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Goal 4 Long Life Pavement Rehabilitation Strategies—Rigid: Laboratory Strength, Shrinkage, and Thermal Expansion of Hydraulic Cement Concrete Mixes

Report prepared for the California Department of Transportation (Caltrans)

By

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EXECUTIVE SUMMARY

This report presents the results of laboratory work on flexural and compressive strength, free shrinkage, coefficient of thermal expansion, and elastic modulus performed on six concrete mixes. The six concrete mixes are typical of those used, or have been considered for use, for the Caltrans Long Life Pavement Rehabilitation Strategies for rigid pavements (LLPRS-Rigid).

The work presented in this report was completed as part of Goal 4 of the Partnered Pavement Research Program Strategic Plan, and completes the following objectives of the test plan for that research goal:

- Evaluation of, and development of recommendations for test methods for strength gain, ultimate strength and stiffness, thermal expansion, and shrinkage.
- Development of laboratory data regarding the properties of various high early-strength concrete mixes, and comparison with a typical Type I/II mix.
- Development of laboratory data regarding the effects of important mix design and construction variables on mechanical properties.

This report includes descriptions of the concrete materials, mix designs, test methods, and specimen preparation methods used for the study. It presents flexural (ASTM C 78) and compressive strength data (ASTM C 39), an evaluation of the practice of using compressive strength data to estimate flexural strength data, and conclusions regarding the mixes tested and the use of strength tests for design and construction quality control and assurance. The strength of the concrete determines its ability to withstand stress and stress repetitions without cracking, and greater strength results in greater resistance to cracking.

This report also presents shrinkage test data and conclusions regarding the mixes and the use of shrinkage testing. Shrinkage causes stresses in the concrete, in addition to load. Greater strength often comes at the cost of greater shrinkage, and mix design is often a balancing act between strength and shrinkage. Free shrinkage was tested on concrete beams (ASTM C157-93) and mortar beams (ASTM C 596-96).

Data are presented for coefficient of thermal expansion along with a comparison of two methods of measuring coefficient of thermal expansion. The coefficient of thermal expansion is a measure of how much the concrete expands or contracts with changes in its temperature, and high expansion and contraction increases stresses in concrete slabs through friction with the underlying layers, and through curling caused by different temperatures between the top and bottom of the slab. The Coefficient of Thermal Expansion (CTE) was tested twice using ASTM C531 and the Army Corps of Engineers Test CRD-C39-81.

Stiffness is a measure of the deformation of the concrete under load. In general, higher stiffness results in greater stresses, from interaction with expansion and contraction caused by shrinkage and curling.

The appendices to this report contain details of the test methods used that are not standard ASTM or Caltrans tests, detailed mix designs, all test data obtained from the study, and specifications for the Fast Setting Hydraulic Cement Concrete (FSHCC) in effect at the time this study was planned in 1998.

The aggregate source was the same for five of the six mixes. Three categories of hydraulic cement were used as follows:

- **Portland cement:**
    - Type I/II portland cement, referred to as “Type I/II”;
    - Type III portland cements from two manufacturers, referred to as “Type III-A” and “Type III-B.”

- **Calcium Sulfoaluminate cements.** Cement from two manufacturers, both meeting the 1998 Caltrans Fast Setting Hydraulic Cement (FSHC) specifications, referred to as "CSA-A" and "CSA-B";
- **Calcium Aluminate cement, referred to as "CA."**

One mix design was developed for each of the six cements. The objective of each mix design was to optimize the mix properties while obtaining a minimum flexural strength of 2.8 MPa (400 psi) for the construction closure duration applicable to the given cement type. This strength criterion was developed through mechanistic analysis and has been determined to be adequate for opening the pavement to traffic while minimizing the risk that a substantial portion of the concrete pavement fatigue life will be exhausted before the concrete has reached its long-term strength.

Caltrans uses various construction closure durations to complete concrete pavement rehabilitation and reconstruction projects. Seven- to ten-hour overnight closures on weeknights are typically used for replacement of individual failed slabs. For these types of closures to be successful, the mix must reach the minimum traffic opening strength within two to eight hours. Weekend closures lasting 55 hours, from 10 p.m. Friday night to 5 a.m. Monday morning, and 72-hour closures on weekdays are used for reconstruction of entire lanes. The construction closure duration and desired time to reach the minimum flexural strength are summarized below for each of the cement types.

For the six concrete mixes studied, the design variables were cement type and admixtures, water/cement ratio, and curing conditions.

Each of the performance related properties tested was measured under various conditions to study the effects of important mix design and construction variables. Statistical analysis was

Closure Duration and Time to Reach Minimum Beam Strength for Each Mix.

Mix Name	Cement Type	Intended Construction Window	Desired Time to Reach Minimum Strength
Type I/II	Portland Cement Type I/II	New construction, or long-term continuous closure	28 days
Type III-A	Portland Cement Type III	55-hour weekend, or short-term continuous closure	12 to 16 hours
Type III-B	Portland Cement Type III	55-hour weekend, or short-term continuous closure	12 to 16 hours
CSA-A	CSA	7- to 10-hour overnight, or 55-hour weekend	4 to 8 hours
CSA-B	CSA	7- to 10-hour overnight, or 55-hour weekend	4 to 8 hours
CA	CA	7- to 10-hour overnight, or 55-hour weekend	4 to 8 hours

performed to evaluate the importance of factors and the significance of the differences across the experiment variables. The conclusions are summarized as follows.

1. Cement type, curing condition, and water/cement ratio should all be considered important for concrete mix design as the strength gain. The cement type is the most important factor, assuming an optimized mix design. Curing condition (moisture condition and temperature) follows cement type in terms of significant effect on concrete strength. Finally, the 10-percent increase in water content from the target mix can reduce the strength by more than 10 percent.
2. The compressive and flexural strengths respond differently to environmental factors. A cold environment causes the greatest reduction in compressive strength while a dry condition is most detrimental to the flexural strength. Therefore, there is no unique correlation between the two kinds of strengths. The reasonably accurate prediction of flexural strength from compressive strength, or vice versa, is only possible within a range of curing conditions, and does not include many scenarios that may be

encountered in the field. Although the compressive strength test has less variability than the flexural strength test, they are not interchangeable if precise data are needed.

3. The correlation between the elastic modulus and compressive strength conformed to what is given in ACI-318 for the portland cement Type I/II mix at 28 days under the standard moist curing. Additional data is needed to extend the conclusion to non-portland cement concrete. The study has shown, however, that the correlation at other ages or under other curing conditions does not conform to ACI-318.
4. While mix design has the greatest effect on concrete strength gain, the curing condition is a more important factor in shrinkage than the mix design. Generally, high temperature and low moisture result in greater shrinkage. However, the extent to which temperature and moisture affect shrinkage depends on the cement type. Calcium sulfoaluminate cements from different manufacturers had distinct shrinkage performances because their chemical compositions are very different.
5. The tested coefficient of thermal expansion had a range from 8 to $12 \times 10^{-6}/^{o}C$ for the group of six mixes included in this study from two measuring methods. These results conform to the data reported in literature. The results of this study show that the Army Corps of Engineers method (CRD) uses a more reasonable temperature range to measure the coefficient of thermal expansion. According to the CRD method, the portland cement mixes have slightly lower coefficient of thermal expansion than calcium sulfoaluminate mixes.

In addition to providing basic information regarding the performance related properties of these mixes, the data included in this report will provide input for mechanistic-empirical analysis of LLPRS-Rigid pavements in the future. The work included in this report can be repeated for other mix types, such as the new Type III based mixes which achieve the target opening flexural strength of 2.8 MPa in 4 to 8 hours.

1.0 INTRODUCTION

Within the state of California, rigid pavements were used extensively for construction of the interstate highway system. Rigid pavements make up approximately 32 percent of the lane-kilometers in the California Department of Transportation (Caltrans) highway network. Most of these rigid pavements are in urban areas and/or routes with high traffic volumes and heavy trucks.

It has been estimated that approximately 90 percent of the rigid pavements were constructed between 1959 and 1974.(*1*) These pavements were designed for 20-year lives based on traffic volumes and loads estimated at that time.(*2*) Currently, 30 to 45 years after their construction, many California rigid pavements are in need of rehabilitation. In 1995, rigid pavements accounted for 41 percent of the lane-kilometers requiring immediate attention. Approximately 80 percent of the rigid pavements needing rehabilitation are located in urban areas in Southern California. Most of the rest are in urban areas in the San Francisco Bay Area, with a smaller number in other rural and urban areas.(*3*) Prior to 1996, all rigid pavements in California were constructed with slabs made of portland cement concrete (PCC). The typical portland cement type used in California is Type I/II, which meets ASTM specifications for both Type I and Type II portland cement.

In 1997, Caltrans engineers and policy makers determined that existing strategies of urban pavement maintenance and rehabilitation were providing diminishing returns in terms of additional pavement life due to the structural damage incurred by the pavements since their initial construction. The agency costs of applying lane closures in urban areas is very large compared to the actual costs of materials and placement. The accumulated structural and ride quality deterioration on many urban freeway pavements results in increased need for maintenance and rehabilitation forces to be in the roadway, which in turn increases Caltrans costs and safety risks. In addition, the costs to Caltrans clients—the pavement users—are increasing due to the increasing frequency of lane closures which cause delays, and the additional vehicle operating costs from deteriorating ride quality.

A need for new lane replacement strategies was identified. These strategies must not require long-term closures and therefore, the material used must develop sufficient strength before opening to traffic when using Type I/II PCC. High construction productivity and speed is desired to minimize traffic delays during rehabilitation or reconstruction.

A need was also identified for longer pavement lives than the currently assumed design life of 20 years. Longer pavement life postpones future maintenance and rehabilitation, and the associated traffic disruptions, agency costs, and potential for accidents.

To meet these needs, Caltrans established the following objectives for Long Life Pavement Rehabilitation Strategies in 1997 (*4*):

1. provide 30 or more years of service life,
2. require minimal maintenance, although zero maintenance is not a stated objective,
3. have sufficient production to rehabilitate or reconstruct about 6 lane-kilometers within a construction window of 55 hours (10 p.m. Friday to 5 a.m. Monday).

In 1998, Caltrans selected a set of strategies to meet these objectives and established a plan for their evaluation. These strategies included the use of high early strength hydraulic cements, different base types, dowels, and tied concrete shoulders. Specifications were developed by Caltrans for Fast Setting Hydraulic Cement Concrete (FSHCC) mixes intended to provide high early strength.

The accelerated pavement testing capability that Caltrans had developed with the UC-Berkeley Contract Team (UCB Contract Team) was included in the LLPRS-Rigid evaluation plan. The test plan for the UCB Contract Team work was developed in 1997–98 and included objectives for laboratory testing of mechanical properties and chemical durability, accelerated pavement testing of full-scale test sections with the Heavy Vehicle Simulator, and mechanistic-empirical analyses.(*5*) An additional objective of evaluating the construction process and construction productivity for urban freeway rehabilitation and reconstruction was added to the test plan in 1999.

The objectives included in the LLPRS-Rigid Test Plan for mechanical tests were:

1. Produce data necessary to develop effective laboratory tests for materials to be used in LLPRS-Rigid projects. Variables to be considered included strength gain, ultimate strength and stiffness, fatigue properties, thermal expansion, heat generation, and shrinkage.
2. Develop information regarding effects of the properties developed in Objective 1 on concrete performance to establish specification limits.
3. Produce information on the effects of construction and mix design variables on the properties to be measured in Objective 1. This information can be used to develop specifications for mix design, quality control, and quality assurance.
4. Develop information needed for mechanistic modeling of the pavement structure under traffic loading and environmental conditions. Information needed includes stiffness, fatigue life, strength gain and ultimate strength, and thermal characteristics, in order to calculate critical stresses in the pavement structure.

1.1 Objectives Included in this Report

The work presented in this report covers the following LLPRS-Rigid evaluation objectives:

- Evaluation and recommendations regarding test methods for strength gain, ultimate strength and stiffness, thermal expansion, and shrinkage.
- Development of laboratory data regarding the properties of various high early-strength concrete mixes, and comparison with a typical Type I/II mix, as well as recommendations regarding specification limits based on the data in this report and information previously reported by the UCB Contract Team.(*5*)
- Development of laboratory data regarding the effects of important mix design and construction variables on mechanical properties, and recommendations regarding specifications for mix design, quality control, and quality assurance. The mechanical properties data included in this report provide input data for mechanistic-empirical analysis of LLPRS-Rigid pavements for several mix types used by Caltrans.

1.2 Previous Studies and Reports Related to LLPRS-Rigid

Four reports were prepared as part of the initial evaluation of LLPRS-Rigid. These reports covered a preliminary evaluation of the proposed LLPRS-Rigid strategies and the effects of design inputs using existing pavement design methods;(*6*) a preliminary evaluation of design and construction issues;(*7*) an overview of concrete durability issues applicable to cement types proposed for use in LLPRS-Rigid;(*8*) and the results of a trial accelerated pavement test on a concrete pavement.(*9*)

Full-scale pavement test sections were constructed on State Route 14 at Palmdale (Los Angeles County) in 1998. The pavements included one set of test sites to evaluate the fatigue properties of field slabs with a mix meeting the FSHCC specification, and another set to evaluate the effects of dowels, tied shoulders, and wide truck lanes on performance. The contractor for the Palmdale test sections used cement blended from a typical FSHCC cement and a portland cement. The construction and instrumentation of the test pavements and strength data are reported in Reference (*10*).

The slabs at the Palmdale test sections were constructed with joint spacing typical of previous Caltrans construction (3.7, 4.0, 5.5, and 5.8 m). All of the 5.5- and 5.8-m slabs cracked within 3 months after construction in June, 1998, and prior to any Heavy Vehicle Simulator (HVS) loading. Analytical studies of the cracking indicated that the early cracking was attributable to differential shrinkage and thermal gradients. The analyses also provided an understanding of the mechanism responsible for longitudinal cracking, which is common in the western states.(*11*)

HVS testing for LLPRS-Rigid was completed at Palmdale in January, 2001. A report documenting the fatigue evaluation results on half of the Palmdale test sections on the "South Tangent" was produced in 2002.(*12*) A second-level analysis report on the South Tangent was also completed in 2002.(*13*) Reports have also been prepared documenting the results of the evaluation of dowels, tied concrete shoulders, and wide truck lanes on the "North Tangent" at Palmdale.(*14*) A second-level analysis report on the North Tangent that includes a procedure for analyzing Falling Weight Deflectometer data to determine the built-in warping in the slab caused by differential shrinkage has also been prepared.(*15*) A report documenting FWD deflection data measured on all the Palmdale sections is underway as well.(*16*)

The sulfate resistance of the cements included in this report was evaluated in a study using mortar specimens subjected to an accelerated test. The results of these tests are reported in Reference (*17*). Another study using an accelerated test to evaluate the alkali-aggregate reaction resistance of the cements is reported in Reference (*18*).

The initial assumption of the Caltrans LLPRS-Rigid strategies was that the use of FSHCC that reaches strengths sufficient for opening to traffic in 4to 8 hours would increase construction productivity for urban freeway reconstruction and reduce the time needed to complete a project. Caltrans also initially assumed that FSHCC would increase pavement life for some designs that had previously used Type I/II cement. A construction productivity analysis system was developed by the UCB contract team for urban concrete freeway reconstruction with LLPRS-Rigid strategies. The analysis system and a parametric evaluation of construction productivity is presented in Reference (*19*). Caltrans built a demonstration project using an LLPRS-Rigid strategy and FSHCC in the summer of 1999. The results of this pilot project and analysis of construction productivity using the UCB system (CA4PRS software) are reported in Reference (*20*).

1.3 Scope of this Report

Chapter 2 of this report describes the concrete materials, mix designs, test methods, and specimen preparation methods used for this study. Chapter 3 presents flexural and compressive strength data, an evaluation of the practice of using compressive strength data to estimate flexural strength data, and conclusions regarding the mixes tested and the use of strength tests for design and construction quality control and assurance. Chapter 4 presents shrinkage test data and conclusions regarding the mixes and the use of shrinkage testing. Chapter 5 presents coefficient of thermal expansion data. Chapter 6 includes a summary and recommendations based on the information presented.

Appendix A contains the details of the test methods used that are not standard ASTM or Caltrans tests. Appendix B contains the detailed mix designs. Appendix C contains all test data obtained from the study. Appendix D contains specifications for the Fast Setting Hydraulic Cement Concrete (FSHCC) in effect at the time this study was planned in 1998.

2.0 TEST PROGRAM

Six concrete mixes designed for concrete pavement application were used for this study. The aggregate source was the same for five of the six mixes. The concrete mixes were tested for flexural strength, compressive strength, compressive elastic modulus, shrinkage, and coefficient of thermal expansion. Descriptions of the mix designs, specimen preparation, and test methods are included in this chapter.

2.1 Materials

Three categories of hydraulic cement were used as follows:

- **Portland cement:**
  - Type I/II portland cement, referred to as "Type I/II";
  - Type III portland cements from two manufacturers, referred to as "Type III-A" and "Type III-B."
- **Calcium Sulfoaluminate cements.** Cement from two manufactures, both meeting the Caltrans Fast Setting Hydraulic Cement (FSHC) specifications as of 1998 (see Appendix D), referred to as CSA-A and CSA-B;
- **Calcium Aluminate cement, referred to as CA.**

Each of these cements was obtained in one shipment from each respective manufacturer within 14 days before specimen preparation, and stored in a warehouse. Their chemical compositions in oxides were analyzed (Table 2.1) and presented in a previous report.(*17*) Table 2.2 lists the compounds of some of the cements.

Table 2.1 Designation, Classification, and Chemical Oxide Analysis of Cements Included in This Study (17)

Component	Type I/II	Type III-A	Type III-B	CSA-A	CSA2-B	CA
SiO_2	21.24	21.05	20.50	15.59	15.40	9.06
Al_2O_3	3.57	3.79	4.15	13.96	12.88	26.29
Fe_2O_3	3.82	4.02	3.70	1.49	2.63	3.44
CaO	64.72	64.22	64.27	50.19	53.02	36.97
MgO	1.69	1.26	1.27	1.35	2.03	0.97
TiO_2	0.31	0.36	0.34	0.53	0.70	1.17
Mn_2O_3	0.04	0.04	0.04	0.05	0.04	0.04
P_2O_5	0.32	0.35	0.28	0.14	0.01	0.07
Cr_2O_3	0.04	0.03	0.04	0.04	0.03	0.04
ZrO_2	0.00	0.00	0.00	0.05	0.06	0.09
Na_2O	0.18	0.23	0.20	0.23	0.39	1.24
K_2O	0.10	0.13	0.20	0.44	0.32	0.03
SO_3	2.27	2.45	2.33	14.20	10.81	8.73
Ig. Loss	1.43	1.83	2.42	2.17	1.96	12.19
Total	*99.72*	*99.77*	*99.73*	*100.42*	*100.27*	*100.33*

Note: Composition provided is for the cement only.

Table 2.2 Designation, Classification, and Compounds of the Cements Used in This Study (17)

Cement	Name in This Report	Description	Bogue Composition
Portland cement	Type I/II	Type I/II with fly ash	C_3S =66.13 C_2S = 11.00 C_3A=3.00 C_4AF =11.62 (*17*)
	Type III-A	Type III	C_3S =66.03 C_2S = 8.96 C_3A=4.74 C_4AF =11.26 (*17*)
	Type III-B	Type III	*Not Available*
Calcium aluminate cement	CA	Primarily CA	With CA from 40 percent upwards
Calcium sulfoaluminate cement	CSA-1	C_2S, C_3S, C_4AF, C_3A, $C\bar{S}$, and $C_4A_3\bar{S}$	*Not Available*
	CSA-2	Primarily C_2S and $C_4A3\bar{S}$	*Not Available*

Note: For all formulae, C=CaO; S=SiO_2; A=Al_2O_3; F=Fe_2O_3; and $\bar{S}$ =SO_3 ;

Two types of coarse aggregate were included in the study:

- uncrushed gravel from Hanson Aggregate Company in Pleasanton, California (referred to as "gravel" in this report), and
- crushed aggregate (referred to as "crushed stone") from Kaiser in Pleasanton, California.

The same gradation, meeting Caltrans standard specifications, was used for all the mixes Table 2.3 and Figure 2.1).

Caltrans uses various construction closure durations to complete concrete pavement rehabilitation and reconstruction projects. Seven- to ten-hour overnight closures on weeknights are typically used for replacement of individual failed slabs. For these types of closures to be successful, the mix must reach the minimum traffic opening strength within two to eight hours. Weekend closures lasting 55 hours, from 10 p.m. Friday night to 5 a.m. Monday morning, and 72-hour closures on weekdays are used for reconstruction of entire lanes, including removal of

Table 2.3 Aggregate Gradations of Laboratory Mixes

Sieve size		Caltrans Specification Target Grading (percentage)		Maximum Density 0.45 Power	Blended Grading	Coarse (%) max. 37.5 mm	Medium (%) max. 25.0 mm	Sand (%) max. 9.5 mm
(mm)	(in.)	Lower	Upper					
50	2	100.0	100.0	100.0	100.0	100.0	100.0	100.0
37.5	1 ½	90.0	100.0	100.0	97.7	94.0	100.0	100.0
25	1	50.0	86.0	83.3	69.7	23.0	96.0	100.0
19	¾	45.0	75.0	73.6	60.1	10.0	77.0	100.0
12.5	½			61.0	48.5	2.0	43.0	100.0
9.5	3/8	38.0	55.0	53.9	42.4	1.0	20.0	100.0
4.75	4	30.0	45.0	39.5	37.5	0.0	2.0	100.0
2.36	8	23	38	28.8	32.4	0.0	1.0	87.0
1.18	16	17.0	33.0	21.1	22.2	0.0	0.0	60.0
0.6	30	10.0	22.0	15.6	13.3	0.0	0.0	36.0
0.3	50	4.0	10.0	11.4	5.9	0.0	0.0	16.0
0.15	100	1.0	6.0	8.3	1.9	0.0	0.0	5.0
0.075	200	0.0	3.0	6.1	0.7	0.0	0.0	2.0

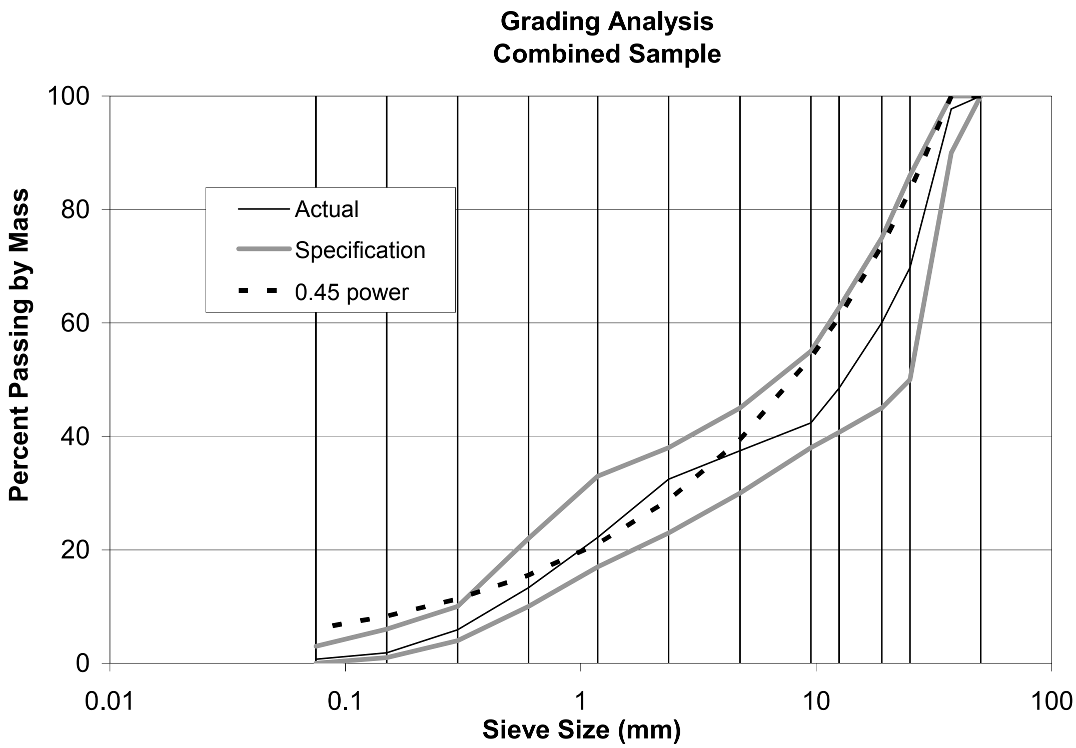

Figure 2.1. Grading analysis.

the existing slabs and replacement with new slabs that are tied to the adjacent lanes and contain dowels on the transverse joints. Some projects also require the removal and replacement of the existing base layer.(*1–4, 6, 7, 19, 20*) The construction closure duration and desired time to reach the minimum flexural strength are summarized in Table 2.4 for each of the cement types.

The mix designs for the Type I/II and Type III-A mixes were performed by the UCB contract team at the UC Pavement Research Center Laboratory in Richmond, California (PRC). The Type III-B, CSA-A, CSA-B, and CA mixes were designed at the PRC laboratory by staff from each cement manufacturer working with the UCB Contract Team researchers. These mix designs were performed by the respective cement providers who were encouraged to make the best concrete possible. This approach was used in order to provide each manufacturer the opportunity to maximize the performance of their product, and to avoid arbitrary decisions by the UCB contract team researchers that could create bias in the study against any material.

Table 2.4 Intended Closure Window and Desired Time to Reach Minimum Beam Strength for Each Mix.

Mix Name	Cement Type	Intended Construction Window	Desired Time to Reach Minimum Strength
Type I/II	Portland Cement Type I/II	New construction, or long-term continuous closure	28 days
Type III-A	Portland Cement Type III	55-hour weekend, or short-term continuous closure	12 to 16 hours
Type III-B	Portland Cement Type III	55-hour weekend, or short-term continuous closure	12 to 16 hours
CSA-A	CSA	7- to 10-hour overnight, or 55-hour weekend	4 to 8 hours
CSA-B	CSA	7- to 10-hour overnight, or 55-hour weekend	4 to 8 hours
CA	CA	7- to 10-hour overnight, or 55-hour weekend	4 to 8 hours

2.1.1 Type I/II Portland Cement Mix

The Type I/II mix was the baseline for the study. This mix was designed to follow current Caltrans practice for typical portland cement concrete used in pavements for which construction closure time is not an issue. The mix design was performed by the UCB contract team at the UC Pavement Research Center Laboratory in Richmond, California (PRC).

2.1.2 Type III-A Portland Cement Mix

The Type III-A mix was also designed to provide the minimum strength required for opening to traffic using the same aggregate as the other mixes, with the time to reach opening strength applicable to lane reconstruction in a 55-hour weekend closure. The mix design was performed by the UCB contract team.

2.1.3 Type III-B Portland Cement Mix

The Type III-B mix was designed to be representative of the “fastest” portland cement mix applicable to lane reconstruction in a 55-hour weekend closure in 1999. Mixes meeting the flexural strength requirement in four to eight hours have since been developed, although their strength gain has not been found to be consistently reproducible using the laboratory equipment used for this study, even under the direction of the manufacturers. The Caltrans headquarters concrete laboratory, Translab, has had similar experiences.

At Translab, to overcome the problem of poor reproducibility when preparing laboratory specimens with these mixes, the development of the four- to eight-hour Type III mixes utilized a full-scale drum mixer truck. This method of mixing was not feasible for this study at the UCPRC laboratory. Therefore, these mixes were not included in this study. The Type III-B mix differs from the other mixes studied in its use of the crushed stone aggregate, which was intended to improve its strength.

2.1.4 Calcium Sulfoaluminate (CSA-A, CSA-B) and Calcium Aluminate (CA) Mixes

The CSA-A, CSA-B, and CA mixes were designed by staff from each cement manufacturer working with the UCB contract team researchers at the UCB laboratory in order to meet Caltrans requirements for FSHCC. The mix design process for each mix required multiple trial batches and flexural tests, and was not considered completed until both UCB and the cement manufacturer were satisfied.

2.2 Design Variables

For the six concrete mixes studied, the design variables were cement type and admixtures, water/cement ratio, and curing conditions. The following sections present details of each of these variables.

2.2.1 Cement Type and Admixtures

Table 2.5 lists the materials used in each mix design. Cement, water, aggregate, and admixtures were selected and proportioned by the mix designers (the UCB contract team for Type I/II and Type III-A mixes, and the cement manufacturers for the Type III-B, CSA-A, CSA-B and CA mixes, as discussed in Section 2.2).

Table 2.5 Cement Type and Additives for Each Mix Design

Mix	Cement Type	Aggregate	Air Entrainment Agent	Super Plasticizer (Retarders) (HRWR)	Stabilizer	Accelerator	Fly Ash
TypeI/II	PC Type I/II	Rounded Gravel	Micro-Air	None	None	None	Type F
Type III-A	PC Type III	Rounded Gravel	Micro-Air	Rheobuild 3000FC	None	Pozzutec 20	None
Type III-B	PC Type III	Crushed Stone	None	ADVA	Recover	Polarset	None
CSA-A	CSA	Rounded Gravel	None	ADVA	Recover	None	None
CSA-B	CSA	Rounded Gravel	None	ADVA	UC Delay	None	None
CA	CA	Rounded Gravel	None	None	None	None	None

* HRWR= High range water reducer

2.2.2 Water/Cement Ratio

Table 2.6 lists the materials and quantities used in each mix design. The “target” mix designs have been optimized for the cements used. The only comparable material variables among the target mixes are the cement type and aggregate type. For each of the six target mixes, an additional mix was provided with a 10-percent higher water/cement ratio (referred to as "+ 10% w" mixes).

Table 2.6 Water/Cement Ratio for Each Mix Design

Mix Name (Cement Type)	Mix type	Water/ cement ratio	Cement content kg/m^3	Aggregate content kg/m^3	Aggregate (%) by weight	Aggregate (%) by volume	Cement/ Aggregate (by volume)
Type I/II	Target	0.42	362.49	1864.91	78.37	71.77	0.17
	+10% w	0.46	362.49	1870.01	77.98	70.86	0.17
Type III-A	Target	0.38	446.14	1851.38	75.58	70.16	0.21
	+10% w	0.42	446.14	1851.62	75.06	68.98	0.20
Type III-B	Target	0.36	474.62	1831.63	74.69	69.72	0.22
	+10% w	0.40	474.62	1831.44	74.17	68.52	0.22
CSA-A	Target	0.37	390.38	1942.97	78.42	72.53	0.18
	+10% w	0.41	390.38	1942.98	77.96	71.50	0.18
CSA-B	Target	0.37	415.29	1874.31	76.85	70.67	0.20
	+10% w	0.41	415.29	1874.16	76.36	69.59	0.20
CA	Target	0.32	390.38	1955.10	79.14	74.10	0.18
	+10% w	0.35	390.38	1923.71	78.50	72.91	0.18

2.2.3 Curing Conditions

To evaluate the effect of curing conditions on strength development and shrinkage, specimens were subjected to various curing conditions. Table 2.7 summarizes the evaluation of the effect of curing conditions and lists the temperature and moisture history of the specimens. The first curing regime is conventional moist room temperature at 23ºC and 97 percent relative humidity (RH), which served as the "Standard" curing condition. The second curing regime is 20ºC and 50 percent RH, designated the "Dry" condition in which moisture is not supplied to the concrete. The third regime is 10ºC and 50 percent RH, representing a "Cold" condition.

A fourth regime combined a high temperature of 40ºC and close to zero relative humidity, referred to as "Dry and Hot." The "Dry and Hot" specimens were cured in a forced air

Table 2.7 Specimen Curing Regimes

Curing Regime	Conditions	Specimen Age (days)	Temperature (ºC)	Moisture
Standard	23ºC + 97% RH	1–3	23	In lime water
		3–90	23	97% RH
Dry	20ºC + 50% RH	1–3	20	In lime water
		3–90	20	50 % RH
Cold	10ºC + 50% RH	1–3	10	In lime water
		3–90	10	50 % RH
Dry and Hot	40ºC + ~0% RH (humidity not controlled)	1–3	40	In lime water
		3–90	40	Not controlled

oven with no humidity control. This regime was designed to measure shrinkage in an extreme environment.

2.3 Concrete Specimen Preparation

The concrete batching, mixing, and specimen casting followed ASTM C192 (*21*) with the minor alteration of using an electric vibrator to consolidate the mix in the molds. The coarse aggregate was washed prior to mixing. The beam molds were heated, along with the fine and coarse aggregates. Warm water was used for all of the mixes. The concrete mixer used has a 0.26 m^3 (9 cu. ft.) capacity. The batch size for all of the mixes was 0.20 m^3 (7 cu. ft.), which provided enough material to cast eight beams and eight cylinders.

The concrete was placed in beam molds in one lift and then vibrated with an electric vibrator to consolidate the concrete (Figure 2.2). The cylinders were placed in two lifts and then consolidated with the electric vibrator. Standard tests performed on all mixes for all batches included slump (ASTM C143) (*22*), percent air content (ASTM C231) (*23*), and unit weight of the fresh concrete (ASTM C 138) (*24*). After finishing (Figure 2.3), the specimens were transported to the curing room.

Figure 2.2. Specimen casting.

Figure 2.3. Specimen finishing.

2.4 Mortar Bar Specimen Preparation

For shrinkage and coefficient of thermal expansion tests, steel pins were cast into mortar bars to serve as length measurement reference points. The mortar bars for the shrinkage test were maintained under the same temperature and humidity conditions as the concrete beams used for the shrinkage test.

2.5 Test Methods

The tests included flexural strength, compressive strength, compressive elastic modulus, shrinkage, and coefficient of thermal expansion. Brief descriptions of each test are included in this chapter. Detailed descriptions of the standard and modified test methods are included in Appendix A.

2.5.1 Flexural Strength Test

The dimensions of the flexural beam specimens were 152 × 152 × 745 mm (6 × 6 × 18 in.). The beams were tested using the third-point loading configuration, following ASTM C 78 (*25*). As shown in Figure 2.4, the tests were performed using an MTS flexural beam load frame and a computer controlled hydraulic actuator . The tests were conducted at an ambient temperature of about 15 to 20ºC. The plan for comparison of the flexural and compressive strength tests versus beam age is shown in Table 2.8.

Table 2.8 Strength Test Frequency (Compressive and Flexural)

Mix	Test 1	Test 2	Test 3	Test 4
Type I/II	7 Days	14 Days	28 Days	90 Days
Type III-A	12 Hours	1 Day	7 Days	90 Days
Type III-B	8 Hours	1 Day	7 Days	90 Days
CSA-A	4 Hours	1 Day	7 Days	90 Days
CSA-B	4 Hours	1 Day	7 Days	90 Days
CA	4 Hours	1 Day	7 Days	90 Days

Figure 2.4. Flexural test configuration.

2.5.2 Compressive Strength Test

Compressive strength tests were performed on cylindrical specimens of 152 × 457 mm (6 × 18 in.) following ASTM C 39 (*26*). The tests were performed using a Cox and Sons load frame and hydraulic actuator under computer control, as shown in Figure 2.5. All tests were performed at ambient temperatures of about 15 to 20ºC.

2.5.3 Shrinkage Test

Free shrinkage was tested on concrete beams (ASTM C157-93) (*27*) and mortar beams (ASTM C 596-96) (*28*) for all six mixes. The concrete beams were 76.2 × 76.2 × 285 mm (3 × 3 × 11.2 in.), and the mortar beams were 25 × 25 × 285 mm (1 × 1 × 11.2 mm). As shown in Figure 2.6, steel pins were cast in the ends of the beams to serve as length measurement reference points.

Figure 2.5. Compressive strength test configuration.

Figure 2.6. Shrinkage test configuration.

The concrete prisms were demolded one day after casting and then stored in lime water for two days under their designated temperature (Table 2.7). The shrinkage reference length was measured at three days when the prisms were removed from the lime water, and therefore the measured dimensional change for the shrinkage test based on this 3-day measurement excluded thermal change. The length measurement was performed at 3 days, 7 days, 14 days, 28 days, and 90 days.

2.5.4 Coefficient of Thermal Expansion Tests

The Coefficient of Thermal Expansion (CTE) was tested twice using two different CTE tests. The first test was ASTM C531 (*29*). The second test was the Army Corps of Engineers Test CRD-C39-81 (referred to as CRD, see Appendix A). The CTE beam specimen dimensions for both tests are 76.2 × 76.2 × 285 mm (3 × 3 × 11.2 in.), the same as the shrinkage beams. The major differences between the two test procedures are summarized in Table 2.9.

Table 2.9 Comparison of ASTM and Army Corps of Engineers Test Methods

	Curing		**Measurement**	
Test Method	**Curing Condition**	**Age**	**Temperature Range**	**Moisture Condition**
ASTM C531	Air	28 days	20–100ºC	Air
CRD C39-81	Immersed in Water	28 days	10–60ºC	Immersed in Water

ASTM 531 was developed to determine linear shrinkage and the coefficient of thermal expansion of mortars, grouts, and monolithic surfacing. The specimens were first oven dried for 3 days to eliminate the effect of drying shrinkage. The test requires measuring the length of concrete samples twice: first after heating the specimens at 100ºC for 24 hours, and then again after curing at 20ºC room for 24 hours.

For the CRD test method, the samples were first cured in water for three days to reduce the effect of drying shrinkage. Then the samples were cured at 5ºC in the water bath and then stored for 24 hours in a 60ºC water bath. The length was then measured. The specimens were then returned to the 5ºC water bath and stored for 24 hours. The length was then again measured.

The coefficient of thermal expansion for both test methods is calculated by dividing the change in length by the change in temperature.

3.0 STRENGTH TEST RESULTS

Failure modes in a concrete element are determined by its stress state: uniaxial tension, uniaxial compression, or multiaxial stress combinations. A concrete pavement consists of relatively thin slabs on a subgrade or base course and, because of its much higher modulus of elasticity, most of the load carrying capacity is derived from the concrete slab itself. The slab's reaction to external loadings, such as traffic forces and restrained deformations, is that of a deflected beam subjected to flexural or bending loads, and the stress state could be a combination of tensile, compressive, and/or shear stresses. Because the concrete material has a much smaller capacity for tension than compression (around one tenth), it is the tensile strengths that determine its failure. Therefore, the flexural strength or modulus of rupture (MR) must be known to complete a concrete pavement design.

Adequate strength must be achieved in a newly paved concrete slab in order to avoid excessive damage and shortened fatigue resulting from traffic load. For these purposes:

- The opening strength MR must be greater than the tensile stress (σ) induced in the slab by traffic loading. An opening strength of at least 2.8 MPa (400 psi) has been determined to be adequate for opening the pavement to traffic while minimizing the risk that a substantial portion of the concrete pavement fatigue life will be exhausted before the concrete has reached its long-term strength.(*7*)
- The thickness of the slab has to be sufficient. For thin slabs, the 2.8 MPa opening strength may be insufficient with moving loads.

The strength of concrete is developed by hydration of cement, in which the cement reacts with water and forms a firm and hard bonding mass, the hydrated cement paste, as discussed in following section for each of the cements used. The hydration rate and cement strength both depend on the cement type and curing condition. For a given curing condition and at each age, the water/cement ratio is the largest single factor influencing the strength of a fully compacted concrete. The strength of the concrete is generally inversely proportional to the water/cement ratio (Abram's rule). However, other factors such as aggregate content and aggregate properties (e.g., shape and size) also influence the concrete strength.

3.1 Cement Properties and Hydration Mechanisms

Because of different hydration rates, different cements need different curing times to achieve the minimum opening strength. Table 3.1 lists the three main categories of concrete included in this study and their respective opening times.

Table 3.1 Cement Types and Minimum Curing Times to Achieve Minimum Opening Strength

Cement Type	Mix Name	Time to Reach Minimum Strength 2.8 MPa (400 psi)
Portland Cement	Type I/II	28 days
	Type III-A	12 to 16 hours
	Type III-B	12 to 16 hours
Calcium Sulfoaluminate Cement	CSA-A	4 to 8 hours
	CSA-B	4 to 8 hours
Calcium Aluminate Cement	CA	4 to 8 hours

3.1.1 Portland Cement

Portland cement, by the definition of ASTM C150 (*30*), is hydraulic cement produced by pulverizing clinker primarily consisting of hydraulic calcium silicates, and containing one or more types of calcium sulfate as an interground addition. Recognizing other materials may be added or blended in the production of hydraulic cement, ASTM C 1157 (*31*) uses the term “blended cement” for a hydraulic cement consisting of portland cement and other appropriate inorganic materials.

There are four major compounds constituting portland cement:

- tricalcium silicates (C_3S),
- dicalcium silicates (C_2S),
- tricalcium aluminate (C_3A),
- and tetracalcium aluminoferrite (C_4AF).

In the following shortened names used by cement chemists, each letter describes one oxide: C=CaO; S=SiO_2; A=Al_2O_3; and F=Fe_2O_3. According to ACI 225R-99 (*32*), five types of portland cement are categorized for different applications, and the properties of each cement type are controlled by the limiting contents of the four compounds (a practice in the United States). Among these compounds, the two calcium silicate compounds are the main phases and make up 75–80 percent of the portland cement. However, small amounts of the other two phases, especially C_3A, are also present. The quantity of C_3A significantly influences the early reactions and later durability of the cement paste, and accounts for the main difference between Type II and Type III cement. The portland cements used in this study and their compound compositions (Bogue composition) are shown in Table 2.2. The oxide compositions are shown in Table 2.1.

The cement hydration products, calcium silicate hydrates (C-S-H), are formed by reactions of the silicate compounds (C_3S and C_2S) with water, as shown in Equations 1 and 2.(*33*)

$$2C_3S + 6H \Rightarrow C_3S_2H_3 + 3CH \quad \textbf{(1)}$$

$$2C_2S + 4H \Rightarrow C_3S_2H_3 + CH \quad \textbf{(2)}$$

The approximate compositions of the calcium silicate hydrates are $C_3S_2H_3$, which make up 50 to 60 percent of the volume of solids in a hydrated cement paste. Although it is not fully understood, the structure of C-S-H determines the properties of the paste, such as strength and permeability.

The aluminates (C_3A) are present in much smaller amounts than the silicates, however, they are important for early strength and subsequent durability. The reaction of C_3A with water is immediate and produces ettringite ($C_6A\overline{S}H_{32}$) which contributes to setting and early strength development. The high sulfate form of the ettringite is unstable with age because the sulfate ions in the solution decrease as the hydration continues, and the ettringite is converted into a low-sulfate form, monosulfate ($C_4A\overline{S}H_{18}$) by the reaction shown in Equation 3.

$$C_6A\overline{S}_3H_{32} + 2C_3A \Rightarrow C_4A\overline{S}H_{18} \quad \textbf{(3)}$$

If the concrete is located where sufficient sulfate ions are present, the monosulfate can be converted back to the ettringite at later age. This process of deterioration caused by the expansive ettringite is known as sulfate attack.

3.1.2 Calcium Sulfoaluminate Cement

Calcium sulfoaluminate cement is manufactured with ground cement clinker with a main phase of $4CaO{\cdot}3Al_2O_3{\cdot}Ca_2SO_3{\cdot}(C_4A_3\overline{S})$. Oxide analysis shows it to be rich in SO_3 ($\overline{S}$). Unlike portland cements which have a limited amount of $\overline{S}$, CSA-A cement has 14.2 percent of $\overline{S}$ and the CSA-B cement has 10.8 percent. As shown in Table 2.1, the potential application of this cement lies in its non-expansive formula. However, the engineering properties of CSA cement hydrates are not as well documented as those of portland cement. Part of the reason for the lack of information on CSA cement is that the compound compositions are not consistent among manufacturers. Rather, the cement composition depends on the raw materials used, which could include limestone, bauxite, or aluminous clay and gypsum.(*34*) For example, the two CSA cements used in this study have very different compositions: the CSA-B has two main phases, C_2S and $C_4A_3\overline{S}$, while the CSA-A has the four main phases of portland cement, as well as $C_4A_3\overline{S}$.

Despite the variation in composition, the principal hydrated matrix of CSA cements is made of ettringite by the following reactions:

$$C_4A_3\overline{S} + 2C\overline{S}H_2 + 34H \Rightarrow C_3A.3C\overline{S}.32H + 2AH_3 \quad \textbf{(4)}$$

$$C_4A_3\overline{S} + 8C\overline{S}H_2 + 6Ca(OH)_2 + 74H \Rightarrow 3C_3A.3C\overline{S}.32H \quad \textbf{(5)}$$

$$A_3H_3 + 3C\overline{S}H_2 + 3Ca(OH)_2 + 20H \Rightarrow C_3A.3C\overline{S}.32H \quad \textbf{(6)}$$

The ettringite is stable because there is sufficient sulfate to avoid the conversion to monosulfate, which is the most significant difference from portland cement hydrates. The expansibility of ettringite has been found to be dependent on:

- alkalinity of hydrate,
- particle size of the cement; and
- miscrostructure of the hydrates.(*35*)

3.1.3 Calcium Aluminate Cement

Unlike calcium silicate hydrates, the composition of hydrates from CA cement is very sensitive to temperature. The possible hydration reactions are as follows (*36*):

$$CA + 10H \Rightarrow CAH10 \quad \textbf{(7)}$$

$$2CA + 11H \Rightarrow C2AH8 + AH3 \quad \textbf{(8)}$$

$$3CA + 12H \Rightarrow C3AH6 + 2AH3 \quad \textbf{(9)}$$

$$2CAH10 \Rightarrow C2AH8 + AH3 + 9H \quad \textbf{(10)}$$

$$3C2AH8 \Rightarrow 2C3AH6 + AH3 + 9H \quad \textbf{(11)}$$

Among the hydrates, CAH_{10} and C_2AH_8 are metastable phases, which might convert to the stable phase C_3AH_6 and γ-AH_3 (gibbsite). For curing regimes with temperature ranging from 10 to 23ºC, both hydrates C_2AH_8 and CAH_{10} are formed. At 40ºC, CAH_{10} no longer forms and the stable hydrate C_3AH_6 occurs early. Compared to the stable phase, the metastable phases combine more water and have low densities, and this can lead to different strength and shrinkage performance for CA concretes cured at different temperatures.

3.2 Compressive Strength

Figure 3.1 shows the compressive strength of the six mixes under the Standard curing regime (23ºC and 97% RH, as shown in Table 2.7). Their compressive strengths increased continuously with time to 90 days, except that the strength of the CA mix started to drop between 14 days and 90 days. The phenomenon of CA concrete becoming more porous as the metastable phases of CAH_{10} and C_2AH_8 convert to the stable and denser phase C_3AH_6 and γ-AH3 (gibbsite) is well understood.

Although the 90-day strengths ranged from 30 to 70 MPa across the six mixes, their strength development rates were similar. Strength gain was rapid at early age with more than 50 percent of the 90-day strength achieved by the first day for all of the early strength mixes.

The ranking of the strength at 7 days is:

Type I/II < Type III-A < CSA-A ≅ Type III-B < CSA-B ≅ CA

The ranking of the strength at 90 days is:

Type I/II < Type III-A < CA< CSA-A ≅ CSA-B < Type III-B

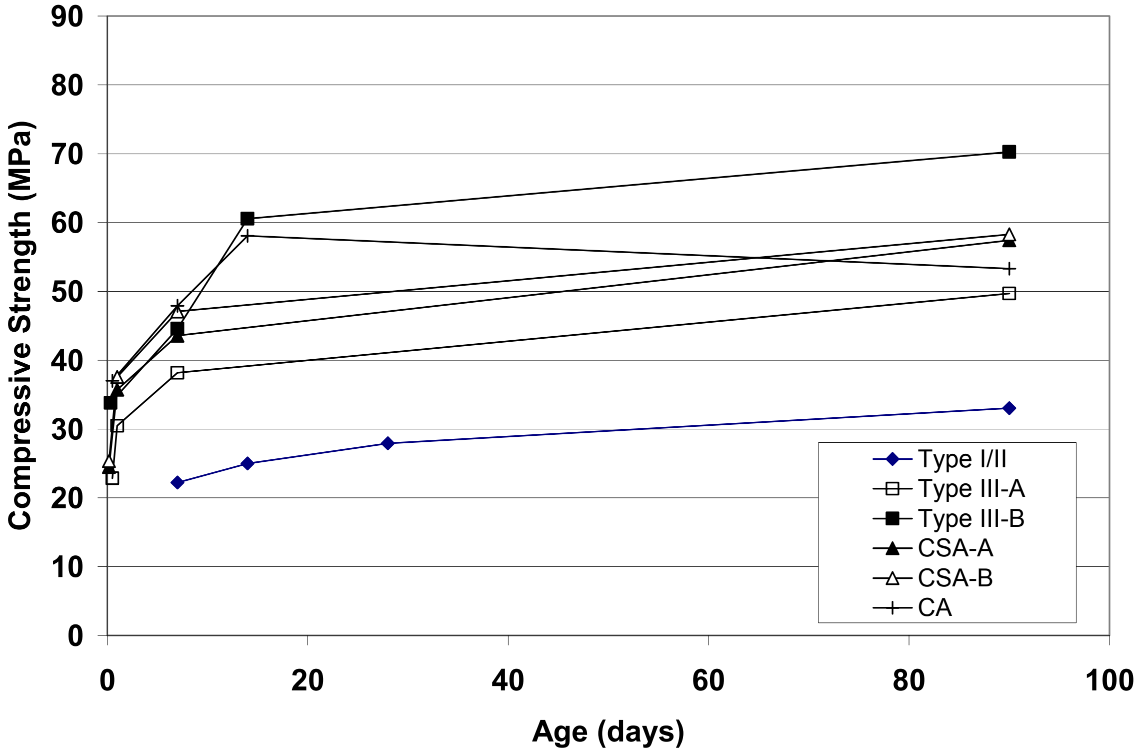

Figure 3.1. Compressive strength of the target mixes at 23ºC and 97 percent relative humidity (Standard curing regime).

When the water content was increased by 10 percent, the Type I/II , Type III-A, Type III-B, and CA cement mixes showed a significant strength reduction of more than 10 percent at each age, compared to the target water/cement ratio (Table 3.2). The two CSA mixes behaved differently: the 10-percent increase in water content had less effect on the strength of the CSB-B mix than on the other mixes. The CSA-A mix strength was actually higher by more than 10 percent for the mix containing 10 percent additional water.

When the curing temperature was reduced to 10ºC (Cold curing regime), it greatly retarded the early strength development. For example, the compressive strength of the Type III-A mix dropped by 73 percent at 12 hours, as shown in Table 3.3 and Figure 3.2. The Cold curing regime did not greatly affect the 90-day strength, with less than 10 percent strength reduction for most mixes.

Table 3.2 Difference in Compressive Strength of All Cement Mixes with Increase in Water Content of 10 Percent

Age	Cement Type					
	Type I/II	Type III-A	Type III-B	CSA-A	CSA-B	CA
4 hours				37.1%	-2.5%	
8 hours						
12 hours		-14.7%				-19.0%
1 day		-11.6%		10.1%	6.1%	
7 days	-18.4%	-7.0%	-10.5%	13.5%	-4.2%	-8.0%
14 days	-14.1%		-8.9%			-17.0%
28 days	-13.5%					
90 days	-10.1%	-8.9%	-8.1%	8.2%	-4.2%	-12.3%

Table 3.3 Difference in Compressive Strength, 23 C versus 10ºC Curing Temperature

Age	Cement Type					
	Type I/II	Type III-A	Type III-B	CSA-A	CSA-B	CA
4 hours				-48.9%	-21.7%	
8 hours			-81.4%			
12 hours		-73.0%				
1 day		-33.1%		-31.9%	4.1%	
7 days	-3.4%	5.2%	-30.8%	-15.7%	-10.6%	-4.4%
14 days	6.7%		-9.9%			-11.2%
28 days	7.3%					
90 days	-4.2%	-9.5%	2.3%	-23.6%	-7.8%	3.4%

In contrast, the Dry curing regime (20ºC + 50% RH) decreased the 90-day strength significantly, as shown in Table 3.4 and Figure 3.3. It should be noted that at 10ºC, the vapor pressure is so low that it causes negligible moisture loss from concrete to its environment at 50 percent RH, as confirmed by the negligible shrinkage of the specimens subjected to this curing regime (Section 4). Therefore, although they have the same relative humidity, the Cold curing regime is not as dry as the Dry curing regime.

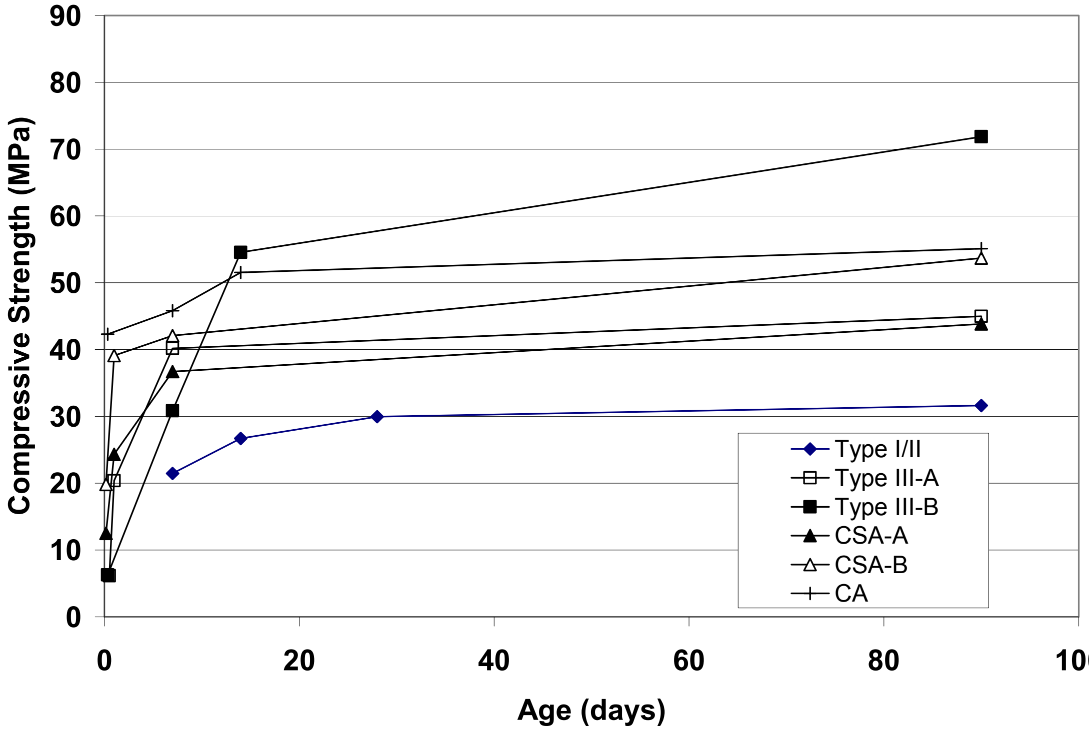

Figure 3.2. Compressive strength of the target mixes at 10ºC and 50 percent relative humidity (Cold curing regime).

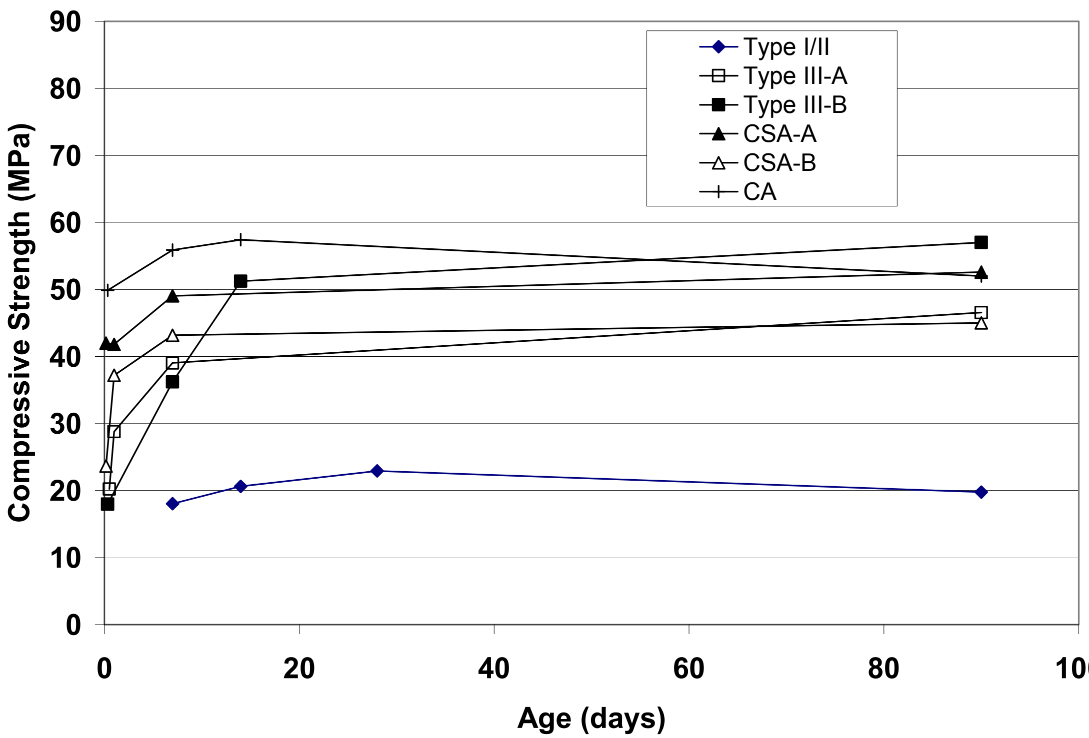

Figure 3.3. Compressive strength of the target mixes at 20ºC and 50 percent relative humidity (Dry curing regime).

Table 3.4 Difference in Compressive Strength, 97 Percent Relative Humidity versus 50 Percent Relative Humidity

Age	Cement Type					
	Type I/II	**Type III-A**	**Type III-B**	**CSA-A**	**CSA-B**	**CA**
4 hours				71.7%	-6.7%	
8 hours			-46.8%			
12 hours		-11.5%				
1 day		-5.6%		17.0%	-1.0%	
7 days	-18.8%	2.2%	-18.8%	12.6%	-8.3%	16.7%
14 days	-17.6%		-15.4%			-1.1%
28 days	-17.9%					
90 days	-40.1%	-6.3%	-18.8%	-8.4%	-22.7%	-2.4%

3.3 Flexural Strength by Cement Type

3.3.1 Type I/II Portland Cement + 15 Percent Fly Ash

Figure 3.4 shows the flexural strength of the Type I/II mix cured under three curing regimes. In both the Standard and Cold regimes (Table 2.7), the flexural strength increases continuously over time. There is no major difference in the early strength development between these two regimes, but the 90-day strength under Cold regime was 20 percent greater than in the Standard regime. This may have been caused by a finer distribution of hydrates formed in the Cold regime. In contrast to the other two curing regimes, flexural strength ceased to develop under the Dry curing regime. This phenomenon is further discussed in the Section 3.4.

Table 3.5 shows the flexural strength check as to whether the Type I/II mixes reached its target strength, 2.8 MPa, at 28 days. As can be seen, the mixes cured under the Standard and Cold conditions reached the target strength. By increasing the water content by 10 percent, the 28-day flexural strength decreased but still reached the target strength. However, in the Dry curing regime, both the target and +10% w mixes failed to reach the target strength.

