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HIGH PERFORMANCE CONCRETE IN OKLAHOMA DESIGNED FOR PRECAST/PRESTRESSED BRIDGE BEAMS

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HIGH PERFORMANCE CONCRETE IN OKLAHOMA DESIGNED FOR PRECAST/PRESTRESSED BRIDGE BEAMS

A Dissertation APPROVED FOR THE
SCHOOL OF CIVIL ENGINEERING AND ENVIRONMENTAL SCIENCE

BY

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Abstract

High performance concrete (HPC) is becoming the building material of choice for many different applications. By definition, HPC is concrete meeting specific performance requirements that cannot always be achieved using conventional constituent materials and normal mixing, placing and curing practices. HPC must be developed at the local level, given the uniqueness of local constituents and the economic practicality of employing many of these local constituents. Today there are a wide variety of cements, supplementary cementitious materials, aggregates, and admixtures in use.

One likely application of HPC is in highway bridges. According to the Federal Highway Administration (FHWA), nearly 200,000 bridges or 30% of all bridges nationwide are inadequate and in a state of decline. These bridges will need to be replaced and HPC could offer an economical solution. HPC is more structurally efficient than conventional concrete; use of HPC in precast/prestressed concrete bridge beams allows an increase in span length and/or beam spacing. The objective of this research was to seize the advantages of HPC for Oklahoma and, in the process, to advance the field of HPC in general.

The research involved identifying locally available cements and aggregates suitable for producing HPC, developing HPC mixture proportions for precast/prestressed

bridge beams and, finally, demonstrating HPC at a precast/prestressed concrete plant in Oklahoma. The test group included eight cements and four coarse aggregates. Variables examined in developing HPC mixtures included water/cementitious materials (w/cm) ratio, supplementary cementitious materials, and cementitious material content. Additionally, heat curing was evaluated in parallel with ASTM standard curing. Criteria for comparing HPC mixtures included workability, compressive strength, splitting tensile strength, and modulus of elasticity. Several HPC mixtures, distinguished as having adequate workability and potential to achieve compressive strength of 60 MPa (8,700 psi) at 1 day and 100 MPa (14,500 psi) by 28 or 56 days, were selected for trial at a precast/prestressed concrete plant.

It was learned that all cements and aggregates in the test group appear suitable for producing HPC, but some cements and aggregates are better in precast/prestressed concrete applications. Cement selection is crucial to early strength gain while the choice of coarse aggregate is more important for ultimate strength development. The w/cm as well as the water/cement (w/c) ratio are useful statistics for today's increasingly complex HPC mixtures. Heat curing was damaging to ultimate strength potential and, in some HPC mixtures, even failed to accelerate early strength gain relative to standard curing. Achieving high early strength in harmony with adequate workability and high ultimate strength is a challenge facing the precast/prestressed concrete industry in construction of bridge beams. Also, difficulties with reproducibility can be encountered when trying to advance HPC technology from the laboratory to commercial manufacture. Prior to application of HPC, trial batches at the intended commercial facility under anticipated working conditions are essential to verify concrete qualities. Adjustments to the mixture proportions may be necessary.

1. Introduction

High performance concrete (HPC) is the concrete of the future. With potential to enhance structural efficiency, speed of construction and durability, it is becoming the building material of choice for many different applications. By definition, HPC is concrete meeting specific performance requirements that cannot always be achieved using conventional constituent materials and normal mixing, placing and curing practices.[1]

HPC has been the subject of much recent research activity. This is apparent from the large number of academic papers issued on the subject during the last few years.[2] These efforts have come a long way toward establishing the fundamentals of HPC technology. But while the fundamentals are universal in concept, HPC must be developed at the local level given the uniqueness of local constituents and the economic practicality of employing many of these local constituents. Today there are a wide variety of cements, supplementary cementitious materials, aggregates and admixtures in use. Different constituents can produce concrete with vastly different properties. Some constituents may have limited suitability for HPC production.

1.1. Objective

One likely application of HPC is in highway bridges. According to the Federal Highway Administration (FHWA), nearly 200,000 bridges or 30% of all bridges nationwide are inadequate and in a state of decline. Many of these bridges will need to be replaced. Use of HPC in precast/prestressed bridge beams could offer an economical solution. In terms of structural efficiency, use of HPC allows an increase in span length and/or beam spacing over conventional concrete. The objective of this research was to demonstrate the advantages of HPC for Oklahoma and, in the process, to advance the field of HPC in general.

The research involved identifying locally available cements and aggregates suitable for producing HPC, developing HPC mixture proportions for precast/prestressed bridge beams and, finally, demonstrating HPC at a precast/prestressed concrete plant in Oklahoma. It is believed that precast/prestressed bridge beams are an excellent vehicle in which to showcase the newest advances in HPC technology.[3] Specifically, the goals of the research were to:

- Identify suitable cements local to the Oklahoma region
- Identify suitable aggregates local to the Oklahoma region
- Assess the adequacy of the ACI equations for predicting compressive strength, splitting tensile strength, flexural strength and modulus of elasticity of HPC made with local cements and aggregates

- Design HPC mixtures for precast/prestressed bridge beams using local cements and aggregates together with supplementary cementitious materials and chemical admixtures
- Assess the utility of the water/cementitious materials (w/cm) ratio for predicting HPC compressive strength
- Evaluate the effect of heat curing on HPC containing *Type III* cement
- Assess the repeatability and normality of HPC compressive strength tests
- Implement HPC technology at a precast/prestressed concrete plant in Oklahoma

1.2. Scope

The research consisted of a comprehensive trial batching effort. Trial batching is necessary to assess the quality and suitability of constituent materials. There are tests that can be performed on individual constituents to help determine quality and suitability, but these tests do not replace the need for trial batching. The ACI 318 "Building Code Requirements for Structural Concrete and Commentary" requires trial batching.[4] It is the only way to actually evaluate the interaction among the constituents of concrete and optimize mixture proportions.[5]

The research was divided into four phases:

- Cement Study
- Aggregate Study
- Mixture Proportion Study
- Demonstration of HPC at a Precast/Prestressed Concrete Plant

A group of eight cements was selected from Oklahoma and neighboring states Texas, Arkansas and Kansas to be representative of all cements available within the region. The group included several different types of cement from three manufacturers and six plants. These cements are currently in use or could readily be used in Oklahoma. There were four ASTM[6] C150 *Type I* cements, two *Type I/II's*, one *Type II* and one *Type III*. The cements were compared in two HPC mixtures with discrete strength levels, called Class 1 and Class 2. Class 1 mixtures were designed to achieve a compressive strength of 60 MPa (8,700 psi) at 28 days. Class 2 mixtures were designed to achieve 75 MPa (10,900 psi) at 28 days.

Next, a group of four coarse aggregates was selected from Oklahoma to be representative of all coarse aggregates available within the state. The group included limestone, rhyolite, granite and river gravel. These coarse aggregates are currently in use or could readily be used in Oklahoma. Each of the coarse aggregates was separated into a precise or "standard" gradation, different from the gradation available for purchase at the quarry. Both the "quarry-acquired" and "standard" gradations of each aggregate were evaluated in HPC mixtures. The "quarry-acquired" approach allowed examination of the aggregates in a manner consistent with commercial production. The "standard" approach allowed examination of the type, shape and texture of aggregates independent of grading. HPC mixtures were designed to achieve about 75 MPa (10,900 psi) at 28 days.

Following identification of suitable cements and coarse aggregates, HPC mixture proportions were developed for precast/prestressed bridge beams. As a methodical approach, trial batches were arranged into matrices. In each matrix, certain mixture variables were examined independently, changing one variable at a time. Among the variables examined were:

- Water/cementitious materials (w/cm) ratio
- Supplementary cementitious materials — replacement rates and combinations
- Cementitious materials content
- Coarse aggregate content
- Chemical admixtures — addition rates and combinations

In the manufacture of precast/prestressed concrete bridge beams, heat curing is regularly employed for accelerating strength gain. A variety of HPC mixtures were examined under a number of heat curing schemes in parallel with ASTM standard curing. The objective was to determine how these mixtures respond to heat curing in terms of strength development.

Several HPC mixtures, distinguished as having adequate workability and potential to achieve 60 MPa (8,700 psi) at 1 day and 100 MPa (14,500 psi) by 28 or 56 days, were selected for trial at a precast/prestressed concrete plant in Oklahoma. Difficulties can be encountered trying to advance HPC technology from the laboratory to commercial manufacture. One difficulty is in measuring the moisture content of the aggregates. Improved quality control procedures are often required. Oklahoma has limited experience using HPC in precast/prestressed bridge beams. Before commencement of the research, Oklahoma had not designed and built a concrete bridge with compressive strength more than 55 MPa (8,000 psi).[7]

The properties of individual constituent materials were established prior to batching concrete and verified periodically, usually whenever a new supply of materials arrived. This involved testing cement fineness and (coarse, intermediate and fine) aggregate absorption, specific gravity, grading and dry rodded unit weight. When batching, fresh concrete properties (slump, unit weight, air content, and temperature) were determined consistently. Ambient conditions were also recorded. Concrete was tested for compressive strength, splitting tensile strength, flexural strength (modulus of rupture), elastic modulus and length change at various ages of 18 hrs, 1 day, 3 days, 7 days, 28 days and 56 days. These properties are necessary in the design of precast/prestressed concrete bridge beams. All experimental procedures — analysis of concrete materials, batching concrete and testing concrete — conformed to the appropriate ASTM specifications.

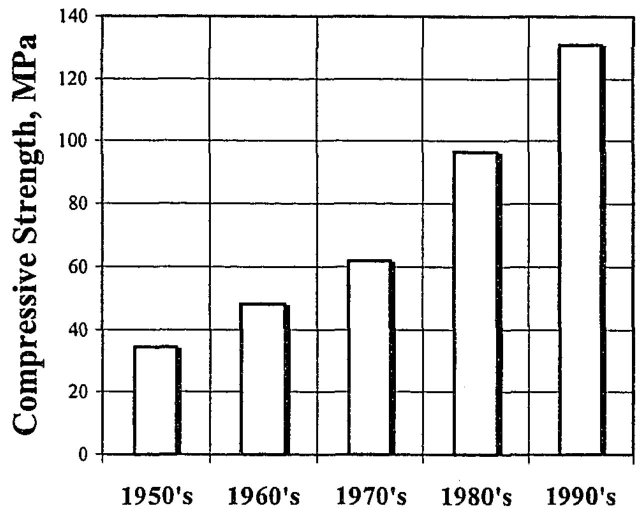
[1] Russell, H. G., "ACI Defines High Performance Concrete," *Concrete International*, Vol. 21, No. 2, February 1999, pp. 56-57.
[2] Helland, S., "Application of HPC in Infrastructure: An Overview in the Perspective of FIP and CEB," *Proceedings of the PCI/FHWA International Symposium on High Performance Concrete*, New Orleans, October 1997, pp. 60-71.
[3] Rabbat, B. G., "Group Promotes Benefits of High Performance Concrete Bridges," *Ascent*, Winter 2001, pp. 18-23.
[4] ACI 318, *Building Code Requirements for Structural Concrete and Commentary*, American Concrete Institute, 1999.
[5] Carrasquillo, Ramon L., *SHRP (Federal Highway Administration's Strategic Highway Research Program) High Performance Concrete Bridge Showcase*, FHWA in cooperation with the Texas Department of Transportation, University of Texas at Austin and Texas A&M University, Perry, OK, August 1996.
[6] American Society for Testing and Materials, *Annual Book of ASTM Standards*, Vol. 4.01 and 4.02, 1995.
[7] Conversation with Jack Schmiedel, Oklahoma Department of Transportation, Bridge Division, January 2003.

2. Background

High performance concrete (HPC) has been the result of the collaborative efforts of government, industry, and academia. Civil engineers gradually began to see the importance in assessing the quality of constituent materials and having a systematic way of proportioning cement, aggregates and water. Chemical admixtures were first developed in the 1930s and allowed increases in strength and durability.[1] The practice of using supplementary cementitious materials in concrete mixtures, like the volcanic ash used by the ancient Romans, has been growing since the 1970s.[1] The American Concrete Institute (ACI) organized a committee on high strength concrete in 1989. The progression of concrete compressive strength in buildings and bridges, from about 35 MPa (5,000 psi) in the 1950s to 130 MPa (19,000 psi) in the 1990s is shown in Figure 2.1.[2] In the early 1900s, compressive strengths of 14 MPa (2,000 psi) were typical.[3]

At first, civil engineers were intent on increasing compressive strength as a solution to the columns of very tall buildings. Successful in this goal, "high strength concrete" is found in the columns of some of the tallest skyscrapers in the world.[4] The term "high strength concrete" was modified to "high performance concrete" when properties other than compressive strength became the point of emphasis, often influencing the selection of materials and mixture proportions.[5] On one tall building project, a high strength was specified in order to exploit the associated high modulus of elasticity, which was of paramount importance. On many bridge projects, while high strength is wanted in beams for extending span and/or spacing, improving durability is the main objective in bridge decks and substructures.[6]

Figure 2.1.
The Progression of Concrete Strength in Buildings and Bridges After 1950



2.1. Defining "High Performance Concrete"

Broadly defined by ACI, HPC is "concrete meeting special combinations of performance and uniformity requirements that cannot always be achieved routinely using conventional constituents and normal mixing, placing and curing practices."[7] To the extent possible, local materials and normal methods are employed. HPC is defined by many as having a minimum compressive strength of 41.4 MPa (6,000 psi) at 28 days.[8] The Precast/Prestressed Concrete Institute (PCI), a little more restrictive, states that HPC offers a minimum strength of 55.2 MPa (8,000 psi).[9]

High strength concrete (HSC) is a category of HPC where compressive strength is the main objective. Furthermore, several subcategories of HSC are defined by the Federal Highway Administration (FHWA).[2] "High early strength concrete" is concrete developing compressive strength of at least 34.5 MPa (5,000 psi) at 1 day and designed with a water/cementitious materials (w/cm) ratio less than or equal to 0.35. "Very high strength concrete" is concrete having a strength of 69.0 MPa (10,000 psi) at 28 days and a w/cm less than or equal to 0.35.

HPC mixtures are frequently produced with a more extensive array of cementitious materials, aggregates and chemical admixtures than conventional concrete. The variety of constituents in HPC is necessary to achieve a wide range of performance criteria, which may include:

- Workability, or ease of placement, consolidation and finishing
- Accelerated strength gain
- High ultimate strength
- Increased elastic modulus
- Increased tensile strength
- Volume stability
- Lower permeability

- Resistance to chemical attack and other kinds of deterioration
- Improved freeze/thaw durability

Performance criteria are established for a specific application.[10] Some applications may require high compressive strength, while others may require high modulus of elasticity or improved durability. Compressive strength is the standard measure of concrete quality. Many of the other performance criteria show some degree of correlation with compressive strength but each requires individual specification and testing.

High early strength is the concrete characteristic most desired in construction of precast/prestressed bridge beams, where productivity depends on timely release of prestressing force. The concrete strength required for release usually governs the mixture design.[11] But achieving high early strength alone is insufficient; other concrete characteristics are essential as well. The challenge unique to the precast/prestressed concrete industry is achieving high early strength in harmony with adequate workability and high ultimate strength. In construction of bridge beams, the industry is now encountering the need to achieve 60 MPa (8,700 psi) inside of 1 day and 100 MPa (14,500 psi) by 28 or 56 days as span and spacing continue to expand. Adequate workability is required for efficient placement and consolidation into narrow, congested sections. While not necessarily incompatible or conflicting, these performance requirements are increasingly at odds as the limits of high performance concrete (HPC) are pushed.

2.2. Fundamentals of HPC Production

There is no single formula for producing HPC. HPC shares with conventional concrete the basic constituents of cement, coarse and fine aggregates, and water. But HPC is typically distinguished from conventional concrete by one or more of the following:

- A low water/cementitious materials (w/cm) ratio
- Purposeful selection of quality cement and aggregates
- The use of supplementary cementitious materials
- The use of chemical admixtures

2.2.1. Low w/cm

A governing concept behind HPC is design of a low w/cm. Compressive strength and other concrete characteristics are generally enhanced as the w/cm is lowered.[12,13] Simply explained, lowering the w/cm reduces the porosity of the hardened cement paste.[3] Most HPC mixtures are designed with w/cm's between 0.25 and 0.45. In conventional concrete, w/cm's between 0.45 and 0.50 are more typical. The AASHTO "Standard Specifications for Highway Bridges" designates a maximum w/cm of 0.40 for HPC intended for use in prestressed concrete members.[14] The ACI 318 "Building Code Requirements for Structural Concrete and Commentary" limits the w/cm to a maximum of 0.50 when concrete is designed to have low permeability when exposed to water. A maximum w/cm of 0.40 is allowed for concrete under severe exposure conditions.[15]

The w/cm is determined on the basis of mass. It logically replaced the water/cement (w/c) ratio to account for supplementary cementitious materials.[8] HPC mixtures often contain supplementary cementitious materials as partial replacement of cement.

The w/cm is recognized as the most important variable in achieving HSC.[3,5] The relationship between the w/cm and compressive strength was first recognized in conventional concrete and then extended to HSC.[8] But concrete technology is changing and advancing at a rapid pace and old rules need to be examined again. It needs to be demonstrated if this traditional variable continues to provide useful information for today's high performance concrete (HPC) mixtures, now designed with increasing complexity and a broad variety of cementitious materials, aggregates and chemical admixtures. The utility of the w/cm in a simple linear regression model to predict HPC strength is unknown. A modified version of the w/cm has been suggested for improving a regression model.[16,17] A modified version of the w/cm would hope to specify the contribution over time of individual cementitious materials based on physical and chemical characteristics.

There is a point when decreasing the w/cm fails to increase compressive strength. Having a low w/cm may result in an incomplete cement hydration due to lack of water required for the process.[18,19] The theoretical minimum w/cm for complete cement hydration varies widely from about 0.20 to 0.40. It depends on the specific combination of cementitious materials and the physical and chemical characteristics of those cementitious materials. In reality, the minimum w/cm for complete cement hydration also depends on the effectiveness of chemical admixtures and mixing.[12,20,21] But having a w/cm below the minimum required for complete cement hydration may be beneficial in the context of concrete durability. Autonomous healing of small cracks is then possible as water enters and reacts with the previously unhydrated cement.[21]

Lowering the w/cm is detrimental to workability of the fresh concrete, and use of a superplasticizer is usually necessary to provide adequate workability when the w/cm is less than 0.40.[12,22] When working in summer, HPC mixtures designed at low w/cm's may be especially difficult to place, consolidate and finish. Workability requirements put a practical limit on how low the w/cm can be designed.

2.2.2. Cements

Production of HPC requires purposeful selection of quality cement. Cement is manufactured in various types, the most common classified as ASTM C 150 *Type I*, *Type II* or *Type III*. The chemical and physical characteristics of cement vary by type and source. *Type I* cement is the most widely available of the cement types and is employed for general purpose. *Type II* cement has a low heat of hydration, moderate sulfate resistance, and could have the best ultimate strength potential. The relatively slow rate of hydration of a *Type II* cement produces a uniform, dense chemical structure. *Type III* cement is commonly used in precast/prestressed concrete applications where high early strength is desired. Typically, *Type III* cement is ground finer than *Type I* and *Type II* cements. With an increased total surface area of cement, use of *Type III* cement can enhance the rate of hydration and accelerate early strength development, but may also result in workability problems, especially when working in summer.[3]

Portland cement is produced from raw materials that contain calcium oxide, silica, alumina, and iron oxide. Raw materials are ground to powder, blended, and fed into a kiln. Burning inside a kiln changes the raw mix chemically into cement clinker. Clinker is then ground with a small amount of gypsum into cement. Gypsum is added to regulate the setting time. The average diameter of a cement particle is approximately 10 μm. There is a broad range of particle sizes and, in 1 kg (2.2 lb) of cement, there are about 15 trillion particles.

There are four principal chemical compounds in cement.[12] These compounds are presented in Table 2.1 with their chemical formulas and abbreviations. Different types of cement contain the same four principal compounds, but in different amounts.

Table 2.1. Chemical Compounds in Cement

Compound	Chemical Formula	Abbreviation
Tricalcium Silicate	$3CaO \cdot SiO_2$	C_3S
Dicalcium Silicate	$2CaO \cdot SiO_2$	C_2S
Tricalcium Aluminate	$3CaO \cdot Al_2O_3$	C_3A
Tetracalcium Aluminoferrite	$4CaO \cdot Al_2O_3 \cdot Fe_2O_3$	C_4AF

Tricalcium silicate (C_3S) and dicalcium silicate (C_2S) constitute about 75% of cement. Tricalcium aluminate (C_3A) and tetracalcium aluminoferrite (C_4AF) are present in smaller quantities. Cement hydration results in the formation of two main products, calcium silicate hydrate (CSH) and calcium hydroxide. CSH is the strong glue that binds the aggregate particles together, but calcium hydroxide itself contributes little to strength. Each of the four compounds reacts differently. C_3S drives early strength development. C_2S influences strength development over the long term. Stating an approximate rule, C_3S contributes most to strength development during the first four weeks and C_2S contributes most to strength development from four weeks onwards.

At an age of about one year, the two compounds contribute almost equally to the ultimate strength.[3] C_3A and C_4AF are useful in the manufacturing process where these compounds reduce the clinker burning temperature. During the early hydration period, C_3A releases a large amount of heat and contributes slightly to early strength development. Without gypsum, C_3A would cause rapid set. C_4AF makes no appreciable contribution to strength. The cement compound transformations are as follows:

- C_3S + Water = CSH + Calcium Hydroxide
- C_2S + Water = CSH + Calcium Hydroxide
- C_3A + Water + Calcium Hydroxide = Tetracalcium Aluminate Hydrate
- C_4AF + Water + Calcium Hydroxide = Calcium Aluminoferrite Hydrate
- C_3A + Water + Gypsum = Calcium Monosulfoaluminate Hydrate + Ettringite

One hurdle to widespread adoption of HPC technology is the unknown suitability of locally available constituent materials.[23] Different cements can make concrete with vastly different strength development characteristics because of differences in chemical composition and fineness.[8] Selection of the type and source of cement is one of the most important decisions in HPC production.[5,24]

2.2.3. Aggregates

Production of HPC requires purposeful selection of quality aggregates. Coarse aggregate mineralogical characteristics, grading, shape, surface texture, elastic modulus (stiffness), and cleanliness can influence concrete properties. Many varieties of coarse aggregates have proved suitable for HPC production but some aggregates are better than others. No simple guidance on the selection of coarse aggregate is available.[3]

Coarse aggregate may have a more pronounced effect in HPC than in conventional concrete.[25,26] In conventional concrete, compressive strength is typically limited by the capacity of the cement paste or by the capacity of the bond between coarse aggregate and cement paste. In HPC, where the cement paste and coarse aggregate/cement paste bond are enhanced by design of a low w/cm and use of supplementary cementitious materials, ultimate strength potential may be limited by the intrinsic strength of the coarse aggregate itself.[19,20,27,28]

Smaller sizes of coarse aggregate and crushed coarse aggregate are recommended for use in HPC. Smaller sizes of coarse aggregate have more surface area for a given aggregate content, which improves coarse aggregate/cement paste bond and enhances ultimate strength potential.[5,8] The crushing process eliminates potential zones of weakness within the parent rock with the effect that smaller particles are likely to be stronger than larger ones.[19] Coarse aggregate with a rough surface texture is generally more suitable for use in HPC than coarse aggregate with a smooth surface texture because of the superior bond that it provides.[3,29]

Designing HPC to act more like a homogenous material can enhance ultimate strength potential.[3,8,30] This can be achieved by increasing the similarity between the elastic moduli of coarse aggregate and cement paste. Having like elastic moduli will reduce stress at the location of the coarse aggregate/cement paste bond. While using a coarse aggregate with greater stiffness has been found to increase the elastic modulus of concrete, it is sometimes to the detriment of ultimate strength potential.[27,31,32]

Coarse aggregate occupies the largest volume of any of the constituent materials in concrete. In HPC, coarse aggregate volumes typically range between 50% and 70%. The optimum amount depends on the maximum size of coarse aggregate and the fineness modulus of the fine aggregate.[8] As the maximum size of coarse aggregate increases, the optimum amount of coarse aggregate in concrete also increases. As the fineness modulus of the fine aggregate increases, the optimum amount of coarse aggregate in concrete decreases.

2.2.4. Supplementary Cementitious Materials

Supplementary cementitious materials such as fly ash, silica fume and ground, granulated blast furnace (GGBF) slag are frequently employed in HPC mixtures. Sometimes called mineral admixtures, supplementary cementitious materials are classified as cementitious, pozzolanic, or both cementitious and pozzolanic. Cementitious materials have the ability to set and harden in the presence of water, similar to portland cement. ASTM C 989 slag, which is created with iron in a blast furnace, is a cementitious material. ASTM C 1240 silica fume, which results from the reduction of quartz with coal in a manufacturing process, is a pozzolanic material. Alone, pozzolanic materials possess little or no cementitious value but, with water, chemically react with the calcium hydroxide released by cement hydration to form additional CSH:

- Pozzolan + Calcium Hydroxide + Water = CSH

The concrete of the ancient Romans was found to contain volcanic ash, a natural pozzolan. ASTM C 618 *Class C* fly ash exhibits both cementitious and pozzolanic properties. Fly ash is residue from the combustion of coal in electric power plants. There are several classes of fly ash and several grades of slag. *Class C* fly ash and high activity index *Grade 120* slag were employed in this research because these are most conducive to the high early strength gain needed in the manufacture of precast/prestressed concrete bridge beams.

Supplementary cementitious materials are added to HPC as a partial replacement of cement. Typical replacement rates are 20% for fly ash, 10% for silica fume and 40% for slag. Fly ash and silica fume are sometimes used together. ACI 318 places limitations on the amount of fly ash, silica fume, and slag that can be included in concrete exposed to deicing chemicals.[15] However, this requirement is usually not applicable to bridge beams. A number of structures have been built using HPC with fly ash contents over 50% of the total cementitious materials.[33]

The use of supplementary cementitious materials can improve both fresh and hardened concrete properties. Partial replacement of cement with fly ash enhances fresh concrete workability at a given w/cm. (When workability of a mixture is more than satisfactory, there exists the option of lowering the w/cm.) The enhanced workability is due to the delayed pozzolanic reactivity and, in part, to the spherical shape of fly ash particles. Cement particles, by contrast, are rough and angular in shape. Silica fume, unlike fly ash, may reduce workability.[29] Although silica fume is pozzolanic in nature and spherical in shape, it is also extremely fine, with an average diameter about 100 times smaller than average cement particles.[12] The use of fly ash and slag can reduce peak curing temperatures and the potential for thermal cracking. But fly ash and slag may also retard setting time and curb early strength development. Mixtures with partial replacement of cement with fly ash or slag may require 28 days or longer to equal or exceed the strength of a control mixture with cement only. Fly ash, silica fume and slag are likely to increase the ultimate strength gain of concrete and are often essential to the production of HSC. Supplementary cementitious materials are also known to contribute to concrete's pumpability and finishability. Moreover, by reducing permeability and improving resistance to chemical attack, supplementary cementitious materials can greatly enhance durability. It has been observed that many modern concrete structures designed without supplementary cementitious materials often begin to deteriorate in 20 years or less, while many Roman concrete structures with volcanic ash continue to be in good condition after 2,000 years.[34]

Another compelling incentive to employ supplementary cementitious materials is to reduce the environmental impact of concrete. Burning of cement kilns is energy intensive and emits carbon dioxide (CO_2), a greenhouse gas. The manufacture of a certain mass of cement generally results in an equal mass of CO_2 being discharged into the atmosphere.[3] Globally, cement manufacture is accountable for about 7% of the amount of CO_2 discharged into the atmosphere.[34] Protecting the environment is becoming a ubiquitous mandate and, more frequently, civil engineers will be called to meet infrastructure demands in ways that are less harmful to the environment and sustainable into the future. Use of supplementary cementitious materials can reduce the environmental impact of concrete by conserving cement.[35] Supplementary cementitious materials are mainly industrial byproducts that, in most cases, would otherwise be headed for landfill disposal. Of the supplementary cementitious materials, fly ash is the most abundantly available. But currently it is believed that just 10% of the concrete produced worldwide uses fly ash, consuming only 6% of the total supply.[36,37]

2.2.5. Chemical Admixtures

Chemical admixtures are an increasingly widespread constituent of HPC; HPC mixtures that do not contain one or more chemical admixtures are considered the exception.[3] A wide variety of chemical admixtures are available, including water reducers, superplasticizers, retarders, accelerators and air entrainers. Chemical admixtures are normally liquids that are added directly to the concrete during mixing. Water reducing and superplasticizing admixtures are used to reduce the quantity of water required for a given workability. Initially developed in the 1970s, water reducing admixtures allow water content to be reduced up to 10% while superplasticizers, also called high range water reducers, allow up to 30% less water. Retarding admixtures are used to delay the initial set of concrete when there are difficult placement conditions or to offset the accelerating effect that hot weather has on the setting of concrete. Accelerating admixtures are used to increase early strength gain but may cause unwanted rapid stiffening that results in placement problems. Air entraining admixtures improve the durability of concrete exposed to moisture during cycles of freezing and thawing. Air entraining admixtures have been in use since the 1930s.

Superplasticizers are regarded by some as essential to today's HPC.[38] A superplasticizer can furnish adequate workability at a very low w/cm and are usually required when the w/cm is below 0.40. Superplasticizers work by relaxing the natural attraction between cement particles and water, which allows the cement particles to disperse and makes the mixing water free to provide workability to the fresh concrete. This action ultimately facilitates a more complete hydration process. But the workability afforded by a superplasticizer is temporary and loss of workability can be rapid. Also, superplasticizers are largely ineffective in reducing viscosity in fresh concrete. Adding water will reduce viscosity, but adding water increases the w/cm. Superplasticizers are unnecessary in conventional concrete, where excess water is present to provide workability.

It is necessary to check the compatibility between cement and superplasticizer in concrete. Cements with high fineness and/or high C_3A content may require a high addition rate. Excessive addition of superplasticizer may cause segregation and retard set.[3,8]

2.3. ACI Guidelines

ACI 211's "Guide for Selecting Proportions for High Strength Concrete with Portland Cement and Fly Ash" and ACI 363's "State-of-the-Art Report on High Strength Concrete" are important sources of information on constituent materials, mixture proportions, mixing, placing, and curing, and test data. However helpful, these references do not replace the requirement of trial batching. These references are limited in scope to concrete with compressive strength less than 83 MPa (12,000 psi) and do not address the subject of "high early strength concrete," the category of HPC in precast/prestressed bridge beams.

2.4. Advantages of HPC

With potential to enhance structural efficiency, speed of construction and durability, HPC can be economical from the perspectives of both initial construction costs and life cycle costs. Efficient structural designs result in a major conservation of materials and labor. HPC's increased strength and modulus of elasticity allow a reduction in the number and/or size of structural members and also allow the versatility of longer spans. Speed of construction is possible due to HPC's accelerated strength gain; with increased productivity and lower labor costs the results. On roadway projects, speed of construction is necessary to eliminate hazards and diminish the inconvenience to the traveling public. The enhanced durability of HPC promises to ease maintenance costs and extend service life. The FHWA is choosing to shift emphasis from initial costs to life cycle costs and, as this change occurs, durability will become increasingly important.[9] Structures today are normally designed for service lives of 50 years, but in the future, structures will be designed for service lives of 100 years or more.[34]

HPC is finding increased application in precast/prestressed bridge beams where the advantages are readily apparent.[11,39]

- For a given beam spacing, HPC allows an increase in maximum span length, thereby requiring fewer piers
- For a given span length, HPC allows an increase in beam spacing, thereby requiring fewer beams
- With HPC, shallower sections are possible, thus providing more roadway clearance
- Enhanced durability of HPC results in longer life for bridge members and fewer repairs

Precast/prestressed bridge beams in excess of 50 m (164 ft) in length have been constructed with HPC.[40] Innovative beam shapes and 15.2 mm (0.6 in) diameter prestressing strands are replacing standard shapes and 12.7 mm (0.5 in) strands. There are constraints, however. Bed capacity, transportation difficulties, instability during transport and erection and vertical deflection requirements could impose a practical limit on span length.[6] With many of the standard beam shapes, there is little benefit to be gained by increasing compressive strength beyond 100 MPa (14,500 psi). This is because sufficient prestressing force cannot be incorporated into the beam to take advantage of higher concrete strength.

