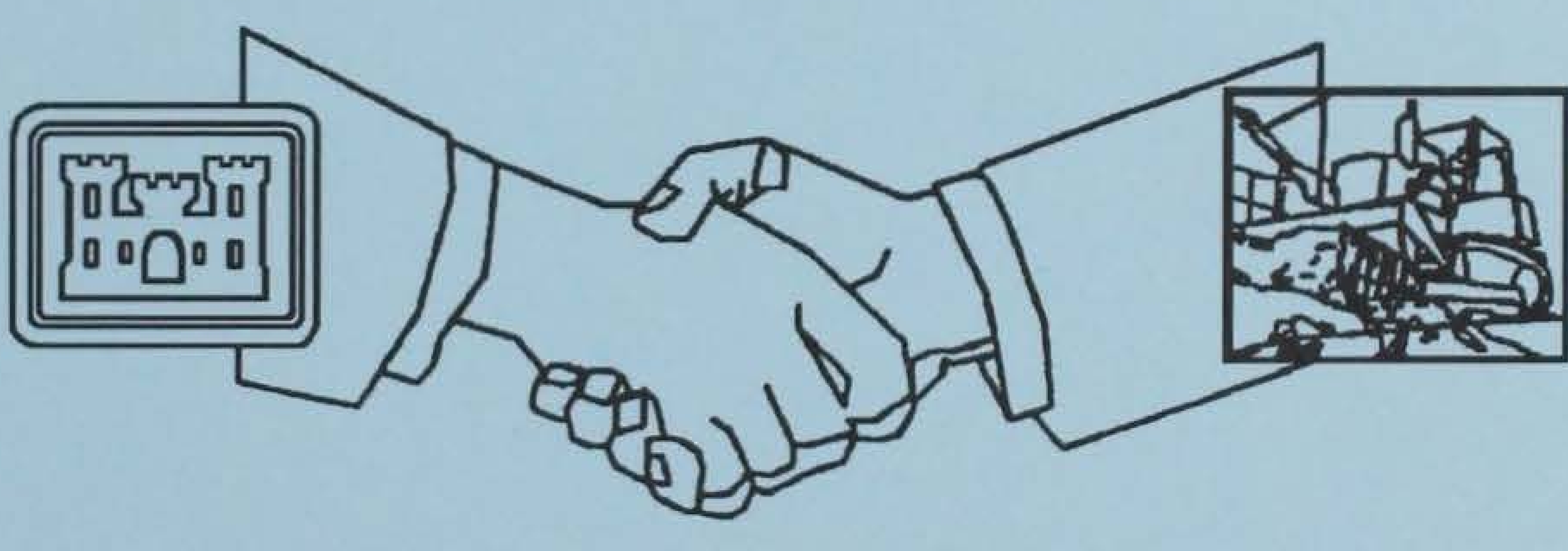
Final Report
CPAR-SL-94-2
April 1994

CONSTRUCTION PRODUCTIVITY ADVANCEMENT RESEARCH (CPAR) PROGRAM

Performance of Concretes Proportioned with Pyrament Blended Cement

by

Tony B. Husbands, Philip G. Malone, Lillian D. Wakeley



A Corps/Industry Partnership to Advance Construction Productivity and Reduce Costs

Construction Productivity Advancement
Research (CPAR) Program

Technical Report
CPAR-SL-94-2
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Performance of Concretes Proportioned with Pyrament Blended Cement

by Tony B. Husbands, Philip G. Malone, Lillian D. Wakeley

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Waterways Experiment Station
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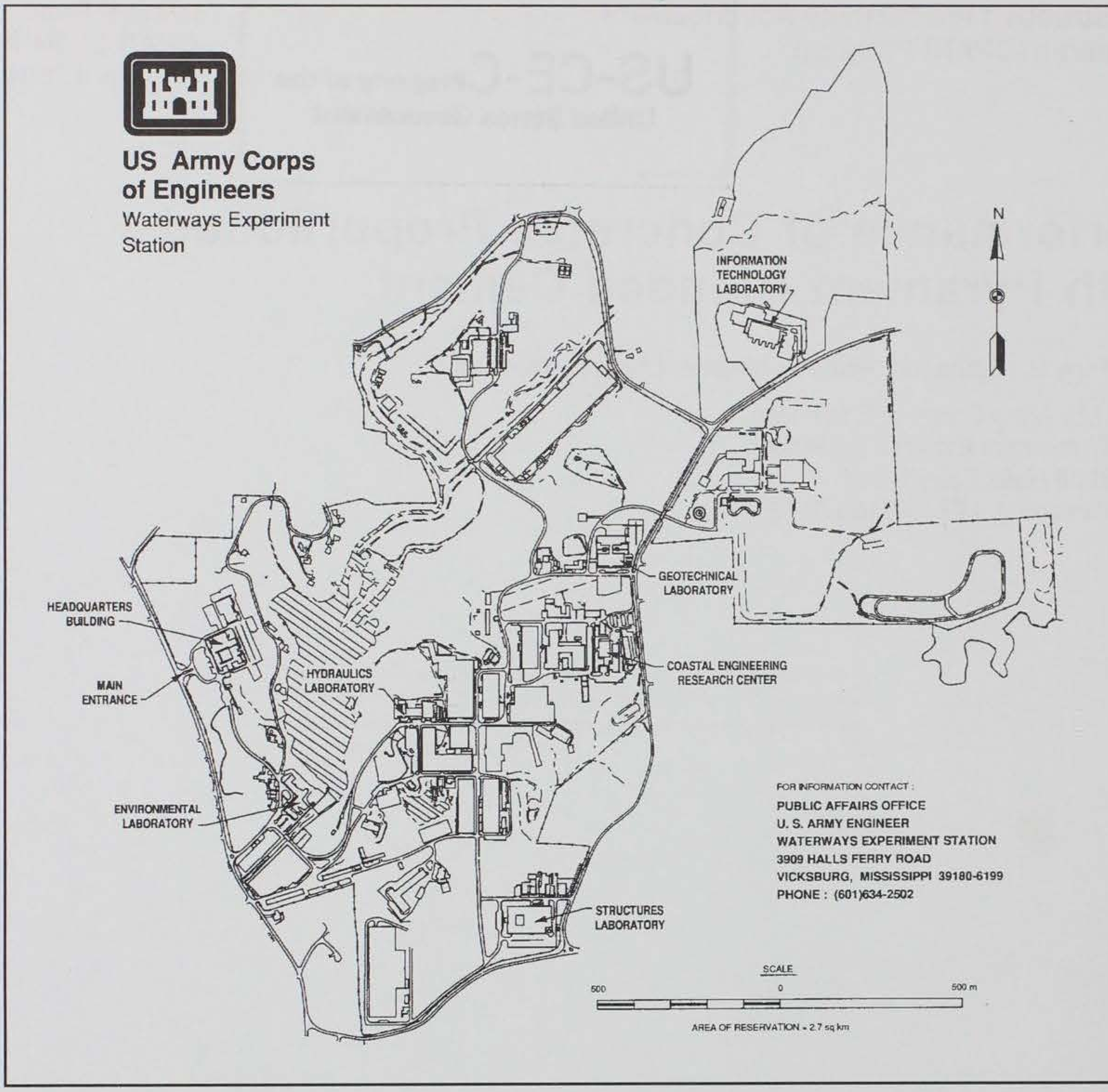

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Preface

This study was conducted at the Structures Laboratory (SL), U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, U.S. Army Corps of Engineers (USACE), under the Construction Productivity Advancement Research (CPAR) Program. The work was conducted from January 1990 to September 1993 under the project entitled "Use of a High-Performance Blended Cement System in Concrete Construction," Work Unit No. 32609. The USACE Technical Monitors were Dr. Tony Liu (CECW-EG) and Dr. D. Chen (CEMP-E). Mr. William F. McCleese was the WES CPAR Point-of-Contact.

The evaluation of the high-performance cement and concrete made with this cement and summarized in this report was part of a joint research program which was cost-shared by the USACE CPAR program and Pyrament/Lone Star Industries, Inc. USACE funds were used to support the research and testing conducted by WES, and Pyrament/Lone Star Industries, Inc., provided materials, technical information, and funds for supporting the WES research efforts.

Pyrament is a registered trademark of Pyrament/Lone Star Industries, Inc., Houston, TX.

The study was conducted under the general supervision of Mr. Bryant Mather, Director, SL; Mr. James T. Ballard, Assistant Director, SL; and Mr. Kenneth L. Saucier, Chief, Concrete Technology Division (CTD). Dr. Lillian D. Wakeley, CTD, was the Principal Investigator, and Mr. Tony B. Husbands, CTD, was the Project Coordinator. Dr. Philip G. Malone, CTD, also participated in data analysis and preparation of this report. Other CTD personnel engaged in laboratory testing and data analysis included Messrs. D. Bean, P. Collins, J. Cook, M. Hammons, M. Lloyd, B. Neeley, and T. Poole. Mr. Dick Benzinger, Pyrament/Lone Star Industries, Inc., was the CPAR industry partner's representative and reviewed this report.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Bruce K. Howard, EN.

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet	0.02832	cubic metres
Fahrenheit degrees	5/9	Celsius degrees or kelvins*
feet	0.3048000	metres
gallons	3.785412	litres
inches	25.4	millimetres
pounds (force) per square inch	0.006894757	megapascals
pounds (mass)	0.4535924	kilograms
pounds (mass) per cubic foot	16.01846	kilograms per cubic metre
pounds (mass) per cubic yard	1.6875	kilograms per cubic metre

[1] To obtain Celsius (C) temperature readings from Fahrenheit (F) readings, use the following formula: C = (5/9) (F-32). To obtain kelvin (K) readings, use K = (5/9) (F-32) + 273.15.

1 Introduction

The CPAR Program

The Corps of Engineers Construction Productivity Advancement Research (CPAR) Program is a cost-shared research and development program to facilitate development and application of advanced technologies. It permits the Corps to enter into an agreement with U.S. construction industry representatives to promote and assist in the advancement of ideas and technologies that will have a direct positive impact on construction productivity. The CPAR program has received strong support from the U.S. construction industry, and numerous projects have been funded and pursued successfully since the program was initiated in 1989.

In 1989 the U.S. Army Engineer Waterways Experiment Station (WES) and the Pyrament Lonestar Corp. (P/LS) signed a Cooperative Research and Development Agreement to begin a multiyear joint research project on high-performance blended hydraulic cement products. This agreement was enacted within the Corps. Because of the potential benefits of this developing technology for both the Federal Government and the private sector, this research on high-performance concrete was well suited to the CPAR program.

Blended Hydraulic Cements

Blended hydraulic cements are produced by blending two or more types of fine materials to change the properties or the production costs or both of a cementitious product. Most blended hydraulic cements conform to the requirements of the American Society for Testing and Materials (ASTM) C 595 (ASTM 1992b), a specification that recognizes five separate classes of blended cements based on whether pozzolan or slag is blended with the portland cement. Type IP blended cements of ASTM C 595 typically are manufactured by blending pozzolan with a portland cement or a portland blast-furnace slag cement, by intergrinding portland cement clinker and pozzolan, or by a combination of intergrinding and blending. Type IP blended cements are used in general construction where lower heat of hydration is desired. Strengths through 28 days are typically lower for the Type IP as compared to Type I (Kosmatka and Panarese 1990). The cement used in this study meets most of the requirements of a Type IP cement.

Pyrament Blended Cements

Pyrament blended cement products, especially Pyrament 505, have been used in trials for evaluating construction materials for rapid runway repair (Wakeley, Husbands, and White 1991). Alberta Transportation and Utilities tested PBC-XT and PBC-XXT to determine their compatibility with selected aggregates from Alberta (Morgan 1992).

PBC-XT was also included in tests of very early strength concretes conducted under the Strategic Highway Research Program (Zia et al. 1993, Zia and Hansen 1993).

Additionally, Pyrament has commissioned many studies to document the performance data the company provides for its products. Several studies on PBC were performed by the Ferguson Structural Engineering Laboratory, University of Texas at Austin (Carrasquillo undated a-f). The usefulness of PBC and PBC-XT in wet and dry shotcrete was evaluated by Hardy BBT Limited (Hardy BBT Limited 1989a,b). Wheat (1992) reported the results of a study of corrosion behavior of steel in reinforced concrete made using PBC.

Much of the interest in Pyrament blended cement products comes from the properties of high early strength and high ultimate strength obtained with these products. This is opposite of what is typically expected from a Type IP cement. Morgan (1992) credits the presence of alkali activators (in part) for the early strength gain. Tests run by HBT Agra Ltd. showed the alkali content of Pyrament blended cements was high (Na_2O equivalent values in the range of 2.2 to 3.0 percent) when compared to local Alberta cements (0.57 to 0.78 percent Na_2O equivalent). The high alkali content has raised the question of alkali-aggregate reactions and other questions of compatibility and corrosivity.

The product examined in this investigation, Pyrament Blended Cement, Extended Setting Time (PBC-XT), comes closest to being a portland-pozzolan cement, ASTM Type IP. PBC-XT differs from a standard Type IP cement in that it contains interground functional additions. A functional addition is any material added to change the water requirement, flow properties, time of setting, or air-entraining capabilities of the product. The functional addition or additions in PBC-XT meet the requirements of ASTM C 688 (ASTM 1991a) in that chlorides are excluded from the manufacturing process. PBC-XT is currently labelled as a Blended Hydraulic Cement Type IP (Modified).

The processing and functional additions developed for use in these fast-setting products are discussed in the patent description (U.S. Patent Office 1989). The principal components designated in the patent are portland cement, fly ash, kaolin (as metakaolin), slag, potassium carbonate, and admixtures to control setting and reduce the water requirement. The cement composition includes a number of features that depart significantly from the chemical composition of ordinary portland cement, especially the use of kaolin (metakaolin) as a pozzolan and the addition of potassium carbonate.

P/LS was manufacturing and marketing two high-performance blended cements, Pyrament Blended Cement (PBC), and Pyrament Blended Cement-Extended Setting Time (PBC-XT), at the start of this study. The difference in the two blended cements, PBC and PBC-XT, is in the length of time after mixing during which the concrete can be transported, placed, and finished. PBC has a final setting time of 30 to 45 min compared to 90 to 120 min for PBC-XT. The company was also producing two prepackaged concrete repair materials, Pyrament 505, a packaged mortar mixture; and Pyrament SAC-PAC, a repair system that included cement, sand, gravel, and a container of water packed in a mixing/carrying pail.

Objectives of this Study

The focus of this CPAR study is concrete made with PBC-XT cement. The cement has been advertised by its manufacturer as a rapid construction material due to its ability to gain high strength quickly after placement. The rapid rate of increase of both compressive and flexural strengths of PBC-XT concretes have made them attractive for use in repair projects where time-out-of-service is very costly. In new construction, PBC-XT concretes offer the properties needed to put a structure or pavement in service very quickly.

Rapid and high-strength gain in themselves, however, do not guarantee that the concrete or concrete structure will exhibit long-term durability to all potential service hazards. Measurable properties other than strength will indicate different aspects of durability. This report describes an extensive laboratory investigation to evaluate other aspects of the durability of PBC-XT concretes in addition to their strength and effects of variables such as temperature on handling and subsequent properties.

The objectives of this study were:

a. To examine the performance of PBC-XT in concretes and to determine if users can make better concrete for certain applications using this cement.

b. To expand the existing database on the strength and durability of concretes made with nontypical cements and expand the database of high-performance concretes.

c. To develop data on the performance of PBC-XT under potential field conditions that include low temperatures, high-sulfate and high-chloride environments, and with two different aggregates.

2 Materials and Test Methods

In this program standard testing procedures were applied to concrete mixtures made from representative aggregates that are of a quality that would be widely available throughout the United States. The preparation of materials followed the general guidelines specified by the manufacturer of PBC-XT.

Pyrament Cement

PBC-XT was selected for the study because among the Pyrament cement products it is considered to suit the widest variety of construction applications. P/LS provided to WES four pallets (10,000 lb) of PBC-XT cement, manufactured at its plant in Houston, TX, for the bulk of the study. This cement was received at WES in November 1989 and was assigned laboratory number CPAR-1 RBC-2. Later in the study P/LS shipped to WES one pallet (2,500 lb) of PBC-XT cement, manufactured at its plant in Greencastle, IN, for comparative testing. This cement was received at WES in December 1990 and was assigned laboratory number CPAR-1 RBC-5. A portion of a shipment from the same source arrived later and was assigned laboratory number CPAR-1 RBC-6. The results of tests conducted on RBC-2 are presented in Table 1.

Aggregates and Concrete Mixtures

Two coarse aggregates and one fine aggregate were included in the different concrete mixtures of this study. The fine aggregate, Concrete Technology Division (CTD) serial No. WESSC-7 S-1, was a natural siliceous sand with some chalcedony present. The sand was considered potentially deleterious when used with high-alkali cements. Test results for these aggregates (grading, specific gravity, and absorption) are given in Table 2. A 3/4-in. crushed limestone, CTD serial No. CPAR-1 MG-1, was one of the coarse aggregates selected for this study, and a 1-in. river gravel, CTD serial No. CPAR-1 G-1, was the other coarse aggregate selected. The test results for these two aggregates are given in Tables 3 and 4. The two coarse aggregates represent typical varieties of dolomitic and siliceous aggregates

Table 1
Test Results for Pyrament/Lone Star Blended Cement Extended Setting Time (PBC-XT)

CTD No. CPAR-1, RBC-2	
Chemical Determination	**Results**
MgO (%)	2.11
SO_3 (%)	2.94
Loss on ignition (%)	4.75
Insoluble residue (%)	8.76
Na_2O (%)	0.48
K_2O (%)	3.42
Physical Tests	
Blaine fineness (mg^2/kg)	490
Autoclave expansion (%)	0.073
Specific gravity	2.86
Initial time of setting (min.)	53
Final time of setting (min.)	65
Air content (%)	15.4/14.8
Heat of hydration, 7 days (cal/g)	86
Heat of hydration, 28 days (cal/g)	95

with consistent mineralogic compositions, hardnesses, and particle shapes, so that the interaction of these factors with Pyrament cement would be explored in this study. Additionally, CPAR-1 G-1 contained some chalcedony that made it potentially a sensitive aggregate that could produce deleterious effects with a high-alkali cement. The results of a petrographic examination for all three aggregates are presented in Appendix A.

Two coarse aggregates and three cement contents were used to proportion the different concrete mixtures for testing. The cement contents of the concrete mixtures were 6.0 sacks (564 lb), 7.0 sacks (658 lb), and 8.0 sacks (752 lb) per cubic yard of concrete. The laboratory designation of each mixture given in Table 5 indicates aggregate type river gravel (RG), limestone (L), and cement content (6, 7, 8).

No admixtures were used with the concretes. The information provided by the manufacturer states that the cement is a complete cement system without the need for use of admixtures. Given that the cement contains proprietary functional additions to control its workability and setting time, P/LS recommends against use of admixtures because of the potential for chemical interactions between such admixtures and components of the Pyrament cement system. Such chemical interactions could modify the physical properties and performance of the concrete. The mixing water was adjusted to obtain a slump of 4-1/2 $\pm$ 1/2 in. Detailed mixture proportions are given in Tables 6 through 11.

Table 2
Test Data on Fine Aggregate
WESSC-7 S-1 Natural Sand
Cobb Industrial Corp., Coushatta, LA

Sieve Analysis (CRD-C 105)	
Sieve No.	**Cumulative % Passing**
No. 4	99.3
No. 8	84.5
No. 16	63.8
No. 30	49.8
No. 50	12.8
No. 100	0.9
No. 200	0.2
<No. 200	0
Additional Tests	
Free moisture, CRD-C 104 (%)	2.89
Bulk specific gravity, SSD, CRD-C 107, 108 (%)	2.63
Absorption, CRD-C 107, 108 (%)	0.4

Table 3
Test Data on Coarse Aggregate (Crushed Limestone)
CPAR-1 MG-1
Vulcan Materials, Calera, AL

Sieve Analysis (CRD-C 105)	
Sieve Designation	**Cumulative % Passing**
1 in.	100
3/4 in.	99
1/2 in.	71
3/8 in.	48
No. 4	11
Additional Tests	
Bulk specific gravity, SSD, CRD-C 107, 108 (%)	2.7
Absorption, CRD-C 107, 108 (%)	0.5

Table 4
Test Data on Coarse Aggregate (Natural Gravel)
CPAR-1 G-1
Mississippi Materials Co., Vicksburg, MS

Sieve Analysis (CRD-C 105)	
Sieve Designation	**Cumulative % Passing**
1-1/2 in.	100
1 in.	90
3/4 in.	57
1/2 in.	30
3/8 in.	17
No. 4	2
Additional Tests	
Bulk specific gravity, SSD, CRD-C 107, 108 (%)	2.55
Absorption, CRD-C 107, 108 (%)	2.1

Table 5
Summary of Concrete Mixtures

		Cement Content	
Mixture Designation	**Coarse Aggregate**	**sacks* per yd^3**	**lb per yd^3**
RG-6	River gravel	6	564
RG-7	River gravel	7	658
RG-8	River gravel	8	752
L-6	Limestone	6	564
L-7	Limestone	7	658
L-8	Limestone	8	752

* A "sack" or "bag" of cement is 1/4 of a barrel (376 lb), that is 94 lb. Measurement of cement in these units is not standard in professional concrete engineering.

Table 6
Concrete Mixture Proportions for Mixture RG-6

Materials	Serial No.	Size Range	Bulk Specific Gravity	Absorption (%)
Pyrament cement	CPAR-1 RBC-2		2.85	
Fine aggregate	WESSC-7 S-1	No. 4 - 200	2.63	0.4
Coarse aggregate	CPAR-1 G-1	No. 4 - 1 in.	2.55	2.1

Materials	SSD Weights in 1-yd^3 Batch (lb)	Solid Volume in 1 yd^3 (cu ft)
Portland cement	564	3.171
Fine aggregate	1,491	9.082
Coarse aggregate	1,766	11.101
Water	143	2.296
Air		1.350
Total		27.000
Water-cement ratio	0.254	
Slump (in.)	--	
Air content (%)	5	
Sand/aggregate (% vol)	45	
Actual cement factor (lb/cu yd)	564	

Table 7
Concrete Mixture Proportions for RG-7

Materials	Serial No.	Size Range	Bulk Specific Gravity	Absorption (%)
Pyrament cement	CPAR-1 RBC-2		2.85	
Fine aggregate	WESSC-7 S-1	No. 4 - 200	2.63	0.4
Coarse aggregate	CPAR-1 G-1	No. 4 - 1 in.	2.55	2.1

Materials	SSD Weights in 1-yd^3 Batch (lb)	Solid Volume in 1 yd^3 (cu ft)
Portland cement	658	3.700
Fine aggregate	1,450	8.838
Coarse aggregate	1,719	10.803
Water	144	2.309
Air		1.350
Total		27.000
Water-cement ratio	0.219	
Slump (in.)	--	
Air content (%)	5	
Sand/aggregate (% vol)	45	
Actual cement factor (lb/cu yd)	658	

Table 8
Concrete Mixture Proportions for Mixture RG-8

Materials	Serial No.	Size Range	Bulk Specific Gravity	Absorption (%)
Pyrament cement	CPAR-1 RBC-2		2.85	
Fine aggregate	WESSC-7 S-1	No. 4 - 200	2.63	0.4
Coarse aggregate	CPAR-1 G-1	No. 4 - 1 in.	2.55	2.1

Materials	SSD Weights in 1-yd^3 Batch (lb)	Solid Volume in 1 yd^3 (cu ft)
Portland cement	752	4.229
Fine aggregate	1,373	8.365
Coarse aggregate	1,694	10.646
Water	150	2.296
Air		1.350
Total		27.000

Water-cement ratio	0.200	
Slump (in.)	--	
Air content (%)	5	
Sand/aggregate (% vol)	44	
Actual cement factor (lb/cu yd)	752	

Table 9
Concrete Mixture Proportions for Mixture L-6

Materials	Serial No.	Size Range	Bulk Specific Gravity	Absorption (%)
Pyrament cement	CPAR-1 RBC-2		2.85	
Fine aggregate	WESSC-7 S-1	No. 4 - 200	2.63	0.4
Coarse aggregate	CPAR-1 MG-2	No. 4 - 3/4 in.	2.77	0.5

Materials	SSD Weights in 1-yd^3 Batch (lb)	Solid Volume in 1 yd^3 (cu ft)
Portland cement	564	3.171
Fine aggregate	1,460	8.899
Coarse aggregate	1,860	10.447
Water	143	2.296
Air		1.350
Total		27.000

Water-cement ratio	0.247	
Slump (in.)	4	
Air content (%)	5	
Sand/aggregate (% vol)	46	
Actual cement factor (lb/cu yd)	564	

Table 10
Concrete Mixture Proportions for Mixture L-7

Materials	Serial No.	Size Range	Bulk Specific Gravity	Absorption (%)
Pyrament cement	CPAR-1 RBC-2		2.85	
Fine aggregate	WESSC-7 S-1	No. 4 - 200	2.63	0.4
Coarse aggregate	CPAR-1 MG-2	No. 4 - 3/4 in.	2.77	0.5

Materials	SSD Weights in 1-yd^3 Batch (lb)	Solid Volume in 1 yd^3 (cu ft)
Portland cement	658	3.700
Fine aggregate	1,460	8.899
Coarse aggregate	1,806	10.447
Water	163	2.604
Air		1.350
Total		27.000
Water-cement ratio	0.247	
Slump (in.)	4	
Air content (%)	5	
Sand/aggregate (% vol)	46	
Actual cement factor (lb/cu yd)	658	

Table 11
Concrete Mixture Proportions for Mixture L-8

Materials	Serial No.	Size Range	Bulk Specific Gravity	Absorption (%)
Pyrament cement	CPAR-1 RBC-2		2.85	
Fine aggregate	WESSC-7 S-1	No. 4 - 200	2.63	0.4
Coarse aggregate	CPAR-1 MG-1	No. 4 - 3/4 in.	2.77	0.5

Materials	SSD Weights in 1-yd^3 Batch (lb)	Solid Volume in 1 yd^3 (cu ft)
Portland cement	752	4.229
Fine aggregate	1,382	8.421
Coarse aggregate	1,779	16.292
Water	169	2.708
Air		1.350
Total		27.000
Water-cement ratio	0.225	
Slump (in.)	5	
Air content (%)	5	
Sand/aggregate (% vol)	45	
Actual cement factor (lb/cu yd)	752	

Preparation of Test Samples

Two different types of concrete mixers were used to mix the concrete for tests. The larger concrete batches, 8 cu ft in size, were mixed in a revolving drum concrete mixer. Smaller batches of concrete were mixed in a rocking-and-tilting mixer. Each batch of concrete was mixed for 10 min after the addition of the mixing water. The size and type (bars, cylinders, etc.) of specimens prepared from each batch were determined by the specific tests planned for that batch.