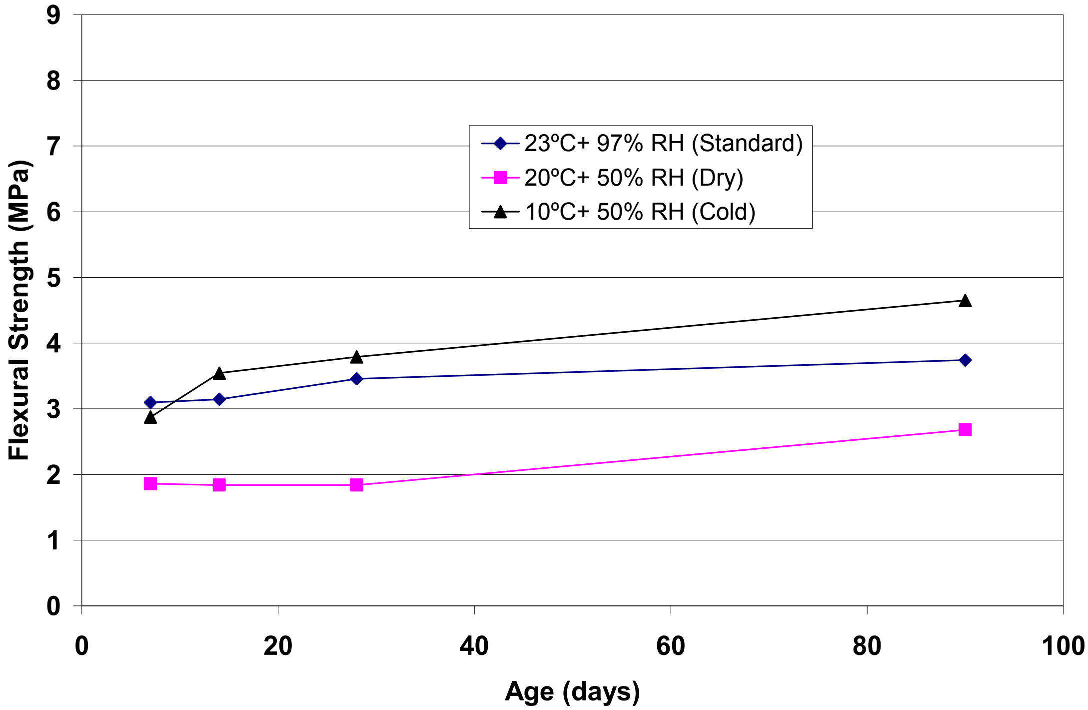

Figure 3.4a. Target mix.

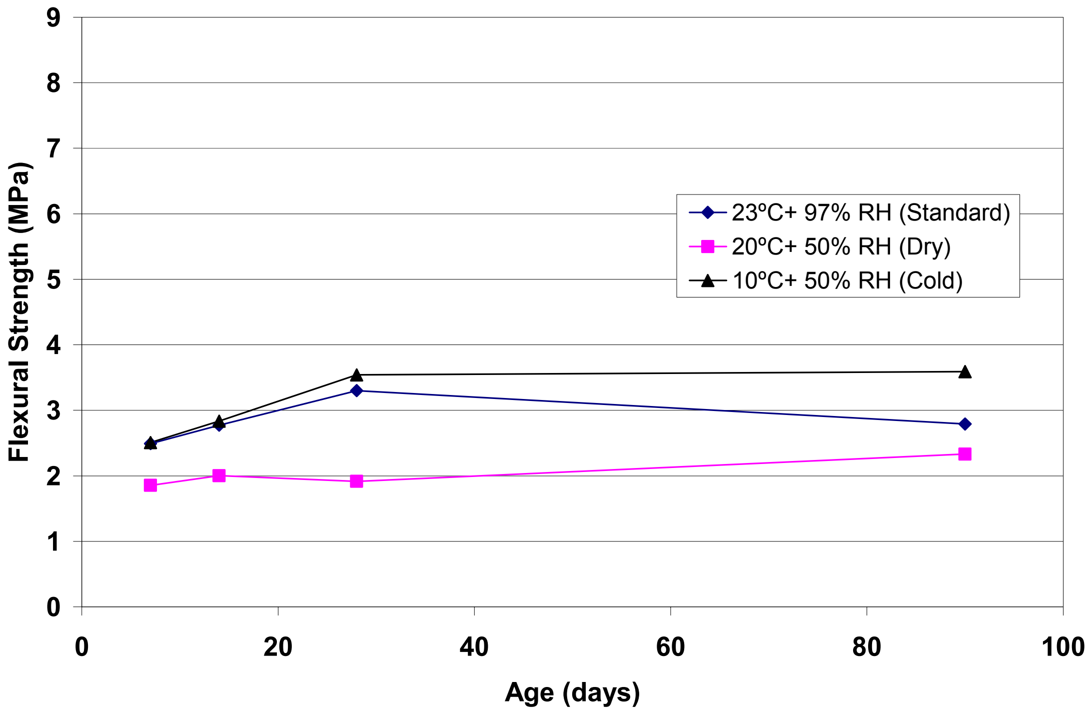

Figure 3.4b. Mix with 10 percent additional water (+10% w).

Figure 3.4. Flexural strength of the Type I/II portland cement concrete mixes.

Table 3.5 Flexural Target Strength Check for Type I/II Portland Cement

Curing Conditions		Mix Design	Strength at 28 Days (MPa)	Reached the Target Strength of 2.8 MPa at 28 Days?
Standard	23ºC+ 97% RH	Target mix	3.46	Yes
		+10% w mix	3.30	Yes
Dry	20ºC+ 50% RH	Target mix	1.84	No
		+10% w mix	1.91	No
Cold	10ºC+ 50% RH	Target mix	3.79	Yes
		+10% w mix	3.54	Yes

3.3.2 Type III-A Portland Cement

Figure 3.5 shows the flexural strength of the Type III-A mix for the three curing regimes. The Cold regime retarded the early strength development, but benefited the long term strength, so that its 90-day flexural strength was even higher than that obtained under the Standard regime. This conforms to the general tendency for rapid hardening to lead to a lower long-term strength. Like all the other mixes in the Dry regime, the strength dropped for a short period between 1 day and 7 days.

The target strength of this concrete is 2.8 MPa between 12 and 16 hours. The strength was checked for this mix at 12 hours in Table 3.6. The results showed that the target strength at 12 hours was achieved only under the Dry curing condition at the target water/cement ratio.

Table 3.6 Flexural Target Strength Check on Type III-A Portland Cement

Curing Conditions		Mix Design	Strength at 12 Hours (MPa)	Reached the Target Strength of 2.8 MPa at 12 Hours?
Standard	23 C+ 97% RH	Target mix	2.61	No
		+10% w mix	2.51	No
Dry	20 C+ 50% RH	Target mix	3.06	Yes
		+10% w mix	2.52	No
Cold	10 C+ 50% RH	Target mix	1.57	No
		+10% w mix	1.82	No

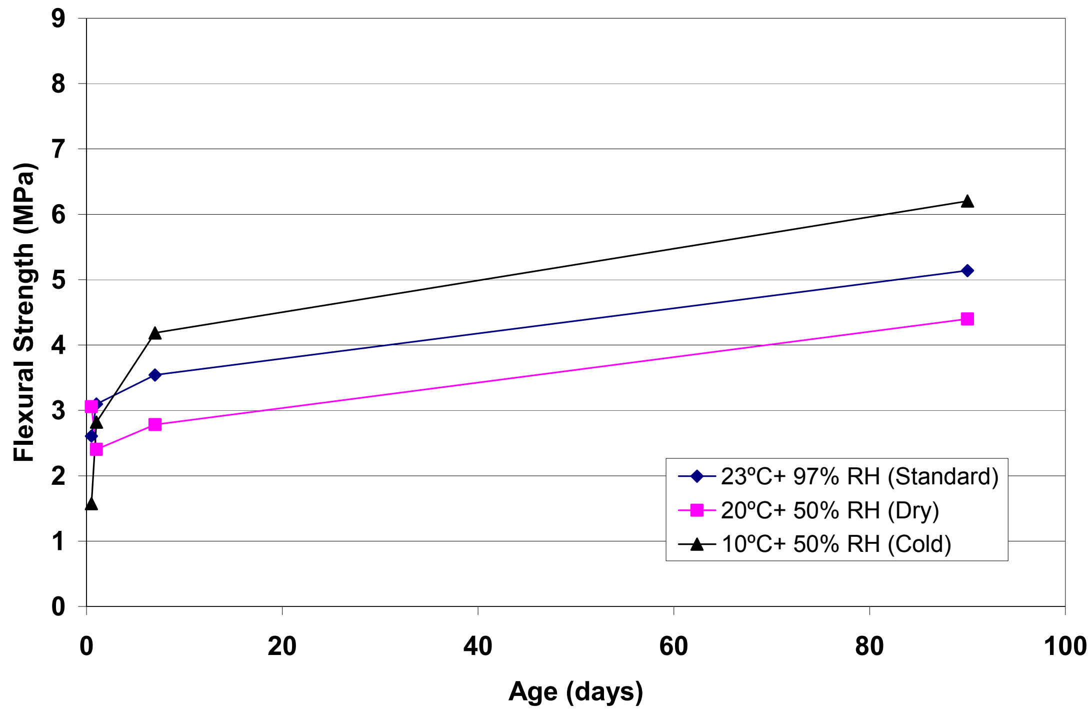

Figure 3.5a. Target mix.

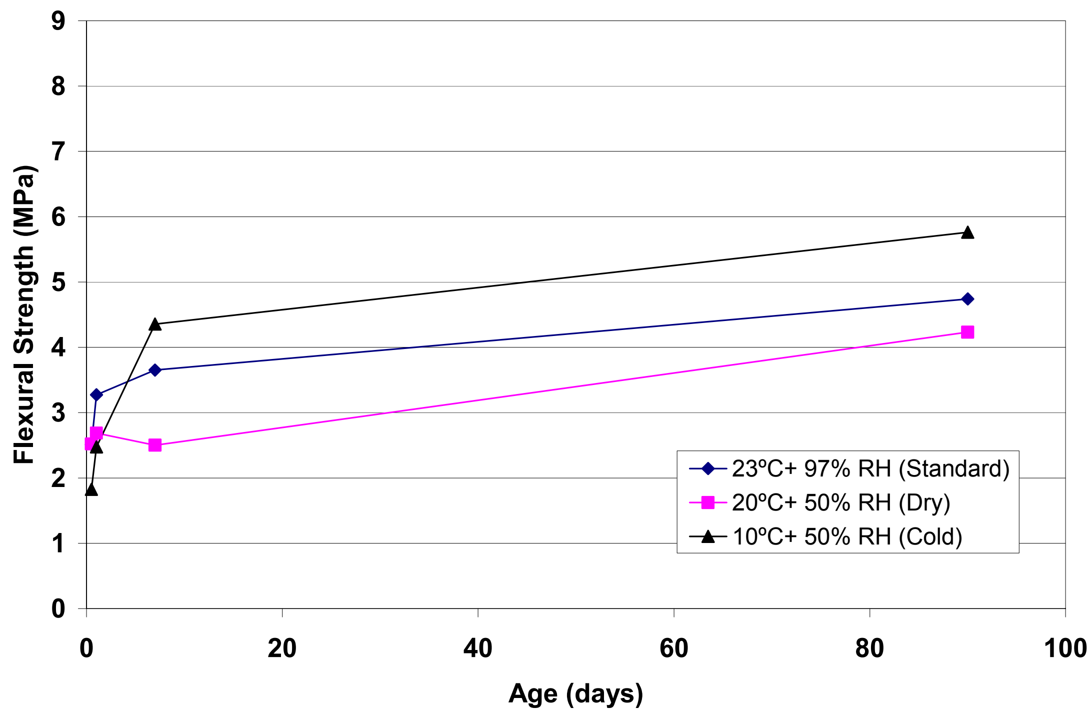

Figure 3.5b. Mix with 10 percent additional water (+10% w).

Figure 3.5. Flexural strength of the Type III-A portland cement concrete mixes.

3.3.3 Type III-B Portland Cement

Figure 3.6 shows the flexural strength of the Type III-B mix under the three curing regimes. The effect of curing regime on strength development was similar to that observed with the Type III-A mix in that:

- the short-term flexural strength was reduced when cured using the Cold regime,
- the long-term flexural strength was greater when cured using the Cold regime, and
- under the Dry regime, the strength dropped for a short period between day 1 and day 7 before increasing again.

The initial strength check at 8 hours for this mix is shown in Table 3.7, although the target strength was for 12–16 hours. The target strength was achieved under the Standard curing regime (23ºC + 97% RH) at 8 hours for both the target mix and the +10% w mix. Under the Dry regime, the target mix achieved more than 2.8 MPa at 8 hours, but by adding 10 percent more water, it failed to meet the target strength. Under the Cold regime, the mix failed to reach 2.8 MPa at 8 hours.

Table 3.7 Flexural Target Strength Check on Type III-B Portland Cement

Curing Conditions		**Mix design**	**Strength at 8 Hours (MPa)**	**Reached the Target Strength of 2.8 MPa at 8 Hours?**
Standard	23 C+ 97% RH	Target mix	3.67	Yes
		+10% w mix	3.28	Yes
Dry	20 C+ 50% RH	Target mix	3.00	Yes
		+10% w mix	2.35	No
Cold	10 C+ 50% RH	Target mix	1.88	No
		+10% w mix	2.39	No

In summary, compared with the Type I/II mix, both the Type III-A and Type III-B mixes developed high early strength in the Standard moist curing regime, which was attributed to the rapid hydration of larger amounts of C_3S (greater than 55 percent, up to 77 percent for Type III).

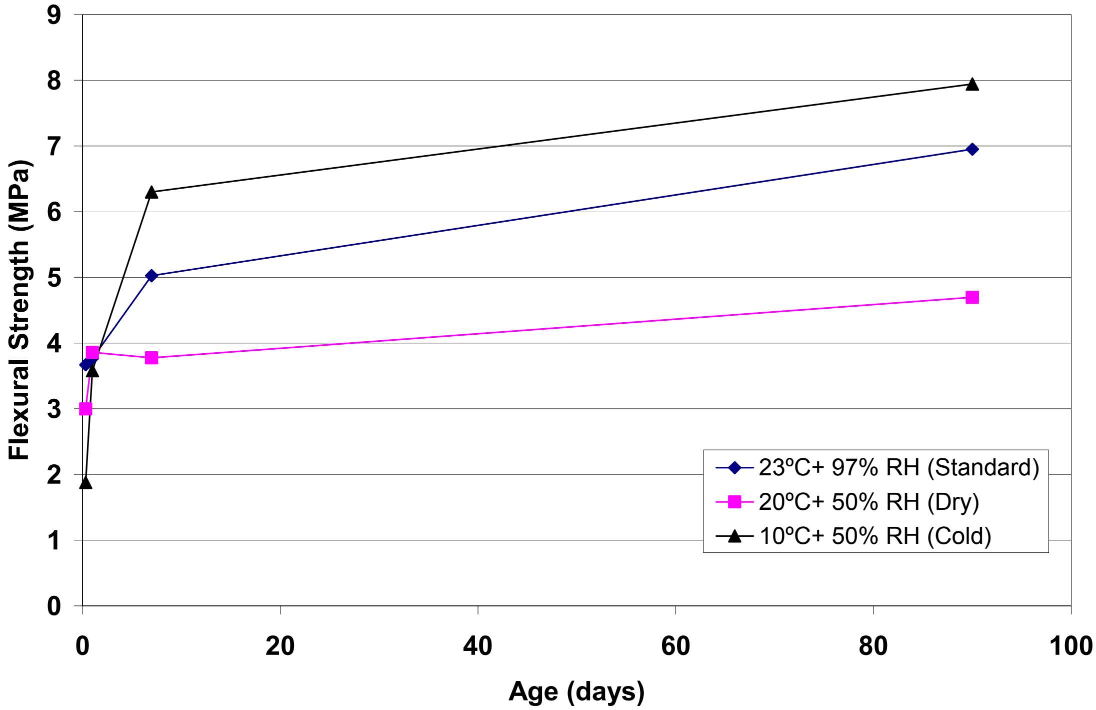

Figure 3.6a. Target mix.

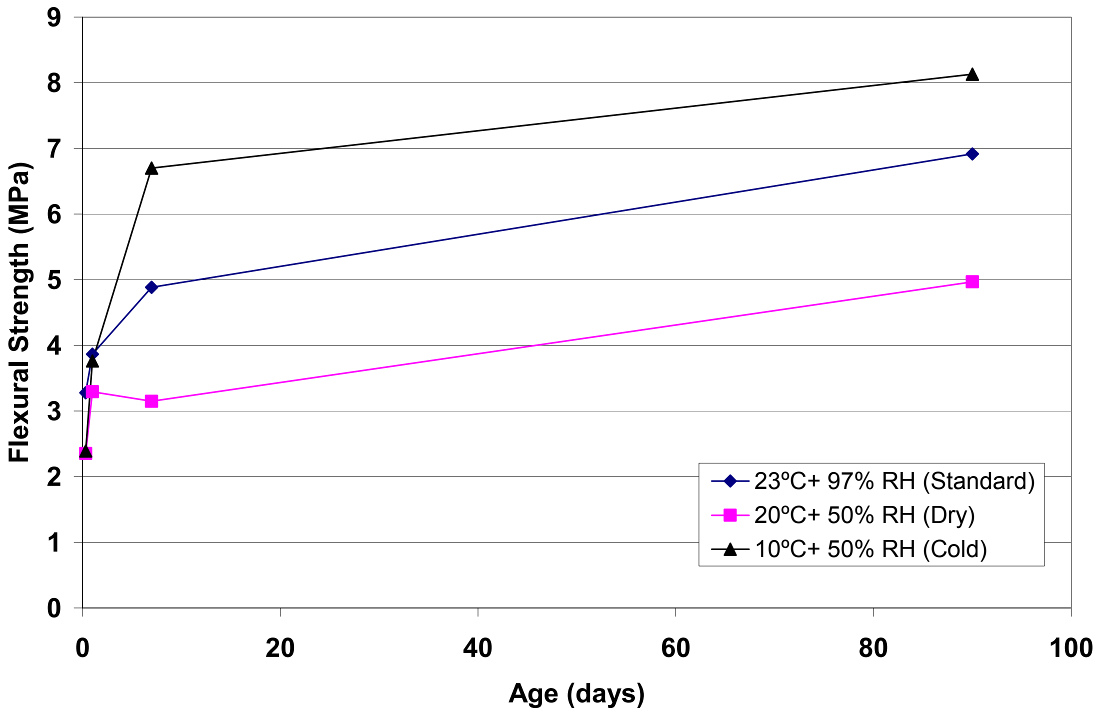

Figure 3.6b. Mix with 10 percent additional water (+10% w).

Figure 3.6. Flexural strength of the Type III-B portland cement concrete mixes.

For example, the Type III-A cement contained 66 percent C_3S. However, curing temperature has a significant effect on the ability of these two mixes to achieve high early strength. In the Cold regime, the benefit of using Type III cement (its high early strength gain) was suppressed.

3.3.4 Calcium Sulfoaluminate Cement A (CSA-A)

As shown in Figure 3.7, the strength gain patterns of the CSA-A mix under all the three curing regimes are similar to those of the Type III mixes. The early flexural strength was suppressed cured under the Cold regime, but the long-term strength was greater. The strength of this concrete mix at 4 hours reached the target strength of 2.8 MPa under the Standard and Dry regimes, but not under the Cold regime, as shown in Table 3.8. Adding 10 percent more water to the mix reduced the strength under the Standard regime to below 2.8 MPa at 4 hours. Like the Type III mixes, its early strength was greatly affected by curing temperature.

Table 3.8 Flexural Target Strength Check on Calcium Sulfoaluminate –A Cement (CSA-A)

Curing Conditions		Mix Design	Strength at 4 Hours (MPa)	Reached the Target Strength of 2.8 MPa at 4 Hours?
Standard	23 C+ 97% RH	Target mix	3.50	Yes
		+10% w mix	2.25	No
Dry	20 C+ 50% RH	Target mix	3.41	Yes
		+10% w mix	3.04	Yes
Cold	10 C+ 50% RH	Target mix	1.97	No
		+10% w mix	2.25	No

3.3.5 Calcium Sulfoaluminate Cement B (CSA-B)

As shown in Figure 3.8, the strength gain for the CSA-B concrete mix is similar to the CSA-A mix, except that the early strength was not affected as much in the Cold regime and the 90-day strength appeared to be affected more in the Dry regime than the CSA-A mix. Table 3.9

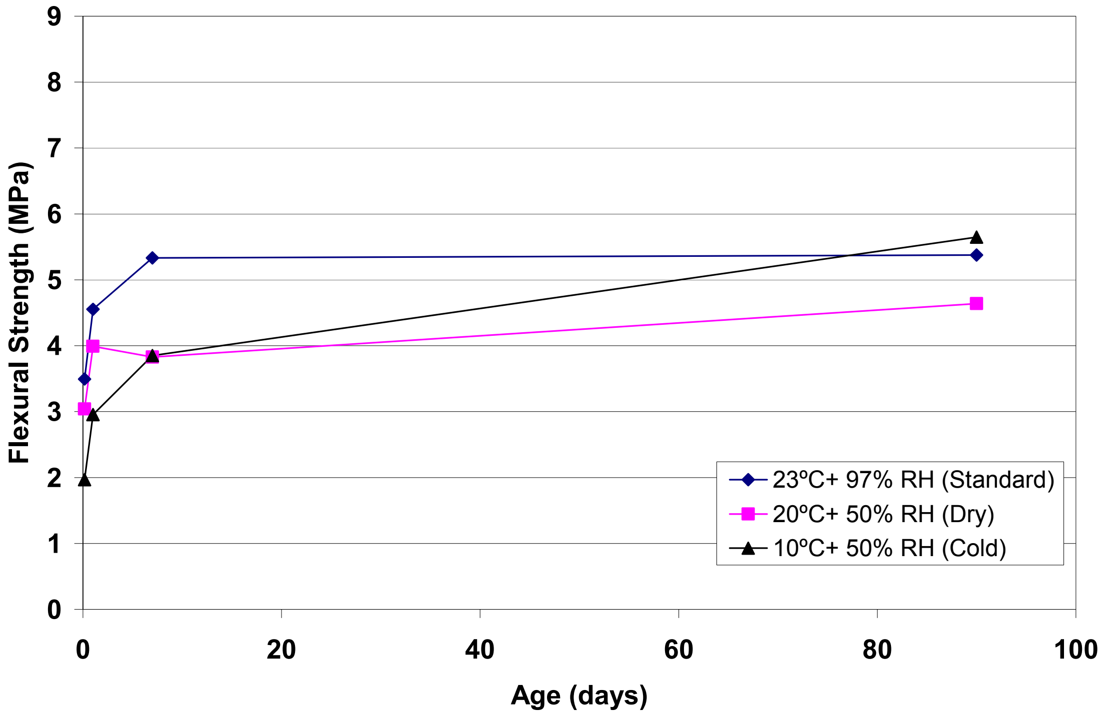

Figure 3.7a. Target mix.

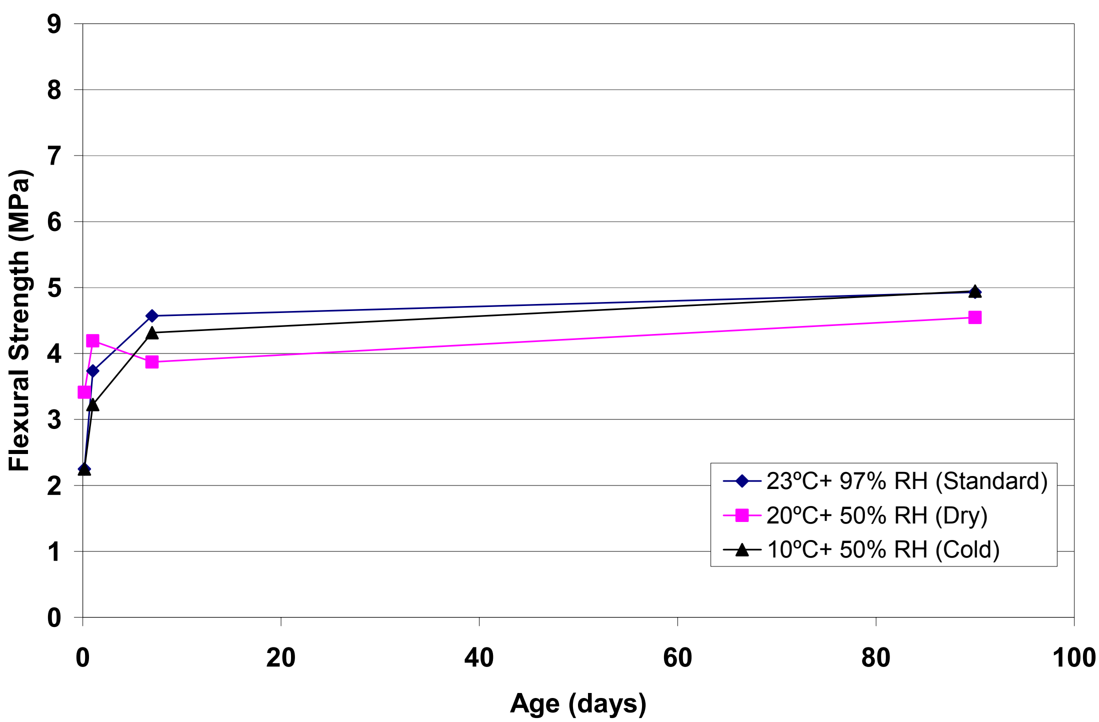

Figure 3.7b. Mix with 10 percent additional water (+10% w).

Figure 3.7. Flexural strength of the Calcium Sulfoaluminate – A (CSA-A) mixes.

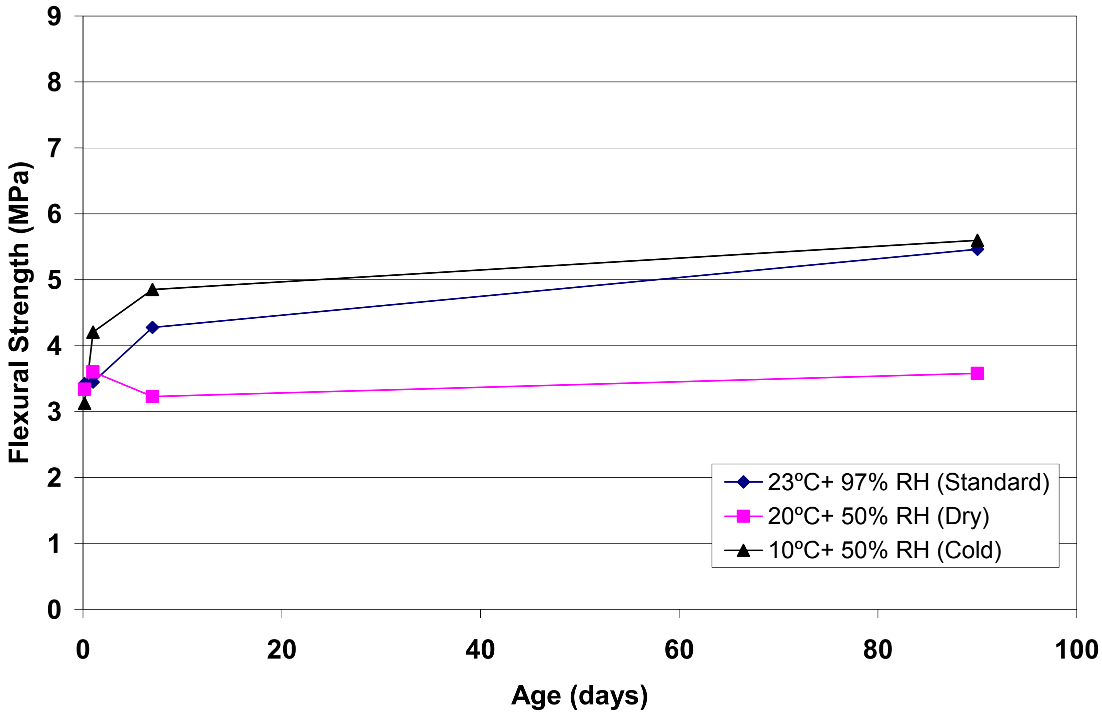

Figure 3.8a. Target mix.

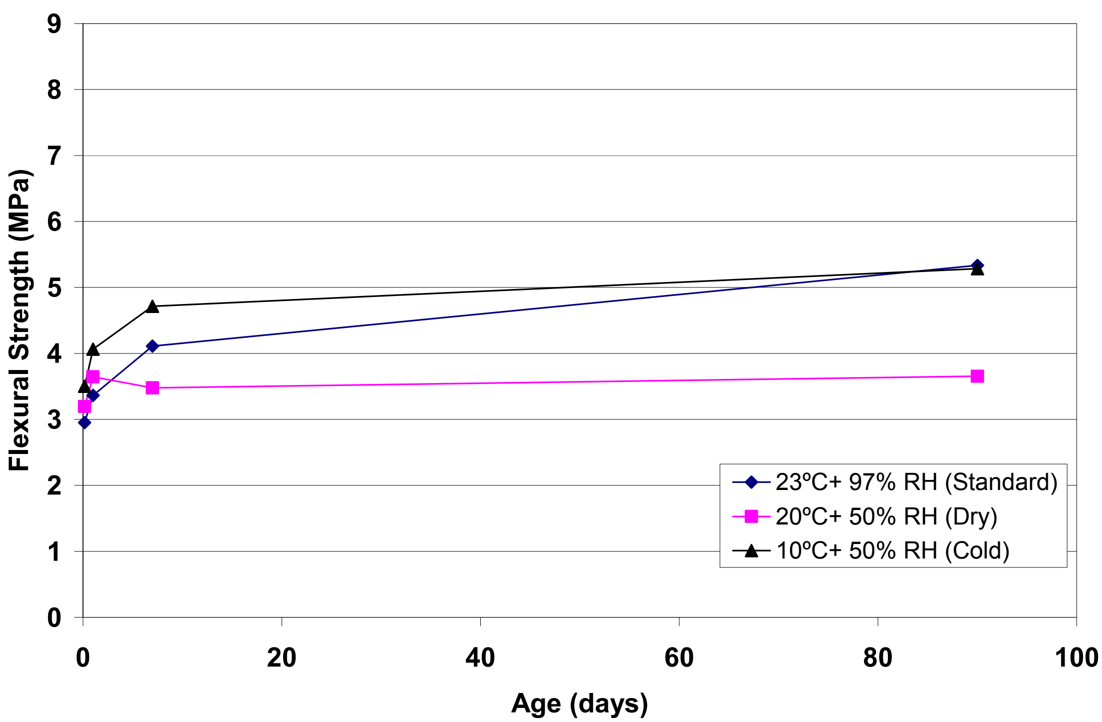

Figure 3.8b. Mix with 10 percent additional water (+10% w).

Figure 3.8. Flexural strength of the Calcium Sulfoaluminate – B (CSA-B) mixes.

Table 3.9 Flexural Target Strength Check on Calcium Sulfoaluminate – B Cement (CSA-B)

Curing Conditions		Mix Design	Strength at 4 Hours	Reach the Target Strength of 2.8 MPa at 4 Hours?
Standard	23ºC+ 97% RH	Target mix	3.42	Yes
		+10% w mix	2.95	Yes
Dry	20ºC+ 50% RH	Target mix	3.34	Yes
		+10% w mix	3.20	Yes
Cold	10ºC+ 50% RH	Target mix	3.13	Yes
		+10% w mix	3.50	Yes

shows that both the target and +10% w mixes reached the target strength at 4 hours for all curing regimes. Compared to CSA-A, this CSA-B cement could potentially be used in a Cold regime and still achieve high early strength.

3.3.6 Calcium Aluminate Cement

Compared to all the other mixes, the most notable features of the CA mix are as follows (Figure 3.9):

- the long-term strength at 90 days decreased instead of showing continuous development; and
- over time, the strength under the Cold regime was lower than that under the Standard regime.

The strength reduction over time observed in the CA concrete is well understood in terms of the conversion process, described in Section 3.1.3 of this report. However, the strength reduction was not observed under the Cold regime up to 90 days, which might be explained by the fact that the slower hardening process also postponed the conversion process. Similar to all the other mixes, under the Dry regime the flexural strength decreased, and then increased again after one day.

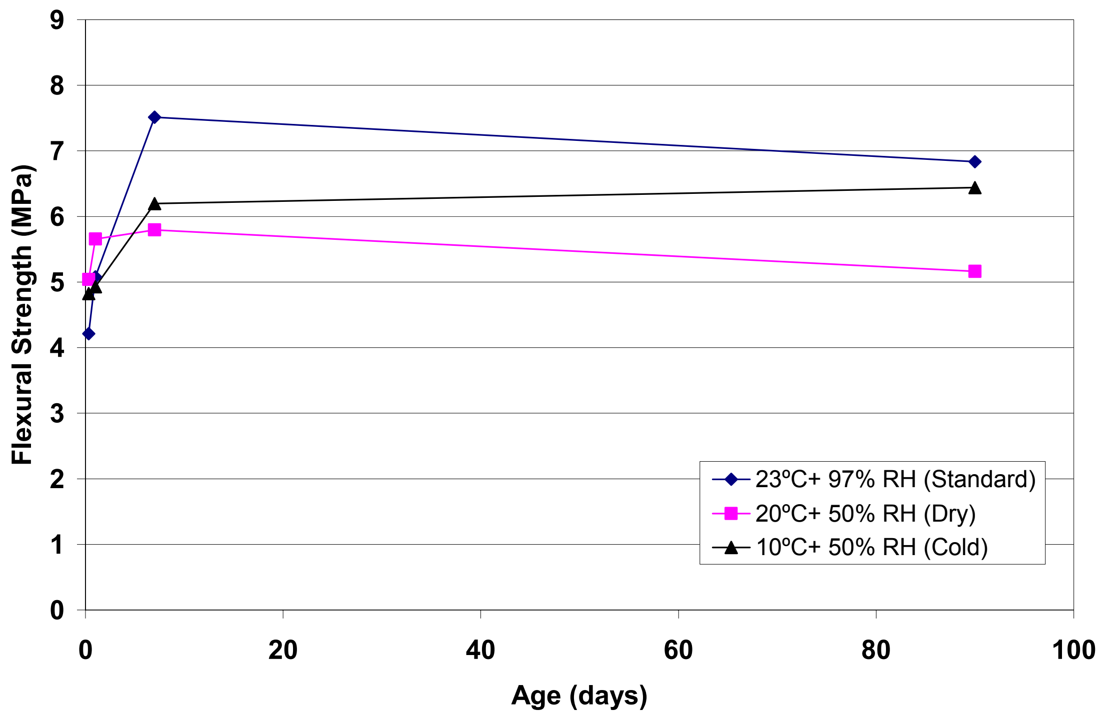

Figure 3.9a. Target mix.

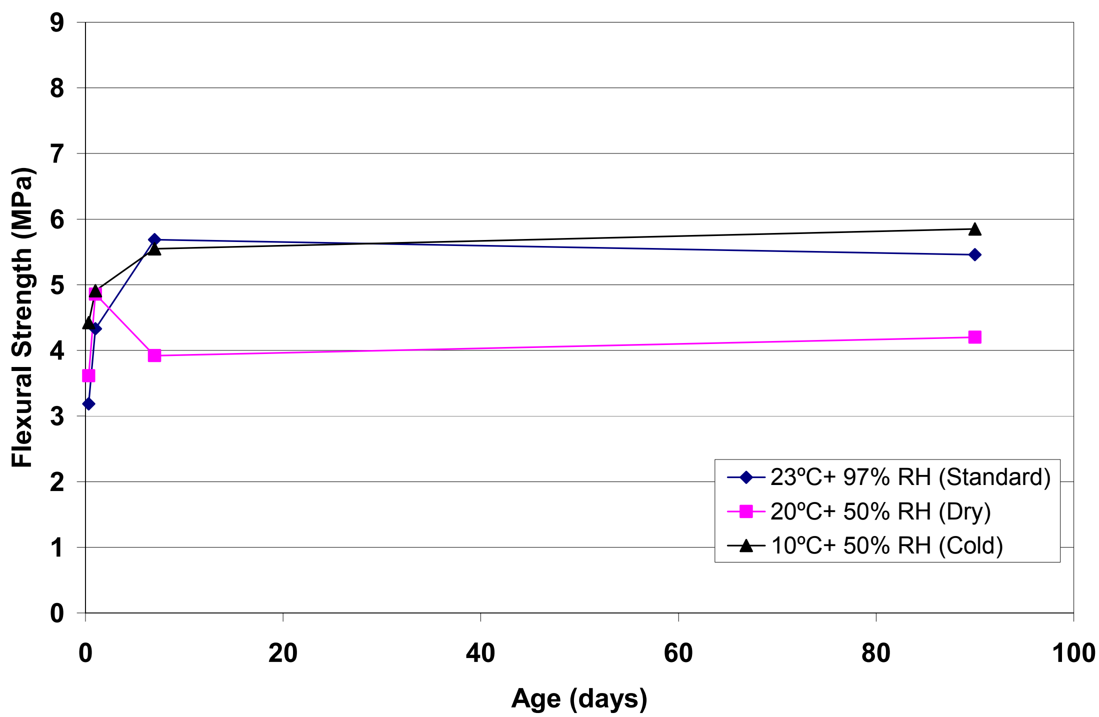

Figure 3.9b. Mix with 10 percent additional water (+10% w).

Figure 3.9. Flexural strength of the Calcium Aluminate (CA) mixes.

The target strength was achieved at 8 hours in all of the curing regimes, as shown in Table 3.10.

Table 3.10 Flexural Target Strength Check on Calcium Aluminate Cement (CA)

Curing Conditions		**Mix Design**	**Strength at 8 hours**	**8-Hour Target Strength of 2.8 Reached?**
Standard	23 C+ 97% RH	Target mix	4.21	Yes
		+10% w mix	3.19	Yes
Dry	20 C+ 50% RH	Target mix	5.04	Yes
		+10% w mix	3.61	Yes
Cold	10 C+ 50% RH	Target mix	4.82	Yes
		+10% w mix	4.42	Yes

3.4 Flexural Strength by Curing Condition

Under the Standard curing regime, all six mixes developed flexural strength over time following a pattern similar to that of compressive strength development. As shown in Figure 3.10, flexural strength continued to increase up to 90 days, except that the strength of the CA concrete started to decrease between 14 days and 90 days due to the conversion process (described in Section 3.1.3). The flexural strengths had a wide range among the 6 mixes; for example, the-90-day strength ranged from 3.8 to 6.9 MPa. Most of the 90-day strength of the mixes was achieved before 7 days.

The ranking of the flexural strengths at 7 days is

Type I/II < Type III-A < CSA-B < Type III-B < CSA-A ≅ CA

For comparison, the ranking of the compressive strength at 7 days was,

Type I/II < Type III-A < CSA-A ≅ Type III-B < CSA-B ≅ CA

These rankings show that the development of the flexural strength and compressive strength was consistent except for the CSA mixes, which traded places.

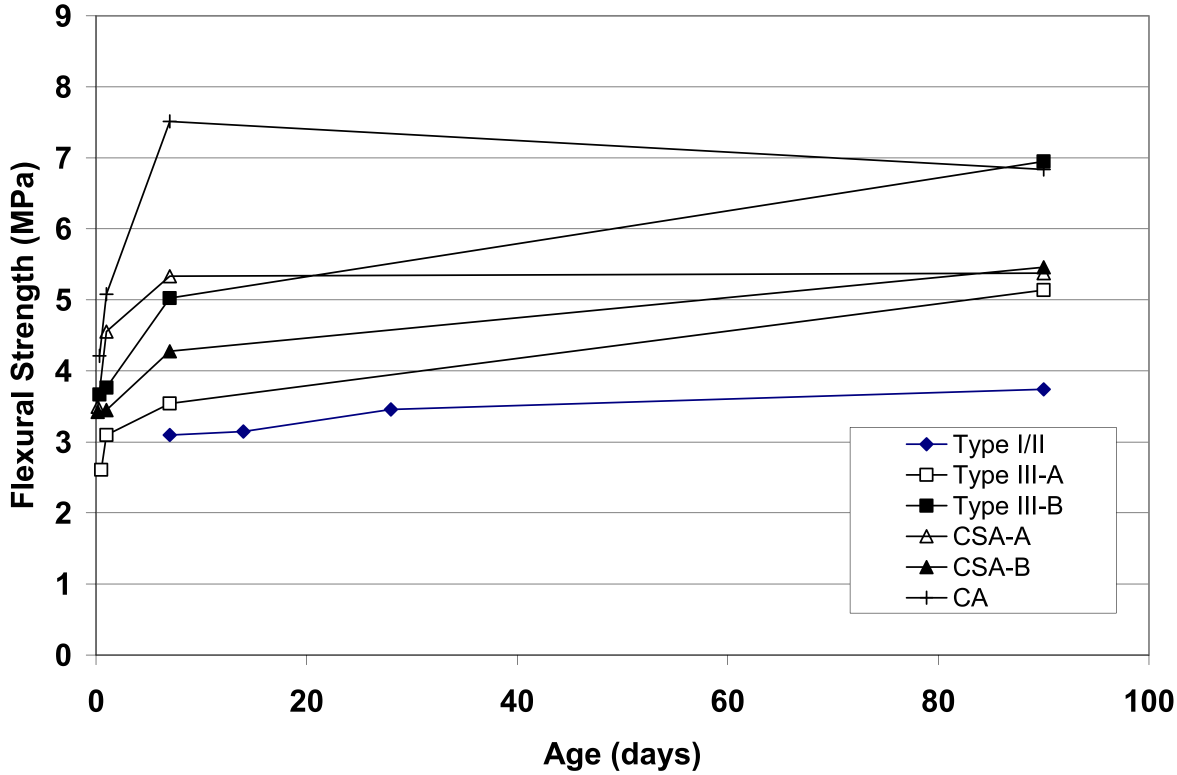

Figure 3.10. Flexural strength of the target mixes at 23ºC and 97 percent relative humidity (Standard curing regime).

Under the Cold curing regime (Figure 3.11), the most significant difference from the Standard regime is that the flexural strength continued to increase rapidly up to the measurement at 90 days. In spite of the early strength being lower for the specimens cured under the Cold regime, the 90-day strengths were similar to those of the specimens cured under the Standard regime. In contrast, the Dry curing regime (20ºC + 50% RH) had significantly lower long-term strengths, as shown in Table 3.11. Recalling the discussion in Section 3.3, it can be concluded that temperature and moisture have similar effects on the flexural strength as on the compressive strength.

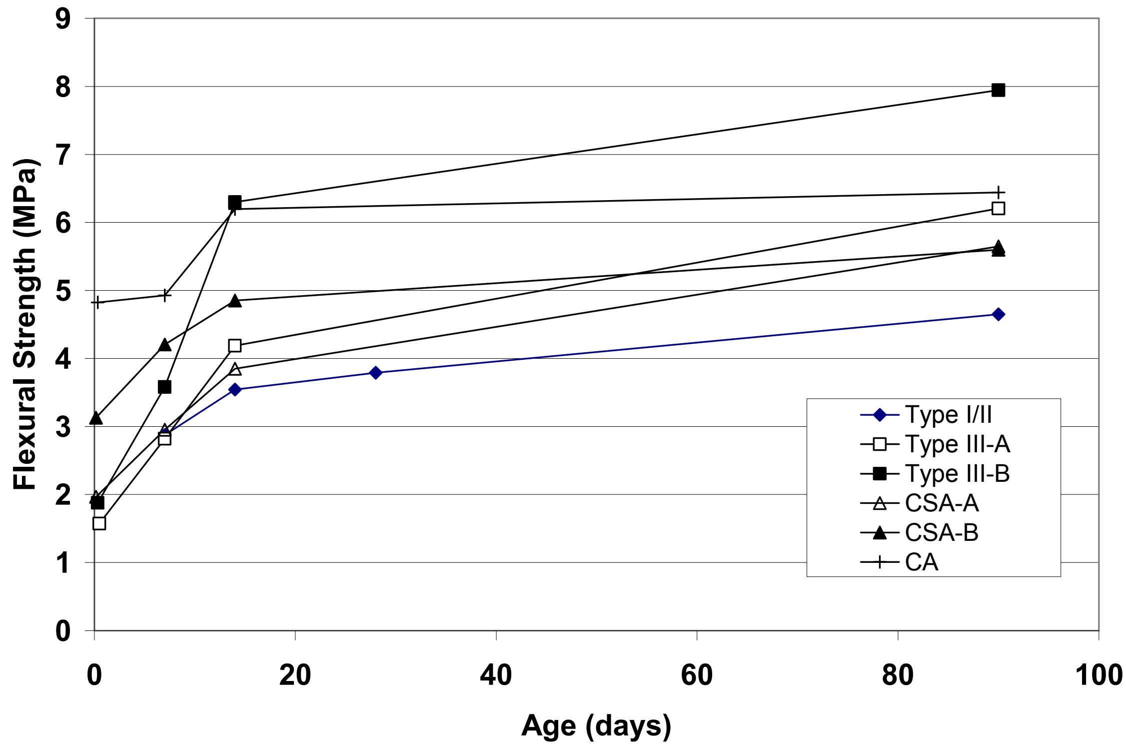

Figure 3.11. Flexural strength of the target mixes at 10ºC and 50 percent relative humidity (Cold curing regime).

Table 3.11 90-day Flexural Strengths for the Three Curing Regimes

Curing Conditions		**Type I/II**	**CSA-A**	**Type III-B**	**CA**	**Type III-A**	**CSA-B**
Standard	23ºC+ 97% RH	3.74	5.38	6.95	6.83	5.14	5.46
Dry	20ºC+ 50% RH	2.68	4.64	4.70	5.16	4.40	4.39
Cold	*10ºC+ 50% RH*	*4.65*	*5.65*	*7.94*	*6.44*	*6.20*	*5.60*

However, under the Dry curing regime, the fluctuation of the flexural strength gain with time occurred in all the mixes, as shown in Figure 3.12. The fluctuation consisted of strength loss between 4, 8, and 12 hours or one day to 7 days, followed by strength recovery by 90 days. This phenomenon was previously observed by several researchers investigating the effect of moisture on the flexural strength of concrete.(*37, 38*) They presented two explanations for this:

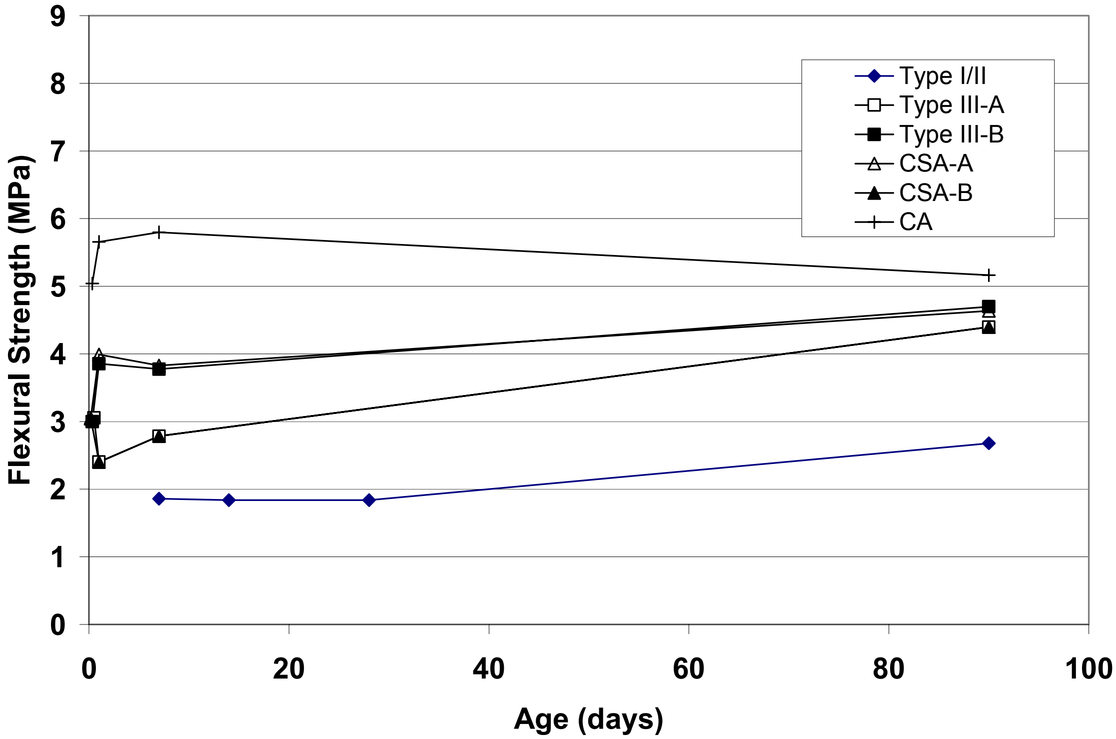

Figure 3.12. Flexural strength of the target mixes at 20ºC and 50 percent relative humidity (Dry curing regime).

1. **Macro-level.** Differential shrinkage develops on cross sections of the concrete specimen. The outer layers shrink more than the inner layers so that tensile stresses develop on the outer layers and compression stresses on the inside layers. These stresses are self balanced, as illustrated in Figure 3.13. This process does not influence the compressive loading capacity, but will decrease the tensile (flexural) loading capacity.
2. **Micro-level.** Tensile stresses develop in the cement paste surrounding the more rigid aggregate when the paste is undergoing drying shrinkage and the aggregates restrain the change in volume. This results in a weaker bond between the two phases, which affects the flexural strength.

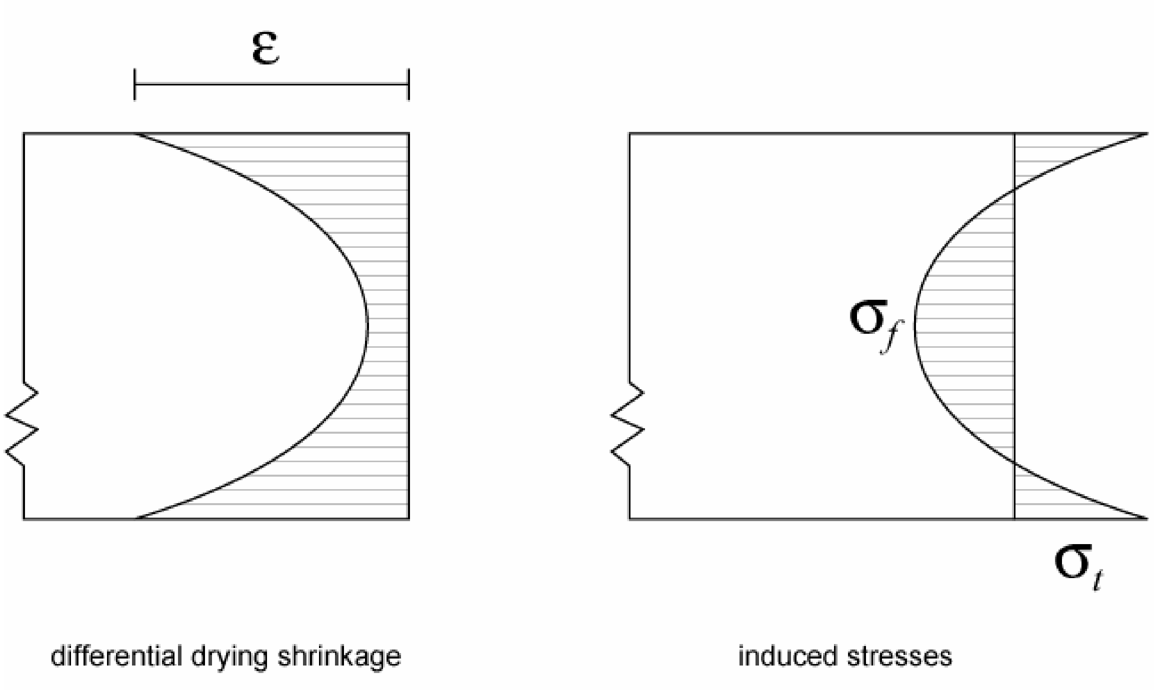

Figure 3.13. Self-balanced stress on the beam cross section caused by drying shrinkage gradient.

Proper identification of the period during which strength decreases is important for pavement applications. Removal of specimens from moist curing immediately after the target strength is achieved could result in a temporary reduction in strength, which could contribute to early cracking.

3.5 Comparison of Flexural and Compressive Strength Results

3.5.1 Variability of the Test Results

Two specimen replicates were used for each strength measurement. The coefficient of variation (CV)—the ratio between the standard deviation and the mean value as a percentage—was calculated for each pair. The CV is a measure of the precision of the test results and is used to indicate 1) the quality control of the concrete mixing; and 2) the variability of the strength test.

Figure 3.14 shows the histograms of constant CV intervals and the cumulative distribution function for both the compressive and flexural strength tests. From the cumulative percentage curves alone (Figure 3.15), it can be seen that 80 percent of all the compressive strength test pairs had a CV less than 6.6 percent, which is the precision required in ASTM C39. Of the flexural strength test pairs, 70 percent had a CV less than 7.0 percent, which is the CV reported from the multilaboratory data study in ASTM C 78.

Statistically, the compressive strength test had less variability than the flexural strength test. For example, 68 percent of the compressive test pairs and 58 percent of the flexural strength test pairs had a CV less than 5 percent, as shown in Table 3.12. It should be noted that the CV requirements for the compressive strength test (ASTM C 39) (*26*) and the flexural strength test (ASTM C 78) (*25*) were derived from conventional Portland cement, not high early strength cement concrete.

The compressive strengths ranged from less than 10 to 80 MPa measured over time and across all mixes. The flexural strengths ranged from 1 to 9 MPa over time and across all mixes. Figure 3.16 shows the variation versus strength of each test pair and indicates that no correlation exists between the variability and strength level, although some authors have reported that the variation increases with strength.(*39*) No apparent correlation was found between the variability of the strength test pair and the curing regimes of the specimens either, as shown in Figure 3.17.

However, variability of the tests is very different among the specimens with different cements, as shown in Figure 3.18. No data is available in this study to attribute test variability to inherent material variability in the lab or difference in the casting uniformity.

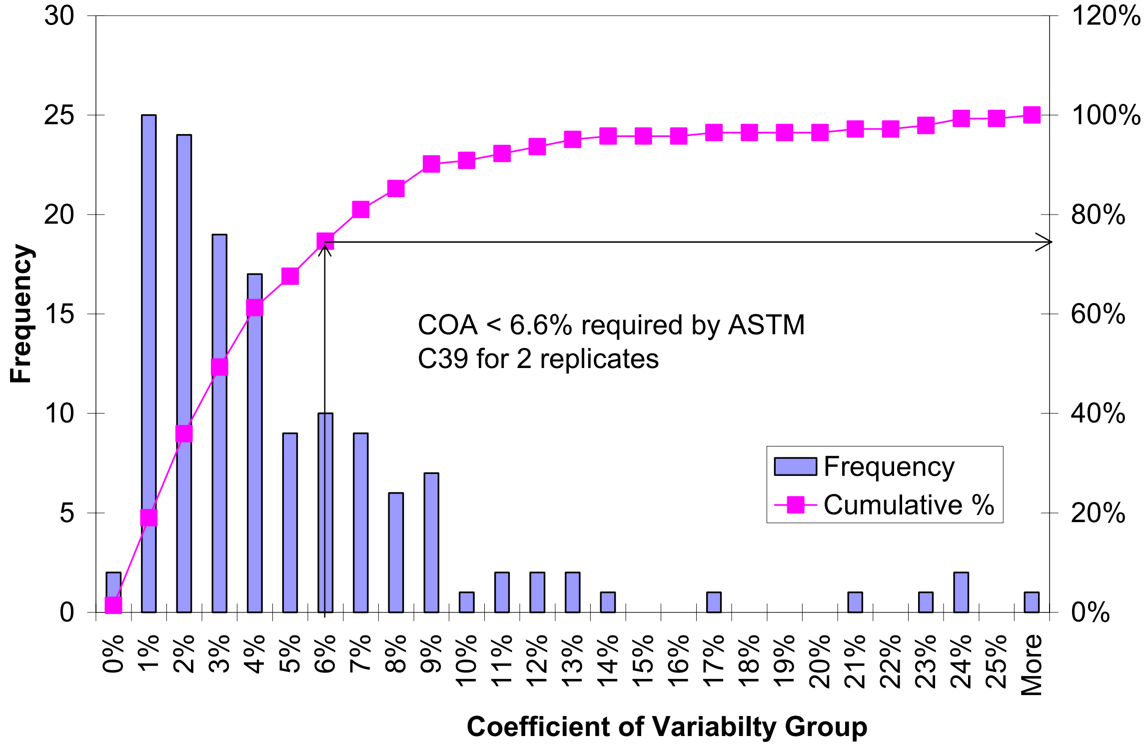

Figure 3.14a. Compressive strength.

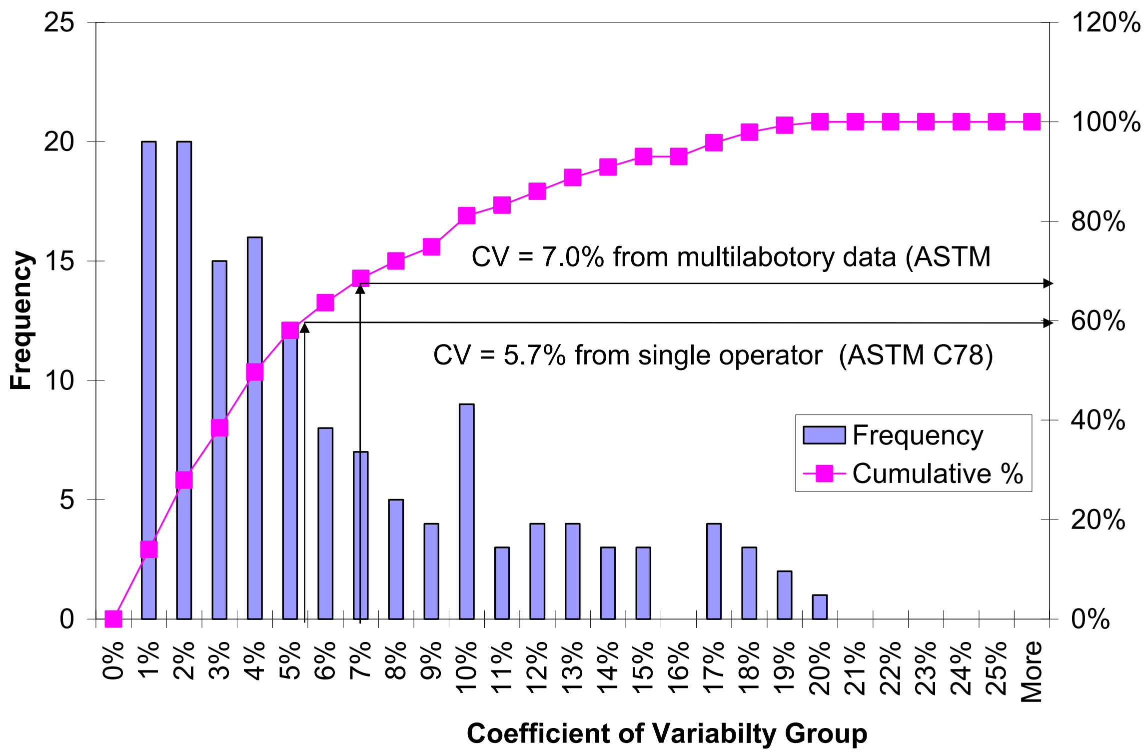

Figure 3.14b. Flexural strength.

Figure 3.14. Histogram of constant coefficient of variation intervals and cumulative distribution function for flexural and compressive strength tests.

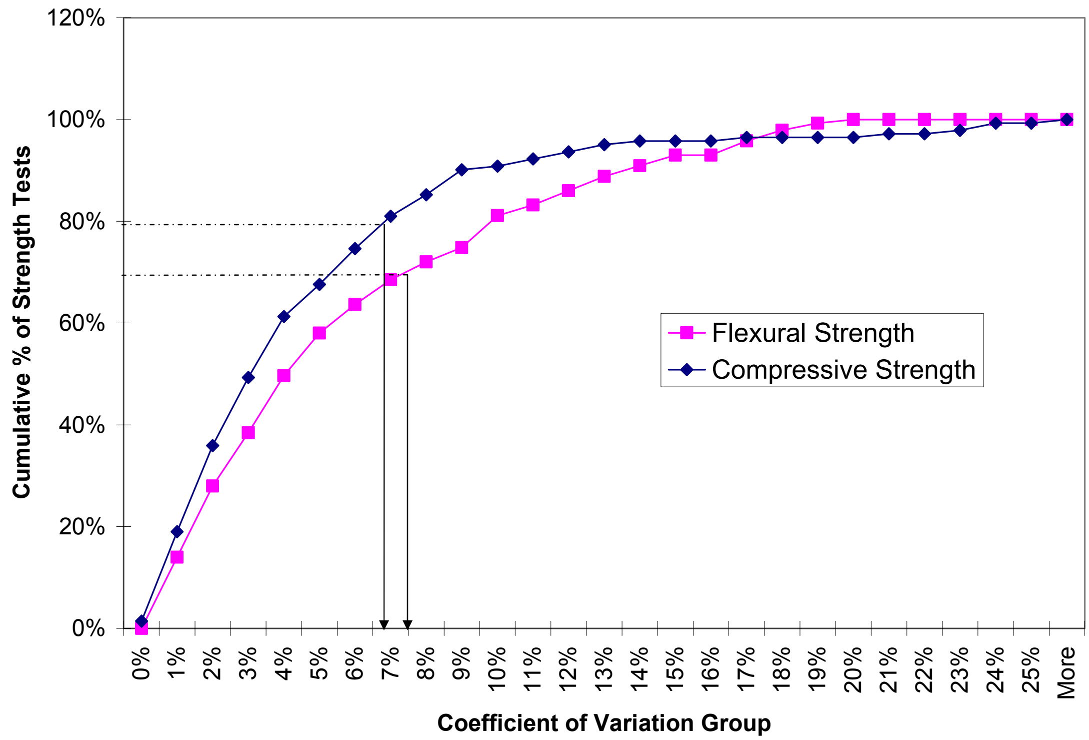

Figure 3.15. Comparison of the cumulative distribution for compressive and flexural strength tests.