The unit cost of HPC can be 70% more than conventional concrete, although it is highly conditional on required strength and locale.[41] As the design strength increases, the unit cost increases. The higher unit cost of HPC is due to the newness of the technology and reflects the need for expertise, additional trial batching and expanded quality control procedures. The choice of quality cementitious materials and aggregates as well as the addition of various chemical admixtures also increases expense. Still, in many cases, the higher unit cost of HPC doesn't upset its economic feasibility. In bridges, several studies have found that HPC beats conventional concrete in a life cycle cost analysis and often has lower initial costs too.[9] The unit cost is sure to decline as HPC grows in familiarity through frequency of application and as the bidding process for awarding HPC contracts becomes more competitive.[42]

2.5. Challenges to Broader HPC Use

There is risk inherent in the use of any new technology and the use of HPC in the United States remains fairly rare. In general, HPC is slow to enter new markets as a direct result of limited local research and demonstration projects. Among the challenges to successful HPC production is:

- Consistency of constituent materials
- Quality control issues in batching
- Fresh concrete workability
- Curing

- Skill of the personnel
- Repeatability and reproducibility
- Project specifications

2.5.1. Consistency of Constituent Materials

It is important that the constituent materials remain constant throughout the course of a project. Variability in the characteristics of the constituent materials can significantly influence the properties of an HPC mixture.[43,44] When materials change, additional trial batching may be necessary. In particular, the consistency of supplementary cementitious materials can be a problem. Supplementary cementitious materials are not manufactured specifically for use in concrete but instead are industrial byproducts. Fly ash is considered to have more variability than silica fume and slag.[3]

2.5.2. Quality Control Issues in Batching

Strict quality control procedures are required when batching HPC. A chief quality control concern is regulating the quantity of water in a mixture and batching the concrete as designed. The uncertainty of aggregate moisture makes this difficult. Too often, tests to determine aggregate moisture content are sporadic and infrequent.[44]

2.5.3. Fresh Concrete Workability

HPC mixtures may require more effort to place, consolidate, and finish than conventional concrete.[22] Providing satisfactory workability for a sufficiently long time is seen as one of the greatest difficulties in HPC production.[20] In particular, rapid workability loss can be a problem in precast/prestressed concrete applications with *Type III* cement, which causes rapid hydration and setting. Summer temperatures can also diminish workability. Because HPC workability can be very sensitive to concrete temperature, special measures to reduce fresh concrete temperature may be necessary.

2.5.4. Curing

HPC is more sensitive than conventional concrete to poor curing practices. Conventional concrete contains excess water that rises to the surface after finishing. With little or no excess water in HPC, surface cracks can easily result. Moist curing should be initiated as soon as possible after finishing. The necessary duration of moist curing depends on a number of variables, including the cement type and combination of cementitious materials in the mixture, size and shape of the concrete member, required strength and durability, and ambient weather. Due to the frequent use of supplementary cementitious materials in HPC that sometimes slow strength gain, continuous moist curing may need to be provided for an extended period.[12,45,46]

Curbing the heat of hydration during curing is necessary in structural members with HPC. High heat of hydration can lead to cracking and durability problems. The chemical reaction between cement and water is highly exothermic. A number of variables, such as type and fineness of cement, cement content, chemical admixtures and initial concrete temperature can influence the rate and total heat of hydration.[47,48] Most building codes limit peak curing temperatures.[49] The type of forms, amount of exposed surface area and ambient temperature affect dissipation of heat.

Speed of construction is an important consideration in the manufacture of precast/prestressed concrete bridge beams. Heat curing is normally employed to enhance the speed of construction. Typically, steam is applied to beams with forms in place and a tarp over the top to prevent loss of heat and moisture. A typical heat curing cycle consists of an initial delay period prior to steaming, a period for increasing the temperature, a period for keeping the maximum temperature constant, and a period for decreasing the temperature. A cycle may last 18 to 24 hrs. A maximum temperature of 65 °C (150 °F) is usually optimum, although temperatures as high as 82 °C (180 °F) are common. Excessive rates of heating and cooling should be avoided to prevent damaging volume changes. An initial delay period is necessary for concrete to set.

With conventional concrete, heat curing is effective in accelerating early strength gain but may diminish ultimate strength potential. Heat curing causes a rapid cement hydration, but the physical structure that grows is more porous and less complete. Under high temperature, the products of hydration build up quickly within the vicinity of cement particles and, with insufficient time available to disperse, subsequent hydration is hampered and porosity of the space between cement particles increases. Also associated with heat curing is the increased presence of very fine cracks caused by the thermal expansion of air bubbles.[3] Retrogression of strength may occur as a result.

In construction of bridge beams, the precast/prestressed concrete industry is now encountering the need to achieve 60 MPa (8,700 psi) inside of 1 day and 100 MPa (14,500 psi) by 28 or 56 days. These demanding strength requirements are raising new questions about curing processes. The effects of heat curing on HPC, and in particular HPC designed with *Type III* cement, are largely unknown. Heat curing of HPC designed with *Type III* cement has been shown to increase early strength gain by more than 50% relative to ASTM standard curing.[50] Likewise, heat curing has been shown to increase the rate of strength gain. In 1 day, mixtures subjected to heat curing can gain as much as 90% of corresponding strength at 28 days, where 60% is a typical value under standard curing.[29,51] While it is generally agreed that heat curing enhances the early strength development of HPC with *Type III* cement, there is no consensus on how heat curing affects ultimate strength potential. According to different studies, ultimate strength potential, as measured at 28 or 56 days, may be negatively impacted by heat curing or, conversely, insensitive to the curing scheme, whether heat curing or standard curing. The negative impact of heat curing was found to be 25% on average.[26,50]

2.5.5. Skill of the Personnel

Improved education is necessary to ensure a high level of competence for all those involved with HPC.[49] The most significant hurdle in design and construction of HPC bridges was identified as inadequate training and inexperience of the personnel involved.[52] With many projects, the workforce is now required to show ACI certification as evidence of formal training. The National Concrete Bridge Council (NCBC), a group of federal and state engineers, professors and industry representatives, has a goal of training 500 engineers and 2,000 construction personnel each year in HPC bridge technology.[53]

2.5.6. Repeatability and Reproducibility

Knowledge of the batch-to-batch repeatability statistics is necessary to commercially implement HPC. Without knowledge of the repeatability statistics, use of HPC can be erratic and uneconomical. ACI 363 has suggested standards of repeatability.

Difficulties can arise when attempting to reproduce HPC beyond the confines of the laboratory. Prior to application of HPC, trial batches at the intended commercial facility under anticipated working conditions are required by ACI 318 to verify concrete qualities. Adjustments to the mixture proportions and batching and curing procedures may be necessary. Experience with HPC shows that in most cases laboratory trial batches exhibit strengths and other properties different from those achieved in production.[54] Recent studies have recommended a 15% allowance to account for the strength decrease from lab to field.[22,55] Even when conditions in the field are ideal, a strength reduction of 10% is believed to be realistic.[5]

2.5.7. Project Specifications

Proper specifications are needed to uphold construction practices and make success with HPC technology possible. Recently, there has been a move away from prescriptive specifications, which define the course of action for achieving certain goals, toward performance specifications, which state only the goals themselves. This move is thought to encourage innovation and progress and to be conducive to economy.[9,56] The age at which acceptance tests are specified is also under review. Testing at 56 or 91 days, rather than the traditional 28 days, is sometimes more reasonable because HPC can continue to gain strength over an extended period of time and, due to the construction process, structural elements may not experience full loads until well after 28 days.[8,12]

2.6. Bridges and HPC

According to the FHWA, nearly 200,000 bridges or 30% of all bridges nationwide are inadequate and in a state of decline.[9] These bridges will need to be repaired or replaced as economically as possible. Precast/prestressed concrete has become the most common bridge construction alternative; since 1975, more bridges have been built with precast/prestressed concrete than with steel, reinforced concrete or timber. During the last 50 years, timber and steel bridges have endured the most structural deficiencies while precast/prestressed concrete bridges have had by far the fewest deficiencies.[9]

Given the woeful condition of bridges nationwide and the performance record of precast/prestressed concrete, clearly there is potential for HPC. To promote the implementation of HPC, the FHWA recently funded demonstration bridge projects in several states.[57] Demonstration projects can accelerate the pace of technology transfer by providing opportunities to build partnerships between research, industry and government, gain familiarity with local concrete materials, and identify problems in construction practices.[58] Within the next several years, the FHWA envisions building several HPC bridges in every state, including Oklahoma.[59]

The chief objective of this research was to develop HPC mixtures for precast/prestressed bridge beams, where application of HPC can allow extended span length and/or beam spacing, among other benefits. Compressive strength targets were 60 MPa (8,700 psi) at 1 day and 100 MPa (14,500 psi) by 28 or 56 days. High early strength gain is needed to allow transfer of prestressing force inside of a one day production schedule, which is typical in the industry.

To place this research objective in context with the existing state of knowledge, Table 2.2 includes information on the HPC bridges that were recently built in several states as part of the FHWA's program to showcase the use of HPC. Mixture proportions and compressive strength values of the precast/prestressed concrete beams in these bridges are presented in Table 2.2.[60] The three major cement types were employed to produce HPC. Six of the nine mixtures contained *Type III* cement, while two mixtures had *Type I* cement and one mixture had *Type I/II* cement. All mixtures contained *Class C* fly ash and/or silica fume as supplementary cementitious materials, up to 32% of the total cementitious materials content. Texas' HPC contained *Type III* cement and fly ash, with fly ash making up 32% of the total cementitious materials. Mixtures from Nebraska and Washington employed both fly ash and silica fume. Cementitious materials contents ranged from 454 kg/m^3 (765 lb/yd^3) in Colorado to 594 kg/m^3 (1,000 lb/yd^3) in Nebraska and Washington. Different types of coarse aggregate, local to the respective region, included limestone, gravel and traprock in maximum sizes between 10 mm ($^3/_8$ in) and 19 mm ($^3/_4$ in). Limestone was the coarse aggregate of choice in four mixtures, including Texas'. Each mixture contained high range water reducing (HRWR) admixture, or superplasticizer. Water reducing/set retarding

(WR/SR) and air entraining (AE) admixtures were present in some of the mixtures. New Hampshire's HPC contained a corrosion inhibiting (CI) admixture. The w/cm's ranged from 0.24 to 0.33. Nebraska's HPC had the lowest w/cm of 0.24, with Texas at 0.25. Texas's HPC had the highest specified strength at release, 60.7 MPa (8,800 psi), as well as the highest design strength, 90.3 MPa (13,100 psi). Strength at release is usually measured at 1 day while the design strength is measured at 28 or 56 days. Most of the bridge beams were subjected to steam curing. Average strength at release was 47.9 MPa (6,950 psi). Average design strength was 71.4 MPa (10,400 psi). The results of the FHWA showcase are illustrated in Figure 2.2 together with the goals of this research. In most cases, the goals of this research greatly surpass the results achieved in the FHWA showcase.

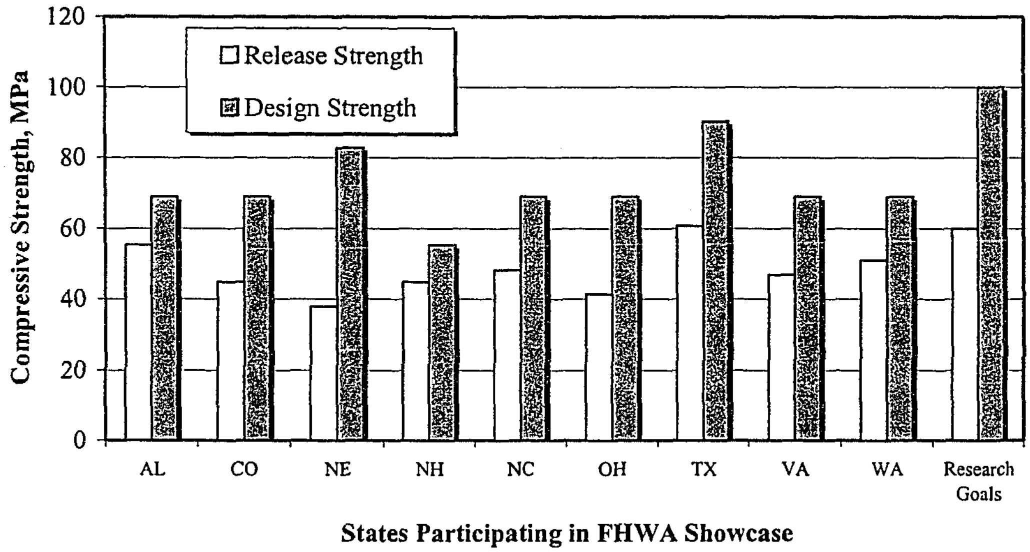
Table 2.2. HPC Showcase Projects

		AL	CO	NE	NH	NC	OH	TX	VA	WA
Cement	kg/m^3	447	433	445	461	534	502	398	446	432
Fly Ash (*Class C*)	kg/m^3	78.9	—	119	—	—	—	187	—	132
Silica Fume	kg/m^3	—	20.8	29.7	29.7	29.7	59.3	—	44.5	29.7
Coarse Aggregate	kg/m^3	1,140	1,050	1,100	1,100	1,190	1,050	1,140	991	1,110
Fine Aggregate	kg/m^3	634	808	587	638	537	550	644	801	528
Mixing Water	kg/m^3	147	130	142	162	163	155	147	139	157
WR/SR Admixture	L/m^3	—	1.41	1.16	0.54	1.39	1.08	1.04	1.16	1.12
AE Admixture	L/m^3	1.35	—	—	0.39	0.23	0.81	—	0.27	—
CI Admixture	L/m^3	—	—	—	19.8	—	—	—	—	—
HRWR Admixture	L/m^3	8.70	3.38	8.70	7.97	3.13	7.85	7.74	8.01	8.32
Cement Type		*III*	*III*	*I*	*III*	*I/II*	*III*	*III*	*I*	*III*
CA Type		Limestone	—	Limestone	Traprock	—	Gravel	Limestone	Limestone	Gravel
Maximum Size CA	mm	19	10	13	19	19	10	13	13	13
w/cm		**0.28**	**0.29**	**0.24**	**0.33**	**0.30**	**0.28**	**0.25**	**0.28**	**0.27**
Curing Scheme[a]		H	—	H	H	—	H	A	H	H
Specified Compressive Strength at Release	MPa	55.2	44.8	37.9	44.8	48.3	41.4	60.7	46.9	51.0
Design Compressive Strength	MPa	69.0	69.0	82.8	55.2	69.0	69.0	90.3	69.0	69.0

[a] H: Steam curing; A: Ambient curing

1 kg/m^3 = 1.686 lb/yd^3, 1 L/m^3 = 25.85 $floz/yd^3$, 25.4 mm = 1 in, 1 MPa = 145 psi

Figure 2.2.
FHWA Showcase Projects and the Goals of this Research



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3. Research Program and Procedures

3.1. Overview

A research program was initiated at the University of Oklahoma, first to identify local materials from Oklahoma and neighboring states that are suitable for producing HPC and then to develop mixture proportions for precast/prestressed bridge beams, where there is a need for HPC. As a conclusion, HPC technology was demonstrated at a precast/prestressing facility in Oklahoma.

In studying concrete, trial batching is necessary to evaluate materials and optimize mixtures. The research program consisted of a comprehensive trial batching effort organized into four phases:

- Cement Study
- Aggregate Study
- Mixture Proportion Study
- Demonstration of HPC at a Precast/Prestressed Concrete Plant

As a methodical approach to evaluating materials and optimizing mixtures, trial batches were arranged into matrices. In each matrix, certain mixture variables were examined independently, changing one variable at a time and maintaining all other variables constant. Among the variables examined in this way were:

- Water/cementitious material (w/cm) ratio
- Cements — type and source
- Supplementary cementitious materials — replacement rates and combinations
- Cementitious material content
- Coarse aggregates — type, grading and content
- Chemical admixtures — addition rates and combinations

Twelve batching matrices were conceived, ranging in size from two-by-two to nine-by-seven. Table 3.1 is an index of the batching matrices, specifying which variables were examined in each matrix. One, two or three variables were isolated in a matrix. The batching matrices are included in Appendix B.

In each matrix, a cell represents a single mixture design. ACI 211[1] and ACI 363[2] reports were useful in designing mixture proportions. Many mixtures were batched multiple times for accuracy or as an assessment of repeatability. Some mixtures with characteristics that were central to the scope of interest appear in more than one matrix. Mixture 27, one such mixture, was batched six times and appears in five matrices. It had a w/cm of 0.28 and 500 kg/m^3 (843 lb/yd^3) of cementitious material with 20% fly ash replacement of cement. Sometimes cells were left blank where it was impossible to batch a mixture due to workability problems or where the mixture was outside the scope if interest. Of all the variables, the w/cm was examined most frequently and is found in six of the twelve matrices.

Table 3.1. An Index of the Batching Matrices

VARIABLES EXAMINED	BATCHING MATRIX 1	2	3	4	5	6	7	8	9	10	11	12
WATER/CEMENTITIOUS MATERIAL RATIO				●	●	●	●			●	●	
CEMENT TYPE & SOURCE	●						●					
CEMENTITIOUS MATERIAL CONTENT				●			●	●				
SUPPLEMENTARY CEMENTITIOUS MATERIALS				●	●				●	●		
COARSE AGGREGATE SOURCE		●										●
AGGREGATE GRADING		●	●									
COARSE AGGREGATE CONTENT												●
CHEMICAL ADMIXTURES						●		●	●	●	●	

Matrix 1 — *Cement Study*
Matrices 2 and 3 — *Aggregate Study*
Matrices 4 through 12 — *Mixture Proportion Study*

Altogether, the study involved 130 HPC mixture designs comprising a diversity of materials and proportions. Appendix A is a glossary of abbreviations. Appendix D contains mixture proportions and testing results from the *Cement Study* and *Aggregate Study*. Appendix E contains mixture proportions and testing results from the *Mixture Proportion Study* and *Plant Demonstration*. Appendix F contains interesting details about the entire research program and Appendix G provides helpful unit conversions (SI and US customary units) for concrete materials.

3.2. Cement Study

The first phase of the research centered on identification of local, readily available cements suitable for production of HPC. A group of eight cements was chosen to encompass different cement types, manufacturers and plant locations and to be representative of all cements available within Oklahoma and neighboring states. As presented in Table 3.2, the group included cements from three manufacturers and six plants in Oklahoma, Texas, Arkansas, and Kansas with four ASTM C 150 *Type I's*, two *Type I/II's*, one *Type II* and one *Type III*. *Type I/II* cement meets the standards for both *Type I* and *Type II* cements, but is not a blend. Cement chemical compositions and fineness values appear in Chapter 4. These cements are currently in use or could readily be used in Oklahoma. Each of the cements was evaluated in two HPC mixtures with discrete strength levels, called Class 1 and Class 2. Class 1 mixtures were designed to achieve a compressive strength of about 60 MPa (8,700 psi) at 28 days. Class 2 mixtures were designed to achieve 75 MPa (10,880 psi) at 28 days. Batching Matrix 1, Table 3.3 portrays the *Cement Study*. Solid circles mark the mixtures that were batched. Results and analysis of the *Cement Study* are presented in Chapter 4. Criteria for comparing mixtures included workability, compressive strength, splitting tensile strength and modulus of elasticity.

Table 3.2. Cement Sources

Cement Identification	Cement Type	Manufacturer	Plant Location
C1	*Type I*	Lonestar	Pryor, OK
C2	*Type I/II*	Lonestar	Pryor, OK
C3	*Type I*	Ash Grove	Midlothian, TX
C4	*Type I*	Ash Grove	Foreman, AR
C5	*Type I/II*	Ash Grove	Chanute, KS
C6	*Type I*	Holnam	Ada, OK
C7	*Type II*	Holnam	Ada, OK
C8	*Type III*	Holnam	Midlothian, TX

Table 3.3.
Batching Matrix 1 — Cement Study

		Class 1	Class 2
Cement	C1	●	●
	C2	●	●
	C3	●	●
	C4	●	●
	C5	●	●
	C6	●	●
	C7	●	●
	C8	●	●

3.3. Aggregate Study

Four coarse aggregates were selected, each of different type and quarry location to be representative of the coarse aggregates currently available for concrete work in Oklahoma. Like the cements, the coarse aggregates were assessed in HPC mixtures to determine their suitability for HPC production. The test group presented in Table 3.4 included limestone, rhyolite, granite and river gravel. All aggregates were quarried in Oklahoma. Each of the coarse aggregates was separated into a precise or "standard" gradation, different from the gradation available for purchase at the quarry. The "standard" gradation was selected to meet the No. 7 grading requirements of ASTM C 33 and was uniform for all four aggregates. The "quarry-acquired" aggregates met or nearly met a No. 7 or No. 8 gradation. Aggregate gradations appear in Chapter 5. Both the "quarry-acquired" and "standard" gradations of each aggregate were evaluated in HPC mixtures. Batching Matrix 2 portrays the *Coarse Aggregate Study* and is presented as Table 3.5. Solid circles mark the mixtures that were batched. The "quarry-acquired" approach allowed examination of the aggregates in a way consistent with commercial production. The "standard" approach allowed examination of the effect of type, shape and texture of aggregates independent of grading. HPC mixtures were designed to achieve about 75 MPa (10,900 psi) at 28 days. Results and analysis of the *Coarse Aggregate Study* are presented in Chapter 5. Criteria for comparing mixtures included workability, compressive strength, splitting tensile strength, flexural strength and modulus of elasticity.

Table 3.4. Coarse Aggregate Sources

Coarse Aggregate Identification	Aggregate Type	Quarry Location
LI	Limestone	Davis, OK
RH	Rhyolite	Davis, OK
GN	Granite	Snyder, OK
GV	River Gravel (Weathered Sandstone)	Broken Bow, OK

Table 3.5.
Batching Matrix 2 — Coarse Aggregate Study

		Quarry–Acquired Gradation	Standard Gradation
Aggregate Type	Limestone	●	●
	Rhyolite	●	●
	Granite	●	●
	River Gravel	●	●

In several other mixtures, in an effort to enhance workability, an intermediate aggregate was introduced to increase the fineness modulus. The intermediate aggregate selected was limestone from Davis, Oklahoma, too coarse to satisfy the fine aggregate grading requirements of ASTM C 33 and too fine to satisfy the coarse aggregate grading requirements. The fineness modulus was increased from 2.5 to 3.3 by blending the intermediate aggregate with fine aggregate. This work, called the *Fine Aggregate Study*, is portrayed in Batching Matrix 3, Table 3.6, and presented in Chapter 5.

Table 3.6.
Batching Matrix 3 —
Fine Aggregate Study

	Fineness Modulus	
	2.5	3.3
First Mixture	●	●
Second Mixture	●	●

3.4. Mixture Proportion Study

Materials identified in the *Cement Study* and *Coarse Aggregate Study* with potential for producing high early strength and high ultimate strength were selected for the next phase, to optimize HPC mixture proportions for precast/prestressed bridge beams. The *Mixture Proportion Study* concentrated on *Type III* cement and No. 8 crushed limestone coarse aggregate. The *Mixture Proportion Study* was more extensive than the *Cement Study* and *Aggregate Study* in terms of the number of variables, mixtures and batches. Batching Matrices 4 through 12, presented as Tables 3.7 through 3.15, illustrate the *Mixture Proportion Study*. In these tables, solid circles mark the mixtures that were batched. Results and analysis of the *Mixture Proportion Study* are presented in Chapters 6, 7, 8 and 9.

Two *Type III* cements were used in the *Mixture Proportion Study*. Cement from the second brand, Ash Grove *Type III* from Chanute, Kansas was employed when manufacture of the first brand, C8 in Table 3.2, was discontinued. Batching Matrices 4, 5, 8, 9, 10 and 12 contained C8 while Batching Matrices 6 and 11 contained Ash Grove/Chanute *Type III*. Batching Matrix 7 compared the two different cements. All mixtures in the *Mixture Proportion Study* contained river sand from Dover, Oklahoma as fine aggregate and various chemical admixtures.

In Batching Matrix 4, Table 3.7, mixtures with *Type III* cement as the only cementitious material and mixtures in which cement was partially replaced with *Class C* fly ash at rates of 10% and 20% were evaluated over a range of w/cm's and cementitious material contents. The w/cm's ranged from 0.32 to 0.26. Cementitious material contents ranged from 400 to 750 kg/m^3 (674 to 1,265 lb/yd^3). The main objective was to learn the effects of changing the content of cement at a w/cm of 0.30.

Batching Matrix 5, Table 3.8, shows how supplementary cementitious materials in various quantities and combinations were evaluated in mixtures with w/cm's ranging from 0.32 to 0.26. The supplementary cementitious materials included fly ash, silica fume and ground, granulated blast furnace (GGBF) slag. Each of these mixtures was designed with 500 kg/m^3 (843 lb/yd^3) of cementitious material. The main objective was to learn which combination of supplementary cementitious materials was best for precast/prestressed concrete applications.

Chemical admixtures in different addition rates and combinations were evaluated in mixtures with various w/cm's, as displayed in Batching Matrix 6, Table 3.9. Corrosion inhibiting/strength accelerating (CI/SA), water reducing and superplasticizing admixtures were examined. The w/cm's ranged from 0.28 to 0.22. Each of these mixtures was designed with 600 kg/m^3 (1,012 lb/yd^3) of cementitious material, and *Type III* cement with 10% fly ash and 5% silica fume. The main objective was to learn the optimum amount of the CI/SA admixture.

Similar mixtures with two brands of *Type III* cement were compared in Batching Matrix 7, Table 3.10. These mixtures had 10% fly ash and 5% silica fume replacement of cement. The main objective was to compare the two cements at a w/cm of 0.24.

Batching Matrix 8, Table 3.11 shows mixtures examined with two superplasticizer addition rates and three cement contents. These mixtures were designed with a w/cm of 0.28. The main objective was to determine the optimum amount of superplasticizer.

Mixtures with various fly ash replacement rates, up to 20%, and various chemical admixture rates were examined in Batching Matrix 9, Table 3.12. These mixtures were designed with a w/cm of 0.28 and 500 kg/m^3 (843 lb/yd^3) of cementitious material. The main objective was to determine the optimum amount of fly ash.

In Batching Matrix 10, Table 3.13, mixtures with cement as the only cementitious material and mixtures with 20% fly ash replacement were evaluated under several different addition rates of an air entraining (AE) admixture. Each of these mixtures was designed with 500 kg/m^3 (843 lb/yd^3) while w/cm's ranged from 0.30 to 0.24. The main objective was to determine the effects of air entrainment and fly ash.

Batching Matrix 11, Table 3.14 shows mixtures with w/cm's of 0.28, 0.26 and 0.24 and various addition rates of an AE admixture. These mixtures were designed with 600 kg/m^3 (1,012 lb/yd^3) of cementitious material and had 10% fly ash and 5% silica fume replacement. The main objective was to determine the effects of air entrainment and w/cm.

Three types of coarse aggregate were evaluated in Batching Matrix 12, Table 3.15. The aggregates included limestone, rhyolite and granite. Coarse aggregate contents ranged from 50% to 75%. These mixtures were designed with a w/cm of 0.28 and contained 500 kg/m^3 (843 lb/yd^3) of cementitious material with 20% fly ash replacement. The main objective was to determine the optimum coarse aggregate content.

Table 3.7.
Batching Matrix 4 — Changing Cementitious Material Content

Cementitious Material Content, kg/m^3	Cement Only			10% Fly Ash		20% Fly Ash	
	w/cm 0.32	w/cm 0.30	w/cm 0.28	w/cm 0.30	w/cm 0.28	w/cm 0.28	w/cm 0.26
400	●	●				●	
450	●	●				●	
475		●					
500	●	●	●	●	●	●	●
550		●	●	●	●	●	●
600		●	●			●	●
650		●	●				
700		●					
750		●					

1 $kg/m^3 = 1.686\ lb/yd^3$

Table 3.8.
Batching Matrix 5 — Combinations of Supplementary Cementitious Materials

Fly Ash / Slag	Replacement, %	Silica Fume Replacement, %	w/cm 0.32	w/cm 0.30	w/cm 0.28	w/cm 0.26
Cement Only			●	●	●	
Fly Ash Replacement, %	10	0		●	●	
Fly Ash Replacement, %	20	0			●	●
Fly Ash Replacement, %	0	5		●	●	
Fly Ash Replacement, %	0	7.5		●	●	
Fly Ash Replacement, %	0	10		●		
Fly Ash Replacement, %	10	5			●	●
Fly Ash Replacement, %	10	7.5			●	●
Slag, %	10	5		●		
Slag, %	10	7.5		●		

Table 3.9.
Batching Matrix 6 — Amount of CI/SA Admixture

Corrosion Inhibitor/Strength Accelerator Addition, L/m³		Water Reducer & Superplasticizer Addition, mL/100 kg of cementitious material	w/cm 0.28	w/cm 0.26	w/cm 0.24	w/cm 0.22
	0		0 1,000		●	●	
			300 1,300			●	●
	20		300 700	●	●		
			0 1,000		●		
			300 1,000	●	●	●	
	30		390 650		●		
			300 1,000		●		
	40		300 1,000		●		
	50		300 1,300		●		

4.951 L/m³ = 1 gal/yd³, 65.2 mL/100 kg = 1 floz/100 lb

Table 3.10. Batching Matrix 7 — Two *Type III* Cements

	Cementitious Material Content, kg/m³				
	500		550	600	
	w/cm 0.28	**w/cm** 0.26		**w/cm** 0.24	**w/cm** 0.22
Holnam/Midlothian *Type III* Cement	●	●	●	●	
Ash Grove/Chanute *Type III* Cement				●	●

1 kg/m³ = 1.686 lb/yd³

Table 3.11. Batching Matrix 8 — Amount of Superplasticizer

		Water Reducer & Superplasticizer Addition, mL/100 kg of cement	
		300 1,300	300 2,000
Cement Content, kg/m³	500	●	●
	550	●	●
	600	●	●

1 kg/m³ = 1.686 lb/yd³, 65.2 mL/100 kg = 1 floz/100 lb

Table 3.12. Batching Matrix 9 — Fly Ash Replacement

		Fly Ash Replacement, %			
		0	10	15	20
Water Reducer & Superplasticizer Addition, mL/100 kg of cementitious material	400 900		●	●	●
	200 1,100			●	
	200 1,300			●	
	300 1,300	●	●		●
	300 2,000	●			

65.2 mL/100 kg = 1 floz/100 lb

Table 3.13. Batching Matrix 10 — AE Admixture and Fly Ash

		Cement Only		20% Fly Ash	
		w/cm 0.30	w/cm 0.26	w/cm 0.28	w/cm 0.24
Addition of AEA, mL/100 kg of cementitious material	0	●		●	
	900	●		●	
	1,200	●	●	●	●

65.2 mL/100 kg = 1 floz/100 lb

Table 3.14. Batching Matrix 11 —
AE Admixture and w/cm

Addition of AEA, mL/100 kg of cementitious material	w/cm 0.28	w/cm 0.26	w/cm 0.24
0	●	●	●
250	●	●	●
500		●	
750			●

65.2 mL/100 kg = 1 floz/100 lb

Table 3.15. Batching Matrix 12 — Coarse Aggregate Content

Aggregate Type	Coarse Aggregate Content (Volume of dry rodded coarse aggregate per unit volume of concrete), %					
	50	55	60	65	70	75
Limestone	●	●	●	●	●	●
Rhyolite			●	●		
Granite			●	●		

3.5. Demonstrating HPC at a Precast/Prestressed Concrete Plant

Several HPC mixtures, distinguished as having adequate workability and potential to achieve 60 MPa (8,700 psi) at 24 hrs and 100 MPa (14,500 psi) by 28 or 56 days, were selected for trial at a precast/prestressing plant in Oklahoma. Results and analysis of the *Demonstration of HPC at a Precast/Prestressing Plant* are presented in Chapter 10. Difficulties can be encountered trying to advance HPC technology from the composure of the laboratory to the commotion of commercial manufacture. A chief difficulty is accurately determining the moisture content of the aggregates.