Test specimens were consolidated by vibration and removed from the molds 3 to 5 hr after mixing, depending on the requirements of the testing. Most specimens were stored in laboratory air until time of testing, except for the test beams prepared for the freezing and thawing test, which were placed in limewater after removal from the molds. Test specimens typically were covered with a plastic sheet within a few minutes after being removed from the molds, to reduce air circulation over the specimens during the first 24 hr. In general, the sample preparation followed ASTM standard practice C 31-91 (ASTM 1992a). A number of specimens were moist-cured for specific tests. These were placed in a moist curing room immediately after removal from the molds and left there until time of test.

Test Methods

Preparation and testing of specimens followed standard procedures of ASTM, U.S. Army Corps of Engineers, or American Association of State Highway Transportation Officials (AASHTO). The test performed and the applicable method or specification are given in Table 12. Test results are presented in Chapter 3.

Compressive Strength

The unconfined compressive strengths of specimens of each concrete were determined according to ASTM C 39-86 (ASTM 1992c). Batches of each of the six concrete mixtures were prepared on three separate occasions. Twenty-one 4- by 8-in. cylinders were cast from each batch of concrete. Three concrete cylinders from each batch of concrete were tested at the following ages: 4 hr, 6 hr, 1 day, 7 days, 28 days, 6 months, and 1 year.

Flexural Strength

The flexural strength of each concrete was determined according to ASTM C 78-87 (ASTM 1992e), using specimens from the same batches of concrete that were prepared for making cylinders for compressive strength testing.

Table 12
Summary of Sample Testing Protocols

Type of Test	Test Method or Specification
Unconfined Compressive Strength	ASTM C 39-86 (ASTM 1992c)
Flexural Strength	ASTM C 78-87 (ASTM 1992e)
Freezing and Thawing Resistance	ASTM C 666-84 (Procedure A) (ASTM 1990c)
Abrasion Resistance	ASTM 1138-89 (ASTM 1991c)
Bond Strength to Hardened Concrete	ASTM C 882-87 (ASTM 1990a)
Effect of Low Temperatures on Strength Gain	Modified ASTM C 39-86 (ASTM 1992c)
Drying Shrinkage	ASTM C 157-89 (ASTM 1991e)
Creep	ASTM C 512-87 (ASTM C 1992d)
Sulfate Resistance, Mortar Bar	ASTM C 1012-87 (ASTM 1988)
Sulfate Resistance, Concrete Beams	ASTM C 1012-87 (ASTM 1988)
Scaling Resistance to Deicing Chemicals	ASTM C 672-84 (ASTM 1990d)
Chloride Permeability	AASHTO T 259-80 (ASTM 1990b)
Chloride Permeability (Rapid)	AASHTO T 277-89 (AASHTO 1990a)
Potential Alkali-Aggregate Reactivity	ASTM C 227-87 (ASTM 1990b)
Long-Term Durability	Outdoor Exposure developed by WES

Seven 6- by 6- by 36-in. beams were cast from each batch of concrete. One concrete beam from each batch was tested at the following ages: 4 hr, 6 hr, 1 day, 7 days, 28 days, 6 months, and 1 year. Two measurements were obtained from each beam when tested.

Resistance to Damage in Cycles of Freezing and Thawing

The resistance of the concretes to damage from cyclic freezing and thawing was determined according to ASTM C 666-84, Procedure A (ASTM 1990c). Three beams of 3.5 by 4.5 by 16 in. were prepared from a batch of concrete. Six beams were prepared from two batches of concrete mixed on different days. Test specimens were stored in lime-saturated water beginning at 1 day age and continuing until tests were started at 14 days age. All test specimens were subjected to 300 cycles of freezing and thawing. Test specimens prepared from mixtures L-7 and L-8 were tested for an additional 200 cycles of freezing and thawing.

Abrasion Resistance

The abrasion resistance was determined for the three concrete mixtures containing river gravel according to ASTM C 1138-89, Standard Test Method for Abrasion Resistance of Concrete (Underwater Method) (ASTM 1991c). Three test specimens from each of the three concrete mixtures, RG-6, RG-7, and RG-8, were cast and allowed to cure in laboratory air for 28 days, then soaked under water for 7 days before being tested. Each test specimen was tested for 72 hr. Specimen mass was measured every 12 hr during testing, and the volume of erosion was calculated relative to initial mass.

Bond Strength to Hardened Concrete

Test specimens were prepared and tested according to a method modified from ASTM C 882-87 (ASTM 1990a), slant-shear bond test. The test method was modified to bond PBC-XT cement concrete directly to existing concrete using 4- by 8-in. cylinders as described by Wakeley, Husbands, and White (1991). The recipient concrete was prepared from a concrete mixture containing a 3/8-in. pea gravel and having a compressive strength of at least 6,000 psi. Half sections of a 4- by 8-in. cylinder were cast from the recipient concrete mixture and moist cured for 28 days. The elliptical bonding surfaces of the half cylinders were prepared by light sandblasting and dried before preparation of test specimens. Three of the test specimens from each concrete mixture were tested for bond strength at the following ages: 6 hr, 1 day, and 28 days.

Effect of Low Temperatures on Strength Gain

Concrete cylinders, 4 by 8 in., were cast from concrete mixture L-8 for determination of strength gain at low temperatures. Concrete was mixed in a large refrigerated room, conditioned at 40 °F, using an electric portable concrete blade mixer. The concrete mixer was placed inside the temperature-controlled room 24 hr or longer before mixing was started. An environmental chamber, which could be adjusted to maintain different temperatures, was used to store test specimens after they were cast, and to condition the PBC-XT cement and the two aggregates to the test temperature prior to mixing. The mixing water was adjusted to two temperatures for the tests, 73 and 150 °F. Five temperatures, 40, 30, 20, 10, and 0 °F, were selected for the tests. The cement and aggregates were conditioned to the test temperature except for 0 °F, for which they were used at 73 °F. The hot mixing water was used in batching the concretes tested at 30, 20, and 10 °F.

The concrete mixture for each batch was approximately 1 cu ft in volume (137 lb). Each batch of concrete was mixed for 10 min after the addition of the mixing water. Ten cylinders were prepared from each batch of concrete, nine for testing and one for thermal monitoring. The concrete cylinders were placed in the environmental chamber 25 to 30 min after mixing was started. A thermocouple wire was placed in the middle of one cylinder to measure the temperature of the concrete with time.

Concrete cylinders were tested for compressive strengths at the following ages: 6 hr, 24 hr, and 7 days. Three of the cylinders were removed from the environmental chamber 15 min before time of test. They were capped with a hot sulfur compound within 10 min after being removed from the chamber and tested within 5 min of the designated test age.

Drying Shrinkage

Three concrete beams measuring 3 by 3 by 10 in. were cast from each of the six concrete mixtures. The initial length of each beam was measured 4 hr from the time of mixing. The beams were stored in laboratory air at 72 °F and 50 percent relative humidity. Shrinkage of the beams was monitored for a period of 365 days by measuring the length change according to ASTM C 1012-87 (ASTM 1988).

Creep

Specific creep was determined according to ASTM C 512-87 (ASTM 1992d) modified to include continuous data acquisition by computer. The specimens tested were 6 in. in diameter by 16 in. in length. Creep specimens were cast in steel forms with the longitudinal axis horizontal. These forms accommodated Carlson strain meters placed at the center of the specimens oriented along the longitudinal axis of the cylinder. Steel bearing plates were attached to the ends of the specimen by embedded mechanical anchors. These plates provided a smooth plane surface for applying the compressive force. A bituminous moisture barrier was applied to the surface of each creep specimen immediately after the molds were removed, to prevent moisture from entering or leaving the specimen.

The apparatus used to perform the creep tests was a hydraulic loading frame designed to maintain a constant stress by means of a gas pressure regulator in series with a gas-over-oil accumulator and hydraulic ram. The desired applied stress was set by means of a gas pressure regulator. The test device accommodated two specimens loaded in series. Two control cylinders were also monitored to determine the strains not associated with the applied loads. The creep specimens were loaded to 25 percent of the unconfined compressive strength at the age of loading as determined from unconfined compressive tests on companion 4- by 8-in. cylinders. The following measurements were recorded using a digital data acquisition unit:

a. Applied stress, by a pressure transducer located in the gas pressure regulator output line.

b. Strain and temperature in the loaded specimen, by a Carlson strain meter embedded in the center of the specimen.

c. Strain and temperature in the control specimen, by a Carlson strain meter embedded in the center of the specimen.

d. Time, by an internal clock in the computer data-acquisition unit.

The strains recorded by the control cylinders were subtracted from the measured strains to obtain corrected creep strain. These corrected strains were divided by the applied stress to obtain creep strain per unit stress (specific creep).

Sulfate Resistance

The resistance to sulfate attack of PBC-XT cement and concrete prepared from the cement was measured using the following test methods.

a. *Mortar bar.* Mortar bars were prepared and tested according to ASTM C 1012-87 (ASTM 1988). The mixing water was adjusted to obtain a flow of 110 ± 5 for the mortar. The mortar bars were stored in the mixed sulfate solution specified in the test method.

b. *Concrete beams.* Three 3- by 3- by 10-in. beams were cast from each of the six concrete mixtures. The beams were removed from the molds after curing in air for 24 hr and the initial length measured. The beams were then placed in a solution of 10 percent magnesium and sodium sulfate. The length change was measured according to ASTM C 1012-87 (1988).

Scaling Resistance to Deicing Chemicals

Three test specimens measuring 8 by 12 by 3 in. were cast from each of the six concrete mixtures and tested according to ASTM C 672-84 (ASTM 1990d). All specimens were demolded 4 hr after mixing. The surface around the top edge of each specimen, a strip approximately 1/2 in. wide, was abraded slightly soon after removal from the molds. An epoxy-resin mortar was then placed around the edge of the dike to maintain the pond of deicing solution (a 4-percent calcium chloride solution). The test was started 24 hr after mixing. Specimens were tested for 50 cycles of freezing and thawing.

Chloride Permeability

Two test methods were used for determining the chloride permeability of PBC-XT concretes: AASHTO T 259-80, "Resistance of Concrete to Chloride

Ion Penetration (AASHTO 1990b)," and AASHTO T 277-89, "Rapid Determination of the Chloride Permeability of Concrete (AASHTO 1990a)." Test specimens were prepared from mixtures containing only the limestone coarse aggregate. Cement content and water-cement ratio are the greatest contributing factors for permeability, so it was not considered necessary to test concretes with both coarse aggregates. Also, using limestone aggregate made it easier to drill into test specimens to obtain samples for analysis.

Chloride penetration testing by AASHTO T 259-80

Specimens were prepared for exposure to a chloride solution by continuous ponding, as described in AASHTO T 259-80 (AASHTO 1990b).

Two test specimens measuring 8 by 12 by 3 in. were cast from each of the concrete mixtures L-6, L-7, and L-8. Test specimens were stripped from the molds 4 hr after mixing. An epoxy-resin mortar was then placed around the top edge of the specimens, as a dike, to contain a 3-percent sodium chloride solution which was poured onto the top of the specimens 24 hr after mixing.

After ponding with the sodium chloride solution for 90 days, the specimens were rinsed off with tap water and brushed lightly with a steel bristle brush to remove any salt deposits on the top surface. Six holes were drilled into the top surface of each test specimen to obtain powered samples 0 to 1/2 in., 1/2 to 1 in., and 1 to 1-1/2 in. Chloride content of the powdered sample was determined in accordance with AASHTO T 260-82 (AASHTO 1990c). The analytical method follows T 259-80 (AASHTO 1990b).

Chloride permeability testing by AASHTO T 277-89

AASHTO T 277-89 is the rapid-chloride permeability (RCP) test described by Whiting (1981, 1988). In this test, the permeability of a concrete to chlorides is estimated relatively by measuring the number of coulombs that can pass through sample in a 6-hr test, following appropriate preconditioning. The test is designed for specimens that have been moist cured for 28 days. Testing of Pyrament-cement concrete samples was conducted on samples as young as 7 days.

Test specimens were prepared by casting 4- by 8-in. cylinders from the concrete mixtures being tested. The concrete cylinders were moist cured until time of testing. A few concrete cylinders cast earlier in the test program also were tested when 1 year old. A 2-in. slice was cut from the top of each cylinder using a diamond blade saw. The slices of concrete were allowed to dry before coating the sides with a fast-setting epoxy resin paste 1 day before testing. Then, as described in the test, they are exposed to a sodium chloride solution and a 60-volt direct current power supply. A concrete with low permeability will pass only a low current during this test.

Potential Alkali Reactivity

The potential for expansion due to alkali-aggregate reaction was determined according to ASTM C 227-87 (ASTM 1990b). Mortar bars 1- by 1- by 10-in. were prepared from PBC-XT cement using crushed Pyrex glass as aggregate.

Later in the study, an aggregate was shipped to WES from Vulcan Material Company, North Carolina, as requested by P/LS. The aggregate was a crushed 3/4-in. stone from Gold Hill Quarry, North Carolina, which has been reported to be a source for reactive aggregates. The aggregate was assigned laboratory number 920185. A similar aggregate was used in studies of high-performance concrete conducted for the Strategic Highway Research Program by Zia et al. (1993).

The aggregate was tested to determine if it was potentially reactive using the quick chemical and the mortar-bar methods as described in ASTM C 289-87 (ASTM 1992f) and ASTM C 227-87 (ASTM 1990b), respectively. A portland cement (RBC-5) having a total alkali content of 1.15 percent was used in preparing the mortar bars.

Concrete beams measuring 3 by 3 by 10 in. were prepared from a concrete mixture identical to L-8 except that the reactive aggregate above was substituted for the limestone aggregate. The beams were stripped from the molds after 5 hr and tested in an exposure similar to that prescribed in to ASTM C 227-87 (ASTM 1990b).

Long-Term Durability Testing

Eighteen concrete beams measuring 6 by 6 by 36 in., prepared from the six concrete mixtures described in Tables 6 through 11, were placed at Treat Island, Maine, in August 1990. Treat Island Severe Weathering Exposure Station has been in use by the U.S. Army Corps of Engineers since 1936. Its location makes it useful for exposing concretes to severe natural weathering. The specimens are installed at mean-tide elevation. The tidal range is approximately 20 ft, and the alternating conditions of immersion of the specimens in seawater and exposure to cold air provide numerous cycles of freezing and thawing of the concrete during the winter.

In winter, the combination of air and water temperatures creates a condition in which specimens at the mean-tide elevation are thawed to temperature of about 37 °F when covered with water and are frozen to temperatures as low as -10 °F when exposed to air. The depth of freezing may vary with the size of the specimen. During an average winter, the specimens are subjected to over 100 cycles of freezing and thawing. During the summer of each year, an inspection and testing team visits the exposure to conduct the annual inspection and testing of all specimens by visual and nondestructive methods.

Measurements were made on the 18 beams each year in 1991, 1992, and 1993. The beams were cleaned by scraping with a wide putty knife to remove the mud and vegetation and washed with low-pressure (5 psi) salt water spray. Care was taken not to damage intact concrete. The samples were then photographed and ultrasonic pulse velocities were measured using the method outlined in ASTM C 597-83 (ASTM 1991f). The velocity meter was calibrated by making measurements on a reference bar at the start and periodically during the testing. Transducers 50 mm in diameter were used with a coupling medium made of kaolinite and glycerol. The dynamic Young's modulus (E) was measured using methods described in ASTM C 215-85 (ASTM 1991d).

3 Test Results

Compressive Strength

The individual compressive strength test results from each specimen tested at each age are given in Appendix B. The average of the individual test results for each concrete mixture and age is given in Table 13.

Table 13
Summary of Unconfined Compressive Strength Measurement*

Time of Test	RG-6	L-6	RG-7	L-7	RG-8	L-8
4 hr	2,340	2,380	3,090	3,790	3,750	4,110
6 hr	2,640	2,770	3,630	4,370	4,190	4,900
24 hr	4,430	4,620	5,270	6,070	5,940	6,380
7 day	6,940	7,250	8,150	9,340	8,840	9,590
28 day	8,900	8,800	9,370	10,180	9,980	10,670
6 mo	8,900	9,530	9,880	10,120	10,380	10,920
1 yr	9,360	9,430	10,380	11,090	10,770	11,670

* Average of three individual test results (psi).

High compressive strengths were obtained at ages of 4 and 6 hr. Compressive strengths values ranging from 2,340 to 4,110 psi, were obtained 4 hr after mixing was started. The average compressive strength of the two eight-sack mixtures at 4 hr was 3,930 psi compared to 2,360 psi for the two six-sack mixtures, or 67 percent higher. The 24-hr strengths ranged from 4,430 to 6,380 psi. From examining the results above, it is evident that high early strengths are dependent on the cement content.

The concrete mixtures continued to gain strength up to the end of the testing (1 year) as indicated by the test data. High ultimate strengths ranging from 9,360 to 11,670 psi were obtained from the different concrete mixtures. The difference in strengths between the six-sack mixtures and the eight-sack mixtures after 1 year storage was 1,820 psi. This is a difference of

19 percent which is significantly lower than the 66-percent difference at the 4-hr age.

Flexural Strength

The individual flexural strength results for each specimen tested and the average test results for each age are given in Appendix C. The average test results for the concrete mixtures prepared with the river gravel and the limestone aggregates were plotted in Figures 1 and 2, respectively. Similar to the compressive strength test results, high early strengths were obtained from the different concrete mixtures, and higher cement contents contributed to significantly higher strengths at the early ages of 4 and 6 hr. Flexural strengths, near and exceeding 500 psi, were obtained 4 hr after addition of the mixing water for the seven-sack and eight-sack mixtures. The concrete mixtures continued to gain strength with time up to 6 months, which can be seen in Figures 1 and 2. The flexural strengths ranging from 865 to 1,020 psi were obtained after 6 months. A reduction in flexural strength was measured between 6 months and 1 year, which could not be explained at that time. No loss of compressive strength was observed between 6 months and 1 year.

Before the 1-year tests were performed, preliminary tests had shown that there was a significant difference in flexural strength between specimens cured in laboratory air and cured in moist air. A significant difference in flexural strengths after 28 days was observed between the air-cured and moist-cured specimens. However, there was no significant difference between the compressive strengths of specimens that could be attributed to curing methods. One of the flexural strength specimens from concrete mixture RG-6, which was 1 year old, was placed in lime water for 5 days before being tested. The test results obtained from this test specimen were 1,100 and 1,090 psi. These strengths were approximately 50 percent higher than the results obtained from the other two specimens from that mixture which were 1 year old.

A moist-cured flexural strength test specimen will give a very reduced value for strength if it is allowed to surface dry even to an apparently minor degree. Surface drying puts the surface in tension. The flexural test measures the total tension in the surface: that applied by the testing machine and that due to surface drying. Only tension applied by the machine is recorded and used to compute strength. If a specimen has a uniform moisture content, either essentially saturated (moist cured) or dry (constant mass), the strength may not be very different.

Properties of PBC-XT Concrete Moist Cured and Air Cured

The original Project Plan stated that all test specimens would be air cured in the laboratory. As the study progressed, it was decided that a comparison should be made between moist-curing and air-curing specimens. Two

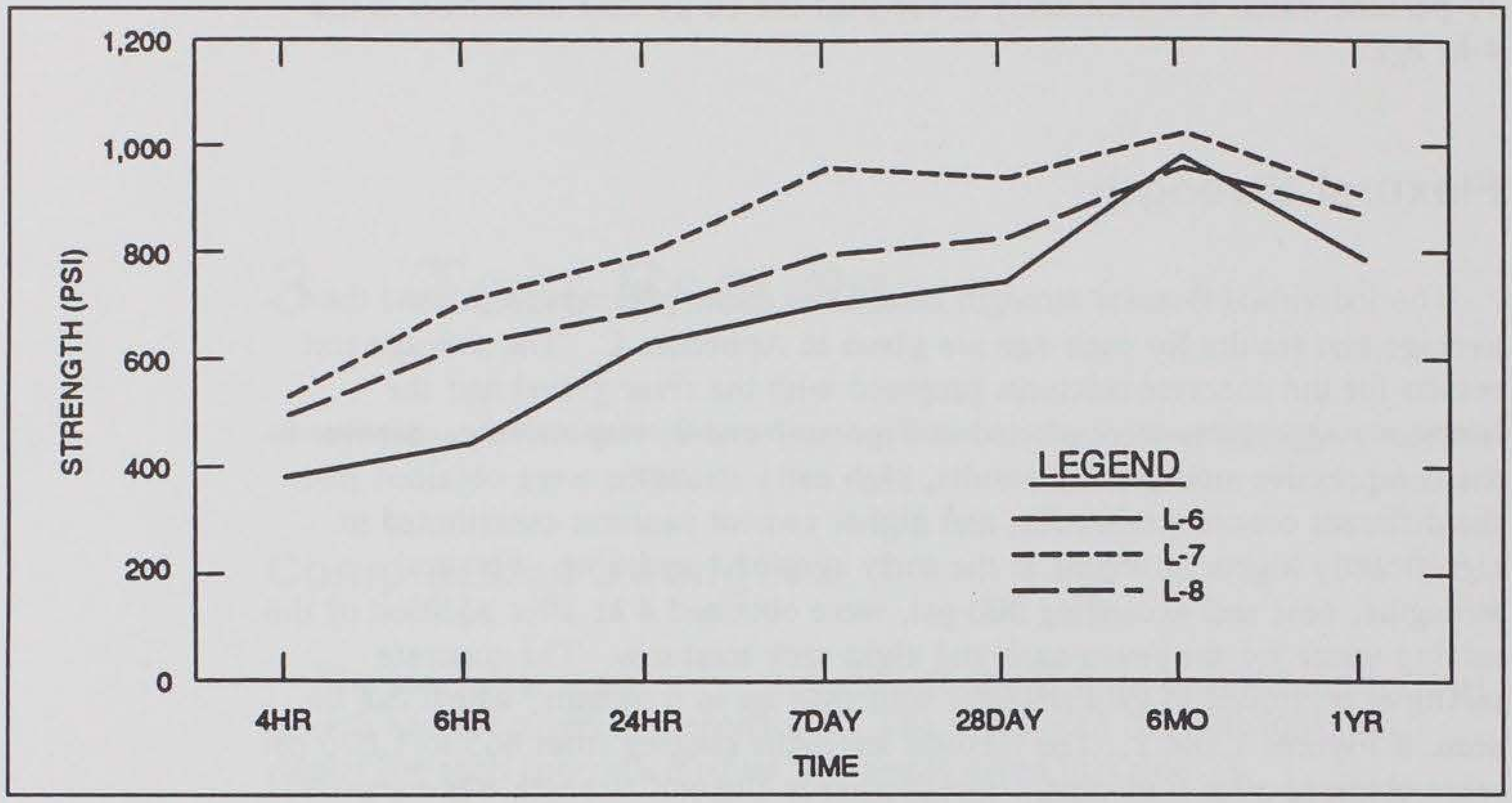

Figure 1. Results of flexural strength tests for PBC-XT concrete with river gravel

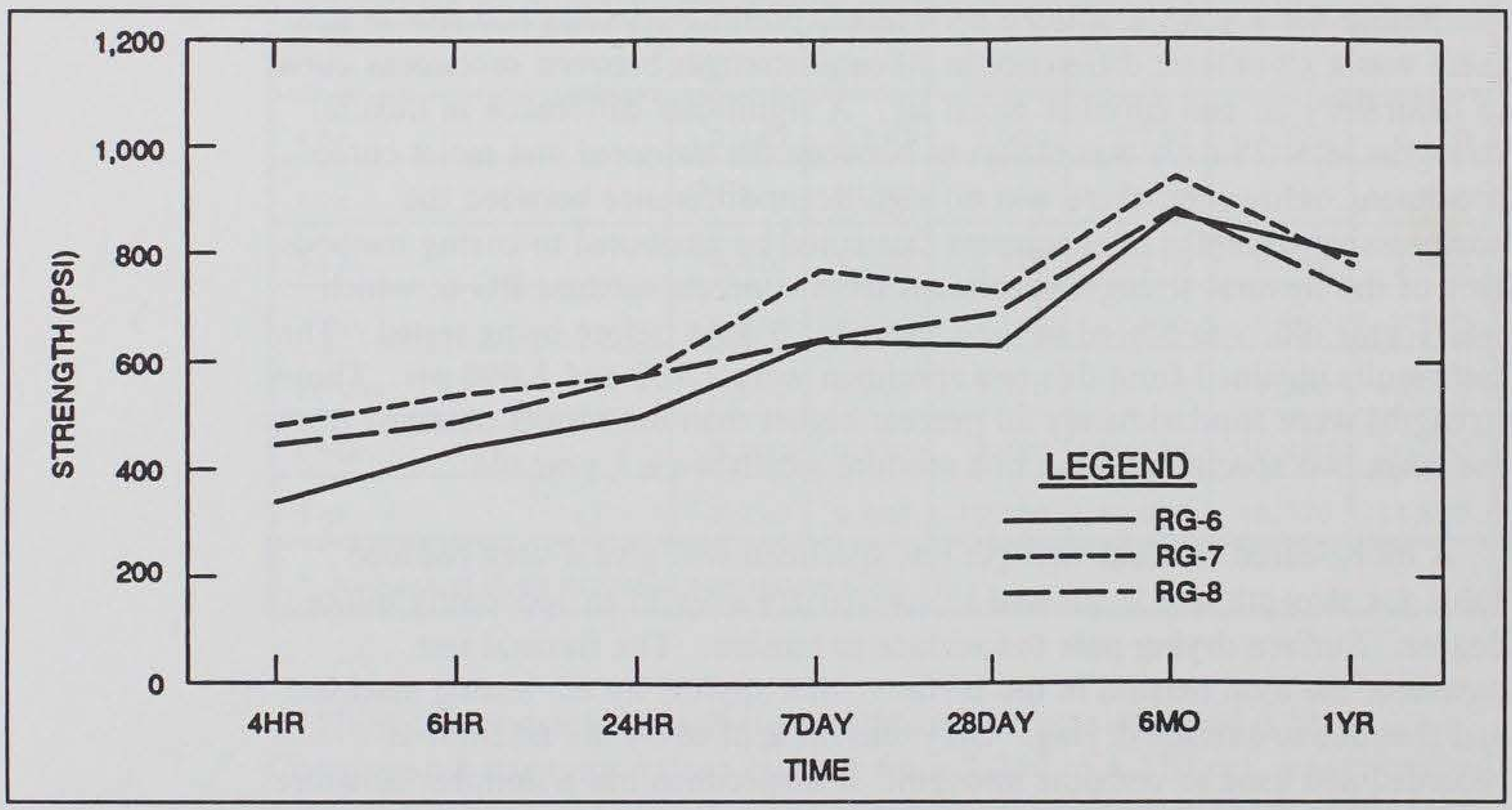

Figure 2. Results of flexural strength tests for PBC-XT concrete with crushed limestone

mixtures, L-7 and L-8, were selected for these tests. Test specimens were prepared from two batches of concrete for each mixture. Half of the test specimens from each batch of concrete were left in the laboratory to cure in air and the remaining half were placed in a moist-curing room 6 hr after being cast. All specimens were tested at 28 days after casting. The average test results are given in Table 14.