3.5.2 Correlation between Tensile (Flexural) and Compressive Strength

It is known that the compressive strength and tensile strength are closely related. Both characteristics are functions of cement type, aggregate type, and mix design. However, there is no direct proportionality between the two tests.(*33*)

Figure 3.19 shows a plot of the average flexural strengths versus compressive strengths, including all the curing ages and curing conditions. The general trend is that greater compressive strength indicates greater tensile strength, however, a great deal of variability exists in this relationship. For example, the regression shown in Figure 3.19 using a power relation has an R-squared value of 0.6. This is in part due to the different effects of strength parameters of various conditions: mix design, curing age, and curing condition.

Table 3.12 Coefficient of Variation of the Strength Tests

CV	Flexural Strength		Compressive Strength	
	Number of Tests	**Cumulative %**	**Number of Tests**	**Cumulative %**
0%	0	.00%	2	1.41%
1%	20	13.99%	25	19.01%
2%	20	27.97%	24	35.92%
3%	15	38.46%	19	49.30%
4%	16	49.65%	17	61.27%
5%	**12**	**58.04%**	**9**	**67.61%**
6%	8	63.64%	10	74.65%
7%	7	68.53%	9	80.99%
8%	5	72.03%	6	85.21%
9%	4	74.83%	7	90.14%
10%	**9**	**81.12%**	**1**	**90.85%**
11%	3	83.22%	2	92.25%
12%	4	86.01%	2	93.66%
13%	4	88.81%	2	95.07%
14%	3	90.91%	1	95.77%
15%	**3**	**93.01%**	**0**	**95.77%**
16%	0	93.01%	0	95.77%
17%	4	95.80%	1	96.48%
18%	3	97.90%	0	96.48%
19%	2	99.30%	0	96.48%
20%	**1**	**100.00%**	**0**	**96.48%**
21%	0	100.00%	1	97.18%
22%	0	100.00%	0	97.18%
23%	0	100.00%	1	97.89%
24%	0	100.00%	2	99.30%
25%	**0**	**100.00%**	**0**	**99.30%**
More	0	100.00%	1	100.00%

Figure 3.20 shows the same data divided into 3 groups by curing condition. It is clear that compared to the Standard curing regime, the Dry curing regime affected the flexural strength more than the compressive strength. Figure 3.21 shows the data divided into 6 groups by mix. Except for the Type I/II mix, the mixes all followed the general rule that flexural strength increases with compressive strength.

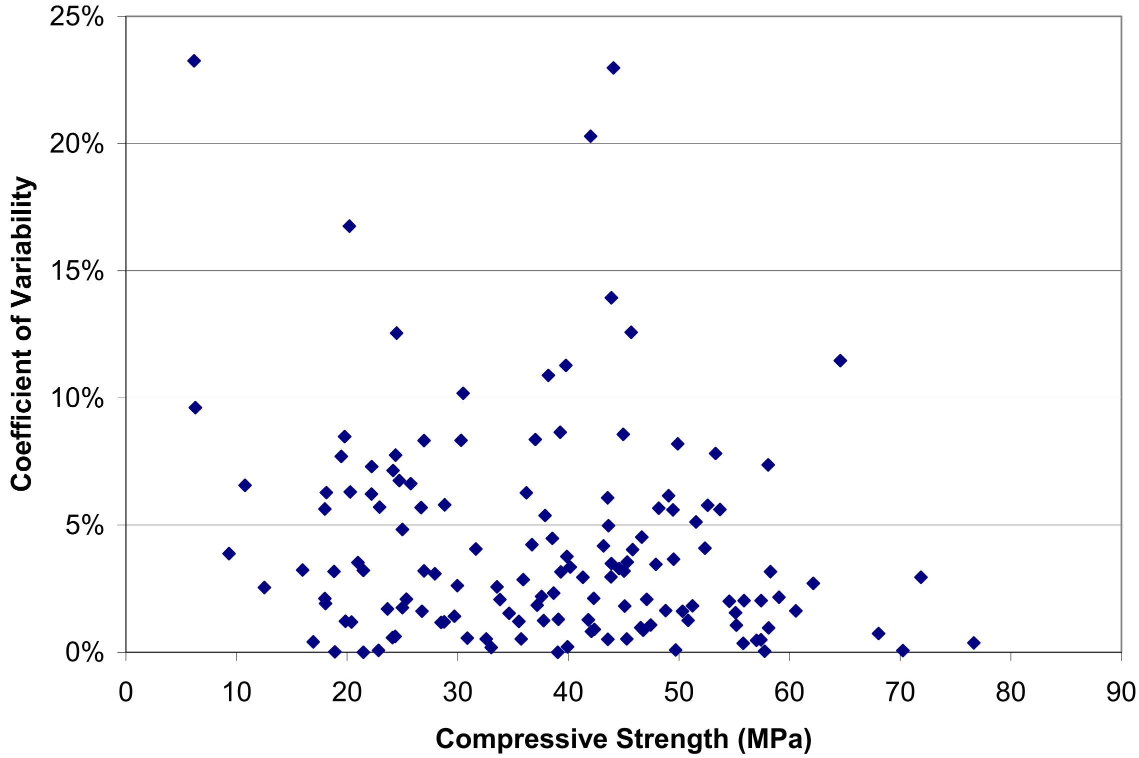

Figure 3.16a. Compressive strength.

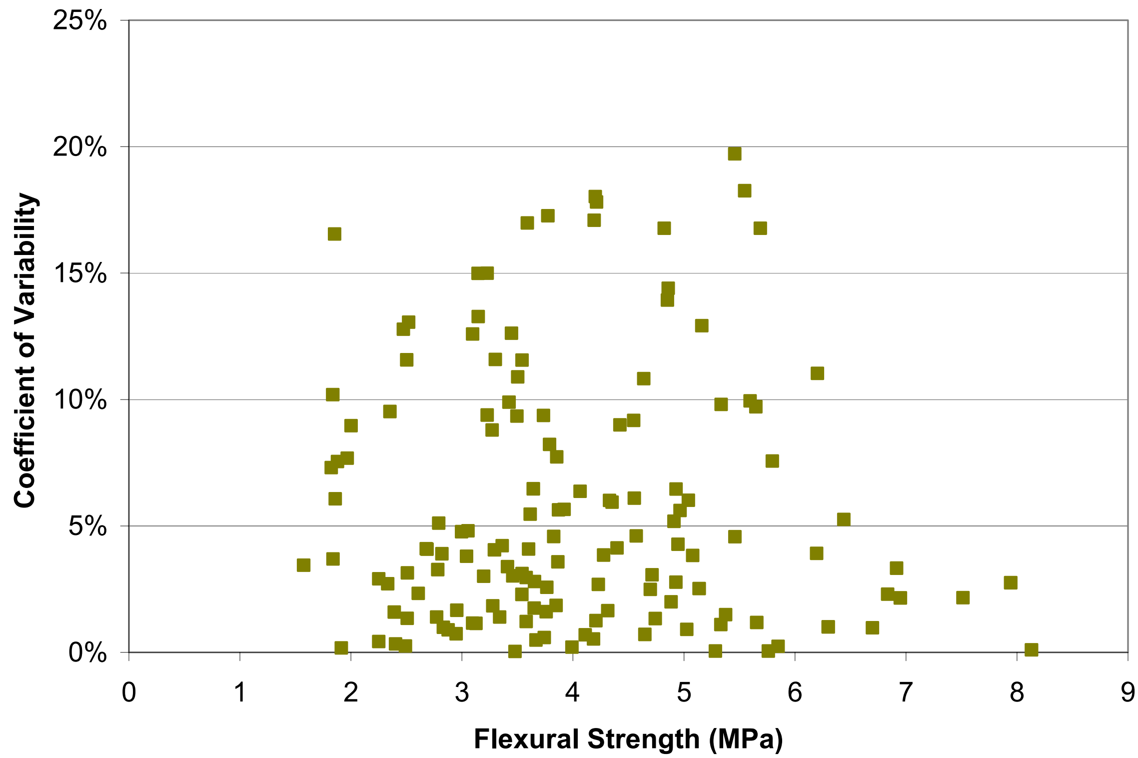

Figure 3.16b. Flexural strength.

Figure 3.16. Variation of results versus measured strength for compressive and flexural strength tests.

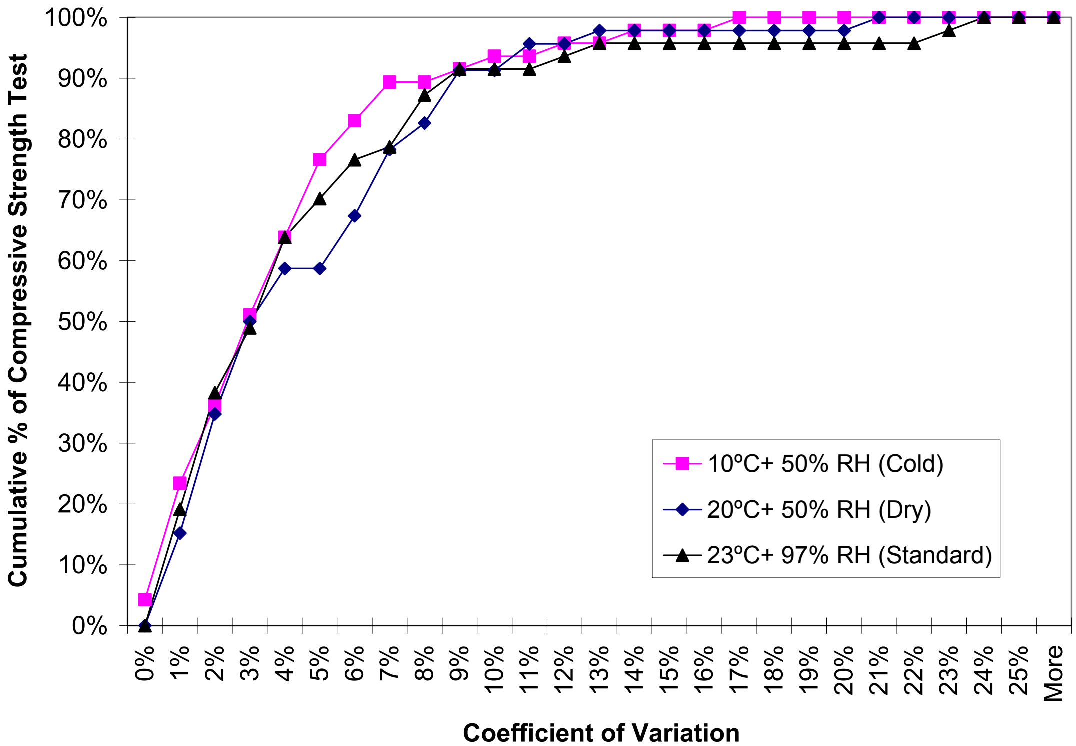

Figure 3.17. Compressive strength test variability by curing condition.

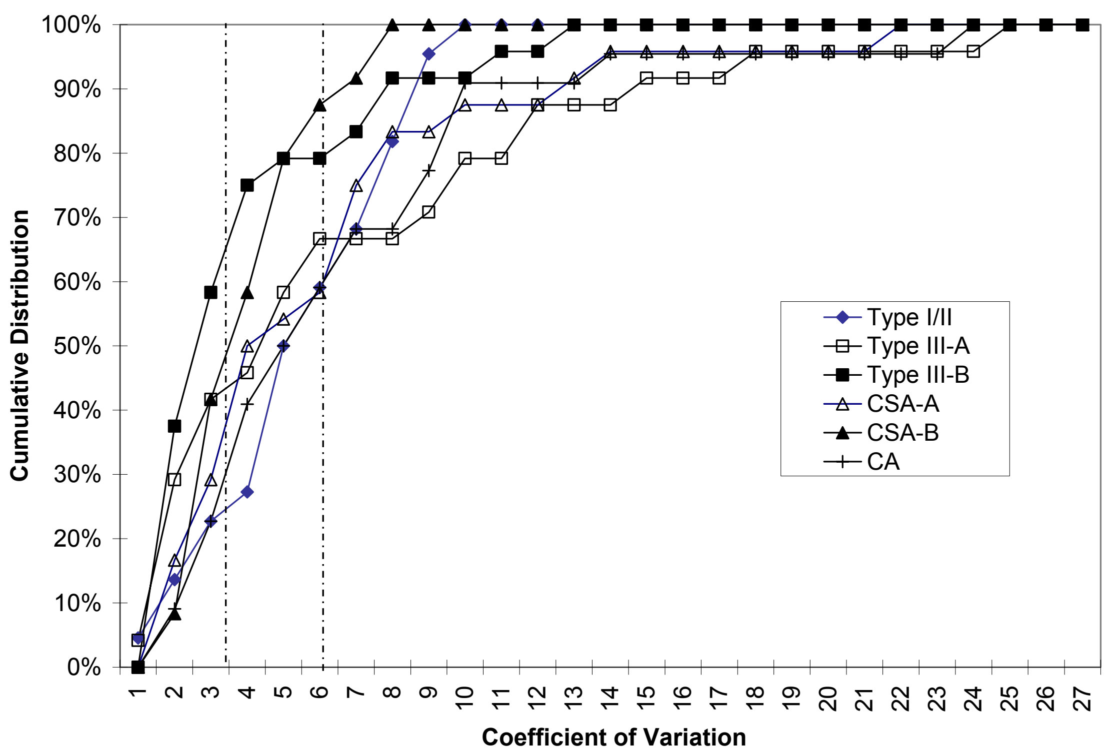

Figure 3.18. Flexural strength test variability by cement type.

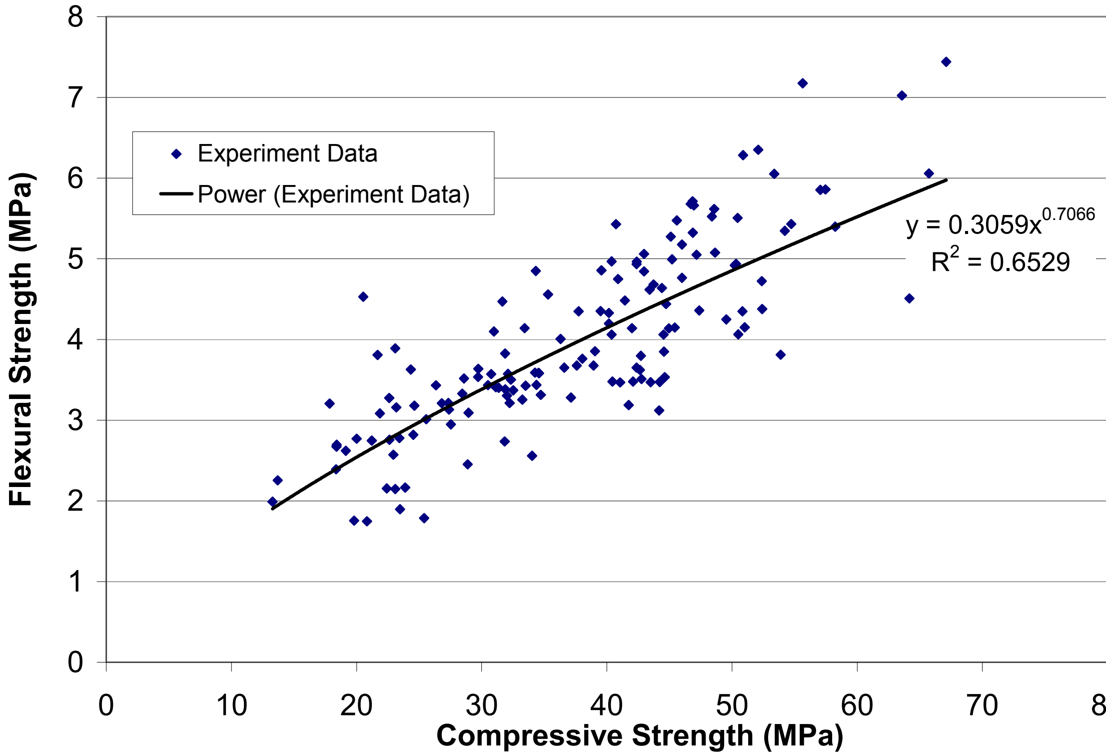

Figure 3.19. Correlation of compressive strength and flexural strength test results.

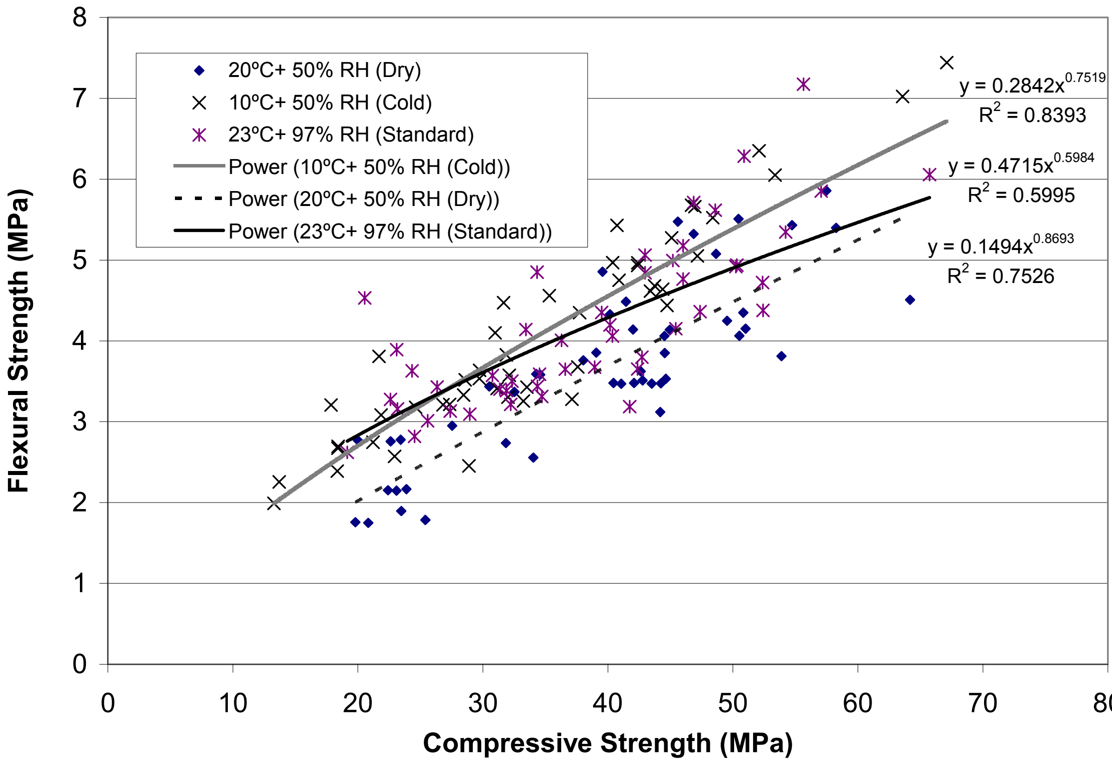

Figure 3.20. Correlation of compressive strength and flexural strength test results by curing condition.

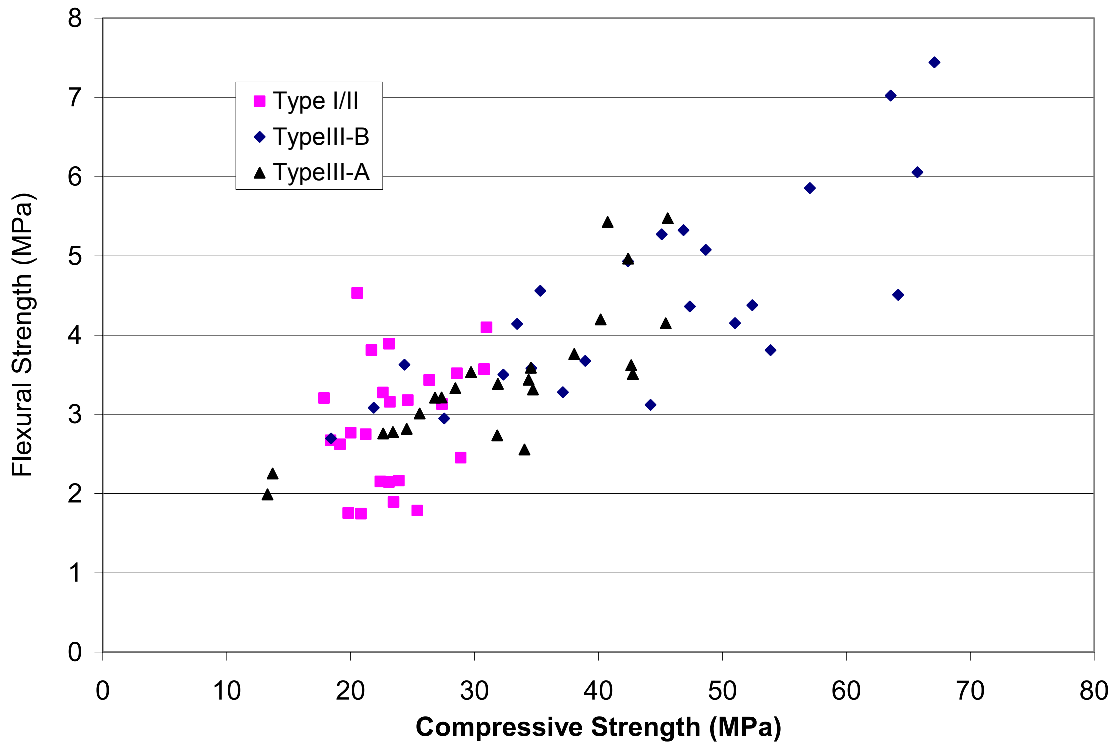

Figure 3.21a. Portland cements (Type I/II, Type III-A, and Type III-B).

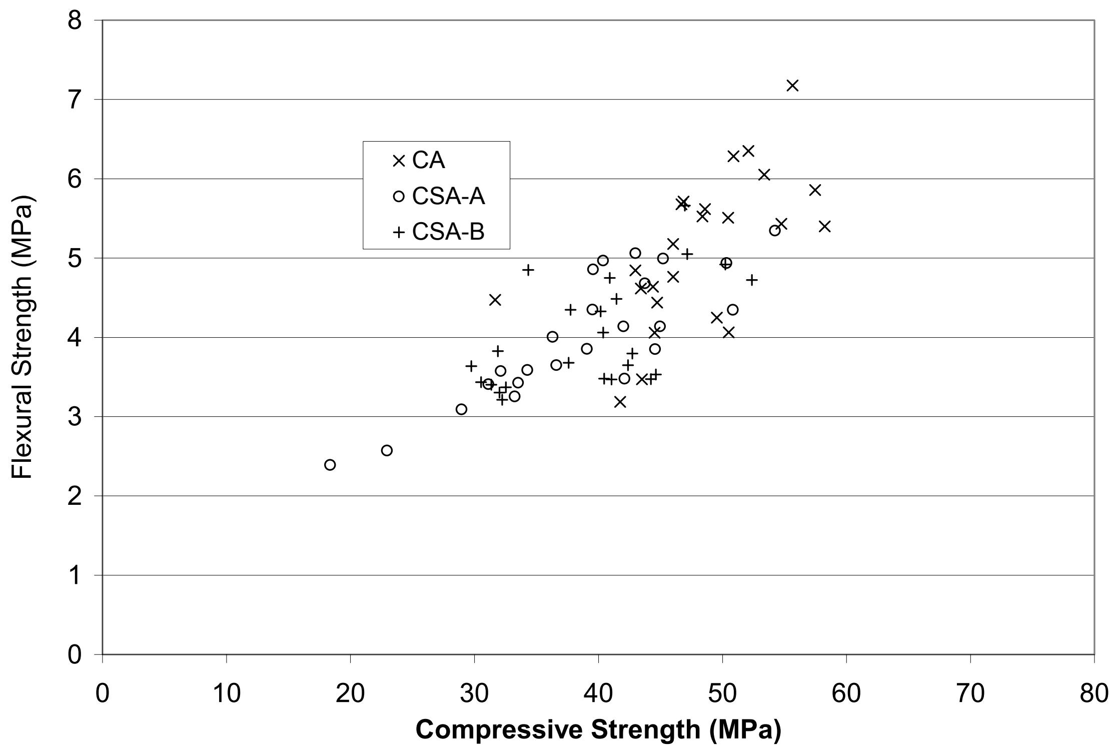

Figure 3.21b. Calcium Sulfoaluminate (CSA-A, CSA-B) and Calcium Aluminate (CA).

Figure 3.21. Correlation of concrete compressive strength and flexural strength test results by cement type.

Although no unique correlation exists among the two strengths, the tensile strength (f_t) has been related to compressive strength (f_c), and for portland cement mixes, it ranged between a lower limit $f_t = 0.95(f_c/10)^{2/3}$ and an upper limit $f_t = 1.85(f_c/10)^{2/3}$.(*40*) Figure 3.22 shows that most of the data from this study fall between the two limits.

Generally, the tensile strength (herein referred to as flexural strength) increased with the compressive strength, but non-linearly and at a lower rate. In other words, the greater the compressive strength, the lower the tensile/compressive strength ratio. The ratio is determined by various factors that affect both the concrete matrix and the transition zone. Figure 3.23 shows the flexural/compressive ratio with compressive strength for all data grouped by curing regime. The data indicate the overall trend of a reduced tensile/compressive strength ratio with increased compressive strength level, especially for those data obtained from the specimens in the Standard

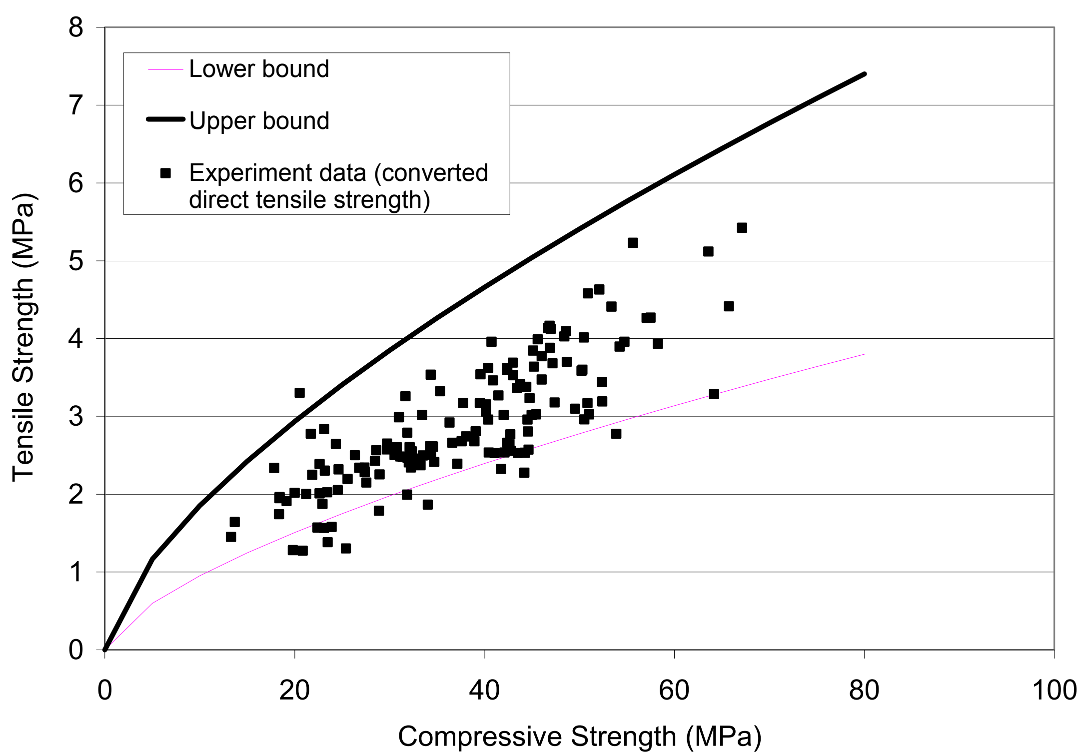

Figure 3.22. Estimation of tensile strength from compressive strength test results.

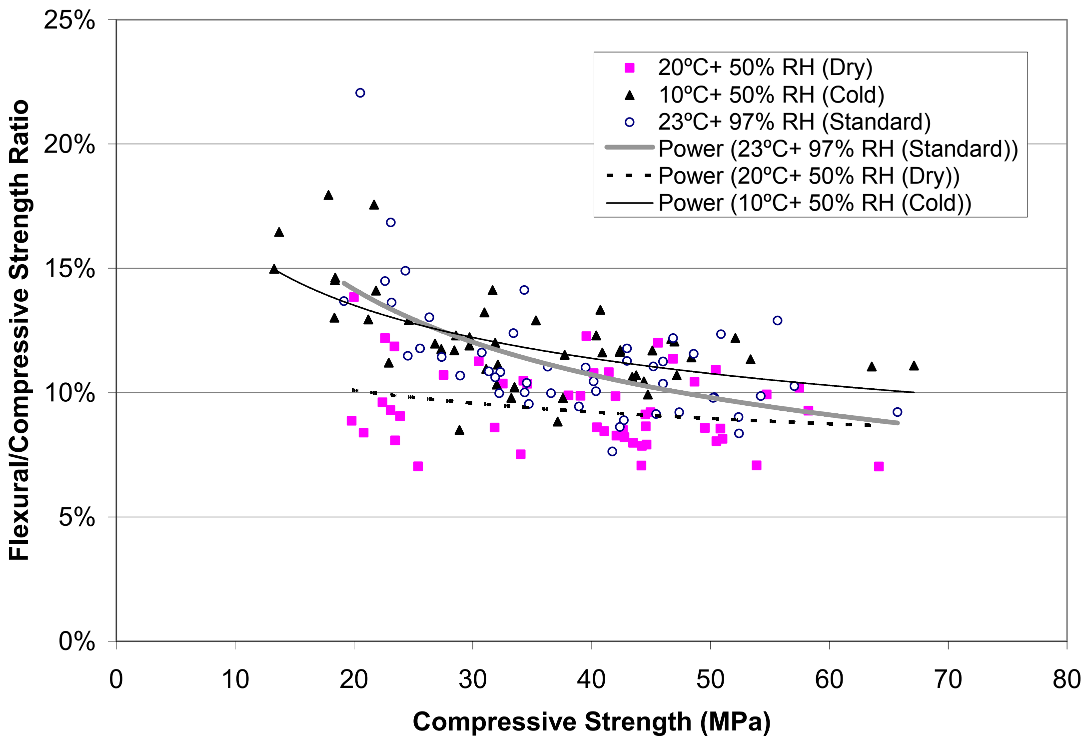

Figure 3.23. Ratio of flexural to compressive strength for a range of compressive strengths.

curing regime (23ºC + 97% RH) and the Cold regime (10ºC + 50% RH). The tensile/compressive strength ratio from the Standard and Cold regimes varied from 10 to 15 percent (note that flexural strength is greater than direct tensile strength). However, the data obtained from the Dry curing regime (20ºC + 50% RH) does not appear to follow this trend and the ratios as a whole were lower than those from the Standard and Cold curing regimes. The early drying shrinkage and the shrinkage gradient in the Dry curing regime had a stronger effect on flexural strength than on compressive strength, which resulted in the lower ratio. It is possible that this early detrimental effect is much greater for flexural strength than compressive strength so that the flexural strength is low regardless of compressive strength, resulting in poor correlation between the tensile/compressive strength ratio and the compressive strength.

3.6 Prediction of Modulus of Elasticity from Compressive Strength

ACI building Code 318-99 (*41*) provides a correlation that has the elastic modulus E_c proportional to the compressive strength f_c (28-day strength) raised to the power 0.5:

- for concrete density w_c between 1500 and 2500 kg/m^3, $E_c = 0.043 w_c^{1.5}\sqrt{f_c}$ (MPa)
- for normal weight concrete, $E_c = 4700\sqrt{f_c}$ (MPa)

Figure 3.24 shows the measured E_c versus E_c calculated by f_c at 28 days, according to the correlation given in ACI -318 for normal weight concrete. The Standard curing regime (23ºC + 97% RH) resulted in a good fit. From the non-standard curing conditions, the tested results deviated from the predicted values.

At other curing ages, however, such a correlation doesn't necessarily exist. It is known that the strength and the modulus of elasticity are not influenced by curing age to the same

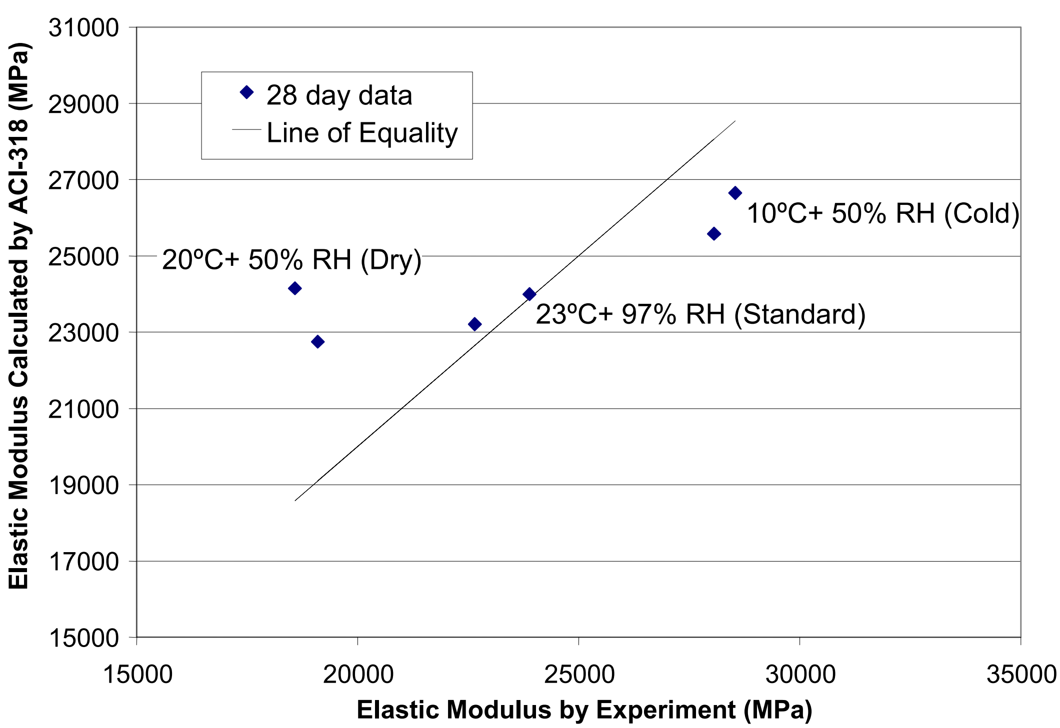

Figure 3.24. Compressive strength and modulus of elasticity at 28 days.

degree (*33*), and at later ages (from three months to one year) the elastic modulus increases faster than compressive strength. Figure 3.25 shows the data from this study obtained from early age up to 90 days, in which each compressive strength and elastic modulus was normalized to the initial measurement. The data points of each mix were from different curing ages, connected by solid lines in sequence. It is clear that the development of the elastic modulus with curing age did not follow the compressive strength, and the two properties do not have a unique correlation. The relationship among them depend on both the age and cement type. It is possible that the chemical interactions between the cement pastes and aggregates in the transition zone vary for different cement types and curing ages.

In summary, the estimation of the elastic modulus from compressive strength by ACI-318, or vice versa, is only valid for 28-day strength and the standard curing regime, and it should

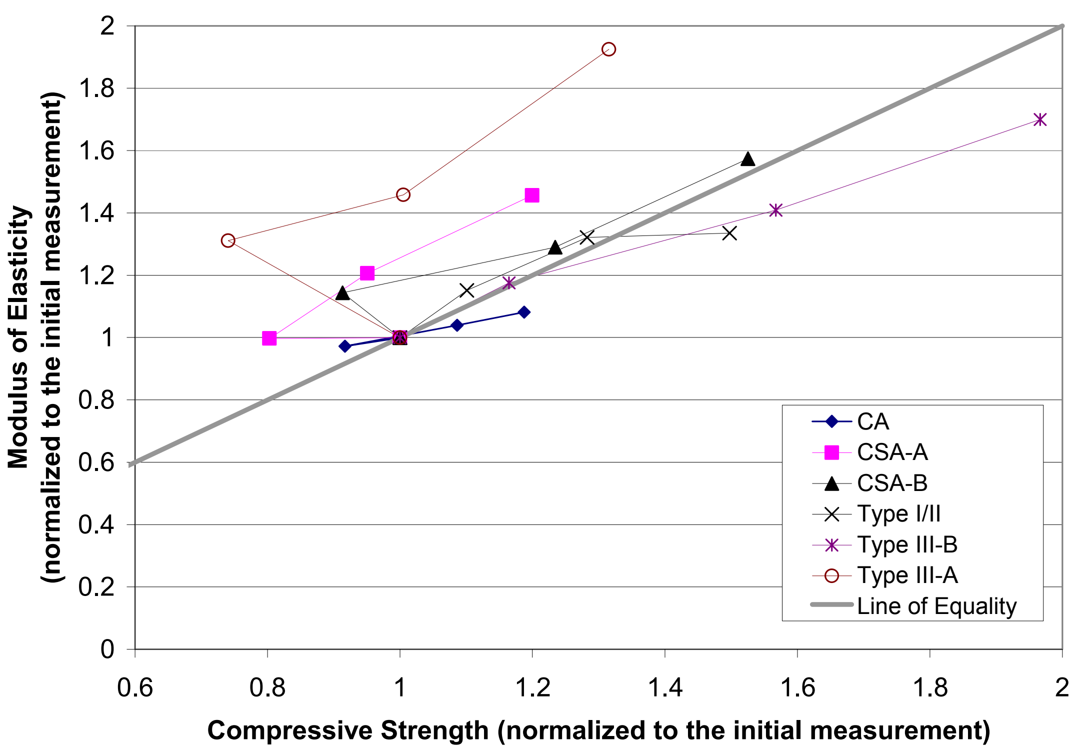

Figure 3.25. Compressive strength and modulus of elasticity by specimen age.

not be used at other ages and for other curing conditions. This is important because the elastic modulus is a key variable for calculating slab stresses due to differential shrinkage (warping) and temperature gradient (curling) for early-age cracking.

3.7 Importance of Variables for Strength Development

From the data developed in this study, it is clear that both compressive and flexural concrete strength are influenced by the coupled effects of cement type, curing regime, and specimen age, and that these couplings become more complicated when the variable of water/cement ratio is added. A statistical sensitivity analysis was performed to better understand the importance of these factors in the strength development and to evaluate each factor level. The analysis was performed using the statistical software S-Plus.

Figure 3.26 shows the overall sensitivity analysis of the compressive and flexural strength to the variables in this study: water/cement ratio, cement type, and curing regime. The long horizontal bar in this figure and similar figures that follow is the average strength from all data. Each vertical bar represents a variable for analysis, labeled on the horizontal axis. Each short horizontal bar on the vertical bars represents the mean value of the data for that factor level. The length of the vertical bars gives the range of values by changing the factor levels inside a variable. The wider the range, the more sensitive the strength is to that variable.

Overall observations shown in Figure 3.26 are as follows:

1. Cement type is the single biggest factor for the strength development, followed by curing regime and water/cement ratio.
2. The average strength level ranks the same for compressive and flexural strength **CA> Type III-B>CSA-B≅CSA-A>Type III-A>Type II.**

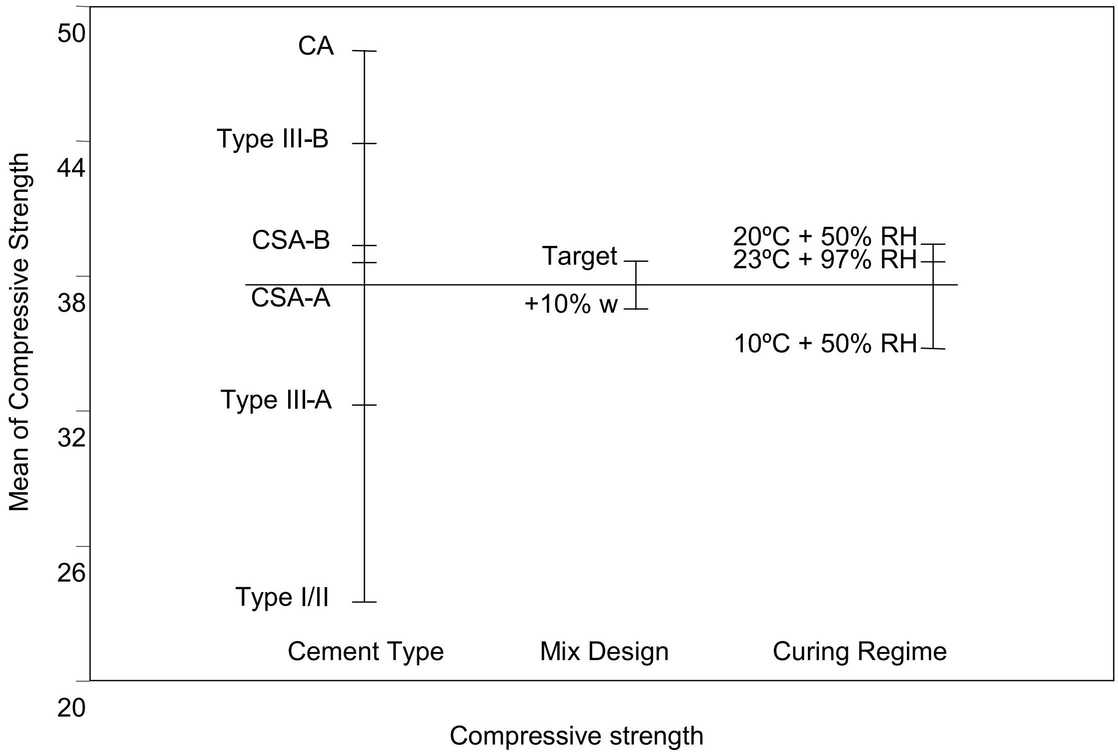

Figure 3.26a. Compressive strength.

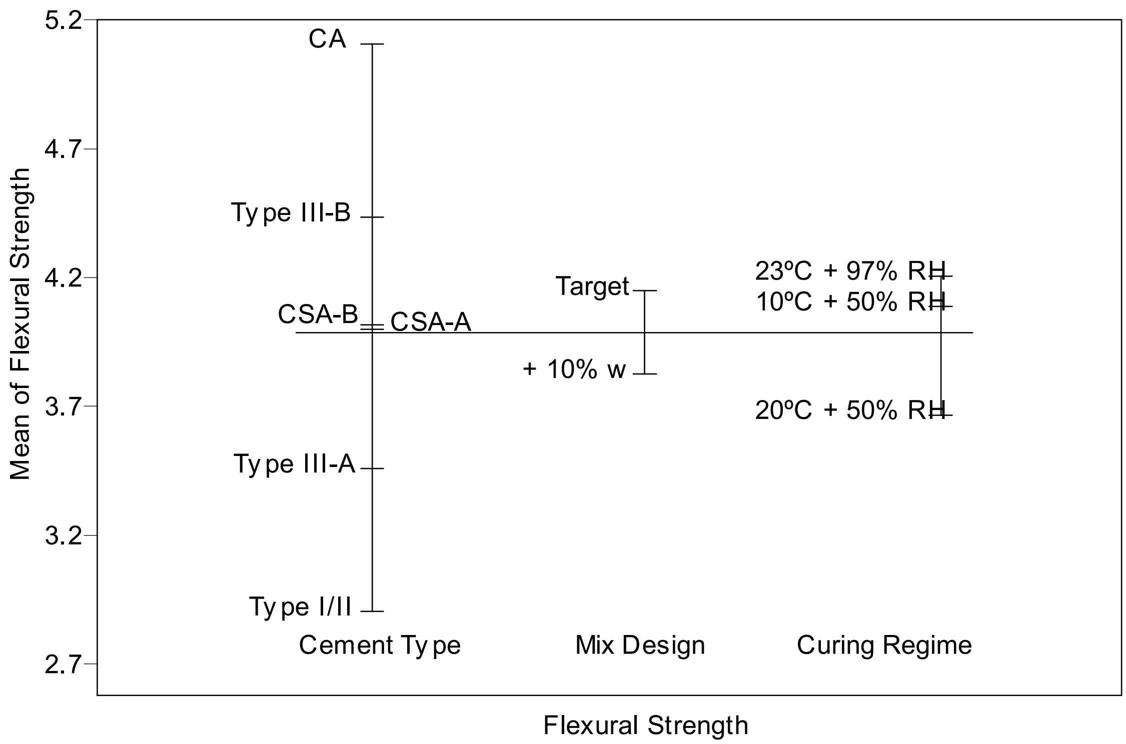

Figure 3.26b. Flexural strength.

Figure 3.26. Factors analysis for compressive (a) and flexural (b) strength development.

3. The flexural strength is somewhat more sensitive to an increase in the water/cement ratio than compressive strength.
4. The curing regimes have different effects on the compressive and flexural strengths. On average, the Dry regime (20ºC + 50% RH) is the most detrimental for flexural strength, while the Cold regime (10ºC + 50% RH) is the most detrimental for compressive strength.

Figure 3.27 shows in detail how the curing type, water/cement ratio, and age affect the flexural strength for each cement type. It can be seen that age is the most important factor in the strength development for each of the cements, with the exception of Type I/II. Particularly notable are the following qualitative observations:

1. The Type I/II mix is more sensitive to curing regime than curing age. Two possible reasons for this are, a) the overall strength level is low for this concrete so that the difference in strengths over age is not as significant; b) the 15 percent fly ash content made this concrete more sensitive to the curing regime.
2. Among the six mixes, the CA mix is most sensitive to water/cement ratio.
3. Among the six mixes, the Type III-A mix is least sensitive to curing regime.

Figure 3.28 shows the sensitivity of the flexural/compressive strength ratio to cement type, curing regime, and water/cement ratio. The flexural/compressive strength ratio is most sensitive to curing regime, then cement type, and then least sensitive to water/cement ratio. The Cold curing regime resulted in a larger flexural/compressive strength ratio, and the Dry regime resulted in a smaller flexural/compressive strength ratio, as the curing condition ranked as follows in favor of the ratio:

10ºC + 50% RH > 23ºC + 97% RH > 20ºC + 50% RH
Cold > Standard > Dry

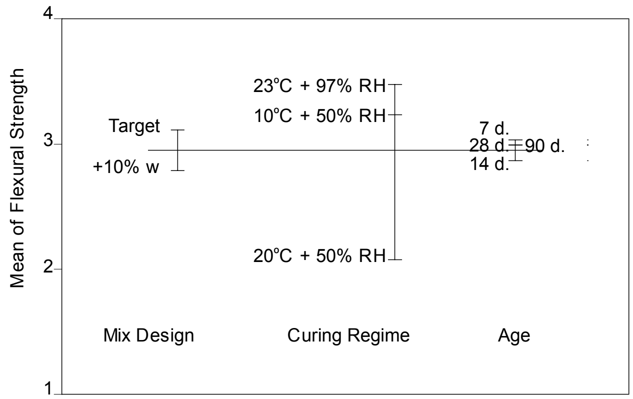

Figure 3.27a. Type I/II Portland cement.

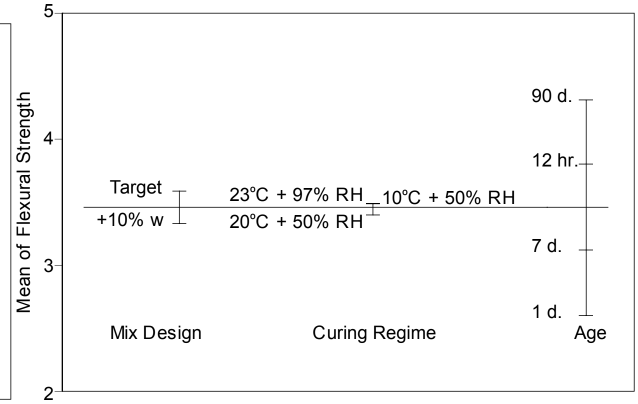

Figure 3.27b. Type III-A Portland cement.

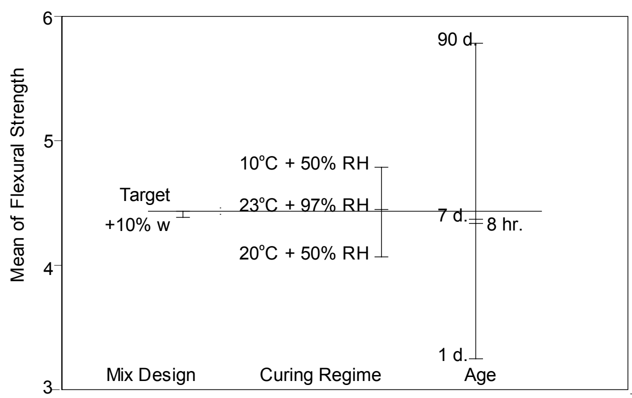

Figure 3.27c. Type III-B Portland cement.

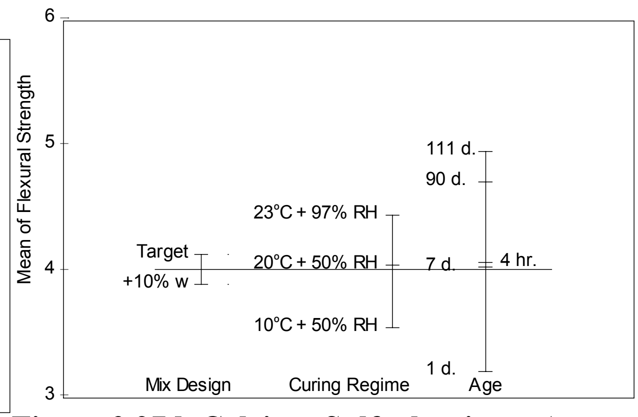

Figure 3.27d. Calcium Sulfoaluminate A (CSA-A)

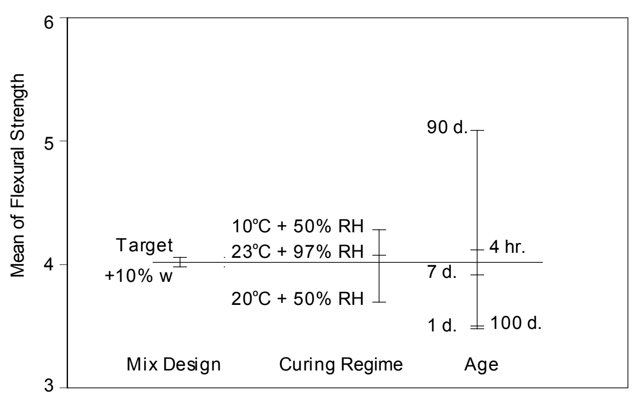

Figure 3.27e. Calcium Sulfoaluminate B (CSA-B).

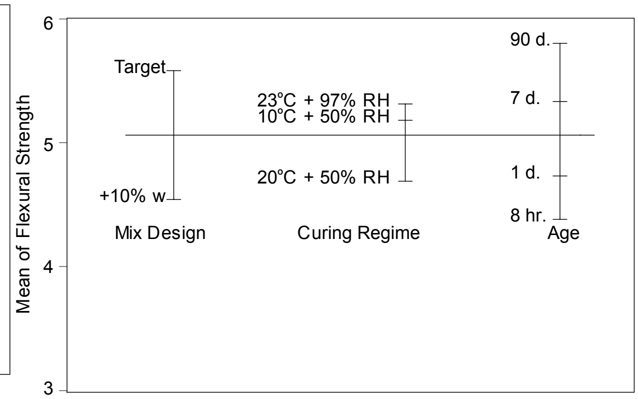

Figure 3.27f. Calcium Aluminate (CA).

Figure 3.27. Factors analysis for flexural strength development for all cement types.

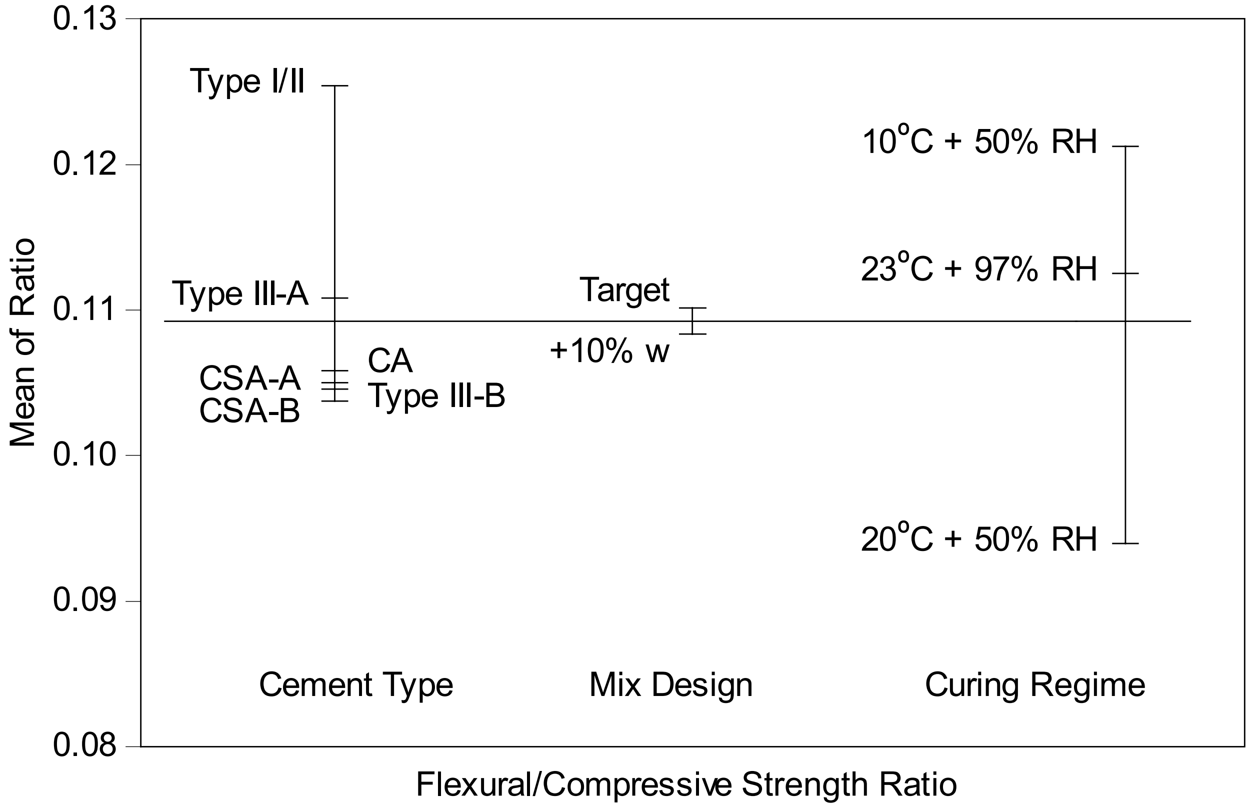

Figure 3.28. Factors analysis for the flexural/compressive strength ratio.

3.8 Conclusions

The following conclusions can be drawn from the results presented in this chapter:

1. Among the variables of cement type, curing condition, and water/cement ratio, the cement type is the factor that most affects both compressive and flexural strength.
2. After cement type, the strength is influenced most by curing age, followed by curing regime and water/cement ratio.
3. The Dry curing regime is more detrimental to flexural strength than compressive strength because of the tensile stresses developed as a result of a drying shrinkage gradient in the beam.

4. The flexural strength is less under the dry curing environment than under the moist curing environment.
5. A universal correlation does not exist between compressive strength and flexural strength but depends primarily on concrete mix and curing regime. However, there is a bounded correlation. Although the compressive strength test had less variability than the flexural strength test, the coefficients of variation were similar. Therefore, continued use of the flexural test for pavement design and quality control is recommended because the compression does not measure the strength properties controlling performance (tension) and not much is gained from using the compression test in terms of reduced variability.
6. The elastic modulus and the compressive strength can be related by ACI-318,(*41*) but only for 28-day data and for portland cement mixes under standard curing conditions. The correlation at 28 days for non-portland cement was not examined as part of this study and needs further investigation. The correlation given by ACI-318 is not intended for other ages of concrete or other curing conditions, as confirmed by the data produced by this study.

4.0 SHRINKAGE TEST RESULTS

The objective of this part of the study is to evaluate the free shrinkage of the concrete mixes and to characterize the influence of certain basic parameters of this deformation. Drying shrinkage, the most common reason for dimensional changes in concrete, is due to the loss of water from the mix to the surrounding environment. This deformation, when restrained, can lead to cracking of concrete pavement, especially at early ages when the tensile strength has not sufficiently developed to resist the shrinkage-induced tensile stress. The drying shrinkage characteristics must be known and understood for a candidate concrete mix in order to properly design concrete pavements. Drying shrinkage characteristics are used with the strength gain properties to evaluate the risk of early-age cracking, and used with strength and traffic load to evaluate long term cracking risk.

The cementitious materials included in this study may be classified into three categories: portland cements and blends, calcium aluminate cements and blends, and calcium sulfoaluminate cements. Since many of the cementitious materials under consideration have not been used extensively for pavement construction in the United States, it is essential to characterize their dimensional stability under various exposures. In this study, the six concrete mixes were designed to achieve the target flexural strength at the specified age. The mix design variables were: cement type, water/cement ratio, cement content, aggregate, aggregate cement ratio (volumetric ratio), chemical admixtures. As these mix designs were "optimized" to meet a target strength at a particular age, their dimensional stability needs to be addressed in order to have a comprehensive evaluation of their application to concrete pavement construction. In order to simulate the various climatic exposures, four curing regimes were used to represent variations in both moisture and temperature (Table 2.7). The correlation of drying shrinkage with environmental moisture content is well understood in the literature, but the temperature dependency of shrinkage is rather unsystematic, and seems to depend on the cement type used.(*42*)

In this chapter, the experiment results for each mix design are presented first, with the discussion focused on the how the curing regimes and water/cement ratio influence both the early dimensional change and development of drying shrinkage. For this purpose, both the mortar shrinkage and concrete shrinkage are presented for each concrete mix. The mix designs under each curing condition are then compared against each other. Finally, the effects of the mix and curing variables are evaluated for their statistical significance, and conclusions and recommendations are presented.

4.1 Basic Principles of Shrinkage

Shrinkage after hardening of concrete is defined as the decrease of concrete volume caused by changes in the moisture content of concrete and physico-chemical changes, without stress attributable to actions external to the concrete (ACI-209R).(*43*) The total shrinkage is made up of three kinds of shrinkage, as follows:

1. **Drying shrinkage.** When water moves out of a porous body which is not fully rigid, contraction takes place;(*35*)
2. **Autogenous shrinkage.** Contraction takes place in the volume of cement and water with the hydration process. For instance, the hydration products of portland cements have a volume about 7 percent less than the reagents.(*44*)
3. **Carbonation shrinkage.** Contraction takes place as the various hydration products are carbonated in the presence of CO_2.

It should be noted that the total measured dimensional change is called shrinkage in this report, meaning that it is the decrease in the volume in a controlled environment. No effort was made to differentiate between the drying shrinkage, autogenous shrinkage, and carbonation shrinkage.

Moisture and temperature are the two primary factors causing dimensional change in the concrete. The physical interaction of moisture content and concrete's volumetric change can be understood by looking at a few basic equations critical to the phenomenon. First the Kelvin equation provides the vapor pressure (relative humidity) above a meniscus in a cylindrical pore of radius *r* as:

$$\ln(RH) = \frac{-2\gamma V_m}{rRT} \qquad \textbf{(4)}$$

where *RH* is the relative humidity,
γ is the surface tension of the pore solution (N/m),
V_m is its molar volume (m^3/mol),
r is the radius of the largest water-filled cylindrical pore (m),
R is the universal gas constant (8.314 J/(mol·K)), and
T is absolute temperature (K).