3.6. Experimental Procedures

Batching and testing procedures generally conformed to the ASTM standards[3] listed in Table 3.16. Every effort was made to reduce variability through consistency of materials, practice and equipment.

Table 3.16. Applicable ASTM Standards

EVALUATING CONSTITUENT MATERIALS	**C 204**	Cement Fineness by Air Permeability
	C 702	Reducing Field Samples of Aggregate to Testing Size
	C 33	Concrete Aggregates
	C 136	Sieve Analysis of Aggregates
	C 127, C 128	Specific Gravity and Absorption of Aggregates
	C 29	Unit Weight and Voids in Aggregate
BATCHING & CURING CONCRETE	**C 192**	Making and Curing Concrete in the Laboratory
	C 31	Making and Curing Concrete in the Field
	C 566	Total Moisture Content of Aggregate by Drying
DETERMINING CONCRETE PROPERTIES	**C 1064**	Temperature of Fresh Concrete
	C 143	Slump
	C 138, C 231	Unit Weight, Yield, and Air Content
	C 403	Time of Setting (Penetration Resistance)
	C 617	Capping Cylinders
	C 1231	Use of Unbonded Caps
	C 39	Compressive Strength
	C 496	Splitting Tensile Strength
	C 78	Flexural Strength (Simple Beam with Third Point Loading)
	C 469	Modulus of Elasticity
	C 157, C 490	Length Change

3.6.1. Establishing Material Properties

Individual material properties were established prior to batching concrete and verified periodically, usually whenever a new supply of materials arrived. Supplies were obtained in multiple deliveries over a period of four years. Cementitious materials and aggregate properties can change over time, both inadvertently and by design of the manufacture, but remained uniform over the course of this research. An adequate supply of cementitious materials and aggregates was usually secured for an entire batching matrix. Besides ensuring uniformity, obtaining materials in bulk helped streamline productivity.

Analysis of concrete materials conformed to the appropriate ASTM specifications. Cement fineness was determined with the Blaine air permeability apparatus. Aggregate properties included absorption, specific gravity, grading and dry rodded unit weight. These results agreed with those available from the manufacturers. Cement chemical compositions were provided by the manufacturers and were not independently confirmed.

W.R. Grace & Co. provided the various chemical admixtures employed in the research. These are presented in Table 3.17. Additional information about the admixtures is included in Appendix C.

Table 3.17. Chemical Admixtures

All chemical admixtures were manufactured by W.R. Grace & Co.	
WRDA with Hycol	ASTM C 494 *Type A* water reducer
Daratard 17	ASTM C 494 *Type B/D* set retarder/water reducer
Daravair 1000	ASTM C 260 air entrainer
DCI	ASTM C 494 *Type C* corrosion inhibitor with secondary set and strength accelerating properties
Daracem 19	ASTM C 494 *Type A/F* high range water reducer
ADVA Flow	ASTM C 494 *Type F* high range water reducer

3.6.2. Batching and Testing Concrete

During this research, the following batching and testing results were recorded:

- Mixture identification
- Mixture proportions, mixture proportions adjusted for aggregate moisture, batch size and batch quantities
- Date, time and facility where the mixture was batched
- Aggregate moisture contents
- Stock of constituent materials

- Testing schedule — specifying the number of cylinders, beams and prisms at each age and for each test
- Changes to the established mixture proportions or batching sequence
- Mixing duration
- Measures to control concrete temperature
- Ambient conditions — air temperature and relative humidity
- Fresh concrete properties — concrete temperature, slump, workability, unit weight, air content and time of setting
- Curing scheme(s)
- Labor force
- Work duration
- Compressive strength — specifying the age of test, curing, cylinder size and end preparation
- Splitting tensile strength, flexural strength (modulus of rupture), modulus of elasticity and length change — specifying the age of test and curing

A set of forms included as Figures 3.1, 3.2, 3.3 and 3.4 were helpful in recording the information. However, not all of the above information was recorded or applicable every batch.

Concrete mixture proportions were designed by the absolute volume method. The water fraction of chemical admixtures was included in the amount of mixing water. A similar adjustment was made when batching with silica fume, which was available in slurry form.

Accounting for the water in chemical admixtures is important because HPC mixtures can have substantial addition rates. If chemical admixtures are ignored in the calculation, then a mixture designed with 500 kg/m^3 (843 lb/yd^3) of cementitious material and 130 kg/m^3 (219 lb/yd^3) mixing water would have a w/cm of 0.260. But with addition of 1.5 L/m^3 (39 $floz/yd^3$) water reducer, 7.5 L/m^3 (194 $floz/yd^3$) superplasticizer and 30 L/m^3 (6.1 gal/yd^3) corrosion inhibitor/strength accelerator, each of which consist of about 60% water, the actual w/cm is 0.307, a difference that could dramatically alter concrete workability, strength and durability.

Figure 3.1. Batching & Testing Concrete — Working Form 1

MIXTURE	MIX PROPORTIONS		BATCH
[ ]	*SSD AGGREGATES*	*ADJUSTED FOR AGGREGATE MOISTURE*	*BATCH SIZE* [ ]
CEMENT			
FLY ASH			
SILICA FUME			
OTHER CEMENTITIOUS MATERIAL			
COARSE AGGREGATE			
INTERMEDIATE AGGREGATE			
FINE AGGREGATE			
MIXING WATER			
ADMIXTURES — WR			
ADMIXTURES — WR/SR			
ADMIXTURES — AE			
ADMIXTURES — CI/SA			
ADMIXTURES — HRWR			

Correcting aggregate weights to compensate for moisture (Terms defined in Appendix A, Glossary)

$$W_{AG_C} = \frac{W_{AG_{SSD}}}{\left(1+\frac{AB_{AG}}{100}\right)} \cdot \left(1+\frac{MC_{AG}}{100}\right)$$

Correcting mixing water for aggregate moisture (Terms defined in Appendix A, Glossary)

$$W_{W_C} = W_W - \sum_{AG}\left[\frac{W_{AG_{SSD}}}{\left(1+\frac{AB_{AG}}{100}\right)} \cdot \left(\frac{MC_{AG}-AB_{AG}}{100}\right)\right]$$

Figure 3.2. Batching & Testing Concrete — Working Form 2

MIXTURE	TESTING SCHEDULE — INDICATE NUMBER OF CYLINDERS, BEAMS, PRISMS					
		f'_c	f_t	f_r	E_c	ε_{sh}
	18 hrs	☐				
	24 hrs	☐			☐	☐ ↓
DATE	3 days	☐				↓
TIME	7 days	☐			☐	↓
FACILITY	28 days	☐	☐	☐	☐	↓
BATCH SIZE	56 days	☐				↓

AGGREGATE MOISTURE CONTENTS			CHANGES TO ESTABLISHED PROPORTIONS/SEQUENCE	
CA	IA	FA	MIXING DURATION	
			MEASURES TO CONTROL CONCRETE TEMPERATURE	
			AIR TEMPERATURE	RH

IDENTIFY STOCK OF CONSTITUENT MATERIALS WITH VARIABLE PROPERTIES		FRESH CONCRETE PROPERTIES
☐	CEMENT	CONCRETE TEMPERATURE
☐	FLY ASH	SLUMP
☐	OTHER CEM. MATERIAL	WORKABILITY
☐	COARSE AGGREGATE	UNIT WEIGHT
☐	INTERMEDIATE AGGREGATE	AIR CONTENT
☐	FINE AGGREGATE	TIME OF SETTING

CURING SCHEME(S)	
LABOR FORCE	WORK DURATION

MIXTURE

Figure 3.3.
Batching &Testing Concrete — Working Form 3

AGE	CURING	CYL DIAM	END PREP	f_c'	
		☐ 100 ☐ 150	☐ NP ☐ SC	1 2 3	4 5 6
		☐ 100 ☐ 150	☐ NP ☐ SC	1 2 3	4 5 6
		☐ 100 ☐ 150	☐ NP ☐ SC	1 2 3	4 5 6
		☐ 100 ☐ 150	☐ NP ☐ SC	1 2 3	4 5 6
		☐ 100 ☐ 150	☐ NP ☐ SC	1 2 3	4 5 6
		☐ 100 ☐ 150	☐ NP ☐ SC	1 2 3	4 5 6
		☐ 100 ☐ 150	☐ NP ☐ SC	1 2 3	4 5 6
		☐ 100 ☐ 150	☐ NP ☐ SC	1 2 3	4 5 6

MIXTURE

Figure 3.4.
Batching & Testing Concrete — Working Form 4

f_t	AGE	CURING	$P_{failure}$		
			1	2	3

f_r	AGE	CURING	BEAM DIMENSIONS		$P_{failure}$
			b	*d*	1
			b	*d*	2
			b	*d*	3

E_c	AGE	CURING	$0.4f_c'$	$\sigma_{50\mu\varepsilon}$	$\mu\varepsilon_{0.4f_c'}$
				1a	1a
				1b	1b
				2a	2a
				2b	2b
				1a	1a
				1b	1b
				2a	2a
				2b	2b

ε_{sh}	AGE	CURING	MEASUREMENT		
		↓	1i	2i	3i
			1	2	3
			1	2	3
			1	2	3
			1	2	3

3.6.2.1. Correcting Batch Weights for Aggregate Moisture

Batch weights were adjusted to compensate for moisture in the aggregates. At the lab, a simple and reliable routine to determine aggregate moisture was followed. One day or earlier before batching, coarse and fine aggregates of sufficient quantity were removed from indoor bins or from stockpiles outside and thoroughly turned over with a shovel to ensure uniform moisture for sampling. Aggregate moisture contents were determined by oven drying representative samples. Aggregates were stored in sealed containers until batching. At the precast/prestressing plant, prior to batching, coarse and fine aggregate samples were collected from big, uncovered stockpiles. Samples were extracted from a portion of the stockpile where aggregate would likely be lifted for the next batch. Moisture contents were determined by drying samples on a hot plate, a procedure that required more than an hour. Sampling at the plant was repeated in the event of rain or new material deliveries.

Regulating the water content in an HPC mixture is crucial. Without accurate adjustment of batch weights, the moisture released or absorbed by the aggregates can undermine the properties of an HPC mixture. Experience indicates that HPC mixtures designed with low w/cm's leave little latitude for error. As an example, assume the absorption capacity of a coarse aggregate is 1.0% and the moisture content at the time of batching is 2.2%. A mixture is designed with a w/cm of 0.260, having 156 kg/m^3

(263 lb/yd^3) mixing water and 970 kg/m^3 (1,635 lb/yd^3) coarse aggregate (dry). If moisture content adjustment is neglected, the additional water contributed by the coarse aggregate increases the actual w/cm of this mixture to 0.279, a difference that could significantly change concrete properties.

3.6.2.2. Batching Concrete

At the lab, batch quantities of cementitious materials, aggregates and mixing water were determined to the nearest of 0.005 kg (0.01 lb) and liquid chemical admixtures and silica fume slurry were measured to within 1 mL (0.03 floz). At the precast/prestressed concrete plant, the automated measuring system was within the tolerances of ASTM C 31. When batching at the plant with materials that were not stocked on site, these materials were measured to lab accuracy and added to the mixer by hand. At both lab and plant, silica fume slurry, because of its potential for settling, was agitated prior to measurement.

A revolving drum, tilting mixer with a rated capacity of 0.170 m^3 (6 ft^3) was used for lab trial batching. Generally, a batch of about 0.075 m^3 (2.6 ft^3) was sufficient for the number of molds and tests, with some surplus. At the plant using a revolving blade, pan mixer, trial batches were 0.765 m^3 (1 yd^3) in size. It was more than the amount needed but, at 20% of capacity, it was the smallest quantity that could be mixed effectively.

Mixing time was often extended beyond the ASTM specified duration and continued until the concrete appeared uniform.[4,5] HPC can be more viscous than conventional concrete. The necessary time of mixing was influenced by the nature of the mixture, batch size, concrete temperature and mixer efficiency. While ASTM specifies a final mixing period of 2 minutes, it is believed that 10 to 15 minutes are more realistic of commercial practice where transport of the concrete is necessary.[6]

A consistent batching sequence was followed throughout the research program. Coarse aggregate was added to the mixer first, together with most of the mixing water or crushed ice. Mixing started at this point and continued for 2 to 10 minutes to allow the coarse aggregate to absorb some moisture. (If coarse aggregates are allowed to absorb some water, then they can act as tiny reservoirs distributed throughout the concrete, slowly releasing water for continued cement hydration and strength gain.[2] Dry coarse aggregates may absorb chemical admixtures during mixing and impair workability.) After this period, cementitious materials, intermediate and fine aggregate and the remaining mixing water or crushed ice were combined gradually over 5 minutes while the mixer was running. Water reducing, set retarding/water reducing, air entraining and/or corrosion inhibiting/strength accelerating admixtures were also introduced during this time. Chemical admixtures were dispensed individually to avoid possible interaction. Mixing was paused for 3 minutes for initial slump measurement. Finally, a superplasticizer was introduced, followed by 3 to 6 minutes of additional mixing. Concrete was discharged into a wheelbarrow.

Trial batching at the precast/prestressing plant was performed during the summer months. Work usually proceeded in the heat of the afternoon and without the benefit of ice to chill the mixing water. These circumstances were dictated by the busy schedule at the commercial facility. As such, the practicality of the mixtures was tested under adverse conditions. Hot weather can severely worsen fresh concrete workability. Lab batching, conversely, had the benefit of ice or heated mixing water for seasonal temperature control. Crushed ice included in the mixing water regularly reduced the fresh concrete temperature 5 to 10 °C (9 to 18 °F) below ambient temperature, which sometimes climbed above 35 °C (95 °F). At the lab, materials were generally maintained within 20 to 30 °C (68 to 86 °F) before batching, as specified by ASTM C 192.

Molds were lightly coated with oil prior to batching. All test specimens were consolidated by rodding and moved carefully to avoid skewing the shape of the mold or disturbing the concrete. Caps were fitted on cylinders undergoing ambient curing, to prevent evaporation. Work was completed within one hour of concrete discharge or prior to initial set. (Sometimes initial set occurred in less than one hour.)

3.6.2.3. Curing Concrete

In this research program, HPC was examined under the various curing schemes described in Table 3.18. In the abbreviations for curing schemes, "S" is standard, "H" is heat, "M" is moist and "A" is ambient. Most mixtures were evaluated only under standard curing (S/M). In some mixtures, heat curing was evaluated in parallel with standard curing. To accomplish this, concrete specimens from a single mixture were divided into two or more sets, one set for standard curing and one or more sets for heat curing. Heat curing was expected to accelerate early strength gain. Each of the heat curing schemes was an attempt to simulate the curing practices typical in construction of precast/prestressed concrete bridge beams.

Under standard curing (S/M), cylinders, (flexural strength) beams and (length change) prisms were cured at 23 ± 1.7 °C (73.4 ± 3.1 °F) and 50 ± 4% relative humidity (RH) during the initial 24 hrs. A chamber at the lab was equipped to provide these conditions. Occasionally, a number of cylinders were removed at 18 hours for compressive strength testing. The remaining molds were removed at 24 hours. After 24 hrs and until tested, cylinders and beams were moist cured (underwater) as specified by ASTM C 192 at a temperature of 23 °C (73.4 °F). Prisms remained at 23 °C (73.4 °F) and 50% RH.

Table 3.18. Curing Schemes

STANDARD	**S/M**	Cured at 23 °C and 50% relative humidity (RH) for the first 24 hrs, then moist cured (underwater) at 23 °C, as specified by ASTM C 192
AMBIENT	**A/M**	Cured under ambient conditions (inside or outside, but always under a tarp) for first 24 hrs, then moist cured at 23 °C
MODERATE HEAT	**H1/M**	After 3 hr delay under standard conditions (23 °C and 50% RH) to reach initial set, steadily cured at 42 °C for 21 hrs, then moist cured at 23 °C
	H2/M	Cured at 42 °C for first 24 hrs, then moist cured at 23 °C
	H2/A	Cured at 42 °C for first 24 hrs, then placed under ambient conditions (inside building)
	H3/M	Cured at about 30 °C for first 24 hrs, then moist cured at 23 °C
INTENSE HEAT	**H4/M**	After 3 hr delay under standard conditions (23 °C and 50% RH), steam cured to a peak of 71 °C for 21 hrs (temperature climbing at a rate of about 10 °C/hr), then moist cured at 23 °C
	H5/M	After 6 hr delay under standard conditions (23 °C and 50% RH), cured at 60 °C for 18 hrs, then moist cured at 23 °C
	H6/M	After 4 hr delay under standard conditions (23 °C and 50% RH), cured at 60 °C for 14 hrs, returned to standard conditions for 6 hrs, then moist cured at 23 °C
P/P PLANT HEAT	**H7/M**	After 2 to 4 hr delay next to beams under tarp, steam cured to a peak of 60 to 65 °C for roughly 12 hrs (temperature climbing at a maximum rate of 22 °C/hr), remaining under tarp for another 2 to 6 hrs (until temperature under tarp fell to within 10 °C of outside air and labor force arrived), then moist cured at 23 °C

$T(°C) = 5/9[T(°F) - 32]$

The various curing schemes, with the exception of H2/A, differed only during the initial 24 hrs. After 24 hrs, cylinders and beams were moist cured (underwater) at a temperature of 23 °C (73.4 °F) until tested while prisms were cured at 23 °C (73.4 °F) and 50% RH.

Heat curing at the lab was classified as either moderate or intense based on peak temperature. In both cases, the procedures were similar (except for H4/M). After casting, and in most cases after a delay period of 3 to 6 hrs to allow concrete to reach initial set, specimens were placed into a water bath inside a tank and immersed up to the mold's rim. The tank was covered and encased with insulating material. The temperature of the water bath was regulated with a heating element. Under moderate heat curing (H1/M, H2/M, H2/A and H3/M), the bath temperature was maintained at 42 °C (108 °F) or 30 °C (86 °F). With intense heat curing (H5/M and H6/M), the bath temperature was maintained at 60 °C (140 °F). Another method (H4/M) involved generating steam by boiling a pot of water inside the tank with the temperature reaching 71 °C (160 °F).

When batching moved to a precast/prestressed concrete plant, some test specimens were simultaneously heat cured with production beams under a tarp (H7/M). To make this possible, trial batching at the plant usually began immediately after a set of beams was finished. Test specimens were placed on the edge of the beam's form.

3.6.2.4. Testing Schedule and Procedures

The testing schedule for each of the four phases of the research is presented in Table 3.19. The *Cement Study* and *Aggregate Study* had more comprehensive testing schedules than the *Mixture Proportion Study* and *Plant Demonstration*. In all phases of the research, as portrayed in Table 3.19, fresh concrete properties and compressive strength at 1 day, 28 days and 56 days were systematically tested.

Fresh concrete properties (slump, unit weight, air content, and temperature) were determined regularly and measured within minutes after discharge from the mixer. The slump test is a measure of consistency and provides an indication of workability. Workability was described subjectively with terms like "sticky," "rocky" or "creamy." (These are not standard descriptions.) Air content was measured by the pressure method. Time of setting was determined by the penetration resistance method. Ambient conditions (air temperature and relative humidity) were also recorded. These measures are staples of many quality assurance/quality control programs.

Concrete cylinders were cast in 100 x 200 mm (4 x 8 in) plastic molds made with a stiff rim. Infrequently, 150 x 300 mm (6 x 12 in) cylinders were molded. Flexural strength beams were cast in 152 x 152 x 508 mm (6 x 6 x 20 in) steel molds. Length change prisms were cast in 76 x 76 x 286 mm (3 x 3 x 11.25 in) steel molds.

Cylinders were tested for compressive strength using neoprene pads (85 durometer hardness) seated in steel or aluminum rings. The pads were inspected before each test and replaced if worn. (Pads typically lasted for 10 to 20 cylinder breaks.) A few times cylinders were prepared with a sulfur capping compound. Tests conformed to the procedures of ASTM C 39 and were performed within the allowed time frame at ages of 18 hrs, 24 hrs, 3 days, 7 days, 28 days and/or 56 days. Cylinders were tested in a moist condition. The ASTM loading rate, specific to each test, was observed. Two to five cylinders were tested at each age. Testing machines at both the lab and plant had adequate load capacity and stiffness for testing high strength concrete.[7] Also, bearing plate thickness was adequate, allowing uniform load transfer to the concrete cylinder.[8]

Splitting tensile strength and flexural strength (modulus of rupture) tests were performed at 28 days. Tests for elastic modulus were conducted at 1, 7 and/or 28 days. Length change measurements were initiated at 24 hrs and continued through 56 days. (Unfortunately, the length change instrument was accidently damaged during the research leaving many of the testing results in error.) Two or three specimens were typical for testing splitting tensile strength, flexural strength, elastic modulus and length change.

Table 3.19. Testing Schedule

		CEMENT STUDY	AGGREGATE STUDY	MIXTURE PROPORTION STUDY	P/P PLANT BATCHING *HPC Demonstration*
FRESH CONCRETE PROPERTIES		●	●	●	●
TIME OF SETTING		○			
HEAT CURING				○	●
COMPRESSIVE STRENGTH	18 hrs			○	○
COMPRESSIVE STRENGTH	24 hrs	●	●	●	●
COMPRESSIVE STRENGTH	3 days	●	●		
COMPRESSIVE STRENGTH	7 days	●	●	○	
COMPRESSIVE STRENGTH	28 days	●	●	●	●
COMPRESSIVE STRENGTH	56 days	●	●	●	●
COMPRESSIVE STRENGTH	Alternate cylinder size and/or preparation			○	○
SPLITTING TENSILE STRENGTH	28 days	●	●		
FLEXURAL STRENGTH (MOR)	28 days	○	●		○
ELASTIC MODULUS	1, 7, and/or 28 days	●	●	○	○
LENGTH CHANGE	Up to 56 days	●		○	○

● Main objective — systematically tested

○ Secondary objective — tested at irregular intervals

[1] ACI 211.4, "Guide for Selecting Proportions for High-Strength Concrete with Portland Cement and Fly Ash," *ACI Manual of Concrete Practice*, Part 1, American Concrete Institute, 1997.
[2] ACI 363, "State-of-the-Art Report on High Strength Concrete," *ACI Manual of Concrete Practice*, Part 1, American Concrete Institute, 1997.
[3] American Society for Testing and Materials, *Annual Book of ASTM Standards*, Vols. 4.01 and 4.02, 1995.
[4] ACI 318, *Building Code Requirements for Structural Concrete and Commentary*, American Concrete Institute, 1999.
[5] Neville, A., "What Everyone Who is 'in' Concrete Should Know About Concrete," *Concrete International*, Vol. 21, No. 4, April 1999, pp. 57-61.
[6] Zia, P. and Hillmann, R. S., "Development of High Early Strength Concrete for Prestressed Concrete Applications," *North Carolina Department of Transportation in cooperation with the Federal Highway Administration*, June 1995.
[7] ACI 363.2, *Guide to Quality Control and Testing of High-Strength Concrete*, American Concrete Institute, 1998.
[8] Burg, R. G., Caldarone, M. A., Detwiler, G., Jansen, D. C. and Willems, T. J., "Compression Testing of HSC: Latest Technology," *Concrete International*, Vol. 21, No. 8, August 1999, pp. 67-76.

4. Comparing Different Cements in HPC

4.1. Introduction

One hurdle to widespread adoption of HPC technology is the unknown suitability of locally available constituent materials.[1] A study was performed to determine the suitability of cements from Oklahoma and neighboring states for production of HPC. Different cements can make concrete with vastly different strength development characteristics because of differences in chemical composition and fineness.[2] Selection of the type and source of cement is one of the most important decisions in HPC production.[3,4]

The *Cement Study* described in this chapter was the first phase of the research program. Following identification of suitable cements and coarse aggregates, HPC mixture proportions were developed and HPC technology was demonstrated at a precast/prestressing facility in Oklahoma.

4.2. Experimental Program

A group of eight cements was selected from Oklahoma and neighboring states Texas, Arkansas and Kansas to be representative of all cements available within the region. As presented in Table 3.2, the group included several different types of cement from three manufacturers and six plants, identified as C1 through C8. These cements are currently in use or could readily be used in Oklahoma. There were four ASTM[5] C 150 *Type I's*, two *Type I/II's*, one *Type II* and one *Type III*.

The eight cements were evaluated in HPC mixtures to determine their suitability for HPC production. Criteria for comparing the mixtures included:

- Fresh concrete slump
- Time of set
- Compressive strength at ages of 1, 3, 7, 28 and 56 days
- Splitting tensile strength at 28 days
- Modulus of elasticity at 28 days

These criteria are important in the design and manufacture of precast/prestressed concrete bridge beams.

The cement chemical composition as provided by the manufacturers and Blaine fineness for each of the cements are reported in Table 4.1.

Table 4.1. Cement Chemical Composition & Fineness

CEMENT IDENTIFICATION & TYPE		C1 *Type I*	C2 *Type I/II*	C3 *Type I*	C4 *Type I*	C5 *Type I/II*	C6 *Type I*	C7 *Type II*	C8 *Type III*
SiO_2	%	20.5	20.7	20.7	20.6	21.6	21.5	22.4	19.7
Al_2O_3	%	5.6	4.9	6.0	6.5	4.9	4.9	3.9	5.8
Fe_2O_3	%	2.5	4.6	2.7	2.3	3.2	2.5	3.9	2.7
CaO	%	65.0	64.4	—	66.1	63.7	65.1	64.8	63.0
MgO	%	1.6	1.5	1.0	1.4	2.2	2.2	1.7	0.9
SO_3	%	2.8	2.2	2.9	2.6	2.4	2.7	2.0	4.2
Alkali	%	0.85	0.53	—	0.32	0.50	—	—	0.54
C_3S	%	56.5	57.6	54.4	54.1	54.0	58.0	56.0	58.2
C_2S	%	16.9	17.4	18.4	18.5	21.0	18.0	22.0	12.8
C_3A	%	10.8	5.2	11.4	12.4	8.0	9.0	4.0	10.7
C_4AF	%	7.2	13.3	—	8.6	10.0	8.0	12.0	—
Blaine fineness, m^2/kg		351	348	339	360	361	369	363	549

All cements except C1 (*Type I*) contained less than 0.60% alkali, qualifying as low alkali cements. C8 (*Type III*) is distinguished by high fineness, high tricalcium silicate (C_3S), a compound that is largely accountable for concrete set and early strength gain, and low dicalcium silicate (C_2S), a compound which mainly contributes to strength development at ages beyond one week. C2 (*Type I/II*), C5 (*Type I/II*) and C7 (*Type II*) had reduced amounts of tricalcium aluminate (C_3A), a compound that emits a significant amount of heat during the first few days of hydration.

Each cement was tested in two HPC mixtures with discrete compressive strength levels, called Class 1 and Class 2. Class 1 mixtures were designed to achieve about 60 MPa (8,700 psi) at 28 days. Class 2 mixtures were designed to achieve roughly 75 MPa (10,880 psi) at 28 days. The two mixture classes were established at these compressive strength levels because HPC strength could pragmatically be specified in the range between 60 and 75 MPa (8,700 and 10,880 psi) in Oklahoma. Mixture proportions, presented in Table 4.2, were designed in consultation with personnel at a local precast/prestressed concrete company and calculated by the absolute volume method. Class 1 mixtures contained about 7 sacks of cement at a water/cementitious material (w/cm) ratio of 0.406. Class 2 mixtures contained about $8^1/_4$ sacks of cement at a w/cm of 0.346. Supplementary cementitious materials, although often utilized in HPC, were excluded from these mixtures to isolate the performance of the cement. Crushed limestone coarse aggregate was used for both mixture classes. Limestone is the most abundantly available aggregate in Oklahoma. Class 1 mixtures contained limestone meeting the No. 67 grading requirements of ASTM C 33 with a nominal maximum size of 19 mm ($^3/_4$ in). Class 2 limestone met a No. 8 gradation with a nominal maximum size of 10 mm ($^3/_8$ in). Smaller size coarse aggregates possess more surface area for a given aggregate content, which improves aggregate/paste bond and enhances strength potential.[2,3] Lower w/cm and smaller size coarse aggregate were expected to enhance strength of the Class 2 mixtures relative to the Class 1 mixtures. Both mixture classes contained an ASTM C 494 *Type B/D* set retarding/water reducing admixture and a *Type A/F* superplasticizer.

**Table 4.2. Cement Study —
Mixture Proportions (SSD Aggregates)**

		CLASS 1	CLASS 2
Cement	kg/m^3	385.5	462.6
Coarse Aggregate (CA)	kg/m^3	1,052.8[a]	1,008.3[b]
Fine Aggregate (FA)[c]	kg/m^3	794.8	753.3
Mixing Water	kg/m^3	154.2	157.2
SR/WR Admixture[d]	L/m^3	0.77	0.89
HRWR Admixture[e]	L/m^3	3.02	4.18
w/cm		**0.406**	**0.346**
CA Content	%	64.9	62.1
CA/FA		1.32	1.34
Calculated Air Content	%	2.31	2.68
Calculated Unit Weight	kg/m^3	2,392	2,387

[a] Crushed limestone meeting the No. 67 grading requirements of ASTM C 33 and having a bulk specific gravity of 2.67, absorption of 1.2% and dry rodded unit weight of 1,621 kg/m^3

[b] Crushed limestone meeting the No. 8 grading requirements of ASTM C 33 and having a bulk specific gravity of 2.67, absorption of 1.2% and dry rodded unit weight of 1,623 kg/m^3

[c] Natural river sand having a bulk specific gravity of 2.63, absorption of 0.7% and fineness modulus of 2.47

[d] ASTM C 494 *Type B/D* set retarding/water reducing admixture

[e] ASTM C 494 *Type A/F* superplasticizer

1 kg/m^3 = 1.686 lb/yd^3, 1 L/m^3 = 25.85 $floz/yd^3$, 1 kg/m^3 = 0.06243 lb/ft^3

4.3. Experimental Procedures

Work was performed in the laboratory. Batching and testing procedures conformed to the applicable ASTM standards except mixing time, which was often extended beyond the duration specified in ASTM C 192. Mixing continued until the concrete appeared uniform.[6] Batch weights were adjusted for aggregate moisture.

Fresh conrete slump was measured in conformance with ASTM C 143. Slump was measured initially after combining all materials except superplasticizer. Final slump was measured after introducing superplasticizer, additional mixing and discharge. ASTM C 403 time of setting was measured by the penetration resistance method. Unit weight, air content, and fresh concrete temperature were also measured.

Concrete cylinders for determining compressive strength, splitting tensile strength and elastic modulus were cast in 100 x 200 mm (4 x 8 in) plastic molds and consolidated by rodding. Cylinders were cured at 23 °C (73.4 °F) and 50% relative humidity during the initial 24 hrs. Molds were removed at 24 hrs and thereafter, until tested, cylinders were moist cured (under water) as specified by ASTM C 192 at a temperature of 23 °C (73.4 °F).