Table 14 Properties of PBC-XT Concrete Moist Cured and Air Cured			
Curing Condition	**Concrete Mixture**	**Property**	**Test Results**
Moist	7 sack	Compressive strength, psi	8,670
Moist	8 sack	Compressive strength, psi	9,580
Air	7 sack	Compressive strength, psi	10,180
Air	8 sack	Compressive strength, psi	10,640
Moist	7 sack	Flexural strength, psi	1,345
Moist	8 sack	Flexural strength, psi	1,430
Air	7 sack	Flexural strength, psi	820
Air	8 sack	Flexural strength, psi	940
* All test specimens were cured for 28 days.			

The results obtained from measuring the flexural strengths of beams from various cures and storage conditions were notably different. The flexural strengths for the moist-cured specimens were 1,345 and 1,430 psi compared to 820 and 940 psi for the air-cured specimens, a difference of approximately 60 percent. The difference in compressive strengths was much lower with the air-cured specimens being approximately 10 percent higher. Drying generally increases compressive strength.

Effect of Different Storage Conditions on Strength

Following the determination that storage conditions appeared to affect measured flexural strength more than it did compressive strength, a limited test program was designed to determine the effects of different storage conditions on the strength of one of the PBC-XT concretes. Test specimens were prepared from concrete mixture L-8 to determine the effect of different storage conditions on compressive and flexural strength. The different storage conditions used for the tests are presented in Table 15.

Table 15 Storage Conditions for PBC-XT Concrete	
Condition Designation	**Description of Storage Condition**
A	Stored under water until time of test.
B	Stored in laboratory air until time of test.
C	Stored under water, then placed in laboratory 3 days before time of test.
D	Stored in laboratory air, then placed under water 3 days before time of test.

After casting, all of the test specimens were placed in laboratory air for 24 hr before being stripped from the molds. They were then placed in the designated storage conditions. Specimens were tested at 7, 28, and 180 days. Sixteen concrete beams, 6- by 6- by 36-in., were cast from two batches of concrete, and 36 concrete cylinders, 4- by 8-in., were cast from a third batch of concrete. One beam was tested for the 7- and 180-day strengths and two beams were tested for the 28-day strengths. Three cylinders were tested at each age for each storage condition.

The average of the test results for both compressive and flexural strengths are plotted in Figures 3 and 4. The different storage conditions had no strong effect on the measured compressive strengths. The compressive strengths for the test specimens that were stored in air until time of test were approximately the same as the others stored at different conditions. There was, however, a large difference in the flexural strengths of specimens stored in different conditions, as illustrated in Figure 4. The flexural strength values measured for specimens continuously stored in air were much lower than values for specimen from the other storage conditions, especially at the later ages. The compressive strengths of specimens that were stored in air and then placed under water 3 days before tests were 485 psi higher at 180 days than those that were stored in air and not wetted before testing. Test data obtained from this study indicate that notable differences in measured flexural strength results from differences in the amount of free moisture inside a specimen at the time of test, a difference that would affect the measured flexural strength of any concrete and is not unique to PBC concretes. This observation would explain the low flexural strengths obtained at the later ages in the study.

Effect of Additional Mixing Water on Strength

During one of the early inspections of a field application, it was observed that concretes used in the field had higher slumps than did those used for our laboratory evaluation. To determine the effect of additional mixing water on properties of the concrete, additional mixing water was added to concrete mixture L-8 to obtain a slump of 8 in. The water-cement ratio was increased from 0.23 to 0.28 to obtain the 8-in. slump. Two batches of concrete were mixed to prepare test specimens for compressive strengths, flexural strengths, and resistance to freezing and thawing. The compressive and flexural strength results are given in Table 16 and compared with the results obtained for the 4-in. slump materials tested earlier.

The increase in mixing water to obtain the higher slump lowered the strengths as expected. At the early test age of 6 hr, the compressive strength was reduced from 4,900 psi to 3,300 psi, and the flexural strength was reduced from 690 psi to 470 psi. High ultimate strengths were obtained with the higher slump concrete as indicated by 28-day age compressive and flexural strengths of 8,880 and 800 psi, respectively.

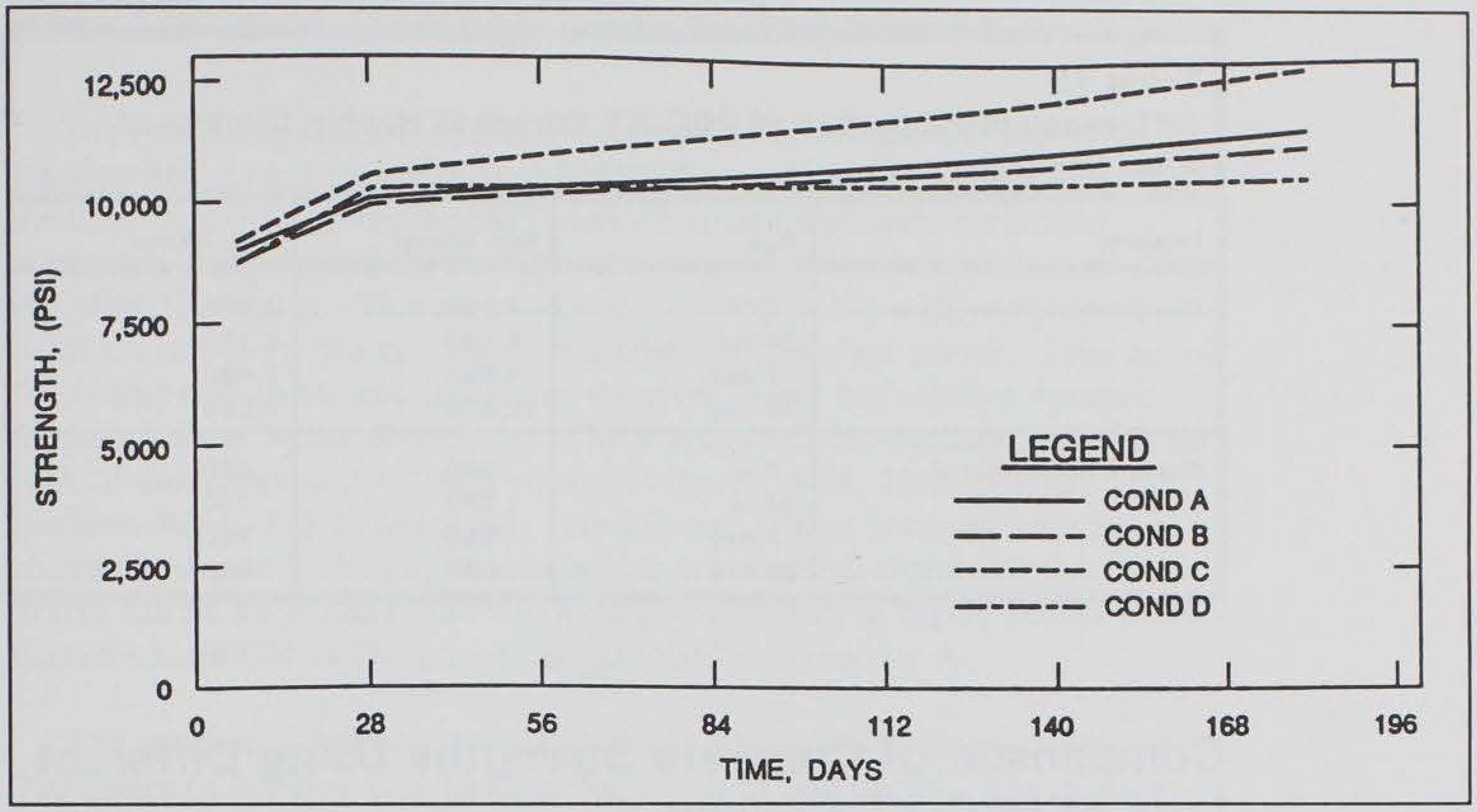

Figure 3. Results of compressive strength testing of PBC-XT concrete stored under different conditions. Conditions are summarized in Table 17

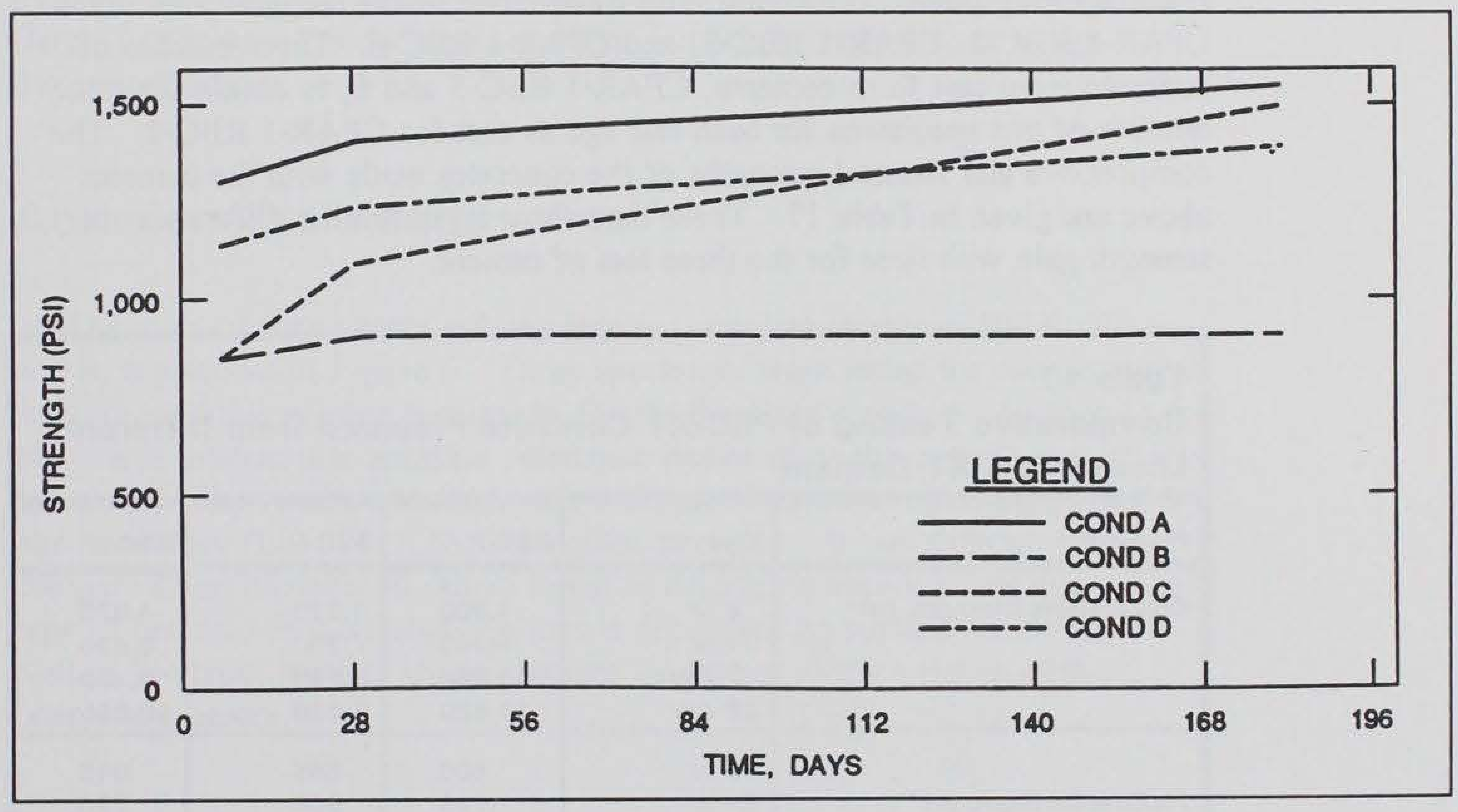

Figure 4. Flexural strength results of PBC-XT concrete stored at different conditions

Table 16
Difference in Properties of PBC-XT Concrete Having Slumps of 4-in. and 8-in.

Property	Age	4-in. Slump	8-in. Slump
Compressive Strength, psi	6 hr	4,900	3,300
	24 hr	6,380	5,110
	7 day	9,590	7,480
	28 day	10,670	8,880
Flexural Strength, psi	6 hr	690	470
	24 hr	790	730
	7 day	955	780
	28 day	940	800

Comparison of Concrete Strengths Using Different Lots of PBC-XT Cement

Compressive and flexural strength specimens were prepared from concrete mixture, L-8, using different lots of PBC-XT cement from two different manufacturing plants. The laboratory designation of the cements used are, CPAR-1 RBC-2, CPAR-1 RBC-5, and CPAR-1 RBC-6. Three batches of concrete were cast from cements, CPAR-1 RBC-5 and 6, to obtain the same number of test specimens for each test age as cast for CPAR-1 RBC-2. The compressive and flexural strengths of the concretes made with the cements above are given in Tabie 17. These data show no definitive differences in strength gain with time for the three lots of cement.

Table 17
Comparative Testing of PBC-XT Concrete Prepared from Different Lots of PBC-XT Cement

Property	Age	RBC-2	RBC-5	RBC-6
Compressive Strength, psi*	6 hr	4,900	4,220	4,070
	24 hr	6,300	7,200	6,630
	7 day	9,590	9,560	9,400
	28 day	10,670	9,620	10,680
Flexural Strength, psi*	6 hr	600	565	515
	24 hr	790	905	770
	7 day	955	910	900
	28 day	940	855	930

* Average of 3 specimens.

Resistance to Damage by Freezing and Thawing

The relative dynamic modulus of each specimen tested after 300 cycles of freezing and thawing are shown in Table 18. Test specimens prepared from the three mixtures containing the limestone coarse aggregate performed adequately, as indicated by the high relative dynamic modulus values (94.7 to 98) after 300 cycles. There was a large variation in the relative dynamic modulus values for the specimens prepared with the river gravel. Four out of the twenty-one specimens containing the river gravel had relative dynamic modulus values below 60 percent. The average relative dynamic modulus for each of the mixtures containing river gravel were 81.9, 73.7, and 76.1 for mixtures RG-6, RG-7, and RG-8, respectively. These averages were all above 60 percent. The large variation for the mixtures containing the river gravel can be attributed to the variation in the amount of highly porous chert particles identified in this gravel, as described in Appendix A.

Test specimens from mixtures L-7 and L-8 were tested for an additional 200 cycles of freezing and thawing, for a total of 500 cycles. The relative dynamic modulus of all specimens tested was greater than 90 percent after the 500 cycles of testing. Specimens prepared from mixture L-8, which had a slump of 8 in., were tested. The results obtained were very comparable to the results obtained from the lower slump (4-in.) concrete. The average relative dynamic modulus versus time for these test specimens are shown in Figure 5. Batch 1 showed a low dynamic modulus, but Batch 2 maintained a high dynamic modulus.

Abrasion Resistance

The plots of time versus volume loss for concrete mixtures, RG-6, 7, and 8, are shown in Figure 6. Three specimens were tested for each concrete mixture, and the average test results for the three are reported. As seen in the plots, it is evident that abrasion resistance increased as the cement content was increased. The results obtained were comparable to other concretes, tested by our laboratory (Liu 1981), having similar strengths. It was difficult to compare these mixtures to others tested to determine improvement due to the type of cement, because abrasion loss is dependent on surface conditions as well as the type, particle shape, amount, and other characteristics of the coarse aggregates.

Table 18
Results of Tests of Resistance of PBC-XT Concretes to 300 Cycles of Rapid Freezing and Thawing

Mixture	Test Specimen No.	Relative Dynamic Modulus, %
L-6	1	95.8
L-6	2	95.8
L-6	3	95.8
L-6	4	94.7
L-6	5	95.8
L-6	6	95.8
L-7	1	96.9
L-7	2	96.9
L-7	3	96.9
L-7	4	95.9
L-7	5	96.9
L-7	6	96.9
L-7	7	96.9
L-7	8	95.9
L-7	9	96.9
L-8	1	98.0
L-8	2	97.0
L-8	3	98.0
L-8	4	95.9
L-8	5	96.9
L-8	6	95.9
RG-6	1	85.0
RG-6	2	77.8
RG-6	3	85.7
RG-6	4	61.3
RG-6	5	92.5
RG-6	6	88.8
RG-7	1	40.2
RG-7	2	83.2
RG-7	3	79.2
RG-7	4	59.8
RG-7	5	89.6
RG-7	6	90.4
RG-8	1	89.0
RG-8	2	91.3
RG-8	3	58.6
RG-8	4	33.2
RG-8	5	93.5
RG-8	6	94.6
RG-8	7	77.0
RG-8	8	87.7
RG-8	9	60.0

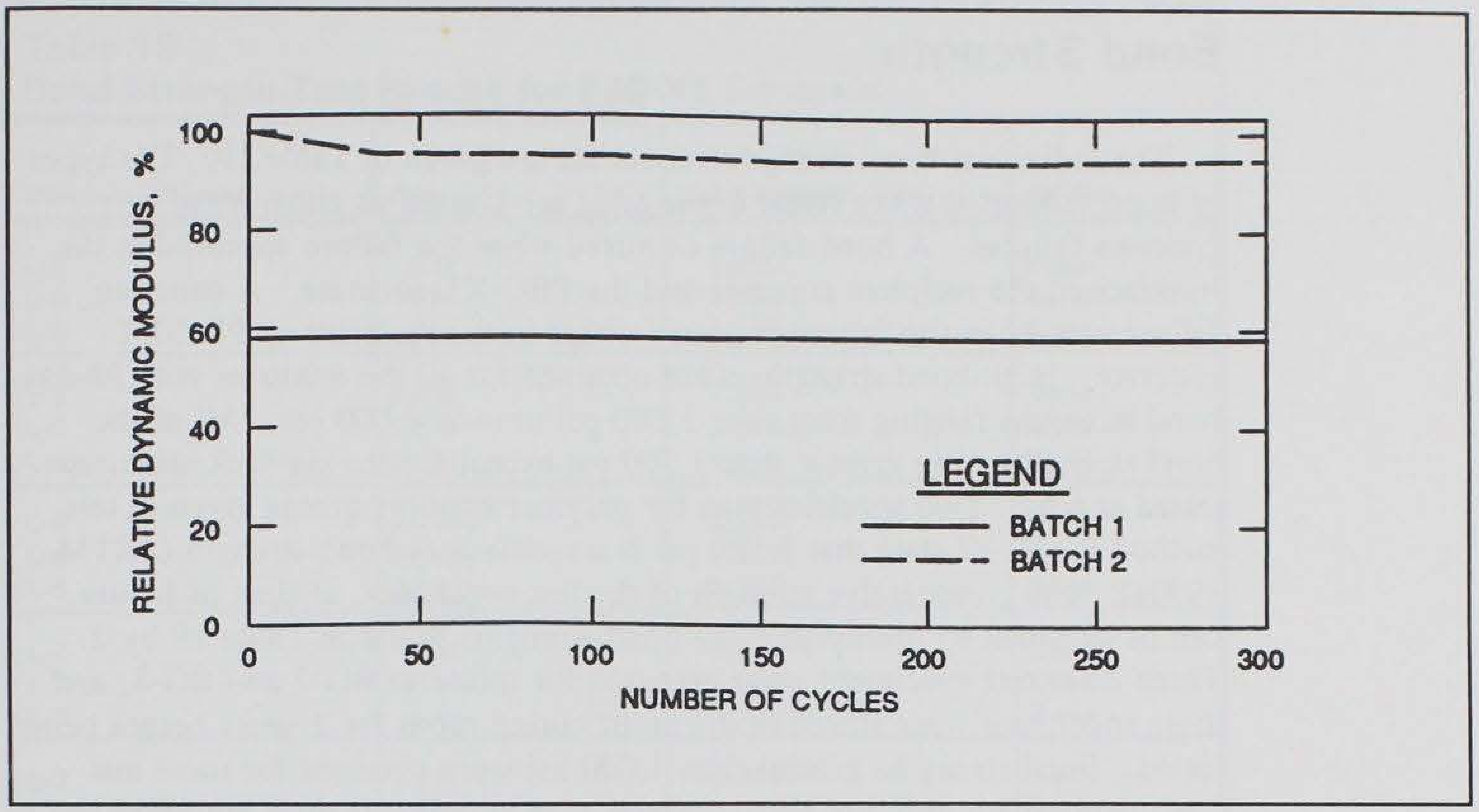

Figure 5. Resistance to freezing and thawing of 8-in. slump concrete prepared with PBC-XT

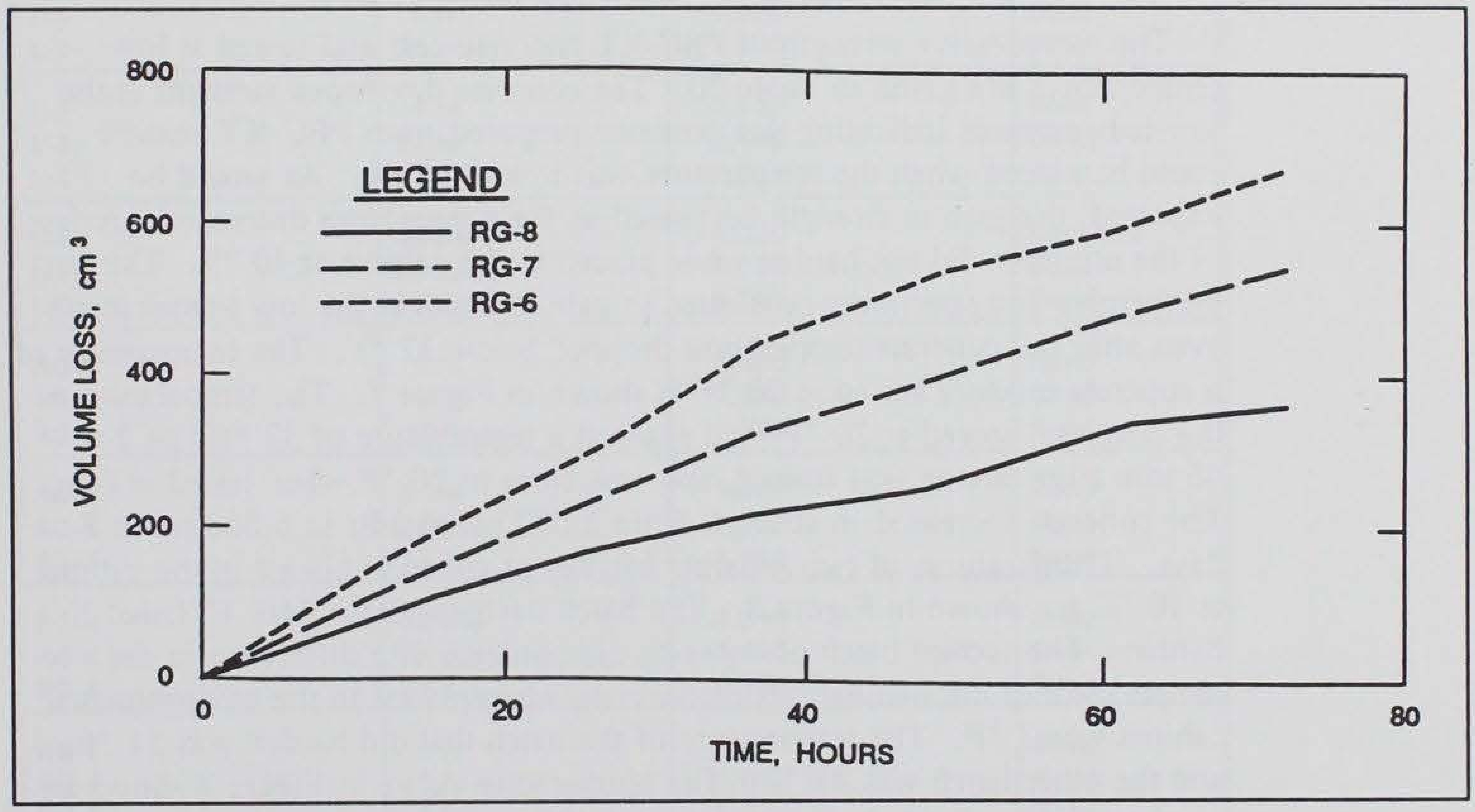

Figure 6. Results of abrasion resistance testing of PBC-XT concretes

Bond Strength

The individual bond strength test results are given in Table 19. The types of bond failures that are listed in the table are classed as either bond or concrete failures. A bond failure occurred when the failure appeared at the interface of the recipient concrete and the PBC-XT concrete. A concrete failure was when the failure appeared either in the recipient or PBC-XT concrete. High-bond strengths were obtained for all the mixtures with 28-day bond strengths ranging from near 3,000 psi to over 4,000 psi. All of the bond strengths were greater than 1,500 psi except for the six-sack mixtures tested at 6 hr. Two specifications for polymer bonding grouts given in test method C 882-87 state that 1,500 psi is a satisfactory bond strength (ASTM 1990a). The compressive strength of the test specimens, at time of failure, can be obtained by multiplying the bond strengths found in Table 19 by 2. Three extra test specimens were prepared for mixtures RG-7 and RG-8, and these specimens were stored in the moist curing room for 2 years before being tested. Bond strengths greater than 4,000 psi were obtained for these test specimens which indicates that long exposure to moisture does not affect the bonding capabilities of concrete.

Strength Gain at Low Temperatures

The compressive strength of PBC-XT concrete cast and stored at low temperatures are given in Table 20. The concrete developed strength at the low temperatures indicating that concrete prepared from PBC-XT cement could be placed when the temperature was low as 10 °F. As would be expected, the gain in strength decreased as the temperature decreased. A few of the mixtures did not harden when placed in the cabinet at 10 °F. The best performing test specimens continued to gain strength at the low temperatures even after the concrete temperature dropped below 32 °F. The temperature of a concrete mixture stored at 20 °F is shown in Figure 7. The temperature of the concrete, stored at 20 °F, had reached a temperature of 32 °F just 2 hr 45 min after mixing was started, and was close to 20 °F when tested at 6 hr. The concrete increased in strength from 2,680 psi at 6 hr to 6,560 psi at 7 days. Temperatures of two separate batches of concrete placed in the cabinet at 10 °F are shown in Figure 8. The batch designated as "Mix 1" failed to harden. The second batch of concrete did harden. The difference in the temperature of the two batches of concrete when placed in the environmental cabinet was 3 °F. The temperature of the batch that did harden was 51 °F, and the other batch was 48 °F. The temperature curve in Figure 8 shows an exothermic reaction between 90 min and 120 min after mixing.