This equation indicates that as internal relative humidity decreases, the surface tension will increase and, at a same relative humidity, as temperature increases, surface tension will increase. Note that the capillary tension, σ_{cap} (Pa), in the pore liquid is given by:

$$\sigma_{cap} = \frac{2\gamma}{r} \qquad \textbf{(5)}$$

So, as the water loss in concrete proceeds, the capillary tension increases, causing the solid phases in concrete to contract.

Besides the physical interaction of the moisture and the dimensional change, the chemical reactions under different moisture and temperature conditions also influence the dimension of a concrete.

4.2 Expansion at Three Days

Shrinkage specimens were cured under the four regimes shown in Table 2.7. They were first cured for three days in lime water at their respective curing temperatures (20, 23, 10, and 40ºC) before being placed under the curing regime.

At 20ºC, all six mixes except Type II exhibited expansion, as shown in Figure 4.1. The average expansion of the six mixes was less than 100 microstrain. The phenomenon of expansion at early age in portland cements is primarily caused by absorption of water by the Calcium silicate hydrates (C-S-H) hydration products and is well known. The water molecules act against the cohesive force of the cement and tend to force the gel particles farther apart resulting in an expansion pressure.(*35*) Powers explained that ingress of water also makes the surface tension of the gel decrease, which causes a further small expansion.(*44*) Internal pressure from the growth of the C-S-H network or the ettringite formation has also been proposed as a contribution to the expansion, for instance in the calcium sulfoaluminate cements.(*45*)

At 20ºC, the expansion ranks in the order:

Type II < Type III-A < CSA-B=CA < Type III-B < CSA-A

The CSA-A expanded the most because the major matrix material is ettringite, which is expansive. Comparing the two CSA cements, the CSA-B cement exhibited less expansion than the CSA-A, which may be caused by the difference in their chemical compositions. As shown in Table 2.2, the CSA-B has only two main compounds, $C_4A_3\overline{S}$ and C_2S, while the CSA-A has six compounds of C_2S, C_3S, C_4AF, C_3A, $C\overline{S}$, and $C_4A_3\overline{S}$. Hydration of C_2S produces less lime than C_3S (Equation 2 in Section 3.2). The ettringite formed under conditions of low alkalinity has been found to be not expansive,(*46*) which could explain why the CSA-B cement exhibited less expansion than CSA-A at three days.

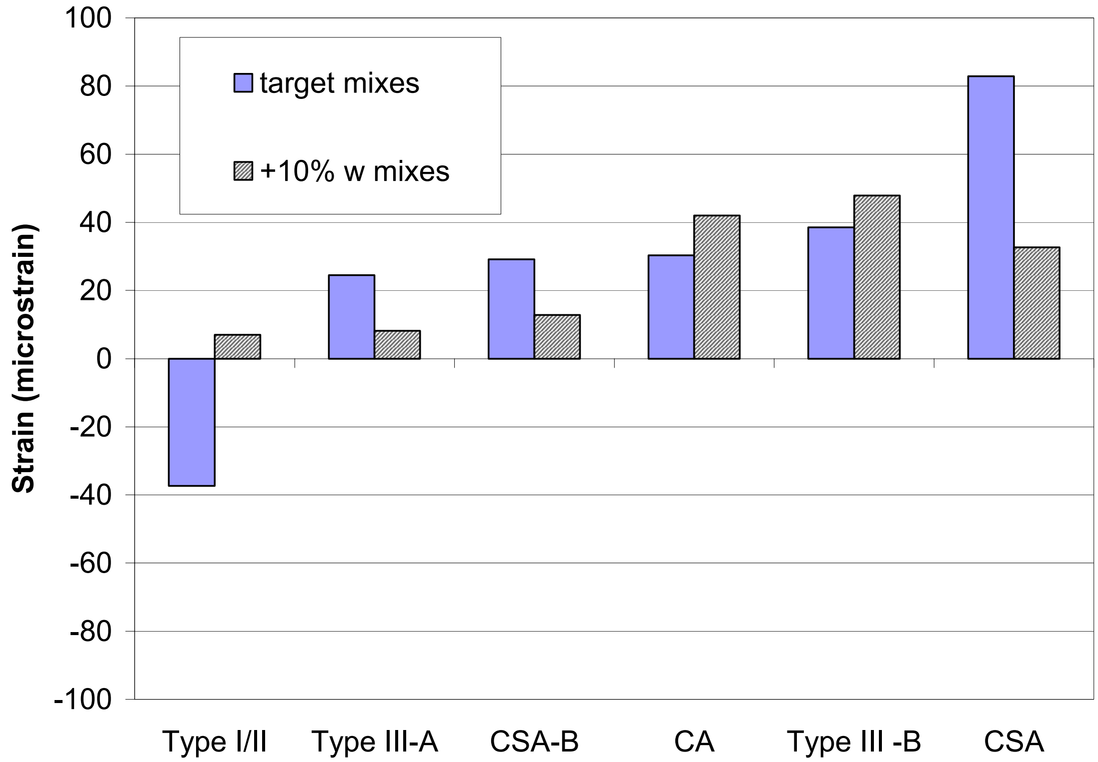

Figure 4.1. Expansion at 3 days, 20ºC.

Figures 4.2–4.7 show the dimensional change of the six mixes under each of the four curing regimes. The higher temperature of the (Hot curing regime) caused considerable expansion in all mixes. At 10ºC (Cold curing regime), all of the mixes contracted, indicating that the contraction caused by the lower temperature is greater than the expansion caused by ettringite formation. The volume change of the concretes at this age came both from the thermal effect and the moisture diffusion between the capillary pores and the gel.

When a concrete is heated, the expansion pressure is increased as the capillary surface tension is decreased, and the expansion effect overcomes the contraction by loss of the gel water. When the concrete is cooled, the contraction by the diffusion of the capillary water to the gel pore overcomes the gel expansion by absorption of water.(*35*)

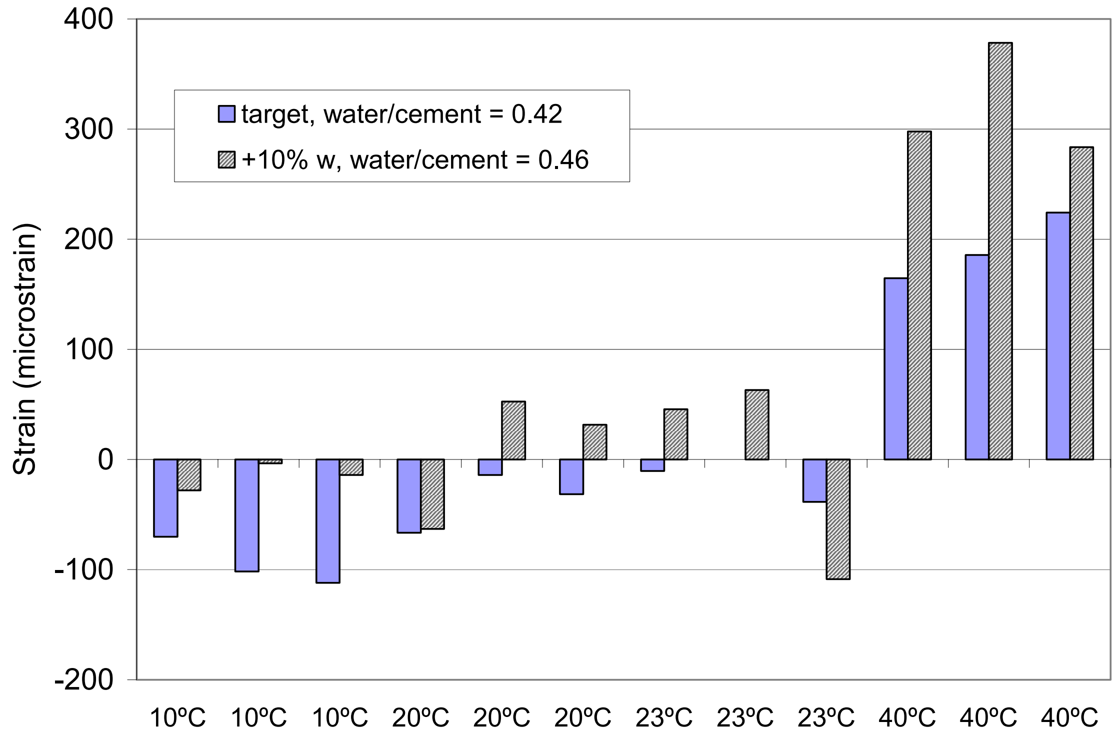

Figure 4.2. Dimensional change of Type I/II portland cement at 3 days for all curing regimes.

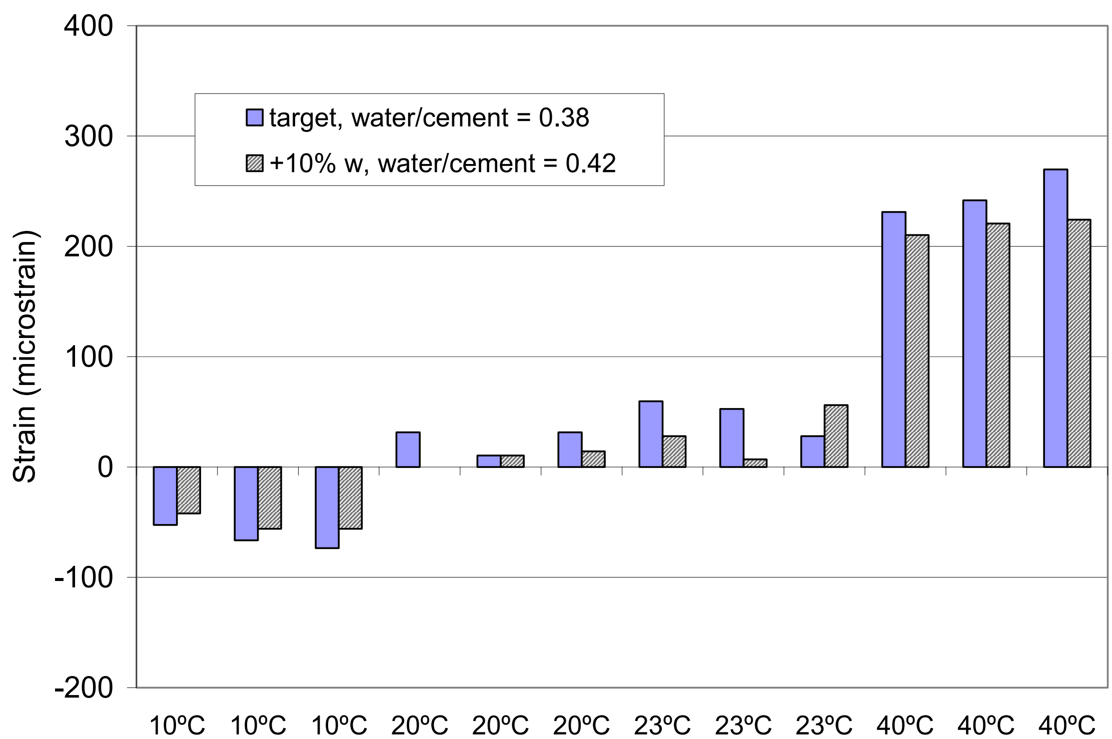

Figure 4.3. Dimensional change of Type III-A portland cement at 3 days for all curing regimes.

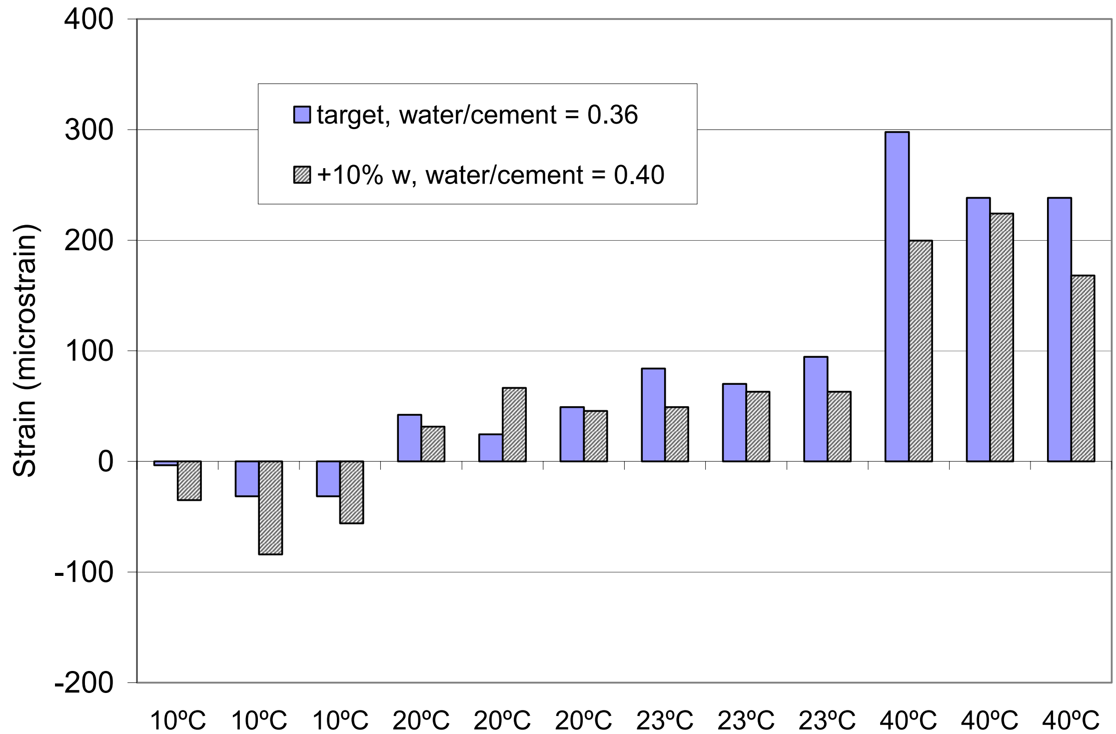

Figure 4.4. Dimensional change of Type III-B portland cement at 3 days for all curing regimes.

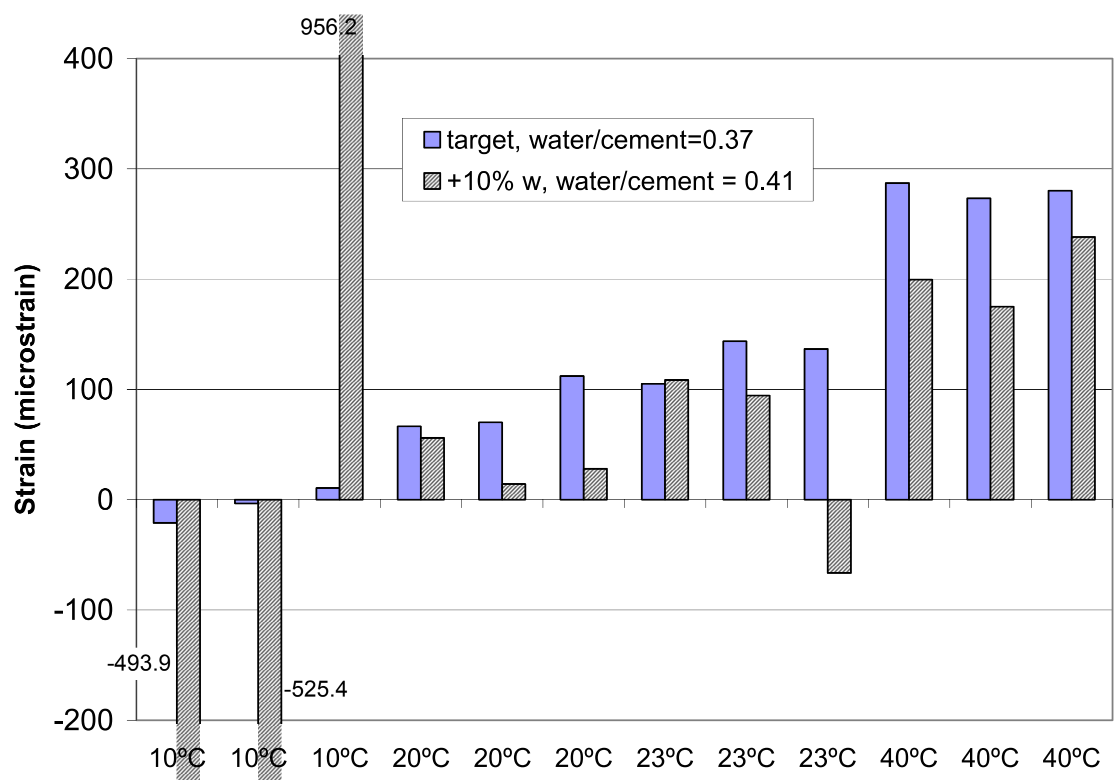

Figure 4.5. Dimensional change of Calcium Sulfoaluminate cement – A (CSA-A) at 3 days for all curing regimes.

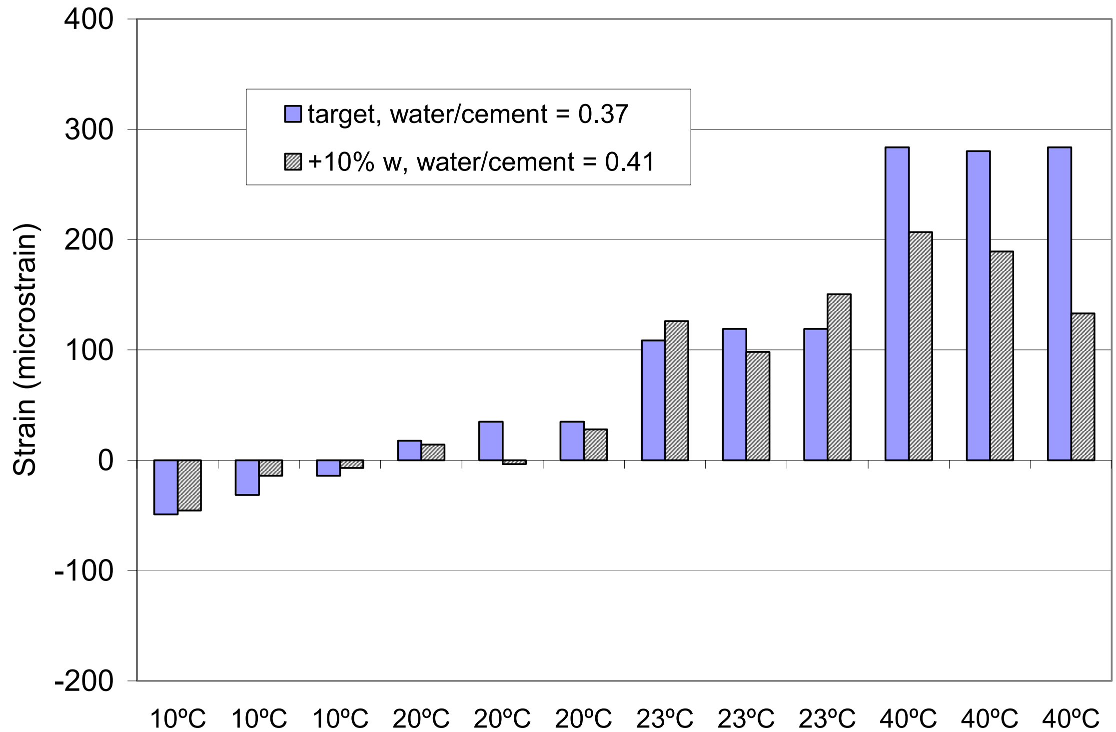

Figure 4.6. Dimensional change of Calcium Sulfoaluminate cement – B (CSA-B) at 3 days for all curing regimes.

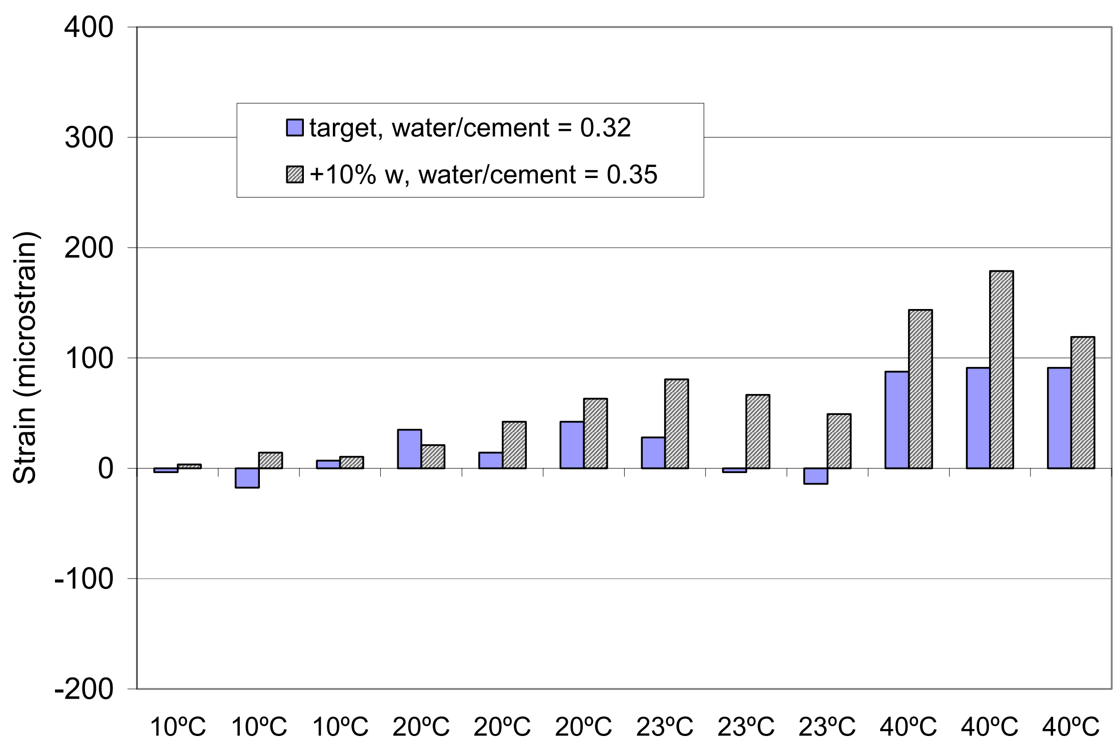

Figure 4.7. Dimensional change of Calcium Aluminate cement (CA) at 3 days for all curing regimes.

For the non-portland cements, the various curing temperatures could have also affected the hydrates formed. For example, the hydration of the CA cement is sensitive to temperature. The expansion of CA cement (Figure 4.7) at 40ºC did not exceed the expansion at other temperatures as much as for the other cements. As explained in Section 3.1.3, this is because at 40ºC, the metastable phase CAH_{10} no longer forms and the stable hydrate C_3AH_6 occurs early. Compared with the metastable phases, C_3AH_6 combines less water and has less porosity, and therefore experiences less expansion.

It is interesting to note that the effect of the water/cement ratio on the volume change varies for the different cement types, especially at the high temperature (40ºC). For example, the calcium aluminate (CA) cement and the Type I/II cement mixes showed more expansion as 10 percent more water was used, while the opposite occurred for the fast-setting CSA mixes and the Type III mixes. At the lower temperature of 10ºC, the net volume change is small and the effect of water content is reduced.

4.3 Shrinkage by Cement Type

After three days, all of the concrete and mortar specimens were removed from the water and maintained at the temperature and humidity conditions of the four curing regimes shown in Table 2.7. Thereafter, the volume change of the specimens was calculated based on the length measured at three days. Under these isothermal conditions, the measured volumetric change was deemed shrinkage because the moisture loss was the primary factor. However, continued physico-chemical changes inside the cement could also cause the deformation in the specimens, so the observed shrinkage is not necessarily completely attributable to moisture conditions.

4.3.1 Type I/II Portland Cement + 15 Percent Fly Ash

As shown in Figure 4.8, the shrinkage was similarly small for both the concrete and mortar under the Standard and Cold regimes. For the Cold regime, the low temperature results in a low vapor pressure, which offsets the effect of the low moisture content.

Under the low humidity of the Dry curing regime, the shrinkage in both the concrete and mortar was significantly greater than for the other curing regimes. For example, the 90-day shrinkage was 631 microstrain in the concrete, compared with 52 microstrain under the Standard curing regime. The shrinkage in the mortar was greater than in the concrete (781 microstrain at 90 days). The shrinkage under the Dry and Hot regime was similar to that under the Dry regime in both the concrete and mortar specimens. It can be seen that both the temperature and the humidity under which the specimens were cured had significant effects on shrinkage.

4.3.2 Type III-A Portland Cement

As shown in Figure 4.9, the temperature and moisture content had similar effects on Type III-A cement as on the Type I/II. However, the shrinkage in the Type III-A cement was much greater than that of the Type I/II mix.

When the temperature was 10ºC (Cold curing regime) or the moisture was 97 percent RH (Standard regime), the shrinkages in the Type III-A concrete and mortar specimens were less than 200 microstrain through 90 days. In the Type III-A concrete specimens, the Dry, and Dry and Hot curing regimes resulted in greater shrinkage, up to 845 microstrain and 945 microstrain at 90 days in concrete, respectively (Figure 4.9). The shrinkage of mortar in these 4 regimes follows the same trend as the concrete, except that the shrinkage was greater in the mortar specimens.

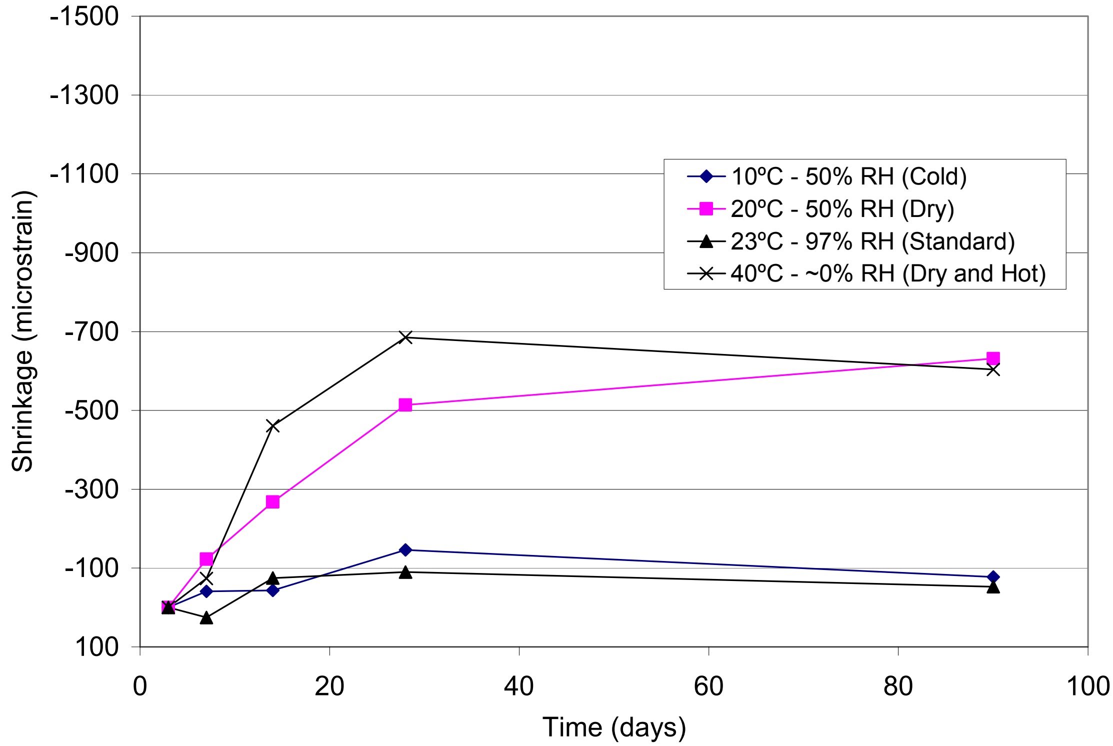

Figure 4.8a. Concrete specimens.

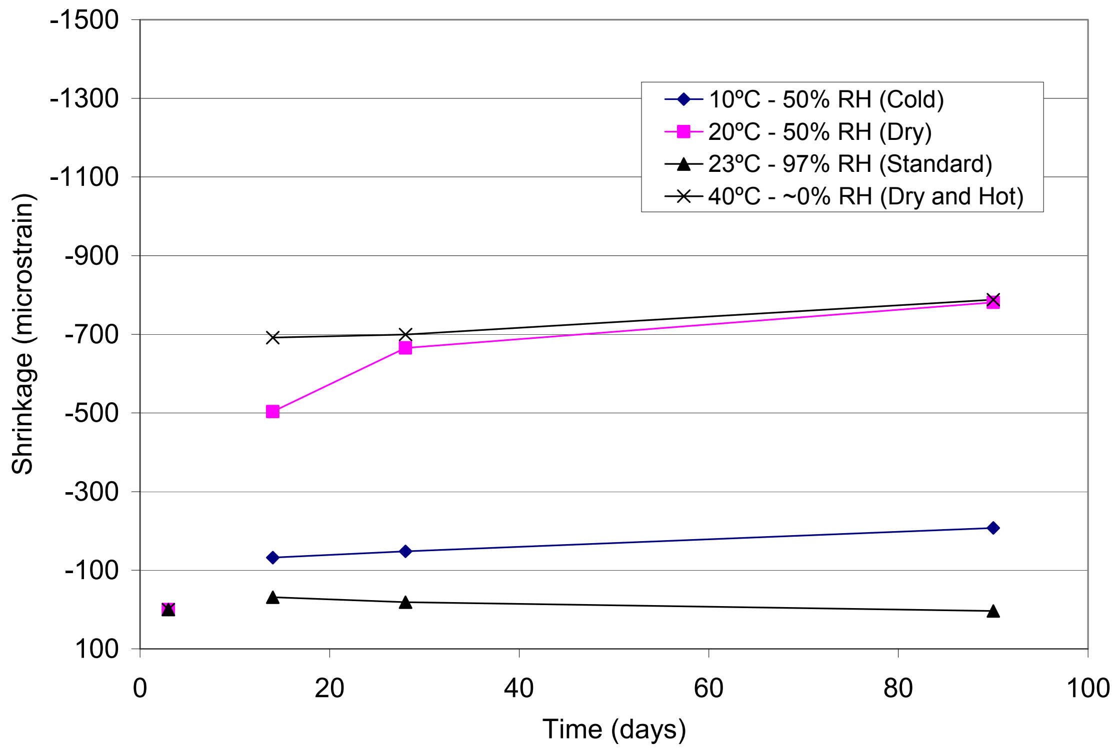

Figure 4.8b. Mortar specimens.

Figure 4.8. Shrinkage of the Type I/II portland cement concrete and mortar specimens.

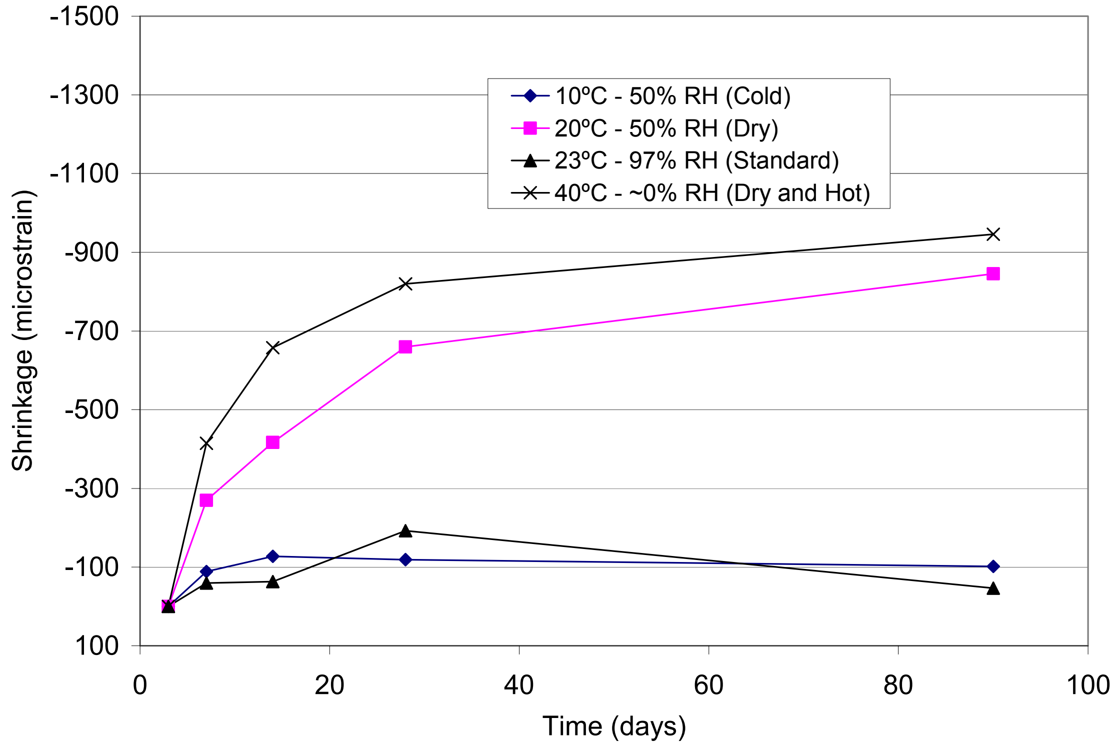

Figure 4.9a. Concrete specimens.

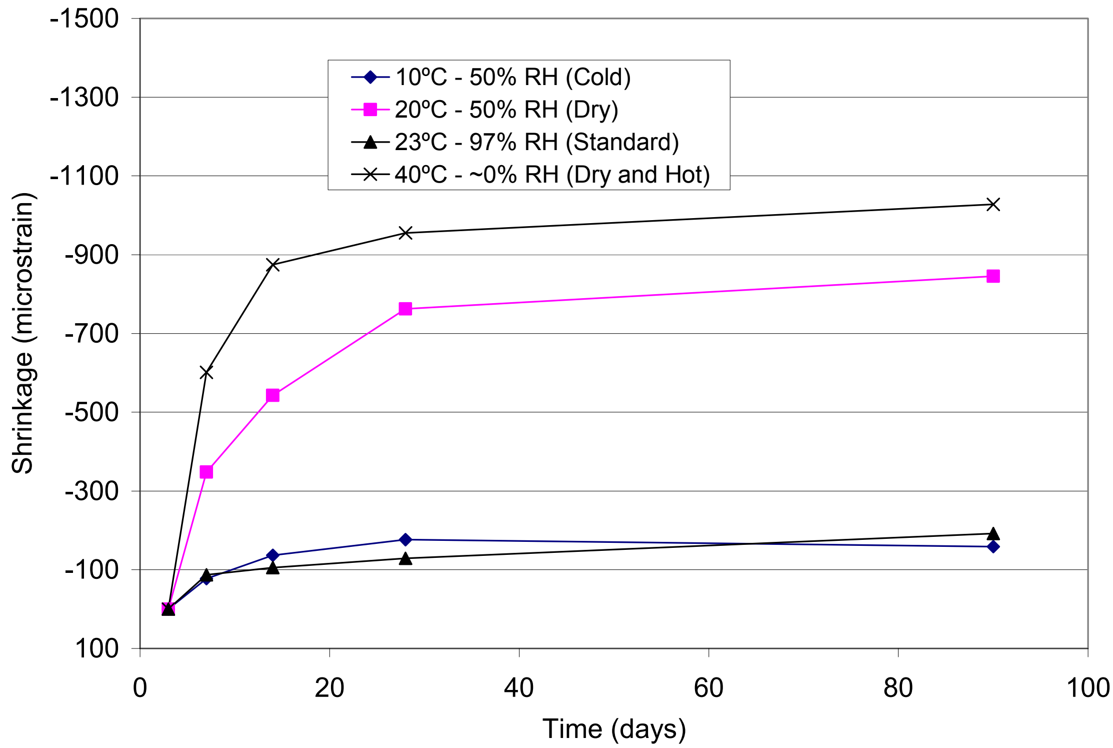

Figure 4.9b. Mortar specimens.

Figure 4.9. Shrinkage of the Type III-A portland cement concrete and mortar specimens.

4.3.3 Type III-B Portland Cement

The shrinkage curves for the Type III-B cement concrete and mortar specimens with respect to time are shown in Figure 4.10.

The shrinkage of the Type III-B cement mortar bar was very similar to that of the Type III-A, across all the curing regimes, as shown in Table 4.1. Despite the fact that the two Type III cements were from different manufacturers, the relative performance of both Type III cements is expected be consistent due to the ASTM specifications on chemical compositions. The slight difference is likely attributable to the different water/cement ratios of the two mixes—the water/cement ratio was 0.36 for Type III-B and 0.38 for Type III-A.

Table 4.1 Mortar Bar Shrinkage in Type III-A and Type III-B Cements

Curing type	Specimen Age (days)	Type III-A (microstrain)	Type III-B (microstrain)
Cold: 10ºC, 50% RH	3	0.0	0.0
	7	-77.1	-73.6
	14	-136.6	-98.1
	28	-176.3	-86.4
	90	-158.8	-170.5
Dry: 20ºC, 50% RH	3	0.0	0.0
	7	-347.9	-428.5
	14	-542.9	-665.5
	28	-762.4	-709.9
	90	-845.3	-829.0
Standard: 23ºC, 97% RH	3	0.0	0.0
	7	-87.0	-136.6
	14	-105.7	-130.8
	28	-129.0	-17.5
	90	-192.1	21.0
Dry and Hot: 40ºC, humidity not controlled	3	0.0	0.0
	7	-601.3	-658.5
	14	-874.5	-916.5
	28	-955.0	-958.6
	90	-1027.4	-1109.2

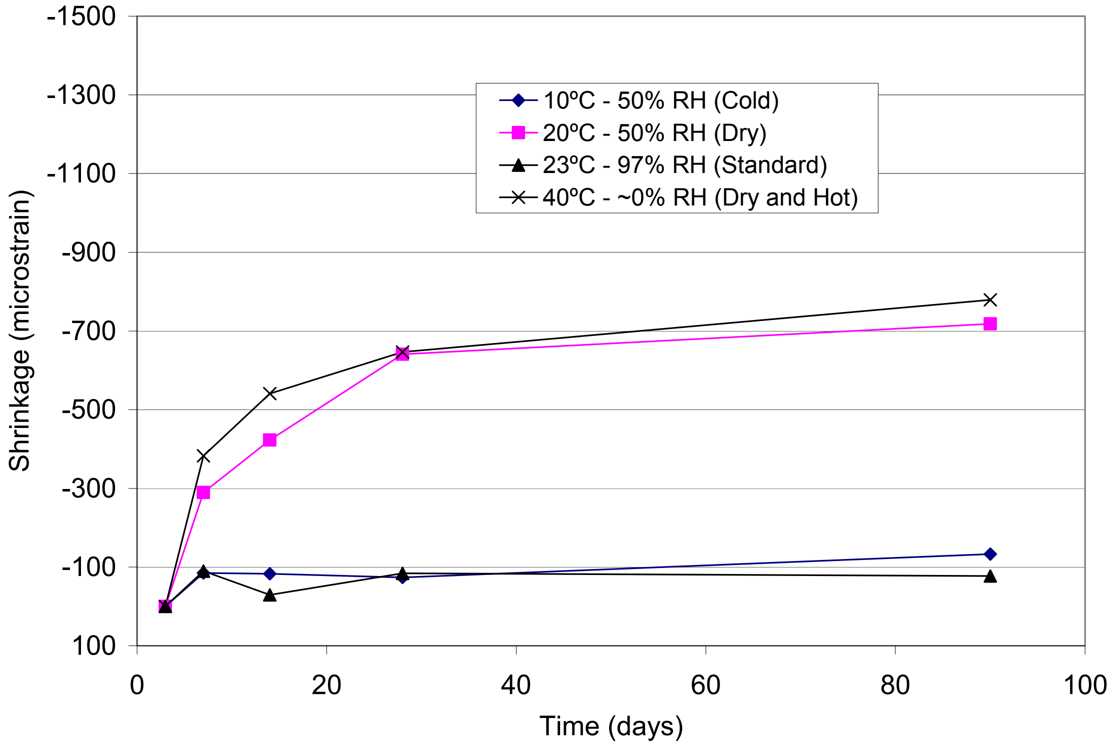

Figure 4.10a. Concrete specimens.

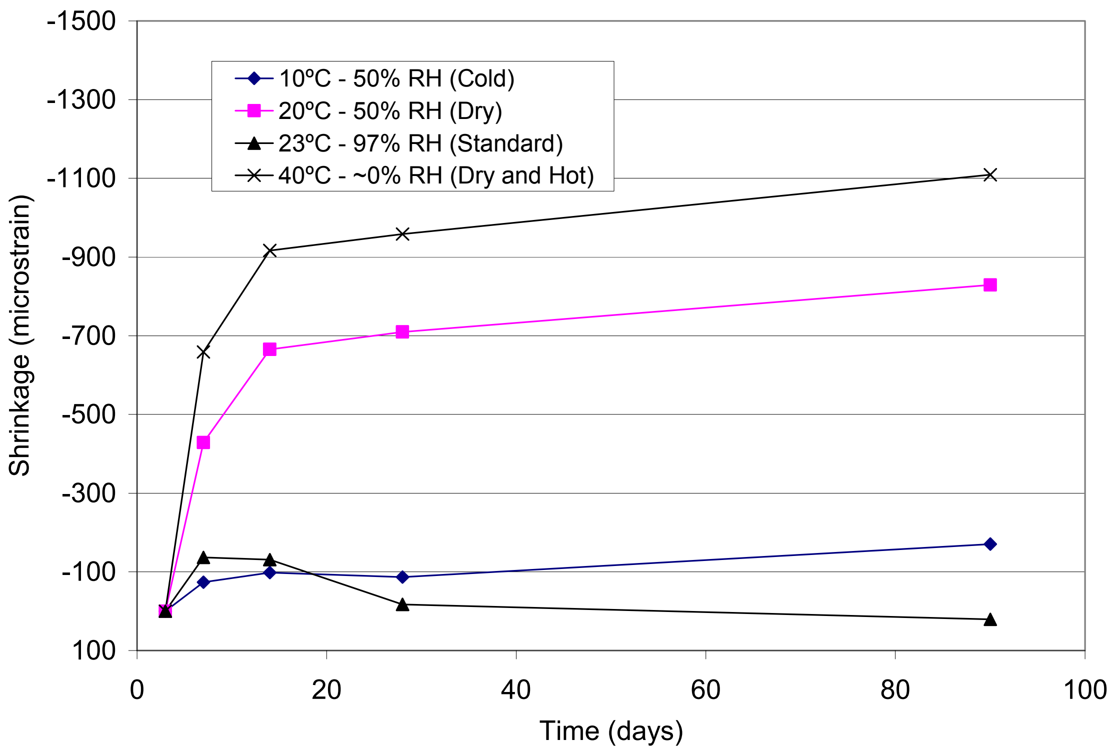

Figure 4.10b. Mortar specimens.

Figure 4.10. Shrinkage of the Type III-B portland cement concrete and mortar specimens.

As shown in Figure 4.10 the shrinkage of the Type III-B concrete mix was also similar to that of cement Type III-A for all curing regimes, except that the absolute values were smaller. The difference could be attributable to different types of aggregate—crushed stone was used in the Type III-B mix; rounded gravel was used for the Type III-A mix.

4.3.4 Calcium Sulfoaluminate Cement A (CSA-A)

As shown in Figure 4.11, negligible shrinkage occurred in both the concrete and mortar specimens of the CSA-A cement under the Standard (23 microstrain at 90 days in the concrete) and Cold regimes (51 microstrain at 90 days in the concrete).

For the concrete cured under the Dry regime, the shrinkage increased steadily to 370 microstrain at 90 days, which was low compared to 631.6 microstrain for the Type I/II concrete. However, under Dry and Hot curing regime, the shrinkage increased significantly to 614 microstrain at 90 days.

It is interesting to note that up to 28 days, the mortar showed a similar amount of shrinkage as the concrete under both the Dry and Oven curing regimes. This would suggest that the addition of coarse aggregate did reduce the shrinkage. It is also interesting to note that the concrete did not exhibit expansion under the Standard curing regime, which may be due to the fact that the expansive ettringite matrix had already formed at 3 days.

4.3.5 Calcium Sulfoaluminate Cement B (CSA-B)

The CSA-B concretes showed shrinkage once removed from the water under all of the curing regimes. It can be seen in Figure 4.12 that the early shrinkage of this mix was more sensitive to temperature than moisture conditions, as no difference is found between the Standard curing regime and Dry curing regime at 7 days.

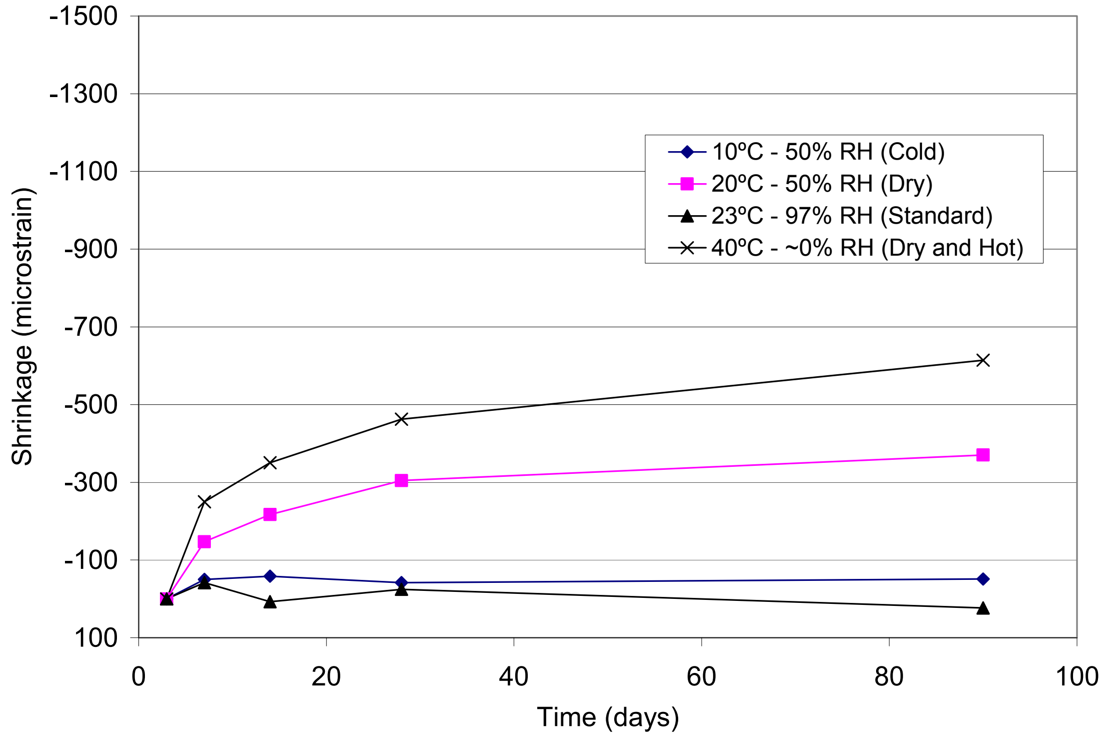

Figure 4.11a. Concrete specimens.

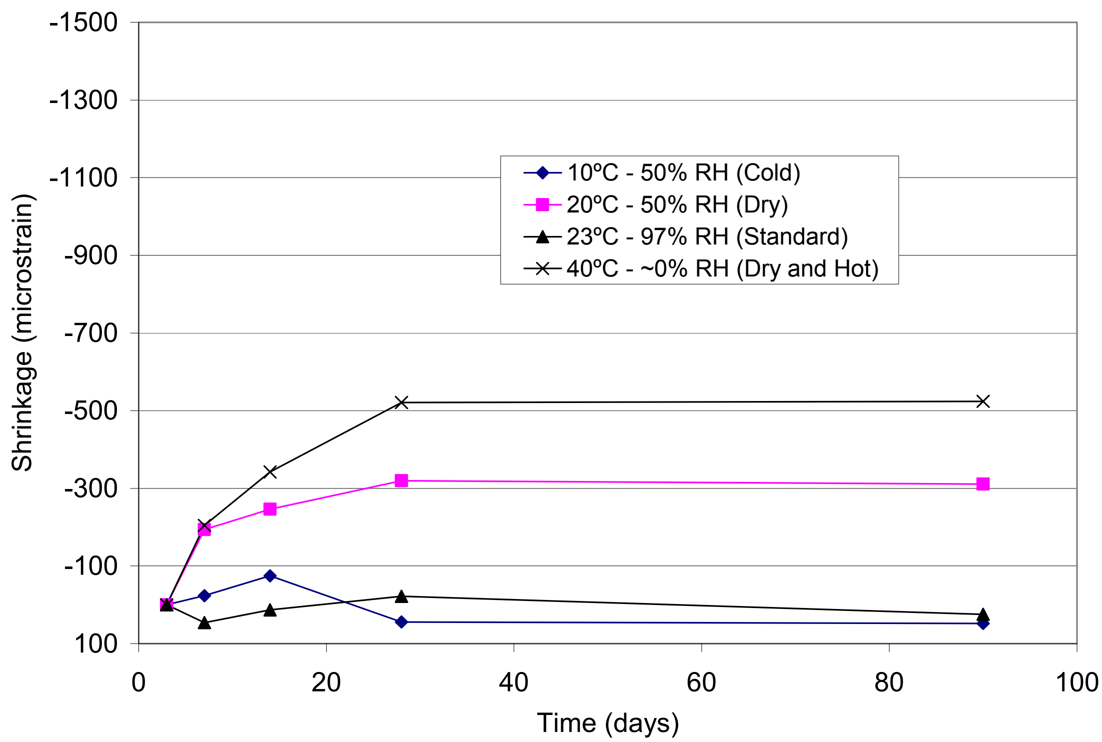

Figure 4.11b. Mortar specimens.

Figure 4.11. Shrinkage of the Calcium Sulfoaluminate – A (CSA-A) concrete and mortar specimens.

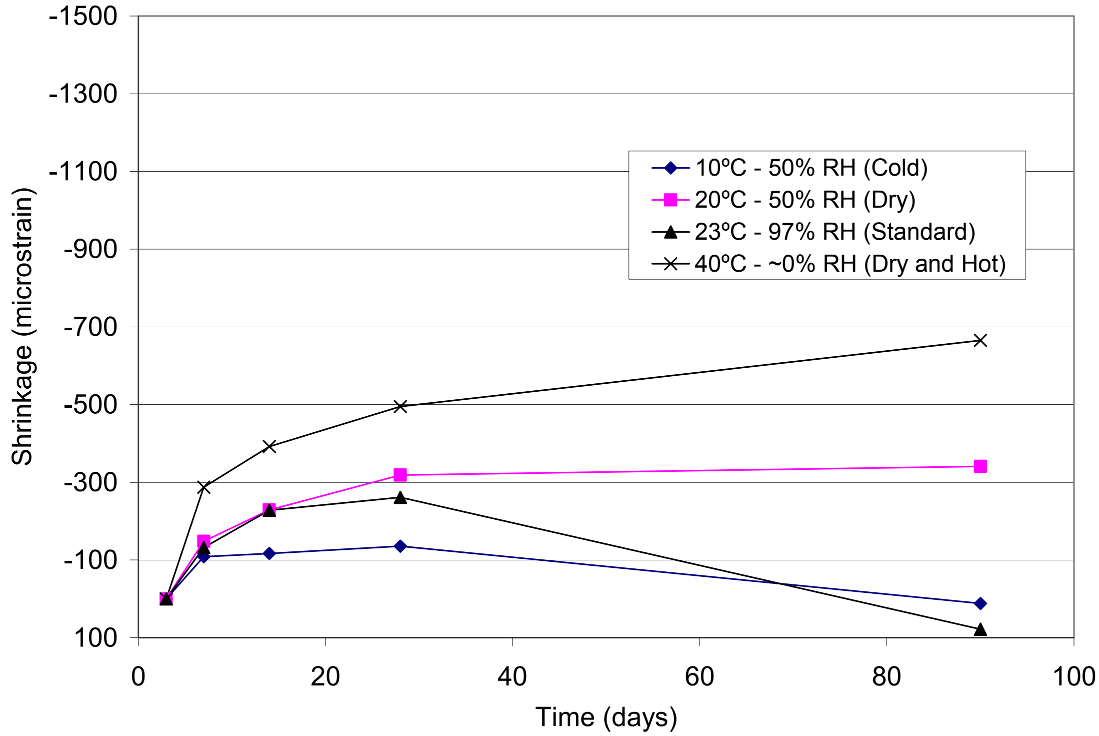

Figure 4.12a. Concrete specimens.

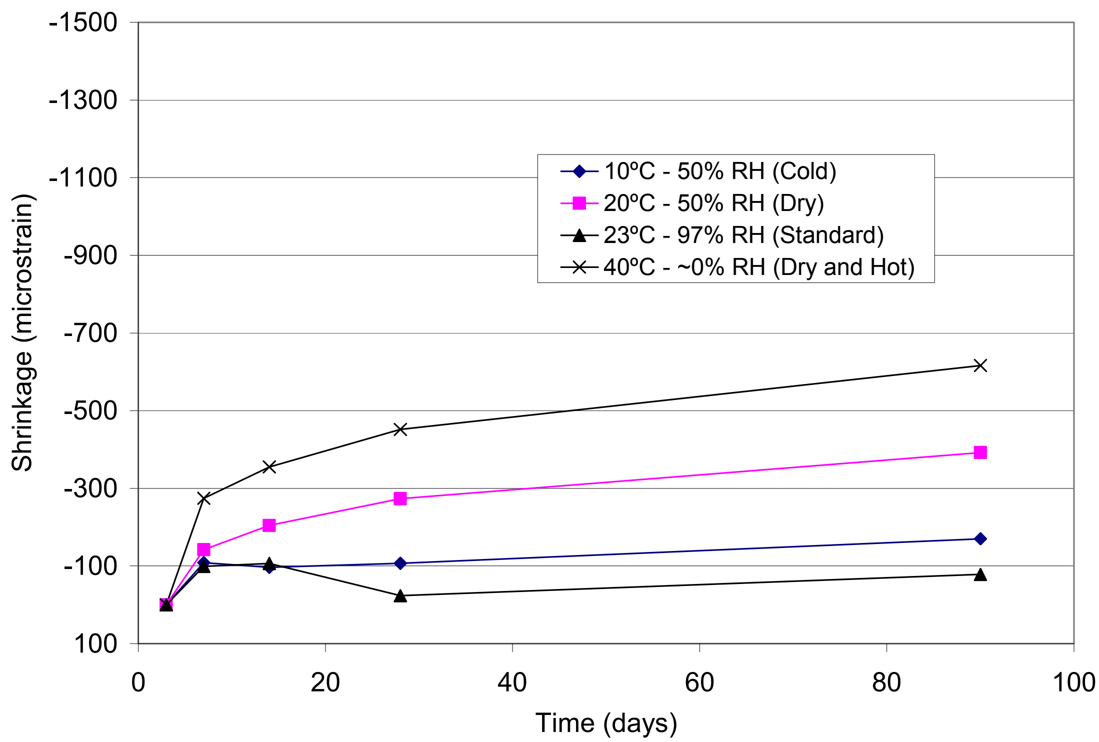

Figure 4.12b. Mortar specimens.

Figure 4.12. Shrinkage of the Calcium Sulfoaluminate – B (CSA-B) concrete and mortar specimens.

The trend is that higher temperature causes increased shrinkage. This result is probably related to the stability of ettringite, which can be transformed from needle-like crystals to a prismatic tile form with increased temperature.(*47*) Similar trends were found in the mortar specimens.

Similar to the CSA-A mix, the CSA-B mortar showed a similar amount of shrinkage as the concrete, with the coarse aggregate in the mix not reducing the shrinkage.

Note that even when enough moisture was present under the standard curing regime, the shrinkage of the concrete specimens continued until 28 days, or sometime between 28 days and 90 days, however, this was not true of the mortar specimens. There could be a temporary period when moisture was not accessible to the concrete specimens, and between 28 days and 90 days the concrete started to expand because of late ettringite formation as the unhydrated clinker continued to react with water when it was available again.

4.3.6 Calcium Aluminate Cement (CA)

The shrinkage curves of the CA concrete and mortar are shown in Figure 4.13. Under the Standard curing regime, the CA concrete mix did not shrink, rather it expanded continuously to 90 days with a total of 155 microstrain expansion. The mortar specimens exhibited shrinkage before 14 days and expanded afterward, possibly because the moisture was temporarily not accessible.

Under the Dry curing regime, the concrete showed significant shrinkage, and the shrinkage occurred more rapidly than for the portland cements. As shown in Table 4.2, nearly half of the total shrinkage in the CA cement concrete samples occurred by 7 days (210 microstrain), compared to about 14 days for the Type I/II mix. After 28 days, the shrinkage rate decreased. At 90 days, shrinkage in the CA concrete specimens reached 443 microstrain.

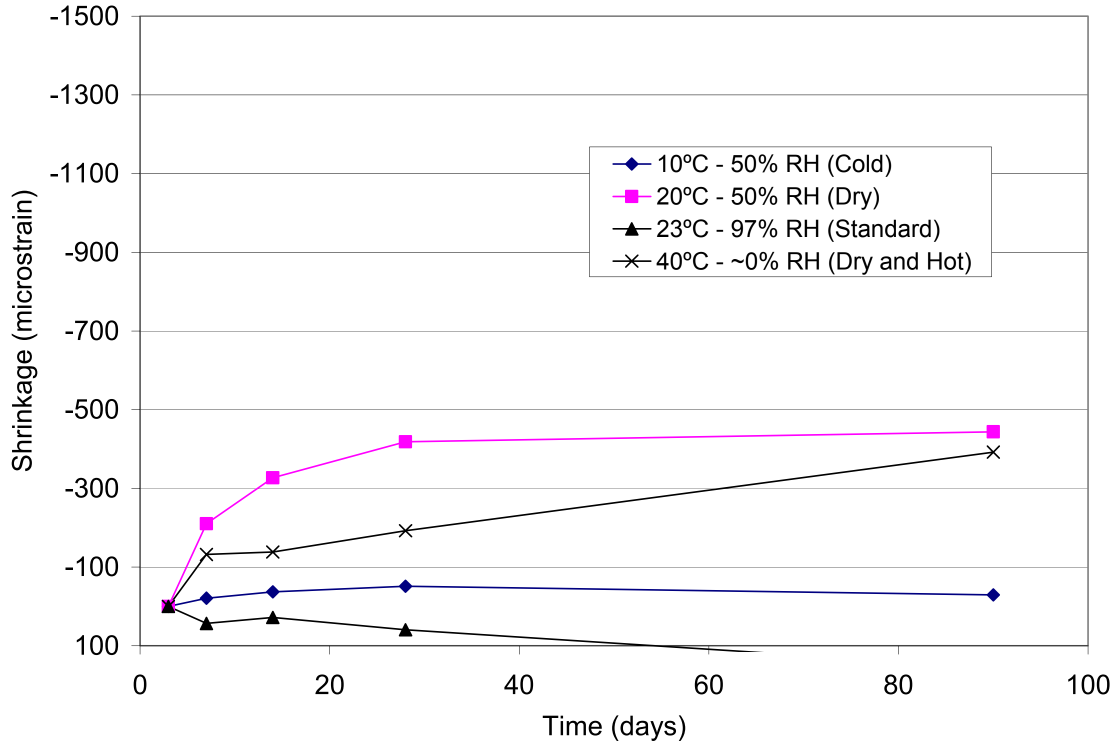

Figure 4.13a. Concrete specimens.