Cylinders were tested for compressive strength using neoprene pads seated in steel or aluminum rings. Tests followed the procedures of ASTM C 39 and were performed at ages of 1, 3, 7, 28 and 56 days. Typically, three cylinders were tested at each age. ASTM C 496 splitting tensile strength and ASTM C 469 elastic modulus tests were performed at 28 days. Typically, three cylinders were tested for splitting tensile strength and two cylinders for modulus of elasticity.

4.4. Experimental Results

A summary of the fresh concrete testing results, specifically slump and set time, is presented in Table 4.3. A summary of the testing results on hardened concrete, specifically compressive strength, splitting tensile strength and elastic modulus, is presented in Table 4.4. The average compressive strength at 28 days for Class 1 mixtures was 61.6 MPa (8,930 psi). The average compressive strength at 28 days for Class 2 mixtures was 76.5 MPa (11,090 psi). These values were both near the targeted levels.

Most mixtures were batched between three and five times to increase accuracy of the final results. The results reported in Tables 4.3 and 4.4 represent an average of the individual batch results. The individual batch results were determined as an average of the results of the test cylinders. Unfortunately, manufacture of C7 was discontinued after the first round of batching; mixtures containing C7 were batched only once.

Also, time of setting was measured on only one batch. Complete testing results of the *Cement Study* are included in Appendix D.

The coefficient of variation (CV) is one way to assess the effect of cement characteristics on concrete performance. The CV is the standard deviation expressed as a percent of the average result. The average result and the CV of the performance criteria was calculated in Table 4.4. A larger CV indicates that the choice of cement had a larger effect on concrete performance. The CV of compressive strength results at 28 days was 3.8% for Class 1 and 5.3% for Class 2. With splitting tensile strength results at 28 days, the CV was 4.2% and 7.6% for Class 1 and Class 2 mixtures, respectively. Likewise, modulus of elasticity results at 28 days yielded 2.4% and 2.2%. Based on the CVs, it can be stated that differences among cements influenced splitting tensile strength more significantly than compressive strength and compressive strength more significantly than modulus of elasticity at an age of 28 days. In agreement, one study found that different types and brands of cement had more effect on compressive strength than on the modulus of elasticity of HPC.[7]

Table 4.3. Summary of Testing Results — Fresh Concrete

			C1 *Type I*	C2 *Type I/II*	C3 *Type I*	C4 *Type I*	C5 *Type I/II*	C6 *Type I*	C7 *Type II*	C8 *Type III*	AVG
CLASS 1	No. of Batches		4	4	5	3	3	3	1	3	
	Initial Slump	mm	40	40	30	30	40	20	60	10	**30**
	Final Slump	mm	230	270	220	260	240	180	—	120	**220**
	Initial Set	h:m	8:50	9:50	11:10	11:50	—	—	17:30	6:50	**11:00**
	Final Set	h:m	9:40	10:30	12:20	13:10	—	—	19:00	7:40	**12:10**
CLASS 2	No. of Batches		3	3	4	3	3	3	1	5	
	Initial Slump	mm	0	20	0	0	0	10	10	0	**5**
	Final Slump	mm	250	260	250	230	260	230	—	220	**240**
	Initial Set	h:m	11:30	30:00	11:30	—	—	10:40	19:20	8:20	**13:10**
	Final Set	h:m	12:50	31:40	13:40	—	—	11:30	20:40	9:10	**14:20**

25.4 mm = 1 in

Table 4.4. Summary of Testing Results — Hardened Concrete

				C1 *Type I*	C2 *Type I/II*	C3 *Type I*	C4 *Type I*	C5 *Type I/II*	C6 *Type I*	C7 *Type II*	C8 *Type III*	AVG	CV (%)
CLASS 1	No. of Batches			4	4	5	3	3	3	1	3		
	Compressive Strength	1 d	MPa	23.4	5.5	22.3	20.1	21.3	15.3	16.8	*39.9*	**20.6**	47
		3 d	MPa	41.7	36.9	43.6	46.0	44.1	42.8	41.6	*50.4*	**43.4**	8.9
		7 d	MPa	48.2	49.6	52.5	54.5	50.3	51.8	50.4	*57.3*	**51.8**	5.7
		28 d	MPa	57.1	61.1	61.0	63.3	61.8	62.3	60.8	*65.3*	**61.6**	3.8
		56 d	MPa	61.1	67.6	65.8	*67.9*	67.5	65.2	64.3	—	**65.6**	3.7
	Spl. Tensile Strength	28 d	MPa	4.20	4.45	4.67	4.36	4.45	4.29	4.50	*4.76*	**4.46**	4.2
	Elastic Modulus	28 d	GPa	41.4	42.1	43.5	*44.3*	42.8	42.2	41.4	42.7	**42.6**	2.3
CLASS 2	No. of Batches			3	3	4	3	3	3	1	5		
	Compressive Strength	1 d	MPa	32.1	0.0	36.9	22.2	12.4	22.4	10.0	*52.5*	**23.6**	71
		3 d	MPa	—	48.5	59.9	56.3	57.8	50.7	47.0	*65.4*	**55.1**	12
		7 d	MPa	61.5	62.7	69.0	64.9	67.0	61.9	60.7	*72.1*	**65.0**	6.3
		28 d	MPa	71.8	76.5	81.5	77.1	77.6	73.7	71.3	*82.2*	**76.5**	5.3
		56 d	MPa	77.0	81.5	86.7	80.2	81.9	79.0	73.7	*87.3*	**80.9**	5.7
	Spl. Tensile Strength	28 d	MPa	5.04	4.88	5.12	5.25	4.94	4.39	4.76	*5.70*	**5.01**	7.6
	Elastic Modulus	28 d	GPa	41.5	42.6	42.8	43.7	*43.8*	41.4	41.8	42.5	**42.5**	2.2

Best marks are in italics
1 MPa = 145 psi, 1 GPa = 145 ksi

4.5. Analysis and Discussion of Results

4.5.1. Slump and Time of Setting

Measured prior to addition of superplasticizer, the initial slumps observed were evidence of the low w/cm's of these mixtures. Initial slumps were an average 30 mm ($1^1/_4$ in) for Class 1 mixtures and 5 mm ($^1/_4$ in) for Class 2 mixtures. Mixtures containing C8 (*Type III*) commonly had zero initial slump due to the high fineness of the cement.

After addition of superplasticizer, final slumps generally exceeded 200 mm (8 in) for both mixture classes. An initial slump of 25 to 50 mm (1 to 2 in) is recommended prior to addition of a superplasticizer[3,8] however, in this instance, the superplasticizer was powerful enough to overcome the small initial slumps.

It was observed that the addition rate of superplasticizer was satisfactory for both Class 1 and Class 2 mixtures containing C8 (*Type III*) but excessive for the other mixtures with *Type I, I/II* or *II* cements. As presented in Table 4.2, the addition rate of superplasticizer was 3.0 L/m^3 (78 floz/yd^3) for Class 1 mixtures and 4.2 L/m^3 (108 floz/yd^3) for Class 2 mixtures. In some cases, the addition of superplasticizer temporarily caused segregation of the coarse aggregate and retarded the time to set.

On average, time to reach final set was about 12 hrs in Class 1 and 14 hrs in Class 2. A Class 2 mixture containing C2 (*Type I/II*) experienced a delay in setting beyond 24 hrs (which prevented strength testing at 1 day). Mixtures containing C7 (*Type II*) also experienced a substantial delay in setting, as presented in Table 4.3. Mixtures containing C8 reached final set the quickest, 8 hrs in Class 1 and 9 hrs in Class 2. In the interest of this study, a uniform addition rate of chemical admixtures was maintained for all mixtures, but in practice the addition rate and effectiveness of each chemical admixture must be evaluated for different cements or cementitious combinations under conditions to be expected at the job site.

4.5.2. Compressive Strength

Compressive strength results are illustrated in Figures 4.1, 4.2, 4.3, 4.4 and 4.5 for ages of 1, 3, 7, 28 and 56 days, respectively. Mixtures with C8 (*Type III*) achieved the best compressive strength in both classes at all ages, most extensively at early ages. The chemical composition and fineness of C8 produced rapid strength gain. At 1 day in Class 1, C1 (*Type I*) was second best and C3 (*Type I*) was third while in Class 2, C3 was second best and C1 was third. In both classes at 1 day, mixtures with C2 (*Type I/II*) achieved the lowest compressive strength. At 28 days in Class 1, C4 (*Type I*) was second best and C6 (*Type I*) was third while in Class 2, C3 was second best and C5 (*Type I/II*) was third. At 28 days, C1 performed poorest in Class 1 and C7 (*Type II*) performed poorest in Class 2. There were some inconsistencies in the results. For example, at 28 days C3 was sixth best in Class 1 and second in Class 2.

Modest differences in compressive strength were observed between mixtures with C1 (*Type I*) and C2 (*Type I/II*), cements of the same manufacturer and plant location but different in type. As displayed in Table 4.1, C2 differed from C1 principally by reduced C_3A content. Mixtures with C2 experienced a delay in setting time that impaired early strength development. Eventually, however, the strength of mixtures with C2 surpassed that with C1.

When comparing mixtures with C3 (*Type I*) and C4 (*Type I*), cements of the same manufacturer and type but different plant location, the results were inconclusive as to which cement produced the highest compressive strength. The two cements were very similar in chemical composition; C4 had slightly higher fineness. C3 produced higher strength in Class 2 mixtures while C4, after the first day, had an edge in Class 1.

With the proximity of many of the compressive strength results, it is necessary to assess whether the observed differences were statistically significant. Confidence intervals are presented in Table 4.5 for both Class 1 and Class 2 mixtures at ages of 1, 28 and 56 days. The confidence intervals were constructed using the test results of the individual cylinders. With 95% certainty, the confidence intervals enclose the true compressive strength. The confidence interval is

$$\bar{f}_c \pm t \cdot \left(\frac{s}{\sqrt{n}} \right)$$

where $\bar{f}_c$ is the average compressive strength value, t is the statistic applicable to small samples, s is the standard deviation, and n is the total number of test cylinders.[9] If the confidence intervals are distinct from one another, then it is likely that the differences observed between the mixtures are statistically significant. Conversely, if the confidence intervals share values, then it is likely that the differences observed between the mixtures are within the experimental variability and are statistically insignificant.

In both Class 1 and Class 2 mixtures at 1 day, C8 (*Type III*) was distinctly best while C2 (*Type I/II*) was distinctly poorest. The other cements produced compressive strength results that were statistically alike at 1 day. At 28 and 56 days in both Class 1 and Class 2, the differences observed between the mixtures were statistically insignificant.

Figure 4.1. Compressive Strength (1 day)

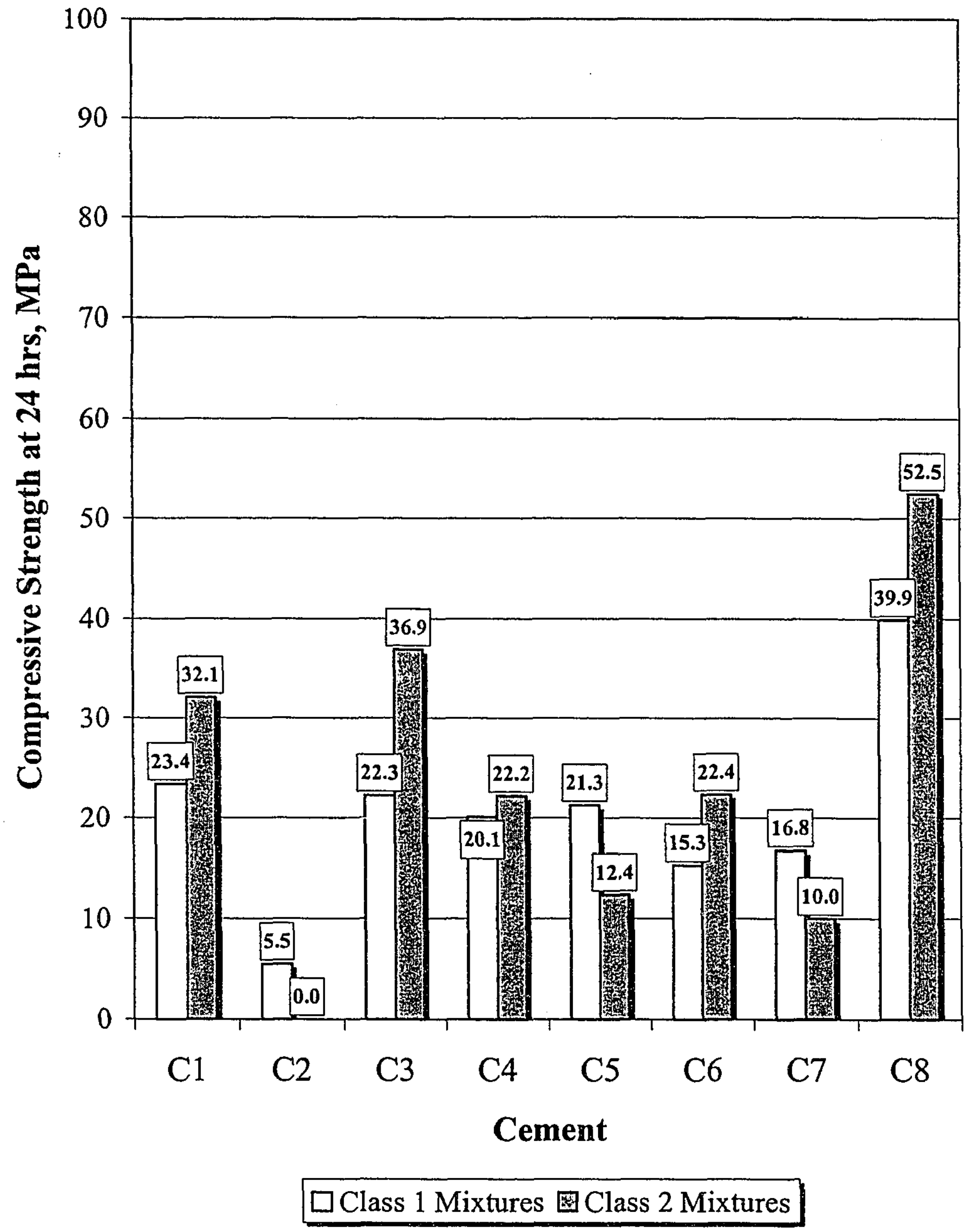


Figure 4.2. Compressive Strength (3 days)

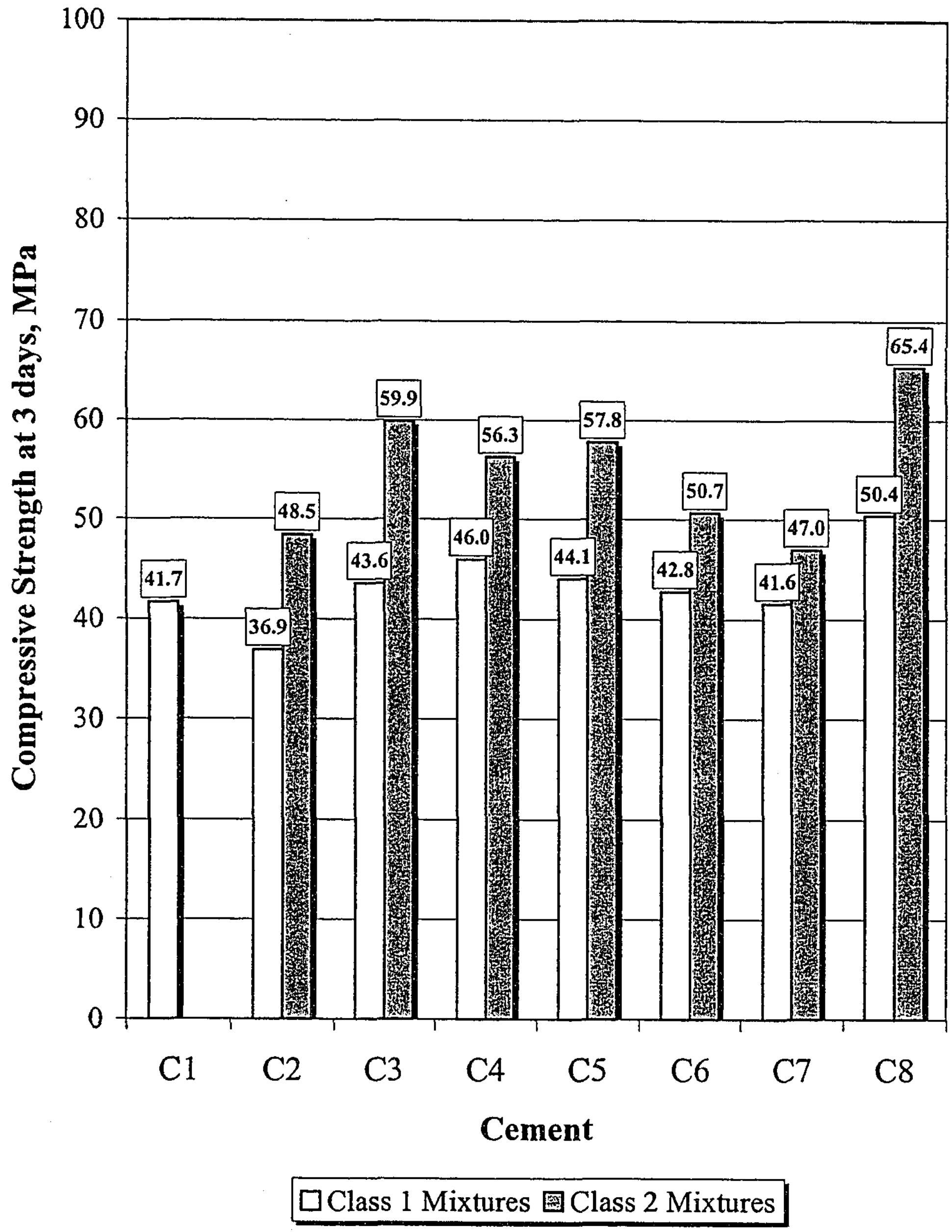


Figure 4.3. Compressive Strength (7 days)

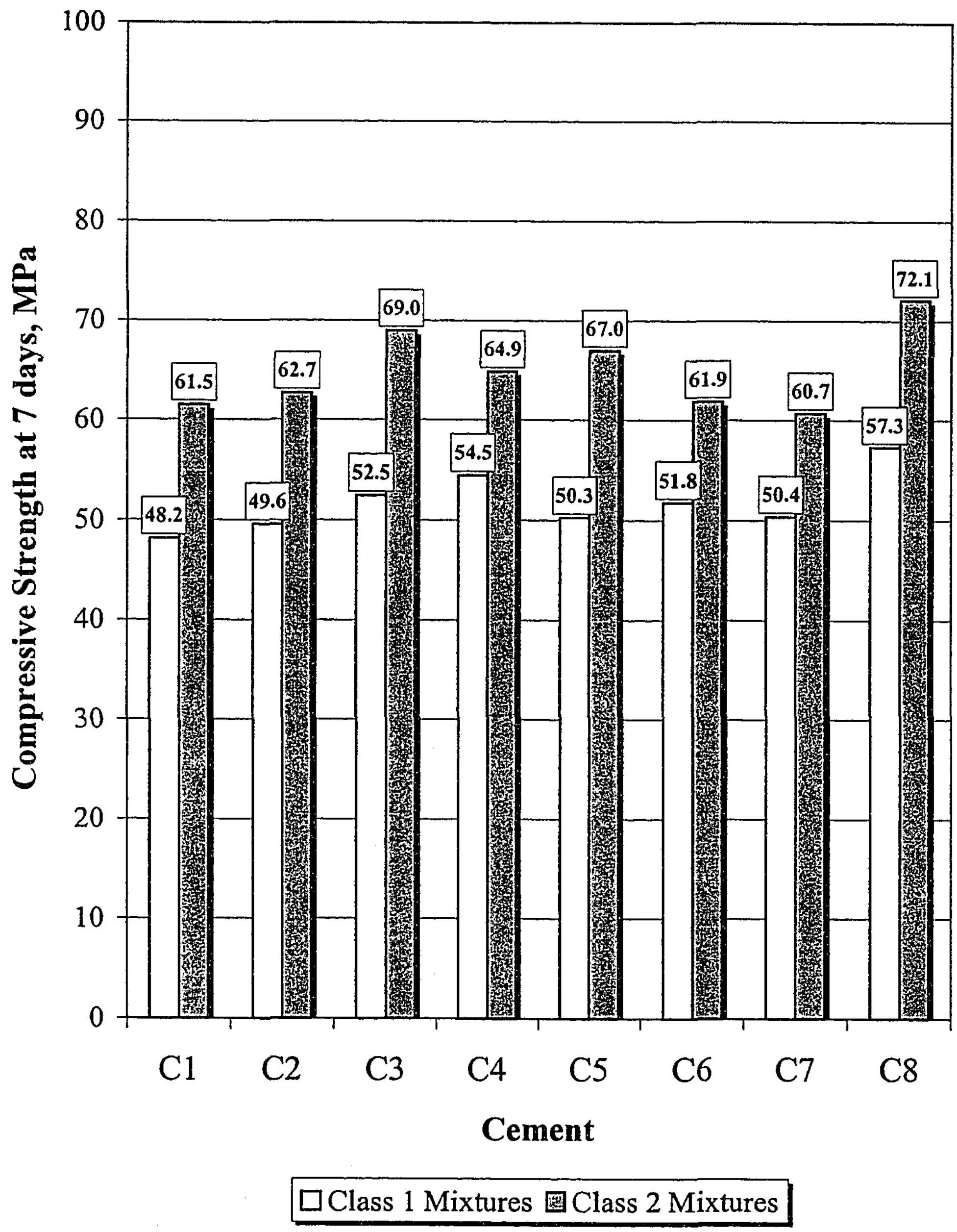


Figure 4.4. Compressive Strength (28 days)

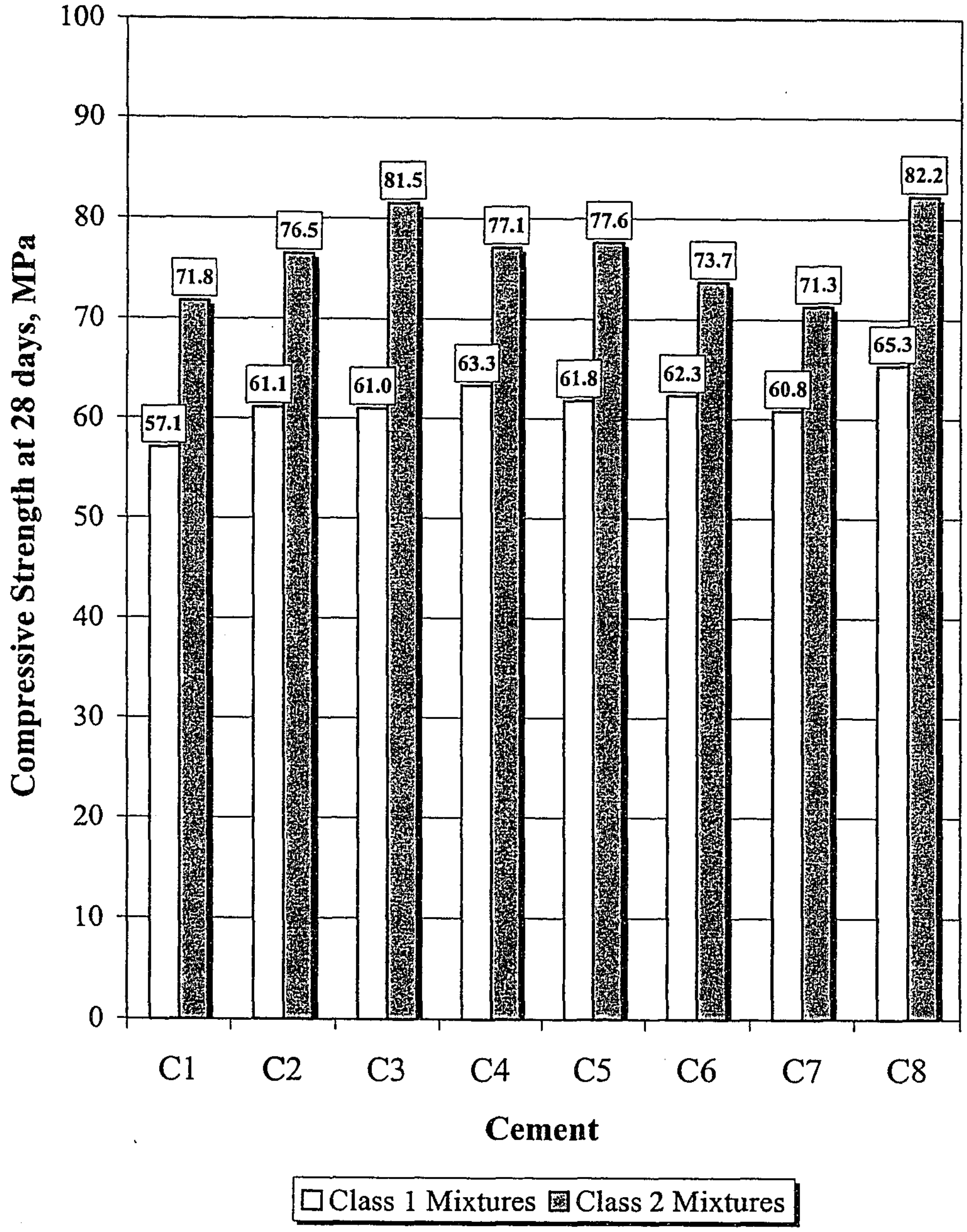


Figure 4.5. Compressive Strength (56 days)

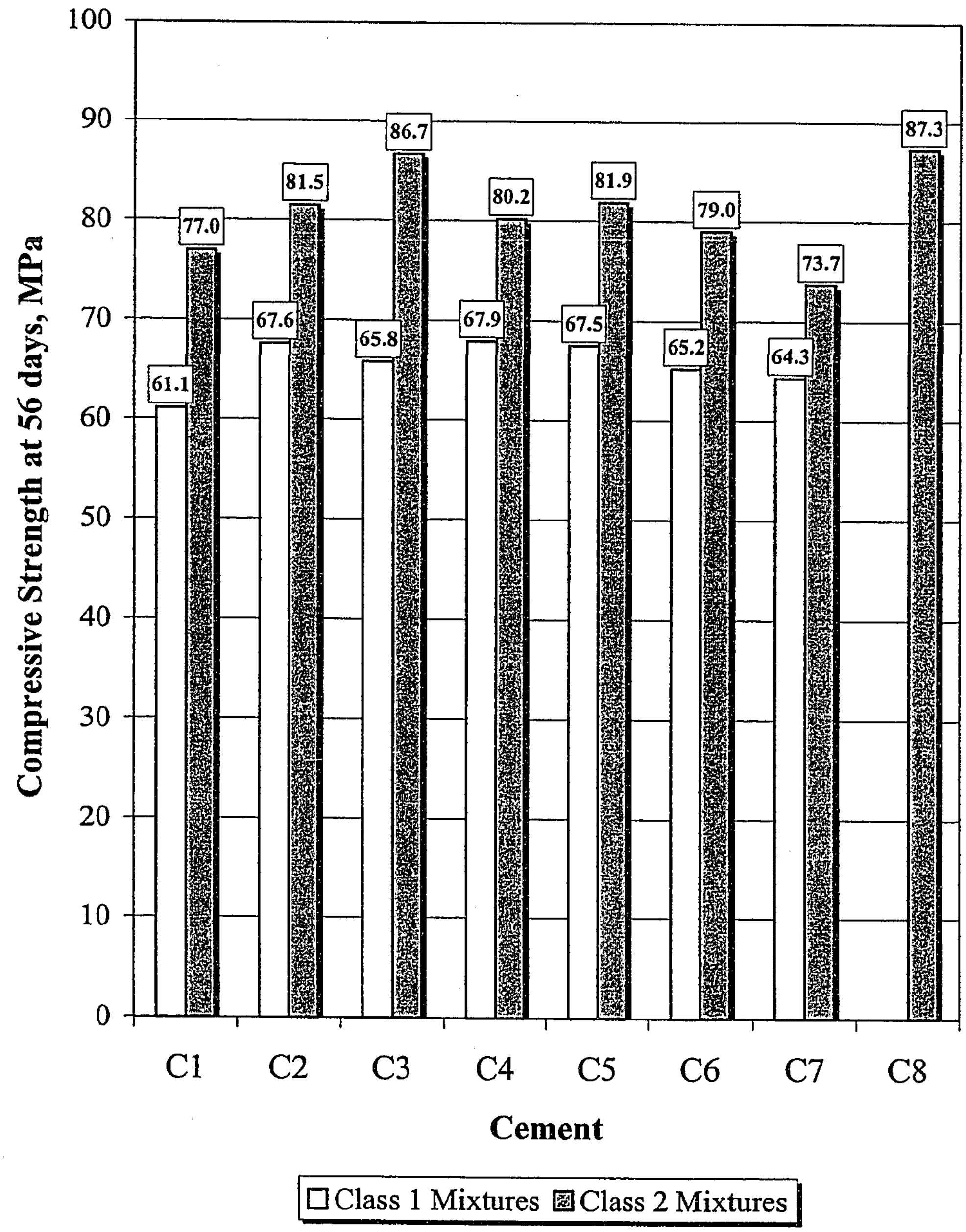


Table 4.5. Confidence Intervals for Assessing Statistical Significance

			C1	C2	C3	C4	C5	C6	C7	C8
CLASS 1	Compressive Strength at 1 d	MPa	21.1	5.0	20.1	18.1	19.2	13.8	15.1	35.9
		MPa	25.7	6.1	24.5	22.1	23.4	16.8	18.5	43.9
	Compressive Strength at 28 d	MPa	51.4	55.0	54.9	57.0	55.6	56.1	54.7	58.8
		MPa	62.8	67.2	67.1	69.6	68.0	68.5	66.9	71.8
	Compressive Strength at 56 d	MPa	55.0	60.8	59.2	61.1	60.8	58.7	57.9	—
		MPa	67.2	74.4	72.4	74.7	74.3	71.7	70.7	—
CLASS 2	Compressive Strength at 1 d	MPa	28.9	0.0	33.2	20.0	11.2	20.2	9.0	47.3
		MPa	35.3	0.0	40.6	24.4	13.6	24.6	11.0	57.8
	Compressive Strength at 28 d	MPa	64.6	68.9	73.4	69.4	69.8	66.3	64.2	74.0
		MPa	79.0	84.2	89.7	84.8	85.4	81.1	78.4	90.4
	Compressive Strength at 56 d	MPa	69.3	73.4	78.0	72.2	73.7	71.1	66.3	78.6
		MPa	84.7	89.7	95.4	88.2	90.1	86.9	81.1	96.0

1 MPa = 145 psi

ACI 209 provides empirical equations for predicting compressive strength development at various ages relative to strength at 28 days.[10] Four equations were adapted to account for differences of cement type, either *Type I* or *Type III*, and curing method, either standard curing or steam curing. Standard curing was the method employed in this *Cement Study.* Steam curing is a method that accelerates early strength gain but which was not employed here. The ACI 209 equations for steam curing are included for purposes of analysis only.