Table 19
Bond Strength Test Results for PBC-XT Concrete

Concrete Mixture	Age	Bond Strength, psi	Type of Bond Failure
L-6	6 hr	1,050	Bond
L-6	6 hr	1,150	Bond
L-6	6 hr	1,180	Bond
L-6	24 hr	1,790	Bond
L-6	24 hr	2,350	Bond
L-6	24 hr	1,260	Bond
L-6	28 day	2,750	Bond
L-6	28 day	2,590	Bond
L-6	28 day	3,380	Bond
L-7	6 hr	1,750	Bond
L-7	6 hr	1,660	Bond
L-7	6 hr	1,720	Bond
L-7	24 hr	2,700	Bond
L-7	24 hr	2,610	Bond
L-7	24 hr	2,310	Bond
L-7	28 day	>4,460	Concrete
L-7	28 day	>4,280	Concrete
L-7	28 day	2,890	Bond
L-8	6 hr	1,750	Bond
L-8	6 hr	1,850	Bond
L-8	6 hr	1,700	Bond
L-8	24 hr	2,630	Bond
L-8	24 hr	2,440	Bond
L-8	24 hr	2,630	Bond
L-8	28 day	>4,300	Concrete
L-8	28 day	3,780	Bond
L-8	28 day	3,580	Bond
RG-6	6 hr	1,080	Bond
RG-6	6 hr	1,030	Bond
RG-6	6 hr	980	Bond
RG-6	24 hr	1,820	Bond
RG-6	24 hr	2,090	Bond
RG-6	24 hr	1,990	Bond
RG-6	28 day	3,340	Bond
RG-6	28 day	>3,640	Concrete
RG-6	28 day	3,160	Bond
RG-7	6 hr	1,610	Bond
RG-7	6 hr	1,580	Bond
RG-7	6 hr	1,670	Bond
RG-7	24 hr	2,600	Bond
RG-7	24 hr	2,610	Bond
RG-7	24 hr	2,610	Bond

(Continued)

Table 19 (Concluded)			
Concrete Mixture	**Age**	**Bond Strength, psi**	**Type of Bond Failure**
RG-7	28 day	3,740	Bond
RG-7	28 day	>3,980	Concrete
RG-7	28 day	3,800	Bond
RG-8	6 hr	1,640	Bond
RG-8	6 hr	1,630	Bond
RG-8	6 hr	1,830	Bond
RG-8	24 hr	2,840	Bond
RG-8	24 hr	2,620	Bond
RG-8	24 hr	2,440	Bond
RG-8	28 day	>4,460	Concrete
RG-8	28 day	>4,080	Concrete
RG-8	28 day	>4,260	Concrete

Table 20
Effect of Low Temperature on Compressive Strength of PBC-XT Concretes, Psi

	Storage Temperature, °F			
Age	45	30	20	10
6 hr	4,380	3,310	2,680	2,510
24 hr	5,520	4,950	4,300	4,200
7 days	8,740	7,360	6,560	6,130

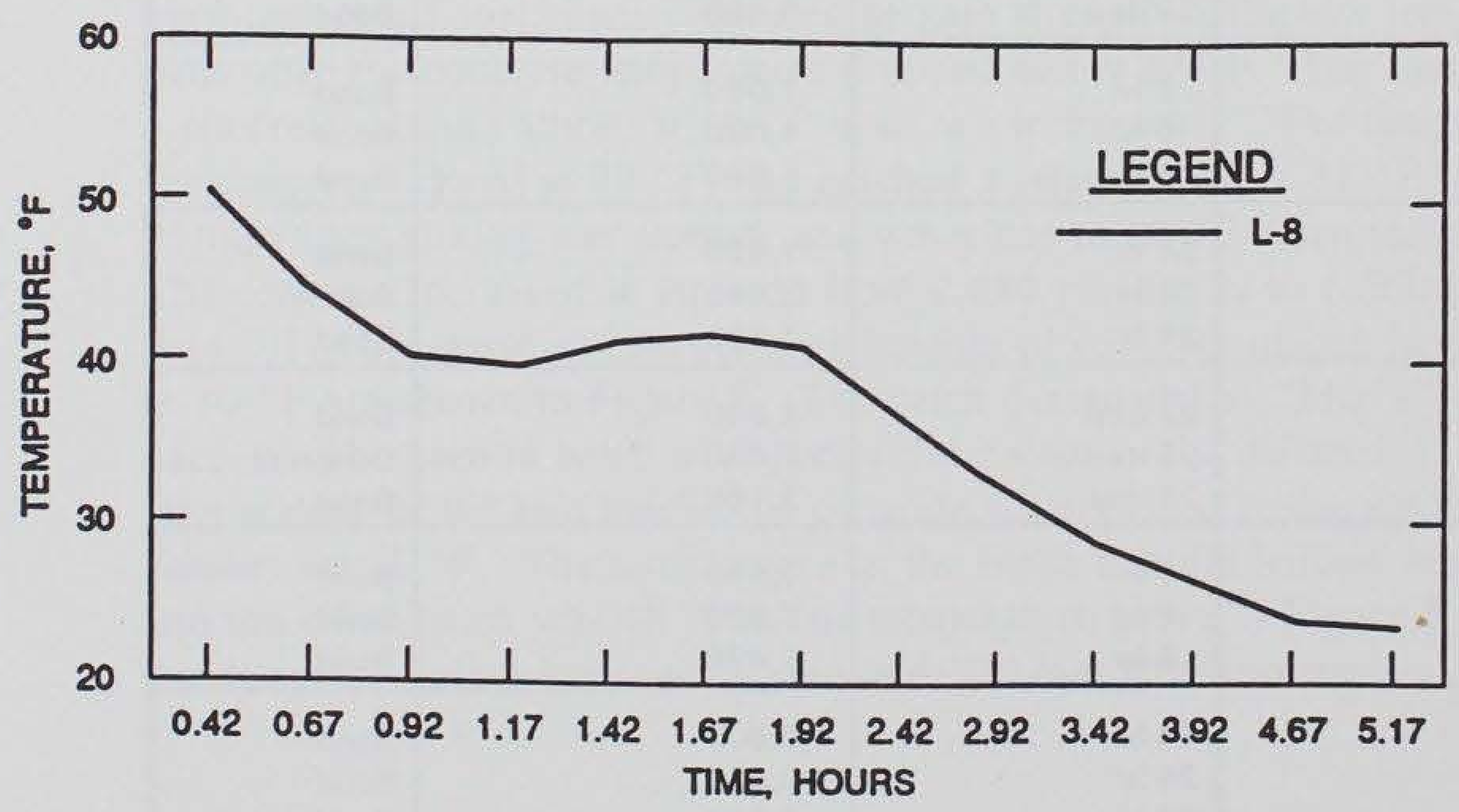

Figure 7. Temperature of PBC-XT concrete stored at 20 °F

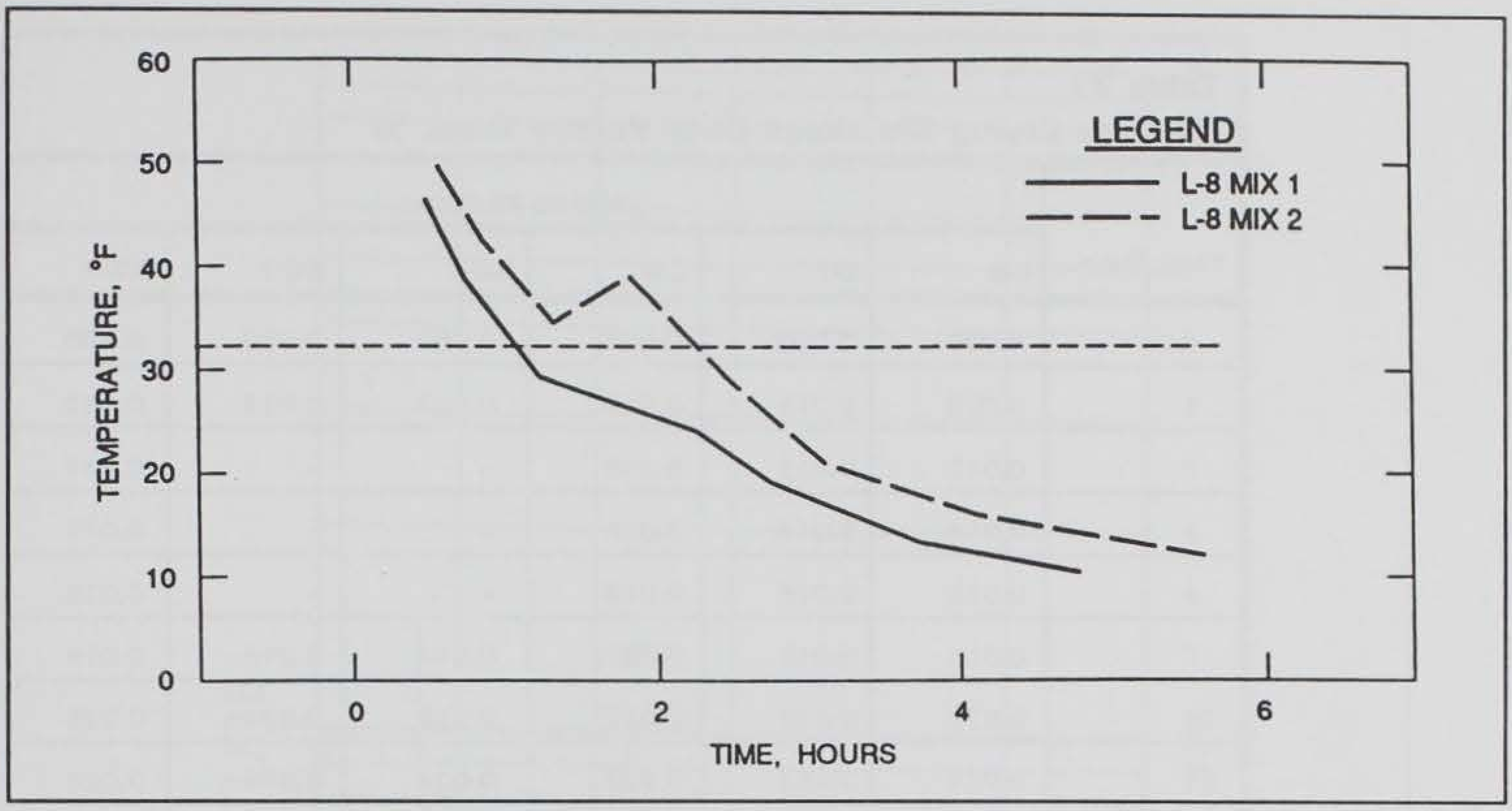

Figure 8. Temperature of PBC-XT concrete mixture L-8 stored at 10 °F

Drying Shrinkage

The results from the drying shrinkage tests are presented in Table 21. Average test results for the six- and eight-sack mixtures are plotted in Figure 9. The measured shrinkage for PBC-XT concrete was very low. The shrinkage after 1 year for the six concrete mixtures ranged from a low of 0.026 percent to a high of 0.034 percent. There was very little difference in the shrinkage of the different mixtures. The six-sack river gravel mixture (RG-6) was slightly lower than the others which could be attributed to the lower cement content.

Creep

Creep tests were conducted on an eight-sack mixture prepared with river gravel aggregate. Figure 10 shows the variation in total specific strain through the duration of the 142-day test. The initial strengths of the test cylinders prepared from the mixtures were 5,690 and 5,900 psi after 1-day curing. Specimens were loaded at 1,470 psi, or 25 percent of their unconfined compressive strength. Figure 11 shows the same data as Figure 10 with the elastic strains subtracted to yield specific creep in millionths/psi.

From the data the instantaneous elastic modulus is calculated as the reciprocal of the initial specific strain. The elastic modulus (E) was 5.71×10^6 psi. The specific strain-log time curve is nonlinear in the range from 1 day to 10 days and the creep rate calculation method given in

Table 21
Average Drying Shrinkage Data Versus Time, %

Time, Days	Concrete Mixtures					
	L-6	L-7	L-8	RG-6	RG-7	RG-8
0.2	0.000	0.000	0.000	0.000	0.000	0.000
1	0.008	0.011	0.015	0.007	0.012	0.012
2	0.012	0.013	0.018	--	--	0.014
3	0.014	0.014	0.018	--	--	0.017
4	0.015	0.015	0.019	--	--	0.018
7	0.015	0.019	0.021	0.014	0.019	0.019
28	0.023	0.022	0.027	0.019	0.024	0.025
56	0.024	0.026	0.029	0.024	0.030	0.026
90	0.025	0.027	0.029	0.025	0.032	0.028
180	0.029	0.031	0.031	0.026	0.033	0.031
365	0.032	0.031	0.032	0.026	0.034	0.032

Average of 3 test specimens.

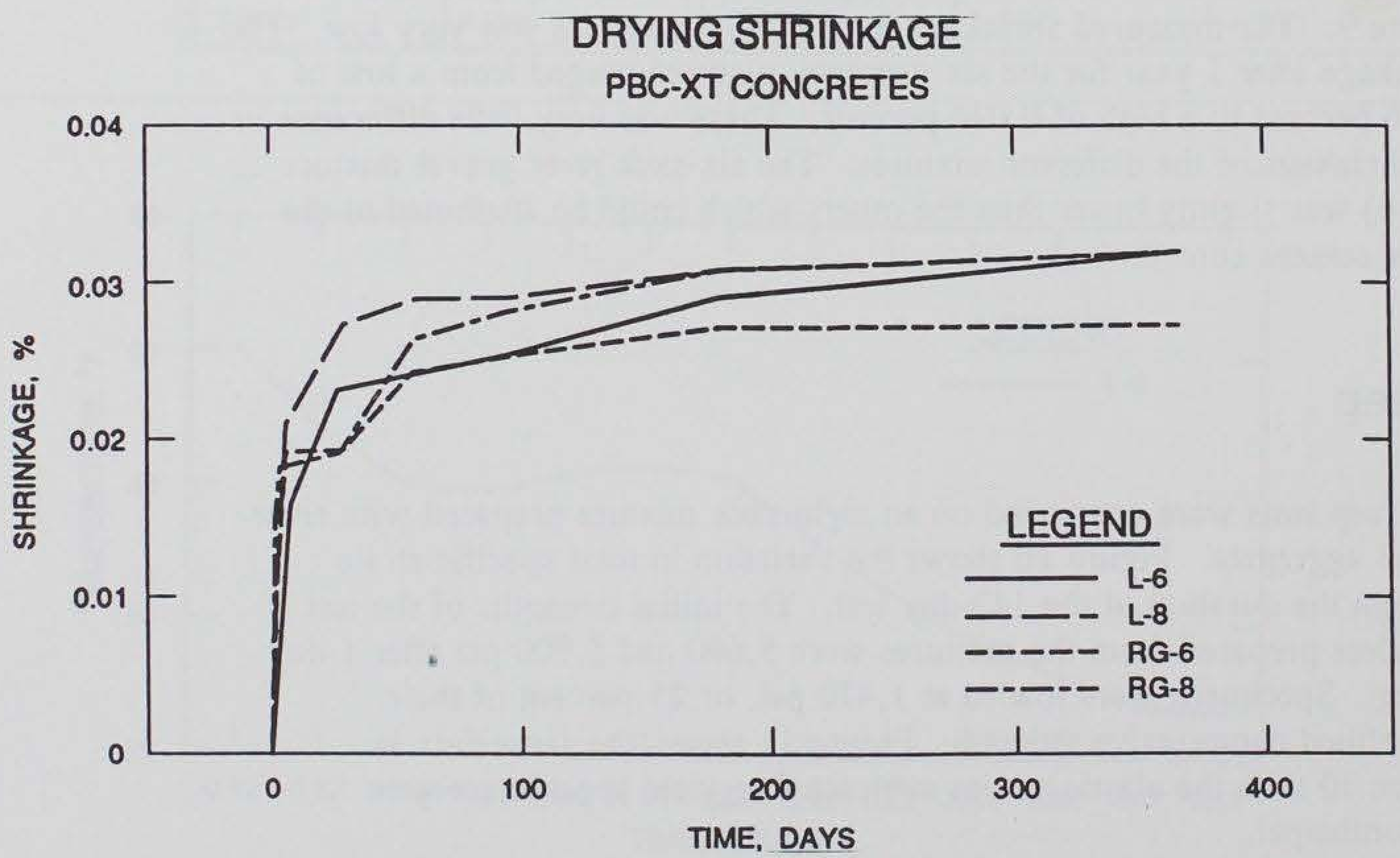

Figure 9. Results of drying shrinkage testing of six-sack and eight-sack PBC-XT concrete

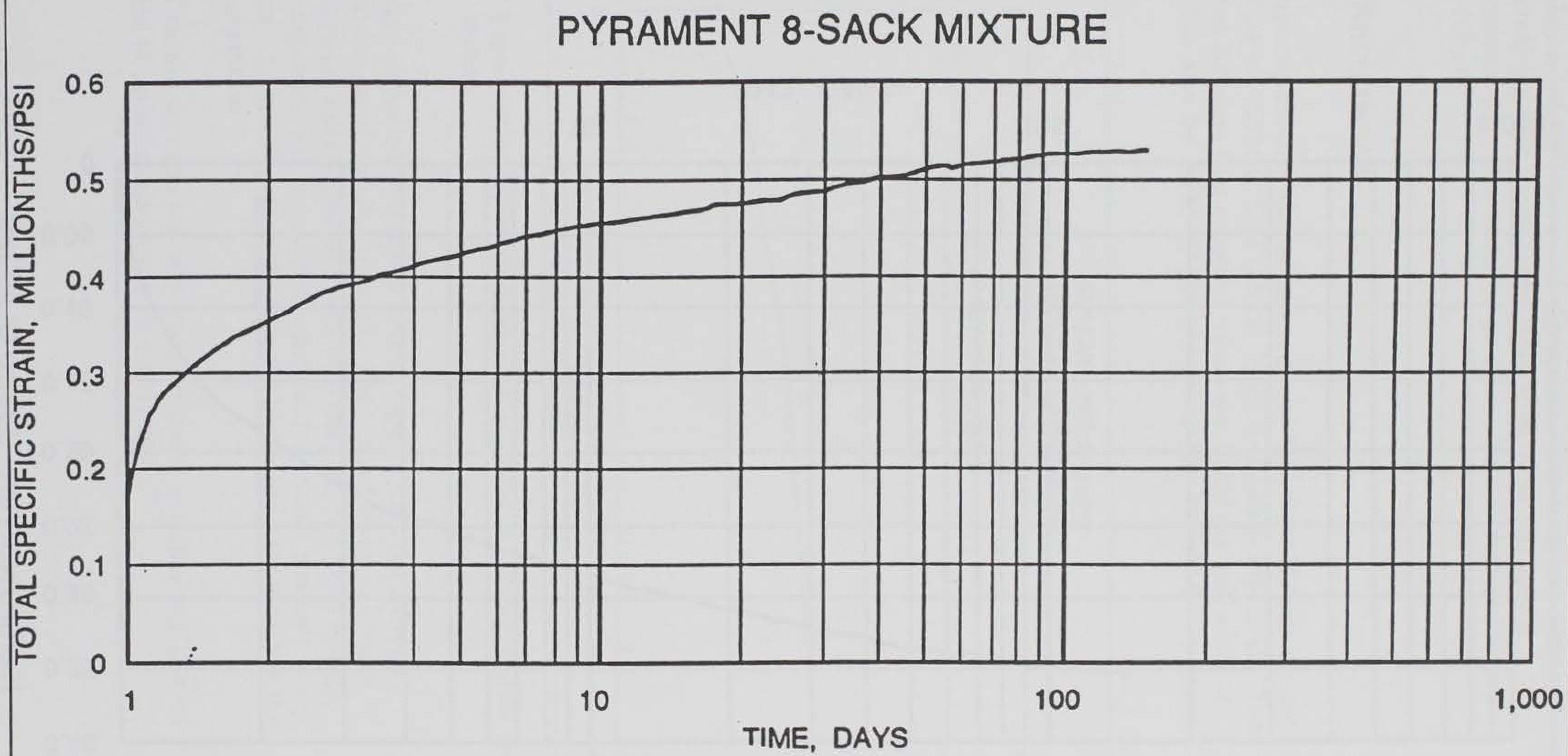

Figure 10. Variation in total specific strain with age for mixture RG-8

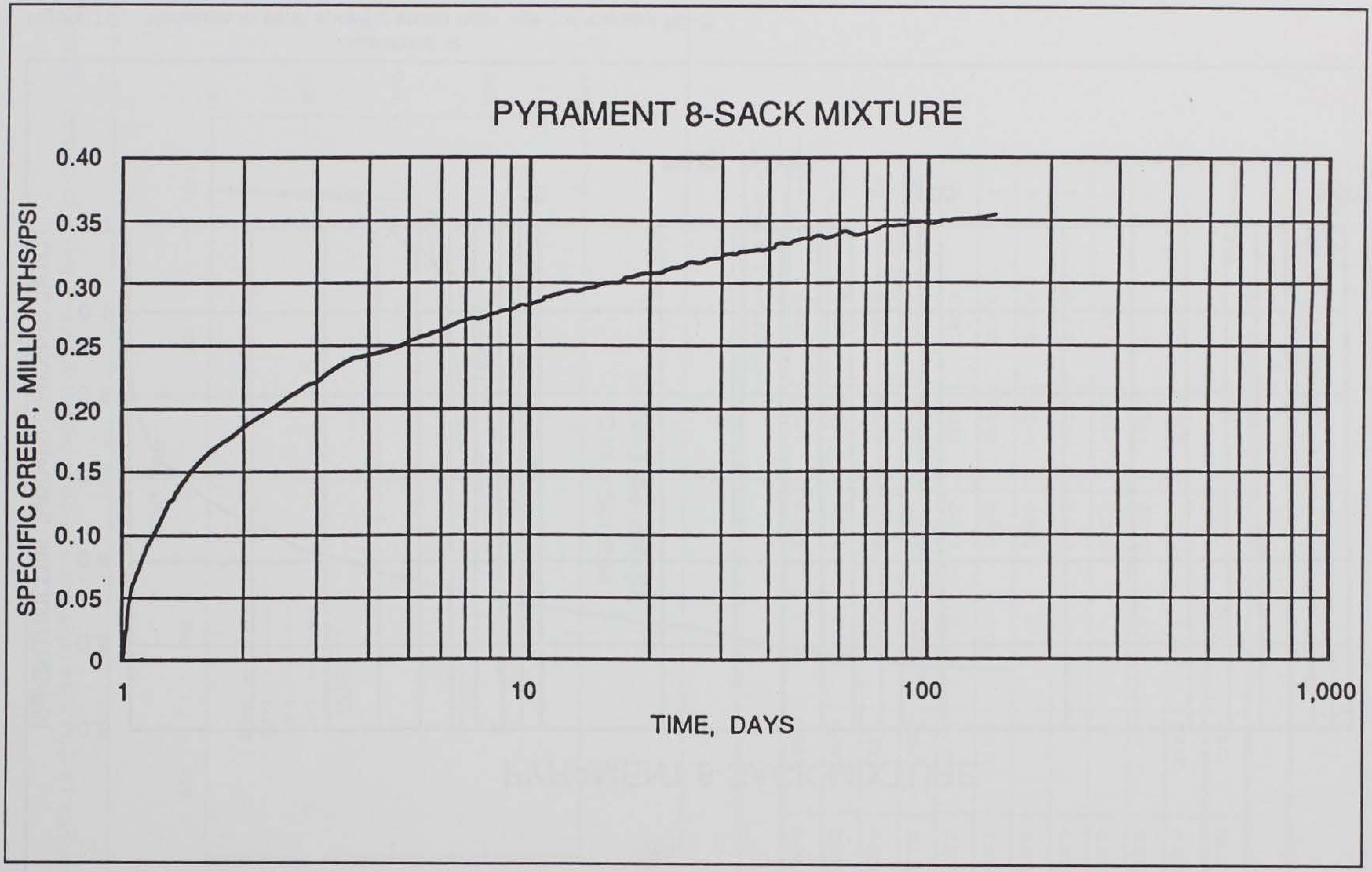

Figure 11. Variation in specific creep with age for mixture RG-8

ASTM C 512 (ASTM 1992d) was not appropriate. The creep rate (slope of the specific creep-log time curve) in the range from 10 to 100 days is 0.069 millionths/psi/day. The sustained modulus after 142 days under load was 1.90×10^6 psi.

Sulfate Resistance

The average expansion of mortar bars prepared from PBC-XT cement and tested according to ASTM C 1012 (ASTM 1988) is shown in Figure 12. The expansion after 205 days (last measured value) was 0.059 percent, which is significantly less than the ASTM C 595 (ASTM 1992b) limit of 0.10 percent at 180 days.

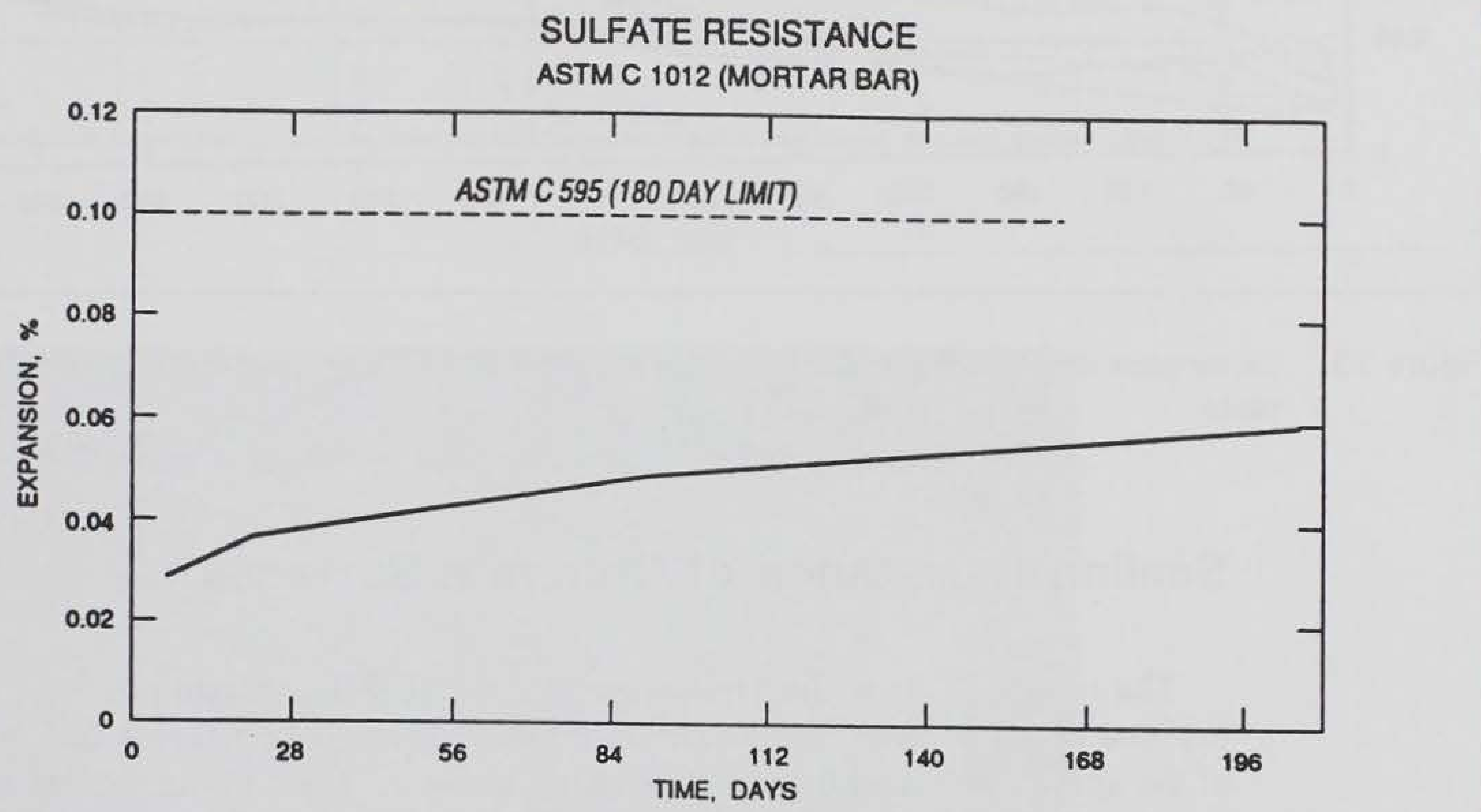

Figure 12. Expansion of mortar bars prepared with PBC-XT during sulfate resistance testing

The average expansion of concrete beams prepared from the different concrete mixtures are shown in Figure 13. The expansions up to 2 years stored in the mixed sulfate solutions were very low. After 2 years storage, the greatest expansion was for concrete mixture, L-8, which was only 0.061 percent. As can be seen in the plot, the higher the cement content the greater the expansion.