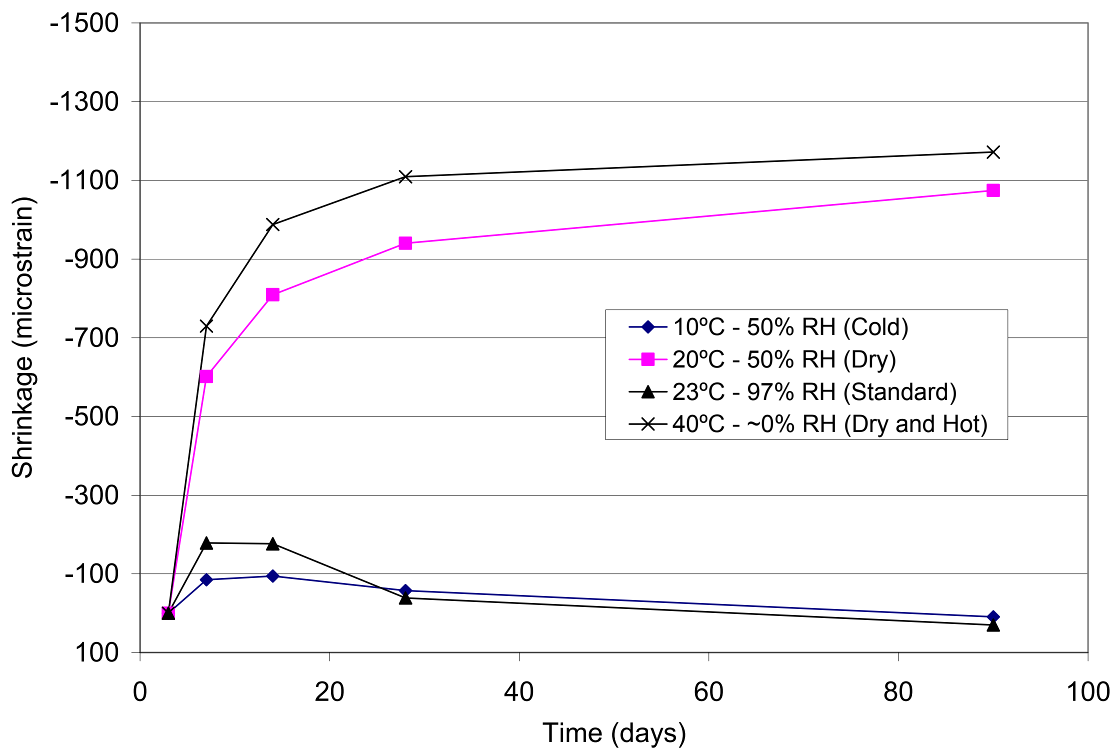

Figure 4.13b. Mortar specimens.

Figure 4.13. Shrinkage of the Calcium Aluminate (CA) concrete and mortar specimens.

Table 4.2 Ratio of Shrinkage/Total Shrinkage in Concrete Specimens at 90 days, 20ºC and 50 Percent Relative Humidity, (Dry Curing Regime)

Age (days)	Concrete Type					
	Type I/II	**Type III-A**	**Type III-B**	**CSA-A**	**CSA-B**	**CA**
3	0.00	0.00	0.00	0.00	0.00	0.00
7	0.19	0.32	0.40	0.40	0.44	0.47
14	0.42	0.49	0.59	0.59	0.67	0.74
28	0.81	0.78	0.89	0.82	0.93	0.94
90	1.00	1.00	1.00	1.00	1.00	1.00
90 day shrinkage (microstrain)	-340	-370	-443	-631	-718	-845

The mortar specimens showed enormous shrinkage up to 600 microstrain at 7 days under the Dry curing regime. It is notable that the coarse aggregate in the concrete significantly reduced the shrinkage compared the mortar mix, in contrast to the CSA cements.

Under the Cold curing regime, the shrinkage was reduced dramatically. For example, the shrinkage was 51 microstrain at 28 days, and 29 microstrain at 90 days. The results show that both temperature and moisture are equally important for the shrinkage of CA concrete. Under the Dry and Hot curing regime, the total shrinkage at 90 days was 392.3 microstrain, which is similar to that under the Dry curing regime.

4.4 Shrinkage by Curing Condition

Figure 4.14 shows the shrinkage of all the concrete mixes under each curing condition over time. Figure 4.15 shows the shrinkage of the mortar specimens.

4.4.1 Standard Curing Regime

Under the Standard curing regime, the shrinkage in all the concrete and mortar specimens was negligible. All of the mixes showed dimensional fluctuation, with alternating shrinkage and expansion, as shown in Table 4.3. The dimensional change of the specimens must be related to

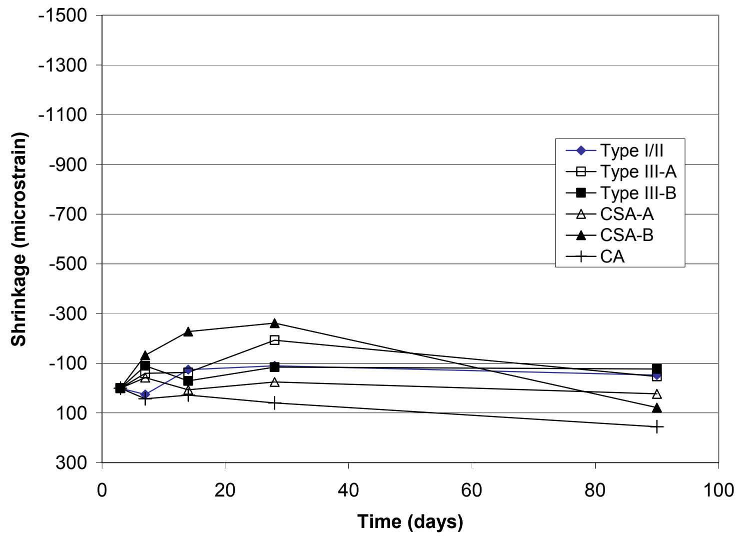

Figure 4.14a. 23ºC + 97%RH (Standard).

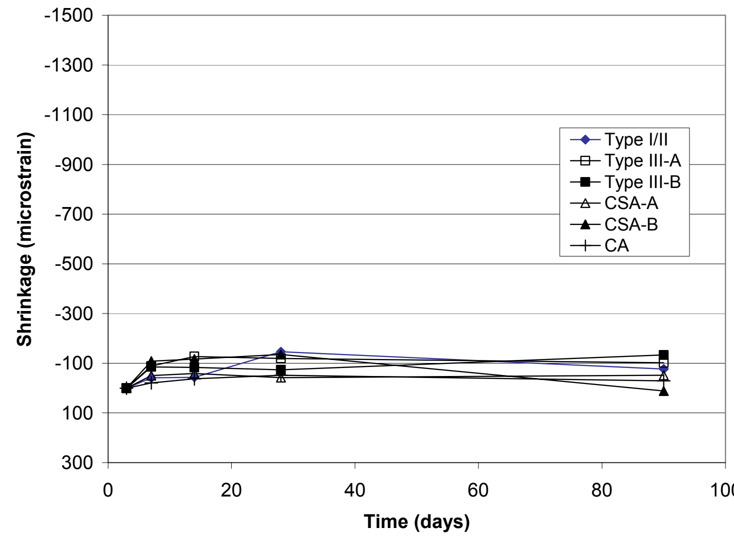

Figure 4.14b. 10ºC + 50%RH (Cold)

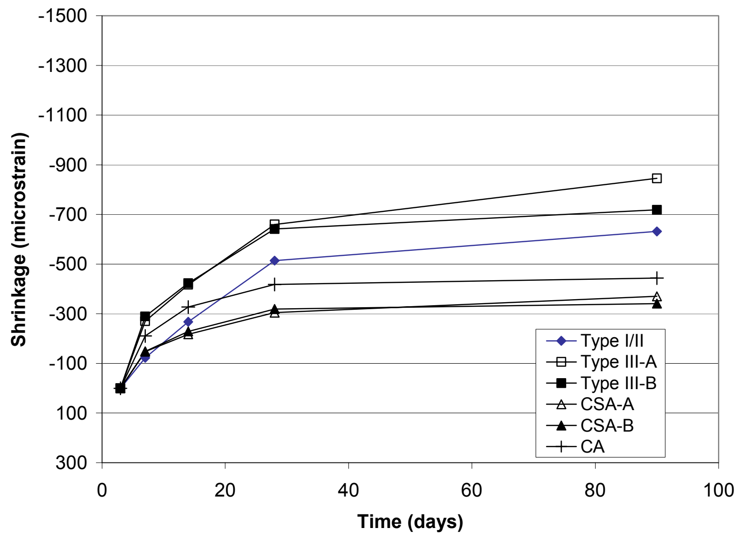

Figure 4.14c. 20ºC + 50% RH (Dry).

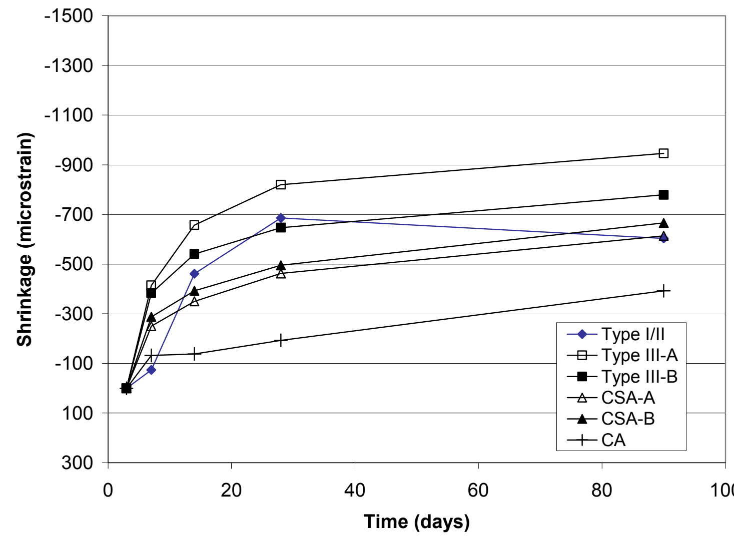

Figure 4.14d. 40ºC + ~0% RH (Dry and Hot).

Figure 4.14. Shrinkage of the concrete specimens at all four curing regimes.

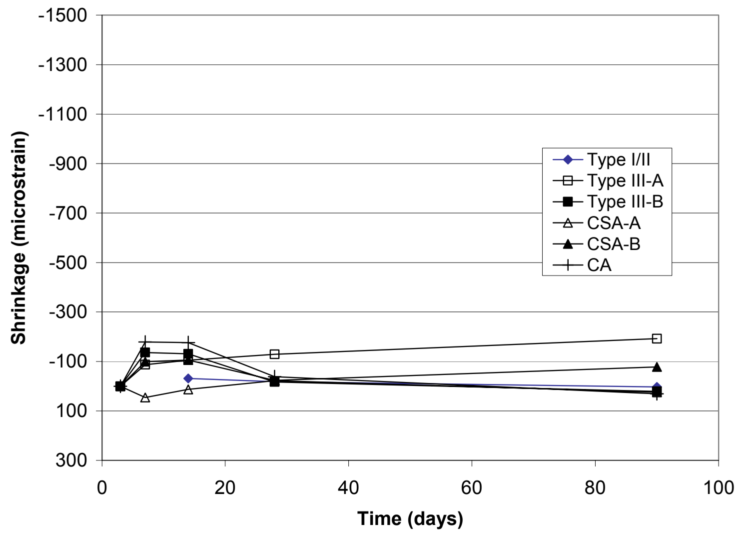

Figure 4.15a. 23ºC + 97%RH (Standard).

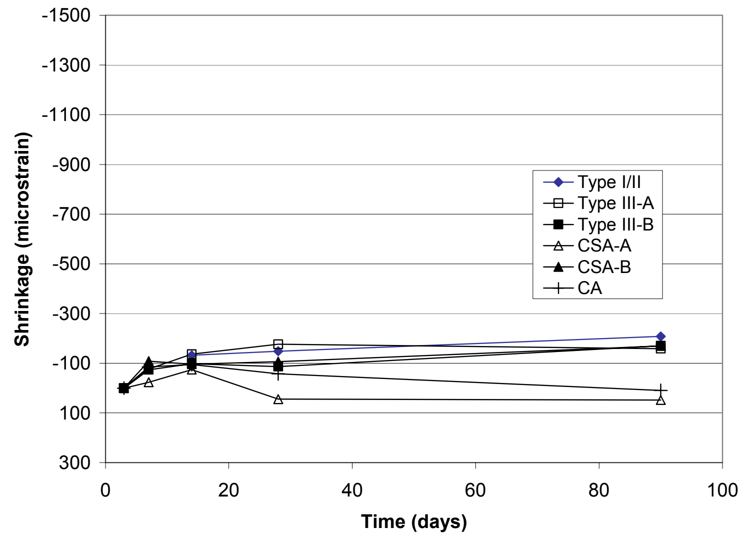

Figure 4.15b. 10ºC + 50%RH (Cold)

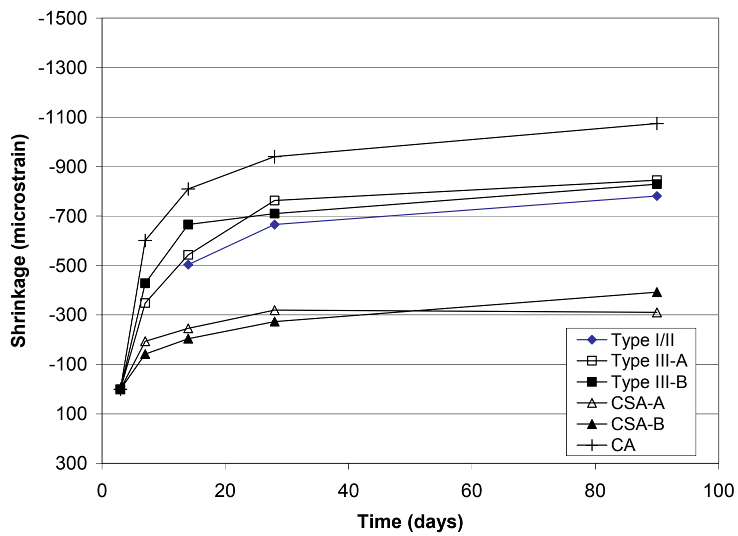

Figure 4.15c. 20ºC + 50% RH (Dry).

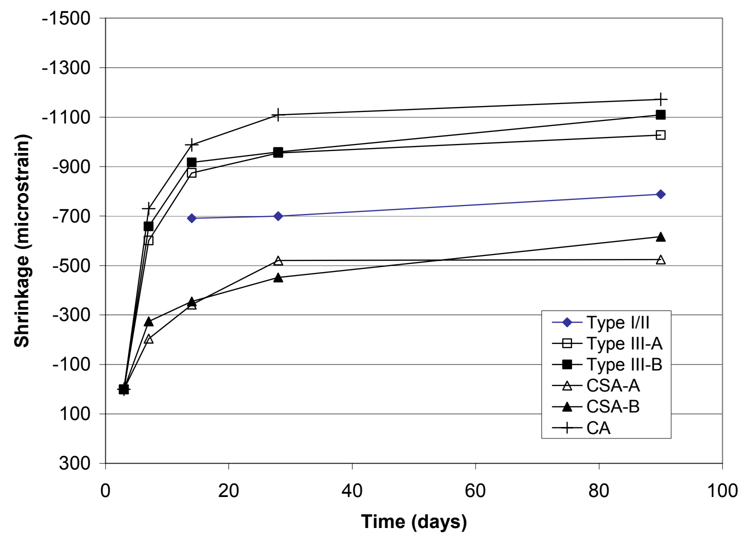

Figure 4.15d. 40ºC + ~0% RH (Dry and Hot).

Figure 4.15. Shrinkage of the mortar specimens for all four curing regimes.

Table 4.3 Ratio of Shrinkage/Total Shrinkage in Concrete Samples at 90 days, 23ºC and 97 Percent Relative Humidity (Standard Curing Regime)

Age	CSA-B	CSA-A	CA	Type III-A	Type I/II	Type III-B
3	0.00	0.00	0.00	0.00	0.00	0.00
7	-1.69	1.80	0.72	1.28	-0.49	1.17
14	-2.91	-0.30	1.28	1.35	1.42	0.38
28	-3.34	1.05	1.76	4.13	1.71	1.09
90	1.00	1.00	+1.00	1.00	1.00	1.00
90-day shrinkage (microstrain)	78.2	23.4	-29.2	-46.7	-52.5	-77.1

the fluctuation of free water available to the specimens. Note that 97 percent RH was dynamically controlled and achieved by periodic spraying of water mist into the air of the curing room.

4.4.2 Dry Curing Regime

In this curing regime with low relative humidity, significant shrinkage took place over the initial 28 days in every mix for both the concrete and mortar specimens. After the initial 28 days, the rate of shrinkage decreased.

For the concrete mixes, most of the total shrinkage occurred in first 28 days, as shown in Table 4.2. At 7 days, more than 40 percent of the total shrinkage measured occurred in the early strength concrete mixes of CA, CSA-A, CSA-B, and Type III-B. For the Type II mix, 19 percent of the total shrinkage measured occurred in the initial 7 days. The difference in shrinkage among the mixes was significant. At 90 days, the shrinkage was up to 845 microstrain for Type III-A and 340 microstrain for the CSA-B.

The ranking of shrinkage at 7 days is as follows:

Type III-B > Type III-A ≅ CA >> CSA-A ≅ CSA-B > Type I/II

At 90 days, shrinkage ranked as follows:

Type III-A > Type III-B > Type I/II >> CA > CSA-A ≅ CSA-B

The concrete specimens developed shrinkage following the same pattern as the respective mortar specimens. The differences among the mixes are more distinct for the mortar specimens than for the concretes. In addition, each of the three groups of cement types [i.e., the portland cements (Type I/II, Type III-A, and Type III-B), the sulfoaluminate cements (CSA-A, CSA-B), and the calcium aluminate cement] exhibited similar shrinkage performance within each group, with the CSA mixes having the best performance overall.

4.4.3 Cold Curing Regime

Under the Cold curing regime (10ºC and 50% RH), both the concrete and mortar specimens for all mixes displayed minor shrinkage compared with the Dry curing regime. Most of the shrinkage occurred before 7 days, with the shrinkage progressing slowly after that, as shown in Table 4.4.

Table 4.4 Ratio of Shrinkage/Total Shrinkage of Concrete Samples at 90 days, 10ºC and 50 Percent Relative Humidity (Cold Curing Regime)

Age	CSA-B	CA	CSA-A	Type I/II	Type III-A	Type III-B
3	0.00	0.00	0.00	0.00	0.00	0.00
7	-9.28	0.72	0.98	0.53	0.87	0.64
14	-9.98	1.28	1.14	0.56	1.25	0.62
28	-11.58	1.76	0.82	1.89	1.17	0.55
90	+1.00	1.00	1.00	1.00	1.00	1.00
90-day shrinkage (microstrain)	11.7	-29.2	-51.4	-77.1	-101.6	-133.1

For the mortar specimens, both CSA-A and CA began to expand somewhat (less than 100 microstrain) after 14 days.

Similar to the Dry curing regime, the mortar shrinkage fell into three distinct groups: the portland cements (Type III-A and Type III-B), the sulfoaluminate cements (CSA-A, CSA-B), and the calcium aluminate cement. It can be seen again that the same cement types had similar shrinkage performances.

Although the relative humidity was the same for both the Dry curing regimes at 20ºC and the Cold curing regime at 10ºC, the vapor pressure at which the maximum moisture can exist in the air without condensation, increases as temperature rises. As shown in Figure 4.16, the vapor pressure at 20ºC is two times that at 10ºC. Therefore, at higher temperatures more moisture is lost from the concrete to the air in the process of achieving dynamic equilibrium. This difference in the loss of water caused the huge difference in the amount of shrinkage between the two curing regimes.

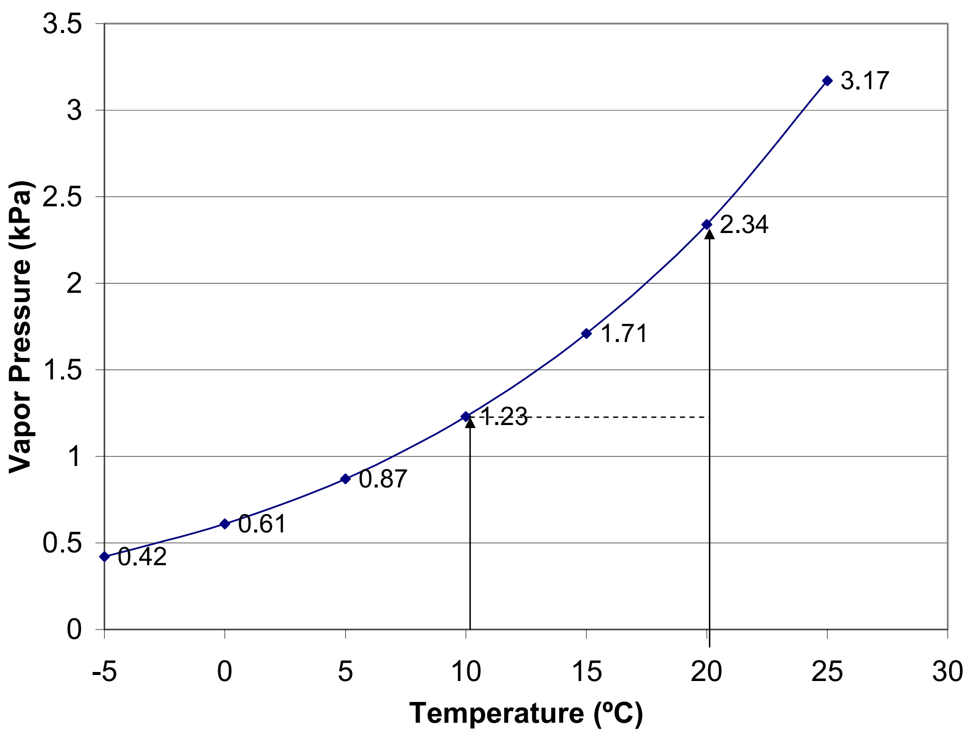

Figure 4.16. Vapor pressure with temperature.

The amount of shrinkage in the concretes at 7 days ranked as follows:

CSA-B > Type III-A > Type I/II > CSA-A ≅ Type III-B > CA

and 90 days as follows:

CSA-B > Type III-A ≅ Type III-B > Type I/II > CSA-A > CA

4.5 Dry and Hot Curing Regime

The Dry and Hot curing regime was designed to simulate the desert climate of high temperature and extremely low moisture. Water in concrete is easily lost to its environment in such conditions. Under the Dry and Hot curing regime, rapid and significant shrinkage occurred in both concrete and mortar specimens, as shown in Table 4.5. For example, at 28 days the shrinkage was 800 microstrain for the Type III-A concrete mix. Note that the difference between cement types in such a curing regime was greater than in other curing regimes, which may be a result of the difference in amount of free water that the specimens can lose. It is interesting to note that the CA cement exhibited the most shrinkage among the mortar specimens and the least shrinkage among the concrete specimens.

Table 4.5 Ratio of Shrinkage/Total Shrinkage of Concrete samples at 90 days, 40ºC and ~0 percent Relative Humidity (Dry and Hot Curing Regime)

Age	CA	Type I/II	CSA-A	CSA-B	Type III-B	Type III-A
3	0.00	0.00	0.00	0.00	0.00	0.00
7	0.34	0.12	0.41	0.43	0.49	0.44
14	0.35	0.76	0.57	0.59	0.69	0.70
28	0.49	1.14	0.75	0.74	0.83	0.87
90	1.00	1.00	1.00	1.00	1.00	1.00
90-day shrinkage (microstrain)	-392.3	-603.6	-614.1	-665.5	-778.8	-945.7

Under the Dry and Hot curing regime, the amount of shrinkage of the concrete mixes at 7 days ranked as follows:

Type III-A > Type III-B > CSA-B > CSA-A > CA > Type I/II

Under the Dry and Hot curing regime, the amount of shrinkage of the concrete mixes at 90 days ranked as follows:

Type III-A > Type III-B > CSA-B > CSA-A ≅ Type I/II > CA

4.6 Factor Analysis

From the analysis, it appears that the effects of cement type and curing regime were coupled with specimen age, which makes the analysis of the effect of increasing the water/cement ratio by 10 percent more complicated. To see the importance of the variables with regard to the shrinkage development, the statistical tool S-Plus was used to test the sensitivity of the shrinkage to the variables, namely, cement type, water/cement ratio, and curing regime; and the statistical significance of the factor levels of each variable.

Figure 4.17 shows the sensitivity analysis of the drying shrinkage to the controlled variables, cement type, and curing regime for the concrete and mortar mixes. The horizontal bar in the figure is an average from all the measured shrinkage data after 3 days; each vertical bar represents a variable for analysis, labeled on the horizontal axis; each short horizontal bar on the vertical bars represents the mean value of the data from a specific factor level of the variable. The length of the vertical bars gives the range of values by changing the factor level inside a variable. The wider the range, the more sensitive shrinkage is to the variable. The plots provide an indication of how important each variable is (i.e., sensitivity) and which factor levels result in increased or decreased shrinkage.

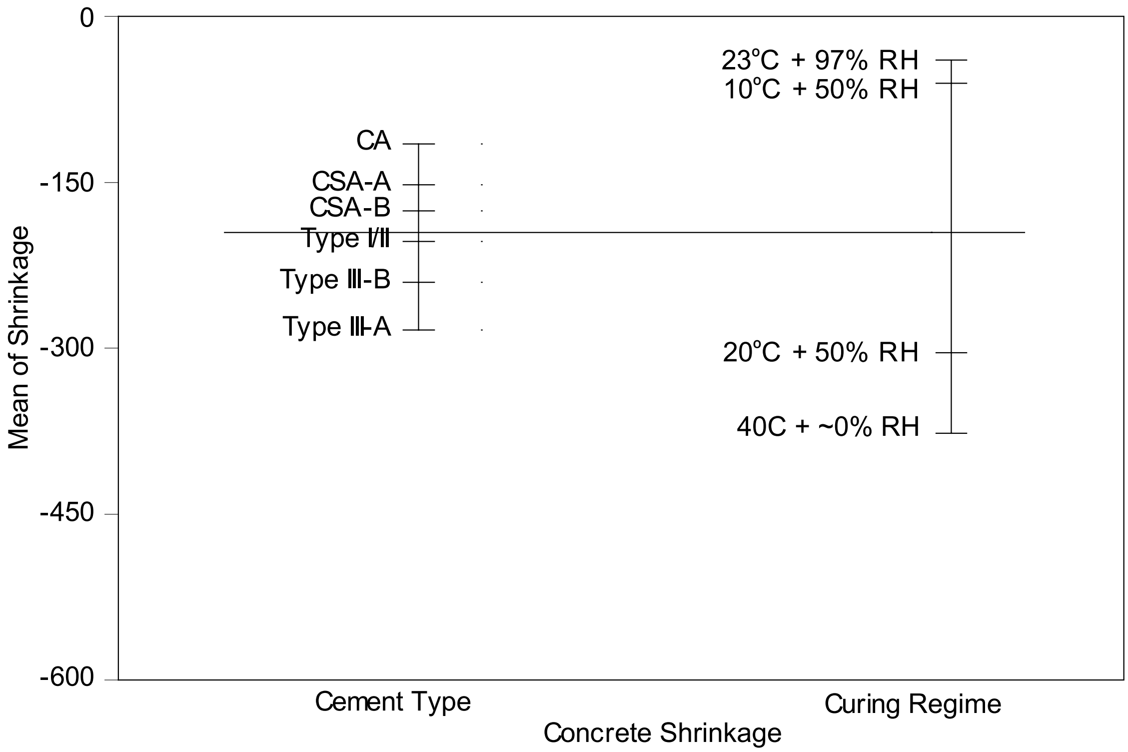

Figure 4.17a. Concrete specimens.

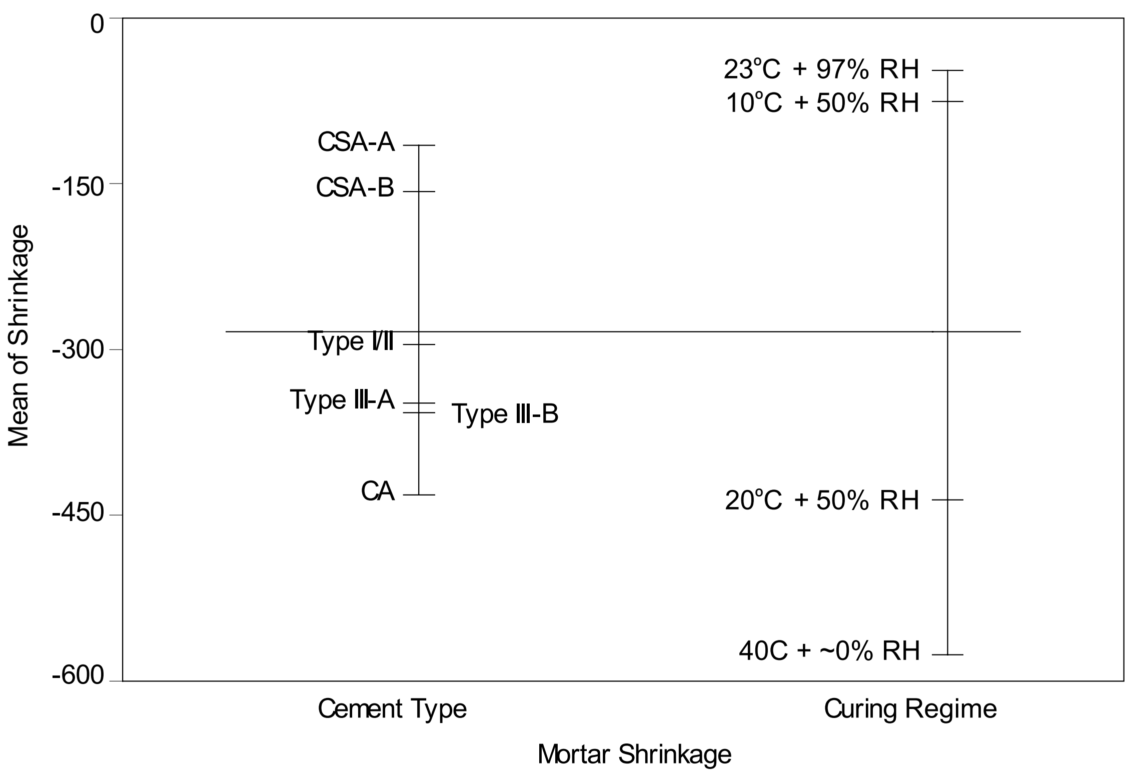

Figure 4.17b. Mortar specimens.

Figure 4.17. Sensitivity of shrinkage to cement type and curing regime.

Two observations can be made regarding this sensitivity analysis: 1) shrinkage is more sensitive to curing regime than to cement type, in both the mortar and concrete mixes, and 2) the ranking of cement type in terms of the shrinkage in the concrete specimens is:

Type III-A > Type III-B > Type I/II > CSA-B > CSA–A > CA.

For the mortar specimens, the ranking is

CA > Type III-A ≅ Type III-B > Type I/II > CSA-B > CSA-A.

The rankings were the same for concrete and mortar except for the CA cement.

Figure 4.18(a–f) shows the sensitivity to water/cement ratio and curing regime for each concrete mix. It can be seen that the effect on shrinkage caused by a 10-percent increase in the water/cement ratio is negligible compared to the effect of the different curing regimes. Although the effect of the water/cement ratio on the shrinkage is different for different cement types, the overall ranking of cement type does not change by using 10 percent more water, as shown in Figure 4.19. These results indicate that curing conditions during construction are more important in controlling shrinkage than are minor changes in water/cement ratio.

The statistical significance of the mean shrinkage measurements for each cement was tested by ANOVA for the concrete mixes, as reported in Table 4.6. The analysis checks the probability that the observed difference in a sample (e.g., between mean values of shrinkage) occurred by random selection from a population of data in which no such differences exist. Or simply stated, the ANOVA reports the probability that an observed difference among specimens is “real.” This probability is called a *P-value*.

Table 4.6 Statistical Significance Analysis Across the Mixes

	Df	**Sum of Square**	**Mean Square**	**F value**	**P value**
Cement	5	743164	148632.7	2.85809	0.01586979
Residuals	235	12168986	52004.2		

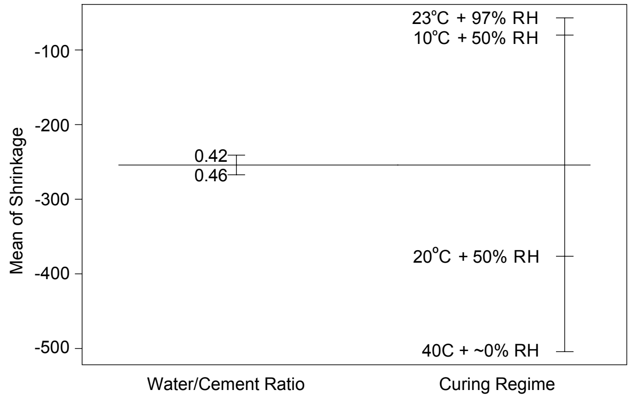

Figure 4.18a. Type I/II Portland cement.

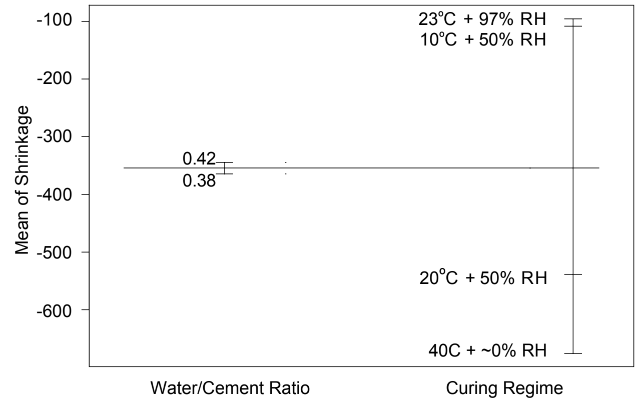

Figure 4.18b. Type III-A Portland cement.

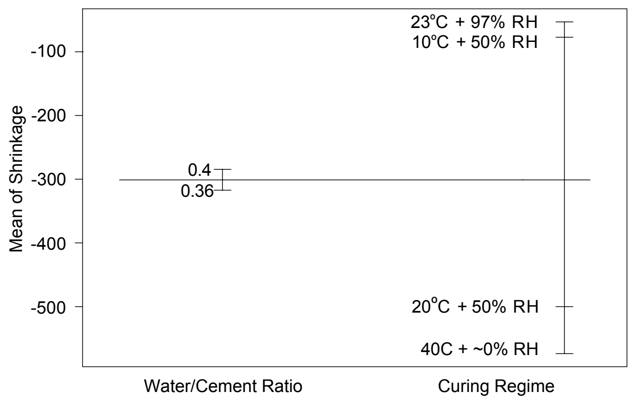

Figure 4.18c. Type III-B Portland cement.

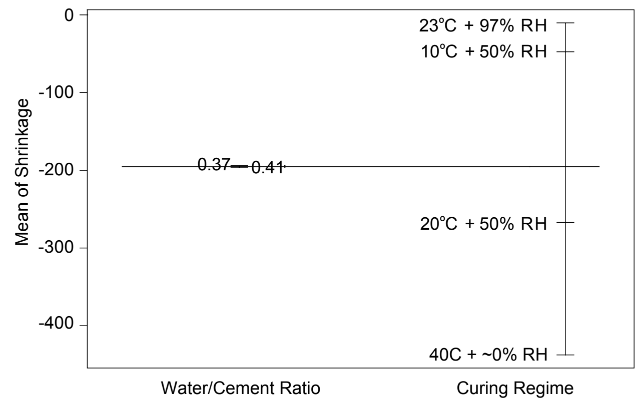

Figure 4.18d. Calcium Sulfoaluminate A (CSA-A)

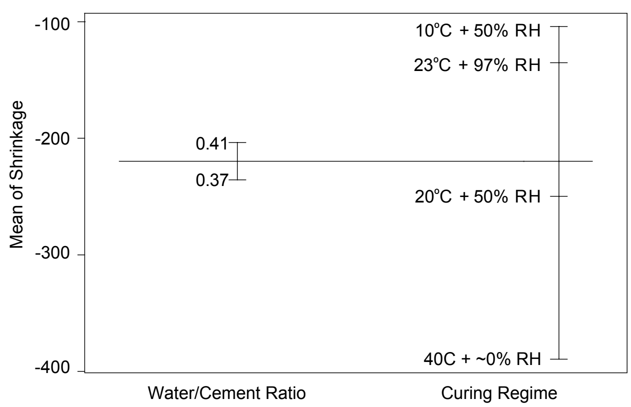

Figure 4.18e. Calcium Sulfoaluminate B (CSA-B)/

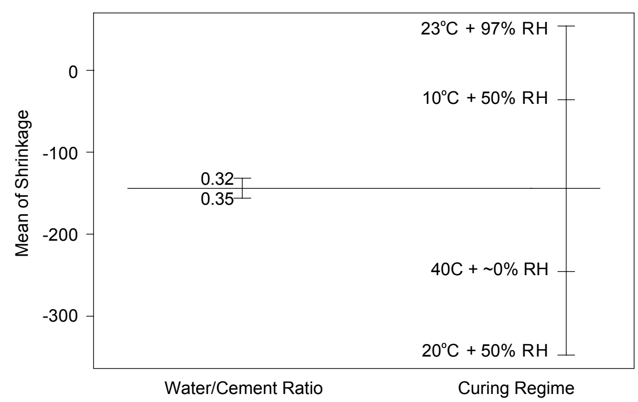

Figure 4.18f. Calcium Aluminate (CA).

Figure 4.18. Sensitivity of shrinkage to water/cement ratio and curing regimes.

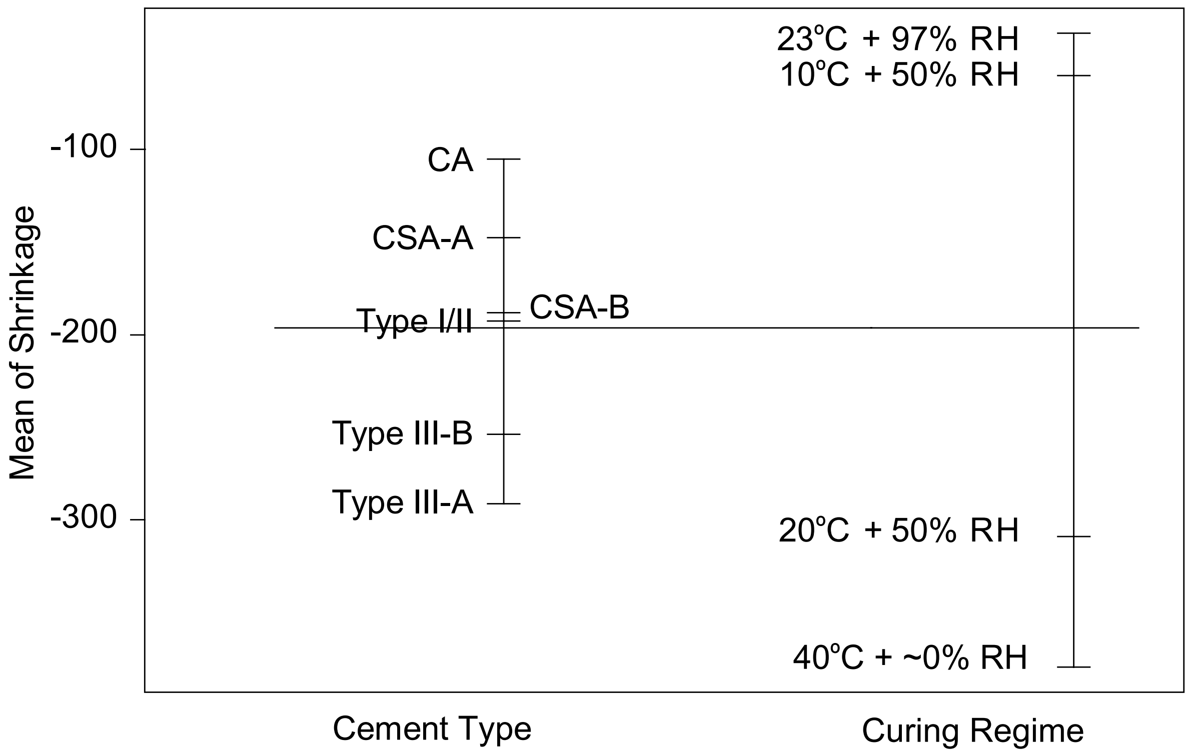

Figure 4.19a. Target mixes.

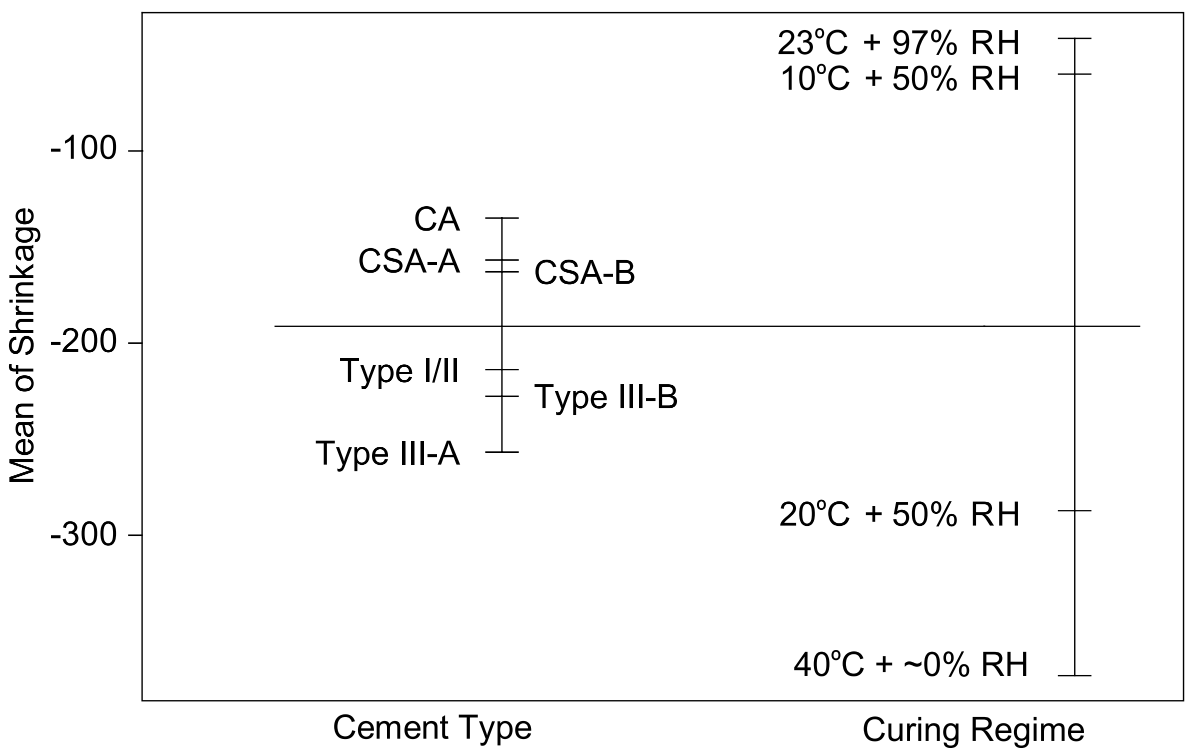

Figure 4.19b. Mixes with 10 percent additional water (+10% w mixes).

Figure 4.19. Sensitivity of shrinkage to water/cement ratio and curing regimes for target and +10% w mixes.

The higher the P-value, the less confidence there is that the observed differences among specimens for a given variable are significant. In many areas of research, a P-value of 5 percent is customarily treated as an acceptable confidence level.(*48*) As shown in Table 4.6, the P-value is 1.6 percent, which means high confidence that the cement type has significant effect on shrinkage.

The statistical significance between the means from the four curing regimes was also tested by ANOVA, as reported in Table 4.7. The P-value is zero, meaning that that there is really high confidence that different curing conditions resulted in different shrinkage.

Table 4.7 Statistical Significance Analysis Across the Curing Conditions

	Df	**Sum of Square**	**Mean Square**	**F value**	**P value**
Exposure	3	5236472	174549	53.66768	0
Residuals	236	7675677	32524		

4.7 Conclusions

The following conclusions are drawn from the results presented in this chapter.

- **Importance of moisture in curing.** This study of free shrinkage in the six concrete and mortar mixes under four curing regimes has indicated that the free shrinkage is significantly different between a moist curing and a dry curing condition. Generally, curing is the process of maintaining satisfactory moisture content and temperature conditions in freshly cast concrete for a definite period of time immediately following placement of the concrete. The process serves two major purposes: a) it prevents or replenishes the loss of moisture from the concrete; b) it maintains a favorable temperature for hydration to occur for a definite period.

- **Climatic considerations.** The results showed that both temperature and moisture are critical for shrinkage of a concrete or mortar mix. Generally, high temperature and low moisture result in more shrinkage. Low temperature can compensate for reduced moisture in controlling shrinkage as shown by the similar results for the Standard (23ºC and 97% RH) and the Cold (10ºC and 50% RH) curing regimes. This effect was shown to be at least partly attributable to the ability of colder air to hold more moisture vapor. However, different cement types react differently to these two factors.
- **Water/cement ratio.** The influence of water/cement ratio depends on the cement type, climatic exposure, and age. Generally, water/cement ratio was not as important in controlling shrinkage as the curing regime and cement type.
- **Performance of non-portland cement.** In general, the non-portland cements exhibited less shrinkage than the portland cements. With the exception of the Calcium Aluminate cements, the non-portland cements had sensitivities to curing regime and water/cement ratio similar to that of the portland cements. However, it should be noted that variability between batches of non-portland cement from some manufacturers has been observed. It is therefore recommended that shrinkage be measured for each production batch of cement as part of quality control.

5.0 COEFFICIENT OF THERMAL EXPANSION TEST RESULTS

The objectives of this study are to:

1. measure the coefficient of thermal expansion (CTE) of the six concrete mixes;
2. compare the ASTM and US Army Corps of Engineers (CRD) methods of measurement for CTE for concrete pavement construction;
3. generate input data for mechanistic-empirical design.

The coefficient of thermal expansion (CTE) is a measure of a material's expansion or contraction with temperature, which is usually expressed as engineering strain (or microstrain) per unit temperature change. For concrete pavement, the CTE is an important factor in optimizing concrete joint design, calculating stresses, and selecting sealant materials.

The CTE is one of the factors to be considered in the design of PCC pavements for the following reasons:

1. A restrained thermal contraction will create tensile stress in concrete pavement. The magnitude of the tensile stress is proportional to the CTE of the concrete. The tensile stresses due to the thermal contraction can be significant enough to contribute to early-age cracking of a young concrete.
2. Vertical thermal gradients in the pavement slab cause tensile stress due to the interaction of the deformed shape (curling) and the self-weight of the concrete, which creates forces pulling the slab back to a flat shape. The tensile stresses caused by restrained thermal contraction and curling can crack green concrete by themselves. When combined with traffic loads at later ages, these tensile stresses increase the stress/strength ratio, which increases the risk of a single heavy load causing cracking and which may shorten the fatigue life.

The coefficient of thermal expansion is normally represented as a typical value for concrete rather than a mix-specific value, even though it may vary significantly depending on factors such as the type of aggregate and composition of the cement used in a mix. Using a typical value may therefore lead to erroneous assumptions about a pavement's thermal response and lead to an insufficient design.

The CTE of portland cement concrete found in literature ranges from about 8×10^{-6}/°C to 12×10^{-6}/°C. Large CTE values are less desirable because they increase expansion and contraction strains, and therefore increase induced stresses. The range of CTE values for different concretes reflects the variation in the CTE of concrete component materials. Aggregate type has the greatest effect on the CTE of concrete because aggregate comprises about 70 percent by volume of the concrete.(*35*) Aggregates vary widely in their thermal properties. For example, siliceous aggregates such as chert and quartzite have larger thermal coefficients of expansion than pure limestone, granite, and marble. The CTE of hardened cement paste, which is a function of factors such as water/cement ratio, cement fineness, cement composition, and age, also plays a role in the CTE of concrete.

5.1 Experimental Results

Figure 5.1 shows the CTEs of the six concrete mixes studied as measured by ASTM C351. The values are between 10×10^{-6}/ºC and 12×10^{-6}/ºC for the six concrete mixes, and are ranked in the order of:

CSA-B < Type I/II < CSA-A ≅ CA < Type III-B ≅ Type III-A

Figure 5.2 shows the CTEs measured by CRD C39-81. The values are between 8×10^{-6}/ºC and 11×10^{-6}/ºC across the six concrete mixes, and are ranked in the order of:

Type III-B < Type III-A ≅ Type I/II < CA < CSA-B < CSA-A

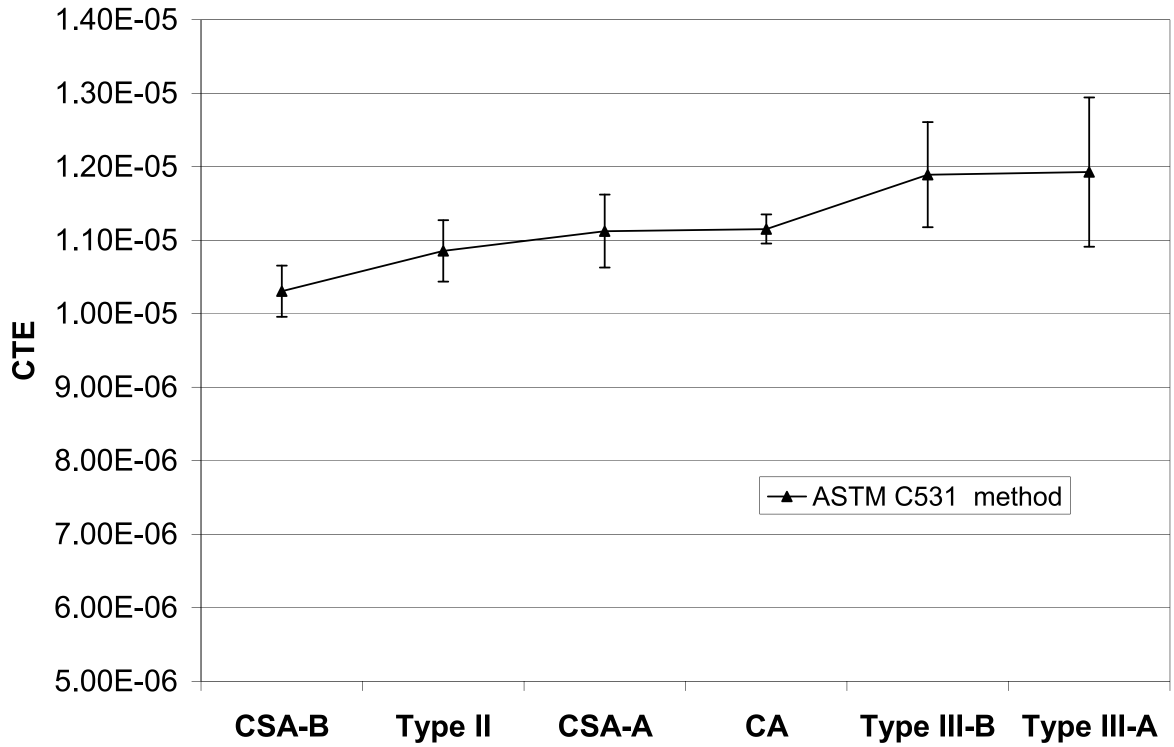

Figure 5.1. Average of coefficient of thermal expansion for each mix by ASTM C531.

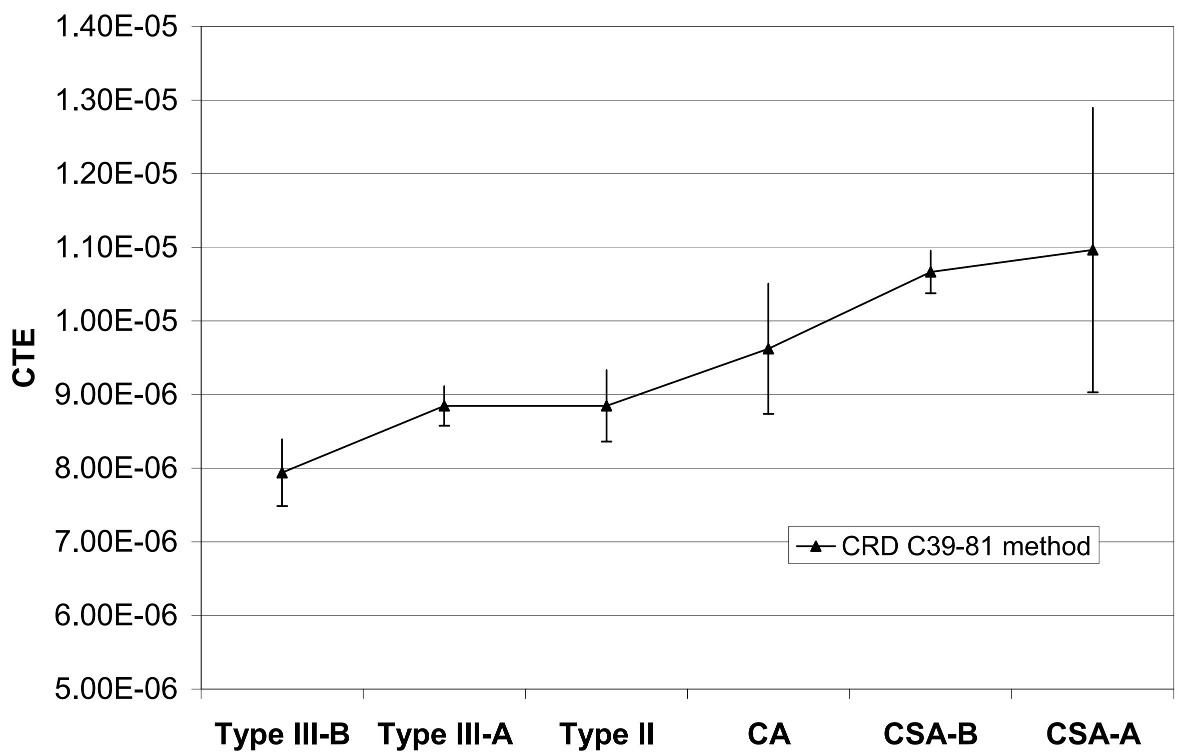

Figure 5.2. Average of coefficient of thermal expansion for each mix by CRD C39-81.

The same coarse aggregate (rounded gravel) was used for five of the six mixes; the exception was the Type III-B mix, which used the crushed stone. Only minor differences exist in the volume of aggregate in the six mixes—the volume of aggregate ranged from 69. 7 to 72.5 percent. The exception was the CA mix, which had 74.1percent aggregate by volume. Therefore, the variation in CTEs among the mixes primarily reflected the variation in cement type and water/cement ratio.

It can be seen from these two figures that the overall CTE values measured using the ASTM method are larger than those measured using the CRD method. In addition, the measured differences between the six concrete mixes are lower using the ASTM method. For concretes made of Calcium Sulfoaluminate cement (CSA-A and CSA-B), the difference in CTE measured by the two methods is negligible. On the other hand, there is a huge difference (15 to 50 percent) for the Type I/II, Type III, and CA cement mixes, as shown in Table 5.1, and as can be seen in Figure 5.3.

Table 5.1 Comparison of the Coefficients of Thermal Expansion Measured by ASTM and CRD Methods

Cement Type	**ASTM**	**CRD**	**(ASTM-CRD)/CRD**
Type III-B	11.9E-06	7.94E-06	49.78%
Type III-A	11.9E-06	8.85E-06	34.84%
Type II	10.9E-06	8.85E-06	22.70%
CA	11.2E-06	9.62E-06	15.90%
CSA-B	10.3E-06	1.07E-05	-3.38%
CSA-A	11.1E-06	11.0E-06	1.47%

The ASTM method measures the length change between 20ºC and 100ºC, and the CRD between 10ºC and 60ºC, as shown in Table 5.2. The reason that the ASTM method produced larger CTE values may be that the higher upper temperature used in the ASTM method causes higher stress levels between the cement paste and the coarse aggregate because of their thermal

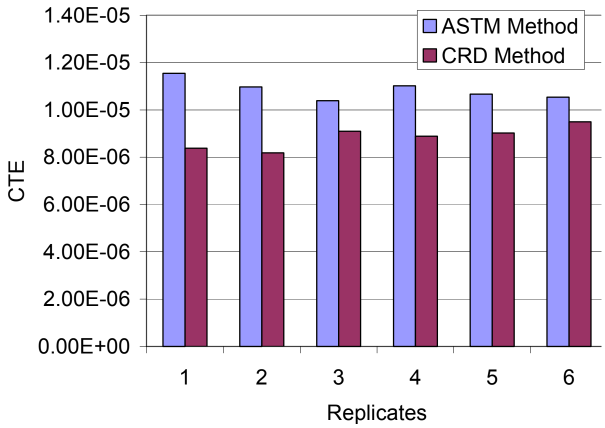

Figure 5.3a. Type I/II-mix.

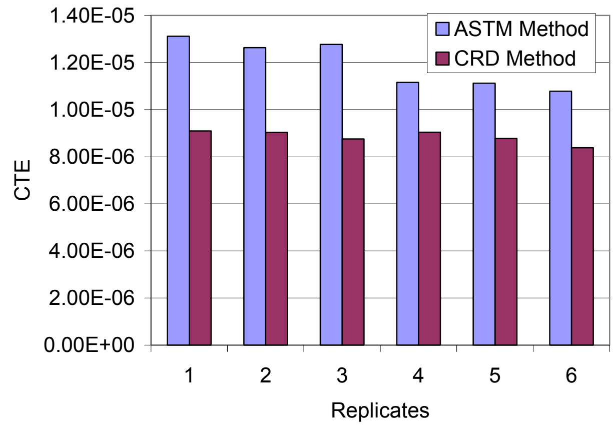

Figure 5.3b. Type III-A mix.

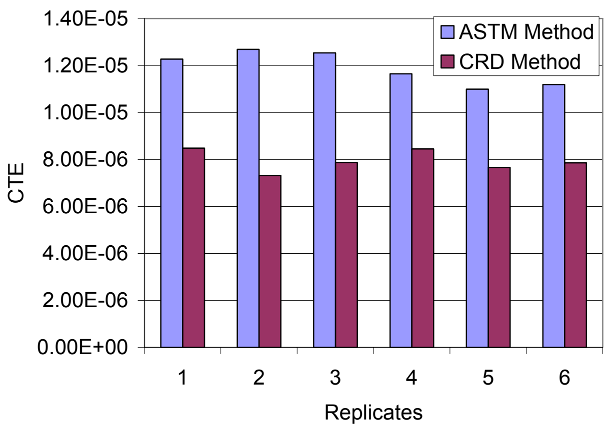

Figure 5.3c. Type III-B-mix.

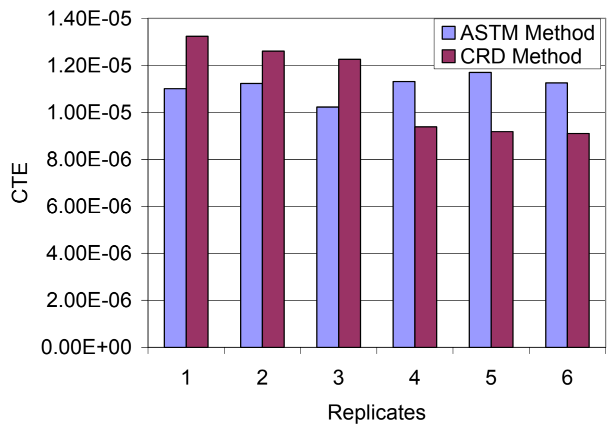

Figure 5.3d. CSA-A-mix.

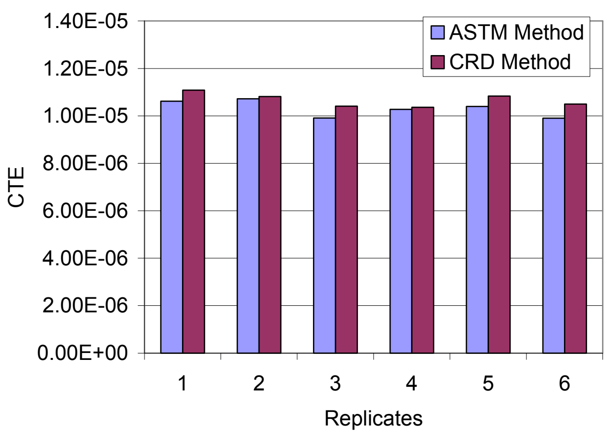

Figure 5.3e. CSA-B-mix.

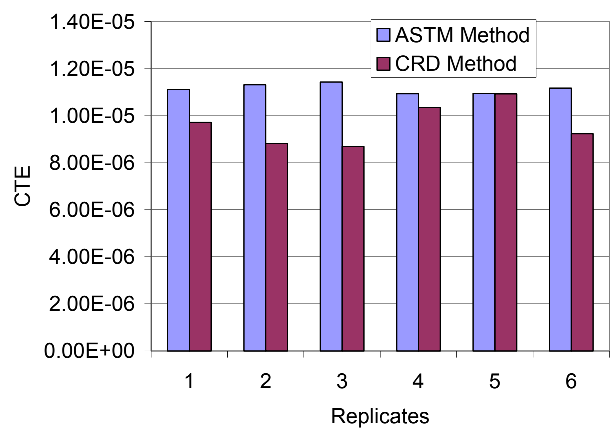

Figure 5.3f. CA-mix.