- ACI 209 (*Type I* cement/standard curing): $f_c^{'}(t)/f_c^{'}(28) = t/(4.0 + 0.85t)$
- ACI 209 (*Type I* cement/steam curing): $f_c^{'}(t)/f_c^{'}(28) = t/(1.0 + 0.95t)$
- ACI 209 (*Type III* cement/standard curing): $f_c^{'}(t)/f_c^{'}(28) = t/(2.3 + 0.92t)$
- ACI 209 (*Type III* cement/steam curing): $f_c^{'}(t)/f_c^{'}(28) = t/(0.70 + 0.98t)$

In these equations, $f_c^{'}$ or, alternatively $\bar{f}_c$ is the average measured compressive strength at a specific age *t* in days. In Figures 4.6 and 4.7, results are compared with ACI 209. Average strength development of mixtures with C1, C2, C3, C4, C5, C6 and C7 (*Types I, I/II, II*) is illustrated in Figure 4.6 ACI 209 is not applicable to concrete containing *Type II* cement, but the results with *Type I/II* and *Type II* cements were included anyway. *Type II* cement typically gains strength more slowly than *Type I* cement. Still, ACI 209 (*Type I* cement/standard curing) underestimated the actual rate of strength development at 1, 3 and 7 days. Actual strength gain at these ages, on average, was between ACI 209's standard curing and steam curing predictions. Strength development of mixtures with C8 (*Type III*) is illustrated in Figure 4.7. In 1 day C8 mixtures gained about 62% of corresponding strength at 28 days. Again, ACI

209 (*Type III* cement/standard curing) underestimated the rate of early strength development. ACI 209 (*Type III* cement/steam curing) more accurately described the early strength gain of the C8 mixtures. These findings are in agreement with the findings of other studies[7,11] confirming that HPC mixtures gain strength more rapidly than conventional concrete mixtures, the basis of the ACI 209 equations.

The range of compressive strength results at each age is illustrated in Figures 4.8 and 4.9 for Class 1 and Class 2 mixtures, respectively. Maximum and minimum strengths, as well as average strength, are labeled at each age. In both mixture classes, the range of the strengths was widest at 1 day and generally narrowed over time. These results demonstrate that the choice of cement in HPC is more crucial to early strength than to strength at 28 or 56 days. However, the addition rates of superplasticizer, excessive for some of the cements, likely exaggerated the differences that were observed at 1 day.

Figure 4.6. Strength Development for C1, C2, C3, C4, C5, C6, C7 (*Types I, I/II, II*)

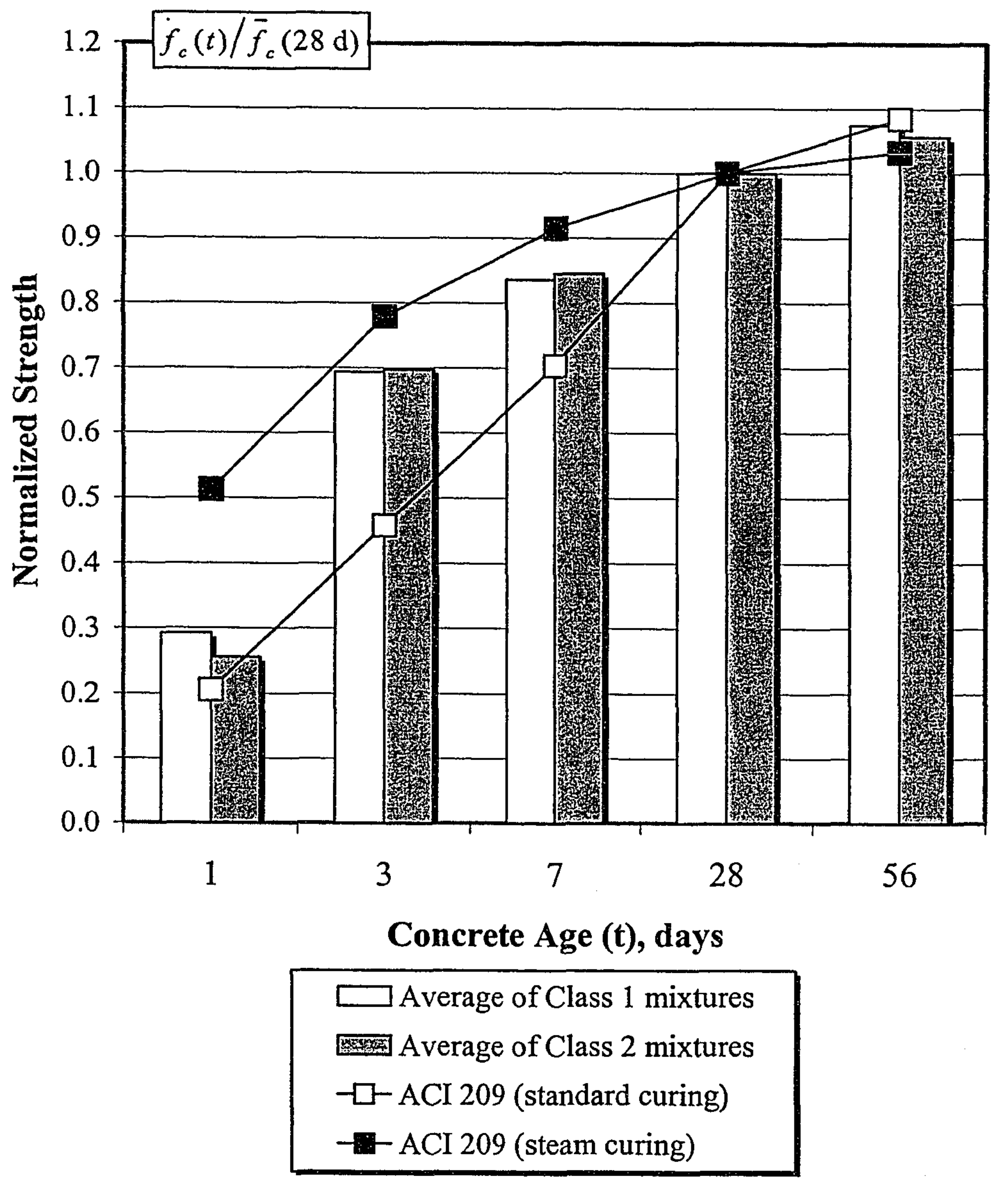


Figure 4.7. Strength Development for C8 (*Type III*)

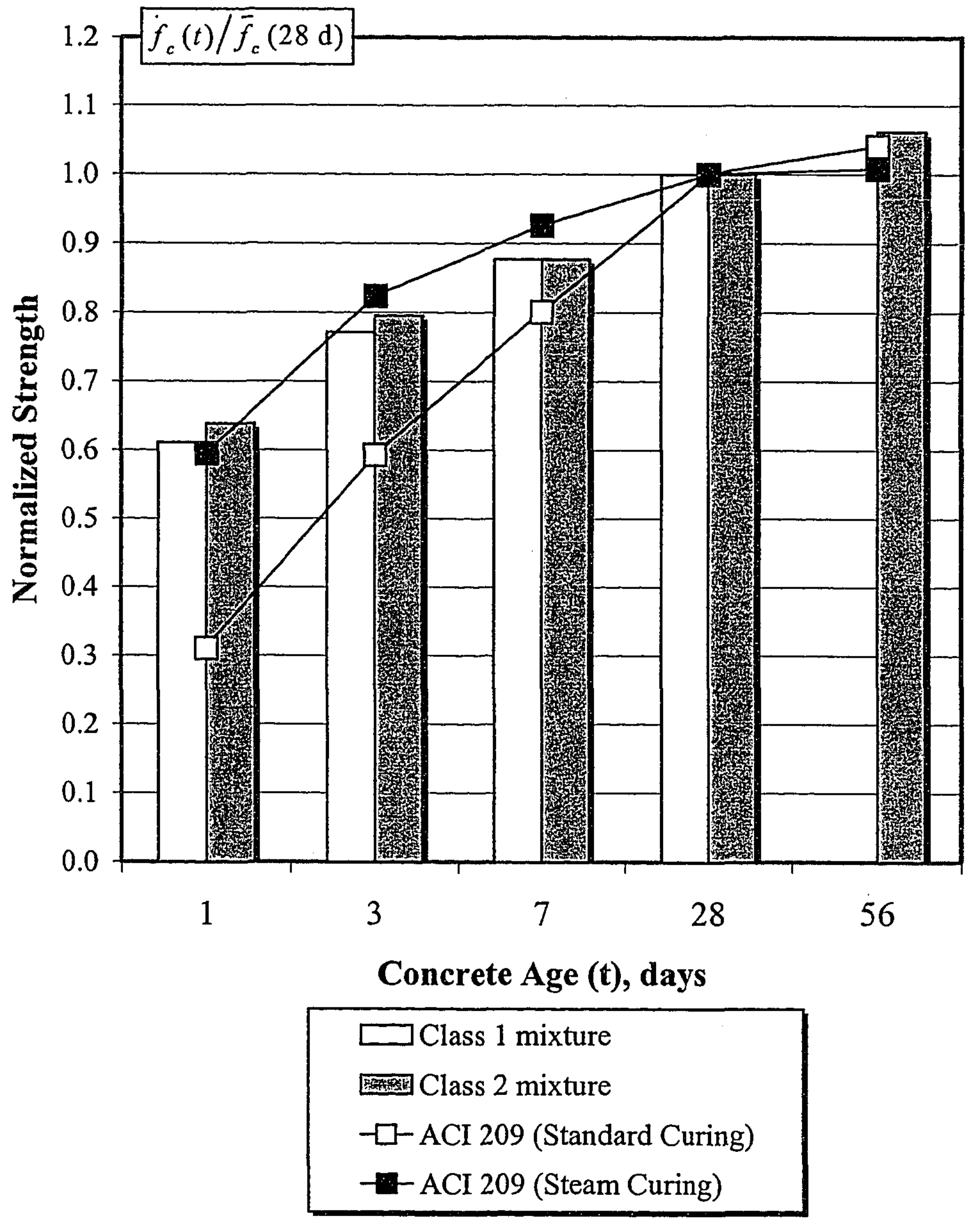


Figure 4.8. Range of Strengths/Class 1 Mixtures

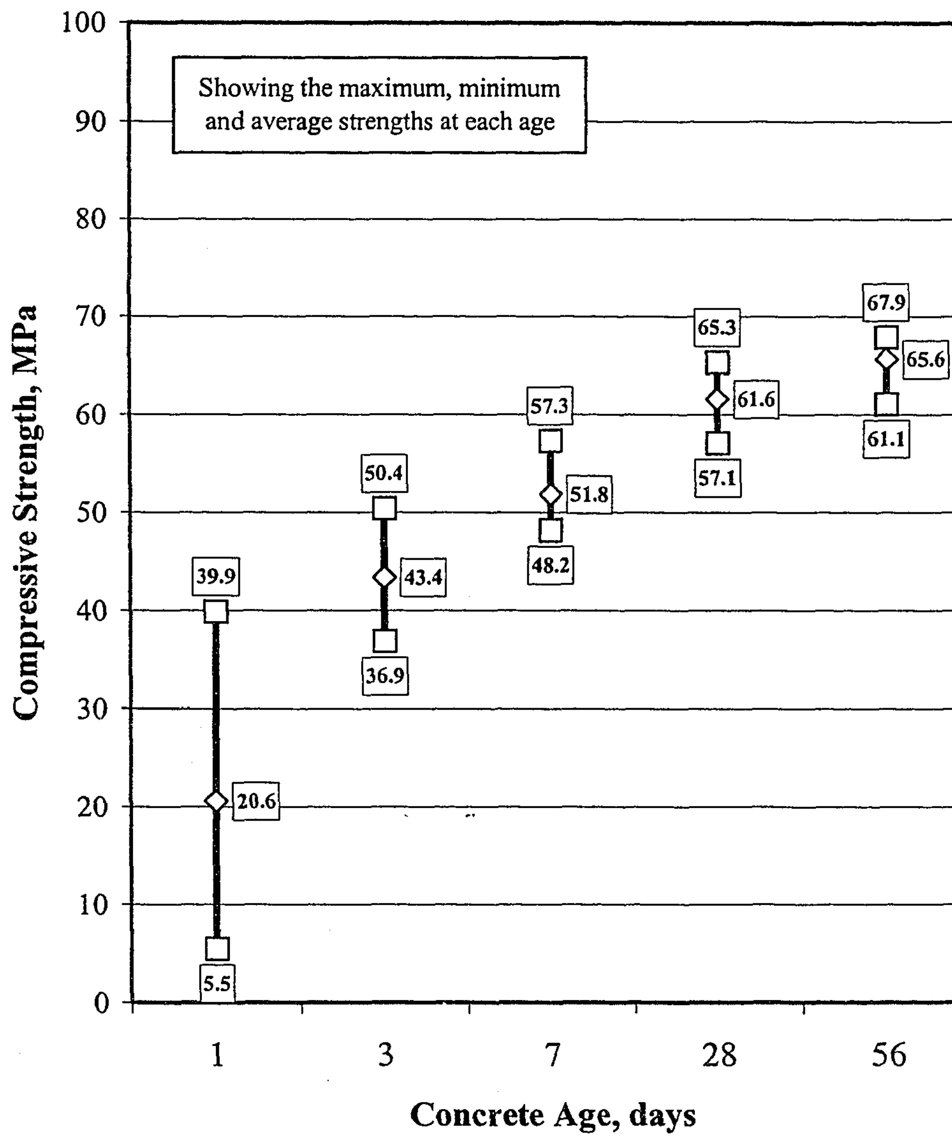
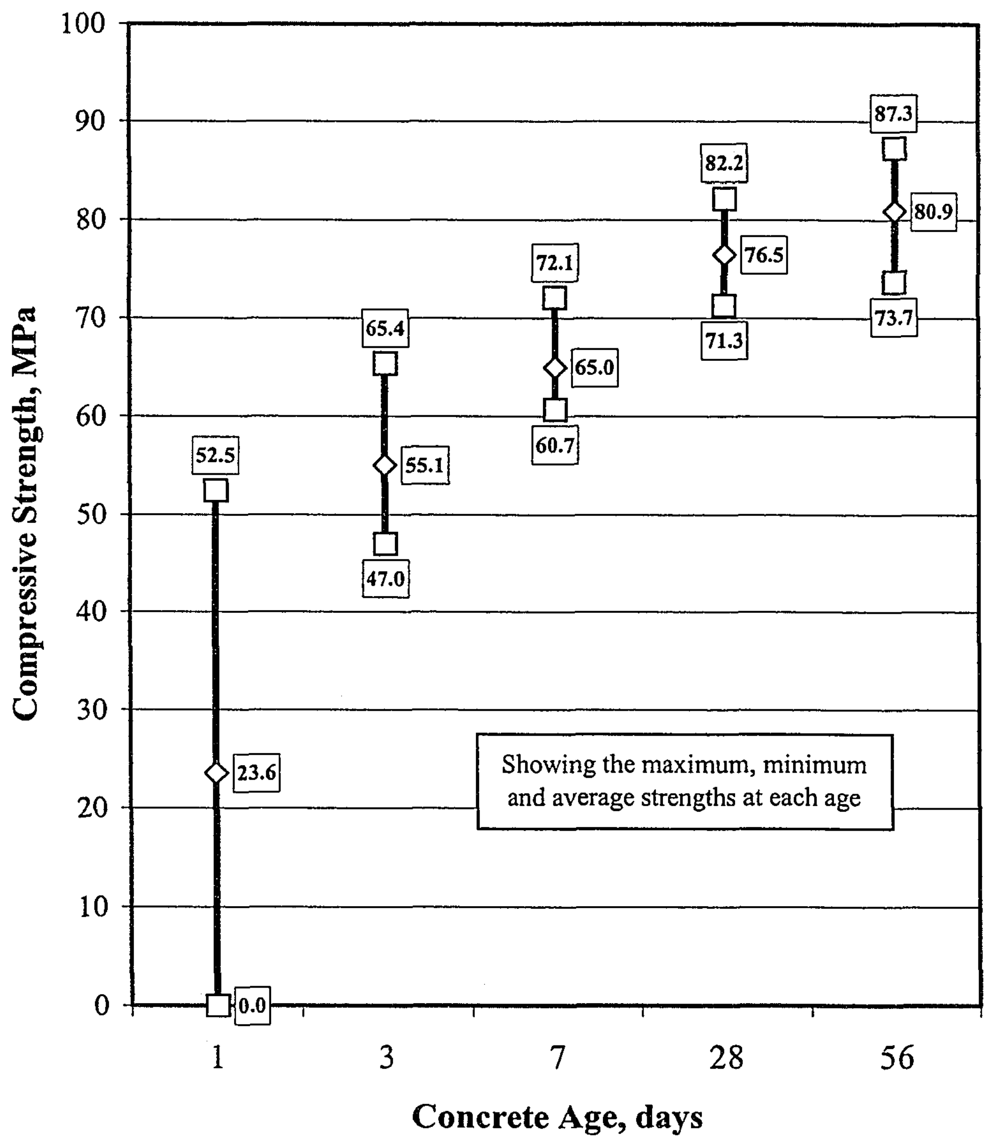


Figure 4.9. Range of Strengths/Class 2 Mixtures



4.5.3. Splitting Tensile Strength

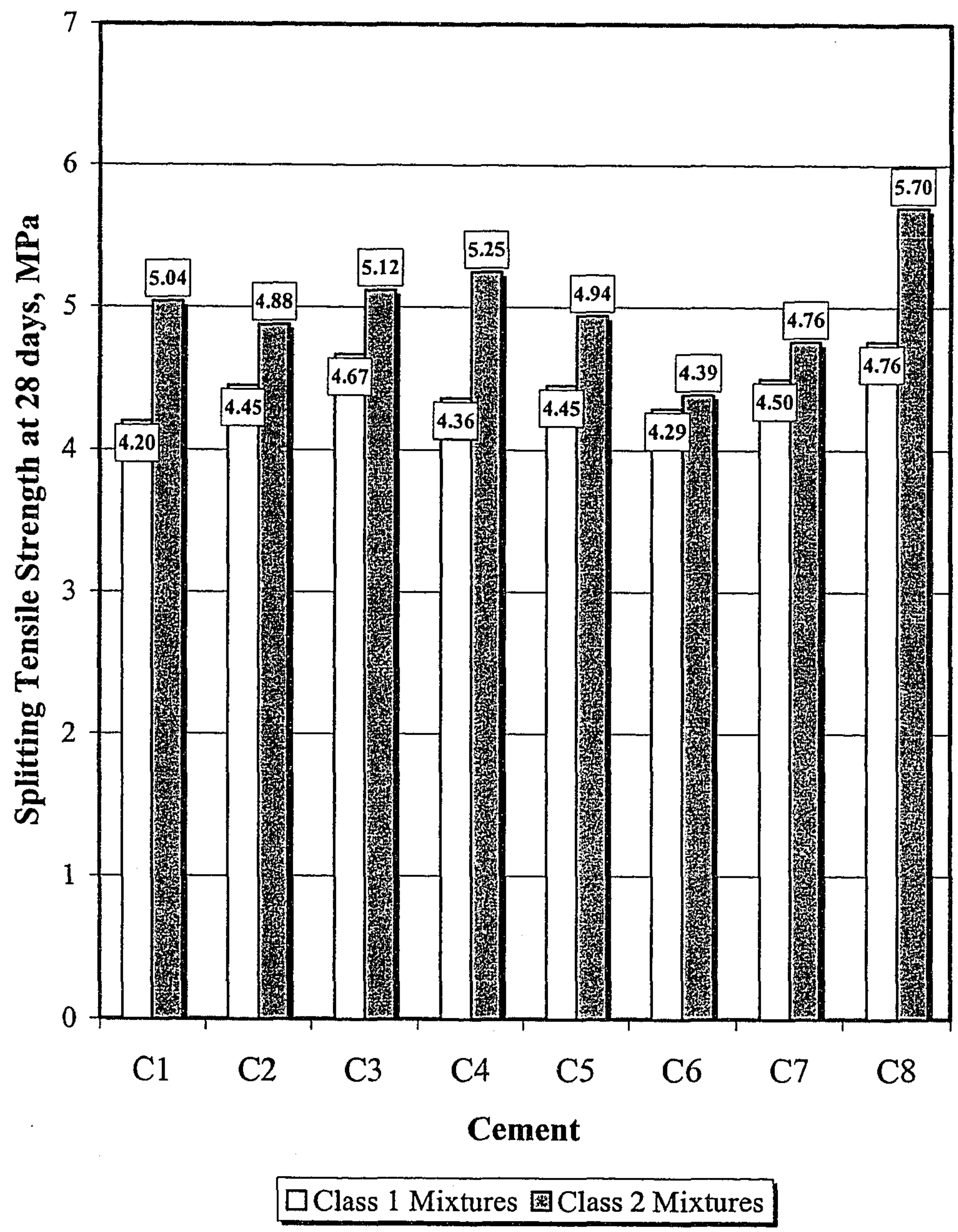
Splitting tensile strength results at 28 days are illustrated in Figure 4.10. Mixtures with C8 (*Type III*) achieved the best splitting tensile strength, 4.76 MPa (690 psi) in Class 1 and 5.70 MPa (825 psi) in Class 2. Class 1 splitting tensile strengths ranged from 4.20 to 4.76 MPa (610 to 690 psi) with an average 4.46 MPa (645 psi). Class 2 splitting tensile strengths ranged from 4.39 to 5.70 MPa (635 to 825 psi) with an average 5.01 MPa (725 psi). Splitting tensile strength, on average, measured 7.2% and 6.6% of compressive strength for Class 1 and Class 2 mixtures, respectively.

Splitting tensile strength results were compared to the ACI 363 prediction in Figure 4.11.

- ACI 363: $f_{sp}^{'} = 0.59\sqrt{f_c^{'}}$ ($f_{sp}^{'} = 7.4\sqrt{f_c^{'}}$)

Here $f_c^{'}$ or, alternatively $\bar{f}_c$ is defined as the average measured compressive strength in MPa (psi). The equation is valid for 21 < $f_c^{'}$ < 83 MPa (3,000 < $f_c^{'}$ < 12,000 psi). ACI 363 overestimated the majority of the results, however, most of the results were within ±10% of ACI 363. Additional lines representing 90% and 110% of ACI 363 are shown in Figure 4.11.

Figure 4.10 Splitting Tensile Strength



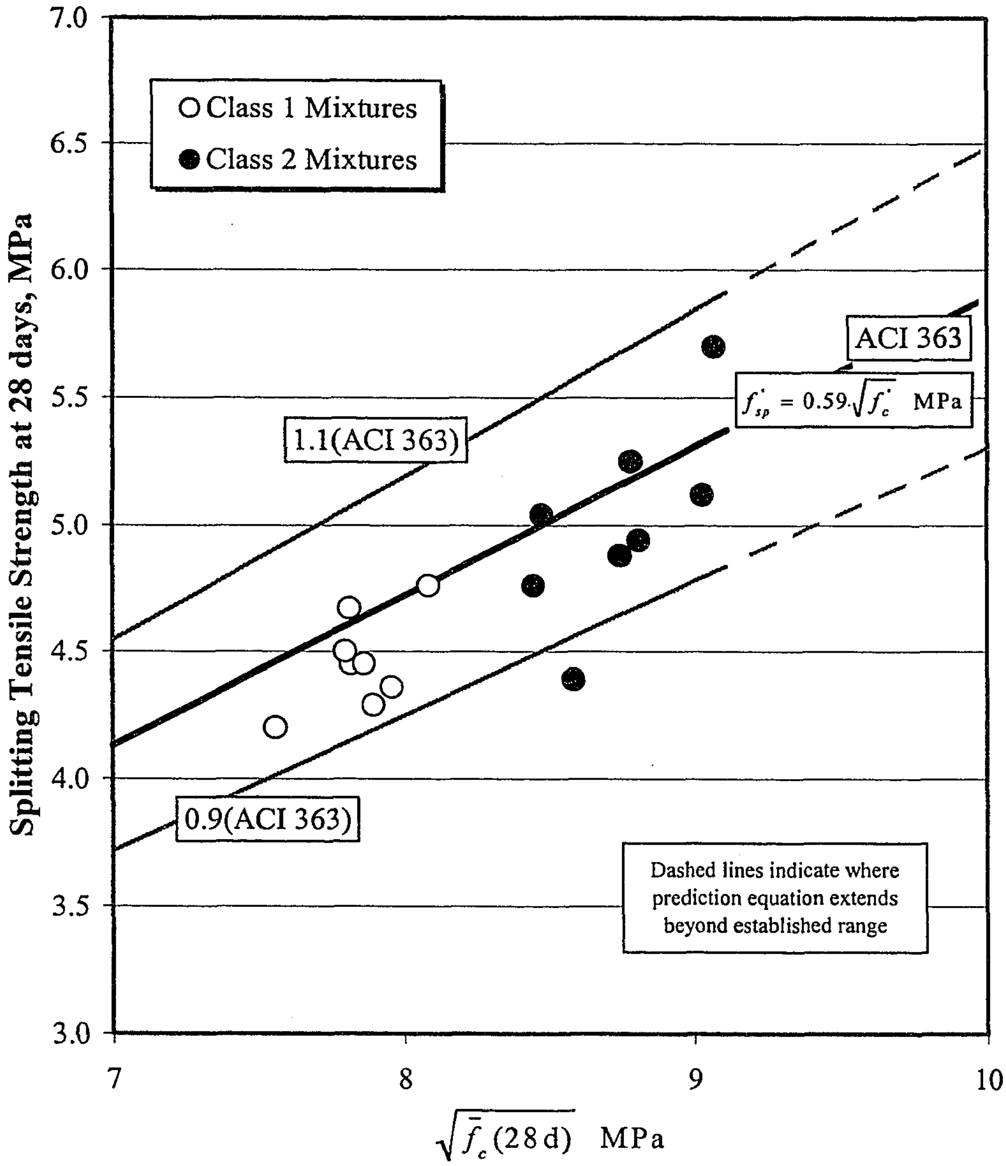


Figure 4.11. Splitting Tensile Strength vs. ACI 363

4.5.4. Modulus of Elasticity

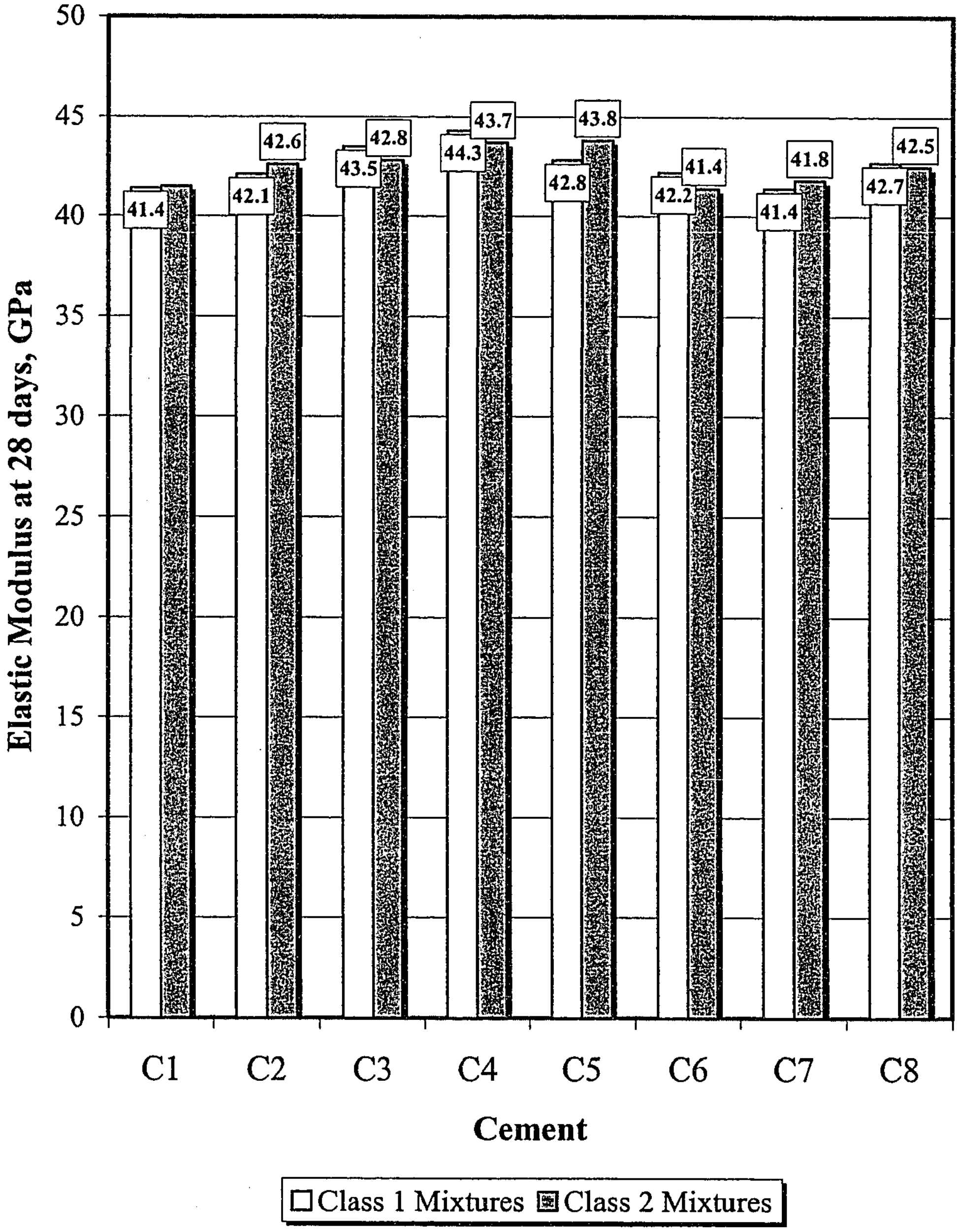
Modulus of elasticity results at 28 days are illustrated in Figure 4.12. The mixture with C4 (*Type I*) achieved the best modulus of elasticity in Class 1, 44.3 GPa (6,420 ksi), while the mixture with C5 (*Type I/II*) was best in Class 2, 43.8 GPa (6,350 ksi). Mixtures with C8 (*Type III*) were fourth best in Class 1 and fifth in Class 2. Modulus of elasticity results ranged from 41.4 to 44.3 GPa (6,000 to 6,420 ksi) in Class 1 with an average 42.6 GPa (6,180 ksi). In Class 2, modulus of elasticity results ranged from 41.4 to 43.8 GPa (6,000 to 6,350 ksi) with an average 42.5 GPa (6,160 ksi).

Elasticity results are displayed in Figure 4.13 together with the ACI 318 and ACI 363 predictions.

- ACI 318: $E_c = 4{,}730\sqrt{f_c'}$ ($E_c = 57{,}000\sqrt{f_c'}$)
- ACI 363: $E_c = 3{,}320\sqrt{f_c'} + 6{,}900$ ($E_c = 40{,}000\sqrt{f_c'} + 1{,}000{,}000$)

In these equations, f_c' or, alternatively $\bar{f}_c$ is defined as the average measured compressive strength in MPa (psi). ACI 318 is valid for concrete with f_c' up to 41 MPa (6,000 psi). ACI 363 is valid for 21 < f_c' < 83 MPa (3,000 < f_c' < 12,000 psi). ACI 363 underestimated the measured elastic moduli by more than 10%. An additional line representing 110% of ACI 363 is shown in Figure 4.13. ACI 318, extended beyond its valid range, underestimated results from the Class 1 mixtures but overestimated some results from the Class 2 mixtures. The relationship between elastic modulus and compressive strength recognized by ACI 318 and ACI 363 was unclear in these results. With higher compressive strength, Class 2 mixtures were expected to have higher elastic moduli, but average elastic moduli results of both classes were nearly identical. The data suggests that the elastic moduli is instead more significantly influenced by the type of coarse aggregate, and both Class 1 and Class 2 mixtures contained limestone.