PBC-XT cement concrete had very good resistance to sulfate attack, even when exposed to sulfate solutions at a very early age.

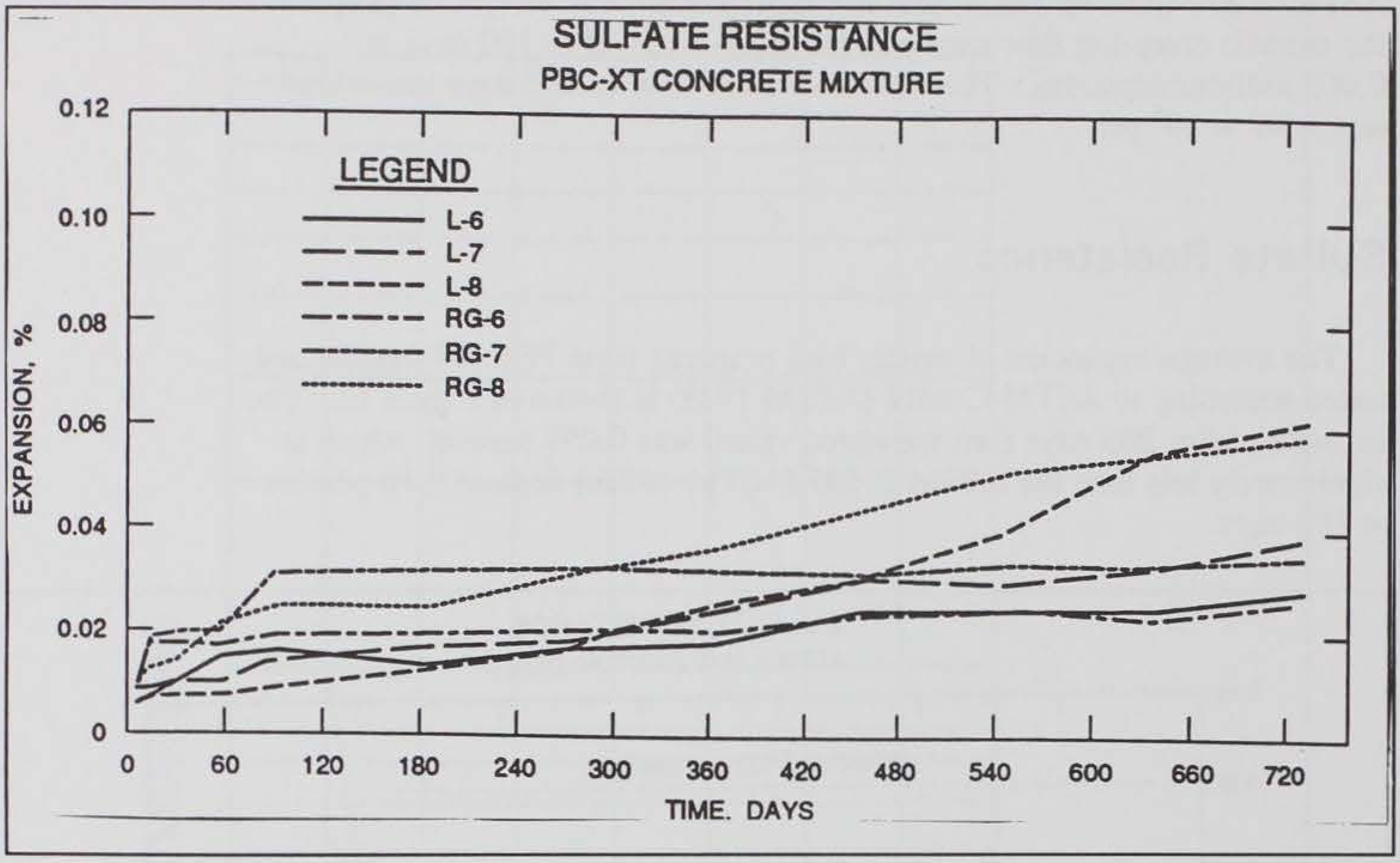

Figure 13. Expansion of concrete beams prepared with PBC-XT during sulfate resistance tests

Scaling Resistance of Concrete Surfaces

The results of the scaling resistance of the PBC-XT concrete mixtures exposed to a 4-percent calcium chloride solution are given in Table 22. None of the specimens tested had a visual rating above 2. Most of the specimens tested had only slight scaling or no scaling, indicating excellent resistance to deicer solution. Specimens prepared from mixture L-7 exhibited more scaling than the other specimens. No explanation could be given for this mixture having more scaling than the others, except that overfinishing could have contributed to the additional scaling. Three test specimens after testing are shown in Figures 14, 15, and 16.

Chloride Permeability

The concentration of chlorides at different depths in PBC-XT concretes, when tested according to AASHTO Designation: T 259 (AASHTO 1990b), are shown in Table 23. The concentration of chlorides at depths below 0.50 in. was extremely low. Results suggest PBC-XT concretes are very resistant to chloride ion penetration.

The results for the rapid chloride permeability tests, AASHTO Designation: T 277 (AASHTO 1990a), are shown in Figure 17. Two

Table 22
Scaling Resistance to Deicing Chemicals for Concretes Prepared from PBC-XT

Concrete Mixture	Test Specimen	Visual Rating	Remarks
L-6	1	1	Slight scaling
	2	1	Slight scaling
L-7	1	2	Slight to moderate scaling
	2	2	Slight to moderate scaling
L-8	1	1	Very light scaling
	2	1	Very light scaling
RG-6	1	2	Scaling around and above some aggregates
	2	2	Scaling around and above some aggregates
RG-7	1	1	Slight scaling
	2	0	No scaling
	1	0	No scaling
RG-8	2	0	No scaling

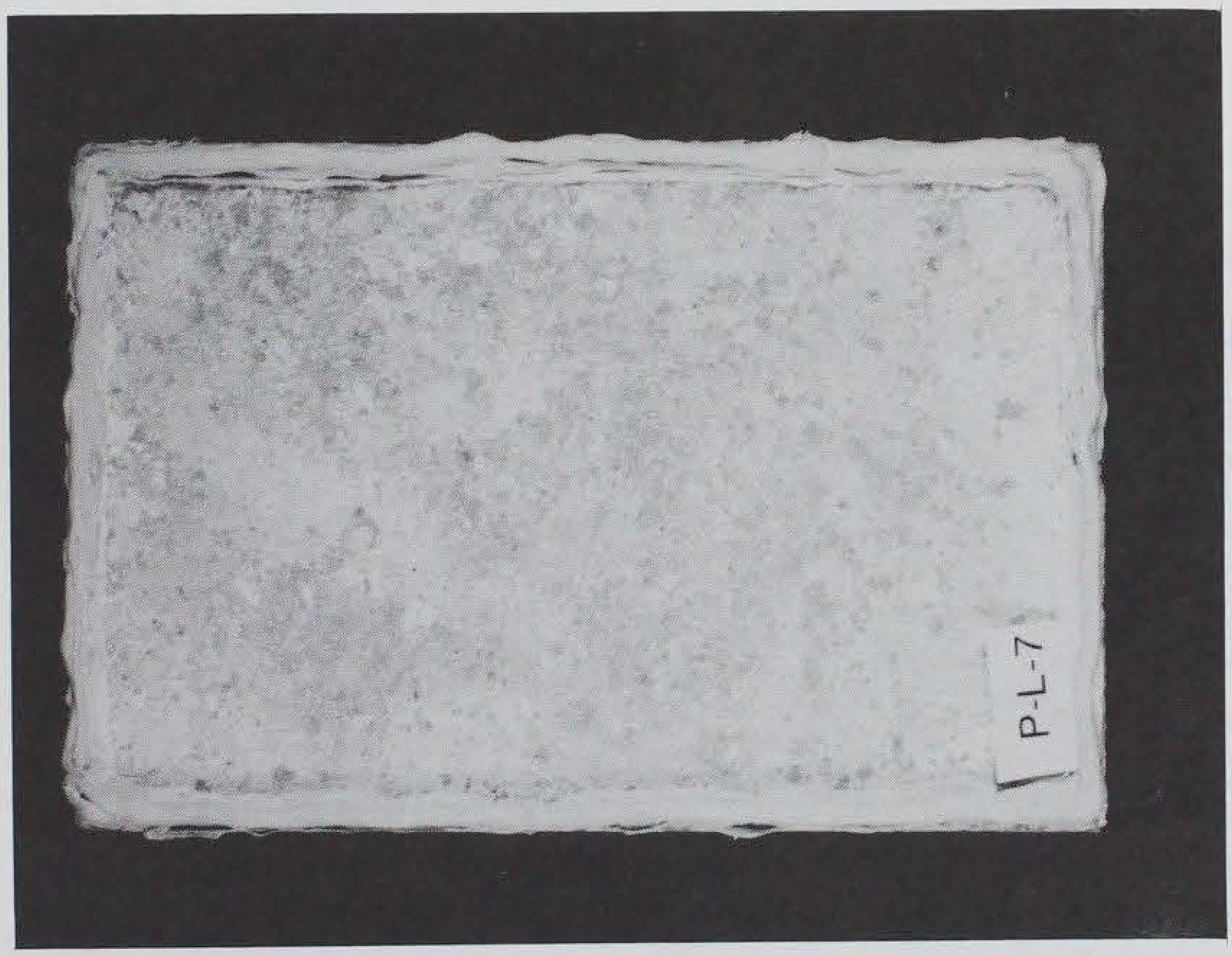

Figure 14. Photo of specimen from mixture L-7 showing the greatest amount of scaling

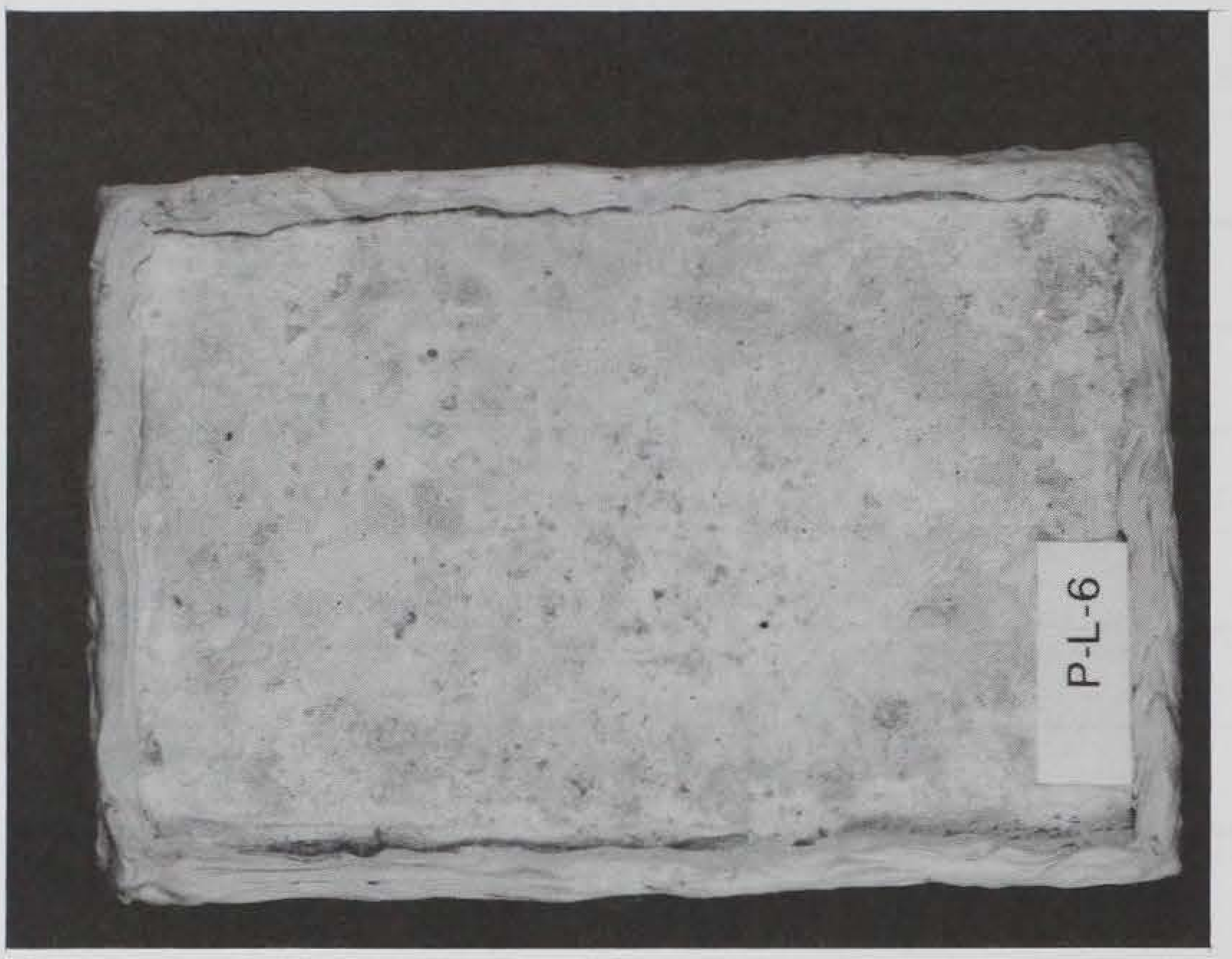

Figure 15. Photo of specimen from mixture L-6 showing slight scaling

Figure 16. Photo of specimen from mixture RG-6 showing scaling around aggregates

Table 23 Chloride Permeability of Concretes Prepared with PBC-XT			
	Depth		
Concrete Mixture	0 - 0.5 in.	0.5 - 1.0 in.	1.0 - 1.5 in.
L-6	0.128	0.004	0.001
L-7	0.124	0.011	0.002
L-8	0.145	0.002	0.001

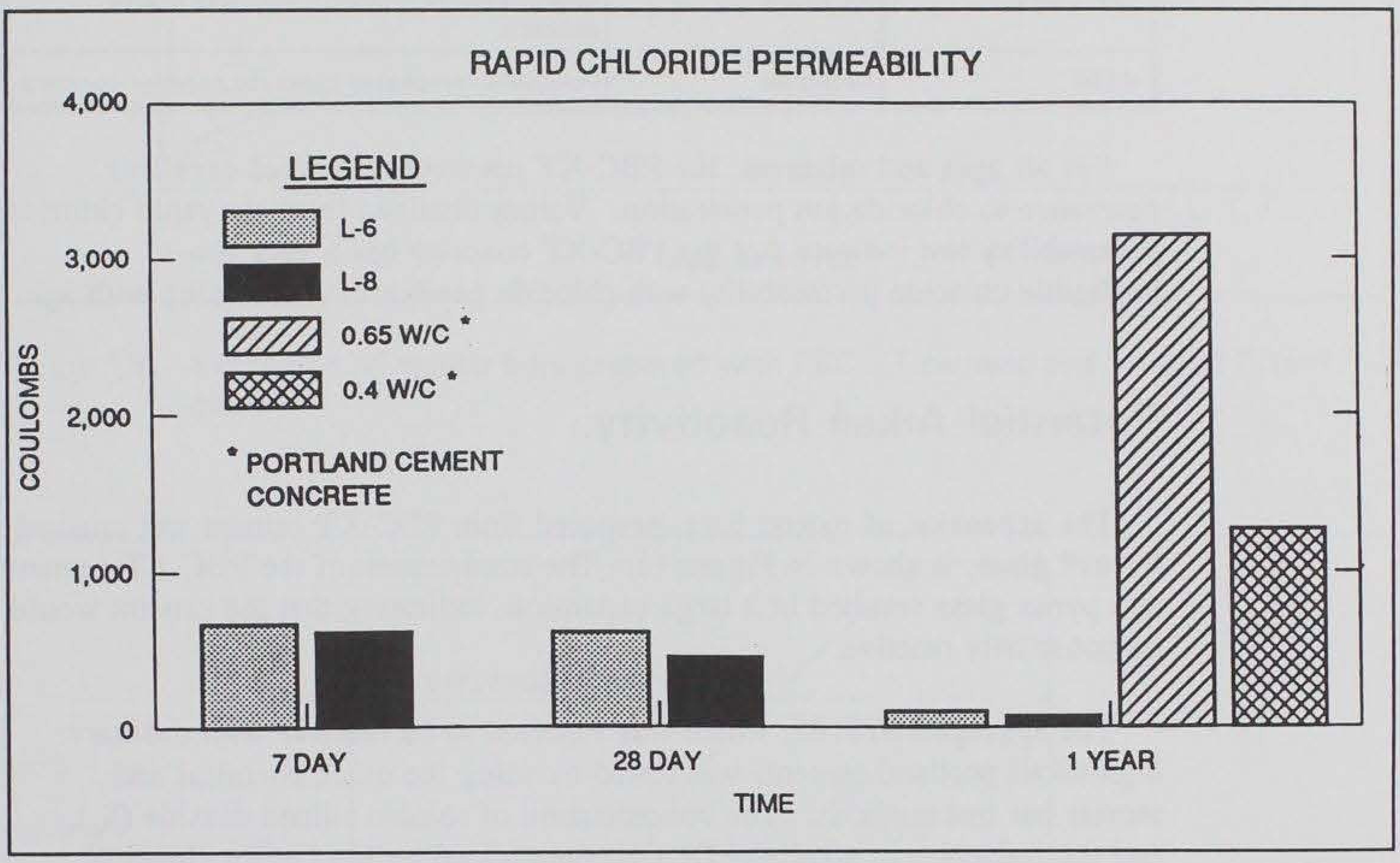

Figure 17. Results of chloride permeability tests of concretes prepared with PBC-XT and ordinary portland cement

ordinary portland cement concretes (OPCC), cast for another study at WES, were tested along with the PBC-XT concretes, and the results for the two OPCC are shown in Figure 17. The electric charge (coulombs) passed through the PBC-XT concretes during the 6-hr test period was considered to be very low, indicating very low permeability to chlorides. The coulombs recorded for the 7-day-old PBC-XT concretes was approximately 700, and the coulombs recorded for the 1-year old specimens ranged from a low of 55 to a high of 125. Coulombs measured for the 1-year-old OPCC test specimens were 3,130 for the concrete having a water-cement ratio of 0.65, and 1,300 for the concrete having a water-cement ratio of 0.40. AASHTO Designation: T 277 (AASHTO 1990a) gives a chloride permeability based on charge passed as shown in Table 24.

Table 24 Chloride Permeability Rating Based on Charge Passed		
Charge Passed (coulombs)	**Chloride Permeability**	**Typical of**
>4,000	High	High water-cement ratio (0.6), conventional PCC
2,000-4,000	Moderate	Moderate water-cement ratio, conventional (0.4-0.5) PCC
1,000-2,000	Low	Low water-cement ratio, conventional (<0.4) PCC
100-1,000	Very Low	Latex-modified concrete Internally sealed concrete
<100	Negligible	Polymer impregnated concrete polymer concrete

For all ages and mixtures, the PBC-XT concretes exhibited excellent resistance to chloride ion penetration. Values obtained from the rapid chloride permeability test indicate that the PBC-XT concrete has a very low to negligible chloride permeability with chloride penetration decreasing with age.

Potential Alkali Reactivity

The expansion of mortar bars, prepared from PBC-XT cement and crushed Pyrex® glass, is shown in Figure 18. The combination of the PBC-XT cement and pyrex glass resulted in a large expansion, indicating that the cement would be potentially reactive.

The aggregate 920185, which was reported to be reactive with ordinary high-alkali portland cement, was tested by using the quick chemical and mortar bar test methods. The concentration of soluble silicon dioxide (S_c), and the reduction in alkalinity (R_c), as determined by the "quick chemical method" are given below:

S_c = 610 mmol/L
R_c = 40 mmol/L

Evaluation of the S_c and R_c using test curves shows that the aggregate would be considered deleterious under guidelines presented in ASTM C 289 (ASTM 1992f).

The expansion of mortar bars prepared from the aggregate and a high-alkali cement are shown in Figure 19. In both cases the expansion of 3- by 3- by 10-in. concrete beams prepared from PBC-XT cement and the reactive aggregate is shown in Figure 20. The expansion of the mortar bars exceeded 0.010 percent at 6 months, which is considered to be excessive as described in ASTM C 33 (ASTM 1993b) and similarly the expansion of the concrete prepared with PBC-XT and the reactive aggregate exceeded the ASTM limit.

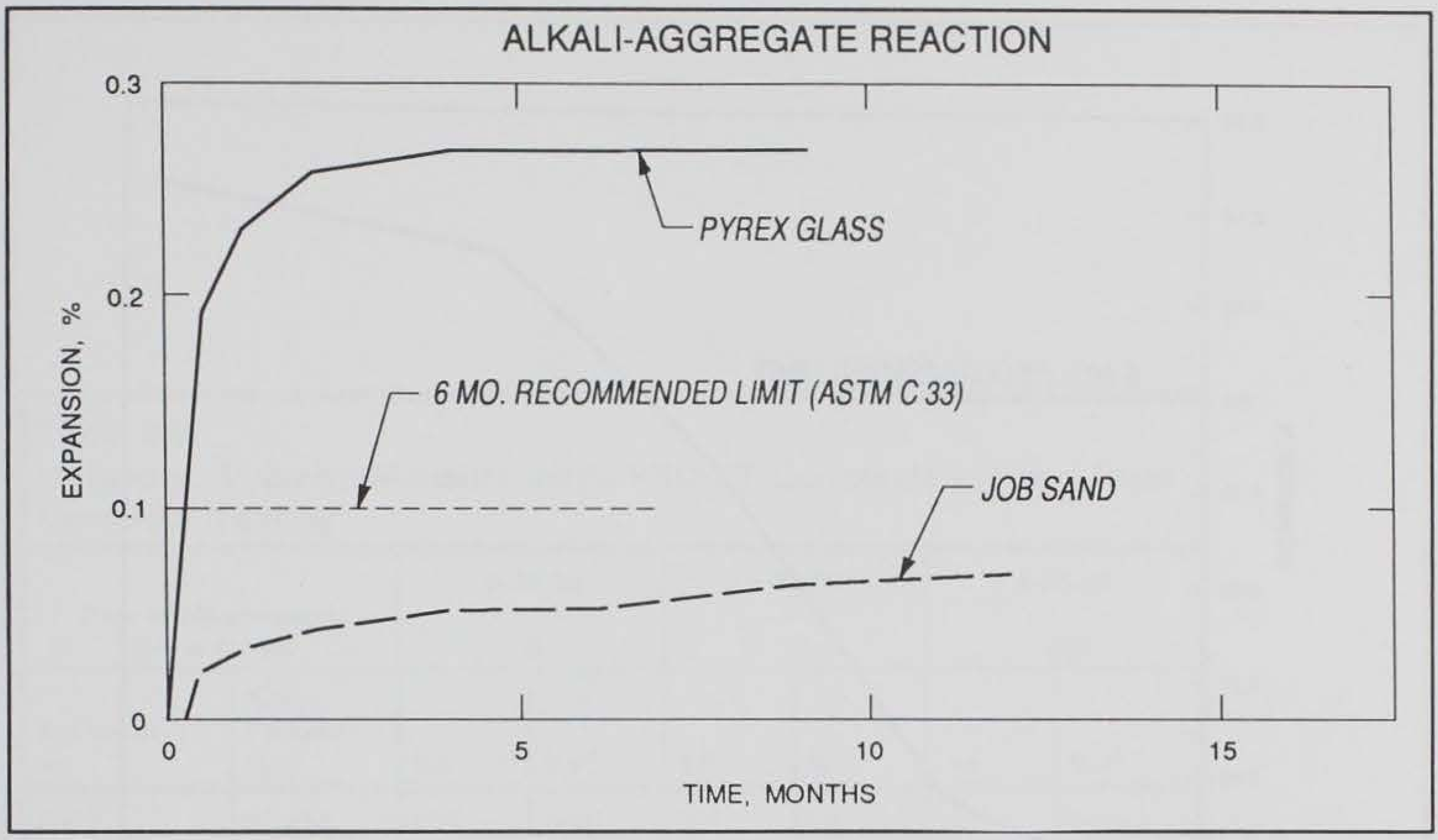

Figure 18. Expansion of mortar bars prepared with PBC-XT cement and crushed Pyrex® glass

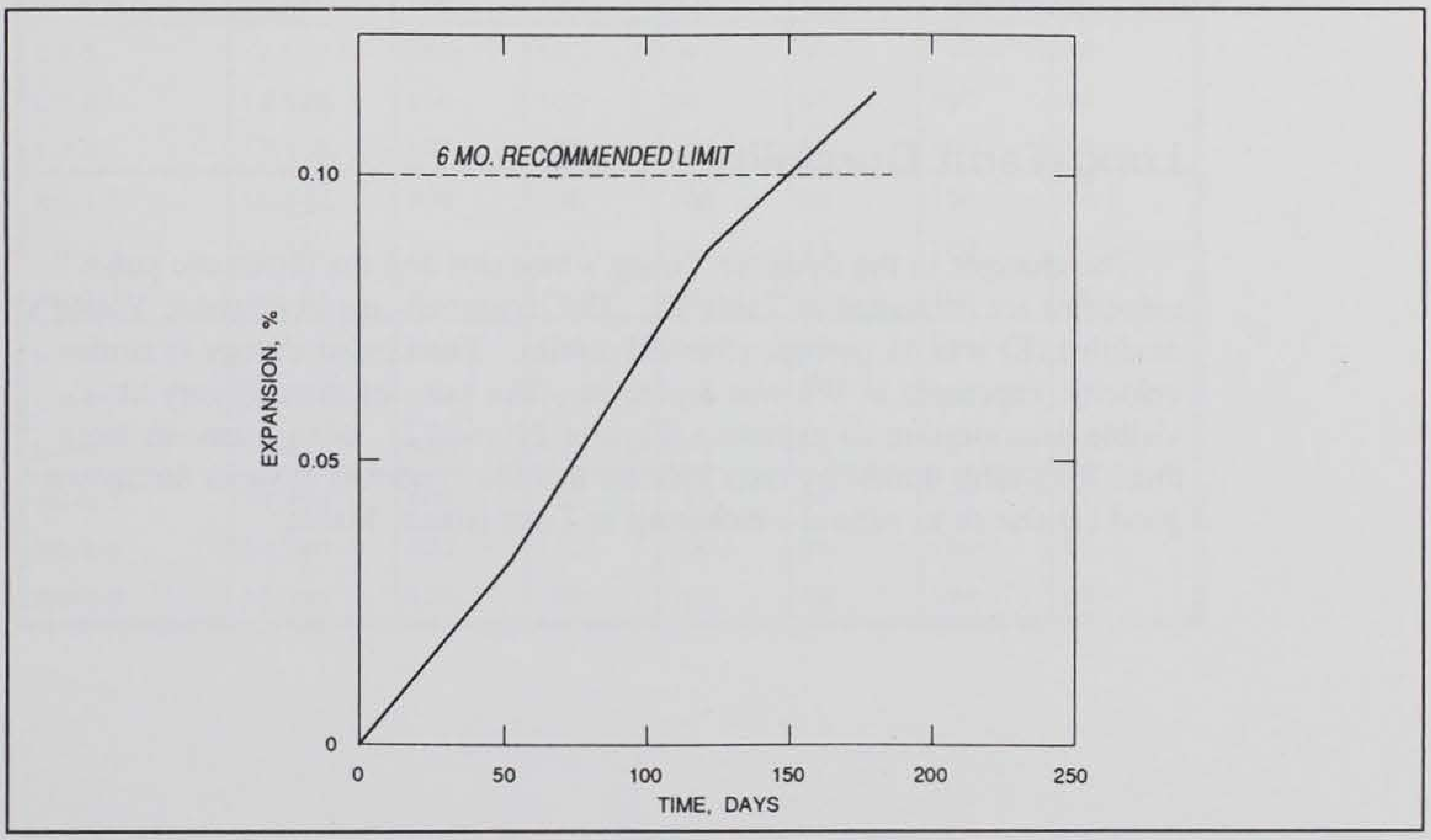

Figure 19. Expansion of mortar bars prepared with high-alkali cement and aggregate 920185 (reactive)