Figure 5.3. Coefficient of thermal expansion for each mix and each replicate for the ASTM and CRD methods.

Table 5.2 Significance Analysis of Coefficient of Thermal Expansion for the Six Mixes

	Df	Sum of Square	Mean Square	F value	P value
Cement	5	4.083209e-11	8.166418e-12	9.573008	0.00001539728
Residuals	30	2.559201e-011	8.530670e-13		

incompatibility (the difference between their individual CTEs). The CTE of cement pastes typically ranges from 11×10^{-6}/ºC and 16×10^{-6}/ºC, while the CTE of the majority of aggregates lies between 5×10^{-6}/ºC and 13×10^{-6}/ºC.(*35*) It has been suggested that temperatures ranges outside of 4ºC to 60ºC may introduce differential movement and a break in the bond between the aggregate and the surrounding paste if there is a difference in CTEs of the two phases of more than 5.5×10^{-6}/ºC. The break in the bond between the aggregate and surrounding paste causes damage to concrete and "loosens" the particles so that the measured CTEs are larger.(*35*)

The temperature range of 10ºC to 60ºC used by the CRD method is more reasonable for concrete pavement than the range of 20ºC to 100ºC used by the ASTM method because it better represents the temperatures occurring in the field. Therefore, the CRD method would provide more representative CTE measurements for pavement design. Statistical analysis of the significance of mean CTEs for all the six mixes are shown in Table 5.2. The P-value is only 0.0015 percent, indicating that the measured CTE is significantly affected by the mix type.

5.2 Conclusions and Comments

The following conclusions can be made from the study presented in this chapter:

1. The CTEs of the 6 mix designs range from 10 to 12×10^{-6}/ºC by using ASTM C 531, and from 8 to 11×10^{-6}/ºC by using CRD C 39-81. Both ranges fit within what has been reported in the literature for concrete materials. The differences among the six mixes reflected the variations in cement type and concrete mix design.

2. The CRD method uses a more reasonable upper temperature than the ASTM method for pavement applications.
3. The CTE measurements by the CRD method indicate that for the same coarse aggregate sources, the portland cement mixes (Type I/II, Type III-A) have slightly lower CTEs than the CSA mixes.

6.0 SUMMARY AND RECOMMENDATIONS

In this study, six concrete mixes were tested for compressive and flexural strength (Chapter 3), shrinkage (Chapter 4), and coefficient of thermal coefficient (Chapter 5). Each of these performance related properties was measured under various conditions to study the effects of important mix design and construction variables. Statistical analysis was performed to evaluate the importance of factors and the significance of the differences across the experiment variables. The conclusions are summarized as follows.

1. Cement type, curing condition, and water/cement ratio should all be considered important for concrete mix design as the strength gain. The cement type is the most important factor, assuming an optimized mix design. Curing condition follows cement type in terms of significant effect on concrete strength. Finally, the 10-percent increase in water content from the target mix can reduce the strength by more than 10 percent.
2. The compressive and flexural strengths respond differently to environmental factors. A cold environment causes the greatest reduction in compressive strength while a dry condition is most detrimental to the flexural strength. Therefore, there is no unique correlation between the two kinds of strengths. The reasonably accurate prediction of one strength from the other is only possible within a range of curing conditions, and does not include many scenarios that may be encountered in the field. Although the compressive strength test has less variability than the flexural strength test, they are not interchangeable if precise data are needed.

   The correlation between the elastic modulus and compressive strength conformed to what is given in ACI-318 for the portland cement Type I/II mix at 28 days under the standard moist curing. Additional data is needed to extend the conclusion to non-portland cement concrete. The study has shown, however, that the correlation at other ages or under other curing conditions does not conform to ACI-318.

3. While mix design has the greatest effect on concrete strength gain, the curing condition is a more important factor in shrinkage than the mix design. Generally, high temperature and low moisture result in greater shrinkage. However, the extent to which temperature and moisture affect shrinkage depends on the cement type. Calcium sulfoaluminate cements from different manufactures had distinct shrinkage performances because their chemical compositions are very different.
4. The tested coefficient of thermal expansion had a range from 8 to 12 × 10^{-6}/ºC for the group of six mixes included in this study from two measuring methods (ASTM C 531 and CRD C 39-81) (*29*, *26*). These results conform to the data reported in literature. The results of this study show that the CRD method uses a more reasonable temperature range to measure the coefficient of thermal expansion. According to the CRD method, the portland cement mixes have slightly lower coefficient of thermal expansion than calcium sulfoaluminate mixes.

The data included in this report will provide input for mechanistic-empirical analysis of LLPRS-Rigid pavements in the future.

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APPENDIX A – ARMY CORPS OF ENGINEERS TEST CRD-C39-81

CRD-C 39-81

TEST METHOD FOR COEFFICIENT OF LINEAR THERMAL EXPANSION OF CONCRETE

1. Scope

1.1 This method covers the determination of the coefficient of linear thermal expansion of concrete test specimens by determinations of length change due to temperature changes. Because the thermal coefficient of concrete varies with moisture condition, being a minimum when saturated or oven dry and a maximum at about 70 percent saturated, it is important to select the relevant moisture condition for the tests to be made.

2. Apparatus

2.1. The apparatus shall consist of:

2.1.1 Heating Bath - A water bath in which concrete specimens can be maintained at a temperature of 140 ± 2 F (60 ± 1.1 C) (Note 1)

2.1.2 Cooling Bath - A water bath in which concrete specimens can be maintained at a temperature of 40 ± 2 F (5 ± 1.1 C). (Note 1)

2.1.3 Length Comparator (Horizontal), Reference Bars, and Inserts - As described in CRD-C 25. (Note 2)

NOTE 1-In the event that the longer storage time required to achieve temperature equilibrium is tolerable and the use of water baths is not desired, heating and cooling rooms or cabinets may be used.

NOTE 2-When laboratory molded specimens are used, strain meters that can be embedded may be used. Such meters are described in CRD-C 54.

3. Procedure

3.1 General - Tests for coefficient of linear thermal expansion require careful control (± 2 F, ± 1.1 C) of the temperature of the specimen which is being tested for length change. Length determinations shall be conducted only when the specimens are in thermal equilibrium. Tests shall be made to determine the minimum heating and cooling periods for attainment of equilibrium by specimens of any particular size and shape. The period which shall be used will be 25 percent greater than the minimum time to insure equilibrium regardless of aggregate type. Further tests will be necessary to determine the maximum permissible time interval between removal of the specimen from the bath and completion of length determination when measurements are made in air. This maximum time interval shall be established so that no discernible change in length wi occur during the course of the determination.

3.2 Test Conditions- When tests on different specimens are to be compared, the specimen must be in a comparable moisture condition an must be tested over the same temperature range Unless other conditions are specified,[1] it is recommended that specimens be tested in a saturated condition (immersed in water at least 48 hr before the starting of the test) and over the temperature range of 40 to 140 F (5 to 60 C). In cases where the data are to be used to evaluate dr rather than saturated concrete or where therma coefficient over a different temperature range i required, the procedures used should be modified so that the results obtained will be most directl applicable to the pertinent conditions. Where sealed specimens are appropriately employed, th sort described in CRD-C 54 are recommended.

4. Calculation and Report

4.1 The coefficient of linear thermal expansion shall be calculated from the measurements b the use of the following formula:

$$C = \frac{(R_h - R_c)}{G\Delta T}$$

where:

C = coefficient of linear thermal expansion of the concrete 10^{6}/deg F (deg C),

R_h = length reading at higher temperature, in. or mm,

R_c = length reading at lower temperature, in. or mm,

[1] Tests using immersed specimens are reported in "Comparison of Methods of Test for Coefficient of Linear Therm Expansion of Concrete", WES MP 6-108, November 1954.

(Issued 1 Jun. 1981)

G = gage length between inserts, in. or mm, and

ΔT = difference in temperature of specimen between the two length readings, deg F or deg C.

4.2 In cases where the length change has been determined between only two temperatures, a single value will be reported. Where readings of length change have been made at various temperatures, the report should include a curve from which any significant variation in coefficient may be determined. In such cases, the coefficients for the several ranges in temperature shall be stated.

4.3 The report should include the test results calculated as indicated above, adequate information to identify the specimens tested, and information on the moisture conditions, temperatures, and procedures used in the test

5. Interpretation

5.1 Powers and Brownyard[2] discussed the effect of moisture content on volume change o concrete during heating and cooling and stated that "from the above, it follows that the therma coefficient of a given sample of concrete is not a constant, unless the sample is completely dry c saturated." Meyers[3] showed that the thermal coefficients of concrete vary over a wide range under different storage conditions as well as witl the kind of concrete.

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APPENDIX B – MIX DESIGN DATA

TARGET MIXES.

Type I/II Portland Cement

Type I/II Mix Design

Date ***4/18/2000***

SSD **Constituents**	**Units**	*6.5 Sack Mix* **Amount**	*7 Sack Mix* **Amount**	*7.5 Sack Mix* **Amount**		Specific Gravity	Absorption Capacity %
Type II Cement	lb/cy	519	559	599		3.15	
Type F Fly Ash	lb/cy	92	99	106		2.3	
Coarse Agg. (1.5")	lb/cy	0	1199	1165	0%	2.68	1.0
Coarse Agg. (1")	lb/cy	1886	789	767	60%	2.68	0.9
Sand	lb/cy	1257	1167	1135	40%	2.68	2.0
Water	lb/cy	256.62	236.88	253.8			
Air Entrainment	oz/cy	2.14	2.30	2.47	*Micro-Air*		
HRWR	oz/cy	0.00	0.00	0.00	*Rheobuild 3000FC*		
W/C Ratio		0.420	0.36	0.36			

Fly ash Replacement % 15

yellow is what was used

Comments

Mix Design is based on SSD weights for one cubic yard
Variable Sack Design
% Fly Ash Replacement
Type II Cement from Kaiser
Type F Fly Ash from ISG International
Target Air - 3%
Coarse Aggregate -Rounded Gravel
Target Strength = 550 psi at 14 days
Micro-Air from Master Builders
Rheobuild 3000FC from Master Builders

Type III-A Portland Cement

	Type III-A					
					Date	***4/25/2000***
Constituents	**Units**	**Amount**			Specific Gravity	Aggregate
Type III Cement	lb/cy	752			3.15	Absorption
Type F Fly Ash	lb/cy	0		Agg.	2.3	Capacity %
Silica Fume	lb/cy	0.0	0%	Percent	2.2	
Coarse Agg. (1.5")	lb/cy	1186		38%	2.68	1.0
Coarse Agg. (1")	lb/cy	874		28%	2.68	0.9
Sand	lb/cy	1061		34%	2.68	2.0
Water	lb/cy	256.4				
HRWR	oz/cy	30.1	*Rheobuild 3000FC*			
Air Entrainment	oz/cy	0.0	*Micro-Air*			
Accelerator	oz/cy	451.2	*Pozzutec 20*			
Entrapped Air	%	1.5				
W/C Ratio		0.38				

** changed - aggregate percents=38,28,34
-keep all other constituents same.

Comments
Mix Design is based on SSD weights for one cubic yard
8 Sack Design
0% Fly Ash Replacement
0% Silica Fume additional
Type III Cement from Kaiser
Type F Fly Ash from ISG International
Target Air - 1.5%
Coarse Aggregate -Rounded Gravel
Target Strength = 400 psi at 12 hours, 600 psi at 7 days
Rheobuild 3000FC, Micro-Air, and Pozzutec 20 from Master Builders
*Add mix water 1st then Pozzutec 20 and finally Rheobuild into plastic concrete

Type III-B Portland Cement

		Type III-B			Date	5/2/2000
		SSD				
Constituents	**Units**	**Amount**		Agg. Percent.	Specific Gravity	Absorption Capacity %
Type III Cement	lb/cy	800			3.15	
*Coarse Agg. (1")	lb/cy	1852		60%	2.68	0.9
Sand	lb/cy	1235		40%	2.68	2.0
Water	lb/cy	246.4			1	
HRWR	oz/cy	64	*ADVA*			
Accelerator	oz/cy	640.0	*Polarset*			
Stabilizer	oz/cy	0.0	*Recover*			
W/C Ratio		0.36				

Comments

8.5 Sack Design

Type III Cement from Kaiser

*Crushed Stone from Kaiser (Radum 1"x#4)

Target Strength = 400 psi at 4 to 12 hours, 600 psi at 7-days

Slump = 3 to 5 inches

Water = Mix water plus accelerator water (8.33 lbs/gal)

Polarset and ADVA from W.R. Grace

-add Polarset after mix Water and ADVA in plastic concrete

-add Recover in dry mix

Calcium Sulfoaluminate A

	CSA-A Mix Design				***Date***	***5/18/2000***
		7 Sack Mix	*7.5 Sack Mix*		Specific	Aggregate
Constituents	**Units**	**Amount**	**Amount**	*Aggregate*	Gravity	Absorption
Rapid Set Cement	lb/cy	658	705	*Percentages*	3.00	Capacity %
Coarse Agg. (1.5")	lb/cy	589	557	18%	2.68	1.0
Coarse Agg. (1")	lb/cy	1474	1391	45%	2.68	0.9
Sand	lb/cy	1212	1144	37%	2.68	2.0
Water	lb/cy	243.5	296.1			
Melament	oz/cy	164.5	176.3			
Recover	oz/cy	98.7	105.8			
Citric Acid	lb/cy	0.00	0.00			
W/C Ratio		0.37	0.42			
Entrapped Air		0.0%	0.0%			

Comments
7 & 7.5 Sack Design - start here
Coarse Aggregate -Rounded Gravel
1.0 hour until final set
Melament is Daracem ML 330 by W.R. Grace

Calcium Sulfoaluminate B

CSA-B Mix Design

Date ***6/16/2000***

Constituents	**Units**	**Amount**	Agg. Percent.	Specific Gravity	Aggregate Absorption Capacity %
Ultimax Cement	lb/cy	700		2.95	
Fly Ash	lb/cy	0		2.3	
Coarse Agg. (1.5")	lb/cy	790	25%	2.68	1.0
Coarse Agg. (1")	lb/cy	947	30%	2.68	0.9
Sand	lb/cy	1422	45%	2.68	2.0
Water	lb/cy	252			
ADVA	oz/cy	40			
UC Delay	oz/cy	70			
Entrapped Air	%	1			
W/C Ratio		0.37			

Comments

Mix Design is based on SSD weights for one cubic yard
7.5 Sack Design
Coarse Aggregate -Rounded Gravel
Target Strength = 400 psi at 4 hours, 600 psi at 7-days
Target Slump = 5 inches
Initial Setting Time = 90 minutes
Final Set = 110 minutes

Calcium Aluminate

CA Mix Design — ***Date*** ***3/19/2001***

Constituents	**Units**	*7 Sack Mix* **Amount**	*7.5 Sack Mix* **Amount**	*8.0 Sack Mix* **Amount**	*Aggregate Percentages*	Specific Gravity	Aggregate Absorption Capacity %
Lafarge CA Cement	lb/cy	658	705	752		3.00	
Coarse Agg. (1.5")	lb/cy	0	0	0		2.68	1.0
Coarse Agg. (1")	lb/cy	1946	1837	1782	60%	2.68	0.9
Sand	lb/cy	1297	1225	1188	40%	2.68	2.0
Water	lb/cy	230.3	282	300.8			
W/C Ratio		0.35	0.40	0.40			
Entrapped Air		1.5%	1.5%	1.5%			

Comments
7 Sack Design - start here
Coarse Aggregate -Rounded Gravel
Target Strength = 400 psi at 8 to 12 hours, 600 psi at 7 days
Target Slump = 3 to 4 inches
* don't think admixtures will be needed
Aggregate Ratio (Coarse to fine) - 66% to 34%

+ 10% WATER MIXES

Type I/II Portland Cement (+10% w)

		Type I/II + 10% Water					
					Date	***4/18/2000***	
SSD		*6.5 Sack Mix*	*7 Sack Mix*	*7.5 Sack Mix*			
Constituents	**Units**	**Amount**	**Amount**	**Amount**		Specific Gravity	Absorption
Type II Cement	lb/cy	519	559	599		3.15	Capacity %
Type F Fly Ash	lb/cy	92	99	106		2.3	
Coarse Agg. (1.5")	lb/cy	1198	1199	1165	38%	2.68	1.0
Coarse Agg. (1")	lb/cy	788	789	767	25%	2.68	0.9
Sand	lb/cy	1166	1167	1135	37%	2.68	2.0
Water	lb/cy	278.9215	236.88	253.8			
Air Entrainment	oz/cy	2.14	2.30	2.47	*Micro-Air*		
HRWR	oz/cy	0.00	0.00	0.00	*Rheobuild 3000FC*		
W/C Ratio		0.457	0.36	0.36			
	Fly ash Replacement %		15				

Comments
Mix Design is based on SSD weights for one cubic yard
Variable Sack Design
% Fly Ash Replacement
Type II Cement from Kaiser
Type F Fly Ash from ISG International
Target Air - 3%
Coarse Aggregate -Rounded Gravel
Target Strength = 550 psi at 14 days
Micro-Air from Master Builders
Rheobuild 3000FC from Master Builders

Type III-A Portland Cement (+10% w)

Type III-A + 10% Water

Date ***4/25/2000***

Constituents	Units	Amount		Agg. Percent	Specific Gravity	Aggregate Absorption Capacity %
Type III Cement	lb/cy	752			3.15	
Type F Fly Ash	lb/cy	0			2.3	
Silica Fume	lb/cy	0.0	0%		2.2	
Coarse Agg. (1.5")	lb/cy	1186		38%	2.68	1.0
Coarse Agg. (1")	lb/cy	874		28%	2.68	0.9
Sand	lb/cy	1061		34%	2.68	2.0
Water	lb/cy	285.0				
HRWR	oz/cy	30.1	*Rheobuild 3000FC*			
Air Entrainment	oz/cy	0.0	*Micro-Air*			
Accelerator	oz/cy	451.2	*Pozzutec 20*			
Entrapped Air	%	1.5				
W/C Ratio		0.418				

** changed - aggregate percents=38,28,34
-keep all other constituents same.

Comments

Mix Design is based on SSD weights for one cubic yard
8 Sack Design
0% Fly Ash Replacement
0% Silica Fume additional
Type III Cement from Kaiser
Type F Fly Ash from ISG International
Target Air - 1.5%
Coarse Aggregate -Rounded Gravel
Target Strength = 400 psi at 12 hours, 600 psi at 7 days
Rheobuild 3000FC, Micro-Air, and Pozzutec 20 from Master Builders
*Add mix water 1st then Pozzutec 20 and finally Rheobuild into plastic concrete

Type III-B Portland Cement (+10% w)

Type III-B + 10% Water

Date ***5/5/2000***

Constituents	**Units**	***SSD*** **Amount**		Agg. Percent.	Specific Gravity	Absorption Capacity %
Type III Cement	lb/cy	800			3.15	
*Coarse Agg. (1")	lb/cy	1852		60%	2.68	0.9
Sand	lb/cy	1235		40%	2.68	2.0
Water	lb/cy	275.2			1	
HRWR	oz/cy	64	*ADVA*			
Accelerator	oz/cy	640.0	*Polarset*			
Stabilizer	oz/cy	0.0	*Recover*			
W/C Ratio		0.40				

Comments

8.5 Sack Design
Type III Cement from Kaiser
*Crushed Stone from Kaiser (Radum 1"x#4)
Target Strength = 400 psi at 8 hours, 600 psi at 7-days
Slump = 3 to 5 inches
Water = Mix water plus accelerator water (8.33 lbs/gal)
Polarset and ADVA from W.R. Grace
-add Polarset after mix Water and ADVA in plastic concrete
-add Recover in dry mix
- test times = 8 and 24 hours, 7 and 90 days.

Calcium Sulfoaluminate A (+10% w)

	CSA-A + 10% Water Mix Design				***Date***	***5/26/2000***
		7 Sack Mix	*7.5 Sack Mix*		Specific	Aggregate
Constituents	**Units**	**Amount**	**Amount**	*Aggregate*	Gravity	Absorption
Rapid Set Cement	lb/cy	658	705	*Percentages*	3.00	Capacity %
Coarse Agg. (1.5")	lb/cy	589	557	18%	2.68	1.0
Coarse Agg. (1")	lb/cy	1474	1391	45%	2.68	0.9
Sand	lb/cy	1212	1144	37%	2.68	2.0
Water	lb/cy	267.8	296.1			
Melament	oz/cy	164.5	176.3			
Recover	oz/cy	98.7	105.8			
Citric Acid	lb/cy	0.00	0.00			
W/C Ratio		0.41	0.42			
Entrapped Air		0.0%	0.0%			

Comments
7 & 7.5 Sack Design - start here
Coarse Aggregate -Rounded Gravel
1.0 hour until final set
Melament is Daracem ML 330 by W.R. Grace

Calcium Sulfoaluminate B (+10% w)

CSA-B Mix + 10% Water Design

Date ***6/16/2000***

Constituents	Units	Amount	Agg. Percent.	Specific Gravity	Aggregate Absorption Capacity %
Ultimax Cement	lb/cy	700		2.95	
Fly Ash	lb/cy	0		2.3	
Coarse Agg. (1.5")	lb/cy	790	25%	2.68	1.0
Coarse Agg. (1")	lb/cy	947	30%	2.68	0.9
Sand	lb/cy	1422	45%	2.68	2.0
Water	lb/cy	278			
ADVA	oz/cy	40			
UC Delay	oz/cy	70			
Entrapped Air	%	1			
W/C Ratio		0.41			

Comments

Mix Design is based on SSD weights for one cubic yard
7.5 Sack Design
Coarse Aggregate -Rounded Gravel
Target Strength = 400 psi at 4 hours, 600 psi at 7-days
Target Slump = 5 inches
Initial Setting Time = 90 minutes
Final Set = 110 minutes

Calcium Aluminate (+10% w)

CA + 10% Water Mix Design | **Date** 4/11/2000

Constituents	**Units**	*7 Sack Mix* **Amount**	*7.5 Sack Mix* **Amount**	*8.0 Sack Mix* **Amount**	*Aggregate Percentages*	Specific Gravity	Aggregate Absorption Capacity %
Lafarge CA Cement	lb/cy	658	705	752		3.00	
Coarse Agg. (1.5")	lb/cy	0	0	0		2.68	1.0
Coarse Agg. (1")	lb/cy	1977	1837	1782	60%	2.68	0.9
Sand	lb/cy	1318	1225	1188	40%	2.68	2.0
Water	lb/cy	210.56	282	300.8			
W/C Ratio		0.32	0.40	0.40			
Entrapped Air		1.5%	1.5%	1.5%			

Comments

7 Sack Design - start here
Coarse Aggregate -Rounded Gravel
Target Strength = 400 psi at 8 to 12 hours, 600 psi at 7 days
Target Slump = 3 to 4 inches
* don't think admixtures will be needed
Aggregate Ratio (Coarse to fine) - 66% to 34%

ALL MIXES DESIGNED AND EVALUATED TO FIND OPTIMAL MIXES.

Mix Design	Number of sacks and Specimen Name	Specimen Age	molded	tested	Measured Strength (psi)	Corrected Strength (psi)	Average Width (in.)	Average Depth (in.)	Length (in)
Batch Date	*11/23/1998*								
Type I/II	CT1123-5A	7 Days	11/23/1998	11/30/1998	315	309	6.00	6.06	21
	CT1123-5B	7 Days	11/23/1998	11/30/1998	310	307	6.13	5.97	21
	CT1123-5C	14 Days	11/23/1998	12/7/1998	400	404	6.00	5.97	21
	CT1123-5D	28 Days	11/23/1998	12/21/1998	398	398	6.00	6.00	21
Type I/II	CT1123-5.5A	7 Days	11/23/1998	11/30/1998	280	289	5.94	5.94	21
	CT1123-5.5B	7 Days	11/23/1998	11/30/1998	270	276	5.88	6.00	21
	CT1123-5.5C	14 Days	11/23/1998	12/7/1998	370	374	6.00	5.97	21
	CT1123-5.5D	28 Days	11/23/1998	12/21/1998	358	369	5.94	5.94	21
Type I/II	CT1123-6A	7 Days	11/23/1998	11/30/1998	235	235	6.00	6.00	21
	CT1123-6B	7 Days	11/23/1998	11/30/1998	265	265	6.00	6.00	21
	CT1123-6C	14 Days	11/23/1998	12/7/1998	350	356	5.97	5.97	21
	CT1123-6D	28 Days	11/23/1998	12/21/1998	330	333	6.00	5.97	21
	12/7/1998								
Type I/II	CT1207-5A	7 Days	12/7/1998	12/14/1998	450	445	6.06	6.00	21
	CT1207-5B	14 Days	12/7/1998	12/21/978	520	520	6.00	6.00	21
	CT1207-5C	14 Days	12/7/1998	12/21/1998	528	528	6.00	6.00	21
	CT1207-5D	28 Days	12/7/1998	1/4/1999	550	553	5.97	6.00	21
Type I/II	CT1207-5.5A	7 Days	12/7/1998	12/14/1998	415	409	6.09	6.00	21
	CT1207-5.5B	14 Days	12/7/1998	12/21/978	543	532	6.00	6.06	21
	CT1207-5.5C	14 Days	12/7/1998	12/21/1998	490	480	6.00	6.06	21
	CT1207-5.5D	28 Days	12/7/1998	1/4/1999	500	508	5.97	5.97	21
Type I/II	CT1207-6A	7 Days	12/7/1998	12/14/1998	450	445	6.06	6.00	21
	CT1207-6B	14 Days	12/7/1998	12/21/978	500	490	6.00	6.06	21
	CT1207-6C	14 Days	12/7/1998	12/21/1998	488	488	6.00	6.00	21
	CT1207-6D	28 Days	12/7/1998	1/4/1999	510	515	6.00	5.97	21
Batch Date	12/2/1998								
Type III-B	MB1202-8.5A	4 Hours	12/2/1998	12/2/1998	110	110	6.00	6.00	21
	MB1202-8.5B	8 Hours	12/2/1998	12/2/1998	298	300	5.97	6.00	21
	MB1202-8.5C	1 Day	12/2/1998	12/3/1998	520	520	6.00	6.00	21
	MB1202-8.5D	7 days	12/2/1998	12/9/1998	670	670	6.00	6.00	21
Batch Date	12/3/1998								
Type III-B	MB1203-8.5A	4 Hours	12/3/1998	12/3/1998	100	100	6.00	6.00	21
	MB1203-8.5B	8 Hours	12/3/1998	12/3/1998	245	248	6.06	5.94	21
	MB1203-8.5C	1 Day	12/3/1998	12/4/1998	515	512	6.03	6.00	21
	MB1203-8.5D	7 Days	12/3/1998	12/10/1998	825	825	6.06	5.97	21

Mix Design	Number of sacks and Specimen Name	Specimen Age	molded	tested	Measured Strength (psi)	Corrected Strength (psi)	Average Width (in.)	Average Depth (in.)	Length (in)
Batch Date	12/7/1998	First Batch							
Type III-B	WRG1207-8.5A	4 Hours	12/7/1998	12/7/1998	100	100	6.00	6.00	21
	WRG1207-8.5B	8 Hours	12/7/1998	12/7/1998	295	303	5.97	5.94	21
	WRG1207-8.5C	1 Day	12/7/1998	12/8/1998	550	556	6.00	5.97	21
	WRG1207-8.5D	7 Days	12/7/1998	12/14/1998	812	821	6.00	5.97	21
Batch Date	12/7/1998	Second Batch							
Type III-B	WRG1207-8.5A	28 Days	12/7/1998	1/4/1998	-	-	6.00	6.00	21
	WRG1207-8.5B	8 Hours	12/7/1998	12/7/1998	220	225	6.00	5.94	21
	WRG1207-8.5C	1 Day	12/7/1998	12/8/1998	590	599	5.97	5.97	21
	WRG1207-8.5D	7 days	12/7/1998	12/14/1998	1000	1000	6.00	6.00	21
Batch Date	12/10/1998								
Type III-A	UC1210-7.5A	20 Hours	12/10/98 10:40 AM	12/11/98 7:00 AM	430	430	6.00	6.00	21
	UC1210-7.5B	7 Day	12/10/98 10:40 AM	12/23/98 11:40 AM	670	677	6.00	5.97	21
	UC1210-7.5C	7 Day	12/10/98 10:40 AM	12/23/98 11:40 AM	605	611	6.00	5.97	21
	UC1210-7.5D	32 days	12/10/98 10:40 AM	1/12/99 11:40 AM	445	445	6.00	6.00	21
Batch Date	12/14/1998								
Type III-A	UC1214-7.5A	8 Hours	12/14/98 12:00 AM	12/14/98 12:00 AM	205	203	6.00	6.03	21
	UC1214-7.5B	12 Hours	12/14/98 12:00 AM	12/14/98 12:00 AM	340	347	6.00	5.94	21
	UC1214-7.5C	24 Hours	12/14/98 12:00 AM	12/15/98 12:00 AM	500	508	5.97	5.97	21
	UC1214-7.5D	7 days	12/14/98 12:00 AM	12/21/98 12:00 AM	735	743	5.94	6.00	21
Batch Date	12/15/1998								
CA	LAF1215-7A	8 Hours	12/15/1998 10:00	12/15/1998 10:00	600	600	6.00	6.00	21
	LAF1215-7B	24 Hours	12/15/1998 10:00	12/16/1998 10:00	610	616	6.00	5.97	21
	LAF1215-7C	7 Days	12/15/1998 2:05	12/22/1998 2:05	855	851	6.09	5.97	21
	LAF1215-7D	28 Days	12/15/1998 2:05	1/13/1998 2:05	684	684	6.00	6.00	21
CA	LAF1215-7.5A	7 Hours	12/15/1998 11:10	12/15/1998 7:10	660	660	6.00	6.00	21
	LAF1215-7.5B	24 Hours	12/15/1998 11:10	12/16/1998 11:10	780	792	5.97	5.97	21
	LAF1215-7.5C	7 Days	12/15/1998 2:05	12/22/1998 2:05	990	985	6.03	6.00	21
	LAF1215-7.5D	28 Days	12/15/1998 2:05	1/13/1998 2:05	665	665	6.00	6.00	21
CA	LAF1215-8A	8 Hours	12/15/1998 2:05	12/15/1998 10:05	680	702	5.94	5.94	21
	LAF1215-8B	24 Hours	12/15/1998 2:05	12/16/98 12:40 AM	835	835	6.00	6.00	21
	LAF1215-8C	7 Days	12/15/1998 2:05	12/22/1998 2:05	938	953	5.97	5.97	21
	LAF1215-8D	28 Days	12/15/1998 2:05	1/13/1998 2:05	710	710	6.00	6.00	21

Mix Design	Number of sacks and Specimen Name	Specimen Age	molded	tested	Measured Strength (psi)	Corrected Strength (psi)	Average Width (in.)	Average Depth (in.)	Length (in)
Batch Date	12/16/1998								
CSA-B	ULT1216-8A	4 Hours	12/16/98 12:30 AM	12/16/98 4:30 PM	350	350	6.00	6.00	21
	ULT1216-8B	8 Hours	12/16/98 12:30 AM	12/16/98 8:30 PM	415	419	6.00	5.97	21
	ULT1216-8C	27 Hours	12/16/98 12:30 AM	12/17/98 2:30 PM	600	607	6.00	5.97	21
	ULT1216-8D	7 Days	12/16/98 12:30 AM	12/23/98 12:30 PM	648	648	6.00	6.00	21
CSA-B	ULT1216-7A	4 Hours	12/16/98 3:45 PM	12/16/98 7:45 PM	300	300	6.00	6.00	21
	ULT1216-7B	23 Hours	12/16/98 3:45 PM	12/17/98 2:45 PM	560	569	5.97	5.97	21
	ULT1216-7C	7 Days	12/16/98 3:45 PM	12/23/98 2:45 PM	600	607	6.00	5.97	21
	ULT1216-7D	28 Days	12/16/98 3:45 PM	1/13/98 3:45 PM	540	540	6.00	6.00	21
Batch Date	12/18/1998								
Type III-B	MB1218-8.5A	4 Hours	12/18/98 10:15 AM	12/18/98 3:00 PM	220	218	6.06	6.00	21
	MB1218-8.5B	8 Hours	12/18/98 10:15 AM	12/18/98 6:15 PM	315	313	6.09	5.97	21
	MB1218-8.5C	24 Hours	12/18/98 10:15 AM	12/19/98 10:15 AM	525	531	6.00	5.97	21
	MB1218-8.5D	7 Days	12/18/98 10:15 AM	12/25/98 10:15 PM	795	795	6.00	6.00	21
Batch Date	12/21/1998								
CSA-A	CSA-A1221-7A	4 Hours	12/21/98 11:15 AM	12/21/98 3:15 AM	400	400	6.00	6.00	21
	CSA-A1221-7B	8 Hours	12/21/98 11:15 AM	12/21/98 7:15 PM	437	437	6.06	5.97	21
	CSA-A1221-7C	24 Hours	12/21/98 11:15 AM	12/22/98 11:15 AM	475	465	6.06	6.03	21
	CSA-A1221-7D	7 Days	12/21/98 11:15 AM	12/28/98 12:20 AM	545	545	6.00	6.00	21
Batch Date	12/21/1998								
CSA-A	CSA-A1221-7.5A	4 Hours	12/21/98 12:20 AM	12/21/98 4:20 AM	410	406	6.06	6.00	21
	CSA-A1221-7.5B	8 Hours	12/21/98 12:20 AM	12/21/98 8:20 AM	497	497	6.06	5.97	21
	CSA-A1221-7.5C	24 Hours	12/21/98 12:20 AM	12/22/98 12:20 AM	545	534	6.06	6.03	21
	CSA-A1221-7.5D	7 Days	12/21/98 12:20 AM	12/28/98 12:20 AM	615	615	6.00	6.00	21
Batch Date	1/5/1999								
Type I/II	CT105-6A	7 Days	1/5/99 12:00PM	1/12/99 12:00 PM	310	304	6.00	6.06	21
	CT105-6B	14 Days	1/5/99 12:00PM	1/19/99 12:00PM	370	362	6.13	6.00	21
	CT105-6C	14 Days	1/5/99 12:00PM	1/19/99 12:00PM	315	318	6.00	5.97	21
	CT105-6D	28 Days	1/5/99 12:00PM	2/2/99 12:00PM	391	393	6.03	5.97	21

Mix Design	Number of sacks and Specimen Name	Specimen Age	molded	tested	Measured Strength (psi)	Corrected Strength (psi)	Average Width (in.)	Average Depth (in.)	Length (in)
Batch Date	1/5/1999								
Type I/II	CT105-6.5A	7 Days	1/5/99 2:00PM	1/12/99 2:00 PM	330	327	6.06	6.00	21
	CT105-6.5B	14 Days	1/5/99 2:00PM	1/19/99 2:00PM	390	386	6.06	6.00	21
	CT105-6.5C	14 Days	1/5/99 2:00PM	1/19/99 2:00PM	411	403	6.06	6.03	21
	CT105-6.5D	28 Days	1/5/99 2:00PM	2/2/99 2:00PM	409	405	6.00	6.03	21
Batch Date	1/5/1999								
Type I/II	CT105-7A	7 Days	1/5/99 3:00 PM	1/12/99 3:00 PM	345	345	6.00	6.00	21
	CT105-7B	14 Days	1/5/99 3:00 PM	1/19/99 3:00PM	451	446	6.06	6.00	21
	CT105-7C	14 Days	1/5/99 3:00 PM	1/19/99 3:00PM	399	399	6.00	6.00	21
	CT105-7D	28 Days	1/5/99 3:00 PM	2/2/99 3:00PM	370	368	6.03	6.00	22
Batch Date	1/8/1999								
Type III-A	Type III-A108-7.5A	8 Hours	1/8/99 10:15 AM	1/8/99 6:15 PM	195	197	6.00	5.97	21
	Type III-A108-7.5B	24 Hours	1/8/99 10:15 AM	1/9/99 10:15 PM	300	300	6.06	5.97	21
	Type III-A108-7.5C	14 Days	1/8/99 10:15 AM	1/22/99 10:15 AM	485	480	6.06	6.00	21
	Type III-A108-7.5D	28 Days	1/8/99 10:15 AM	2/5/99 10:15 AM	464	459	6.06	6.00	21
Batch Date	1/8/1999								
CA	LAF108-7A	4 Hours	1/8/99 11:40 AM	1/8/99 3:40 PM	360	360	6.00	6.00	21
	LAF108-7B	8 Hours	1/8/99 11:40 AM	1/8/99 7:40 PM	465	470	6.00	5.97	21
	LAF108-7C	11 Hours	1/8/99 11:40 AM	1/8/99 10:30 PM	450	455	6.00	5.97	21
	LAF108-7D	24 Hours	1/8/99 11:40 AM	1/9/99 11:40 AM	490	490	6.00	6.00	21
Batch Date	**3/19/1999**								
Type I/II	CT319-6A	7 Days	3/19/99 9:35 AM	3/26/99 9:35 AM	240	240	6.00	6.00	21
	CT319-6B	14 Days	3/19/99 9:35 AM	4/2/99 9:35 AM	367	371	6.00	5.97	21
	CT319-6C	14 Days	3/19/99 9:35 AM	4/2/99 9:35 AM	319	322	6.00	5.97	21
	CT319-6D	30 Days	3/19/99 9:35 AM	4/19/99 9:35 AM	385	385	6.00	6.00	21
Type I/II	CT319-6.5A	7 Days	3/19/99 3:00 PM	3/26/99 9:35 AM	340	340	6.00	6.00	21
	CT319-6.5B	14 Days	3/19/99 3:00 PM	4/2/99 9:35 AM	339	343	6.00	5.97	21
	CT319-6.5C	14 Days	3/19/99 3:00 PM	4/2/99 9:35 AM	380	384	6.00	5.97	21
	CT319-6.5D	30 Days	3/19/99 3:00 PM	4/19/99 9:35 AM	500	500	6.00	6.00	21
Type I/II	CT319-7A	7 Days	3/19/99 3:30 PM	3/26/99 9:35 AM	300	300	6.00	6.00	21
	CT319-7B	14 Days	3/19/99 3:30 PM	4/2/99 9:35 AM	357	361	6.00	5.97	21
	CT319-7C	14 Days	3/19/99 3:30 PM	4/2/99 9:35 AM	350	354	6.00	5.97	21
	CT319-7D	30 Days	3/19/99 3:30 PM	4/19/99 9:35 AM	450	450	6.00	6.00	21
25% FLY ASH CONTENT									
Type I/II	CT319-6.5A	7 Days	3/19/99 3:00 PM	3/26/99 9:35 AM	285	282	6.06	6.00	21
	CT319-6.5B	14 Days	3/19/99 3:00 PM	4/2/99 9:35 AM	340	344	6.00	5.97	21
	CT319-6.5C	14 Days	3/19/99 3:00 PM	4/2/99 9:35 AM	360	364	6.00	5.97	21
	CT319-6.5D	30 Days	3/19/99 3:00 PM	4/19/99 9:35 AM	395	395	6.00	6.00	21

Mix Design	Number of sacks and Specimen Name	Specimen Age	molded	tested	Measured Strength (psi)	Corrected Strength (psi)	Average Width (in.)	Average Depth (in.)	Length (in)
Batch Date	3/23/1999								
CA	LAF323-7A	4 Hours	3/23/99 1:00 PM	3/23/99 5:00 PM	255	255	6.00	6.00	21
	LAF323-7B	8 Hours	3/23/99 1:00 PM	3/23/99 9:00 PM	440	440	6.00	6.00	21
	LAF323-7C	44 Hours	3/23/99 1:00 PM	3/24/99 1:00 PM	607	613	6.00	5.97	21
	LAF323-7D	7 DAYS	3/23/99 1:00 PM	3/30/99 1:00 PM	640	554	7.00	5.97	21
Batch Date	3/29/1999								
Type III-A 5% Silica Fume	Type III-A0329-7A1	8 Hours	3/29/99 10:55 AM	3/29/99 10:55 AM	195	197	6.00	5.97	21
	Type III-A0329-7B1	12 Hours	3/29/99 10:55 AM	3/29/99 10:55 AM	280	280	6.06	5.97	21
	Type III-A0329-7C1	24 Hours	3/29/99 10:55 AM	3/30/99 10:55 AM	380	376	6.06	6.00	21
	Type III-A0329-7D1	7 Days	3/29/99 10:55 AM	4/5/99 10:55 AM	535	529	6.06	6.00	21
Type III-A 7.5% Silica Fume	Type III-A0329-7A2	8 Hours	3/29/99 11:50 AM	3/29/99 11:50 AM	190	192	6.00	5.97	21
	Type III-A0329-7B2	12 Hours	3/29/99 11:50 AM	3/29/99 11:50 AM	257	257	6.06	5.97	21
	Type III-A0329-7C2	24 Hours	3/29/99 11:50 AM	3/30/99 11:50 AM	380	376	6.06	6.00	21
	Type III-A0329-7D2	7 Days	3/29/99 11:50 AM	4/5/99 11:50 AM	490	485	6.06	6.00	21
	[1] First mix								
	[2] Second mix								
Batch Date	4/7/1999								
CA	LAF407-7A	4 Hours	4/7/99 9:30 AM	4/7/99 1:30 PM	185	185	6.00	6.00	21
	LAF407-7B	8 Hours	4/7/99 9:30 AM	4/7/99 5:30 PM	480	480	6.00	6.00	21
	LAF407-7C	25 Hours	4/7/99 9:30 AM	4/7/99 9:30 PM	545	551	6.00	5.97	21
	LAF407-7D	12 Days	4/7/99 9:30 AM	4/19/99 9:30 AM	565	571	6.00	5.97	21
		Swiched to Metric System							
Batch Date	1/27/2000								
25% FLY ASH CONTENT									
Type I/II	CT012700-7.5AFS	7 Days	1/27/00 4:00 PM	2/4/00 4:00 PM	460	492	5.94	5.83	21
	CT012700-7.5BFS	14 Days	1/27/00 4:00 PM	2/11/00 4:00 PM		0	6.00	5.97	21
	CT012700-7.5CFS	PRACTICE	1/27/00 4:00 PM	2/9/2000 12:00		0	6.00	5.97	21
	CT012700-7.5DFS	28 Days	1/27/00 4:00 PM	2/25/00 4:00 PM	424	424	6.00	6.00	21
Batch Date	1/27/2000								
25% FLY ASH CONTENT									
Type I/II	CT012700-7AFS	7 Days	1/27/00 5:00 PM	2/4/00 5:00 PM	468	496	5.91	5.87	21
	CT012700-7BFS	14 Days	1/27/00 5:00 PM	2/11/00 5:00 PM		0	6.00	5.97	21
	CT012700-7CFS	PRACTICE	1/27/00 5:00 PM	2/9/00 12:00 PM		0	6.00	5.97	21
	CT012700-7DFS	28 Days	1/27/00 5:00 PM	2/25/00 5:00 PM	458	458	6.00	6.00	21
Batch Date	1/31/2000								
Type III-B (Rounded Stone)	WRG013000-8.5AFS	8 Hours	1/31/00 11:00 PM	1/31/00 7:00 PM	440	440	6.00	6.00	21
	WRG013000-8.5BFS	24 Hours	1/31/00 11:00 PM	1/31/00 11:00 PM	597	660	5.91	5.75	21
	WRG013000-8.5CFS	7 Day	1/31/00 11:00 PM	1/31/00 11:00 PM	871	937	5.91	5.83	21
	WRG013000-8.5DFS	PRACTICE	1/31/00 11:00 PM	1/31/00 11:00 PM		0	6.00	5.97	21

Mix Design	Number of sacks and Specimen Name	Specimen Age	molded	tested	Measured Strength (psi)	Corrected Strength (psi)	Average Width (in.)	Average Depth (in.)	Length (in)
Batch Date	2/2/2000								
Type III-B (Crushed Stone)	WRG020200-8.5AFS	8 Hours	2/2/00 11:15 PM	2/2/00 7:15 PM	512	512	6.00	6.00	21
	WRG020200-8.5BFS	24 Hours	2/2/00 11:15 PM	2/3/00 11:15 PM	763	783	5.97	5.94	21
	WRG020200-8.5CFS	7 Day	2/2/00 11:15 PM	2/9/00 11:15 PM	1013	1024	6.00	5.97	21
	WRG020200-8.5DFS	PRACTICE	2/2/00 11:15 PM	2/9/00 11:15 PM		0	6.00	5.97	21
Batch Date	2/2/2000								
Type III-A	UC020200-7AFS	8 Hours	2/2/00 12:30 PM	2/2/00 10:15 AM	276	279	6.00	5.97	21
	UC020200-7BFS	24 Hours	2/2/00 12:30 PM	2/3/00 12:30 PM	480	480	6.06	5.97	21
	UC020200-7CFS	7 Days	2/2/00 12:30 PM	2/9/00 12:30 PM	583	611	6.00	5.86	21
	UC020200-7DFS	PRACTICE	2/2/00 12:30 PM	2/9/00 12:30 PM		0	6.06	6.00	21
Batch Date	2/8/2000								
CA (First Batch)	LF020800-7A1fs	8 Hours	2/8/00 10:00 AM	2/8/00 6:00 PM	770	747	5.98	6.10	21
	LF020800-7B1fs	24 Hours	2/8/00 10:00 AM	2/9/00 10:00 AM	940	940	6.00	6.00	21
	LF020800-7C1fs	7 Days	2/8/00 10:00 AM	2/15/00 10:00 AM	1084	1095	6.00	5.97	21
	LF020800-7D1fs	28 Days	2/8/00 10:00 AM	3/7/00 10:00 AM		0	6.00	5.97	21
Batch Date	2/8/2000								
CA (Second Batch)	LF020800-7Afs	4 Hours	2/8/00 12:00 PM	2/8/00 4:00 PM	268	300	5.91	5.71	21
	LF020800-7Bfs	8 Hours	2/8/00 12:00 PM	2/8/00 10:00 PM	640	702	5.79	5.83	21
	LF020800-7Cfs	50 Hours	2/8/00 12:00 PM	2/10/00 2:00 PM	777	785	6.00	5.97	21
	LF020800-7Dfs	7 Days	2/8/00 12:00 PM	2/15/00 9:30 AM	1068	1079	6.00	5.97	21
Batch Date	2/11/2000								
Type III-A (No Silica Fume)	UC021100-8AFS	8 Hours	2/11/00 10:00 AM	2/11/00 6:00 PM	333	336	6.00	5.97	21
	UC021100-8AFS	12 Hours	2/11/00 10:00 AM	2/11/00 10:00 PM	367	367	6.06	5.97	21
	UC021100-8AFS	24 Hours	2/11/00 10:00 AM	2/12/00 10:00 AM	526	521	6.06	6.00	21
	UC021100-8AFS	7 Days	2/11/00 10:00 AM	2/18/00 10:00 AM		0	6.06	6.00	21
Batch Date	2/15/2000								
CSA-A	CSA-A021500-7AFS	4 Hours	2/15/00 11:50 AM	2/15/00 3:50 PM	515	517	5.98	6.00	21
	CSA-A021500-7BFS	24 Hours	2/15/00 11:50 AM	2/16/00 11:50 AM	680	680	6.06	5.97	21
	CSA-A021500-7CFS	28 Days	2/15/00 11:50 AM	2/29/00 11:50 AM		0	6.06	6.03	21
	CSA-A021500-7DFS	28 Days	2/15/00 11:50 AM	2/29/00 11:50 AM		0	6.00	6.00	21
Batch Date	2/15/2000								
CSA-A	CSA-A021500-7.5AFS	4 Hours	2/15/00 11:50 AM	2/15/00 3:50 PM	590	634	5.91	5.83	21
	CSA-A021500-7.5BFS	24 Hours	2/15/00 11:50 AM	2/16/00 11:50 AM	781	781	6.06	5.97	21
	CSA-A021500-7.5CFS	28 Days	2/15/00 11:50 AM	2/29/00 11:50 AM		0	6.06	6.03	21
	CSA-A021500-7.5DFS	28 Days	2/15/00 11:50 AM	2/29/00 11:50 AM		0	6.00	6.00	21

APPENDIX C – TEST DATA

COEFFICIENT OF THERMAL EXPANSION (CTE)

Cement Type	Method	Average C'	STDEV	COV
CSA-B	ASTM	1.03E-05	3.48E-07	3.38%
Type II	ASTM	1.09E-05	4.18E-07	3.85%
CSA-A	ASTM	1.11E-05	4.96E-07	4.46%
CA	ASTM	1.12E-05	1.97E-07	1.77%
Type III-B	ASTM	1.19E-05	7.15E-07	6.02%
Type III-A	ASTM	1.19E-05	1.02E-06	8.51%
Type III-B	CRD	7.94E-06	4.53E-07	5.70%
Type III-A	CRD	8.85E-06	2.7E-07	3.05%
Type II	CRD	8.85E-06	4.86E-07	5.49%
CA	CRD	9.62E-06	8.84E-07	9.19%
CSA-B	CRD	1.07E-05	2.89E-07	2.71%
CSA-A	CRD	1.1E-05	1.93E-06	17.64%

COMPRESSIVE STRENGTH

Type I/II Portland Cement

Mix Design	Spec Name	Strength (Mpa)	Curing Regime	Spec Age (days)	Test Date	Test Type	Average Strength (Mpa)
Type I/II Target-28d	CT41800M10-ACS	18.93132	23 C - 97% RH	7	04/25/00	Compressive	
Type I/II Target-28d	CT41800M10-BCS	17.32153	23 C - 97% RH	7	04/25/00	Compressive	18.126425
Type I/II Target-28d	CT41800M10-CCS	21.95673	23 C - 97% RH	14	05/02/00	Compressive	
Type I/II Target-28d	CT41800M10-DCS	20.98099	23 C - 97% RH	14	05/02/00	Compressive	21.46886
Type I/II Target-28d	CT41800M10-ECS	22.93259	23 C - 97% RH	28	05/16/00	Compressive	
Type I/II Target-28d	CT41800M10-FCS	25.37211	23 C - 97% RH	28	05/16/00	Compressive	24.15235
Type I/II Target-28d	CT41800M10-GCS	29.99306	23 C - 97% RH	90	07/17/00	Compressive	
Type I/II Target-28d	CT41800M10-HCS	29.3974	23 C - 97% RH	90	07/17/00	Compressive	29.69523
Type I/II Target-28d	CT41800MT-ACS	23.37181	23 C - 97% RH	7	04/25/00	Compressive	
Type I/II Target-28d	CT41800MT-BCS	21.07862	23 C - 97% RH	7	04/25/00	Compressive	22.225215
Type I/II Target-28d	CT41800MT-CCS	25.86026	23 C - 97% RH	14	05/02/00	Compressive	
Type I/II Target-28d	CT41800MT-DCS	24.1523	23 C - 97% RH	14	05/02/00	Compressive	25.00628
Type I/II Target-28d	CT41800MT-ECS	27.32393	23 C - 97% RH	28	05/16/00	Compressive	
Type I/II Target-28d	CT41800MT-FCS	28.54397	23 C - 97% RH	28	05/16/00	Compressive	27.93395
Type I/II Target-28d	CT41800MT-GCS	33.07331	23 C - 97% RH	90	07/17/00	Compressive	
Type I/II Target-28d	CT41800MT-HCS	32.98556	23 C - 97% RH	90	07/17/00	Compressive	33.029435
Type I/II Target-28d	CT42000a10-acs	19.23627	20 C - 50% RH	7	04/27/00	Compressive	
Type I/II Target-28d	CT42000a10-bcs	18.39216	20 C - 50% RH	7	04/27/00	Compressive	18.814215
Type I/II Target-28d	CT42000a10-ccs	23.17655	20 C - 50% RH	14	05/04/00	Compressive	
Type I/II Target-28d	CT42000a10-dcs	21.22506	20 C - 50% RH	14	05/04/00	Compressive	22.200805
Type I/II Target-28d	CT42000a10-ecs	23.05205	20 C - 50% RH	28	05/18/00	Compressive	
Type I/II Target-28d	CT42000a10-fcs	25.72588	20 C - 50% RH	28	05/18/00	Compressive	24.388965
Type I/II Target-28d	CT42000a10-gcs	21.4982	20 C - 50% RH	90	07/19/00	Compressive	
Type I/II Target-28d	CT42000a10-hcs	20.4517	20 C - 50% RH	90	07/19/00	Compressive	20.97495
Type I/II Target-28d	CT42000at-acs	18.29728	20 C - 50% RH	7	04/27/00	Compressive	
Type I/II Target-28d	CT42000at-bcs	17.80913	20 C - 50% RH	7	04/27/00	Compressive	18.053205
Type I/II Target-28d	CT42000at-ccs	21.22506	20 C - 50% RH	14	05/04/00	Compressive	
Type I/II Target-28d	CT42000at-dcs	20.00524	20 C - 50% RH	14	05/04/00	Compressive	20.61515
Type I/II Target-28d	CT42000at-ecs	22.00555	20 C - 50% RH	28	05/18/00	Compressive	
Type I/II Target-28d	CT42000at-fcs	23.85502	20 C - 50% RH	28	05/18/00	Compressive	22.930285
Type I/II Target-28d	CT42000at-gcs	18.59016	20 C - 50% RH	90	07/19/00	Compressive	
Type I/II Target-28d	CT42000at-hcs	20.96124	20 C - 50% RH	90	07/19/00	Compressive	19.7757
Type I/II Target-28d	ct42100c10-acs	15.61357	10 C 50% RH	7	04/28/00	Compressive	
Type I/II Target-28d	ct42100c10-bcs	16.34469	10 C 50% RH	7	04/28/00	Compressive	15.97913
Type I/II Target-28d	ct42100c10-ccs	21.17624	10 C 50% RH	14	05/05/00	Compressive	
Type I/II Target-28d	ct42100c10-dcs	19.37065	10 C 50% RH	14	05/05/00	Compressive	20.273445
Type I/II Target-28d	ct42100c10-ecs	24.20111	10 C 50% RH	28	05/19/00	Compressive	
Type I/II Target-28d	ct42100c10-fcs	24.00585	10 C 50% RH	28	05/19/00	Compressive	24.10348
Type I/II Target-28d	ct42100c10-gcs	25.36498	10 C 50% RH	90	07/20/00	Compressive	
Type I/II Target-28d	ct42100c10-hcs	28.88019	10 C 50% RH	90	07/20/00	Compressive	27.122585
Type I/II Target-28d	CT42100Ct-acs	21.46749	10 C 50% RH	7	04/28/00	Compressive	
Type I/II Target-28d	CT42100Ct-bcs	21.46749	10 C 50% RH	7	04/28/00	Compressive	21.46749
Type I/II Target-28d	CT42100Ct-ccs	25.61619	10 C 50% RH	14	05/05/00	Compressive	
Type I/II Target-28d	CT42100Ct-dcs	27.76294	10 C 50% RH	14	05/05/00	Compressive	26.689565
Type I/II Target-28d	CT42100Ct-ecs	30.51959	10 C 50% RH	28	05/19/00	Compressive	
Type I/II Target-28d	CT42100Ct-fcs	29.40947	10 C 50% RH	28	05/19/00	Compressive	29.96453
Type I/II Target-28d	CT42100Ct-gcs	30.72747	10 C 50% RH	90	07/20/00	Compressive	
Type I/II Target-28d	CT42100Ct-hcs	32.54458	10 C 50% RH	90	07/20/00	Compressive	31.636025