Figure 4.12. Elastic Modulus



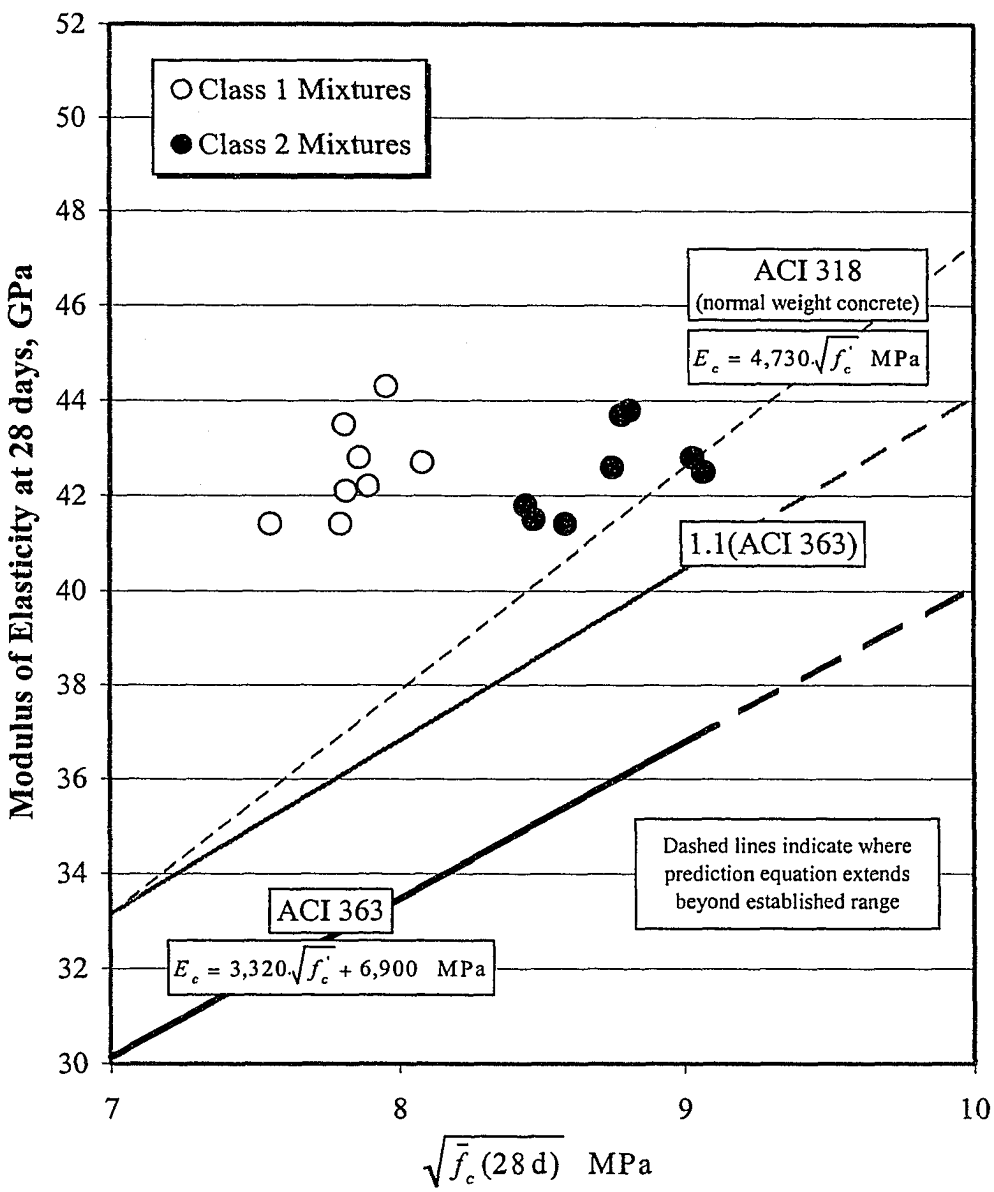


Figure 4.13. Elastic Modulus vs. ACI 318 & ACI 363

4.6. Summary and Conclusions

Trial batching is necessary to assess the quality and suitability of constituent materials in concrete. Eight cements encompassing different types, manufacturers and plant locations were examined in two classes of HPC mixtures. The choice of cement influenced both the fresh and hardened properties of HPC. The results show that all cements appear suitable for producing HPC with these constituent materials and mixture proportions. Mixtures containing a *Type III* cement achieved the highest compressive strength at all ages tested, most significantly at early ages. The compressive strength results with *Type III* cement were statistically significant at 1 day on the basis of 95% confidence intervals, however, the differences observed between mixtures at 28 and 56 days were statistically insignificant. In other words, compressive strength differences among the mixtures were most pronounced at 1 day but diminished over time through 56 days. The wide range in early strength was to some extent due to the retarding effects of chemical admixtures. Superplasticizer addition rates should be adjusted for different cements to avoid an excessive delay in setting time. At 28 days, cement characteristics influenced splitting tensile strength more significantly than compressive strength and compressive strength more significantly than modulus of elasticity, a conclusion based on the coefficient of variation of the test results. The applicability of the ACI prediction equations must be confirmed for different cements in HPC. ACI 209 underestimated the rate of compressive strength development at early ages. ACI 363 was mostly accurate within ±10% in describing splitting tensile strength, but overestimated the majority of the results. ACI 363 underestimated modulus of elasticity by more than 10% while ACI 318, extended beyond its valid range, underestimated most elastic moduli results. The relationship between elastic modulus and compressive strength was not apparent.

[1] Bush, T.D., Russell, B.W., and Freyne S.F., "High Performance Concrete for Transportation Structures," Final Report FHWA/OK 98(07), September 1998.
[2] ACI 363, "State-of-the-Art Report on High Strength Concrete," *ACI Manual of Concrete Practice*, Part 1, American Concrete Institute, 1997.
[3] ACI 211.4, "Guide for Selecting Proportions for High-Strength Concrete with Portland Cement and Fly Ash," *ACI Manual of Concrete Practice*, Part 1, American Concrete Institute, 1997.
[4] Chicago Committee on High Rise Buildings, "High Strength Concrete in Chicago High Rise Buildings," February 1977.
[5] American Society for Testing and Materials, *Annual Book of ASTM Standards*, Vol. 4.01 and 4.02, 1995.
[6] ACI 318, *Building Code Requirements for Structural Concrete and Commentary*, American Concrete Institute, 1999.
[7] Ahmad, S. H. and Zia, P., "High Early Strength Concrete for Prestressed Concrete Applications," *Proceedings of the PCI/FHWA International Symposium of High Performance Concrete*, New Orleans, Louisiana, 1997, pp. 194-205.
[8] Oklahoma Department of Transportation, *Standard Specifications for Highway Construction*, 1997.
[9] Mendenhall, W. and Sincich, T., *Statistics for Engineering and the Sciences*, 4th Ed., Prentice Hall, 1995.
[10] ACI 209, "Prediction of Creep, Shrinkage and Temperature Effects in Concrete Structures," *ACI Manual of Concrete Practice*, Part 1, American Concrete Institute, 1997.
[11] Mokhtarzadeh, A. and French, C., "Mechanical Properties of High Strength Concrete with Consideration for Precast Applications," *ACI Materials Journal*, Vol. 97, No. 2, March/April 2000, pp. 136-147.

5. Comparing Different Aggregates in HPC

5.1. Introduction

The *Aggregate Study* described in this chapter, which included a *Coarse Aggregate Study* and a *Fine Aggregate Study*, was the second phase of the research program. The *Coarse Aggregate Study* was performed to assess the suitability of coarse aggregates from Oklahoma for production of HPC. Coarse aggregates may have a more pronounced effect in HPC than in conventional concrete.[1] In conventional concrete, compressive strength is typically limited by the capacity of the cement paste or by the capacity of the bond between coarse aggregate and cement paste. In HPC, where the cement paste and coarse aggregate/cement paste bond are enhanced by design of a low w/cm and use of supplementary cementitious materials, ultimate strength potential may be limited by the intrinsic strength of the coarse aggregate itself.[2,3,4] In the *Fine Aggregate Study*, the effects of increasing the fineness modulus of fine aggregate were evaluated in HPC mixtures. An intermediate size aggregate was blended with fine aggregate to increase the fineness modulus.

5.2. Experimental Program

A group of four coarse aggregates was selected from Oklahoma to be representative of all coarse aggregates available within the state. As presented in Table 3.4, the group included limestone (LI) and rhyolite (RH) from southern Oklahoma, granite (GN) from southwestern Oklahoma and river gravel (GV), a weathered sandstone, from southeastern Oklahoma. Limestone, rhyolite and granite were crushed aggregates. River gravel was a partially crushed aggregate. These coarse aggregates are currently in use or could readily be used in Oklahoma.

Each of the coarse aggregates was separated into a precise or "standard" gradation, different from the gradation available for purchase at the quarry. Both the "quarry-acquired" and "standard" gradations of each aggregate were evaluated in HPC mixtures. The "quarry-acquired" approach allowed examination of the aggregates in a manner consistent with commercial production. The "standard" approach allowed examination of the type, shape and texture of aggregates independent of grading.

The coarse aggregates were evaluated in HPC mixtures to determine their suitability for HPC production. Criteria for comparing the mixtures included:

- Fresh concrete slump
- Compressive strength at ages of 1, 3, 7, 28 and 56 days
- Splitting tensile strength at 28 days
- Flexural strength (modulus of rupture) at 28 days
- Modulus of elasticity at 28 days

These criteria are important in the design and manufacture of precast/prestressed concrete bridge beams.

Coarse aggregate gradings are presented in Table 5.1. Aggregates in a "quarry-acquired" condition are designated LIq, RHq, GNq and GVq. LIq fit the No. 8 grading requirements of ASTM C 33 with a nominal maximum size aggregate (MSA) of 9.5 mm ($^3/_8$ in). RHq, GNq and GVq fit or nearly fit the No. 7 requirements with a MSA of 15.9 mm ($^5/_8$ in). Aggregates in a "standard" grading are designated LIs, RHs, GNs and GVs. The "standard" grading was selected to meet the No. 7 grading requirements while removing all the fine particles passing the No. 8 sieve size. The "standard" grading was created by sieving each coarse aggregate and then combining individual sizes in the required amounts. In forming LIs, a larger size limestone aggregate from the same quarry was needed to augment the No. 8 limestone.

Table 5.1. Coarse Aggregate Gradings (Percent Passing By Weight)

Sieve Size		ASTM C 33 Requirements		Quarry-Acquired Grading				Standard Grading
		No. 7	**No. 8**	Limestone **LIq**	Rhyolite **RHq**	Granite **GNq**	River Gravel **GVq**	**LIs RHs GNs GVs**
$^3/_4$"	19.05 mm	**100**			100	100	100	100
$^1/_2$"	12.70 mm	**100** **90**	**100**	100	94.3	97.0	91.2	91
$^3/_8$"	9.53 mm	**70** **40**	**100** **85**	94.2	69.4	79.1	67.5	59
#4	4.75 mm	**15** **0**	**30** **10**	16.6	13.1	10.4	11.2	2
#8	2.36 mm	**5** **0**	**10** **0**	3.6	3.0	2.4	1.9	0
#16	1.18 mm		**5** **0**	1.1	2.1	1.3	—	
#100	0.15 mm			0.6	1.2	0.4	—	

LIq meets the No. 8 grading requirements of ASTM C 33
RHq, GVq, and the "standard grading" meet the No. 7 requirements
Except for one sieve ($^3/_8$"), GNq also meets the No. 7 requirements

25.4 mm = 1 in

Coarse aggregate properties are presented in Table 5.2. These included bulk specific gravity, absorption, dry rodded unit weight (DRUW) and void content. Rhyolite possessed the highest specific gravity and absorption. Granite had the lowest absorption. River gravel possessed the highest DRUW and thus the lowest void content in both "quarry-acquired" and "standard" gradings.

HPC mixtures were designed to achieve compressive strength of about 75 MPa (10,880 psi) at an age of 28 days. It was believed that this was sufficient compressive strength so that failure under testing would more likely initiate in the coarse aggregate or at the location of the aggregate/paste bond rather than in the cement paste. The objective was to place emphasis on the coarse aggregates and promote contrast among the mixtures.

Mixture proportions for the *Coarse Aggregate Study*, calculated by the absolute volume method, are reported in Table 5.3. Mixtures were designed with 474.5 kg/m^3 (800 lb/yd^3) ASTM C 150 *Type I* cement and 166.1 kg/m^3 (280 lb/yd^3) ASTM C 618 *Class C* fly ash at a w/cm of 0.281. Coarse aggregate contents were maintained at 63% of the respective DRUW and the actual quantity of coarse aggregate in a mixture varied accordingly. Mixtures containing LIs, for example, had 1,014 kg/m^3 (1,710 lb/yd^3) coarse aggregate, or 63% of its DRUW of 1,605 kg/m^3 (100.2 lb/ft^3). The quantity of fine aggregate was adjusted according to the absolute volume method.

Mixtures also contained an ASTM C 494 *Type B/D* set retarding/water reducing admixture and *Type A/F* superplasticizer.

HPC is often designed with a large amount of cementitious material and, with the abundance of very fine particles, may have limited workability. In an effort to enhance workability and make HPC less "sticky," an intermediate aggregate was blended with a fine aggregate to increase the fineness modulus (FM). A higher FM means the fine aggregate is more coarse. Fine and intermediate aggregate gradings are reported in Table 5.4. The *Fine Aggregate Study* consisted of four mixtures, two mixtures with a FM of 2.5 (fine aggregate only) and two like mixtures with a FM of 3.3 (a blend of fine and intermediate aggregate). In each case, increasing the FM did not change the unit weight of the mixture. Mixture proportions for the *Fine Aggregate Study* are presented in Table 5.5. C3/1 is a "Class 1" mixture from the *Cement Study* described in Chapter 4. LIq is a mixture from the *Coarse Aggregate Study*. C3/1 i and LIq i are like mixtures containing an intermediate aggregate. Criteria for comparing the mixtures included slump, compressive strength at ages of 1, 3, 7 and 28 days and splitting tensile strength at 28 days.

Table 5.2. Coarse Aggregate Properties

		Limestone **LI**	Rhyolite **RH**	Granite **GN**	River Gravel **GV**
Bulk Specific Gravity (SSD)		2.67	2.71	2.62	2.59
Absorption	%	1.2	1.4	0.5	1.3
DRUW (Quarry-Acquired Grading)	kg/m^3	1,623	1,525	1,538	1,644
DRUW (Standard Grading)	kg/m^3	1,605	1,525	1,525	1,624
Void Content (Quarry-Acquired Grading)	%	39.2	43.7	41.3	36.5
Void Content (Standard Grading)	%	39.9	43.7	41.8	37.3

1 kg/m^3 = 0.06243 lb/ft^3

Table 5.3. Coarse Aggregate Study — Mixture Proportions (SSD Aggregates)

Cement[a]	kg/m^3	474.5
Fly Ash[b]	kg/m^3	166.1
Coarse Aggregate (CA)	kg/m^3	957.3 to 1,039.7
Fine Aggregate (FA)[c]	kg/m^3	616.8 to 495.8
Mixing Water	kg/m^3	177.3
SR/WR Admixture[d]	L/m^3	1.25
HRWR Admixture[e]	L/m^3	2.92
w/cm		**0.281**
w/c		0.379
SCM/TCM[f]	%	25.9
CA Content	%	63
CA/FA		1.56 to 2.09
Calculated Air Content	%	1.6
Calculated Unit Weight	kg/m^3	2,357 to 2,402

[a] ASTM C 150 *Type I* cement with a C_3S content of 54.4%, C_2S content of 18.4% and Blaine fineness of 3,390 cm^2/g
[b] ASTM C 618 *Class C* fly ash having specific gravity of 2.65, calcium oxide (CaO) content of 28.4% and pozzolanic activity index of 99%
[c] Natural river sand having a bulk specific gravity of 2.63, absorption of 0.7% and fineness modulus of 2.47
[d] ASTM C 494 *Type B/D* set retarding/water reducing admixture
[e] ASTM C 494 *Type A/F* superplasticizer
[f] Supplementary cementitious materials/total cementitious materials

1 kg/m^3 = 1.686 lb/yd^3, 1 L/m^3 = 25.85 floz/yd^3, 1 kg/m^3 = 0.06243 lb/ft^3

Table 5.4. Fine & Intermediate Aggregate Gradings (Percent Passing By Weight)

Sieve Size		ASTM C 33 Requirements for Fine Aggregate	Intermediate Aggregate	Fine Aggregate
$^3/_8$"	9.53 mm	**100**	100	100
#4	4.75 mm	**100** **95**	94.4	99.1
#8	2.36 mm	**100** **80**	30.0	94.0
#16	1.18 mm	**85** **50**	4.8	81.5
#30	0.60 mm	**60** **25**	1.2	55.3
#50	0.30 mm	**30** **10**	0.2	22.9
#100	0.15 mm	**10** **2**	0.1	4.8
FINENESS MODULUS		**3.1** **2.3**	4.69	2.47

25.4 mm = 1 in

**Table 5.5. Fine Aggregate Study —
Mixture Proportions (SSD Aggregates)**

		C3/1	C3/1 i	LIq	LIq i
Fineness Modulus		2.5	3.3	2.5	3.3
Cement[a]	kg/m^3	385.5	385.5	474.5	474.5
Fly Ash[b]	kg/m^3	—	—	166.1	166.1
Coarse Aggregate (CA)[c]	kg/m^3	1,052.8	1,052.8	1,039.7	1,039.7
Intermediate Aggregate[d]	**kg/m^3**	—	**285.3**	—	**189.2**
Fine Aggregate[e]	**kg/m^3**	**794.8**	**509.5**	**526.1**	**336.9**
Mixing Water	kg/m^3	154.2	154.2	177.3	177.3
SR/WR Admixture[f]	L/m^3	0.77	0.77	1.25	1.25
HRWR Admixture[g]	L/m^3	3.02	3.02	2.92	2.92
w/cm		0.406	0.406	0.281	0.281
SCM/TCM[h]	%	0	0	25.9	25.9
CA Content	%	65	65	63	63
Calculated Air Content	%	2.31	2.47	1.58	1.69
Calculated Unit Weight	kg/m^3	2,392	2,392	2,389	2,389

[a] ASTM C 150 *Type I* cement with a C_3S content of 54.4%, C_2S content of 18.4% and Blaine fineness of 3,390 cm^2/g

[b] ASTM C 618 *Class C* fly ash having specific gravity of 2.65, calcium oxide (CaO) content of 28.4% and pozzolanic activity index of 99%

[c] Crushed limestone meeting the No. 67 (C3/1 and C3/1 i) or No. 8 (LIq and LIq i) grading requirements of ASTM C 33 and having a bulk specific gravity of 2.67 and absorption of 1.2% and DRUW of 1,621 kg/m^3 (No. 67 aggregate) or 1,623 kg/m^3 (No. 8 aggregate)

[d] Limestone screenings having a bulk specific gravity of 2.67, absorption of 1.2% and fineness modulus of 4.69

[e] Natural river sand having a bulk specific gravity of 2.63, absorption of 0.7% and fineness modulus of 2.47

[f] ASTM C 494 *Type B/D* set retarding/water reducing admixture

[g] ASTM C 494 *Type A/F* superplasticizer

[h] Supplementary cementitious materials/total cementitious materials

1 kg/m^3 = 1.686 lb/yd^3, 1 L/m^3 = 25.85 $floz/yd^3$, 1 kg/m^3 = 0.06243 lb/ft^3

5.3. Experimental Procedures

Work was performed in the laboratory. Batching and testing procedures conformed to the applicable ASTM standards[5] except mixing time, which was often extended beyond the duration specified in ASTM C 192. Mixing continued until the concrete appeared uniform.[6] Batch weights were adjusted for aggregate moisture.

Slump was measured in conformance with ASTM C 143. Initial slump was measured after combining all materials except superplasticizer. Final slump was measured after introducing superplasticizer, additional mixing and discharge. Unit weight, air content, and fresh concrete temperature were also measured.

Concrete cylinders for determining compressive strength, splitting tensile strength and elastic modulus were cast in 100 x 200 mm (4 x 8 in) plastic molds. Flexural strength beams were cast in 150 x 150 x 510 mm (6 x 6 x 20 in) steel molds. Both cylinders and beams were consolidated by rodding and were cured at 23 °C (73.4 °F) and 50% relative humidity during the initial 24 hrs. Molds were removed at 24 hrs and thereafter, until tested, cylinders and beams were moist cured (under water) as specified by ASTM C 192 at a temperature of 23 °C (73.4 °F).

Cylinders were tested for compressive strength using neoprene pads seated in steel or aluminum rings. Tests followed the procedures of ASTM C 39 and were performed at ages of 1, 3, 7, 28 and 56 days. ASTM C 496 splitting tensile strength and ASTM C 78 flexural strength tests were performed at 28 days. ASTM C 469 elastic modulus tests were performed at 7 and 28 days. Typically, at each age, three cylinders were tested for compressive strength and splitting tensile strength, three beams for flexural strength and two cylinders for modulus of elasticity.

5.4. Experimental Results

A summary of the testing results of the *Coarse Aggregate Study* is presented in Table 5.6. At 28 days, average compressive strength of the *Coarse Aggregate Study* was 76.1 MPa (11,030 psi), near the targeted level. Splitting tensile strength was determined to be 7.1% of corresponding compressive strength at 28 days, on average. Likewise, on average at 28 days, flexural strength was determined to be 11.7% of corresponding compressive strength. On average at 28 days, splitting tensile strength was determined to be 60.4% of flexural strength, a relationship that was previously found to be about 70%.[8] A summary of the testing results of the *Fine Aggregate Study* is presented in Table 5.7.

Most mixtures were batched more than once to increase accuracy of the final results. One mixture, LIq, was batched six times. If batched more than once, the results that are reported in Tables 5.6 and 5.7 represent an average of the individual batch results. The individual batch results were determined as an average of the results of the test specimens. Complete testing results of the *Aggregate Study* are included in Appendix D.

Table 5.6. Coarse Aggregate Study — Summary of Testing Results

			LIq	LIs	RHq	RHs	GNq	GNs	GVq	GVs	AVG
No. of Batches			6	2	2	2	2	2	2	2	
Initial Slump		mm	30	50	10	30	60	30	*120*	70	**50**
Final Slump		mm	200	240	200	200	*260*	220	230	250	**225**
Compressive Strength	1 d	MPa	27.3	23.3	28.9	25.3	23.7	*30.3*	22.1	24.6	**25.7**
	3 d	MPa	*58.5*	49.6	51.5	52.7	53.2	56.2	43.9	46.5	**51.5**
	7 d	MPa	*71.4*	59.8	62.7	64.2	62.0	69.1	51.8	56.7	**62.2**
	28 d	MPa	*85.1*	73.8	76.0	78.9	76.1	83.8	64.9	70.1	**76.1**
	56 d	MPa	*91.2*	78.6	81.7	83.3	82.4	88.7	70.0	74.6	**81.3**
Spl. Tensile Strength	28 d	MPa	*5.98*	5.03	5.79	5.59	4.90	5.04	5.29	5.26	**5.36**
Flexural Strength	28 d	MPa	9.13	9.18	9.18	*9.29*	8.56	8.69	8.00	9.01	**8.88**
Elastic Modulus	7 d	GPa	40.6	40.0	*40.7*	39.3	*40.7*	40.3	34.7	36.5	**39.1**
	28 d	GPa	42.1	43.5	41.9	42.0	42.6	*44.2*	37.1	39.7	**41.6**

Best marks are in italics
25.4 mm = 1 in, 1 MPa = 145 psi, 1 GPa = 145 ksi

Table 5.7. Fine Aggregate Study — Summary of Testing Results

			C3/1	C3/1 i	LIq	LIq i
Fineness Modulus			**2.5**	**3.3**	**2.5**	**3.3**
No. of Batches			5	1	6	1
Initial Slump		mm	30	30	30	20
Final Slump		mm	220	200	200	150
Compressive Strength	1 d	MPa	22.3	23.2	27.3	23.1
	3 d	MPa	43.6	43.5	58.5	61.4
	7 d	MPa	52.5	58.4	71.4	73.5
	28 d	MPa	61.0	62.4	85.1	89.0
Spl. Tensile Strength	28 d	MPa	4.67	5.22	5.98	6.25

25.4 mm = 1 in, 1 MPa = 145 psi

5.5. Analysis and Discussion of Results

5.5.1. Coarse Aggregate Study

5.5.1.1. Slump

Initial slumps, measured prior to addition of superplasticizer, were an average 50 mm (2 in). It was anticipated that initial slump would be enhanced in mixtures with a "standard" grading over the corresponding "quarry-acquired" grading due to the removal of the aggregate material from the smallest sieve sizes in formation of the "standard" grading. But this hypothesis only proved correct for mixtures with limestone and rhyolite. The spherical shape and smooth surface texture of river gravel aggregates afforded the best initial slump, 120 mm (4 $^3/_4$ in) in the "quarry-acquired" grading and 70 mm (2 $^3/_4$ in) in the "standard" grading. Coarse aggregates with an angular shape and rough surface texture generally hinder workability because more paste is needed to coat these aggregates.

After addition of superplasticizer, final slumps were at minimum 200 mm (8 in) for all mixtures. Little difference in workability was detected among the various mixtures due to the effectiveness of the superplasticizer. Still, mixtures with a coarse aggregate/fine aggregate (CA/FA) ratio by weight of about 1.6 appeared less "harsh" or "rocky" than mixtures with higher CA/FA. The CA/FA was not expressly examined but varied from 1.6 to 2.1 in response to having a constant coarse aggregate content. Mixtures containing river gravel had the highest CA/FA. The CA/FA could be a consideration in proportioning HPC mixtures for applications that have specific placing, consolidating and/or finishing requirements.

5.5.1.2. Compressive Strength

Compressive strength results are illustrated in Figures 5.1, 5.2, 5.3, 5.4 and 5.5 for ages of 1, 3, 7, 28 and 56 days, respectively. Limestone produced a higher strength in a "quarry-acquired" grading than in a "standard" grading. Conversely, rhyolite, granite and river gravel, after the first day, each produced higher strength in a "standard" grading than in a "quarry-acquired" grading.

Among the mixtures containing "quarry-acquired" aggregates (and also overall), LIq achieved the best compressive strength at 3, 7, 28 and 56 days. These results, to some extent, can be attributed to the size of aggregate; and LIq possessed the smallest MSA. Smaller size coarse aggregate has more surface area for a given aggregate content, which improves aggregate/paste bond and enhances strength potential.[7,8] Furthermore, the crushing process eliminates potential zones of weakness within the parent rock with the effect that smaller particles are likely to be stronger than larger ones.[3]

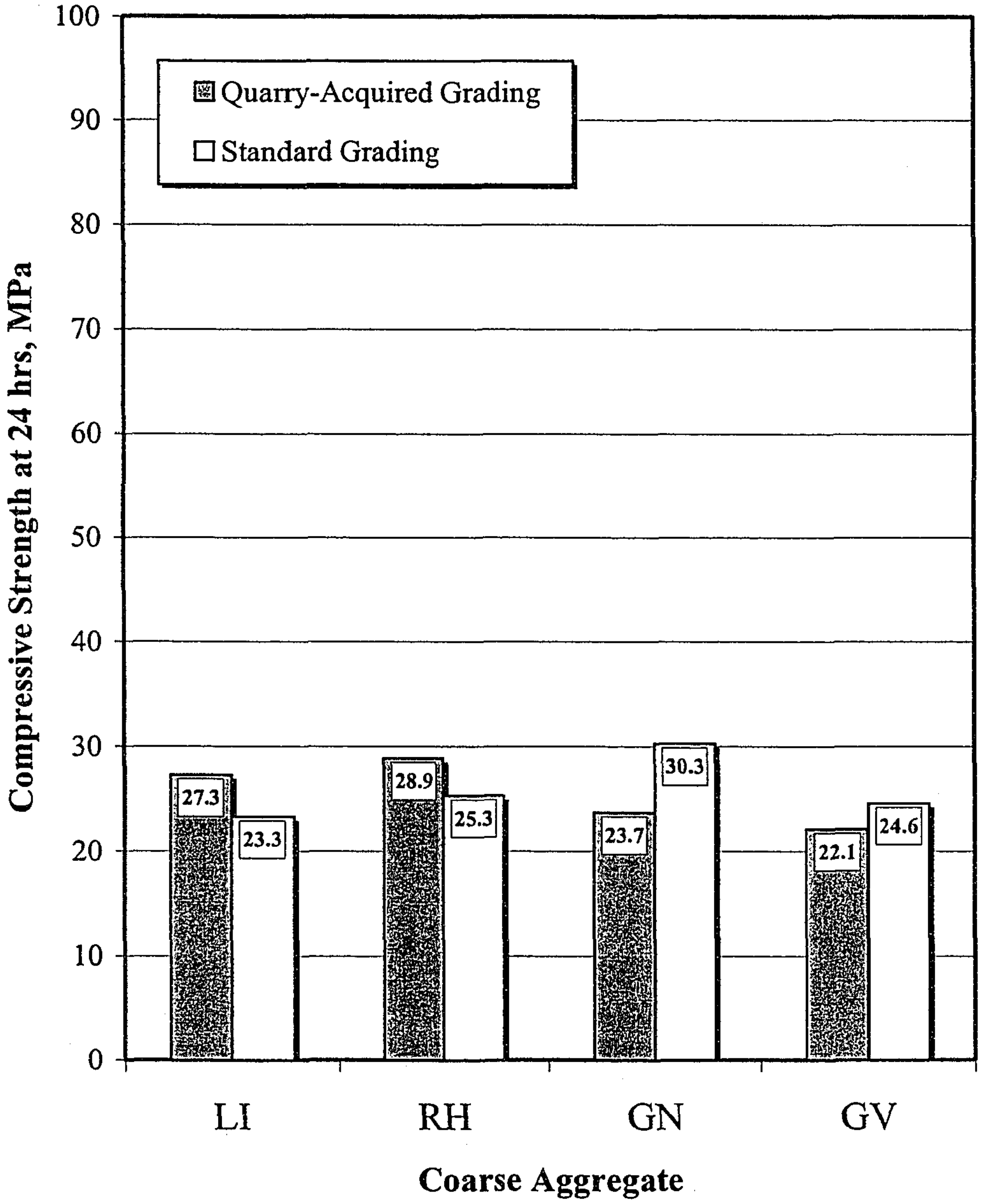


Figure 5.1. Compressive Strength (1 day)

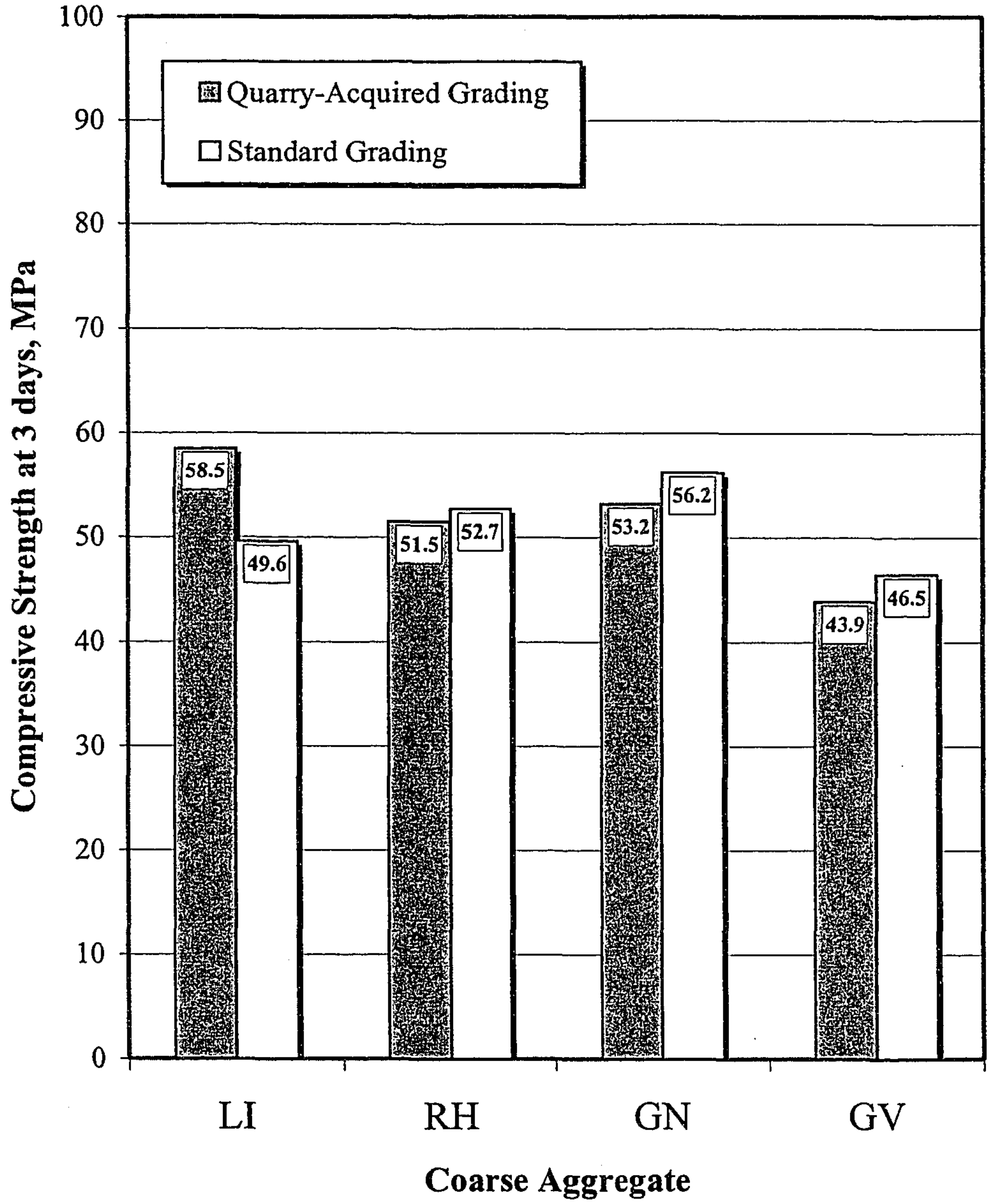


Figure 5.2. Compressive Strength (3 days)