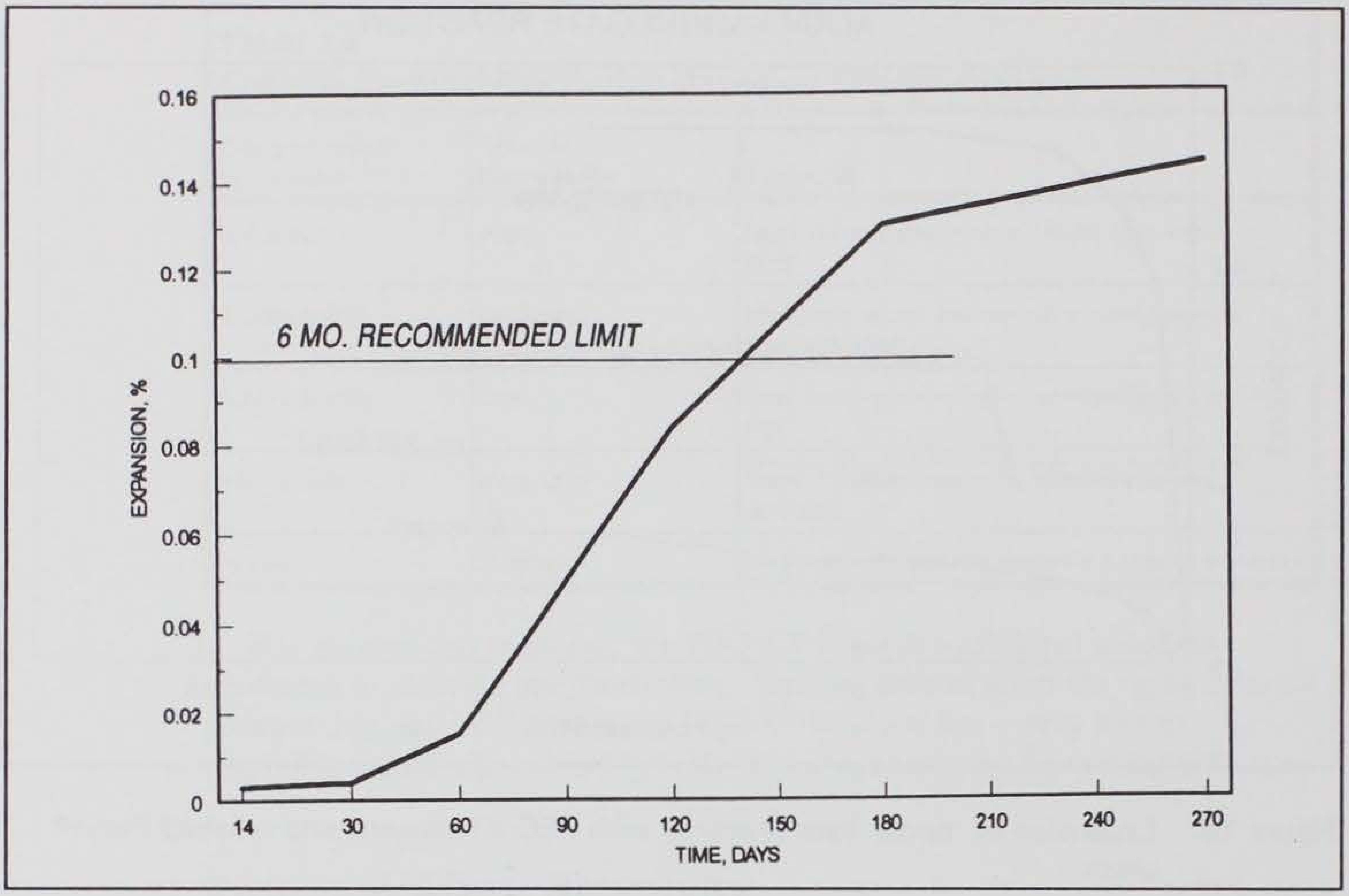

Figure 20. Expansion of concrete beams prepared with PBC-XT cement and aggregate 920185 (reactive)

Long-Term Durability

The changes in the dynamic Young's modulus and the ultrasonic pulse velocities are presented in Table 25. The largest change in dynamic Young's modulus (E) was 11 percent after 198 cycles. The largest change in sonic velocity (expressed at V^2) was 8 percent. The samples showed very little visible deterioration on exposure (Figures 21 and 22). Measurements from these long-term durability tests indicate that the concretes have so far shown good resistance to natural weathering at Treat Island, Maine.

Table 25
Ultrasonic Velocity Measurements PBC-XT Concretes in Long-Term Durability Testing

Date of Measurement No. of Cycles		7-18-90 0		8-22-91 75		8-05-92 198	
Specimen No.	Pulse Velocity (fps)	%E	$\%V^2$	%E	$\%V^2$	%E	$\%V^2$
L-6-7	17,398	100	100	102	99	101	94
L-6-8	17,568	100	100	93	98	93	94
L-6-9	17,442	100	100	94	99	94	96
RG-6-7	16,275	100	100	91	98	89	95
RG-6-8	16,219	100	100	97	98	96	93
RG-6-9	16,630	100	100	101	96	100	92
L-7-7	17,527	100	100	91	96	89	95
L-7-8	17,530	100	100	101	96	100	96
L-7-9	17,438	100	100	101	97	100	96
RG-7-7	16,143	100	100	100	97	100	96
RG-7-7	16,243	100	100	102	97	100	97
RG-7-7	16,028	100	100	101	99	101	96
L-8-7	17,558	100	100	100	97	101	94
L-8-8	17,517	100	100	101	97	102	93
L-8-9	17,496	100	100	102	96	101	95
RG-8-7	16,396	100	100	98	96	97	92
RG-8-8	16,260	100	100	100	98	99	95
RG-8-9	16,138	100	100	101	99	98	96

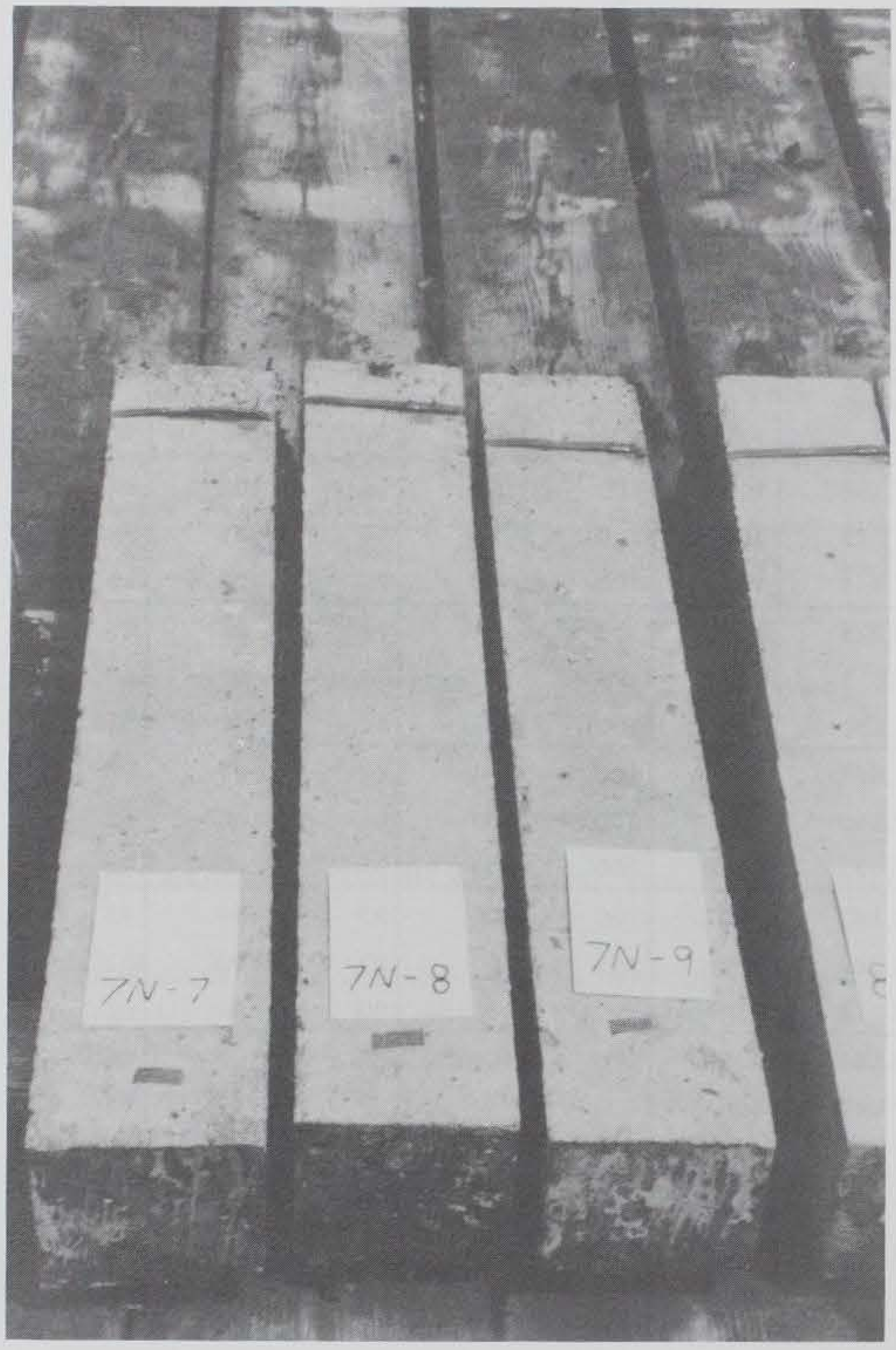

Figure 21. Specimens from long-term durability testing. Photos were taken on August 5, 1992. Sample number 7N-7 corresponds to laboratory sample RG-7-7

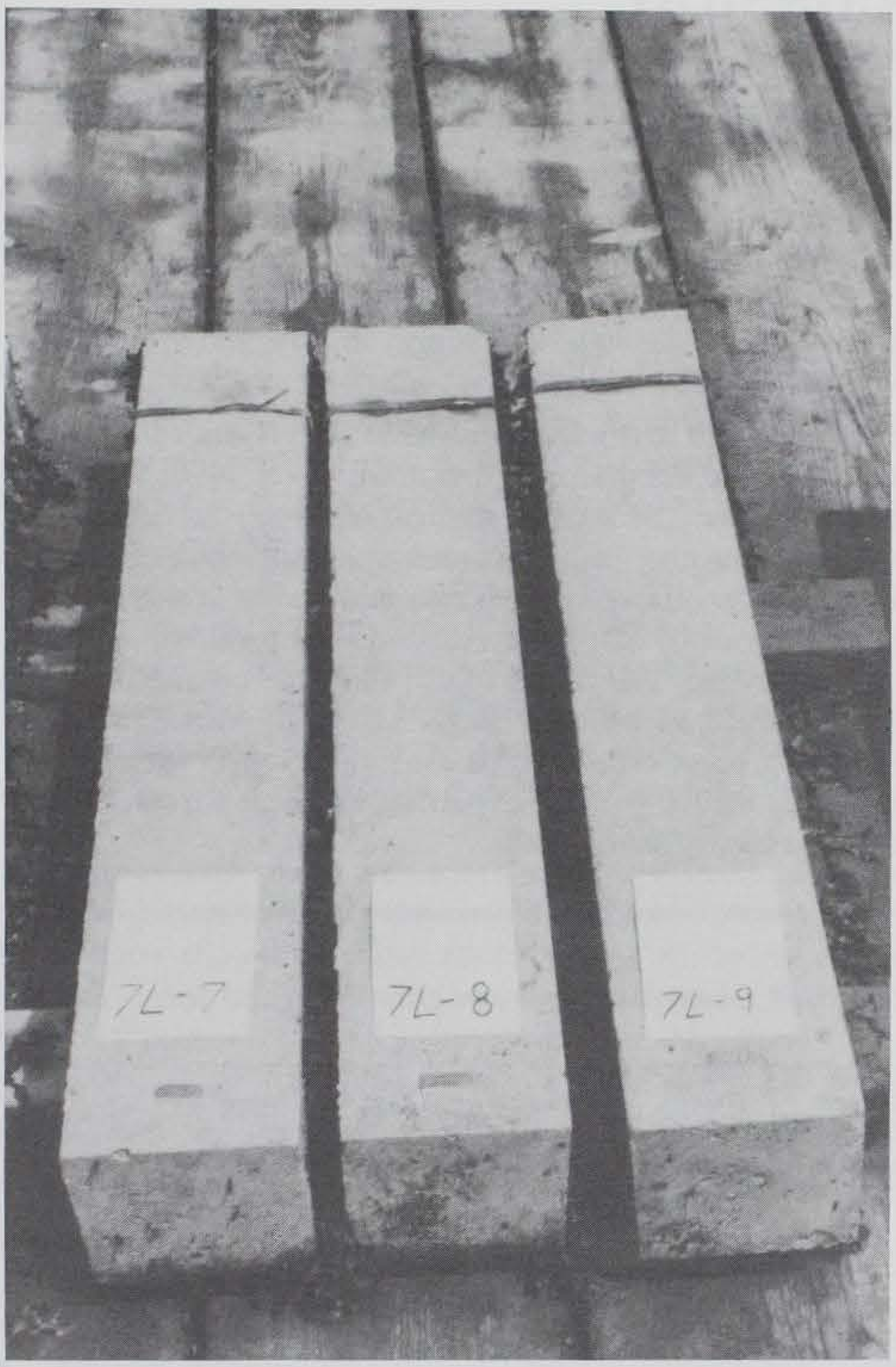

Figure 22. Specimens from long-term durability testing. Photos were taken on August 5, 1992. Sample number 7L-7 corresponds to laboratory sample L-7-7

4 Discussion

Concrete Strength

Compressive strength

The unconfined compressive strengths measured in the present study exceed those advertised by the manufacturer (Pyrament Corp. 1990) for the 4-hr and 7-day cured samples. The average strength of 28-day cured samples is equal to the advertised strength. Table 26 presents a comparison of the results of the unconfined compressive strength tests undertaken in this study with published results obtained by other researchers on comparable (eight-sack) PBC-XT concretes. The results of this study are consistent with strengths measured by others investigators. Regardless of the variations in aggregate and the different water-cement ratios used, the strength gains observed were remarkably similar with 28-day strengths ranging from 7,930 to 12,278 psi with an average of 10,811 psi.

Table 26
Comparison of Average Unconfined Compressive Strengths Reported for PBC-XT Concretes

Referenced Study	Cement Content lb/cu yd	Water-Cement Ratio	4-hr Strength (psi)	1-day Strength (psi)	7-day Strength (psi)	28-day Strength (psi)
Roy, Silsbee, and Wolfe-Confer (1991)	754	0.25	3,396*	6,820	10,086	12,278
Zia et al. (1993)	850	0.23	1,970		9,810	11,820
	850	0.17	2,980		7,560	7,930
	855	0.22	3,140		10,200	12,190
	850	0.23	2,680			
	850	0.17	2,890			
	855	0.22	2,580			
This study (River gravel)	752	0.20	3,750	5,940	8,840	9,980
This study (Crushed limestone)	752	0.225	4,110	6,380	9,590	10,670
Pyrament Corp. (1990)	752	0.25**	2,500	5,000	10,000	

* 5-hour set.
** Estimate from curve presented for water-cement ratio vs. slump.

In related studies using mixtures based on PBC (which is similar to PBC-XT but has a 30-45 min time of setting), Carrasquillo (undated c) reported 28-day strengths of 9,956, 9,217 and 8,410 psi for water-cement ratios that were 0.25, 0.27, and 0.29, respectively. A study evaluating concrete mixtures made by using Pyrament 505 mortar mixture showed a 4-hr unconfined compressive strength of 2,180 psi (Wakeley, Husbands, and White 1991).

The basic Pyrament cement reactions produce a rapid strength gain in mixtures made from all three products (PBC, PBC-XT, or Pyrament 505 mortar mixture).

Flexural strength

Table 27 compares the results from eight-sack mixture of PBC-XT as presented by the manufacturer, published by other investigators, and obtained in the present study. The flexural strengths obtained in this study exceed the manufacturer's expected results for the 4-hr and 6-day curing times, but the highest strength at 28 days was 22 percent lower than the manufacturer's anticipated strength.

Zia et al. (1993) have reported values for modulus of rupture for 28-day cured specimens that fell even further below the manufacturer's target strength. Details on the preparation, curing, and handling of these specimens were not presented. Air-curing may be a factor in the loss of strength between the 7-day and 28-day cured specimens.

In the present study, the flexural strength of mixtures proportioned from PBC-XT increased during the first 6 months of air curing, but specimens for all mixtures showed a decline after 1 year of air curing. It was noted that for samples 1 year old, the flexural strength of air-cured PBC-XT concrete (RG-6) specimens that had been soaked for 5 days prior to testing increased 50 percent over the strengths of similar samples that had not been soaked. The sensitivity of the flexural strength to the internal moisture conditions in the test specimens has been documented (Neville 1973). Low strengths in flexure have been attributed to nonuniform shrinkage prior to testing. Rapid, nonuniform changes in moisture conditions are the major factor in producing low strengths in standard flexural strength testing.

Mixtures prepared with PBC-XT cement demonstrated phenomena similar to those observed with conventional portland cement mixtures.

a. Unconfined compressive strengths are lower in wet specimens than in dry specimens.

b. The modulus of rupture of concrete that is allowed to partially dry is typically lower than saturated specimens of the same material.

c. Drying of wet specimens increases their strength in compression.

Table 27
Comparison of Flexural Strengths of PBC-XT Concretes

Referenced Study	Cement Content lbs/cu yd	Water-Cement Ratio	4-hr Modulus of Rupture (psi)	6-hr Modulus of Rupture (psi)	7-day Modulus of Rupture (psi)	28-day Modulus of Rupture (psi)	6-mo Strength (psi)	1-yr Strength (psi)
Zia et al. (1993)	850 850 855	0.23 0.17 0.23	450 430 460		790 890 1,000	620 770 930		
This study (River gravel - air cured)	752	0.20	475	530	760	715	935	765
This study (Limestone - air cured)	752	0.225	525	690	955	940	1,020	900
This study (Limestone - moist cured)	752					1,430		
Pyrament Corp. (1990)	752	0.25*			800	1,200		

* Estimate from curve presented for water-cement ratio vs. slump.

d. Wetting of dried specimens prior to testing typically reduces their strength in both compression and flexure.

In PBC-XT mixtures, moist-cured samples had higher flexural strengths and lower compressive strengths than similar air-cured samples. Four different storage conditions were used for curing, yielding the following hierarchy in strength: 6-month-old samples that were cured wet and dried had the highest compressive strength, followed by continuously wet-cured samples, continuously air-cured samples, and air-cured samples that were wetted.

When flexural testing was done on 6-month-old specimens, the modulus of rupture was highest for wet-cured specimens that were maintained wet, followed by wet-cured that were allowed to dry, air-cured samples that were wetted, and continuously air-cured samples.

In all cases, testing specimens that were not uniformly wet increases the variation in the data. Conditions other than wet-cured and tested wet are not as reproducible due to the varying degrees of dryness in the test specimens. This moisture content problem is especially critical in flexure tests (Neville 1973).

As in conventional portland-cement concretes, the flexural strength generally increased as the unconfined compressive strength increased.

All samples of PBC-XT concretes cured for over 6 months showed an increase in flexural strength up to 6 months and a decrease when the samples were tested after 1 year of curing, although the unconfined compressive strength continued to increase. The decrease in flexural strength probably can be attributed to the drying effects that occurred during the last 6 months curing period.

In portland-cement concrete the flexural strength or modulus of rupture of normal-weight concrete is approximated using the relationship:

$$\text{Flexural strength (psi)} = X\left(\sqrt{\begin{matrix}\textit{unconfined compressive}\\ \textit{strength (psi)}\end{matrix}}\right)$$

where the value of the coefficient X ranges from 7.5 to 10 (Kosmatka and Panarese 1990). Of the 42 samples of PBC-XT tested, only eight samples showed flexural strengths that were lower than would be predicted for normal-weight portland-cement concrete (Table 28). Additionally, the relationship between flexural strength and compressive strengths depends on the type of coarse aggregate used. When crushed aggregate is used in the mixtures with low water-cement ratios (<0.4), strengths will be up to 38 percent greater than if gravel is used (Neville 1973). Comparing the 28-day-old concretes prepared with gravel to those with crushed aggregate, the maximum increase in modulus of rupture attributable to the crushed-rock aggregate was

Table 28
Relationship between Unconfined Compressive Strength and Flexural Strengths for PBC-XT Mixtures

Mixture	Unconfined Compressive Strength (psi)	Flexural Strength (psi)	$\frac{\text{Flexural Strength}}{\sqrt{\text{unconfined compressive strength}}}$
RG-6 4 hr	2,340	330	6.82
6 hr	2,640	430	8.37
24 hr	4,430	500	7.51
7 day	6,940	630	7.56
28 day	8,900	615	6.52
6 mo	8,900	865	9.17
1 yr	9,360	775	8.01
RG-7 4 hr	3,090	440	7.92
6 hr	3,630	485	8.05
24 hr	5,270	565	7.78
7 day	8,150	735	7.03
28 day	9,370	680	7.02
6 mo	9,880	875	8.80
1 yr	10,380	725	7.12
RG-8 4 hr	3,750	475	7.76
6 hr	4,190	530	8.19
24 hr	5,940	565	7.33
7 day	8,840	760	8.08
28 day	9,980	715	7.16
6 mo	10,380	935	9.18
1 yr	10,770	765	7.37
L-6 4 hr	2,380	370	7.58
6 hr	2,770	435	8.26
24 hr	4,620	620	9.12
7 day	7,250	790	9.28
28 day	8,800	735	7.84
6 mo	9,530	975	9.99
1 yr	9,430	780	8.03
L-7 4 hr	3,790	495	8.04
6 hr	4,370	615	9.30
24 hr	6,070	665	8.54
7 day	9,340	785	8.12
28 day	10,180	815	8.08
6 mo	10,120	960	9.54
1 yr	11,090	865	8.21
L-8 4 hr	4,110	525	8.19
6 hr	4,900	690	9.86
24 hr	6,380	790	9.89
7 day	9,590	955	9.75
28 day	10,670	940	9.10
6 mo	10,920	1,020	9.76
1 yr	11,670	900	8.33

31.5 percent (Table 29). In general, the effect of aggregate type is as important in changing the modulus of rupture in PBC-XT concretes as it is with OPC-based concretes.

Table 29
Comparison of Modulus of Rupture for 28-day Cured Samples Proportioned with Gravel and Crushed Aggregate

Cement Content	Average Modulus of Rupture (psi)		Increase in Modulus with Crushed Aggregate (%)
	Gravel	Crushed Aggregate	
6-sack	615	735	20.5
7-sack	680	815	9.9
8-sack	715	940	31.5

Effects of additional mixing water on strength

WES experience with field applications of Pyrament products had shown that workers unfamiliar with the low water-cement ratio specified by the manufacturer may add water to the mixture. The manufacturer's recommendations indicate a target water-cement ratio between 0.25 and 0.29 for PBC-XT (Pyrament Corp. 1990). To explore the effect on strength of increased water, the present study included tests on specimens from concrete with water-cement ratios of 0.23 (4-in. slump) and 0.28 (8-in. slump). The results are presented in Table 16. The lower water-cement ratio produced higher strengths similar to the behavior of OPC concrete.

Zia et al. (1993) used mixtures that varied with water-cement ratios of 0.17, 0.22, and 0.23. The mixtures with the lowest water-cement ratio (0.17) produced the specimens with the lowest unconfined compressive strengths and the specimens with 0.22 water-cement ratio produced the highest unconfined compressive strengths. Unfortunately each batch used a different type of aggregate. The low water-cement ratio was used with a marine marl that was considered a weak aggregate that had high absorption (Zia et al. 1993). The effect of the aggregate quality is far greater than the effect that the changing water-cement ratio would produce.

Comparison of concrete strengths for different lots of cement

Three different lots of PBC-XT were received from Pyrament Corp. Test specimens prepared with separate lots using mixture L-8 showed less than 10-percent difference in unconfined compressive strength or flexural strength for 28-day cured samples. When 28-day strengths reported by other investigators for concrete with high-quality aggregate proportioned with PBC-XT are compared, most investigators obtain 28-day strengths that are above the manufacturer's target value of 10,000 psi. The lowest values reported by others are less than 12 percent below this target strength.

Mechanical Damage and Bonding

Resistance to freezing and thawing

Pyrament® blended cements are often used in pavement patching operations. Resistance to damage from freezing and thawing often is a critical feature in such concretes made with this material. Although PBC-XT does not contain an air-entraining addition, one or more chemicals in PBC-XT tend to result in an air content of about 3.5 percent (Pyrament Corp. 1990). Zia et al. (1993) reported PBC-XT concrete mixture that varied in air content from 3.6 percent to 6.2 percent. All samples studied typically had more than the manufacturer's recommended air content and sufficient air to produce some resistance to freezing and thawing (Kosmatka and Panarese 1990). Two out of nine samples tested by Zia et al. (1993) and 4 out of 42 samples in the present investigations had relative E values below 60 percent after 300 cycles. In both studies the test results suggested that the character of the aggregate was a critical factor in freeze-thaw resistance. Zia et al. (1993) attributed failure to the deterioration of the river gravel used as aggregate. All samples prepared with marl or crushed granite passed 300 cycles. Similarly, in the present study all of the samples that failed were prepared with river gravel as the coarse aggregate. All of the samples from concrete made with crushed limestone as the coarse aggregate had relative E values of 95 percent or greater (Table 18).