Type III-A Portland Cement

Mix Design	Spec Name	Strength (Mpa)	Curing Regime	Spec Age (days)	Test Date	Test Type	Average Strength (Mpa)
Type III-A Target-12hrs	uc42500ii-acs	17.26997	23 C - 97% RH	0.5	04/25/00	Compressive	
Type III-A Target-12hrs	uc42500ii-bcs	17.00286	23 C - 97% RH	0.5	04/25/00	Compressive	17.136415
Type III-A Target-12hrs	uc42500ii-ccs	24.59876	23 C - 97% RH	1	04/26/00	Compressive	
Type III-A Target-12hrs	uc42500ii-dcs	26.66543	23 C - 97% RH	1	04/26/00	Compressive	25.632095
Type III-A Target-12hrs	uc42500ii-ecs	38.30252	23 C - 97% RH	7	05/02/00	Compressive	
Type III-A Target-12hrs	uc42500ii-fcs	36.10641	23 C - 97% RH	7	05/02/00	Compressive	37.204465
Type III-A Target-12hrs	uc42500ii-gcs	48.59748	23 C - 97% RH	90	07/24/00	Compressive	
Type III-A Target-12hrs	uc42500ii-hcs	53.90621	23 C - 97% RH	90	07/24/00	Compressive	51.251845
Type III-A Target-12hrs	uc42600m10-acs	9.318666	23 C - 97% RH	0.5	04/27/00	Compressive	
Type III-A Target-12hrs	uc42600m10-bcs	12.3737	23 C - 97% RH	0.5	04/27/00	Compressive	10.846183
Type III-A Target-12hrs	uc42600m10-ccs	25.24541	23 C - 97% RH	1	04/27/00	Compressive	
Type III-A Target-12hrs	uc42600m10-dcs	24.33768	23 C - 97% RH	1	04/27/00	Compressive	24.791545
Type III-A Target-12hrs	uc42600m10-ecs	40.27814	23 C - 97% RH	7	05/03/00	Compressive	
Type III-A Target-12hrs	uc42600m10-fcs	36.81395	23 C - 97% RH	7	05/03/00	Compressive	38.546045
Type III-A Target-12hrs	uc42600m10-gcs	49.61984	23 C - 97% RH	90	07/25/00	Compressive	
Type III-A Target-12hrs	uc42600m10-hcs	49.88586	23 C - 97% RH	90	07/25/00	Compressive	49.75285
Type III-A Target-12hrs	uc42600mt-acs	30.34902	23 C - 97% RH	0.5	04/26/00	Compressive	
Type III-A Target-12hrs	uc42600mt-bcs	26.42026	23 C - 97% RH	0.5	04/26/00	Compressive	28.38464
Type III-A Target-12hrs	uc42600mt-ccs	27.81888	23 C - 97% RH	1	04/27/00	Compressive	
Type III-A Target-12hrs	uc42600mt-dcs	26.38186	23 C - 97% RH	1	04/27/00	Compressive	27.10037
Type III-A Target-12hrs	uc42600mt-ecs	40.79097	23 C - 97% RH	7	05/03/00	Compressive	
Type III-A Target-12hrs	uc42600mt-fcs	41.69322	23 C - 97% RH	7	05/03/00	Compressive	41.242095
Type III-A Target-12hrs	uc42600mt-gcs	43.53995	23 C - 97% RH	90	07/25/00	Compressive	
Type III-A Target-12hrs	uc42600mt-hcs	44.24255	23 C - 97% RH	90	07/25/00	Compressive	43.89125
Type III-A Target-12hrs	uc42700a10-acs	18.89018	20 C - 50% RH	0.5	04/28/00	Compressive	
Type III-A Target-12hrs	uc42700a10-bcs	18.89512	20 C - 50% RH	0.5	04/28/00	Compressive	18.89265
Type III-A Target-12hrs	uc42700a10-ccs	27.5679	20 C - 50% RH	1	04/28/00	Compressive	
Type III-A Target-12hrs	uc42700a10-dcs	26.34786	20 C - 50% RH	1	04/28/00	Compressive	26.95788
Type III-A Target-12hrs	uc42700a10-ecs	39.76476	20 C - 50% RH	7	05/04/00	Compressive	
Type III-A Target-12hrs	uc42700a10-fcs	37.32623	20 C - 50% RH	7	05/04/00	Compressive	38.545495
Type III-A Target-12hrs	uc42700a10-gcs	39.55854	20 C - 50% RH	90	07/26/00	Compressive	
Type III-A Target-12hrs	uc42700a10-hcs	48.20696	20 C - 50% RH	90	07/26/00	Compressive	43.88275
Type III-A Target-12hrs	uc42700at-acs	22.60833	20 C - 50% RH	0.5	04/28/00	Compressive	
Type III-A Target-12hrs	uc42700at-bcs	17.8201	20 C - 50% RH	0.5	04/28/00	Compressive	20.214215
Type III-A Target-12hrs	uc42700at-ccs	28.54397	20 C - 50% RH	1	04/28/00	Compressive	
Type III-A Target-12hrs	uc42700at-dcs	29.03102	20 C - 50% RH	1	04/28/00	Compressive	28.787495
Type III-A Target-12hrs	uc42700at-ecs	39.03419	20 C - 50% RH	7	05/04/00	Compressive	
Type III-A Target-12hrs	uc42700at-fcs	39.03419	20 C - 50% RH	7	05/04/00	Compressive	39.03419
Type III-A Target-12hrs	uc42700at-gcs	46.86538	20 C - 50% RH	90	07/26/00	Compressive	
Type III-A Target-12hrs	uc42700at-hcs	46.23112	20 C - 50% RH	90	07/26/00	Compressive	46.54825
Type III-A Target-12hrs	uc53100m10-acs	18.41465	23 C - 97% RH	0.5	05/31/00	Compressive	
Type III-A Target-12hrs	uc53100m10-bcs	20.53452	23 C - 97% RH	0.5	05/31/00	Compressive	19.474585
Type III-A Target-12hrs	uc53100m10-ccs	25.37211	23 C - 97% RH	1	06/01/00	Compressive	
Type III-A Target-12hrs	uc53100m10-dcs	28.54397	23 C - 97% RH	1	06/01/00	Compressive	26.95804
Type III-A Target-12hrs	uc53100m10-ecs	35.83826	23 C - 97% RH	7	06/07/00	Compressive	
Type III-A Target-12hrs	uc53100m10-fcs	35.22829	23 C - 97% RH	7	06/07/00	Compressive	35.533275
Type III-A Target-12hrs	uc53100m10-gcs	45.44537	23 C - 97% RH	90	08/29/00	Compressive	
Type III-A Target-12hrs	uc53100m10-hcs	45.10915	23 C - 97% RH	90	08/29/00	Compressive	45.27726
Type III-A Target-12hrs	uc53100mt-acs	22.82223	23 C - 97% RH	0.5	05/31/00	Compressive	
Type III-A Target-12hrs	uc53100mt-bcs	22.84691	23 C - 97% RH	0.5	05/31/00	Compressive	22.83457
Type III-A Target-12hrs	uc53100mt-ccs	32.68938	23 C - 97% RH	1	06/01/00	Compressive	
Type III-A Target-12hrs	uc53100mt-dcs	28.2999	23 C - 97% RH	1	06/01/00	Compressive	30.49464
Type III-A Target-12hrs	uc53100mt-ecs	35.25297	23 C - 97% RH	7	06/07/00	Compressive	
Type III-A Target-12hrs	uc53100mt-fcs	41.13212	23 C - 97% RH	7	06/07/00	Compressive	38.192545
Type III-A Target-12hrs	uc53100mt-gcs	49.65879	23 C - 97% RH	90	08/29/00	Compressive	
Type III-A Target-12hrs	uc53100mt-hcs	49.72241	23 C - 97% RH	90	08/29/00	Compressive	49.6906
Type III-A Target-12hrs	uc6100c10-acs	9.07569	10 C - 50% RH	0.5	06/02/00	Compressive	
Type III-A Target-12hrs	uc6100c10-bcs	9.58797	10 C - 50% RH	0.5	06/02/00	Compressive	9.33183
Type III-A Target-12hrs	uc6100c10-ccs	16.8822	10 C - 50% RH	1	06/02/00	Compressive	
Type III-A Target-12hrs	uc6100c10-dcs	16.98038	10 C - 50% RH	1	06/02/00	Compressive	16.93129
Type III-A Target-12hrs	uc6100c10-ecs	35.19209	10 C - 50% RH	7	06/08/00	Compressive	
Type III-A Target-12hrs	uc6100c10-fcs	36.64337	10 C - 50% RH	7	06/08/00	Compressive	35.91773
Type III-A Target-12hrs	uc6100c10-gcs	45.14809	10 C - 50% RH	90	08/30/00	Compressive	
Type III-A Target-12hrs	uc6100c10-hcs	48.13401	10 C - 50% RH	90	08/30/00	Compressive	46.64105
Type III-A Target-12hrs	uc6100ct-acs	5.14748	10 C - 50% RH	0.5	06/02/00	Compressive	
Type III-A Target-12hrs	uc6100ct-bcs	7.172467	10 C - 50% RH	0.5	06/02/00	Compressive	6.1599735
Type III-A Target-12hrs	uc6100ct-ccs	20.56634	10 C - 50% RH	1	06/02/00	Compressive	
Type III-A Target-12hrs	uc6100ct-dcs	20.22463	10 C - 50% RH	1	06/02/00	Compressive	20.395485
Type III-A Target-12hrs	uc6100ct-ecs	41.11786	10 C - 50% RH	7	06/08/00	Compressive	
Type III-A Target-12hrs	uc6100ct-fcs	39.21629	10 C - 50% RH	7	06/08/00	Compressive	40.167075
Type III-A Target-12hrs	uc6100ct-gcs	47.6949	10 C - 50% RH	90	08/30/00	Compressive	
Type III-A Target-12hrs	uc6100ct-hcs	42.24718	10 C - 50% RH	90	08/30/00	Compressive	44.97104

Type III-B Portland Cement

Mix Design	Spec Name	Strength (Mpa)	Curing Regime	Spec Age (days)	Test Date	Test Type	Average Strength (Mpa)
Type III -B Target-12hrs	IM42800M10-ACS	25.30136	23 C - 97% RH	0.33	04/29/00	Compressive	
Type III -B Target-12hrs	IM42800M10-BCS	24.68158	23 C - 97% RH	0.33	04/29/00	Compressive	24.99147
Type III -B Target-12hrs	IM42800M10-CCS	39.86349	23 C - 97% RH	1	04/29/00	Compressive	
Type III -B Target-12hrs	IM42800M10-DCS	39.98526	23 C - 97% RH	1	04/29/00	Compressive	39.924375
Type III -B Target-12hrs	IM42800M10-ECS	55.59931	23 C - 97% RH	7	05/05/00	Compressive	
Type III -B Target-12hrs	IM42800M10-FCS	54.77007	23 C - 97% RH	7	05/05/00	Compressive	55.18469
Type III -B Target-12hrs	IM42800M10-GCS	69.82967	23 C - 97% RH	90	07/27/00	Compressive	
Type III -B Target-12hrs	IM42800M10-HCS	59.35371	23 C - 97% RH	90	07/27/00	Compressive	64.59169
Type III -B Target-12hrs	IM42800MT-ACS	33.32561	23 C - 97% RH	0.33	04/28/00	Compressive	
Type III -B Target-12hrs	IM42800MT-BCS	34.31617	23 C - 97% RH	0.33	04/28/00	Compressive	33.82089
Type III -B Target-12hrs	IM42800MT-CCS	45.62088	23 C - 97% RH	1	04/29/00	Compressive	
Type III -B Target-12hrs	IM42800MT-DCS	43.54763	23 C - 97% RH	1	04/29/00	Compressive	44.584255
Type III -B Target-12hrs	IM42800MT-ECS	59.86654	23 C - 97% RH	7	05/05/00	Compressive	
Type III -B Target-12hrs	IM42800MT-FCS	61.25929	23 C - 97% RH	7	05/05/00	Compressive	60.562915
Type III -B Target-12hrs	IM42800MT-GCS	70.28326	23 C - 97% RH	90	07/27/00	Compressive	
Type III -B Target-12hrs	IM42800MT-HCS	70.21526	23 C - 97% RH	90	07/27/00	Compressive	70.24926
Type III -B Target-12hrs	IM5200AT-ACS	26.47017	20 C - 50% RH	0.33	05/02/00	Compressive	
Type III -B Target-12hrs	IM5200AT-BCS	27.08008	20 C - 50% RH	0.33	05/02/00	Compressive	26.775125
Type III -B Target-12hrs	IM5200AT-CCS	42.6207	20 C - 50% RH	1	05/03/00	Compressive	
Type III -B Target-12hrs	IM5200AT-DCS	42.08374	20 C - 50% RH	1	05/03/00	Compressive	42.35222
Type III -B Target-12hrs	IM5200AT-ECS	58.13663	20 C - 50% RH	7	05/09/00	Compressive	
Type III -B Target-12hrs	IM5200AT-FCS	59.94209	20 C - 50% RH	7	05/09/00	Compressive	59.03936
Type III -B Target-12hrs	IM5200AT-GCS	67.69992	20 C - 50% RH	90	07/31/00	Compressive	
Type III -B Target-12hrs	IM5200AT-HCS	68.40746	20 C - 50% RH	90	07/31/00	Compressive	68.05369
Type III -B Target-12hrs	IM5500C10-ACS	10.27083	10 C - 50% RH	0.33	05/05/00	Compressive	
Type III -B Target-12hrs	IM5500C10-BCS	11.27071	10 C - 50% RH	0.33	05/05/00	Compressive	10.77077
Type III -B Target-12hrs	IM5500C10-CCS	32.68938	10 C - 50% RH	1	05/06/00	Compressive	
Type III -B Target-12hrs	IM5500C10-DCS	32.44695	10 C - 50% RH	1	05/06/00	Compressive	32.568165
Type III -B Target-12hrs	IM5500C10-ECS	57.72911	10 C - 50% RH	7	05/12/00	Compressive	
Type III -B Target-12hrs	IM5500C10-FCS	57.76312	10 C - 50% RH	7	05/12/00	Compressive	57.746115
Type III -B Target-12hrs	IM5500C10-GCS	76.85349	10 C - 50% RH	90	08/03/00	Compressive	
Type III -B Target-12hrs	IM5500C10-HCS	76.45805	10 C - 50% RH	90	08/03/00	Compressive	76.65577
Type III -B Target-12hrs	IM5500CT-ACS	6.709002	10 C - 50% RH	0.33	05/05/00	Compressive	
Type III -B Target-12hrs	IM5500CT-BCS	5.855019	10 C - 50% RH	0.33	05/05/00	Compressive	6.2820105
Type III -B Target-12hrs	IM5500CT-CCS	30.73953	10 C - 50% RH	1	05/06/00	Compressive	
Type III -B Target-12hrs	IM5500CT-DCS	30.98339	10 C - 50% RH	1	05/06/00	Compressive	30.86146
Type III -B Target-12hrs	IM5500CT-ECS	55.32348	10 C - 50% RH	7	05/12/00	Compressive	
Type III -B Target-12hrs	IM5500CT-FCS	53.77458	10 C - 50% RH	7	05/12/00	Compressive	54.54903
Type III -B Target-12hrs	IM5500CT-GCS	70.37595	10 C - 50% RH	90	08/03/00	Compressive	
Type III -B Target-12hrs	IM5500CT-HCS	73.36955	10 C - 50% RH	90	08/03/00	Compressive	71.87275
Type III -B Target-12hrs	im6100a10-acs	18.70205	20 C - 50% RH	0.333333	06/01/00	Compressive	
Type III -B Target-12hrs	im6100a10-bcs	17.26997	20 C - 50% RH	0.3333	06/01/00	Compressive	17.98601
Type III -B Target-12hrs	im6100a10-ccs	34.60632	20 C - 50% RH	1	06/02/00	Compressive	
Type III -B Target-12hrs	im6100a10-dcs	37.81437	20 C - 50% RH	1	06/02/00	Compressive	36.210345
Type III -B Target-12hrs	im6100a10-ecs	51.88397	20 C - 50% RH	7	06/08/00	Compressive	
Type III -B Target-12hrs	im6100a10-fcs	50.56378	20 C - 50% RH	7	06/08/00	Compressive	51.223875
Type III -B Target-12hrs	im6100a10-gcs	56.82138	20 C - 50% RH	90	08/30/00	Compressive	
Type III -B Target-12hrs	im6100a10-hcs	57.19729	20 C - 50% RH	90	08/30/00	Compressive	57.009335

Calcium Sulfoaluminate –A

Mix Design	Spec Name	Strength (Mpa)	Curing Regime	Spec Age (days)	Test Date	Test Type	Average Strength (Mpa)
CSA-A Target-4hrs	A Target-4hrs51600r	32.9362	23 C - 97% RH	0.167	05/16/00	Compressive	
CSA-A Target-4hrs	A Target-4hrs51600r	34.15491	23 C - 97% RH	0.167	05/16/00	Compressive	33.545555
CSA-A Target-4hrs	A Target-4hrs51600r	40.20355	23 C - 97% RH	1	05/17/00	Compressive	
CSA-A Target-4hrs	A Target-4hrs51600r	38.44841	23 C - 97% RH	1	05/17/00	Compressive	39.32598
CSA-A Target-4hrs	A Target-4hrs51600r	51.41995	23 C - 97% RH	7	05/23/00	Compressive	
CSA-A Target-4hrs	A Target-4hrs51600r	47.50381	23 C - 97% RH	7	05/23/00	Compressive	49.46188
CSA-A Target-4hrs	A Target-4hrs51600r	63.32799	23 C - 97% RH	90	08/14/00	Compressive	
CSA-A Target-4hrs	A Target-4hrs51600r	60.94699	23 C - 97% RH	90	08/14/00	Compressive	62.13749
CSA-A Target-4hrs	Target-4hrs51800a	28.51216	20 C - 50% RH	0.167	05/18/00	Compressive	
CSA-A Target-4hrs	Target-4hrs51800a	32.08111	20 C - 50% RH	0.167	05/18/00	Compressive	30.296635
CSA-A Target-4hrs	Target-4hrs51800a	39.32708	20 C - 50% RH	1	05/19/00	Compressive	
CSA-A Target-4hrs	Target-4hrs51800a	36.44811	20 C - 50% RH	1	05/19/00	Compressive	37.887595
CSA-A Target-4hrs	Target-4hrs51800a	45.4141	20 C - 50% RH	7	05/25/00	Compressive	
CSA-A Target-4hrs	A Target-4hrs51800a	41.67622	20 C - 50% RH	7	05/25/00	Compressive	43.54516
CSA-A Target-4hrs	Target-4hrs51800a	49.36864	20 C - 50% RH	90	08/16/00	Compressive	
CSA-A Target-4hrs	Target-4hrs51800a	48.23877	20 C - 50% RH	90	08/16/00	Compressive	48.803705
CSA-A Target-4hrs	A Target-4hrs51800A	29.9585	20 C - 50% RH	0.167	05/18/00	Compressive	
CSA-A Target-4hrs	Target-4hrs51800A	42.01079	20 C - 50% RH	0.167	05/18/00	Compressive	42.01079
CSA-A Target-4hrs	A Target-4hrs51800A	41.42501	20 C - 50% RH	1	05/19/00	Compressive	
CSA-A Target-4hrs	A Target-4hrs51800A	42.18137	20 C - 50% RH	1	05/19/00	Compressive	41.80319
CSA-A Target-4hrs	A Target-4hrs51800A	51.19946	20 C - 50% RH	7	05/25/00	Compressive	
CSA-A Target-4hrs	A Target-4hrs51800A	46.929	20 C - 50% RH	7	05/25/00	Compressive	49.06423
CSA-A Target-4hrs	A Target-4hrs51800A	50.44421	20 C - 50% RH	90	08/16/00	Compressive	
CSA-A Target-4hrs	A Target-4hrs51800A	54.74319	20 C - 50% RH	90	08/16/00	Compressive	52.5937
CSA-A Target-4hrs	Target-4hrs52500c	17.7115	10 C - 50% RH	0.167	05/25/00	Compressive	
CSA-A Target-4hrs	Target-4hrs52500c	18.24791	10 C - 50% RH	0.167	05/25/00	Compressive	17.979705
CSA-A Target-4hrs	Target-4hrs52500c	29.98812	10 C - 50% RH	1	05/26/00	Compressive	
CSA-A Target-4hrs	Target-4hrs52500c	27.62636	10 C - 50% RH	1	05/26/00	Compressive	28.80724
CSA-A Target-4hrs	Target-4hrs52500c	42.93772	10 C - 50% RH	7	06/01/00	Compressive	
CSA-A Target-4hrs	A Target-4hrs52500c	36.5951	10 C - 50% RH	7	06/01/00	Compressive	39.76641
CSA-A Target-4hrs	Target-4hrs52500c	49.73667	10 C - 50% RH	90	08/23/00	Compressive	
CSA-A Target-4hrs	Target-4hrs52500c	50.88573	10 C - 50% RH	90	08/23/00	Compressive	50.3112
CSA-A Target-4hrs	A Target-4hrs52500	12.73569	10 C - 50% RH	0.167	05/25/00	Compressive	
CSA-A Target-4hrs	A Target-4hrs52500	12.28594	10 C - 50% RH	0.167	05/25/00	Compressive	12.510815
CSA-A Target-4hrs	A Target-4hrs52500	24.22579	10 C - 50% RH	1	05/26/00	Compressive	
CSA-A Target-4hrs	A Target-4hrs52500	24.44025	10 C - 50% RH	1	05/26/00	Compressive	24.33302
CSA-A Target-4hrs	A Target-4hrs52500	35.6188	10 C - 50% RH	7	06/01/00	Compressive	
CSA-A Target-4hrs	-A Target-4hrs52500	37.81437	10 C - 50% RH	7	06/01/00	Compressive	36.716585
CSA-A Target-4hrs	A Target-4hrs52500	44.77951	10 C - 50% RH	90	08/23/00	Compressive	
CSA-A Target-4hrs	A Target-4hrs52500	42.93991	10 C - 50% RH	90	08/23/00	Compressive	43.85971
CSA-A Target-4hrs	Target-4hrs52600m	26.63965	23 C - 97% RH	0.167	05/26/00	Compressive	
CSA-A Target-4hrs	Target-4hrs52600m	22.29843	23 C - 97% RH	0.167	05/26/00	Compressive	24.46904
CSA-A Target-4hrs	Target-4hrs52600m	35.86014	23 C - 97% RH	1	05/27/00	Compressive	
CSA-A Target-4hrs	Target-4hrs52600m	35.59413	23 C - 97% RH	1	05/27/00	Compressive	35.727135
CSA-A Target-4hrs	Target-4hrs52600m	43.7374	23 C - 97% RH	7	06/02/00	Compressive	
CSA-A Target-4hrs	Target-4hrs52600m	43.42312	23 C - 97% RH	7	06/02/00	Compressive	43.58026
CSA-A Target-4hrs	Target-4hrs52600m	57.60735	23 C - 97% RH	111	09/14/00	Compressive	
CSA-A Target-4hrs	Target-4hrs52600m	57.21189	23 C - 97% RH	111	09/14/00	Compressive	57.40962

Calcium Sulfoaluminate – B

Mix Design	Spec Name	Strength (Mpa)	Curing Regime	Spec Age (days)	Test Date	Test Type	Average Strength (Mpa)
CSA-B Target-4hrs	um61900m10-acs	25.89372	23 C - 97% RH	0.167	06/19/00	Compressive	
CSA-B Target-4hrs	um61900m10-bcs	23.53526	23 C - 97% RH	0.167	06/19/00	Compressive	24.71449
CSA-B Target-4hrs	um61900m10-ccs	38.80219	23 C - 97% RH	1	06/20/00	Compressive	
CSA-B Target-4hrs	um61900m10-dcs	40.9248	23 C - 97% RH	1	06/20/00	Compressive	39.863495
CSA-B Target-4hrs	um61900m10-ecs	45.67244	23 C - 97% RH	7	06/26/00	Compressive	
CSA-B Target-4hrs	um61900m10-fcs	44.5135	23 C - 97% RH	7	06/26/00	Compressive	45.09297
CSA-B Target-4hrs	um61900m10-gcs	55.66519	23 C - 97% RH	90	09/17/00	Compressive	
CSA-B Target-4hrs	um61900m10-hcs	55.94107	23 C - 97% RH	90	09/17/00	Compressive	55.80313
CSA-B Target-4hrs	um61900mt-acs	24.97721	23 C - 97% RH	0.167	06/19/00	Compressive	
CSA-B Target-4hrs	um61900mt-bcs	25.72588	23 C - 97% RH	0.167	06/19/00	Compressive	25.351545
CSA-B Target-4hrs	um61900mt-ccs	38.1484	23 C - 97% RH	1	06/20/00	Compressive	
CSA-B Target-4hrs	um61900mt-dcs	36.98507	23 C - 97% RH	1	06/20/00	Compressive	37.566735
CSA-B Target-4hrs	um61900mt-ecs	46.3871	23 C - 97% RH	7	06/26/00	Compressive	
CSA-B Target-4hrs	um61900mt-fcs	47.77256	23 C - 97% RH	7	06/26/00	Compressive	47.07983
CSA-B Target-4hrs	um61900mt-gcs	59.57584	23 C - 97% RH	90	09/17/00	Compressive	
CSA-B Target-4hrs	um61900mt-hcs	56.96563	23 C - 97% RH	90	09/17/00	Compressive	58.270735
CSA-B Target-4hrs	um62100a10-acs	24.54501	20 C - 50% RH	0.167	06/21/00	Compressive	
CSA-B Target-4hrs	um62100a10-bcs	26.96051	20 C - 50% RH	0.167	06/21/00	Compressive	25.75276
CSA-B Target-4hrs	um62100a10-ccs	37.4266	20 C - 50% RH	1	06/22/00	Compressive	
CSA-B Target-4hrs	um62100a10-dcs	38.09026	20 C - 50% RH	1	06/22/00	Compressive	37.75843
CSA-B Target-4hrs	um62100a10-ecs	44.97916	20 C - 50% RH	7	06/28/00	Compressive	
CSA-B Target-4hrs	um62100a10-fcs	42.81321	20 C - 50% RH	7	06/28/00	Compressive	43.896185
CSA-B Target-4hrs	um62100a10-gcs	44.18167	20 C - 50% RH	100	09/29/00	Compressive	
CSA-B Target-4hrs	um62100a10-hcs	46.45073	20 C - 50% RH	100	09/29/00	Compressive	45.3162
CSA-B Target-4hrs	um62100at-acs	23.9351	20 C - 50% RH	0.167	06/21/00	Compressive	
CSA-B Target-4hrs	um62100at-bcs	23.36632	20 C - 50% RH	0.167	06/21/00	Compressive	23.65071
CSA-B Target-4hrs	um62100at-ccs	36.69438	20 C - 50% RH	1	06/22/00	Compressive	
CSA-B Target-4hrs	um62100at-dcs	37.66573	20 C - 50% RH	1	06/22/00	Compressive	37.180055
CSA-B Target-4hrs	um62100at-ecs	41.89616	20 C - 50% RH	7	06/28/00	Compressive	
CSA-B Target-4hrs	um62100at-fcs	44.44987	20 C - 50% RH	7	06/28/00	Compressive	43.173015
CSA-B Target-4hrs	um62100at-gcs	46.04595	20 C - 50% RH	100	09/29/00	Compressive	
CSA-B Target-4hrs	um62100at-hcs	44.01109	20 C - 50% RH	100	09/29/00	Compressive	45.02852
CSA-B Target-4hrs	um62700c10-acs	28.25602	10 C - 50% RH	0.167	06/27/00	Compressive	
CSA-B Target-4hrs	um62700c10-bcs	28.72672	10 C - 50% RH	0.167	06/27/00	Compressive	28.49137
CSA-B Target-4hrs	um62700c10-ccs	34.26955	10 C - 50% RH	1	06/28/00	Compressive	
CSA-B Target-4hrs	um62700c10-dcs	35.02042	10 C - 50% RH	1	06/28/00	Compressive	34.644985
CSA-B Target-4hrs	um62700c10-ecs	42.17643	10 C - 50% RH	7	07/04/00	Compressive	
CSA-B Target-4hrs	um62700c10-fcs	40.4542	10 C - 50% RH	7	07/04/00	Compressive	41.315315
CSA-B Target-4hrs	um62700c10-gcs	50.84076	10 C - 50% RH	90	09/25/00	Compressive	
CSA-B Target-4hrs	um62700c10-hcs	53.87221	10 C - 50% RH	90	09/25/00	Compressive	52.356485
CSA-B Target-4hrs	um62700ct-acs	19.67341	10 C - 50% RH	0.167	06/27/00	Compressive	
CSA-B Target-4hrs	um62700ct-bcs	20.01457	10 C - 50% RH	0.167	06/27/00	Compressive	19.84399
CSA-B Target-4hrs	um62700ct-ccs	38.74405	10 C - 50% RH	1	06/28/00	Compressive	
CSA-B Target-4hrs	um62700ct-dcs	39.46091	10 C - 50% RH	1	06/28/00	Compressive	39.10248
CSA-B Target-4hrs	um62700ct-ecs	41.84899	10 C - 50% RH	7	07/04/00	Compressive	
CSA-B Target-4hrs	um62700ct-fcs	42.33494	10 C - 50% RH	7	07/04/00	Compressive	42.091965
CSA-B Target-4hrs	um62700ct-gcs	55.83521	10 C - 50% RH	90	09/25/00	Compressive	
CSA-B Target-4hrs	um62700ct-hcs	51.57408	10 C - 50% RH	90	09/25/00	Compressive	53.704645

Calcium Aluminate

Mix Design	Spec Name	Strength (Mpa)	Curing Regime	Spec Age (days)	Test Date	Test Type	Average Strength (Mpa)
CA Target-4hrs	lf41100A10-acs	38.03157	20 C - 50% RH	0.33	04/11/00	Compressive	
CA Target-4hrs	lf41100A10-bcs	39.30404	20 C - 50% RH	0.33	04/11/00	Compressive	38.667805
CA Target-4hrs	lf41100A10-ccs	41.61863	20 C - 50% RH	1	04/12/00	Compressive	
CA Target-4hrs	lf41100A10-dcs	49.74161	20 C - 50% RH	1	04/12/00	Compressive	45.68012
CA Target-4hrs	lf41100A10-ecs	50.37784	20 C - 50% RH	7	04/18/00	Compressive	
CA Target-4hrs	lf41100A10-fcs	51.27735	20 C - 50% RH	7	04/18/00	Compressive	50.827595
CA Target-4hrs	lf41100A10-gcs	47.07764	20 C - 50% RH	90	07/10/00	Compressive	
CA Target-4hrs	lf41100A10-hcs	47.79505	20 C - 50% RH	90	07/10/00	Compressive	47.436345
CA Target-4hrs	lf41100AT-acs	46.98824	20 C - 50% RH	0.33	04/11/00	Compressive	
CA Target-4hrs	lf41100AT-bcs	52.76921	20 C - 50% RH	0.33	04/11/00	Compressive	49.878725
CA Target-4hrs	lf41100AT-ccs	55.08928	20 C - 50% RH	1	04/12/00	Compressive	
CA Target-4hrs	lf41100AT-dcs	56.69632	20 C - 50% RH	1	04/12/00	Compressive	55.8928
CA Target-4hrs	lf41100AT-ecs	56.60308	20 C - 50% RH	7	04/18/00	Compressive	
CA Target-4hrs	lf41100AT-fcs	58.24852	20 C - 50% RH	7	04/18/00	Compressive	57.4258
CA Target-4hrs	lf41100AT-gcs	52.0156	20 C - 50% RH	90	07/10/00	Compressive	
CA Target-4hrs	lf41100AT-hcs	21.65178	20 C - 50% RH	90	07/10/00	Compressive	52.0156
CA Target-4hrs	lf41300c10-acs	36.86331	10 C - 50% RH	0.33	04/13/00	Compressive	
CA Target-4hrs	lf41300c10-bcs	41.66799	10 C - 50% RH	0.33	04/13/00	Compressive	39.26565
CA Target-4hrs	lf41300c10-ccs	42.08483	10 C - 50% RH	1	04/14/00	Compressive	
CA Target-4hrs	lf41300c10-dcs	45.15632	10 C - 50% RH	1	04/14/00	Compressive	43.620575
CA Target-4hrs	lf41300c10-ecs	50.79469	10 C - 50% RH	7	04/20/00	Compressive	
CA Target-4hrs	lf41300c10-fcs	48.23329	10 C - 50% RH	7	04/20/00	Compressive	49.51399
CA Target-4hrs	lf41300c10-gcs	57.70553	10 C - 50% RH	90	07/12/00	Compressive	
CA Target-4hrs	lf41300c10-hcs	58.49479	10 C - 50% RH	90	07/12/00	Compressive	58.10016
CA Target-4hrs	lf41300ct-acs	42.93497	10 C - 50% RH	0.33	04/13/00	Compressive	
CA Target-4hrs	lf41300ct-bcs	41.66799	10 C - 50% RH	0.33	04/13/00	Compressive	42.30148
CA Target-4hrs	lf41300ct-ccs	44.49814	10 C - 50% RH	1	04/14/00	Compressive	
CA Target-4hrs	lf41300ct-dcs	47.10891	10 C - 50% RH	1	04/14/00	Compressive	45.803525
CA Target-4hrs	lf41300ct-ecs	53.40545	10 C - 50% RH	7	04/20/00	Compressive	
CA Target-4hrs	lf41300ct-fcs	49.6703	10 C - 50% RH	7	04/20/00	Compressive	51.537875
CA Target-4hrs	lf41300ct-gcs	55.71894	10 C - 50% RH	90	07/12/00	Compressive	
CA Target-4hrs	lf41300ct-hcs	54.50899	10 C - 50% RH	90	07/12/00	Compressive	55.113965
CA Target-4hrs	lf4400m10-acs	34.98202	23 C - 97% RH	0.33	04/04/00	Compressive	
CA Target-4hrs	lf4400m10-bcs	25.00518	23 C - 97% RH	0.33	04/04/00	Compressive	29.9936
CA Target-4hrs	lf4400m10-ccs	27.594	23 C - 97% RH	1	04/05/00	Compressive	
CA Target-4hrs	lf4400m10-dcs	41.91481	23 C - 97% RH	1	04/05/00	Compressive	44.084045
CA Target-4hrs	lf4400m10-ecs	46.25328	23 C - 97% RH	7	04/11/00	Compressive	
CA Target-4hrs	lf4400m10-fcs	50.10909	23 C - 97% RH	7	04/11/00	Compressive	48.181185
CA Target-4hrs	lf4400m10-gcs	46.4798	23 C - 97% RH	90	07/03/00	Compressive	
CA Target-4hrs	lf4400m10-hcs	47.0557	23 C - 97% RH	90	07/03/00	Compressive	46.76775
CA Target-4hrs	lf4600MT-acs	34.82845	23 C - 97% RH	0.33	04/06/00	Compressive	
CA Target-4hrs	lf4600MT-bcs	39.20531	23 C - 97% RH	0.33	04/06/00	Compressive	37.01688
CA Target-4hrs	lf4600MT-ccs	49.08343	23 C - 97% RH	1	04/07/00	Compressive	
CA Target-4hrs	lf4600MT-dcs	46.74142	23 C - 97% RH	1	04/07/00	Compressive	47.912425
CA Target-4hrs	lf4600MT-ecs	61.08965	23 C - 97% RH	7	04/13/00	Compressive	
CA Target-4hrs	lf4600MT-fcs	55.03992	23 C - 97% RH	7	04/13/00	Compressive	58.064785
CA Target-4hrs	lf4600MT-gcs	50.35645	23 C - 97% RH	90	07/05/00	Compressive	
CA Target-4hrs	lf4600MT-hcs	56.24822	23 C - 97% RH	90	07/05/00	Compressive	53.302335

FLEXURAL STRENGTH

Type I/II Portland Cement

MixDesign	Spec Name	Strength (Mpa)	Curing Regime	Spec Age (days)	Test Date	Test Type	Average Strength (Mpa)
Type I/II Target-28d	CT41800M10-AFS	2.487466	23 C + 97% RH	7	04/25/00	Flexural	
Type I/II Target-28d	CT41800M10-BFS	2.496232	23 C + 97% RH	7	04/25/00	Flexural	2.491849
Type I/II Target-28d	CT41800M10-CFS	2.799433	23 C + 97% RH	14	05/02/00	Flexural	
Type I/II Target-28d	CT41800M10-DFS	2.744866	23 C + 97% RH	14	05/02/00	Flexural	2.7721495
Type I/II Target-28d	CT41800M10-EFS	3.030214	23 C + 97% RH	28	05/16/00	Flexural	
Type I/II Target-28d	CT41800M10-FFS	3.570976	23 C + 97% RH	28	05/16/00	Flexural	3.300595
Type I/II Target-28d	CT41800M10-GFS	2.892864	23 C + 97% RH	90	07/17/00	Flexural	
Type I/II Target-28d	CT41800M10-HFS	2.691362	23 C + 97% RH	90	07/17/00	Flexural	2.792113
Type I/II Target-28d	CT41800MT-AFS	3.121605	23 C + 97% RH	7	04/25/00	Flexural	
Type I/II Target-28d	CT41800MT-BFS	3.071116	23 C + 97% RH	7	04/25/00	Flexural	3.0963605
Type I/II Target-28d	CT41800MT-CFS	2.812437	23 C + 97% RH	14	05/02/00	Flexural	
Type I/II Target-28d	CT41800MT-DFS	3.479178	23 C + 97% RH	14	05/02/00	Flexural	3.1458075
Type I/II Target-28d	CT41800MT-EFS	3.53134	23 C + 97% RH	28	05/16/00	Flexural	
Type I/II Target-28d	CT41800MT-FFS	3.383674	23 C + 97% RH	28	05/16/00	Flexural	3.457507
Type I/II Target-28d	CT41800MT-GFS	3.726675	23 C + 97% RH	90	07/17/00	Flexural	
Type I/II Target-28d	CT41800MT-HFS	3.757503	23 C + 97% RH	90	07/17/00	Flexural	3.742089
Type I/II Target-28d	CT42000a10-afs	2.070278	20 C - 50% RH	7	04/27/00	Flexural	
Type I/II Target-28d	CT42000a10-bfs	1.636692	20 C - 50% RH	7	04/27/00	Flexural	1.853485
Type I/II Target-28d	CT42000a10-cfs	2.128596	20 C - 50% RH	14	05/04/00	Flexural	
Type I/II Target-28d	CT42000a10-dfs	1.874787	20 C - 50% RH	14	05/04/00	Flexural	2.0016915
Type I/II Target-28d	CT42000a10-efs	1.911622	20 C - 50% RH	28	05/18/00	Flexural	
Type I/II Target-28d	CT42000a10-ffs	1.916316	20 C - 50% RH	28	05/18/00	Flexural	1.913969
Type I/II Target-28d	CT42000a10-gfs	2.286562	20 C - 50% RH	90	07/19/00	Flexural	
Type I/II Target-28d	CT42000a10-hfs	2.375939	20 C - 50% RH	90	07/19/00	Flexural	2.3312505
Type I/II Target-28d	CT42000At-afs	1.939647	20 C - 50% RH	7	04/27/00	Flexural	
Type I/II Target-28d	CT42000At-bfs	1.779968	20 C - 50% RH	7	04/27/00	Flexural	1.8598075
Type I/II Target-28d	CT42000At-cfs	1.886359	20 C - 50% RH	14	05/04/00	Flexural	
Type I/II Target-28d	CT42000At-dfs	1.790335	20 C - 50% RH	14	05/04/00	Flexural	1.838347
Type I/II Target-28d	CT42000At-efs	1.969557	20 C - 50% RH	28	05/18/00	Flexural	
Type I/II Target-28d	CT42000At-ffs	1.70488	20 C - 50% RH	28	05/18/00	Flexural	1.8372185
Type I/II Target-28d	CT42000At-gfs	2.756646	20 C - 50% RH	90	07/19/00	Flexural	
Type I/II Target-28d	CT42000At-hfs	2.60152	20 C - 50% RH	90	07/19/00	Flexural	2.679083
Type I/II Target-28d	ct42100c10-afs	2.483298	10 C - 50% RH	7	04/28/00	Flexural	
Type I/II Target-28d	ct42100c10-bfs	2.530788	10 C - 50% RH	7	04/28/00	Flexural	2.507043
Type I/II Target-28d	ct42100c10-cfs	2.852818	10 C - 50% RH	14	05/05/00	Flexural	
Type I/II Target-28d	ct42100c10-dfs	2.813111	10 C - 50% RH	14	05/05/00	Flexural	2.8329645
Type I/II Target-28d	ct42100c10-efs	3.4835	10 C - 50% RH	28	05/19/00	Flexural	
Type I/II Target-28d	ct42100c10-ffs	3.59796	10 C - 50% RH	28	05/19/00	Flexural	3.54073
Type I/II Target-28d	ct42100c10-gfs	3.15847	10 C - 50% RH	90	07/20/00	Flexural	
Type I/II Target-28d	ct42100c10-hfs	4.020141	10 C - 50% RH	90	07/20/00	Flexural	3.5893055
Type I/II Target-28d	CT42100CT-afs	2.85688	10 C - 50% RH	7	04/28/00	Flexural	
Type I/II Target-28d	CT42100CT-bfs	2.893173	10 C - 50% RH	7	04/28/00	Flexural	2.8750265
Type I/II Target-28d	CT42100CT-cfs	3.620958	10 C - 50% RH	14	05/05/00	Flexural	
Type I/II Target-28d	CT42100CT-dfs	3.464952	10 C - 50% RH	14	05/05/00	Flexural	3.542955
Type I/II Target-28d	CT42100CT-efs	4.01035	10 C - 50% RH	28	05/19/00	Flexural	
Type I/II Target-28d	CT42100CT-ffs	3.569691	10 C - 50% RH	28	05/19/00	Flexural	3.7900205
Type I/II Target-28d	CT42100CT-gfs	4.673122	10 C - 50% RH	90	07/20/00	Flexural	
Type I/II Target-28d	CT42100CT-hfs	4.626303	10 C - 50% RH	90	07/20/00	Flexural	4.6497125

Type III-A Portland Cement

MixDesign	Spec Name	Strength (Mpa)	Curing Regime	Spec Age (days)	Test Date	Test Type	Average Strength (Mpa)
Type III-A Target-12hr	uc42700a10-afs	2.287275	20 C - 50% RH	0.5	04/28/00	Flexural	
Type III-A Target-12hr	uc42700a10-bfs	2.75244	20 C - 50% RH	0.5	04/28/00	Flexural	2.5198575
Type III-A Target-12hr	uc42700a10-cfs	2.608521	20 C - 50% RH	1	04/28/00	Flexural	
Type III-A Target-12hr	uc42700a10-dfs	2.763261	20 C - 50% RH	1	04/28/00	Flexural	2.685891
Type III-A Target-12hr	uc42700a10-efs	2.298052	20 C - 50% RH	7	05/04/00	Flexural	
Type III-A Target-12hr	uc42700a10-ffs	2.707465	20 C - 50% RH	7	05/04/00	Flexural	2.5027585
Type III-A Target-12hr	uc42700a10-gfs	4.150066	20 C - 50% RH	90	07/26/00	Flexural	
Type III-A Target-12hr	uc42700a10-hfs	4.310518	20 C - 50% RH	90	07/26/00	Flexural	4.230292
Type III-A Target-12hr	uc42700at-afs	2.951408	20 C - 50% RH	0.5	04/28/00	Flexural	
Type III-A Target-12hr	uc42700at-bfs	3.158802	20 C - 50% RH	0.5	04/28/00	Flexural	3.055105
Type III-A Target-12hr	uc42700at-cfs	2.407052	20 C - 50% RH	1	04/28/00	Flexural	
Type III-A Target-12hr	uc42700at-dfs	2.395794	20 C - 50% RH	1	04/28/00	Flexural	2.401423
Type III-A Target-12hr	uc42700at-efs	2.847207	20 C - 50% RH	7	05/04/00	Flexural	
Type III-A Target-12hr	uc42700at-ffs	2.71863	20 C - 50% RH	7	05/04/00	Flexural	2.7829185
Type III-A Target-12hr	uc42700at-gfs	4.269224	20 C - 50% RH	90	07/26/00	Flexural	
Type III-A Target-12hr	uc42700at-hfs	4.525818	20 C - 50% RH	90	07/26/00	Flexural	4.397521
Type III-A Target-12hr	uc53100m10-afs	2.454031	23 C + 97% RH	0.5	05/31/00	Flexural	
Type III-A Target-12hr	uc53100m10-bfs	2.565331	23 C + 97% RH	0.5	05/31/00	Flexural	2.509681
Type III-A Target-12hr	uc53100m10-cfs	3.476068	23 C + 97% RH	1	06/01/00	Flexural	
Type III-A Target-12hr	uc53100m10-dfs	3.06946	23 C + 97% RH	1	06/01/00	Flexural	3.272764
Type III-A Target-12hr	uc53100m10-efs	3.606711	23 C + 97% RH	7	06/07/00	Flexural	
Type III-A Target-12hr	uc53100m10-ffs	3.696758	23 C + 97% RH	7	06/07/00	Flexural	3.6517345
Type III-A Target-12hr	uc53100m10-gfs	4.786547	23 C + 97% RH	90	08/29/00	Flexural	
Type III-A Target-12hr	uc53100m10-hfs	4.697205	23 C + 97% RH	90	08/29/00	Flexural	4.741876
Type III-A Target-12hr	uc53100mt-afs	2.563446	23 C + 97% RH	0.5	05/31/00	Flexural	
Type III-A Target-12hr	uc53100mt-bfs	2.649419	23 C + 97% RH	0.5	05/31/00	Flexural	2.6064325
Type III-A Target-12hr	uc53100mt-cfs	2.821497	23 C + 97% RH	1	06/01/00	Flexural	
Type III-A Target-12hr	uc53100mt-dfs	3.372808	23 C + 97% RH	1	06/01/00	Flexural	3.0971525
Type III-A Target-12hr	uc53100mt-efs	3.831582	23 C + 97% RH	7	06/07/00	Flexural	
Type III-A Target-12hr	uc53100mt-ffs	3.252511	23 C + 97% RH	7	06/07/00	Flexural	3.5420465
Type III-A Target-12hr	uc53100mt-gfs	5.229183	23 C + 97% RH	90	08/29/00	Flexural	
Type III-A Target-12hr	uc53100mt-hfs	5.046145	23 C + 97% RH	90	08/29/00	Flexural	5.137664
Type III-A Target-12hr	uc6100c10-afs	1.918677	10 C - 50% RH	0.5	06/02/00	Flexural	
Type III-A Target-12hr	uc6100c10-bfs	1.730106	10 C - 50% RH	0.5	06/02/00	Flexural	1.8243915
Type III-A Target-12hr	uc6100c10-cfs	2.696052	10 C - 50% RH	1	06/02/00	Flexural	
Type III-A Target-12hr	uc6100c10-dfs	2.249395	10 C - 50% RH	1	06/02/00	Flexural	2.4727235
Type III-A Target-12hr	uc6100c10-efs	4.536805	10 C - 50% RH	7	06/08/00	Flexural	
Type III-A Target-12hr	uc6100c10-ffs	4.170878	10 C - 50% RH	7	06/08/00	Flexural	4.3538415
Type III-A Target-12hr	uc6100c10-gfs	5.763846	10 C - 50% RH	90	08/30/00	Flexural	
Type III-A Target-12hr	uc6100c10-hfs	5.759737	10 C - 50% RH	90	08/30/00	Flexural	5.7617915
Type III-A Target-12hr	uc6100ct-afs	1.535875	10 C - 50% RH	0.5	06/02/00	Flexural	
Type III-A Target-12hr	uc6100ct-bfs	1.61249	10 C - 50% RH	0.5	06/02/00	Flexural	1.5741825
Type III-A Target-12hr	uc6100ct-cfs	2.742563	10 C - 50% RH	1	06/02/00	Flexural	
Type III-A Target-12hr	uc6100ct-dfs	2.897802	10 C - 50% RH	1	06/02/00	Flexural	2.8201825
Type III-A Target-12hr	uc6100ct-efs	4.201813	10 C - 50% RH	7	06/08/00	Flexural	
Type III-A Target-12hr	uc6100ct-ffs	4.170414	10 C - 50% RH	7	06/08/00	Flexural	4.1861135
Type III-A Target-12hr	uc6100ct-gfs	5.719277	10 C - 50% RH	90	08/30/00	Flexural	
Type III-A Target-12hr	uc6100ct-hfs	6.686936	10 C - 50% RH	90	08/30/00	Flexural	6.2031065

Type III-B Portland Cement

MixDesign	Spec Name	Strength (Mpa)	Curing Regime	Spec Age (days)	Test Date	Test Type	Average Strength (Mpa)
ype III -B Target-12hr	IM42800M10-AFS	3.320681	23 C + 97% RH	0.33	04/29/00	Flexural	
ype III -B Target-12hr	IM42800M10-BFS	3.235366	23 C + 97% RH	0.33	04/29/00	Flexural	3.2780235
ype III -B Target-12hr	IM42800M10-CFS	3.962863	23 C + 97% RH	1	04/29/00	Flexural	
ype III -B Target-12hr	IM42800M10-DFS	3.76748	23 C + 97% RH	1	04/29/00	Flexural	3.8651715
ype III -B Target-12hr	IM42800M10-EFS	4.816104	23 C + 97% RH	7	05/05/00	Flexural	
ype III -B Target-12hr	IM42800M10-FFS	4.953578	23 C + 97% RH	7	05/05/00	Flexural	4.884841
ype III -B Target-12hr	IM42800M10-GFS	7.079564	23 C + 97% RH	90	07/27/00	Flexural	
ype III -B Target-12hr	IM42800M10-HFS	6.753802	23 C + 97% RH	90	07/27/00	Flexural	6.916683
ype III -B Target-12hr	IM42800MT-AFS	3.680199	23 C + 97% RH	0.33	04/28/00	Flexural	
ype III -B Target-12hr	IM42800MT-BFS	3.654944	23 C + 97% RH	0.33	04/28/00	Flexural	3.6675715
ype III -B Target-12hr	IM42800MT-CFS	3.833879	23 C + 97% RH	1	04/29/00	Flexural	
ype III -B Target-12hr	IM42800MT-DFS	3.696904	23 C + 97% RH	1	04/29/00	Flexural	3.7653915
ype III -B Target-12hr	IM42800MT-EFS	4.993533	23 C + 97% RH	7	05/05/00	Flexural	
ype III -B Target-12hr	IM42800MT-FFS	5.058216	23 C + 97% RH	7	05/05/00	Flexural	5.0258745
ype III -B Target-12hr	IM42800MT-GFS	6.843344	23 C + 97% RH	90	07/27/00	Flexural	
ype III -B Target-12hr	IM42800MT-HFS	7.054637	23 C + 97% RH	90	07/27/00	Flexural	6.9489905
ype III -B Target-12hr	IM5200AT-AFS	2.896508	20 C - 50% RH	0.33	05/02/00	Flexural	
ype III -B Target-12hr	IM5200AT-BFS	3.09854	20 C - 50% RH	0.33	05/02/00	Flexural	2.997524
ype III -B Target-12hr	IM5200AT-CFS	3.645031	20 C - 50% RH	1	05/03/00	Flexural	
ype III -B Target-12hr	IM5200AT-DFS	4.066276	20 C - 50% RH	1	05/03/00	Flexural	3.8556535
ype III -B Target-12hr	IM5200AT-EFS	3.313978	20 C - 50% RH	7	05/09/00	Flexural	
ype III -B Target-12hr	IM5200AT-FFS	4.235769	20 C - 50% RH	7	05/09/00	Flexural	3.7748735
ype III -B Target-12hr	IM5200AT-GFS	4.614711	20 C - 50% RH	90	07/31/00	Flexural	
ype III -B Target-12hr	IM5200AT-HFS	4.779869	20 C - 50% RH	90	07/31/00	Flexural	4.69729
ype III -B Target-12hr	IM5500C10-AFS	2.417049	10 C - 50% RH	0.33	05/05/00	Flexural	
ype III -B Target-12hr	IM5500C10-BFS	2.363237	10 C - 50% RH	0.33	05/05/00	Flexural	2.390143
ype III -B Target-12hr	IM5500C10-CFS	3.717386	10 C - 50% RH	1	05/06/00	Flexural	
ype III -B Target-12hr	IM5500C10-DFS	3.802865	10 C - 50% RH	1	05/06/00	Flexural	3.7601255
ype III -B Target-12hr	IM5500C10-EFS	6.653161	10 C - 50% RH	7	05/12/00	Flexural	
ype III -B Target-12hr	IM5500C10-FFS	6.745423	10 C - 50% RH	7	05/12/00	Flexural	6.699292
ype III -B Target-12hr	IM5500C10-GFS	8.126004	10 C - 50% RH	90	08/03/00	Flexural	
ype III -B Target-12hr	IM5500C10-HFS	8.137502	10 C - 50% RH	90	08/03/00	Flexural	8.131753
ype III -B Target-12hr	IM5500CT-AFS	1.97911	10 C - 50% RH	0.33	05/05/00	Flexural	
ype III -B Target-12hr	IM5500CT-BFS	1.778658	10 C - 50% RH	0.33	05/05/00	Flexural	1.878884
ype III -B Target-12hr	IM5500CT-CFS	3.549214	10 C - 50% RH	1	05/06/00	Flexural	
ype III -B Target-12hr	IM5500CT-DFS	3.61081	10 C - 50% RH	1	05/06/00	Flexural	3.580012
ype III -B Target-12hr	IM5500CT-EFS	6.344527	10 C - 50% RH	7	05/12/00	Flexural	
ype III -B Target-12hr	IM5500CT-FFS	6.255311	10 C - 50% RH	7	05/12/00	Flexural	6.299919
ype III -B Target-12hr	IM5500CT-GFS	8.098414	10 C - 50% RH	90	08/03/00	Flexural	
ype III -B Target-12hr	IM5500CT-HFS	7.789531	10 C - 50% RH	90	08/03/00	Flexural	7.9439725
ype III -B Target-12hr	im6100a10-afs	2.193518	20 C - 50% RH	0.33333	06/01/00	Flexural	
ype III -B Target-12hr	im6100a10-bfs	2.510375	20 C - 50% RH	0.33333	06/01/00	Flexural	2.3519465
ype III -B Target-12hr	im6100a10-cfs	3.198128	20 C - 50% RH	1	06/02/00	Flexural	
ype III -B Target-12hr	im6100a10-dfs	3.386667	20 C - 50% RH	1	06/02/00	Flexural	3.2923975
ype III -B Target-12hr	im6100a10-efs	3.443727	20 C - 50% RH	7	06/08/00	Flexural	
ype III -B Target-12hr	im6100a10-ffs	2.852615	20 C - 50% RH	7	06/08/00	Flexural	3.148171
ype III -B Target-12hr	im6100a10-gfs	5.162591	20 C - 50% RH	90	08/30/00	Flexural	
ype III -B Target-12hr	im6100a10-hfs	4.768687	20 C - 50% RH	90	08/30/00	Flexural	4.965639

Calcium Sulfoaluminate – A

MixDesign	Spec Name	Strength (Mpa)	Curing Regime	Spec Age (days)	Test Date	Test Type	Average Strength (Mpa)
CSA-A Target-4hrs	CSA-A Target-4hrs51600mt-afs	3.726887	23 C + 97% RH	0.167	05/16/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs51600mt-bfs	3.265149	23 C + 97% RH	0.167	05/16/00	Flexural	3.496018
CSA-A Target-4hrs	CSA-A Target-4hrs51600mt-cfs	4.356346	23 C + 97% RH	1	05/17/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs51600mt-dfs	4.748562	23 C + 97% RH	1	05/17/00	Flexural	4.552454
CSA-A Target-4hrs	CSA-A Target-4hrs51600mt-efs	5.291579	23 C + 97% RH	7	05/23/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs51600mt-ffs	5.374127	23 C + 97% RH	7	05/23/00	Flexural	5.332853
CSA-A Target-4hrs	CSA-A Target-4hrs51600mt-gfs	5.432085	23 C + 97% RH	90	08/14/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs51600mt-hfs	5.318856	23 C + 97% RH	90	08/14/00	Flexural	5.3754705
CSA-A Target-4hrs	CSA-A Target-4hrs51800a10-afs	3.329372	20 C - 50% RH	0.167	05/18/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs51800a10-bfs	3.492665	20 C - 50% RH	0.167	05/18/00	Flexural	3.4110185
CSA-A Target-4hrs	CSA-A Target-4hrs51800a10-cfs	4.697908	20 C - 50% RH	1	05/19/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs51800a10-dfs	3.685152	20 C - 50% RH	1	05/19/00	Flexural	4.19153
CSA-A Target-4hrs	CSA-A Target-4hrs51800a10-efs	3.715471	20 C - 50% RH	7	05/25/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs51800a10-ffs	4.023719	20 C - 50% RH	7	05/25/00	Flexural	3.869595
CSA-A Target-4hrs	CSA-A Target-4hrs51800a10-gfs	4.842175	20 C - 50% RH	90	08/16/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs51800a10-hfs	4.252686	20 C - 50% RH	90	08/16/00	Flexural	4.5474305
CSA-A Target-4hrs	CSA-A Target-4hrs51800AT-AFS	3.123446	20 C - 50% RH	0.167	05/18/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs51800AT-bFS	2.960165	20 C - 50% RH	0.167	05/18/00	Flexural	3.0418055
CSA-A Target-4hrs	CSA-A Target-4hrs51800AT-cFS	3.986151	20 C - 50% RH	1	05/19/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs51800AT-dFS	3.997595	20 C - 50% RH	1	05/19/00	Flexural	3.991873
CSA-A Target-4hrs	CSA-A Target-4hrs51800AT-eFS	3.950525	20 C - 50% RH	7	05/25/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs51800AT-fFS	3.702785	20 C - 50% RH	7	05/25/00	Flexural	3.826655
CSA-A Target-4hrs	CSA-A Target-4hrs51800AT-gFS	4.282931	20 C - 50% RH	90	08/16/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs51800AT-hFS	4.992969	20 C - 50% RH	90	08/16/00	Flexural	4.63795
CSA-A Target-4hrs	CSA-A Target-4hrs52500c10-afs	2.242966	10 C - 50% RH	0.167	05/25/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs52500c10-bfs	2.256473	10 C - 50% RH	0.167	05/25/00	Flexural	2.2497195
CSA-A Target-4hrs	CSA-A Target-4hrs52500c10-cfs	3.569026	10 C - 50% RH	1	05/26/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs52500c10-dfs	2.884865	10 C - 50% RH	1	05/26/00	Flexural	3.2269455
CSA-A Target-4hrs	CSA-A Target-4hrs52500c10-efs	4.364212	10 C - 50% RH	7	06/01/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs52500c10-ffs	4.263908	10 C - 50% RH	7	06/01/00	Flexural	4.31406
CSA-A Target-4hrs	CSA-A Target-4hrs52500c10-gfs	4.797511	10 C - 50% RH	90	08/23/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs52500c10-hfs	5.096487	10 C - 50% RH	90	08/23/00	Flexural	4.946999
CSA-A Target-4hrs	CSA-A Target-4hrs52500ct-afs	2.07463	10 C - 50% RH	0.167	05/25/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs52500ct-bfs	1.860906	10 C - 50% RH	0.167	05/25/00	Flexural	1.967768
CSA-A Target-4hrs	CSA-A Target-4hrs52500ct-cfs	2.988605	10 C - 50% RH	1	05/26/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs52500ct-dfs	2.919072	10 C - 50% RH	1	05/26/00	Flexural	2.9538385
CSA-A Target-4hrs	CSA-A Target-4hrs52500ct-efs	3.79819	10 C - 50% RH	7	06/01/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs52500ct-ffs	3.899029	10 C - 50% RH	7	06/01/00	Flexural	3.8486095
CSA-A Target-4hrs	CSA-A Target-4hrs52500ct-gfs	5.260518	10 C - 50% RH	90	08/23/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs52500ct-hfs	6.036216	10 C - 50% RH	90	08/23/00	Flexural	5.648367
CSA-A Target-4hrs	CSA-A Target-4hrs52600m10-afs	2.296006	23 C + 97% RH	0.167	05/26/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs52600m10-bfs	2.203405	23 C + 97% RH	0.167	05/26/00	Flexural	2.2497055
CSA-A Target-4hrs	CSA-A Target-4hrs52600m10-cfs	3.486922	23 C + 97% RH	1	05/27/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs52600m10-dfs	3.981705	23 C + 97% RH	1	05/27/00	Flexural	3.7343135
CSA-A Target-4hrs	CSA-A Target-4hrs52600m10-efs	4.421669	23 C + 97% RH	7	06/02/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs52600m10-ffs	4.719484	23 C + 97% RH	7	06/02/00	Flexural	4.5705765
CSA-A Target-4hrs	CSA-A Target-4hrs52600m10-gfs	4.704706	23 C + 97% RH	111	09/14/00	Flexural	
CSA-A Target-4hrs	CSA-A Target-4hrs52600m10-hfs	5.155167	23 C + 97% RH	111	09/14/00	Flexural	4.9299365

Calcium Sulfoaluminate – B

MixDesign	Spec Name	Strength (Mpa)	Curing Regime	Spec Age (days)	Test Date	Test Type	Average Strength (Mpa)
CSA-B Target-4hrs	um61900m10-afs	2.934024	23 C + 97% RH	0.167	06/19/00	Flexural	
CSA-B Target-4hrs	um61900m10-bfs	2.964636	23 C + 97% RH	0.167	06/19/00	Flexural	2.94933
CSA-B Target-4hrs	um61900m10-cfs	3.262614	23 C + 97% RH	1	06/20/00	Flexural	
CSA-B Target-4hrs	um61900m10-dfs	3.463132	23 C + 97% RH	1	06/20/00	Flexural	3.362873
CSA-B Target-4hrs	um61900m10-efs	4.091329	23 C + 97% RH	7	06/26/00	Flexural	
CSA-B Target-4hrs	um61900m10-ffs	4.131543	23 C + 97% RH	7	06/26/00	Flexural	4.111436
CSA-B Target-4hrs	um61900m10-gfs	4.965375	23 C + 97% RH	90	09/17/00	Flexural	
CSA-B Target-4hrs	um61900m10-hfs	5.705047	23 C + 97% RH	90	09/17/00	Flexural	5.335211
CSA-B Target-4hrs	um61900mt-afs	3.183907	23 C + 97% RH	0.167	06/19/00	Flexural	
CSA-B Target-4hrs	um61900mt-bfs	3.663016	23 C + 97% RH	0.167	06/19/00	Flexural	3.4234615
CSA-B Target-4hrs	um61900mt-cfs	3.755292	23 C + 97% RH	1	06/20/00	Flexural	
CSA-B Target-4hrs	um61900mt-dfs	3.140156	23 C + 97% RH	1	06/20/00	Flexural	3.447724
CSA-B Target-4hrs	um61900mt-efs	4.393548	23 C + 97% RH	7	06/26/00	Flexural	
CSA-B Target-4hrs	um61900mt-ffs	4.160738	23 C + 97% RH	7	06/26/00	Flexural	4.277143
CSA-B Target-4hrs	um61900mt-gfs	5.63585	23 C + 97% RH	90	09/17/00	Flexural	
CSA-B Target-4hrs	um61900mt-hfs	5.282866	23 C + 97% RH	90	09/17/00	Flexural	5.459358
CSA-B Target-4hrs	um62100a10-afs	3.127302	20 C - 50% RH	0.167	06/21/00	Flexural	
CSA-B Target-4hrs	um62100a10-bfs	3.262999	20 C - 50% RH	0.167	06/21/00	Flexural	3.1951505
CSA-B Target-4hrs	um62100a10-cfs	3.809833	20 C - 50% RH	1	06/22/00	Flexural	
CSA-B Target-4hrs	um62100a10-dfs	3.476544	20 C - 50% RH	1	06/22/00	Flexural	3.6431885
CSA-B Target-4hrs	um62100a10-efs	3.478208	20 C - 50% RH	7	06/28/00	Flexural	
CSA-B Target-4hrs	um62100a10-ffs	3.479949	20 C - 50% RH	7	06/28/00	Flexural	3.4790785
CSA-B Target-4hrs	um62100a10-gfs	3.727038	20 C - 50% RH	100	09/29/00	Flexural	
CSA-B Target-4hrs	um62100a10-hfs	3.582323	20 C - 50% RH	100	09/29/00	Flexural	3.6546805
CSA-B Target-4hrs	um62100at-afs	3.30721	20 C - 50% RH	0.167	06/21/00	Flexural	
CSA-B Target-4hrs	um62100at-bfs	3.372808	20 C - 50% RH	0.167	06/21/00	Flexural	3.340009
CSA-B Target-4hrs	um62100at-cfs	3.704493	20 C - 50% RH	1	06/22/00	Flexural	
CSA-B Target-4hrs	um62100at-dfs	3.496351	20 C - 50% RH	1	06/22/00	Flexural	3.600422
CSA-B Target-4hrs	um62100at-efs	3.012831	20 C - 50% RH	7	06/28/00	Flexural	
CSA-B Target-4hrs	um62100at-ffs	3.440932	20 C - 50% RH	7	06/28/00	Flexural	3.2268815
CSA-B Target-4hrs	um62100at-gfs	3.654995	20 C - 50% RH	100	09/29/00	Flexural	
CSA-B Target-4hrs	um62100at-hfs	3.505201	20 C - 50% RH	100	09/29/00	Flexural	3.580098
CSA-B Target-4hrs	um62700c10-afs	3.232702	10 C - 50% RH	0.167	06/27/00	Flexural	
CSA-B Target-4hrs	um62700c10-bfs	3.772225	10 C - 50% RH	0.167	06/27/00	Flexural	3.5024635
CSA-B Target-4hrs	um62700c10-cfs	4.247536	10 C - 50% RH	1	06/28/00	Flexural	
CSA-B Target-4hrs	um62700c10-dfs	3.8814	10 C - 50% RH	1	06/28/00	Flexural	4.064468
CSA-B Target-4hrs	um62700c10-efs	4.610673	10 C - 50% RH	7	07/04/00	Flexural	
CSA-B Target-4hrs	um62700c10-ffs	4.814992	10 C - 50% RH	7	07/04/00	Flexural	4.7128325
CSA-B Target-4hrs	um62700c10-gfs	5.28212	10 C - 50% RH	90	09/25/00	Flexural	
CSA-B Target-4hrs	um62700c10-hfs	5.285797	10 C - 50% RH	90	09/25/00	Flexural	5.2839585
CSA-B Target-4hrs	um62700ct-afs	3.152878	10 C - 50% RH	0.167	06/27/00	Flexural	
CSA-B Target-4hrs	um62700ct-bfs	3.1022	10 C - 50% RH	0.167	06/27/00	Flexural	3.127539
CSA-B Target-4hrs	um62700ct-cfs	4.244075	10 C - 50% RH	1	06/28/00	Flexural	
CSA-B Target-4hrs	um62700ct-dfs	4.169508	10 C - 50% RH	1	06/28/00	Flexural	4.2067915
CSA-B Target-4hrs	um62700ct-efs	4.373312	10 C - 50% RH	7	07/04/00	Flexural	
CSA-B Target-4hrs	um62700ct-ffs	5.329139	10 C - 50% RH	7	07/04/00	Flexural	4.8512255
CSA-B Target-4hrs	um62700ct-gfs	5.203303	10 C - 50% RH	90	09/25/00	Flexural	
CSA-B Target-4hrs	um62700ct-hfs	5.989906	10 C - 50% RH	90	09/25/00	Flexural	5.5966045