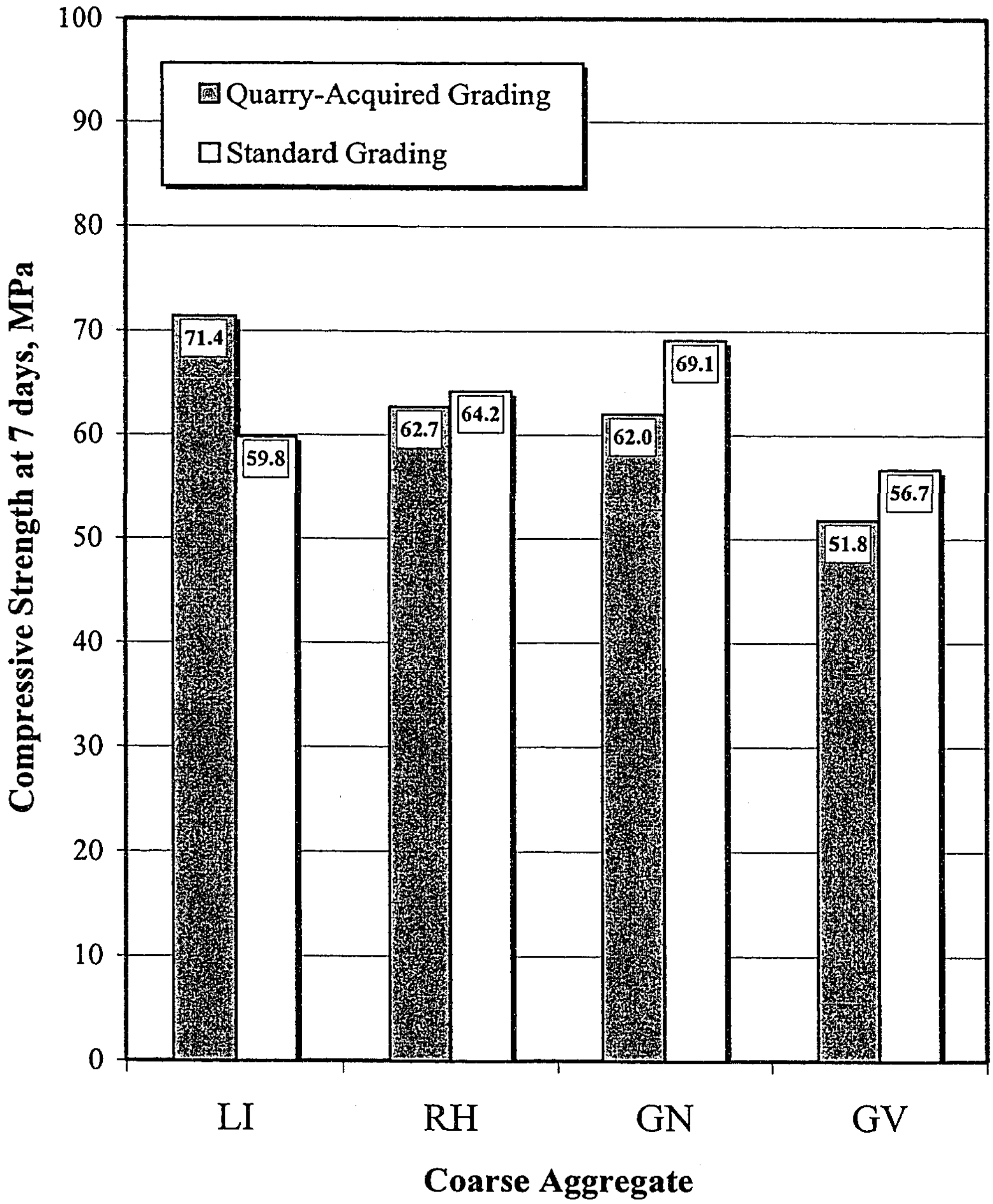


Figure 5.3. Compressive Strength (7 days)

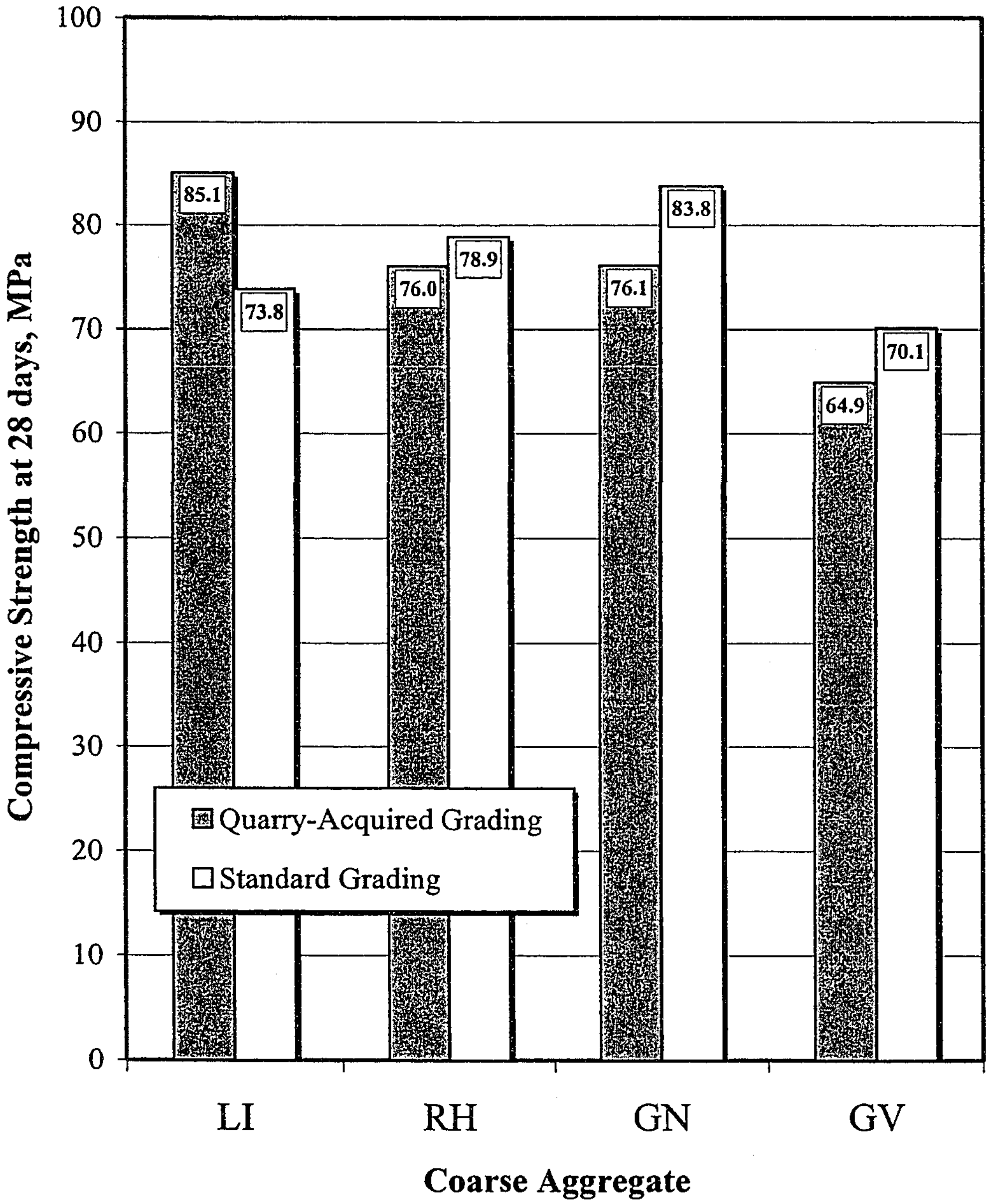


Figure 5.4. Compressive Strength (28 days)

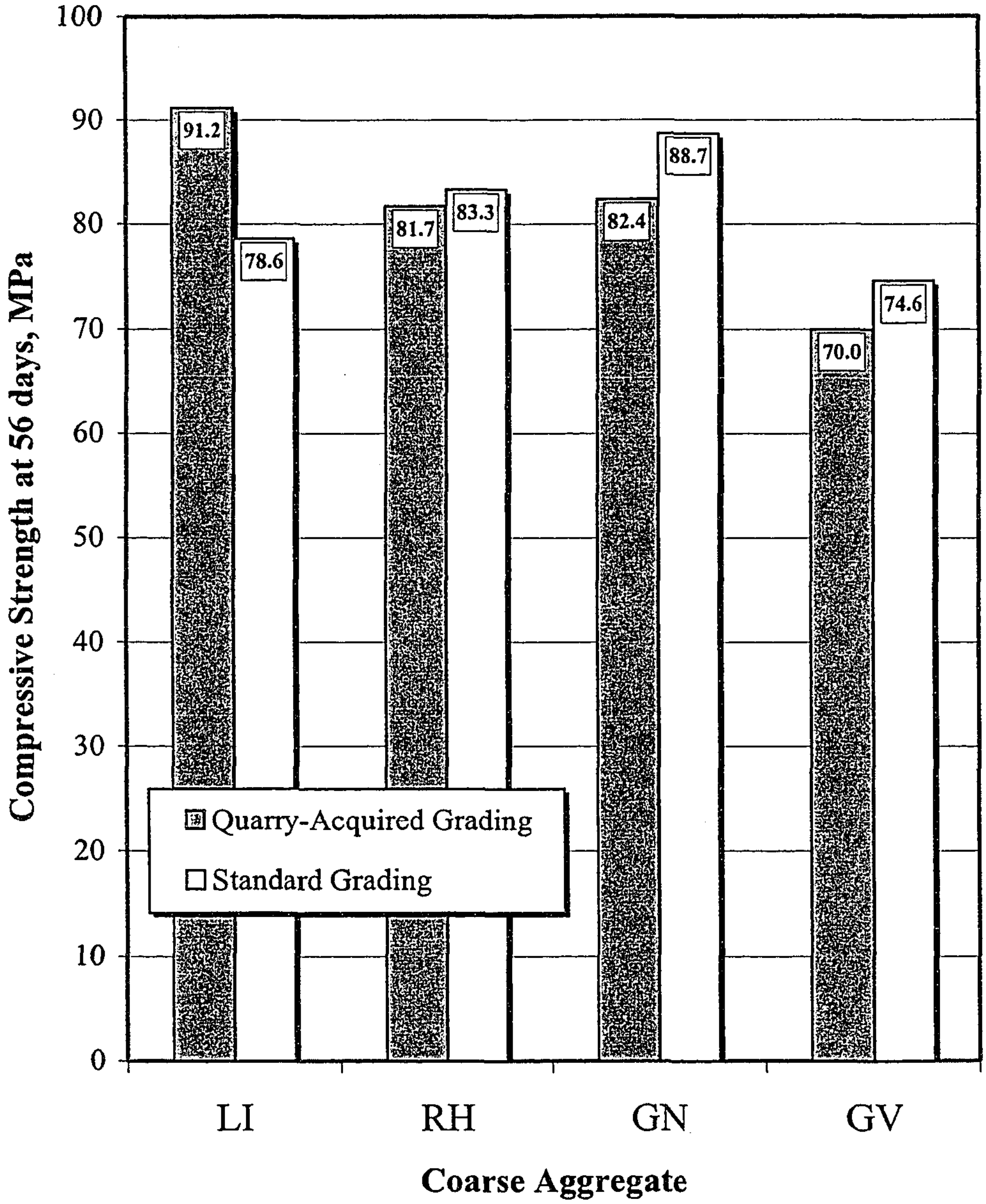


Figure 5.5. Compressive Strength (56 days)

Among the mixtures containing "standard" aggregates, GNs performed best, followed by RHs, LIs and GVs. When the type, shape and texture of aggregates were examined in HPC independent of grading, both granite and rhyolite achieved higher compressive strength than limestone.

Mixtures with river gravel generally achieved the lowest compressive strengths. River gravel coarse aggregates were largely spherical in shape and smooth in texture and it was observed that as many as 50% of the particles were uncrushed. Close visual inspection of the fracture surface of these cylinders after testing revealed that fracture passed around, rather than through many of the river gravel particles, indicating poor aggregate/paste bond. Limestone, rhyolite and granite aggregates had angular shapes and rough surface textures that furnished better aggregate/paste bond. With these test cylinders, fracture passed through the coarse aggregates. Whether fracture initiated in the coarse aggregates is unknown. The observance of fracture passing through the coarse aggregates does not necessarily mean that the compressive strength of the aggregate has been reached.[1]

With the proximity of many of the compressive strength results, it is necessary to assess whether the observed differences were statistically significant. Confidence intervals are presented in Table 5.8 at ages of 1, 28 and 56 days. The confidence intervals were constructed using the test results of the individual cylinders. With 95%

certainty, the confidence intervals enclose the true compressive strength. The confidence interval is

$$\bar{f}_c \pm t \cdot \left(\frac{s}{\sqrt{n}} \right)$$

where $\bar{f}_c$ is the average compressive strength value, t is the statistic applicable to small samples, s is the standard deviation, and n is the total number of test cylinders.[9] If the confidence intervals are distinct from one another, then it is likely that the differences observed between the mixtures are statistically significant. Conversely, if the confidence intervals share values, then it is likely that the differences observed between the mixtures are within the experimental variability and are statistically insignificant. In this case, all of the aggregates produced compressive strength results that were statistically alike at all ages.

The range of compressive strengths of all eight mixtures at each age is illustrated in Figure 5.6. Maximum and minimum strengths as well as average strength are labeled at each age. Differences among the mixtures became more pronounced with concrete age, as compressive strengths increased. At 1 day, the compressive strength results ranged from 22.1 to 30.3 MPa (3,200 to 4,390 psi), a difference of 8.2 MPa (1,190 psi). At 56 days, the compressive strength results ranged from 70.0 to 91.2 MPa (10,150 to 13,220 psi), a difference of 21.2 MPa (3,070 psi). A similar study also concluded that coarse aggregate type has increasing effect as the compressive strength increases.[10] The opposite tendency was observed in the *Cement Study* of Chapter 4, where a wide range of compressive strengths resulted at an early age but narrowed over time. Together, these results indicate that, in HPC, cement selection was crucial to early strength gain while the choice of coarse aggregate was more important to ultimate strength development.

Table 5.8. Confidence Intervals for Assessing Statistical Significance

		LIq	LIs	RHq	RHs	GNq	GNs	GVq	GVs
Compressive Strength at 1 d	MPa	24.6	21.0	26.0	22.8	21.3	27.3	19.9	22.1
	MPa	30.0	25.6	31.8	27.8	26.1	33.3	24.3	27.1
Compressive Strength at 28 d	MPa	76.6	66.4	68.4	71.0	68.5	75.4	58.4	63.1
	MPa	93.6	81.2	83.6	86.8	83.7	92.2	71.4	77.1
Compressive Strength at 56 d	MPa	82.1	70.7	73.5	75.0	74.2	79.8	63.0	67.1
	MPa	100.3	86.5	89.9	91.6	90.6	97.6	77.0	82.1

1 MPa = 145 psi

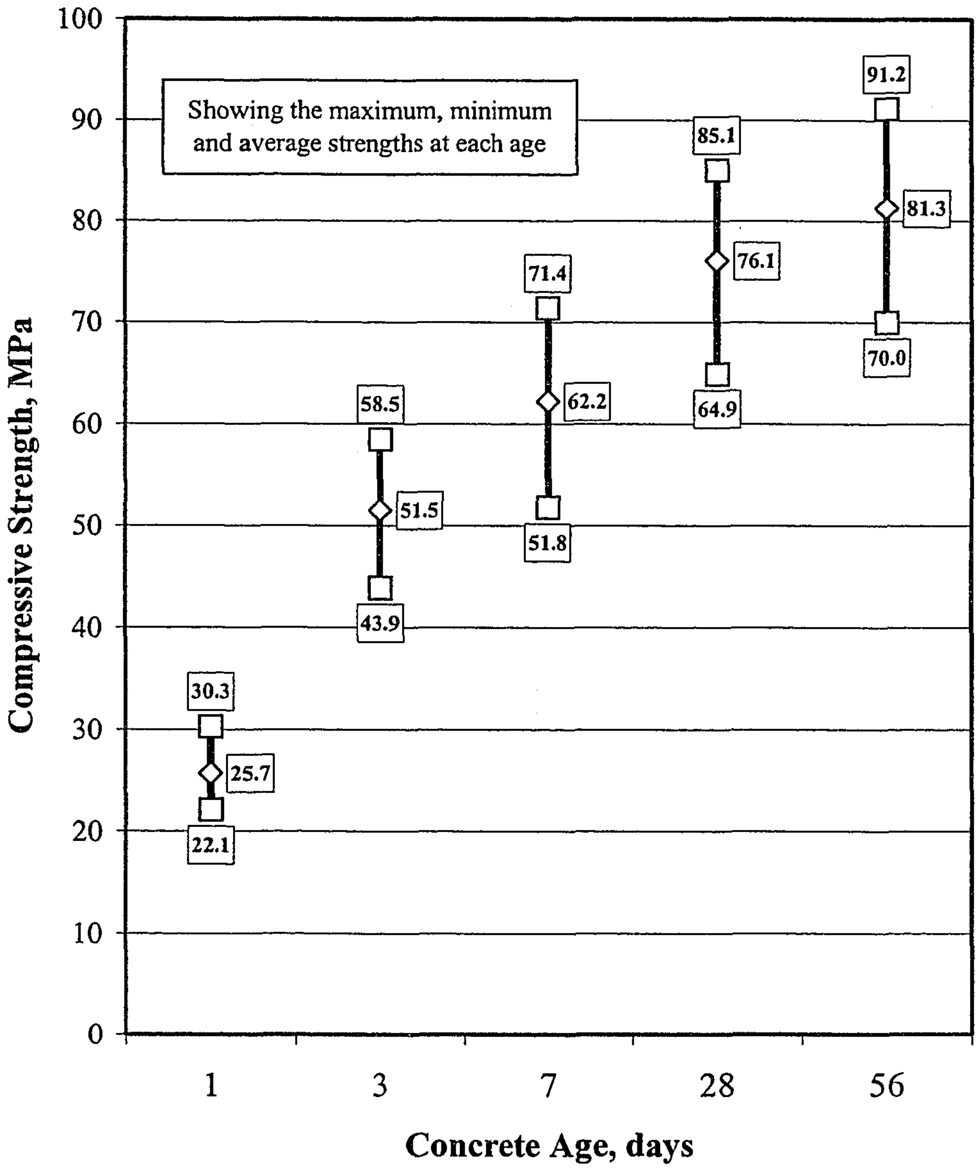


Figure 5.6.
Range of Strengths from Coarse Aggregate Study

5.5.1.3. Splitting Tensile Strength

As displayed in Table 5.6, LIq achieved the best splitting tensile strength at 28 days, 5.98 MPa (865 psi). However, LIs achieved significantly lower splitting tensile, 5.03 MPa (730 psi), likely due to the larger size aggregate. Granite aggregates produced among the lowest splitting tensile strength values. A possible explanation is that granite had the lowest absorption, as presented in Table 5.2.

Splitting tensile strength results were compared to the ACI 363 prediction in Figure 5.7.

- ACI 363: $f'_{sp} = 0.59\sqrt{f'_c}$ ($f'_{sp} = 7.4\sqrt{f'_c}$)

Here f'_c or, alternatively $\bar{f}_c$ is defined as the average measured compressive strength in MPa (psi). The equation is valid for 21 < f'_c < 83 MPa (3,000 < f'_c < 12,000 psi). Most of the results were within ±10% of ACI 363. Additional lines representing 90% and 110% of ACI 363 are shown in Figure

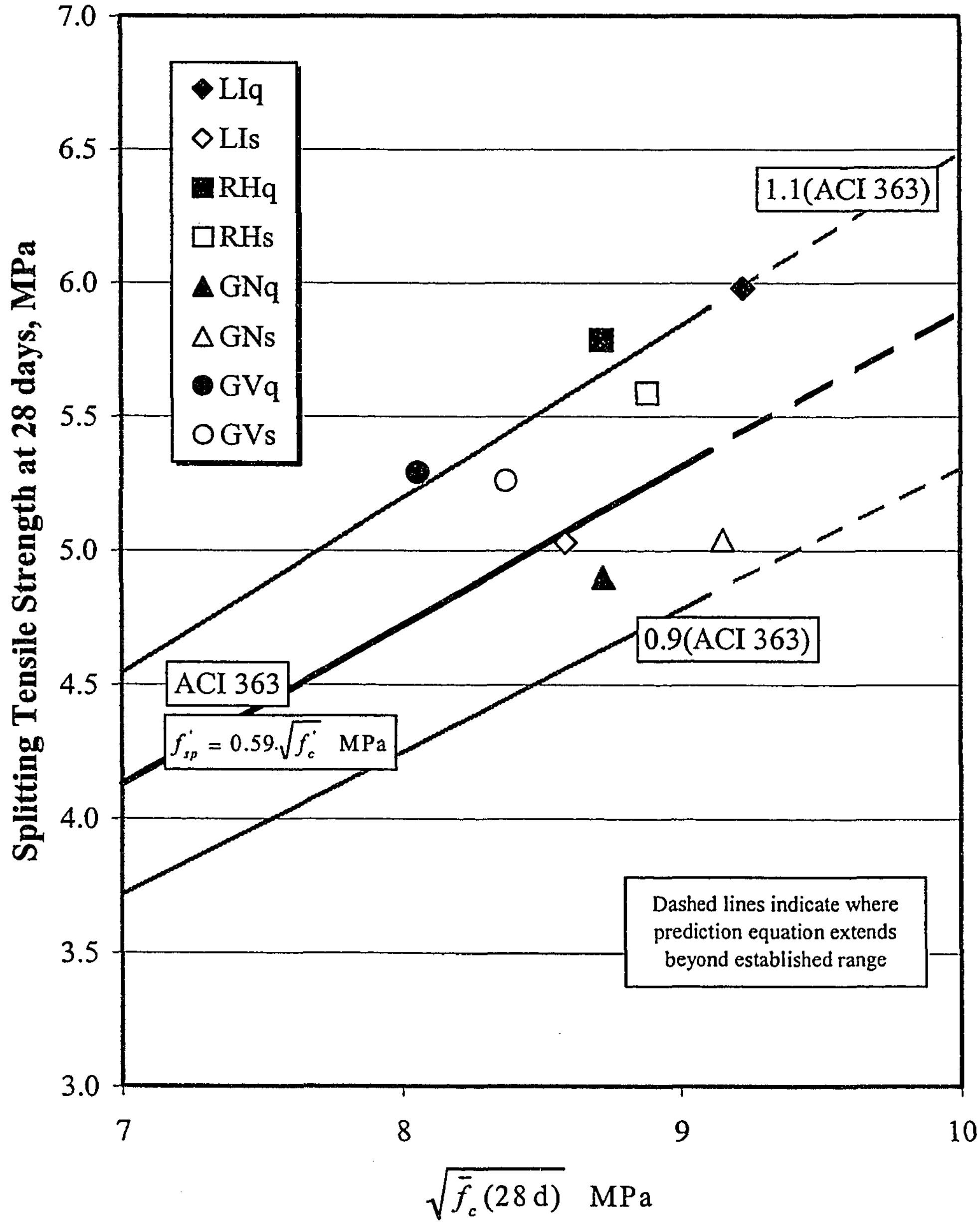


Figure 5.7. Splitting Tensile Strength vs. ACI 363

5.5.1.4. Flexural Strength

As displayed in Table 5.6, RHs achieved the best flexural strength (modulus of rupture) at 28 days, 9.29 MPa (1,345 psi).

Flexural strength results were compared to the ACI 363 prediction in Figure 5.8.

- ACI 363: $f_r' = 0.94\sqrt{f_c'}$ ($f_r' = 11.7\sqrt{f_c'}$)

Here f_c' or, alternatively $\bar{f}_c$ is defined as the average measured compressive strength in MPa (psi). The equation is valid for $21 < f_c' < 83$ MPa ($3{,}000 < f_c' < 12{,}000$ psi). An additional line representing 110% of ACI 363 is shown in Figure 5.8. ACI 363 underestimated the results, sometimes by more than 10%. Again, granite aggregates were conspicuous from the rest of the test group, producing results that were nearest to the ACI 363 prediction.

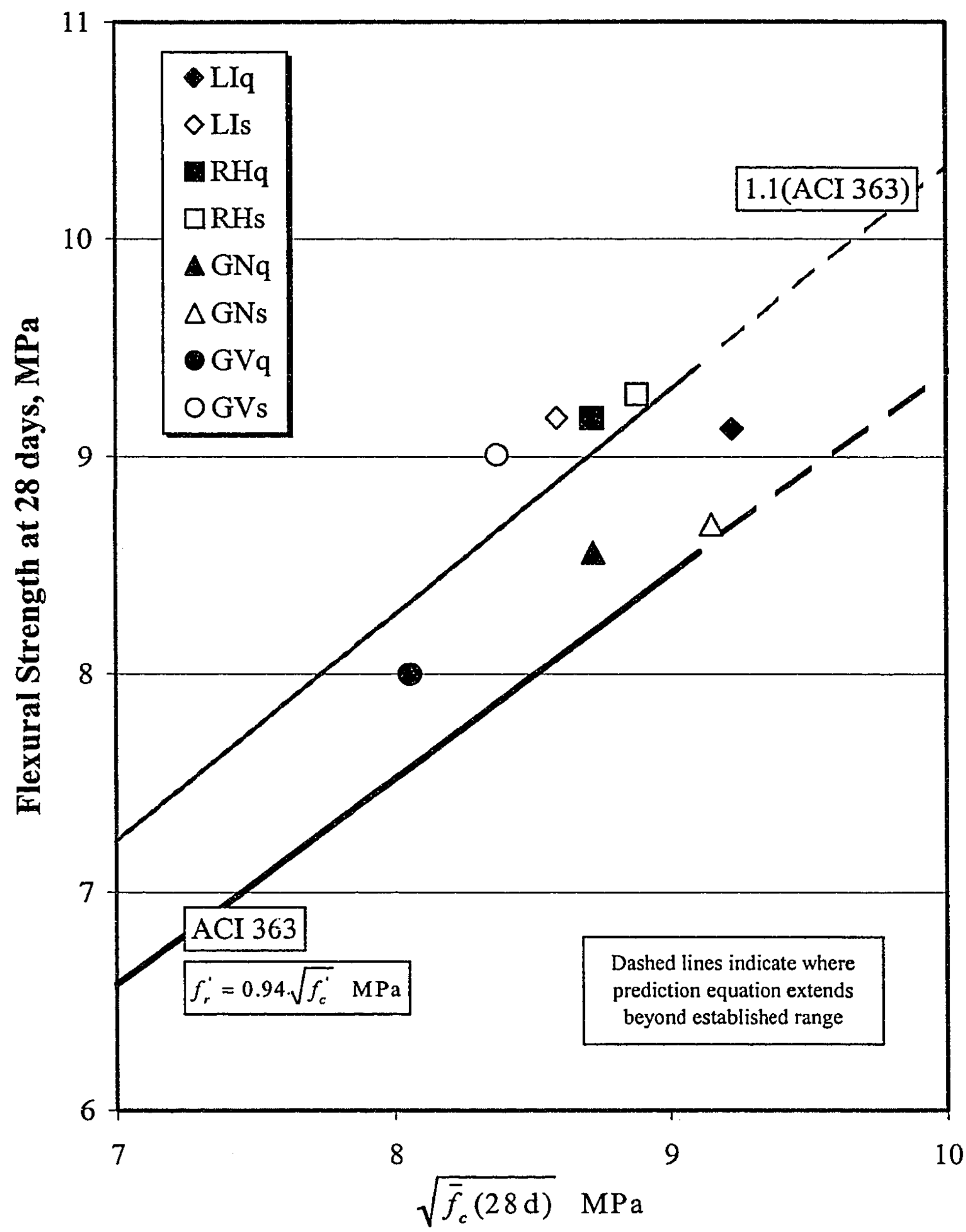


Figure 5.8. Flexural Strength vs. ACI 363

5.5.1.5. Modulus of Elasticity

As displayed in Table 5.6, RHq and GNq achieved the best modulus of elasticity at an age of 7 days, 40.7 GPa (5,900 ksi), while GNs achieved the best result at 28 days, 44.2 GPa (6,400 ksi). At 7 days, on average, elastic moduli results were 94% of corresponding results at 28 days. By contrast, compressive strength results at 7 days, on average, were 82% of corresponding results at 28 days.

Elasticity results at ages of 7 and 28 days are illustrated in Figure 5.9 together with predictions from ACI 318 and ACI 363.

- ACI 318: $E_c = 4{,}730\sqrt{f_c'}$ ($E_c = 57{,}000\sqrt{f_c'}$)
- ACI 363: $E_c = 3{,}320\sqrt{f_c'} + 6{,}900$ ($E_c = 40{,}000\sqrt{f_c'} + 1{,}000{,}000$)

In these equations, f_c' or, alternatively $\bar{f}_c$ is defined as the average measured compressive strength in MPa (psi). ACI 318 is valid for concrete with f_c' up to 41 MPa (6,000 psi). ACI 363 is valid for 21 < f_c' < 83 MPa (3,000 < f_c' < 12,000 psi). ACI 363 underestimated the measured elastic moduli by 10% or more. An additional line representing 110% of ACI 363 is shown in Figure 5.9. ACI 318, extended beyond its valid range, more precisely described the trend but overestimated some of the elasticity results.