Abrasion resistance

Carrasquillo (undated c) performed abrasion testing of PBC-XT concretes using the rotary cutting method (ASTM C 944-90 (ASTM 1991b)). WES tested abrasion resistance using the underwater method (ASTM C 1138-89 (ASTM 1991c)). The arbitrary conditions of the tests are such that values obtained are not quantitatively comparable (Neville 1973). As in other investigations, the abrasion resistance for PBC-based concretes was directly related to the unconfined compressive strength. Samples with comparable unconfined compressive strengths should be expected to have comparable abrasion test results within any consistent testing system when sound aggregate and conventional aggregate grading are used.

Both investigations show comparable trends for increased abrasion resistance with increasing strengths and results obtained with PBC-XT concretes of a given strength are comparable to those of concretes made with ordinary portland cement.

Bond strength

Pyrament blended cement products have wide applications in patching and repair of concrete. The ability of these formulations to adhere strongly to prepared concrete surfaces is a measure of the usefulness of the products. Table 30 compares data on 24-hr bond strengths of PBC-XT blended concretes with other repair products. In this study, PBC-XT when proportioned with a high cement content bonded almost as strongly as the Pyrament® 505 mortar mixture that is designed as a repair material. All of the PBC-XT mixtures formed stronger bond than were reported for the magnesium phosphate cement, but the methyl methacrylate patching cement was stronger than any of the PBC-XT mixtures.

Table 30
Comparison of Data on Bond Strengths for PBC-XT and other Patching Materials

Reference	Designation	Type of Product	24 hr Bond Strength (psi)	Type of Failure
Wakeley, Husbands, and White (1991)	Pyrament 505	PBC-blended cement mortar mix w/aggregate	2,720	Bond
	SET-45	Magnesium phosphate cement & aggregate	1,200	Bond
	Silikal R17AE	Polymer concrete binder (methyl methacrylate) with aggregate	2,760	Concrete
This study	L-6	PBC concrete mix	1,800	Bond
	L-7	PBC concrete mix	2,540	Bond
	L-8	PBC concrete mix	2,567	Bond
	RG-6	PBC concrete mix	1,967	Bond
	RG-7	PBC concrete mix	2,607	Bond
	RG-8	PBC concrete mix	2,633	Bond

Zia et al. (1993) used a direct shear test to examine the bond strength of Pyrament®-XT. The nominal bond strength for a PBC-XT sample after 4 hr was 225 psi. A control sample of conventional portland cement concrete has a nominal bond strength 330 psi after 7 days using the same test procedure. Evaluation of the test result suggests the bond strength of PBC-XT would have been close to or greater than that of the control specimen bond strength after 7 days.

Effects of Low Temperature on Strength Gain

Repair materials typically must be capable of functioning even in cold weather. Testing with PBC-XT was designed to include adverse conditions such as cold temperatures during early hydration to examine the usefulness of PBC-XT in a cold weather construction or repair setting. Previous work done with Pyrament 505® showed that it could gain strength even at low temperatures (Wakeley, Husbands, and White 1991). The 4-hr strength for Pyrament 505® cured at 15 °F was 1,660 psi compared to 1,810 psi at 25 °F and 3,120 psi at 73 °F. In the current study all concrete mixtures proportioned with PBC-XT show appreciable strength gain down to 20 °F. For samples stored at 20 °F a strength of 2,680 psi was measured after 6 hr. In two trials where freshly mixed concretes were stored at 10 °F, one sample showed 2,510 psi after curing 6 hr and a second batch did not set. The temperature records show that there was an exothermic reaction in the first batch (Figure 8) and none in the second. For portland cement concrete, temperatures above 50 °F are required for unheated placement. Cementing reactions are considered to occur down to 25 °F or lower, but the rate of strength gain is negligible (Neville 1973). Tests with PBC-XT indicate the system can consistently operate at 25 °F and perhaps as low as 10 °F.

Shrinkage and Creep

Table 31 shows a comparison of the drying shrinkage measured in the present study with that reported by other investigators. The drying shrinkage can typically be influenced by water-cement ratio and by the amount and character of aggregates. Generally, the lower the amount of water used and the larger the proportion of coarse aggregate the lower the dry shrinkage. Similar trends are evident in earlier reports on PBC and PBC-XT mixtures. The only unusual data reported appear in the study by Zia et al. (1993) where one concrete mixture made with crushed granite showed expansion. This was reported as being due to continued cement hydration caused by the low initial water-cement ratio.

Mixtures proportioned with PBC-XT in this study showed drying shrinkage that is comparable to that of concrete proportioned with OPC. Plots presented in Kosmatka and Panarese (1990) indicate that a shrinkage of -0.020 to -0.025 percent would be usual for mortar proportioned with OPC after 28 days. Samples from the present investigation, proportioned with normal aggregate showed shrinkages ranging from -0.019 to -0.027 percent.

Deformation under long-term loading or creep is a critical factor for concretes in construction applications. A wide variety of factors such as aggregate type, admixtures, and storage conditions can affect creep in portland cement-based concretes. Work with PBC-XT has shown that creep is particularly sensitive to the water-cement ratio used. Carrasquillo (undated b) has shown that the 120-day specific creep can change from 0.303 to 0.434 to 0.575 millionths/psi as the water-cement ratio changes from 0.25 to 0.27 to 0.29.

Table 31
Comparison of Drying Shrinkage for PBC and PBC-XT Proportioned Concrete Mixtures

Referenced Study	Water-Cement Ratio	C:FA:CA	1-day Shrinkage (%)	28-day Shrinkage (%)	56-day Shrinkage (%)	90-day Shrinkage (%)
Zia et al. (1993)	0.17	1:1.7:1.8	-0.00	-0.0059	-0.0059	-0.0131
	0.23	1:1.7:1.8	-0.00	-0.0059	-	+0.0052
	0.22	1:1.7:1.8	-0.00	-0.0079	-0.0079	-0.0144
Carrasquillo (undated) (PBC mixtures)	0.25	1:1.8:2.2	-0.00	-0.019*	-	-
	0.27	1:1.8:2.2	-0.00	-0.025	-0.027	-
	0.29	1:1.8:2.2	-0.00	-0.032	-	-0.034
This study (Limestone)	L-6 0.247	1:2.5:3.3	-0.008	-0.023	-0.024	-0.025
	L-7 0.247	1:2.2:2.7	-0.011	-0.022	-0.026	-0.027
	L-8 0.225	1:1.8:2.4	-0.015	-0.027	-0.029	-0.029
This study (River gravel)	R-6 0.254	1:2.6:3.1	-0.007	-0.019	-0.024	-0.025
	R-7 0.219	1:2.2:2.6	-0.012	-0.024	-0.030	-0.032
	R-8 0.200	1:1.8:2.2	-0.012	-0.025	-0.026	-0.028

* Time is ± 4 days for this data set.
C = Cement
FA = Fine aggregate
CA = Coarse aggregate

The creep testing performed in the present investigation using an eight-sack mixture similar to that used by Carrasquillo (undated d) showed a specific creep of 0.36 millionths/psi after 120 days. This is in excellent agreement with data from Carrasquillo (undated b) considering the differences in mixtures and aggregates used.

The creep measured for PBC-XT concretes in both studies, as Carrasquillo (undated d) noted, is within the range observed for concretes proportioned with OPC with water-cement ratios in the range from 0.2 to 0.5.

Potential Chemical Reactions

Sulfate resistance

Results of sulfate resistance tests for PBC-based mortars have been reported by Pyrament Corp. (1990) as being less than 0.03 percent expansion at 365 days using both the sodium sulfate solution and the sodium and magnesium sulfate solutions described in ASTM C 1012 (ASTM 1988). Carrasquillo (undated f) reported results from sulfate resistance testing for concretes proportioned with PBC and water-cement ratios of 0.25, 0.27, and 0.29. The maximum expansion for samples tested in a sodium sulfate solution was observed in the samples with the highest water-cement ratio. When the solution of sodium and magnesium sulfate was used, all of the specimens showed greater expansion, but only one specimen exceeded the manufacturer's claim of 0.03 percent. The average expansion measured for any mixture never exceeded 0.03 percent.

In the present study mortar bar samples prepared with PBC-XT showed an expansion of 0.059 percent after 205 days of testing. This exceeds other test results but is less than the ASTM limit of 0.10 percent after 6 months (ASTM C 33 (ASTM 1993b)).

The maximum expansion observed was with the eight-sack concrete mixture with limestone aggregate tested for 2 years. These samples showed only 0.061 percent expansion. Comments on the test procedure ASTM C 1012 (ASTM 1988) point out that magnesium sulfate solutions typically have an adverse reaction on length stability of samples prepared from blended cement containing slag because of a reaction of magnesium ion (not sulfate) with slag hydration products. This effect did not occur in the PBC-XT samples, which is consistent with the use of slag in the formulation of PBC-XT.

Deicer scaling resistance

Carrasquillo (undated c) has reported the results of scaling tests (ASTM C 672 (ASTM 1990d)) conducted with batches of concrete made with PBC at water-cement ratios of 0.25, 0.27, and 0.29. None of the samples showed scaling that exceeded visual rating of 2.5 (slight to moderate scaling) after 50 test cycles. The least scaling was observed with samples having water-cement ratios of 0.27. The samples prepared with a water-cement ratio of 0.25 were difficult to finish due to the stiff consistency of the mixture, and this is thought to have contributed to the 2.5 rating given these samples. The samples prepared with the 0.29 water-cement ratio were the easiest to finish but typically are the most susceptible to scaling of the three mixtures tested.

In the present investigation all of the specimens prepared with PBC-XT were judged to show visual rating of 2 or less, indicating only slight scaling or no scaling. The worst scaling was observed with a seven-sack mixture with limestone aggregate. The test procedure is sensitive to surface finish and the slightly higher scaling may have been due to differences in finishing. This study and all the work reported to date indicates that concretes prepared with PBC or PBC-XT have excellent resistance to deicing chemicals.

Chloride permeability

P/LS has reported very low permeability to chloride solutions for concrete proportioned with PBC-XT. Results from rapid chloride permeability (RCP) testing (AASHTO Designation T 277, AASHTO 1990a) showed less than 1,000 coulombs passed at 91 days age (Pyrament Corp. 1990).

In this test, the chloride permeability of a concrete of any age is considered low if it passes fewer than 1,000 coulombs after 6 hr of testing. The chloride permeability of concretes L-6 and L-8 was low by this criterion even as early as 7 days after casting. By the RCP test, a value of 700 coulombs for a 7-day-old concrete is remarkably low.

Carrasquillo (undated c) reported chloride penetration results on PBC concretes obtained using a modified expose-and-sample procedure (modified from ASTM C 672-84, ASTM 1990d). Samples were cured for either 1 day or 28 days prior to being exposed to a calcium chloride solution for the duration of a 50-cycle scaling test (over 50 days exposure). Negligible additional chloride was found below a 1-in. depth in any sample.

Zia et al. (1993) examined chloride permeability for concretes proportioned with PBC-XT using the RCP test (AASHTO T 277-89, AASHTO 1990a). Two sets of samples were tested: one with marl aggregate and one with a river gravel aggregate. Samples were tested at 12 days age. The total charge for the marl sample was 2,670 coulombs, while that for the river gravel was 1,350 coulombs in 6 hr. The batch prepared with marl aggregate would be classed as having moderate chloride ion penetrability, while the batch prepared with river gravel has low chloride permeability. In the series of tests reported in Zia et al. (1993) the samples proportioned with PBC-XT had the lowest permeabilities of any of the fast-setting concretes tested.

Data from the current investigation confirm trends noted in other studies. Chloride penetration was measured using an expose-and-sample test (AASHTO T 259-80, AASHTO 1990b) and the conductivity-based RCP test (AASHTO T 277-89, AASHTO 1990a). The results of the present investigation show even lower chloride penetrability than was measured by Carrasquillo (undated c) even though the duration of exposure to chloride was longer. Similarly, the results of the RCP test indicated less chloride movement in the present investigation than that measured by Zia et al. (1993). Specimens used in the present testing had lower water-cement ratios (averaging 0.23) than those of other investigators. The increased density is the most probable explanation for the improved performance.

Potential alkali reactivity

Previous investigations have shown that the alkali content of Pyrament-based products is considered high in comparison to OPC. In PBC-based cements, Na_2O-equivalent values (percent Na_2O plus 0.658 times percent K_2O) are in the range of 2.2 to 3.0 percent (Morgan 1992). Cement with Na_2O-equivalent values as low as 0.6 percent can cause deleterious reactions with sensitive aggregates (Neville 1973). The potential for expansion reactions has been evaluated in two previous studies and in the current investigation.

Table 32 compares the results of this investigation with those of Morgan (1992) and Carrasquillo (undated a). In all cases aggregates that were known to be reactive with high-alkali portland cements also showed evidence of expansive reactions with PBC-based products. The present study indicates the

Table 32
Comparison of Results from Alkali-Aggregate Reaction Testing for Pyrament Blended Cements

Reference	Product Used	Na_2O Equivalent (%)	Type of Aggregate Used	Known to be Reactive	6-month Expansion (%)	1-year Expansion (%)
Carrasquillo (undated a)	PBC		Pyrex glass	Yes	0.2067	0.2073[1]
			Colorado River sand	No	0.0591	0.0866[1]
			El Paso River sand	Yes	0.1191	0.1318[1]
Morgan (1992)	PBC-XT	3.03	Bearspaw sand	No	0.073	0.094
	PBC-XXT	2.45	Bearspaw sand	No	0.056	0.075
	PBC-XXT	2.19	Spratt gravel[2]	Yes	0.068	--
	PBC-XXT	2.19	Exshaw sand	No	0.026	--
	PBC-XXT	2.19	Bearspaw sand	No	0.085	--
	PBC-XXT	2.19	Bearspaw sand	No	0.039	--
This study	PBC-XT	2.73	Pyrex	Yes	0.280	--
	PBC-XT	2.73	Sand 920185	Yes	0.130	--

[1] Measurement was made 390 days after start of exposure.
[2] The reactive aggregate was the coarse fraction. The fine aggregate was the innocuous Exshaw sand.

need for careful selection of aggregates for use in concretes proportioned with Pyrament products, similar to the care that would be taken with any high-alkali cement.

Long-Term Durability Testing

The results from the long-term durability testing on Treat Island demonstrated that the specimens prepared for this project had good durability after relatively few years of exposure. Because Treat Island is a unique test facility, there are no data published elsewhere comparable to these results from exposure of PBC-XT concrete beams.

5 Conclusions and Recommendations

Summary of Physical and Mechanical Properties

The results of the current investigations of the properties of concretes proportioned with PBC-XT cement are consistent with the manufacturer's published data (Pyrament Corp. 1990) and with previous investigations performed on concretes proportioned from Pyrament products. The properties of these concretes can be summarized as follows:

a. Concretes proportioned with PBC-XT in this study gained compressive strength at approximately the rate indicated in the manufacturer's documentation (Pyrament Corp. 1990) and reported for comparable mixtures examined by other investigators.

b. Concretes proportioned using PBC-XT from three separate lots with similar formulations all showed less than 10-percent difference in unconfined compressive strength after a 28-day curing period.

c. Testing done to determine resistance to freezing and thawing generally gave excellent results. Specimens made with crushed limestone aggregate had values of relative E above 95 percent after 300 cycles. Specimens that had values of relative E <60 percent were proportioned with river gravel that included porous particles. The limited long-term exposure testing undertaken in this project shows that PBC-XT concretes when properly placed and cured showed negligible deterioration after 3 years at Treat Island, Maine.

d. PBC-XT concretes are cold-weather tolerant. Consistent useful strength gains were measured in this study down to 20 °F.

e. The PBC-XT concrete samples tested in the present investigation showed drying shrinkage that was similar to that recorded for concretes proportioned with ordinary portland cement. In samples where good quality aggregate was used, shrinkages ranged from -0.019 to -0.027 percent.

f. Tests conducted for scaling resistance to deicing chemicals showed excellent resistance. The results of the current testing agree with published data on PBC-based concretes.

g. Chloride permeability testing done with both exposure-and-sampling methods and electrical conductivity techniques show the concretes prepared with PBC-XT should be expected to have a high degree of resistance to chloride-ion penetration.

h. In PBC-XT concretes, flexural strength increases with compressive strength generally following the relationship observed for concretes prepared with ordinary portland cements.

i. Flexural strengths obtained with PBC-XT concretes changed in response to the drying conditions of the test beams. In air-cured specimens, all gains in flexural strength followed the manufacturer's advertised strength except for the 28-day cured specimen that were approximately 25 percent lower than the manufacturer's published values.

j. Within the limits of the water-cement ratio specified by the manufacturer (0.25 to 0.29), PBC-XT showed the manufacturer's specified rates of strength gain and generally the lower water-cement ratios produced increased strength.

k. Using crushed aggregate rather than rounded gravel increases the modulus of rupture. This effect is comparable to that observed in other hydraulic-cement concretes.

l. Creep measurements on concrete proportioned with PBC-XT measured over 120 days showed a specific creep of 0.36 millionths/psi. This is within the range observed for concrete made with ordinary portland cement. The values agree with those obtained for other PBC-based concretes prepared by other investigators.

m. Sulfate resistance testing on mortar bars prepared with PBC-XT cement showed an average expansion of 0.059 percent in 205 days. These values are greater than the results obtained by other investigators (<0.030) but less than ASTM limit of 0.10 percent. The maximum expansion observed in 2 years of exposure was 0.061 percent, still well below the ASTM limit of 0.10 percent at 180 days given in ASTM C 595 (ASTM 1992b).

n. The abrasion resistance of concretes proportioned with PBC-XT increased with increasing strength in the same manner as concretes made with ordinary portland cement. Abrasion resistance therefore was good, because of the higher strengths attained by these concretes.

o. Bond strengths measured for concretes proportioned with PBC-XT in this study varied from 1,800 to 2,633 psi. These values are higher than other high early-strength cements such as magnesium phosphate cement and nearly as strong a bond as Pyrament 505 mortar mixture tested previously (2,720 psi).

p. Analysis of samples of PBC-XT used in this test program shows that the cement has a Na_2O-equivalent value of 2.73 percent and this may be capable of producing alkali-aggregate reactions when reactive aggregates are used in PBC-XT concretes. Testing for expansive reactions showed that when used with known reactive aggregates, the 6-month expansion could exceed the ASTM recommended limit of 0.10 percent. Earlier studies conducted with PBC products reported similar results.

Indications for Field Use of PBC-XT Concretes

In simple terms, the objective of this study was to answer the question: It sets fast, but will it last? The laboratory work conducted here answers "yes," as long as the aggregate used is selected carefully for the required properties and is unlikely to participate in alkali-aggregate reactions. These caveats apply, however, any time concrete is proportioned for high performance, regardless of what cement is used.

In discussions about field uses of Pyrament cement-based concretes, anecdotes about difficulty in placing and finishing often are repeated. The work reported here was conducted on a small scale, in controlled conditions, and does not simulate field placement. The WES team observed several field placements during this research, however, all of which were pavement construction or repair. Field personnel on these projects, working with Pyrament the first time, often observed that the mixture looked "harsh" or looked as if it needed more water for proper mixing and placing relative to the concretes in their previous experience. This apparent "harshness" early in the mixing cycle has led some workers to add more water during mixing, leading to a water-cement ratio higher than is recommended, and resulting in shrinkage cracking of the finished surface and lower strength.

Another problem with field performance observed by the WES team was caused by admixture interaction. In one project, PBC-XT was selected for use in a concrete which also included organic fibers added in groups. Air content of the concrete was near 14 percent, or 10 percent higher than was specified, and was accompanied by lower strength. In this case, it was determined that the excess air was entrapped by this particular combination of fibers and Pyrament. In subsequent work at the same jobsite, monofilament instead of grouped fibers was used in the concrete. With this change in fiber type, air content and strength returned to expected values.

The Pyrament cement formulation includes proprietary ingredients in addition to the cementitious components. The presence of these functional additions prevents PBC-XT from meeting the requirements of ASTM C 595 (ASTM 1992b), which specifically prohibits components not listed in the specification. These other components perform as admixtures, to regulate time of setting and perform other functions. They are an integral part of the Pyrament formulation, imparting some of its unique properties. It is likely that any admixture batched separately into these concretes could interact in some unpredicted chemical or physical way with one of the ingredients of Pyrament cement and could lead to performance problems. Thus the manufacturer's statement that Pyrament cement concretes achieve their notable properties "without admixtures" is true, because the constituents needed to achieve these properties already are present. This statement also serves as a recommendation against use of other materials that might interact with components of Pyrament to detract from its performance.

A standard performance specification for blended hydraulic cement has been published by ASTM (1993a). The performance specification removes restrictions on composition in classifying a blended cement. The manufacturer may redesignate PBC-XT and other related products based on a suite of test results that demonstrate properties required by one or more of the basic types of blended hydraulic cements and may indicate options or optional physical requirements that the product meets.

In WES laboratory tests, concretes proportioned with PBC-XT cement showed strong resistance to both chemical and physical attack. These concretes also have the ability to gain strength normally at 20 °F, unique among commercial hydraulic cements. PBC-XT concretes can be expected to give superior performance in applications having combinations of requirements in addition to rapid strength gain, such as high resistance to damage from freezing and thawing and high resistance to ingress of chlorides.

Use of PBC-XT concretes may be appropriate for any job on which the need for rapid strength gain, the need to gain strength at cold temperatures, or the need for a product with increased resistance to penetration by liquids and chlorides justifies the added cost. When proper measures are taken to avoid drying shrinkage cracking, these concretes are appropriate for many small-volume and thin-member applications and other uses excluding mass concrete. Bridge decks, parking garage floors, waste storage tanks, and water systems are examples of applications that might particularly require these properties. The results of this study indicate that when PBC-XT concrete is chosen for a job and appropriate concrete practice is used on the job, the user can expect not only high compressive and flexural strength in a short time, but also a high-performance concrete that will stand up to many potential causes of deterioration in its service environment.

6 Commercialization and Technology Transfer

Availability of Pyrament Blended Cement

Pyrament cement products are manufactured by Lone Star Industries, Inc., at only one facility in the United States, which is in Greencastle, IN. Sale of Pyrament products is promoted by agreement with more than 20 representative firms, and distribution is through normal construction materials suppliers and ready-mixed concrete businesses. Sales and technical service offices are:

Pyrament/Lone Star Industries, Inc.
340 N. Sam Houston Parkway E, Suite 140
Houston, Texas 77060 USA

P/LS manufactures three PBC products, covering a range of engineered setting times from 30 min. to over 2.5 hr. These three cements are available in 50-lb bags, in 25-cu-ft and 50-cu-ft flexible bulk containers (called "super sacks" by P/LS), and in bulk.

P/LS also manufactures the prepackaged concrete-repair mortar mixture, Pyrament 505; and SAC-PAC, the self-contained repair material (to be mixed with premeasured water, also included, in its own container) designed for use by the U.S. Air Force for rapid repair of runways. Pyrament 505 and SAC-PAC both are proportioned with the 30-min setting PBC.

Recent Applications of Pyrament Blended Cements

During this project, the industry partner provided to the WES frequent updates of information about field applications of Pyrament products. A cumulative update of Pyrament concrete users provided in fall 1993 listed over 50 industrial facilities in the United States, 57 military installations in the United States and 7 other countries, and 36 nonmilitary airports. Industrial facilities that have used Pyrament concretes include heavy manufacturing, refining, and coastal structures. PBC concretes have been selected many times for their rapid strength gain, where the most cost-effective option was minimum shutdown time of an operating facility. But these concretes have been selected for other properties as well.

Resistance to abrasion prompted selection of PBC concrete for repair of pavement at the drive-up window of a fast-food business. At least two companies that handle bulk frozen foods have used PBC concretes inside their freezers, where the concrete set and gained strength while freezer operations continued. Because of the resistance of Pyrament concretes to ingress of salts, they have been used for construction of parking-garage decks at a major-league baseball stadium. Improved resistance to chemical attack has prompted their use in equipment pads and floors for many industrial facilities that process chemicals and metals. A list of industrial applications is available from P/LS.

Applications Observed During the CPAR Project

During this CPAR project, the WES team observed eight field applications of Pyrament-cement concretes and patching materials. These included replacement of entire pavement slabs, at both commercial facilities and military bases; spall repairs and repairs under arresting system cables at Air Force Bases; and one highway project, which was coordinated with the Strategic Highway Research Program. Successful applications of Pyrament 505 were observed at temperatures as low as 15 °F.

At Charleston International Airport, which is shared by the Air Force and the city of Charleston, SC, pavement slabs at the intersection of two runways were replaced with PBC-XT concrete. Pyrament cement was selected because a flexural strength of 500 psi was required within 4 hr after placement, so the runways could be used within a few hours of placement. Two pavement slabs were reconstructed each night with work starting at 22:45 and the runways being reopened at 06:45.

The Charleston Airport Authority stated that by using Pyrament cement they were able to keep the airport open during replacement of pavement slabs, at a savings of over $100/min. Air Force personnel have reported satisfactory performance of these slabs, and a multimillion dollar savings by not having to relocate their operations during construction. A video of this project, completed in 1990, is available from P/LS.

Presentations of Information from this Study

Results of the durability studies and of other aspects of this research have been presented at professional meetings and in many informal information exchanges. The WES team published abstracts and presented two papers at the Annual Meeting of the American Society of Civil Engineers in October 1991, after which interest in the Pyrament product booth at this conference increased markedly. Results have been shared with other federal government laboratories during the Interagency Research Coordination Conferences, beginning in 1991. A member of the WES team also served on the Expert Task Group for high-performance concrete of the Strategic Highway Research Program, through which WES research results were distributed to representatives of various federal and state agencies in 1992-93.

Summaries of the work have been distributed at various Air Force conferences, including the MAJCOM Pavements Conference at Tyndall Air Force Base, FL, in April 1993. Pyrament products have been described by the WES team in technical notes and material data sheets distributed through the Repair, Evaluation, Maintenance, and Rehabilitation (REMR) Research Program. Articles derived from this report are in preparation and are to be submitted to other professional and industry publications.

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Appendix A
Petrographic Reports on Aggregates Used

US Army Corps of Engineers Waterways Experiment Station

Petrographic Report

Structures Laboratory
3909 Halls Ferry Road
Vicksburg, Mississippi
39180-6199

Project: Tests of 3/4-in. Limestone Aggregate from the Vulcan Materials Co., Calera, AL

Date: 2 April 1990
JPB

Sample

1. A small sample of crushed limestone aggregate, Concrete Technology Division (CTD) Serial No. CPAR-l MG-l, was furnished to the Petrography and Chemistry Group for petrographic tests. The source of the material was the Vulcan Materials Co., Calera, Alabama. The sample consisted of 3/4-in. aggregate.

Test Procedures

2. Technical Memorandum 6-370* was checked to see if material from the same source had been previously tested by petrographic methods.