Calcium Aluminate

MixDesign	Spec Name	Strength (Mpa)	Curing Regime	Spec Age (days)	Test Date	Test Type	Average Strength (Mpa)
CA Target-4hrs	lf41100A10-afs	3.475199	20 C - 50% RH	0.33	04/11/00	Flexural	
CA Target-4hrs	lf41100A10-bfs	3.754427	20 C - 50% RH	0.33	04/11/00	Flexural	3.614813
CA Target-4hrs	lf41100A10-cfs	5.353318	20 C - 50% RH	1	04/12/00	Flexural	
CA Target-4hrs	lf41100A10-dfs	4.364204	20 C - 50% RH	1	04/12/00	Flexural	4.858761
CA Target-4hrs	lf41100A10-efs	4.076311	20 C - 50% RH	7	04/18/00	Flexural	
CA Target-4hrs	lf41100A10-ffs	3.762959	20 C - 50% RH	7	04/18/00	Flexural	3.919635
CA Target-4hrs	lf41100A10-gfs	3.665452	20 C - 50% RH	90	07/10/00	Flexural	
CA Target-4hrs	lf41100A10-hfs	4.735908	20 C - 50% RH	90	07/10/00	Flexural	4.20068
CA Target-4hrs	lf41100At-afs	4.825909	20 C - 50% RH	0.33	04/11/00	Flexural	
CA Target-4hrs	lf41100At-bfs	5.254456	20 C - 50% RH	0.33	04/11/00	Flexural	5.0401825
CA Target-4hrs	lf41100At-cfs	5.703181	20 C - 50% RH	1	04/12/00	Flexural	
CA Target-4hrs	lf41100At-dfs	5.609248	20 C - 50% RH	1	04/12/00	Flexural	5.6562145
CA Target-4hrs	lf41100At-efs	5.48689	20 C - 50% RH	7	04/18/00	Flexural	
CA Target-4hrs	lf41100At-ffs	6.10667	20 C - 50% RH	7	04/18/00	Flexural	5.79678
CA Target-4hrs	lf41100At-gfs	5.633772	20 C - 50% RH	90	07/10/00	Flexural	
CA Target-4hrs	lf41100At-hfs	4.690956	20 C - 50% RH	90	07/10/00	Flexural	5.162364
CA Target-4hrs	lf41300c10-afs	4.704954	10 C - 50% RH	0.33	04/13/00	Flexural	
CA Target-4hrs	lf41300c10-bfs	4.14227	10 C - 50% RH	0.33	04/13/00	Flexural	4.423612
CA Target-4hrs	lf41300c10-cfs	4.73096	10 C - 50% RH	1	04/14/00	Flexural	
CA Target-4hrs	lf41300c10-dfs	5.091062	10 C - 50% RH	1	04/14/00	Flexural	4.911011
CA Target-4hrs	lf41300c10-efs	4.832214	10 C - 50% RH	7	04/20/00	Flexural	
CA Target-4hrs	lf41300c10-ffs	6.264534	10 C - 50% RH	7	04/20/00	Flexural	5.548374
CA Target-4hrs	lf41300c10-gfs	5.859278	10 C - 50% RH	90	07/12/00	Flexural	
CA Target-4hrs	lf41300c10-hfs	5.839588	10 C - 50% RH	90	07/12/00	Flexural	5.849433
CA Target-4hrs	lf41300ct-afs	5.395625	10 C - 50% RH	0.33	04/13/00	Flexural	
CA Target-4hrs	lf41300ct-bfs	4.251396	10 C - 50% RH	0.33	04/13/00	Flexural	4.8235105
CA Target-4hrs	lf41300ct-cfs	4.830649	10 C - 50% RH	1	04/14/00	Flexural	
CA Target-4hrs	lf41300ct-dfs	5.024294	10 C - 50% RH	1	04/14/00	Flexural	4.9274715
CA Target-4hrs	lf41300ct-efs	6.367083	10 C - 50% RH	7	04/20/00	Flexural	
CA Target-4hrs	lf41300ct-ffs	6.024414	10 C - 50% RH	7	04/20/00	Flexural	6.1957485
CA Target-4hrs	lf41300ct-gfs	6.200911	10 C - 50% RH	90	07/12/00	Flexural	
CA Target-4hrs	lf41300ct-hfs	6.679671	10 C - 50% RH	90	07/12/00	Flexural	6.440291
CA Target-4hrs	lf4400m10-bfs	3.186628	23 C + 97% RH	0.33	04/04/00	Flexural	3.186628
CA Target-4hrs	lf4400m10-cfs	4.147156	23 C + 97% RH	1	04/05/00	Flexural	
CA Target-4hrs	lf4400m10-dfs	4.515096	23 C + 97% RH	1	04/05/00	Flexural	4.331126
CA Target-4hrs	lf4400m10-efs	6.363369	23 C + 97% RH	7	04/11/00	Flexural	
CA Target-4hrs	lf4400m10-ffs	5.014249	23 C + 97% RH	7	04/11/00	Flexural	5.688809
CA Target-4hrs	lf4400m10-gfs	4.696963	23 C + 97% RH	90	07/03/00	Flexural	
CA Target-4hrs	lf4400m10-hfs	6.218682	23 C + 97% RH	90	07/03/00	Flexural	5.4578225
CA Target-4hrs	lf4600MT-afs	3.68266	23 C + 97% RH	0.3	04/06/00	Flexural	
CA Target-4hrs	lf4600MT-bfs	4.743999	23 C + 97% RH	0.33	04/06/00	Flexural	4.2133295
CA Target-4hrs	lf4600MT-cfs	5.216736	23 C + 97% RH	1	04/07/00	Flexural	
CA Target-4hrs	lf4600MT-dfs	4.941787	23 C + 97% RH	1	04/07/00	Flexural	5.0792615
CA Target-4hrs	lf4600MT-efs	7.398316	23 C + 97% RH	7	04/13/00	Flexural	
CA Target-4hrs	lf4600MT-ffs	7.62753	23 C + 97% RH	7	04/13/00	Flexural	7.512923
CA Target-4hrs	lf4600MT-gfs	6.945668	23 C + 97% RH	90	07/05/00	Flexural	
CA Target-4hrs	lf4600MT-hfs	6.723847	23 C + 97% RH	90	07/05/00	Flexural	6.8347575

SHRINKAGE, CONCRETE BEAMS

Type I/II Portland Cement

Cement type	Cement content (kg/m^3)	Water Content	Aggregate type	C/A by volume	Curing Regime	Specimen Age (days)	Average shrinkage
Type I/II	362.49	0.42	Rounded Gravel	0.17	10 C - 50% RH	3	0.0
Type I/II	362.49	0.42	Rounded Gravel	0.17	10 C - 50% RH	7	-40.9
Type I/II	362.49	0.42	Rounded Gravel	0.17	10 C - 50% RH	14	-43.2
Type I/II	362.49	0.42	Rounded Gravel	0.17	10 C - 50% RH	28	-145.9
Type I/II	362.49	0.42	Rounded Gravel	0.17	10 C - 50% RH	90	-77.1
Type I/II	362.49	0.42	Rounded Gravel	0.17	20 C - 50% RH	3	0.0
Type I/II	362.49	0.42	Rounded Gravel	0.17	20 C - 50% RH	7	-122.6
Type I/II	362.49	0.42	Rounded Gravel	0.17	20 C - 50% RH	14	-267.4
Type I/II	362.49	0.42	Rounded Gravel	0.17	20 C - 50% RH	28	-513.7
Type I/II	362.49	0.42	Rounded Gravel	0.17	20 C - 50% RH	90	-631.6
Type I/II	362.49	0.42	Rounded Gravel	0.17	23 C - 97% RH	3	0.0
Type I/II	362.49	0.42	Rounded Gravel	0.17	23 C - 97% RH	7	25.7
Type I/II	362.49	0.42	Rounded Gravel	0.17	23 C - 97% RH	14	-74.7
Type I/II	362.49	0.42	Rounded Gravel	0.17	23 C - 97% RH	28	-89.9
Type I/II	362.49	0.42	Rounded Gravel	0.17	23 C - 97% RH	90	-52.5
Type I/II	362.49	0.42	Rounded Gravel	0.17	40 C + ~0%RH	3	0.0
Type I/II	362.49	0.42	Rounded Gravel	0.17	40 C + ~0%RH	7	-73.6
Type I/II	362.49	0.42	Rounded Gravel	0.17	40 C + ~0%RH	14	-461.2
Type I/II	362.49	0.42	Rounded Gravel	0.17	40 C + ~0%RH	28	-685.3
Type I/II	362.49	0.42	Rounded Gravel	0.17	40 C + ~0%RH	90	-603.6
Type I/II	362.49	0.46	Rounded Gravel	0.17	10 C - 50% RH	3	0.0
Type I/II	362.49	0.46	Rounded Gravel	0.17	10 C - 50% RH	7	-67.7
Type I/II	362.49	0.46	Rounded Gravel	0.17	10 C - 50% RH	14	-106.2
Type I/II	362.49	0.46	Rounded Gravel	0.17	10 C - 50% RH	28	-70.1
Type I/II	362.49	0.46	Rounded Gravel	0.17	10 C - 50% RH	90	-87.6
Type I/II	362.49	0.46	Rounded Gravel	0.17	20 C - 50% RH	3	0.0
Type I/II	362.49	0.46	Rounded Gravel	0.17	20 C - 50% RH	7	-164.6
Type I/II	362.49	0.46	Rounded Gravel	0.17	20 C - 50% RH	14	-295.4
Type I/II	362.49	0.46	Rounded Gravel	0.17	20 C - 50% RH	28	-428.5
Type I/II	362.49	0.46	Rounded Gravel	0.17	20 C - 50% RH	90	-586.1
Type I/II	362.49	0.46	Rounded Gravel	0.17	23 C - 97% RH	3	0.0
Type I/II	362.49	0.46	Rounded Gravel	0.17	23 C - 97% RH	7	-93.4
Type I/II	362.49	0.46	Rounded Gravel	0.17	23 C - 97% RH	14	-95.7
Type I/II	362.49	0.46	Rounded Gravel	0.17	23 C - 97% RH	28	-37.4
Type I/II	362.49	0.46	Rounded Gravel	0.17	23 C - 97% RH	90	-36.2
Type I/II	362.49	0.46	Rounded Gravel	0.17	40 C + ~0%RH	3	0.0
Type I/II	362.49	0.46	Rounded Gravel	0.17	40 C + ~0%RH	7	-520.7
Type I/II	362.49	0.46	Rounded Gravel	0.17	40 C + ~0%RH	14	-567.4
Type I/II	362.49	0.46	Rounded Gravel	0.17	40 C + ~0%RH	28	-541.7
Type I/II	362.49	0.46	Rounded Gravel	0.17	40 C + ~0%RH	90	-580.3

Type III-A Portland Cement

Cement type	Cement content (kg/m^3)	Water Content	Aggregate type	C/A by volume	Curing Regime	Specimen Age (days)	Average shrinkage
Type III-A	446.14	0.38	Rounded Gravel	0.21	10 C - 50% RH	3	0.0
Type III-A	446.14	0.38	Rounded Gravel	0.21	10 C - 50% RH	7	-88.7
Type III-A	446.14	0.38	Rounded Gravel	0.21	10 C - 50% RH	14	-127.3
Type III-A	446.14	0.38	Rounded Gravel	0.21	10 C - 50% RH	28	-119.1
Type III-A	446.14	0.38	Rounded Gravel	0.21	10 C - 50% RH	90	-101.6
Type III-A	446.14	0.38	Rounded Gravel	0.21	20 C - 50% RH	3	0.0
Type III-A	446.14	0.38	Rounded Gravel	0.21	20 C - 50% RH	7	-269.7
Type III-A	446.14	0.38	Rounded Gravel	0.21	20 C - 50% RH	14	-416.8
Type III-A	446.14	0.38	Rounded Gravel	0.21	20 C - 50% RH	28	-659.7
Type III-A	446.14	0.38	Rounded Gravel	0.21	20 C - 50% RH	90	-845.3
Type III-A	446.14	0.38	Rounded Gravel	0.21	23 C - 97% RH	3	0.0
Type III-A	446.14	0.38	Rounded Gravel	0.21	23 C - 97% RH	7	-59.5
Type III-A	446.14	0.38	Rounded Gravel	0.21	23 C - 97% RH	14	-63.0
Type III-A	446.14	0.38	Rounded Gravel	0.21	23 C - 97% RH	28	-192.6
Type III-A	446.14	0.38	Rounded Gravel	0.21	23 C - 97% RH	90	-46.7
Type III-A	446.14	0.38	Rounded Gravel	0.21	40 C + ~0%RH	3	0.0
Type III-A	446.14	0.38	Rounded Gravel	0.21	40 C + ~0%RH	7	-414.5
Type III-A	446.14	0.38	Rounded Gravel	0.21	40 C + ~0%RH	14	-657.3
Type III-A	446.14	0.38	Rounded Gravel	0.21	40 C + ~0%RH	28	-819.6
Type III-A	446.14	0.38	Rounded Gravel	0.21	40 C + ~0%RH	90	-945.7
Type III-A	446.14	0.42	Rounded Gravel	0.21	10 C - 50% RH	3	0.0
Type III-A	446.14	0.42	Rounded Gravel	0.21	10 C - 50% RH	7	-72.4
Type III-A	446.14	0.42	Rounded Gravel	0.21	10 C - 50% RH	14	-131.9
Type III-A	446.14	0.42	Rounded Gravel	0.21	10 C - 50% RH	28	-105.1
Type III-A	446.14	0.42	Rounded Gravel	0.21	10 C - 50% RH	90	-119.1
Type III-A	446.14	0.42	Rounded Gravel	0.21	20 C - 50% RH	3	0.0
Type III-A	446.14	0.42	Rounded Gravel	0.21	20 C - 50% RH	7	-254.5
Type III-A	446.14	0.42	Rounded Gravel	0.21	20 C - 50% RH	14	-402.8
Type III-A	446.14	0.42	Rounded Gravel	0.21	20 C - 50% RH	28	-634.0
Type III-A	446.14	0.42	Rounded Gravel	0.21	20 C - 50% RH	90	-826.6
Type III-A	446.14	0.42	Rounded Gravel	0.21	23 C - 97% RH	3	0.0
Type III-A	446.14	0.42	Rounded Gravel	0.21	23 C - 97% RH	7	-53.7
Type III-A	446.14	0.42	Rounded Gravel	0.21	23 C - 97% RH	14	-79.4
Type III-A	446.14	0.42	Rounded Gravel	0.21	23 C - 97% RH	28	-197.3
Type III-A	446.14	0.42	Rounded Gravel	0.21	23 C - 97% RH	90	-71.2
Type III-A	446.14	0.42	Rounded Gravel	0.21	40 C + ~0%RH	3	0.0
Type III-A	446.14	0.42	Rounded Gravel	0.21	40 C + ~0%RH	7	-364.3
Type III-A	446.14	0.42	Rounded Gravel	0.21	40 C + ~0%RH	14	-589.6
Type III-A	446.14	0.42	Rounded Gravel	0.21	40 C + ~0%RH	28	-750.7
Type III-A	446.14	0.42	Rounded Gravel	0.21	40 C + ~0%RH	90	-864.0

Type III-B Portland Cement

Cement type	Cement content (kg/m^3)	Water Content	Aggregate type	C/A by volume	Curing Regime	Specimen Age (days)	Average shrinkage
Type III -B	474.62	0.36	Crushed Stone	0.22	10 C - 50% RH	3	0.0
Type III -B	474.62	0.36	Crushed Stone	0.22	10 C - 50% RH	7	-85.2
Type III -B	474.62	0.36	Crushed Stone	0.22	10 C - 50% RH	14	-82.9
Type III -B	474.62	0.36	Crushed Stone	0.22	10 C - 50% RH	28	-73.6
Type III -B	474.62	0.36	Crushed Stone	0.22	10 C - 50% RH	90	-133.1
Type III -B	474.62	0.36	Crushed Stone	0.22	20 C - 50% RH	3	0.0
Type III -B	474.62	0.36	Crushed Stone	0.22	20 C - 50% RH	7	-289.6
Type III -B	474.62	0.36	Crushed Stone	0.22	20 C - 50% RH	14	-422.7
Type III -B	474.62	0.36	Crushed Stone	0.22	20 C - 50% RH	28	-641.0
Type III -B	474.62	0.36	Crushed Stone	0.22	20 C - 50% RH	90	-718.0
Type III -B	474.62	0.36	Crushed Stone	0.22	23 C - 97% RH	3	0.0
Type III -B	474.62	0.36	Crushed Stone	0.22	23 C - 97% RH	7	-89.9
Type III -B	474.62	0.36	Crushed Stone	0.22	23 C - 97% RH	14	-29.2
Type III -B	474.62	0.36	Crushed Stone	0.22	23 C - 97% RH	28	-84.1
Type III -B	474.62	0.36	Crushed Stone	0.22	23 C - 97% RH	90	-77.1
Type III -B	474.62	0.36	Crushed Stone	0.22	40 C + ~0%RH	3	0.0
Type III -B	474.62	0.36	Crushed Stone	0.22	40 C + ~0%RH	7	-383.0
Type III -B	474.62	0.36	Crushed Stone	0.22	40 C + ~0%RH	14	-540.6
Type III -B	474.62	0.36	Crushed Stone	0.22	40 C + ~0%RH	28	-646.8
Type III -B	474.62	0.36	Crushed Stone	0.22	40 C + ~0%RH	90	-778.8
Type III -B	474.62	0.4	Crushed Stone	0.22	10 C - 50% RH	3	0.0
Type III -B	474.62	0.4	Crushed Stone	0.22	10 C - 50% RH	7	-37.4
Type III -B	474.62	0.4	Crushed Stone	0.22	10 C - 50% RH	14	-51.4
Type III -B	474.62	0.4	Crushed Stone	0.22	10 C - 50% RH	28	-38.5
Type III -B	474.62	0.4	Crushed Stone	0.22	10 C - 50% RH	90	-113.3
Type III -B	474.62	0.4	Crushed Stone	0.22	20 C - 50% RH	3	0.0
Type III -B	474.62	0.4	Crushed Stone	0.22	20 C - 50% RH	7	-281.4
Type III -B	474.62	0.4	Crushed Stone	0.22	20 C - 50% RH	14	-402.8
Type III -B	474.62	0.4	Crushed Stone	0.22	20 C - 50% RH	28	-590.8
Type III -B	474.62	0.4	Crushed Stone	0.22	20 C - 50% RH	90	-655.0
Type III -B	474.62	0.4	Crushed Stone	0.22	23 C - 97% RH	3	0.0
Type III -B	474.62	0.4	Crushed Stone	0.22	23 C - 97% RH	7	-61.9
Type III -B	474.62	0.4	Crushed Stone	0.22	23 C - 97% RH	14	1.2
Type III -B	474.62	0.4	Crushed Stone	0.22	23 C - 97% RH	28	-49.0
Type III -B	474.62	0.4	Crushed Stone	0.22	23 C - 97% RH	90	-33.9
Type III -B	474.62	0.4	Crushed Stone	0.22	40 C + ~0%RH	3	0.0
Type III -B	474.62	0.4	Crushed Stone	0.22	40 C + ~0%RH	7	-360.8
Type III -B	474.62	0.4	Crushed Stone	0.22	40 C + ~0%RH	14	-506.7
Type III -B	474.62	0.4	Crushed Stone	0.22	40 C + ~0%RH	28	-629.3
Type III -B	474.62	0.4	Crushed Stone	0.22	40 C + ~0%RH	90	-742.6

Calcium Sulfoaluminate – A

Cement type	Cement content (kg/m^3)	Water Content	Aggregate type	C/A by volume	Curing Regime	Specimen Age (days)	Average shrinkage
CSA-A	390.38	0.37	Rounded Gravel	0.18	10 C - 50% RH	3	0.0
CSA-A	390.38	0.37	Rounded Gravel	0.18	10 C - 50% RH	7	-50.2
CSA-A	390.38	0.37	Rounded Gravel	0.18	10 C - 50% RH	14	-58.4
CSA-A	390.38	0.37	Rounded Gravel	0.18	10 C - 50% RH	28	-42.0
CSA-A	390.38	0.37	Rounded Gravel	0.18	10 C - 50% RH	90	-51.4
CSA-A	390.38	0.37	Rounded Gravel	0.18	20 C - 50% RH	3	0.0
CSA-A	390.38	0.37	Rounded Gravel	0.18	20 C - 50% RH	7	-147.1
CSA-A	390.38	0.37	Rounded Gravel	0.18	20 C - 50% RH	14	-217.2
CSA-A	390.38	0.37	Rounded Gravel	0.18	20 C - 50% RH	28	-304.7
CSA-A	390.38	0.37	Rounded Gravel	0.18	20 C - 50% RH	90	-370.1
CSA-A	390.38	0.37	Rounded Gravel	0.18	23 C - 97% RH	3	0.0
CSA-A	390.38	0.37	Rounded Gravel	0.18	23 C - 97% RH	7	-42.0
CSA-A	390.38	0.37	Rounded Gravel	0.18	23 C - 97% RH	14	7.0
CSA-A	390.38	0.37	Rounded Gravel	0.18	23 C - 97% RH	28	-24.5
CSA-A	390.38	0.37	Rounded Gravel	0.18	23 C - 97% RH	90	23.4
CSA-A	390.38	0.37	Rounded Gravel	0.18	40 C + ~0%RH	3	0.0
CSA-A	390.38	0.37	Rounded Gravel	0.18	40 C + ~0%RH	7	-249.9
CSA-A	390.38	0.37	Rounded Gravel	0.18	40 C + ~0%RH	14	-350.3
CSA-A	390.38	0.37	Rounded Gravel	0.18	40 C + ~0%RH	28	-462.3
CSA-A	390.38	0.37	Rounded Gravel	0.18	40 C + ~0%RH	90	-614.1
CSA-A	390.38	0.41	Rounded Gravel	0.18	10 C - 50% RH	3	0.0
CSA-A	390.38	0.41	Rounded Gravel	0.18	10 C - 50% RH	7	-44.4
CSA-A	390.38	0.41	Rounded Gravel	0.18	10 C - 50% RH	14	-45.5
CSA-A	390.38	0.41	Rounded Gravel	0.18	10 C - 50% RH	28	-43.2
CSA-A	390.38	0.41	Rounded Gravel	0.18	10 C - 50% RH	90	-36.2
CSA-A	390.38	0.41	Rounded Gravel	0.18	20 C - 50% RH	3	0.0
CSA-A	390.38	0.41	Rounded Gravel	0.18	20 C - 50% RH	7	-147.1
CSA-A	390.38	0.41	Rounded Gravel	0.18	20 C - 50% RH	14	-219.5
CSA-A	390.38	0.41	Rounded Gravel	0.18	20 C - 50% RH	28	-318.7
CSA-A	390.38	0.41	Rounded Gravel	0.18	20 C - 50% RH	90	-412.1
CSA-A	390.38	0.41	Rounded Gravel	0.18	23 C - 97% RH	3	0.0
CSA-A	390.38	0.41	Rounded Gravel	0.18	23 C - 97% RH	7	-31.5
CSA-A	390.38	0.41	Rounded Gravel	0.18	23 C - 97% RH	14	-36.2
CSA-A	390.38	0.41	Rounded Gravel	0.18	23 C - 97% RH	28	-23.4
CSA-A	390.38	0.41	Rounded Gravel	0.18	23 C - 97% RH	90	45.5
CSA-A	390.38	0.41	Rounded Gravel	0.18	40 C + ~0%RH	3	0.0
CSA-A	390.38	0.41	Rounded Gravel	0.18	40 C + ~0%RH	7	-263.9
CSA-A	390.38	0.41	Rounded Gravel	0.18	40 C + ~0%RH	14	-360.8
CSA-A	390.38	0.41	Rounded Gravel	0.18	40 C + ~0%RH	28	-521.9
CSA-A	390.38	0.41	Rounded Gravel	0.18	40 C + ~0%RH	90	-679.5

Calcium Sulfoaluminate – B

Cement type	Cement content (kg/m^3)	Water Content	Aggregate type	C/A by volume	Curing Regime	Specimen Age (days)	Average shrinkage
CSA-B	415.29	0.37	Rounded Gravel	0.2	10 C - 50% RH	3	0.0
CSA-B	415.29	0.37	Rounded Gravel	0.2	10 C - 50% RH	7	-108.6
CSA-B	415.29	0.37	Rounded Gravel	0.2	10 C - 50% RH	14	-116.8
CSA-B	415.29	0.37	Rounded Gravel	0.2	10 C - 50% RH	28	-135.4
CSA-B	415.29	0.37	Rounded Gravel	0.2	10 C - 50% RH	90	11.7
CSA-B	415.29	0.37	Rounded Gravel	0.2	20 C - 50% RH	3	0.0
CSA-B	415.29	0.37	Rounded Gravel	0.2	20 C - 50% RH	7	-148.3
CSA-B	415.29	0.37	Rounded Gravel	0.2	20 C - 50% RH	14	-228.8
CSA-B	415.29	0.37	Rounded Gravel	0.2	20 C - 50% RH	28	-318.7
CSA-B	415.29	0.37	Rounded Gravel	0.2	20 C - 50% RH	90	-340.9
CSA-B	415.29	0.37	Rounded Gravel	0.2	23 C - 97% RH	3	0.0
CSA-B	415.29	0.37	Rounded Gravel	0.2	23 C - 97% RH	7	-131.9
CSA-B	415.29	0.37	Rounded Gravel	0.2	23 C - 97% RH	14	-227.7
CSA-B	415.29	0.37	Rounded Gravel	0.2	23 C - 97% RH	28	-261.5
CSA-B	415.29	0.37	Rounded Gravel	0.2	23 C - 97% RH	90	78.2
CSA-B	415.29	0.37	Rounded Gravel	0.2	40 C + ~0%RH	3	0.0
CSA-B	415.29	0.37	Rounded Gravel	0.2	40 C + ~0%RH	7	-287.2
CSA-B	415.29	0.37	Rounded Gravel	0.2	40 C + ~0%RH	14	-392.3
CSA-B	415.29	0.37	Rounded Gravel	0.2	40 C + ~0%RH	28	-495.0
CSA-B	415.29	0.37	Rounded Gravel	0.2	40 C + ~0%RH	90	-665.5
CSA-B	415.29	0.41	Rounded Gravel	0.2	10 C - 50% RH	3	0.0
CSA-B	415.29	0.41	Rounded Gravel	0.2	10 C - 50% RH	7	-92.2
CSA-B	415.29	0.41	Rounded Gravel	0.2	10 C - 50% RH	14	-113.3
CSA-B	415.29	0.41	Rounded Gravel	0.2	10 C - 50% RH	28	-138.9
CSA-B	415.29	0.41	Rounded Gravel	0.2	10 C - 50% RH	90	-138.9
CSA-B	415.29	0.41	Rounded Gravel	0.2	20 C - 50% RH	3	0.0
CSA-B	415.29	0.41	Rounded Gravel	0.2	20 C - 50% RH	14	-199.6
CSA-B	415.29	0.41	Rounded Gravel	0.2	20 C - 50% RH	28	-291.9
CSA-B	415.29	0.41	Rounded Gravel	0.2	20 C - 50% RH	90	-338.6
CSA-B	415.29	0.41	Rounded Gravel	0.2	23 C - 97% RH	3	0.0
CSA-B	415.29	0.41	Rounded Gravel	0.2	23 C - 97% RH	7	-128.4
CSA-B	415.29	0.41	Rounded Gravel	0.2	23 C - 97% RH	14	-162.3
CSA-B	415.29	0.41	Rounded Gravel	0.2	23 C - 97% RH	28	-209.0
CSA-B	415.29	0.41	Rounded Gravel	0.2	23 C - 97% RH	90	-37.4
CSA-B	415.29	0.41	Rounded Gravel	0.2	40 C + ~0%RH	3	0.0
CSA-B	415.29	0.41	Rounded Gravel	0.2	40 C + ~0%RH	7	-163.5
CSA-B	415.29	0.41	Rounded Gravel	0.2	40 C + ~0%RH	14	-237.0
CSA-B	415.29	0.41	Rounded Gravel	0.2	40 C + ~0%RH	28	-368.9
CSA-B	415.29	0.41	Rounded Gravel	0.2	40 C + ~0%RH	90	-509.0

Calcium Aluminate

Cement type	Cement content (kg/m^3)	Water Content	Aggregate type	C/A by volume	Curing Regime	Specimen Age (days)	Average shrinkage
CA	390.38	0.32	Rounded Gravel	0.18	10 C - 50% RH	3	**0.0**
CA	390.38	0.32	Rounded Gravel	0.18	10 C - 50% RH	7	**-21.0**
CA	390.38	0.32	Rounded Gravel	0.18	10 C - 50% RH	14	**-37.4**
CA	390.38	0.32	Rounded Gravel	0.18	10 C - 50% RH	28	**-51.4**
CA	390.38	0.32	Rounded Gravel	0.18	10 C - 50% RH	90	**-29.2**
CA	390.38	0.32	Rounded Gravel	0.18	20 C - 50% RH	3	**0.0**
CA	390.38	0.32	Rounded Gravel	0.18	20 C - 50% RH	7	**-210.2**
CA	390.38	0.32	Rounded Gravel	0.18	20 C - 50% RH	14	**-326.9**
CA	390.38	0.32	Rounded Gravel	0.18	20 C - 50% RH	28	**-418.0**
CA	390.38	0.32	Rounded Gravel	0.18	20 C - 50% RH	90	**-443.7**
CA	390.38	0.32	Rounded Gravel	0.18	23 C - 97% RH	3	**0.0**
CA	390.38	0.32	Rounded Gravel	0.18	23 C - 97% RH	7	**43.2**
CA	390.38	0.32	Rounded Gravel	0.18	23 C - 97% RH	14	**28.0**
CA	390.38	0.32	Rounded Gravel	0.18	23 C - 97% RH	28	**59.5**
CA	390.38	0.32	Rounded Gravel	0.18	23 C - 97% RH	90	**155.3**
CA	390.38	0.32	Rounded Gravel	0.18	40 C + ~0%RH	3	**0.0**
CA	390.38	0.32	Rounded Gravel	0.18	40 C + ~0%RH	7	**-131.9**
CA	390.38	0.32	Rounded Gravel	0.18	40 C + ~0%RH	14	**-138.4**
CA	390.38	0.32	Rounded Gravel	0.18	40 C + ~0%RH	28	**-192.6**
CA	390.38	0.32	Rounded Gravel	0.18	40 C + ~0%RH	90	**-392.3**
CA	390.38	0.35	Rounded Gravel	0.18	10 C - 50% RH	3	0.0
CA	390.38	0.35	Rounded Gravel	0.18	10 C - 50% RH	7	-26.9
CA	390.38	0.35	Rounded Gravel	0.18	10 C - 50% RH	14	-54.9
CA	390.38	0.35	Rounded Gravel	0.18	10 C - 50% RH	28	-51.4
CA	390.38	0.35	Rounded Gravel	0.18	10 C - 50% RH	90	-17.5
CA	390.38	0.35	Rounded Gravel	0.18	20 C - 50% RH	3	0.0
CA	390.38	0.35	Rounded Gravel	0.18	20 C - 50% RH	7	-247.5
CA	390.38	0.35	Rounded Gravel	0.18	20 C - 50% RH	14	-331.6
CA	390.38	0.35	Rounded Gravel	0.18	20 C - 50% RH	28	-391.1
CA	390.38	0.35	Rounded Gravel	0.18	20 C - 50% RH	90	-412.1
CA	390.38	0.35	Rounded Gravel	0.18	23 C - 97% RH	3	0.0
CA	390.38	0.35	Rounded Gravel	0.18	23 C - 97% RH	7	1.2
CA	390.38	0.35	Rounded Gravel	0.18	23 C - 97% RH	14	-50.2
CA	390.38	0.35	Rounded Gravel	0.18	23 C - 97% RH	28	33.9
CA	390.38	0.35	Rounded Gravel	0.18	23 C - 97% RH	90	157.6
CA	390.38	0.35	Rounded Gravel	0.18	40 C + ~0%RH	3	0.0
CA	390.38	0.35	Rounded Gravel	0.18	40 C + ~0%RH	7	-218.3
CA	390.38	0.35	Rounded Gravel	0.18	40 C + ~0%RH	14	-230.0
CA	390.38	0.35	Rounded Gravel	0.18	40 C + ~0%RH	28	-195.0
CA	390.38	0.35	Rounded Gravel	0.18	40 C + ~0%RH	90	-465.8

SHRINKAGE, CEMENT MORTAR

Type I/II Portland Cement

Cement type	W/C	Curing Regime	Specimen Age (days)	Average shrinkage
Type I/II	0.42	10 C - 50% RH	3	**0.0**
Type I/II	0.42	10 C - 50% RH	7	
Type I/II	0.42	10 C - 50% RH	14	**-131.9**
Type I/II	0.42	10 C - 50% RH	28	**-148.3**
Type I/II	0.42	10 C - 50% RH	90	**-207.8**
Type I/II	0.42	20 C - 50% RH	3	**0.0**
Type I/II	0.42	20 C - 50% RH	7	
Type I/II	0.42	20 C - 50% RH	14	**-503.2**
Type I/II	0.42	20 C - 50% RH	28	**-665.5**
Type I/II	0.42	20 C - 50% RH	90	**-781.1**
Type I/II	0.42	23 C - 97% RH	3	**0.0**
Type I/II	0.42	23 C - 97% RH	7	
Type I/II	0.42	23 C - 97% RH	14	**-31.5**
Type I/II	0.42	23 C - 97% RH	28	**-18.7**
Type I/II	0.42	23 C - 97% RH	90	**3.5**
Type I/II	0.42	40 C + ~0%RH	3	**0.0**
Type I/II	0.42	40 C + ~0%RH	7	
Type I/II	0.42	40 C + ~0%RH	14	**-691.2**
Type I/II	0.42	40 C + ~0%RH	28	**-699.4**
Type I/II	0.42	40 C + ~0%RH	90	**-788.1**
Type I/II	0.46	10 C - 50% RH	3	0.0
Type I/II	0.46	10 C - 50% RH	7	
Type I/II	0.46	10 C - 50% RH	14	-138.9
Type I/II	0.46	10 C - 50% RH	28	-150.6
Type I/II	0.46	10 C - 50% RH	90	-225.3
Type I/II	0.46	20 C - 50% RH	3	0.0
Type I/II	0.46	20 C - 50% RH	7	
Type I/II	0.46	20 C - 50% RH	14	-477.5
Type I/II	0.46	20 C - 50% RH	28	-639.8
Type I/II	0.46	20 C - 50% RH	90	-765.9
Type I/II	0.46	23 C - 97% RH	3	0.0
Type I/II	0.46	23 C - 97% RH	7	
Type I/II	0.46	23 C - 97% RH	14	-14.0
Type I/II	0.46	23 C - 97% RH	28	-15.2
Type I/II	0.46	23 C - 97% RH	90	-1.2
Type I/II	0.46	40 C + ~0%RH	3	0.0
Type I/II	0.46	40 C + ~0%RH	7	
Type I/II	0.46	40 C + ~0%RH	14	-753.1
Type I/II	0.46	40 C + ~0%RH	28	-763.6
Type I/II	0.46	40 C + ~0%RH	90	-847.6

Type III-A Portland Cement

Cement type	W/C	Curing Regime	Specimen Age (days)	Average shrinkage
Type III-A	0.38	10 C - 50% RH	3	0.0
Type III-A	0.38	10 C - 50% RH	7	-77.1
Type III-A	0.38	10 C - 50% RH	14	-136.6
Type III-A	0.38	10 C - 50% RH	28	-176.3
Type III-A	0.38	10 C - 50% RH	90	-158.8
Type III-A	0.38	20 C - 50% RH	3	0.0
Type III-A	0.38	20 C - 50% RH	7	-347.9
Type III-A	0.38	20 C - 50% RH	14	-542.9
Type III-A	0.38	20 C - 50% RH	28	-762.4
Type III-A	0.38	20 C - 50% RH	90	-845.3
Type III-A	0.38	23 C - 97% RH	3	0.0
Type III-A	0.38	23 C - 97% RH	7	-87.0
Type III-A	0.38	23 C - 97% RH	14	-105.7
Type III-A	0.38	23 C - 97% RH	28	-129.0
Type III-A	0.38	23 C - 97% RH	90	-192.1
Type III-A	0.38	40 C + ~0%RH	3	0.0
Type III-A	0.38	40 C + ~0%RH	7	-601.3
Type III-A	0.38	40 C + ~0%RH	14	-874.5
Type III-A	0.38	40 C + ~0%RH	28	-955.0
Type III-A	0.38	40 C + ~0%RH	90	-1027.4
Type III-A	0.42	10 C - 50% RH	3	0.0
Type III-A	0.42	10 C - 50% RH	7	-82.9
Type III-A	0.42	10 C - 50% RH	14	-127.3
Type III-A	0.42	10 C - 50% RH	28	-176.3
Type III-A	0.42	10 C - 50% RH	90	-163.5
Type III-A	0.42	20 C - 50% RH	3	0.0
Type III-A	0.42	20 C - 50% RH	7	19.3
Type III-A	0.42	20 C - 50% RH	14	-595.4
Type III-A	0.42	20 C - 50% RH	28	-845.3
Type III-A	0.42	20 C - 50% RH	90	-915.4
Type III-A	0.42	23 C - 97% RH	3	0.0
Type III-A	0.42	23 C - 97% RH	7	-98.1
Type III-A	0.42	23 C - 97% RH	14	-171.6
Type III-A	0.42	23 C - 97% RH	28	-302.4
Type III-A	0.42	23 C - 97% RH	90	-110.9
Type III-A	0.42	40 C + ~0%RH	3	0.0
Type III-A	0.42	40 C + ~0%RH	7	-583.8
Type III-A	0.42	40 C + ~0%RH	14	-871.0
Type III-A	0.42	40 C + ~0%RH	28	-907.2
Type III-A	0.42	40 C + ~0%RH	90	-995.9

Type III-B Portland Cement

Cement type	W/C	Curing Regime	Specimen Age (days)	Average shrinkage
Type III -B	0.36	10 C - 50% RH	3	0.0
Type III -B	0.36	10 C - 50% RH	7	-73.6
Type III -B	0.36	10 C - 50% RH	14	-98.1
Type III -B	0.36	10 C - 50% RH	28	-86.4
Type III -B	0.36	10 C - 50% RH	90	-170.5
Type III -B	0.36	20 C - 50% RH	3	0.0
Type III -B	0.36	20 C - 50% RH	7	-428.5
Type III -B	0.36	20 C - 50% RH	14	-665.5
Type III -B	0.36	20 C - 50% RH	28	-709.9
Type III -B	0.36	20 C - 50% RH	90	-829.0
Type III -B	0.36	23 C - 97% RH	3	0.0
Type III -B	0.36	23 C - 97% RH	7	-136.6
Type III -B	0.36	23 C - 97% RH	14	-130.8
Type III -B	0.36	23 C - 97% RH	28	-17.5
Type III -B	0.36	23 C - 97% RH	90	21.0
Type III -B	0.36	40 C + ~0%RH	3	0.0
Type III -B	0.36	40 C + ~0%RH	7	-658.5
Type III -B	0.36	40 C + ~0%RH	14	-916.5
Type III -B	0.36	40 C + ~0%RH	28	-958.6
Type III -B	0.36	40 C + ~0%RH	90	-1109.2
Type III -B	0.4	10 C - 50% RH	3	0.0
Type III -B	0.4	10 C - 50% RH	7	-81.7
Type III -B	0.4	10 C - 50% RH	14	-129.6
Type III -B	0.4	10 C - 50% RH	28	-92.2
Type III -B	0.4	10 C - 50% RH	90	-207.8
Type III -B	0.4	20 C - 50% RH	3	0.0
Type III -B	0.4	20 C - 50% RH	7	-419.1
Type III -B	0.4	20 C - 50% RH	14	-676.0
Type III -B	0.4	20 C - 50% RH	28	-713.4
Type III -B	0.4	20 C - 50% RH	90	-840.6
Type III -B	0.4	23 C - 97% RH	3	0.0
Type III -B	0.4	23 C - 97% RH	7	-165.8
Type III -B	0.4	23 C - 97% RH	14	-171.6
Type III -B	0.4	23 C - 97% RH	28	-10.5
Type III -B	0.4	23 C - 97% RH	90	7.0
Type III -B	0.4	40 C + ~0%RH	3	0.0
Type III -B	0.4	40 C + ~0%RH	7	-698.2
Type III -B	0.4	40 C + ~0%RH	14	-963.2
Type III -B	0.4	40 C + ~0%RH	28	-1005.3
Type III -B	0.4	40 C + ~0%RH	90	-1158.2

Calcium Sulfoaluminate – A

Cement type	W/C	Curing Regime	Specimen Age (days)	Average shrinkage
CSA-A	0.37	10 C - 50% RH	3	0.0
CSA-A	0.37	10 C - 50% RH	7	-23.4
CSA-A	0.37	10 C - 50% RH	14	-74.7
CSA-A	0.37	10 C - 50% RH	28	44.4
CSA-A	0.37	10 C - 50% RH	90	47.9
CSA-A	0.37	20 C - 50% RH	3	0.0
CSA-A	0.37	20 C - 50% RH	7	-193.8
CSA-A	0.37	20 C - 50% RH	14	-246.4
CSA-A	0.37	20 C - 50% RH	28	-319.9
CSA-A	0.37	20 C - 50% RH	90	-310.6
CSA-A	0.37	23 C - 97% RH	3	0.0
CSA-A	0.37	23 C - 97% RH	7	45.5
CSA-A	0.37	23 C - 97% RH	14	12.8
CSA-A	0.37	23 C - 97% RH	28	-22.2
CSA-A	0.37	23 C - 97% RH	90	24.5
CSA-A	0.37	40 C + ~0%RH	3	0.0
CSA-A	0.37	40 C + ~0%RH	7	-204.3
CSA-A	0.37	40 C + ~0%RH	14	-342.1
CSA-A	0.37	40 C + ~0%RH	28	-520.7
CSA-A	0.37	40 C + ~0%RH	90	-524.2
CSA-A	0.41	10 C - 50% RH	3	0.0
CSA-A	0.41	10 C - 50% RH	7	-24.5
CSA-A	0.41	10 C - 50% RH	14	-39.7
CSA-A	0.41	10 C - 50% RH	28	54.9
CSA-A	0.41	10 C - 50% RH	90	63.0
CSA-A	0.41	20 C - 50% RH	3	0.0
CSA-A	0.41	20 C - 50% RH	7	-135.4
CSA-A	0.41	20 C - 50% RH	14	-182.1
CSA-A	0.41	20 C - 50% RH	28	-283.7
CSA-A	0.41	20 C - 50% RH	90	-281.4
CSA-A	0.41	23 C - 97% RH	3	0.0
CSA-A	0.41	23 C - 97% RH	7	56.0
CSA-A	0.41	23 C - 97% RH	14	-2.3
CSA-A	0.41	23 C - 97% RH	28	119.1
CSA-A	0.41	23 C - 97% RH	90	105.1
CSA-A	0.41	40 C + ~0%RH	3	0.0
CSA-A	0.41	40 C + ~0%RH	7	-181.0
CSA-A	0.41	40 C + ~0%RH	14	-289.6
CSA-A	0.41	40 C + ~0%RH	28	-497.4
CSA-A	0.41	40 C + ~0%RH	90	-489.2

Calcium Sulfoaluminate – B

Cement type	W/C	Curing Regime	Specimen Age (days)	Average shrinkage
CSA-B	0.37	10 C - 50% RH	3	0.0
CSA-B	0.37	10 C - 50% RH	7	-108.6
CSA-B	0.37	10 C - 50% RH	14	-96.3
CSA-B	0.37	10 C - 50% RH	28	-106.8
CSA-B	0.37	10 C - 50% RH	90	-169.9
CSA-B	0.37	20 C - 50% RH	3	0.0
CSA-B	0.37	20 C - 50% RH	7	-141.9
CSA-B	0.37	20 C - 50% RH	14	-204.3
CSA-B	0.37	20 C - 50% RH	28	-273.2
CSA-B	0.37	20 C - 50% RH	90	-392.3
CSA-B	0.37	23 C - 97% RH	3	0.0
CSA-B	0.37	23 C - 97% RH	7	-99.2
CSA-B	0.37	23 C - 97% RH	14	-106.2
CSA-B	0.37	23 C - 97% RH	28	-23.4
CSA-B	0.37	23 C - 97% RH	90	-78.2
CSA-B	0.37	40 C + ~0%RH	3	0.0
CSA-B	0.37	40 C + ~0%RH	7	-274.4
CSA-B	0.37	40 C + ~0%RH	14	-354.9
CSA-B	0.37	40 C + ~0%RH	28	-451.8
CSA-B	0.37	40 C + ~0%RH	90	-616.5
CSA-B	0.41	10 C - 50% RH	3	0.0
CSA-B	0.41	10 C - 50% RH	7	-50.2
CSA-B	0.41	10 C - 50% RH	14	-47.9
CSA-B	0.41	10 C - 50% RH	28	-70.1
CSA-B	0.41	10 C - 50% RH	90	-91.1
CSA-B	0.41	20 C - 50% RH	3	0.0
CSA-B	0.41	20 C - 50% RH	7	-131.9
CSA-B	0.41	20 C - 50% RH	14	-209.0
CSA-B	0.41	20 C - 50% RH	28	-287.2
CSA-B	0.41	20 C - 50% RH	90	-288.4
CSA-B	0.41	23 C - 97% RH	3	0.0
CSA-B	0.41	23 C - 97% RH	7	-115.6
CSA-B	0.41	23 C - 97% RH	14	-99.8
CSA-B	0.41	23 C - 97% RH	28	-134.9
CSA-B	0.41	23 C - 97% RH	90	-15.8
CSA-B	0.41	40 C + ~0%RH	3	0.0
CSA-B	0.41	40 C + ~0%RH	7	-304.7
CSA-B	0.41	40 C + ~0%RH	14	-349.1
CSA-B	0.41	40 C + ~0%RH	28	-426.2
CSA-B	0.41	40 C + ~0%RH	90	-144.8

Calcium Aluminate

Cement type	W/C	Curing Regime	Specimen Age (days)	Average shrinkage
CA	0.32	10 C - 50% RH	3	0.0
CA	0.32	10 C - 50% RH	7	-85.2
CA	0.32	10 C - 50% RH	14	-94.6
CA	0.32	10 C - 50% RH	28	-57.2
CA	0.32	10 C - 50% RH	90	9.3
CA	0.32	20 C - 50% RH	3	0.0
CA	0.32	20 C - 50% RH	7	-601.3
CA	0.32	20 C - 50% RH	14	-809.1
CA	0.32	20 C - 50% RH	28	-939.9
CA	0.32	20 C - 50% RH	90	-1074.1
CA	0.32	23 C - 97% RH	3	0.0
CA	0.32	23 C - 97% RH	7	-178.6
CA	0.32	23 C - 97% RH	14	-176.3
CA	0.32	23 C - 97% RH	28	-38.5
CA	0.32	23 C - 97% RH	90	30.4
CA	0.32	40 C + ~0%RH	3	0.0
CA	0.32	40 C + ~0%RH	7	-729.7
CA	0.32	40 C + ~0%RH	14	-987.7
CA	0.32	40 C + ~0%RH	28	-1109.2
CA	0.32	40 C + ~0%RH	90	-1171.6
CA	0.35	10 C - 50% RH	3	0.0
CA	0.35	10 C - 50% RH	7	-112.1
CA	0.35	10 C - 50% RH	14	-156.5
CA	0.35	10 C - 50% RH	28	-127.3
CA	0.35	10 C - 50% RH	90	-22.8
CA	0.35	20 C - 50% RH	3	0.0
CA	0.35	20 C - 50% RH	7	-713.4
CA	0.35	20 C - 50% RH	14	-937.5
CA	0.35	20 C - 50% RH	28	-1108.0
CA	0.35	20 C - 50% RH	90	-1292.5
CA	0.35	23 C - 97% RH	3	0.0
CA	0.35	23 C - 97% RH	7	-135.4
CA	0.35	23 C - 97% RH	14	-177.5
CA	0.35	23 C - 97% RH	28	2.3
CA	0.35	23 C - 97% RH	90	144.8
CA	0.35	40 C + ~0%RH	3	0.0
CA	0.35	40 C + ~0%RH	7	-826.6
CA	0.35	40 C + ~0%RH	14	-1091.1
CA	0.35	40 C + ~0%RH	28	-1231.2
CA	0.35	40 C + ~0%RH	90	-1465.8

APPENDIX D – CALTRANS FAST SETTING HYDRAULIC CEMENT SPECIFICATIONS OF 1998

From: Notice to Contractors and Special Provisions for Construction on State Highway in Los Angeles County Near Palmdale from 0.3 km North of Vincent Ramp Undercrossing to 2.0 km South of California Aqueduct Bridge, District 7, Route 14.

Test	Operating Range	Contract Compliance
Sand Equivalent	31 Min.	28 Min.

Requirements

The coarse aggregate (material retained on the 4.75-mm sieve) shall consist of material of which at least 25 percent by mass shall be crushed particles as determined by California Test 205.

Existing portland cement concrete pavement, and cement treated base to be removed may be processed and used as aggregate for cement treated base. If such material is used for aggregate for cement treated base, the grading shall, at the Contractor's option, conform to either the grading for the class of cement treated base specified herein or to the 37.5-mm, maximum grading for Class 2 aggregate base as provided in Section 26, "Aggregate Bases," of the Standard Specifications.

10-1.21 LEAN CONCRETE BASE

Lean concrete base shall conform to the provisions in Section 28, "Lean Concrete Base," of the Standard Specifications.

10-1.22 ASPHALT CONCRETE

Asphalt concrete shall be Type B and shall conform to the provisions in Section 39, "Asphalt Concrete," of the Standard Specifications.

10-1.23 CONCRETE PAVEMENT

Portland cement concrete pavement shall conform to the provisions in Section 40, "Portland Cement Concrete Pavement," of the Standard Specifications and these special provisions.

The concrete for pavement shall contain a minimum of 375 kg/m^3 of portland cement.

Transverse weakened plane joints in portland cement concrete pavement —shall match existing pavement weakened plane joints and skew and shall be constructed as specified in Sections 40-1.08B, "Weakened Plane Joints," and Section 40-1.08B(1), "Sawing Method," of the Standard Specifications, using a power driven concrete saw. The insert method shall not be used. Longitudinal joints shall be constructed between portland cement concrete lanes and adjacent traffic lanes, and tie bars shall be installed at such joints as provided herein.

Tie bars shall be installed at longitudinal joints between portland cement concrete lanes and adjacent traffic lanes and at transverse contact joints, as shown on the plans. Tie bars shall be deformed reinforcing steel bars conforming to the specifications of ASTM Designation: A 615/A 615M, Grade 300 or 400, ASTM Designation: A 616/A 616M, Grade 350 or 400, or ASTM Designation: A 706/A 706M, and shall be epoxy-coated as specified in Section 52-1.02B, "Epoxy-coated Bar Reinforcement," of the Standard Specifications.

The joint detail shown on the plans for transverse and longitudinal joints, including the foam backer rod and silicone joint sealant shown on the plans, shall not apply.

Full compensation for furnishing and placing epoxy-coated tie bars in portland cement concrete pavement shall be considered as included in the contract price paid per cubic meter for concrete pavement and no separate payment will be made therefor.

10-1.24 FAST-SETTING HYDRAULIC CEMENT CONCRETE PAVEMENT (FSHCCP)

Fast-setting hydraulic cement concrete shall conform to the provisions in Section 40, "Portland Cement Concrete Pavement," of the Standard Specifications and these special provisions.

The combined aggregate grading used in concrete for fast-setting hydraulic cement concrete pavements shall be either the 37.5 mm (1-1/2 inch) maximum or the 25 mm (1 inch) maximum grading. The mix proportions for fast-setting concrete pavement shall be as recommended by the manufacturer of the hydraulic cement and as approved by the Engineer.

Fast-setting concrete pavement shall develop a flexural strength (modulus of rupture) of not less than 2756 kPa not more than 3 hours after completion of final finishing and also shall develop a modulus of rupture of not less than 4134 kPa 7 days after completion. The modulus of rupture shall be considered to be the average of the test results of 3 beam specimens determined by California Test 523.

The provisions in Section 40-1.015, "Cement Content," and Section 90-1.01, "Description," of the Standard Specifications shall not apply to fast-setting concrete pavement. The cement for fast-setting concrete shall be a hydraulic cement as defined in ASTM Designation: C219 and the following requirements:

Property	Test Method	Requirement
Contraction in air	California Test 527 W/CRatio=0.39± 0.010	0.053% max.
Mortar Expansion in Water	ASTM: C1038	0.04% max
Soluble Chloride	California Test 422	0.05% max.
Soluble Chloride	California Test 417	0.30% max.
Thermal Stability	ASTM: C 109	0.90% min.*
Compressive Strength @ 3 hours	ASTM: C 109	17,225 kPa
Compressive Strength @ 3 days	ASTM: C 109	34,450 kPa

*Comparison of compressive strength of cubes cured 1 day in water at 23°C followed by 2 days in water at 50 °C to that of cubes cured 3 days in water at 23°C.

At least 15 days prior to intended use, the Contractor shall furnish a sample of the hydraulic cement proposed for use in the quantity ordered by the Engineer.

A type C accelerating chemical admixture approved by the Engineer and conforming to the requirements in Section 90-4, "Admixtures," of the Standard Specifications may be used. The type C admixture, if used, shall be included in all the testing in the table above. In addition to the admixtures listed in the Department's Approved List of Admixtures, citric acid or borax may be used if requested in writing by the hydraulic cement manufacturer and a sample is submitted to the Engineer.

The penetration requirement in Section 90-6.06, "Amount of Water and Penetration" of the Standard Specifications shall not apply.

The asphaltic emulsion to be applied to the surface of cement treated permeable base prior to placing fast-setting concrete pavement shall have no added water.

Fast-setting concrete pavement shall not be placed when the atmospheric temperature during placement and curing is expected to be below 12.7°C. Fast-setting concrete pavement shall be cured for at least 3 hours following completion of final finishing and shall develop the 3-hour modulus of rupture specified above before opening to public traffic. The method of cure shall be as recommended by the manufacturer of the hydraulic cement and as approved by the Engineer.

Sawing of weakened plane joints shall be completed within 2 hours of completion of final finishing. The minimum depth of the saw cut for the weakened plane joint shall be 25 mm.

Prior to construction of fast-setting concrete pavement, the Contractor shall construct one or more trial slabs to demonstrate that his personnel and equipment and his mixing, placing, curing, and sawing techniques will produce a concrete pavement conforming to these special provisions in the anticipated time period and under similar conditions. The trial slab shall have a dimensions of not less than 3.05 m by 6.10 m and shall be 229 mm thick.

The test specimen to be used for determining 8-hour and 7-day modulus of rupture shall be fabricated during construction of the trial slab. Beams fabricated for the 8-hour test shall be cured under the same conditions as the actual placement trial slab. Beams fabricated for the 7-day test shall be cured in accordance with California Test 523. Testing will be performed by the Engineer. The test results of these beams will be the bases for accepting or rejecting the fast-setting concrete pavement for modulus of rupture requirements. Beams fabricated during construction failing the 7-day modulus of rupture requirement will be cause for rejecting the fast-setting concrete pavement represented by deficient test. Beams fabricated during construction failing the 8-hour modulus of rupture requirement shall be cause for the State to deduct from the Contractor $33 per cubic meter of the concrete pavement represented by deficient test. No single test shall represent more than 76 cubic meters.

Materials resulting from construction of trial slabs and test specimens shall become the property of the Contractor and shall be removed and disposed of outside the highway right of way as provided in Section 7-1.13 of the Standard Specifications.

Transverse weakened plane joints in fast-setting hydraulic cement concrete shall match existing pavement weakened plane joints and shall be perpendicular. Longitudinal joints shall be constructed between fast-setting hydraulic cement concrete and adjacent traffic lanes, and tie bars shall be installed at such joints as provided herein.

Tie bars shall be installed at longitudinal joints between fast-setting hydraulic cement concrete and adjacent traffic lanes and at transverse contact joints, as shown on the plans. Tie bars shall be deformed reinforcing steel bars conforming to the specifications of ASTM Designation: A 615/A 615M, Grade 300 or 400, ASTM Designation: A 616A 616M, Grade 350 or 400, or ASTM Designation: A 706/A 706M, and shall be epoxy-coated as specified in Section 52-1.02B, "Epoxy-coated Bar Reinforcement," of the Standard Specifications.

Epoxy-coated dowels shall be installed at weakened plane joints as shown on the plans.

The joint detail shown on the plans for transverse and longitudinal joints, including the foam backer rod and silicone joint sealant shown on the plans, shall not apply.

Fast setting hydraulic cement concrete pavement will be measured and paid for by cubic meter in the same manner specified for concrete pavement in Section 40, "Portland Cement Concrete Pavement," of the Standard Specifications.

Full compensation for furnishing and placing epoxy-coated tie bars and epoxy coated dowels in fast-setting hydraulic cement concrete pavement shall be considered as included in the contract price paid per cubic meter for fast setting hydraulic cement concrete pavement and no separate payment will be made therefor.

10-1.25 DRILL AND GROUT TIE BARS

Drilling and grouting tie bars shall conform to the details shown on the plans, and the provisions in Section 51-1.13, "Bonding," of the Standard Specifications and these special provisions.

The reinforcing steel tie bars shall conform to the provisions in "Reinforcement" of these special provisions.

10-1.26 ROADSIDE SIGNS

Roadside signs shall be installed at the locations shown on the plans or where directed by the Engineer, and shall conform to the provisions in Section 56-2, "Roadside Signs," of the Standard Specifications and these special provisions.

10-1.27 EDGE DRAINS

Edge drains shall conform to the requirements in Section 68-3, "Edge Drains," of the Standard Specifications.