3. The material was separated into three piles based on their color.

4. Representative particles from each color category were crushed into fine particles. A composite was ground to pass a 45 micrometre (No. 325) sieve and examined by X-ray diffraction (XRD). Another composite was weighed and treated with dilute hydrochloric acid (HCl) for 24 hours to determine the percentage by weight of insoluble material present.

5. A Philips 1800 diffractometer using nickel-filtered copper radiation was used to collect the XRD data.

Results

6. The search of TM6-370 indicated that material from this source had been examined previously. The current material is similar to material examined before; however, it does contain more insoluble residue than the sample examined and reported on 23 March 1987.

7. The three color groups were light gray (N7)**, medium gray (N5)**, and dark gray (N3)**. The examination by XRD showed the major mineral in each group to be dolomite. Potassium feldspar, quartz, and traces of clay were also present. Calcite was also present in each color group.

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* US Army Engineer Waterways Experiment Station, CE, "Test Data-Concrete Aggregates in the Continental U.S.," Technical Memorandum No. 6-370, September 1953 (with periodic supplements), Vicksburg, MS.

** The Rock Color Chart Committee, E. N. Goddard, Chairman," Rock Color Chart," 1984, The Geological Society of America, Boulder. CO.

8. The test for acid insoluble residue showed the following:

Color Group	Insoluble, Percent by Wt
Light gray	9.4
Medium gray	13.8
Dark gray	9.4

Discussion

9. The aggregate is a fine-grained calcitic dolomite. The composition of the aggregate indicates that it is not expected to react with the alkalies in cement.

Special Note

10. This aggregate is being used in concrete prepared under RPP 90-6 and RPP 90-12.

US Army Corps of Engineers
Waterways Experiment
Station

Petrographic Report

Structures Laboratory
3909 Halls Ferry Road
Vicksburg, Mississippi
39180-6199

Project: Tests of Natural Gravel from
Mississippi Materials Co., Vicksburg, MS

Date: 2 April 1990
JPB

Sample

1. A composite sample of natural gravel, Concrete Technology Division (CTD) Serial No. CPAR-l G-l, was furnished the Petrography and Chemistry Group for petrographic tests. The material was purchased from Mississippi Materials Co., Vicksburg, MS. The material came from the Runyon Gravel pit located 7.5 miles south of Hwy 80 on Hwy 27 in Vicksburg, MS. The gravel sample had not been separated into sieve fractions.

Test Procedures

2. Technical Memorandum 6-370* was checked to see if material from the same source had been previously tested by petrographic methods.

3. Particles were examined to determine their shape, porosity, and if coating materials were present.

4. Some particles were examined using the petrographic microscope as grain mounts prepared in oil with an index of refraction of n = 1.544. This test was to determine if chalcedony is present. Chalcedony, if present, is identified as cryptocrystalline siliceous particles with an index of refraction lower than 1.544.

Results

5. The search of TM6-370 indicated that material from this source had been examined previously. The current material is similar to material examined before. The sample contains dense as well as porous chert. The porous particles are either partially or totally porous. Some vuggy particles are also present. A few oolitic and a few fossiliferous particles were present. The particles are blocky or pyramidal with subrounded edges. No coating material was present.

6. Chalcedony was present in the gravel.

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* US Army Engineer Waterways Experiment Station, CE, "Test Data-Concrete Aggregates in the Continental U.S.," Technical Memorandum No. 6-370, September 1953 (with periodic supplements), Vicksburg, MS.

Conclusion

7. The gravel is typical of gravels in this area. Chalcedony is present, and the gravel should be considered potentially deleterious when used as aggregate in high-alkali portland-cement concrete.

Special Note

8. This aggregate is being used in concrete prepared under RPP 90-6.

US Army Corps of Engineers
Waterways Experiment
Station

Petrographic Report

Structures Laboratory
3909 Halls Ferry Road
Vicksburg, Mississippi
39180-6199

Project: Tests of Natural Sand Aggregate
from the Cobb Industrial Corp., Coushatta, LA

Date: 3 April 1990
JPB

Sample

1. Several pounds of natural sand, Concrete Technology Division (CTD) Serial No. WESSC-7 S-l, were furnished to the Petrography and Chemistry Group for petrographic tests. The sand came from the Cobb Industrial Corp., Coushatta, LA. The sand sample had not been separated into sieve fractions.

Test Procedures

2. Technical Memorandum 6-370* was checked to see if material from the same source had been previously tested by petrographic methods.

3. Coarser sand particles were examined using a stereomicroscope. They were separated into chert or quartz. Their shape and porosity were noted. The finer sand particles were examined with a polarizing microscope as grain mounts prepared in oil with an index of refraction of $n = 1.544$. The mineralogy of grains was noted. Chalcedony, if present, can also be identified in grain mounts, it is cryptocrystalline siliceous particles with an index of refraction lower than 1.544.

Results

4. The search of TM6-370 indicated that material from this source had been examined previously. The current material is similar to material examined before.

5. The larger particles in this sample consist of particles of dense, as well as porous pieces. The porous particles are either partially or totally porous, and have a lighter color than the dense particles. Some vuggy particles are also present.

6. As the sand gets finer, more quartz particles are present. Trace amounts of feldspar and sandstone are present in the material passing the 600 μm (No. 30) sieve. Miscellaneous particles of heavy minerals were present in trace amounts. The sands were composed of blocky, pyramidal, spherical, and ellipsoidal particles. The amount of spherical and ellipsoidal particles increased as they became smaller. Many particles were stained with a yellowish-orange iron oxide.

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* US Army Engineer Waterways Experiment Station, CE, "Test Data-Concrete Aggregates in the Continental U.S.," Technical Memorandum No. 6-370, September 1953 (with periodic supplements), Vicksburg, MS.

7. Chalcedony is present in the sand.

Conclusion

8. The sand is similar to that previously examined from the same source. Chalcedony is present, and the sand should be considered potentially deleterious when used as concrete aggregate with high-alkali portland cement.

Special Note

9. This sand is being used in concrete prepared under RPP 90-6 (CPAR High-Performance Blended Cement Concrete) and RPP 90-12 (Durability of Pozzolan Concrete, CW Work Unit 32462).

Appendix B
Unconfined Compressive Strengths for PBC-XT Concretes

Table B1
Unconfined Compressive Strengths, PBC-XT Concretes

Concrete Mixture	Batch	Time of Test	Compressive Strength, psi			Average, psi
RG-6	1	4 hr	2,180	2,240	2,320	2,340
RG-6	2	4 hr	2,440	2,550	2,590	
RG-6	3	4 hr	2,310	2,280	2,180	
RG-6	1	6 hr	2,630	2,690	2,590	2,640
RG-6	2	6 hr	2,560	2,650	2,900	
RG-6	3	6 hr	2,550	2,560	2,660	
RG-6	1	24 hr	4,310	4,500	4,500	4,430
RG-6	2	24 hr	4,540	4,470	4,600	
RG-6	3	24 hr	4,330	4,170	4,450	
RG-6	1	7 day	7,240	7,160	7,080	6,940
RG-6	2	7 day	7,160	7,280	6,760	
RG-6	3	7 day	6,410	6,650	6,760	
RG-6	1	28 day	8,630	8,750	8,360	8,900
RG-6	2	28 day	9,310	9,150	9,190	
RG-6	1	6 mo	8,710	8,630	8,760	8,900
RG-6	2	6 mo	8,750	9,030	8,900	
RG-6	3	6 mo	8,750	9,310	9,270	
RG-6	1	1 yr	9,550	9,790	9,670	9,360
RG-6	2	1 yr	9,230	9,430	9,330	
RG-6	3	1 yr	8,950	9,120	9,230	
RG-7	1	4 hr	3,100	2,860	2,900	3,090
RG-7	2	4 hr	3,020	3,120	3,180	
RG-7	3	4 hr	3,140	3,300	3,180	
RG-7	1	6 hr	3,530	3,490	3,630	3,630
RG-7	2	6 hr	3,630	3,560	3,620	
RG-7	3	6 hr	3,640	3,800	3,750	

(Sheet 1 of 6)

Table B1 (Continued)

Concrete Mixture	Time of Test	Batch Number						Avg.
		1		2		3		
L-8	4 hr	380	375	335	340	400	385	370
L-6	6 hr	420	475	420	410	425	465	435
L-6	24 hr	600	555	695	640	635	595	620
L-6	7 day	750	790	825	740	785	840	790
L-6	28 day	710	670	795	735	745	755	735
L-6	6 mo	910	845	930	895	1165	1095	975
L-6	1 yr	735	820	720	875	795	740	780
L-7	4 hr	500	495	485	470	510	505	495
L-7	6 hr	605	670	665	575	510*	570	615
L-7	24 hr	680	780*	630	650	690	685	665
L-7	7 day	745	745	825	930*	775	835	785
L-7	28 day	840	755	840	840	775	835	815
L-7	6 mo	945	1005	1015	910	935	945	960
L-7	1 yr	780	765	955	945	880	855	865
L-8	4 hr	570	480	650*	520	535	520	525
L-8	6 hr	665	650	705	700	730	695	690
L-8	24 hr	760	800	795	685	875	825	790
L-8	7 day	930	995	860*	935	975	945	955
L-8	28 day	885	895	950	975	985	935	940
L-8	6 mo	990	1010	1185	1115	860	970	1020
L-8	1 yr	860	915	845	920	985	875	900

(Sheet 2 of 6)

Table B1 (Continued)

Concrete Mixture	Batch	Time of Test	Compressive Strength, psi			Average, psi
L-8	1	24 hr	5,330	4,930	5,210	5,270
L-8	2	24 hr	5,320	4,770	5,400	
L-8	3	24 hr	5,440	5,490	5,570	
L-8	1	7 day	7,840	7,800	8,360	8,150
L-8	2	7 day	8,400	8,160	8,240	
L-8	3	7 day	8,400	8,520	7,600	
L-8	1	28 day	9,630	9,150	9,230	9,370
L-8	2	28 day	9,350	9,430	9,550	
L-8	3	28 day	9,630	8,930	9,470	
L-8	1	6 mo	10,110	10,070	9,670	9,880
L-8	2	6 mo	9,150	9,230	10,110	
L-8	3	6 mo	9,150	10,860	10,540	
L-8	1	1 yr	9,710	10,150	10,350	10,380
L-8	2	1 yr	9,470	10,230	10,460	
L-8	3	1 yr	11,100	11,140	10,820	
RG-8	1	4 hr	3,830	3,750	3,630	3,750
RG-8	2	4 hr	3,670	3,770	3,700	
RG-8	3	4 hr	3,950	3,520	3,910	
RG-8	1	6 hr	4,140	4,150	4,170	4,190
RG-8	2	6 hr	4,180	4,390	4,190	
RG-8	3	6 hr	4,080	4,270	4,100	
RG-8	1	24 hr	6,130	5,950	6,090	5,940
RG-8	2	24 hr	5,910	5,830	5,770	
RG-8	3	24 hr	5,830	6,020	5,940	
RG-8	1	7 day	8,150	9,270	9,110	8,840
RG-8	2	7 day	8,310	8,710	8,670	
RG-8	3	7 day	9,150	9,270	8,950	

(Sheet 3 of 6)

Table B1 (Continued)						
Concrete Mixture	**Batch**	**Time of Test**	**Compressive Strength, psi**			**Average, psi**
RG-8	1	28 day	9,150	10,190	10,230	9,980
RG-8	2	28 day	9,310	9,950	9,100	
RG-8	3	28 day	10,350	11,220	9,950	
RG-8	1	6 mo	10,580	10,500	10,540	10,380
RG-8	2	6 mo	10,540	9,950	9,710	
RG-8	3	6 mo	10,900	10,070	10,660	
RG-8	1	1 yr	11,140	10,980	9,990	10,770
RG-8	2	1 yr	10,230	11,420	10,270	
RG-8	3	1 yr	11,530	10,500	10,860	
L-6	1	4 hr	2,380	2,270	2,450	2,380
L-6	2	4 hr	2,230	2,340	2,230	
L-6	3	4 hr	2,470	2,470	2,580	
L-6	1	6 hr	2,860	2,650	2,890	2,770
L-6	2	6 hr	2,700	2,720	2,500	
L-6	3	6 hr	2,850	2,910	2,880	
L-6	1	24 hr	4,710	4,700	4,620	4,620
L-6	2	24 hr	4,300	4,620	4,460	
L-6	3	24 hr	4,630	4,730	4,820	
L-6	1	7 day	6,900	7,540	7,320	7,250
L-6	2	7 day	6,570	7,520	6,790	
L-6	3	7 day	7,520	7,520	7,590	
L-6	1	28 day	8,400	8,120	9,150	8,800
L-6	2	28 day	8,520	8,590	8,760	
L-6	3	28 day	9,190	9,390	9,070	
L-6	1	6 mo	8,750	9,310	9,270	9,530
L-6	2	6 mo	9,830	9,950	9,510	
L-6	3	6 mo	9,950	9,510	9,710	
L-6	1	1 yr	8,800	9,080	8,560	9,430
L-6	2	1 yr	8,480	10,230	10,310	
L-6	3	1 yr	9,510	10,350	9,590	

(Sheet 4 of 6)

Table B1 (Continued)						
Concrete Mixture	**Batch**	**Time of Test**	**Compressive Strength, psi**			**Average, psi**
L-7	1	4 hr	3,530	3,780	3,780	3,790
L-7	2	4 hr	3,820	3,850	3,880	
L-7	3	4 hr	3,870	3,800	3,770	
L-7	1	6 hr	4,530	4,300	4,320	4,370
L-7	2	6 hr	4,730	4,530	4,540	
L-7	3	6 hr	4,080	4,300	4,350	
L-7	1	24 hr	6,090	5,890	6,370	6,070
L-7	2	24 hr	6,300	6,130	6,200	
L-7	3	24 hr	5,740	5,920	6,030	
L-7	1	7 day	8,870	9,550	9,430	9,340
L-7	2	7 day	9,630	9,550	9,470	
L-7	3	7 day	9,150	9,230	9,190	
L-7	1	28 day	10,500	9,550	9,670	10,180
L-7	2	28 day	10,020	10,980	10,820	
L-7	3	28 day	9,470	10,660	9,950	
L-7	1	6 mo	10,540	10,070	10,150	10,120
L-7	2	6 mo	9,880	10,310	10,390	
L-7	3	6 mo	10,740	10,150	10,500	
L-7	1	1 yr	10,740	11,660	10,740	11,090
L-7	2	1 yr	10,940	10,270	10,540	
L-7	3	1 yr	11,340	11,780	11,820	
L-8	1	4 hr	3,880	3,910	4,040	4,110
L-8	2	4 hr	3,930	4,140	4,170	
L-8	3	4 hr	4,360	4,300	4,290	
L-8	1	6 hr	4,710	4,570	4,760	4,900
L-8	2	6 hr	4,720	5,070	4,980	
L-8	3	6 hr	5,150	5,000	5,110	
L-8	1	24 hr	6,470	6,480	6,570	6,380
L-8	2	24 hr	6,300	6,470	6,400	
L-8	3	24 hr	6,330	6,150	6,220	

(Sheet 5 of 6)

Table B1 (Concluded)						
Concrete Mixture	Batch	Time of Test	Compressive Strength, psi			Average, psi
L-8	1	7 day	9,950	9,670	9,550	9,590
L-8	2	7 day	9,750	9,790	8,460	
L-8	3	7 day	9,830	9,270	10,030	
L-8	1	28 day	11,300	11,260	11,180	10,670
L-8	2	28 day	9,870	10,880	10,230	
L-8	3	28 day	10,500	9,950	10,900	
L-8	1	6 mo	10,390	11,300	10,420	10,920
L-8	2	6 mo	11,060	10,540	10,420	
L-8	3	6 mo	11,300	11,110	11,070	
L-8	1	1 yr	12,330	11,780	11,540	11,670
L-8	2	1 yr	11,820	11,780	10,350	
L-8	3	1 yr	12,020	11,780	11,940	

(Sheet 6 of 6)

Appendix C
Flexural Strengths for PBC-XT Concretes

Table C1
Flexural Strength, Psi
PBC-XT Concretes

Concrete Mixture	Time of Test	Batch Number 1		2		3		Avg.
RG-6	4 hr	320	330	340	345	315	320	330
RG-6	6 hr	410	450	455	405	405	440	430
RG-6	24 hr	495	490	525	510	470	510	500
RG-6	7 day	700	660	680	650	535	545	630
RG-6	28 day	605	655	555	600	615	655	615
RG-6	6 mo	905	900	830	865	840	840	865
RG-6	1 yr	780	735	825	760	*	*	775
RG-7	4 hr	385	410	505	455	450	425	440
RG-7	6 hr	500	490	470	460	450	525	485
RG-7	24 hr	555	555	615	595	520	555	565
RG-7	7 day	620	600	615	650	675	650	635
RG-7	28 day	615	680	650	700	675	755	680
RG-7	6 mo	945	905	785	935	860	825	875
RG-7	1 yr	750	720	695	690	725	760	725
RG-8	4 hr	540	470	400	495	455	480	475
RG-8	6 hr	495	510	560	525	545	555	530
RG-8	24 hr	690*	525	580	600	575	535	565
RG-8	7 day	725	800	590*	720	780	755	760
RG-8	28 day	710	670	725	670	785	730	715
RG-8	6 mo	1085	1015	815	780	1015	905	935
RG-8	1 yr	755	805	715	755	745	820	765

(Continued)

* Samples not prepared.

Table C1 (Concluded)

Concrete Mixture	Time of Test	Batch Number						Avg.
		1		2		3		
L-8	4 hr	380	375	335	340	400	385	370
L-6	6 hr	420	475	420	410	425	465	435
L-6	24 hr	600	555	695	640	635	595	620
L-6	7 day	750	790	825	740	785	840	790
L-6	28 day	710	670	795	735	745	755	735
L-6	6 mo	910	845	930	895	1165	1095	975
L-6	1 yr	735	820	720	875	795	740	780
L-7	4 hr	500	495	485	470	510	505	495
L-7	6 hr	605	670	665	575	510*	570	615
L-7	24 hr	680	780*	630	650	690	685	665
L-7	7 day	745	745	825	930*	775	835	785
L-7	28 day	840	755	840	840	775	835	815
L-7	6 mo	945	1005	1015	910	935	945	960
L-7	1 yr	780	765	955	945	880	855	865
L-8	4 hr	570	480	650*	520	535	520	525
L-8	6 hr	665	650	705	700	730	695	690
L-8	24 hr	760	800	795	685	875	825	790
L-8	7 day	930	995	860*	935	975	945	955
L-8	28 day	885	895	950	975	985	935	940
L-8	6 mo	990	1010	1185	1115	860	970	1020
L-8	1 yr	860	915	845	920	985	875	900

Appendix D
Excerpt from "Pyrament Cement Contractors Handbook," 1990

PYRAMENT BLENDED CEMENT (PBC-XT)

90-120 minute set time

PRODUCT DESCRIPTION

With only the addition of high quality aggregates and water, **Pyrament** cement produces a high performance concrete with these unique properties:

- Very high early strength—can achieve compressive strength of 2,500 psi 4 hours after batching.
- Very high ultimate strength—can achieve 10,000 psi compressive and 1,200 psi flexural strengths after 28 days.
- Controlled setting time.
- Excellent freeze/thaw durability.
- Resistant to scaling caused by deicing chemicals.
- Sulfate resistant.
- Low volume change.
- Can be placed at below-freezing temperatures.

Pyrament blended cement is available in three different systems depending upon desired set times:

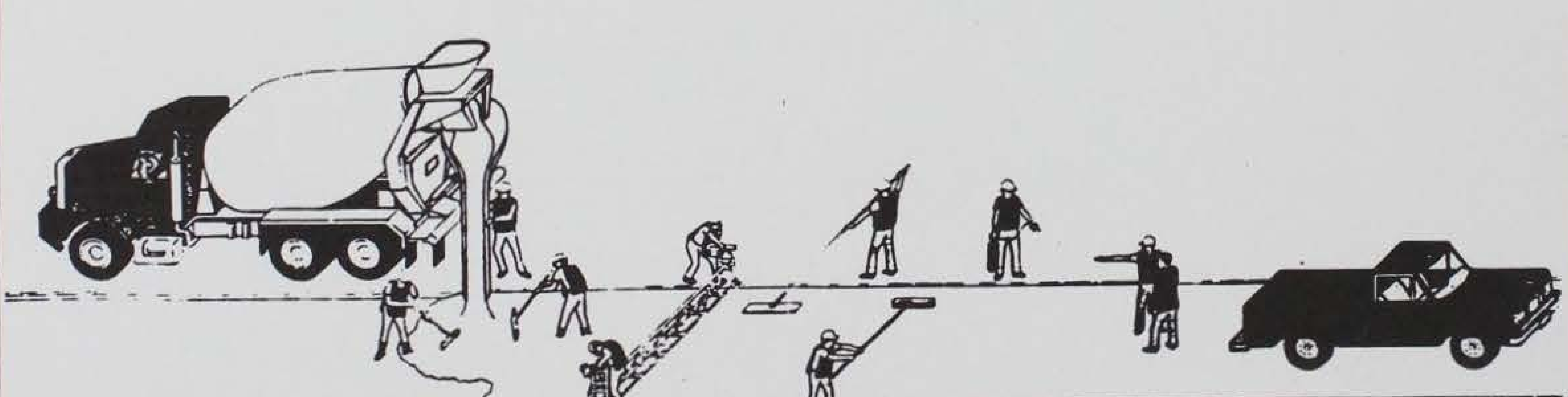
SYSTEM	SET TIME FROM BATCHING
PBC	30-45 minutes
PBC-XT	90-120 minutes
PBC-XXT	160-220 minutes

APPLICATIONS

Pyrament blended cement is a complete cement system which does not require admixtures to achieve high performance properties. It is ideal for all applications where time is critical and when rapid strength gain coupled with high ultimate strength and superior durability are needed:

- Streets and highways
- Airport runways, taxiways and aprons
- Bridges and overpasses
- Military facilities
- Industrial facilities
- Marine and port facilities
- Cold weather construction
- Water and waste water facilities
- Tunnels and viaducts
- Prestressed and precast manufacturing

Pyrament blended cement is available in bulk, super sacks and in 50- pound bags. Standard super sacks contain either 1,880 or 3,760 lbs of material, and they can be ordered in special weights.



12

13

TECHNICAL DATA

Typical high performance concrete data is presented for the following mix design:

Fresh Concrete

PBC-XT: 752 lbs/cy (442 KG/m³)
Slump: 3 in (75mm)
Time of set, ASTM C403:
Final: 90-120 minutes

Hardened Concrete

Compressive Strength, ASTM C39

4 hours:	2,500 psi	(17.0 MPa)
1 day:	5,000 psi	(34.0 MPa)
28 days:	10,000 psi	(69.0 MPa)

Flexural Strength, ASTM C293

4 hours:	500 psi	(3.45 MPa)
1 day:	800 psi	(5.52 MPa)
28 days:	1,200 psi	(8.27 MPa)

Freeze/Thaw Resistance, ASTM C666 (wet-wet method)
Durability factor after 300 cycles: >96

Resistance to Deicer Chemical Scaling, ASTM C672
Visual rating after 50 cycles: 0-2

Sulfate Resistance, ASTM C1012 Modified
Expansion after 365 days:
Solution A- less than 0.03 percent
Solution B- less than 0.03 percent

NOTE: Performance may vary depending upon the mixture proportions and the quality and the characteristics of the aggregates used.

OUTSIDE TESTING

Extensive testing by reputable independent laboratories has indicated additional significant properties of **Pyrament** blended cement concrete:

Very Low Permeability

When tested according to AASHTO Designation T277, "Standard Method of Test for Rapid Determination of the Chloride Permeability of Concrete":
At 91 days: <1,000 coulombs

Excellent Corrosion Protection

1 year:
Potential (V vs. CSE) > -0.20
Probability of Corrosion < 5%

Coefficient of Thermal Expansion

Approx. 5.9 Microstrains / °F.

Modulus of Elasticity

120 days: 5,200,000 psi
(35,850 MPa)

DIRECTIONS FOR USE

With the exception of water/cement ratio, proportioning procedures for **Pyrament** concrete are similar to those used for ordinary portland cement concrete and should be in accordance with "Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete" (ACI 211.1).

Concrete produced using **Pyrament** blended cement requires less water than is normally used with portland cement concrete, therefore initial trial batches are recommended. **Pyrament** concrete will typically have a water/cement ratio between 0.25 and 0.29. Most applications of **Pyrament** cement concrete will have a cement content of 611 to 752 pounds per cubic yard. The specific gravity is 2.90 and the average air content is 3½%.

Depending upon the mix design, **Pyrament** cement concrete can be mixed in conventional equipment and placed using standard placement techniques.

LIMITED WARRANTY

Every reasonable precaution is taken in the manufacture of all **Pyrament** products and in compiling data to assure that they comply with the exacting standards of Lone Star Industries, Inc. No guarantee of results using these products and data is given, because every possible variation in methods of use or conditions under which they are applied cannot be anticipated.

PATENTS

Pyrament blended cement is manufactured under U.S Patent 4,842,649.

REPORT DOCUMENTATION PAGE

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12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

Pyrament Blended Cement (PBC) is known in the construction industry for its ability to gain strength rapidly and achieve very high early strength. The Waterways Experiment Station (WES) conducted a laboratory evaluation of concretes made with PBC to determine if these concretes perform better than concretes made with ordinary portland cement (OPC) in tests of various aspects of concrete durability. For this study, six concretes based on PBC-XT were proportioned with three cement contents and two aggregate types. The objective was to determine if the cement, advertised as giving high early strength and marketed initially as a rapid-construction material, is durable enough to justify its use for long-term performance in addition to shorter construction time.

Concretes prepared from PBC-XT cement were subjected to analyses of its resistance to damage during cycles of freezing and thawing, expansion in a high-sulfate environment, damage from underwater abrasion, penetration of dissolved chlorides, scaling from deicing chemicals, and expansion from chemical interaction between alkalies in the cement and silica in aggregate. In all categories, the PBC-XT cement concretes achieved or exceeded expected performance based on the manufacturer's product literature. In all but the last category, PBC-XT concretes performed better than is generally expected of high-quality OPC concretes.

(Continued)

14. SUBJECT TERMS

Concrete permeability	High-early strength	Rapid-setting concrete
Blended hydraulic cement	High-performance concrete	
Durability	Rapid chloride permeability	

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13. ABSTRACT (Concluded)

As an example of superior performance, PBC-XT concretes made with seven sacks of cement per cubic yard and limestone aggregate were tested to 500 cycles of freezing and thawing according to ASTM C 666, through which they retained >90 percent of their initial dynamic modulus. Also, samples tested for sulfate expansion gave values consistently below the ASTM C 595 limit of 0.1 percent after 180 days. In tests of rapid chloride permeability (AASHTO T 277), PBC-XT concrete samples tested as early as 7 days after casting achieved "low" permeability ratings (<1,000 coulombs). Values for year-old specimens averaged a remarkable 100 coulombs.

Other aspects of performance investigated included: effects of various temperatures and water-cement ratios on workability, time of setting, and rate of strength gain; bonding to existing concrete; drying shrinkage; creep under sustained load; and effects of different storage conditions.