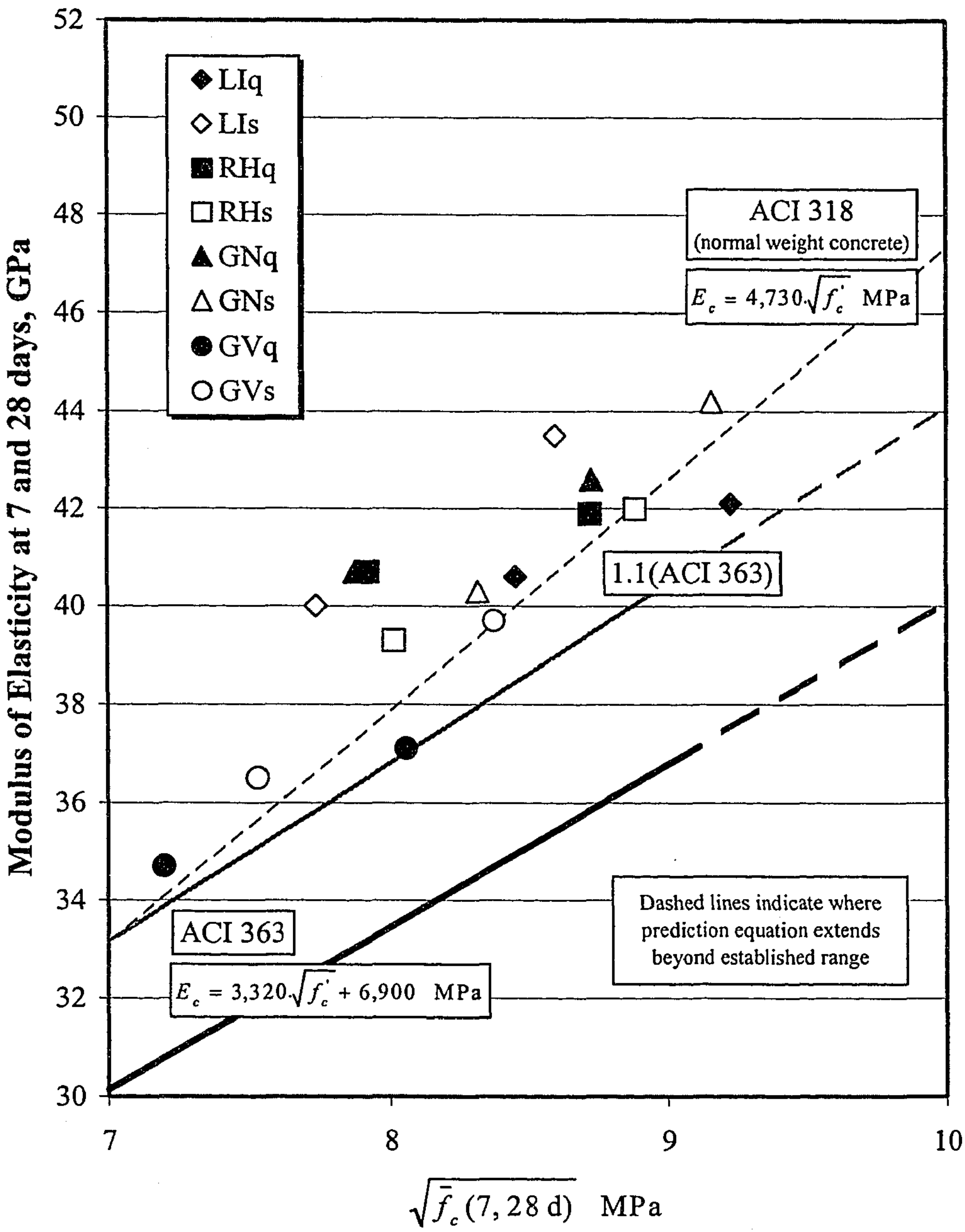


Figure 5.9. Elastic Modulus vs. ACI 318 & ACI 363

Several studies have suggested that the existing ACI prediction equations could be improved by accounting for coarse aggregate type and content.[11] One study recommended a modification to the ACI 318 equation with the introduction of an empirical coarse aggregate coefficient.[12] However, it is difficult or impossible to establish a general coefficient for a certain aggregate type because aggregate properties may vary from one source to another.[10] In another study, various mathematical models were considered that predicted HPC elasticity from the respective elastic moduli and quantity of both coarse aggregate and cement paste.[13,14]

It is recognized that the type of coarse aggregate strongly influences the modulus of elasticity of concrete. A stiff coarse aggregate enhances the elastic modulus; yet too stiff a coarse aggregate can reduce compressive strength by building stress and inducing cracking at the location of the coarse aggregate/cement paste bond. Increasing the similarity between the elastic moduli of aggregate and paste will reduce the magnitude of stress at the aggregate/paste bond and can enhance compressive strength of the concrete.[1,15]

5.5.2. Fine Aggregate Study

Introducing an intermediate aggregate to increase the FM from 2.5 to 3.3 did not enhance slump as anticipated. Actually, as reported in Table 5.7, final slumps diminished slightly in those mixtures with increased FM. Increasing the FM did increase compressive strength by an average of 3% at an age of 28 days and splitting tensile strength by an average of 8% at 28 days. However, the observed differences in compressive strength and splitting tensile strength were statistically insignificant at the 95% confidence level.

5.6. Summary and Conclusions

Trial batching is necessary to assess the quality and suitability of constituent materials in concrete. Four coarse aggregates quarried in Oklahoma, limestone, rhyolite, granite and river gravel, were evaluated in HPC mixtures in both a "quarry-acquired" and "standard" grading. The "quarry-acquired" approach allowed examination of the aggregates in a manner consistent with commercial production. The "standard" approach allowed examination of the type, shape and texture of aggregates independent of grading. The choice of coarse aggregate influenced both the fresh and hardened properties of HPC. On average, HPC mixtures achieved about 75 MPa (10,900 psi) compressive strength at 28 days. The range of the compressive strength results expanded with age. The opposite tendency was observed in a similar study of different cements, where a wide range of compressive strengths resulted at an early age but narrowed with time. Together, these results indicate that, in HPC, cement selection was crucial to early strength gain while the choice of coarse aggregate was more important to ultimate strength development. In terms of compressive strength, limestone (best in "quarry-acquired" grading), granite (best in "standard" grading) and rhyolite — all crushed aggregates and angular in shape and rough in surface texture — demonstrate potential for use in HPC; the smooth and partially uncrushed river gravel aggregates have less potential. The maximum size of aggregate (MSA) influenced compressive strength, with smaller MSA better. However, on the basis of 95% confidence intervals, the compressive strength results at all ages were statistically similar. Granite aggregates produced relatively low splitting tensile strength and flexural strength but, conversely, provided high modulus of elasticity. ACI 363 was mostly accurate within ±10% in describing splitting tensile strength and underestimated flexural strength results, sometimes by more than 10%. ACI 363 underestimated modulus of elasticity by 10% or more while ACI 318, extended beyond its valid range, underestimated most elasticity results. The applicability of these empirical relationships must be confirmed for different coarse aggregates in HPC. Increasing the fineness modulus by introducing an intermediate aggregate did not enhance slump, as expected, but slightly increased compressive strength and splitting tensile strength.

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6. The Utility of the w/cm and w/c for Predicting HPC Strength

6.1. Introduction

The water/cementitious material (w/cm) ratio is recognized as the most important variable in achieving high strength concrete (HSC).[1] It was established that elevated strength gain is possible with a low w/cm. The relationship between the w/cm and strength was first recognized in conventional concrete and then extended to HSC.[2] But concrete technology is changing and advancing at a rapid pace and old rules need to be examined again. It needs to be demonstrated if this traditional variable continues to provide useful information for today's high performance concrete (HPC) mixtures, now designed with increasing complexity and a broad variety of cementitious materials, aggregates and chemical admixtures.

HPC mixtures often contain supplementary cementitious materials as partial replacement of cement. To account for supplementary cementitious materials, the w/cm logically replaced the water/cement (w/c) ratio. But is the w/c itself useful? The w/c is determined by considering only the mass of cement in a mixture, exclusive of supplementary cementitious materials. Accordingly, when a mixture has cement as the only cementitious material, the w/cm and w/c are equivalent. What is the utility of the w/c for predicting compressive strength? In a simple linear regression model, is either the w/cm or w/c favorable at different concrete ages?

6.2. Experimental Program

A study of HPC was performed to assess the suitability of local materials and develop mixture proportions for precast/prestressed bridge beams. High early strength gain was a main objective. Target compressive strengths were 60 MPa (8,700 psi) at 1 day and 100 MPa (14,500 psi) by 28 or 56 days. In the process of evaluating materials and optimizing mixtures, the following variables were examined in HPC trial batches:

- w/cm (and w/c)
- Cements — type and source
- Supplementary cementitious materials — replacement rates and combinations
- Cementitious material content
- Coarse aggregates — type, grading and content
- Chemical admixtures — addition rates and combinations

Altogether, the study comprised 125 HPC mixture designs that represent a diversity of materials and proportions. The w/cm, defined on a mass basis, ranged from 0.406 to 0.220. The w/c ranged from 0.406 to 0.259. Cements were obtained from several manufacturers with plants in Oklahoma, Texas, Kansas and Arkansas and included ASTM C 150 *Types I, I/II, II* and *III*. However, 94 of the mixtures contained *Type III* cement from one of two sources, because *Type III* cement is typically employed in precast/prestressed concrete bridge beams. Cementitious material contents ranged from 386 to 750 kg/m^3 (650 to 1,260 lb/yd^3). Supplementary cementitious materials, which included ASTM C 618 *Class C* fly ash, silica fume and ground, granulated blast furnace slag, were employed in 85 of the mixtures but the replacement rate never exceeded 26%. The majority of mixtures, a total of 102, contained crushed limestone coarse aggregate meeting the No. 8 grading of ASTM C 33. Other mixtures contained rhyolite, granite and river gravel coarse aggregates. All aggregates were quarried in Oklahoma. Coarse aggregate content, in terms of volume, ranged from 50% to 75%. Every mixture contained a superplasticizer, either ASTM C 494 *Type A/F or Type F*, together with various kinds and combinations of other chemical admixtures. These included water reducing, set retarding/water reducing, air entraining and corrosion inhibiting/strength accelerating admixtures.

6.3. Experimental Procedures

Concrete mixture proportions were designed by the absolute volume method. The water fraction of chemical admixtures was included in the amount of mixing water. A similar adjustment was made when batching with silica fume, which was available in slurry form.

Batching and testing were performed in laboratory and procedures generally conformed to the applicable ASTM standards.[3] Corrections to batch weights were made to offset moisture in the aggregates. It was essential to adjust batch weights;

otherwise moisture released or absorbed by the aggregates would alter the w/cm (and w/c) and undermine the authenticity of the results.

Concrete cylinders were cast in 100 x 200 mm (4 x 8 in) plastic molds and consolidated by rodding. Cylinders were cured at 23 °C (73.4 °F) and 50% relative humidity during the initial 24 hrs. After 24 hrs and until tested, cylinders were moist cured (underwater) at a temperature of 23 °C (73.4 °F) as specified by ASTM C 192.

Cylinders were tested for compressive strength at ages of 1, 28 and 56 days. Tests followed the procedures of ASTM C 39. Three to five cylinders were tested at each age. Many mixtures were batched multiple times to increase accuracy of the results. If batched more than once, the result was reported as an average of individual batch results. Complete testing results are included in Appendices D and E.

6.4. Experimental Results

The experimental data are presented in Table 6.1, which includes w/cm and w/c and compressive strength results at 1, 28 and 56 days for 125 HPC mixtures. Average compressive strength results of all mixtures were 47.1 MPa (6,830 psi) at 1 day, 90.0 MPa (13,050 psi) at 28 days and 96.1 MPa (13,930 psi) at 56 days.

Least squares regression analyses was performed on the data to define the relationship between the w/cm and/or w/c and compressive strength measured at ages of 1, 28 and 56 days. Simple linear regression models used only the w/cm or the w/c as an independent variable. Multiple linear regression models used both the w/cm and w/c as independent variables. The coefficient of determination, R^2, was calculated to assess the fit of the regression lines. A summary of the regression lines and corresponding R^2 values is presented in Table 6.2, where $\bar{f}_c$ is the average measured compressive strength at a specific age.

Table 6.1. Experimental Data for Regression Analysis

Mix	w/cm	w/c	Compressive Strength, MPa		
			1 d	28 d	56 d
C1/1	0.406	0.406	23.4	57.1	61.1
C2/1	0.406	0.406	5.5	61.1	67.6
C3/1	0.406	0.406	22.3	61.0	65.8
C4/1	0.406	0.406	20.1	63.3	67.9
C5/1	0.406	0.406	21.3	61.8	67.5
C6/1	0.406	0.406	15.3	62.3	65.2
C7/1	0.406	0.406	16.8	60.8	64.3
C8/1	0.406	0.406	39.9	65.3	—
C1/2	0.346	0.346	32.1	71.8	77.0
C2/2	0.346	0.346	0.0	76.5	81.5
C3/2	0.346	0.346	36.9	81.5	86.7
C4/2	0.346	0.346	22.2	77.1	80.2
C5/2	0.346	0.346	12.4	77.6	81.9
C6/2	0.346	0.346	22.4	73.7	79.0
C7/2	0.346	0.346	10.0	71.3	73.7
C8/2	0.346	0.346	52.5	82.2	87.3
LIq	0.281	0.379	27.3	85.1	91.2
LIs	0.281	0.379	23.3	73.8	78.6
RHq	0.281	0.379	28.9	76.0	81.7
RHs	0.281	0.379	25.3	78.9	83.3
GNq	0.281	0.379	23.7	76.1	82.4
GNs	0.281	0.379	30.3	83.8	88.7
GVq	0.281	0.379	22.1	64.9	70.0
GVs	0.281	0.379	24.6	70.1	74.6
C3/1 i	0.405	0.405	23.2	62.4	—
LIq i	0.281	0.379	23.1	89.0	—
1	0.300	0.300	64.3	93.3	—
2	0.300	0.300	68.7	94.5	—
3	0.300	0.300	66.8	98.2	—
4	0.300	0.300	65.0	93.0	—
5	0.300	0.300	66.4	95.3	—
6	0.300	0.300	61.8	92.9	95.1
7	0.300	0.300	60.0	88.8	93.6
8	0.300	0.300	61.6	85.0	—
9	0.300	0.300	66.1	91.4	96.1
10	0.280	0.280	69.3	100.7	104.9

Table 6.1. Experimental Data for Regression Analysis (Cont'd)

Mix	w/cm	w/c	Compressive Strength, MPa		
			1 d	28 d	56 d
11	0.280	0.280	65.7	96.2	102.0
13	0.300	0.375	48.4	84.7	—
14	0.280	0.280	67.7	95.5	100.9
15	0.280	0.280	65.5	96.3	—
16	0.280	0.280	66.1	95.5	97.6
17	0.280	0.350	53.4	98.8	107.1
18	0.280	0.280	64.5	93.4	99.1
19	0.280	0.350	52.7	98.9	—
20	0.280	0.311	62.1	97.4	104.7
21	0.280	0.329	56.6	94.7	102.6
22	0.280	0.329	57.6	92.8	100.7
23	0.280	0.329	54.2	93.6	100.8
24	0.280	0.280	59.9	91.4	102.0
25	0.280	0.350	47.8	91.7	98.8
26	0.280	0.350	48.0	94.9	103.3
27	0.280	0.350	50.3	93.4	101.6
28	0.280	0.350	49.2	97.2	107.8
29	0.280	0.350	49.8	96.6	100.7
30	0.260	0.325	54.7	101.2	109.5
31	0.260	0.325	55.1	98.0	106.6
32	0.260	0.325	55.5	100.2	110.4
33	0.300	0.333	51.9	91.9	99.8
34	0.280	0.311	58.9	96.0	98.9
35	0.300	0.333	52.9	94.6	99.8
36	0.280	0.311	60.2	99.6	105.1
37	0.320	0.320	51.6	84.3	91.0
38	0.320	0.320	55.1	88.8	95.2
39	0.320	0.320	55.0	89.0	95.2
40	0.280	0.350	31.5	60.7	64.7
41	0.280	0.350	33.0	68.2	70.2
42	0.240	0.300	54.6	85.5	93.4
43	0.280	0.350	52.6	97.0	102.4
44	0.280	0.350	51.3	98.9	102.7
45	0.280	0.350	50.7	94.8	101.3
46	0.280	0.350	48.3	92.8	95.1

Table 6.1. Experimental Data for Regression Analysis (Cont'd)

Mix	w/cm	w/c	Compressive Strength, MPa		
			1 d	28 d	56 d
47	0.280	0.350	56.3	96.8	100.6
48	0.280	0.350	55.7	94.3	95.4
49	0.300	0.300	35.0	52.3	54.6
50	0.300	0.300	42.9	64.1	67.4
51	0.260	0.260	63.0	—	95.2
52	0.280	0.350	56.6	92.7	95.7
53	0.280	0.350	54.4	93.0	99.8
54	0.300	0.333	54.1	93.7	100.7
55	0.300	0.316	55.8	96.0	97.4
56	0.300	0.324	53.1	95.1	104.1
57	0.280	0.329	50.3	97.3	103.7
58	0.280	0.339	49.8	96.5	103.5
59	0.300	0.353	47.2	92.1	98.1
60	0.300	0.364	48.2	91.9	94.7
61	0.280	0.295	61.2	97.9	102.1
62	0.280	0.303	59.9	95.9	97.4
63	0.260	0.306	60.8	98.0	111.0
64	0.260	0.315	60.4	106.1	112.5
65	0.260	0.306	61.5	103.6	110.6
66	0.240	0.282	64.2	104.7	112.4
67	0.280	0.350	48.6	87.0	99.2
69	0.260	0.306	50.3	91.8	98.4
70	0.240	0.282	59.7	102.3	109.9
71	0.260	0.306	54.5	114.2	123.1
72	0.260	0.306	55.6	117.7	125.8
73	0.240	0.282	63.5	119.1	125.4
74	0.260	0.306	54.7	111.3	119.0
75	0.260	0.306	54.9	106.6	114.3
76	0.260	0.306	48.7	99.0	103.3
77	0.280	0.329	48.8	104.9	109.6
78	0.220	0.259	63.7	117.0	122.4
79	0.240	0.282	54.0	112.3	122.0
80	0.260	0.260	62.2	100.1	104.4
81	0.260	0.306	49.0	110.0	115.0
82	0.260	0.306	60.6	111.1	118.7

Table 6.1. Experimental Data for Regression Analysis (Cont'd)

Mix	w/cm	w/c	Compressive Strength, MPa		
			1 d	**28 d**	**56 d**
83	0.289	0.362	64.8	89.3	93.8
84	0.291	0.364	55.6	—	96.6
85	0.287	0.388	34.8	86.6	88.5
86	0.286	0.387	—	83.9	—
87	0.284	0.384	15.1	73.6	—
88	0.283	0.382	25.2	89.8	98.6
89	0.255	0.344	29.8	99.0	—
90	0.256	0.345	22.4	102.4	—
91	0.256	0.345	26.8	86.1	91.8
92	0.281	0.379	25.4	88.0	93.2
93	0.297	0.401	51.9	85.2	—
94	0.282	0.361	52.1	—	—
96	0.313	0.401	52.0	—	—
98	0.280	0.329	54.1	106.7	120.2
99	0.280	0.329	49.7	98.8	107.6
100	0.260	0.306	55.1	107.3	111.5
101	0.240	0.282	61.0	113.6	122.6
102	0.260	0.306	45.0	87.9	90.4
103	0.240	0.282	47.2	78.7	84.5

1 MPa = 145 psi

Table 6.2. Linear Regression Models and Coefficients of Determination

Simple linear regression models using the w/cm	R^2
$\dot{f}_c(1\ \text{d, MPa}) = 111.0 - 219.1(w/cm)$	0.293
$\bar{f}_c(28\ \text{d, MPa}) = 165.1 - 257.2(w/cm)$	0.535
$\bar{f}_c(56\ \text{d, MPa}) = 177.2 - 279.3(w/cm)$	0.512
Simple linear regression models using the w/c	R^2
$\dot{f}_c(1\ \text{d, MPa}) = 151.0 - 311.0(w/c)$	0.530
$\bar{f}_c(28\ \text{d, MPa}) = 171.1 - 242.6(w/c)$	0.409
$\bar{f}_c(56\ \text{d, MPa}) = 181.7 - 257.7(w/c)$	0.366
Multiple linear regression models using the w/cm and w/c	R^2
$\dot{f}_c(1\ \text{d, MPa}) = 156.2 - 65.27(w/cm) - 269.5(w/c)$	0.546
$\bar{f}_c(28\ \text{d, MPa}) = 185.6 - 191.0(w/cm) - 119.1(w/c)$	0.598
$\bar{f}_c(56\ \text{d, MPa}) = 194.8 - 216.7(w/cm) - 107.7(w/c)$	0.550

1 MPa = 145 psi

6.5. Analysis and Discussion of Results

The relationship between w/cm and strength is illustrated in Figures 6.1, 6.2 and 6.3 for the ages of 1, 28 and 56 days, respectively. At 1 day, the regression model provided an R^2 of 0.293. In other words, the model explained 29.3% of the variability existing in the sample of strength values. Regression models with the w/cm as the independent variable were found to be more adequate at 28 and 56 days with R^2 improving to 0.535 and 0.512, respectively.

Figures 6.4, 6.5 and 6.6 illustrate the relationship between w/c and strength at ages of 1, 28 and 56 days, respectively. In this case, R^2 was best at 1 day, 0.530, diminishing to 0.409 at 28 days and to 0.366 at 56 days.

The results from this study confirm that there is a correlation between compressive strength and the w/cm or w/c in HPC. Strength tends to increase when the w/cm or w/c is reduced. However, simple linear regression models failed to return a R^2 more than 0.535. Different types of regression models using either the w/cm or w/c as the independent variable sometimes modestly improved on the simple linear regression models. Different types of regression models included logarithmic, polynomial, power, and exponential trendlines.

Figure 6.1. Concrete Strength & w/cm (1 day)

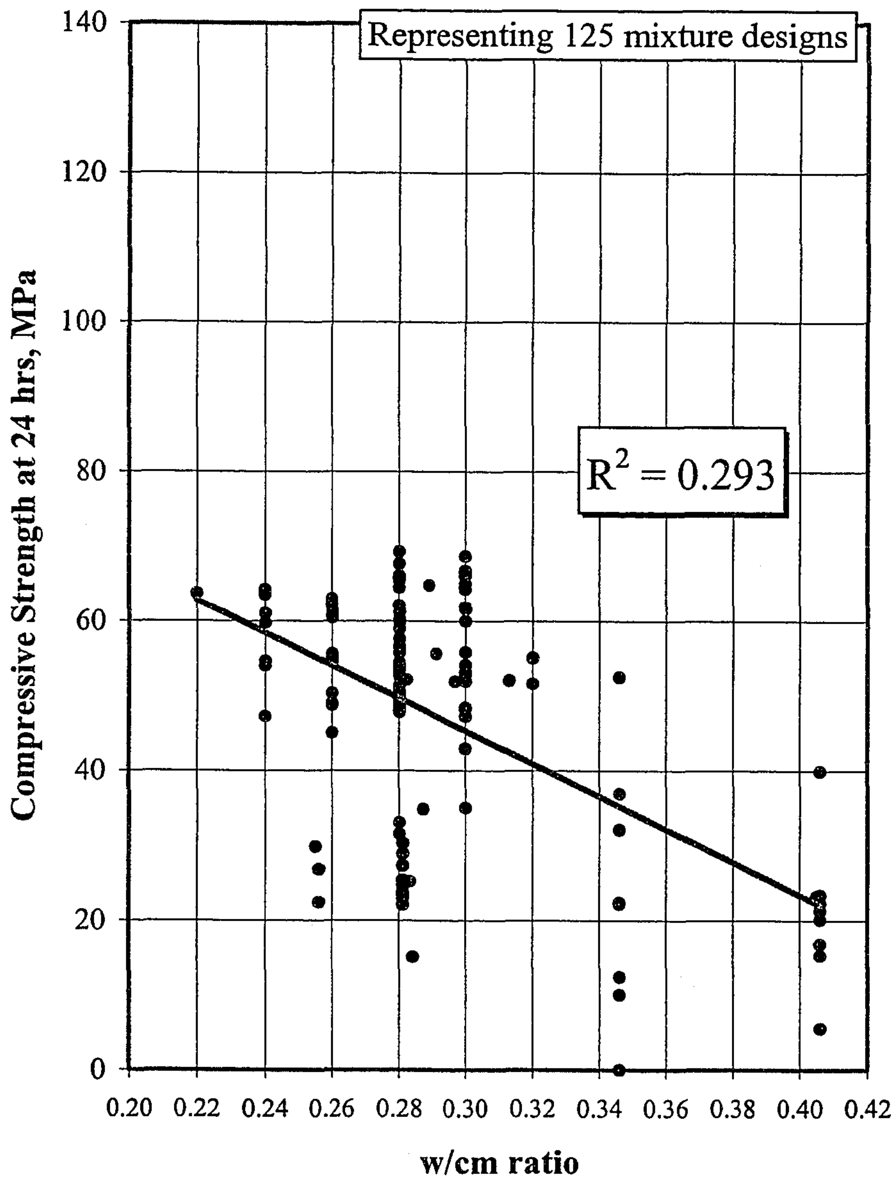


Figure 6.2. Concrete Strength & w/cm (28 days)

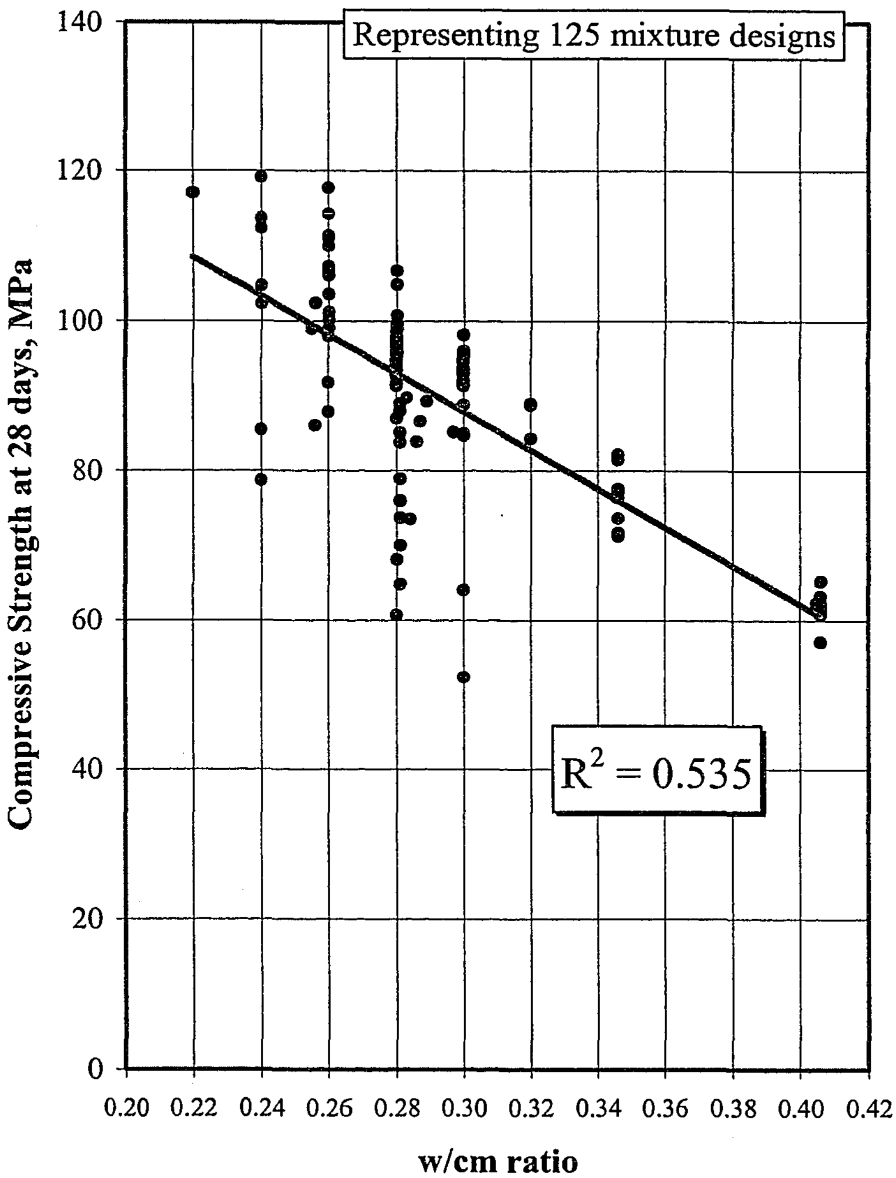


Figure 6.3. Concrete Strength & w/cm (56 days)

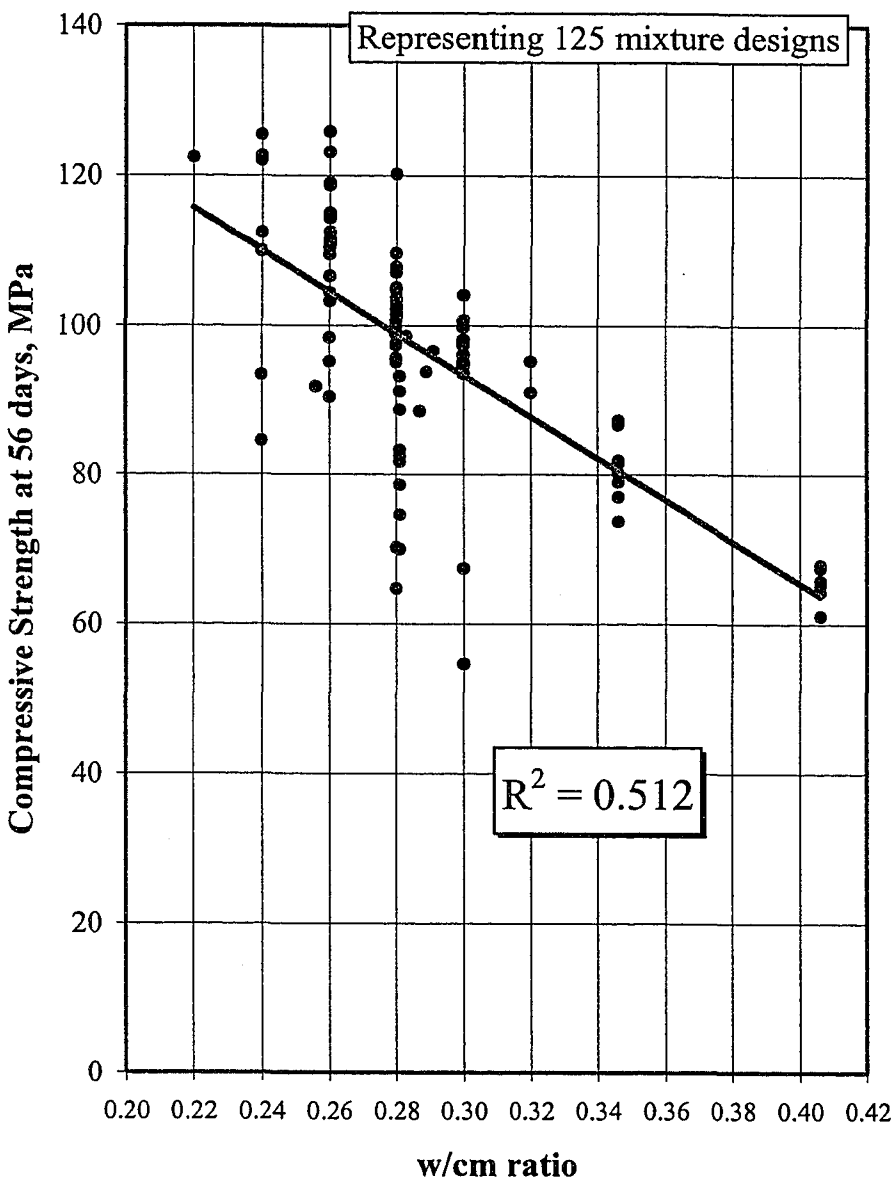


Figure 6.4. Concrete Strength & w/c (1 day)

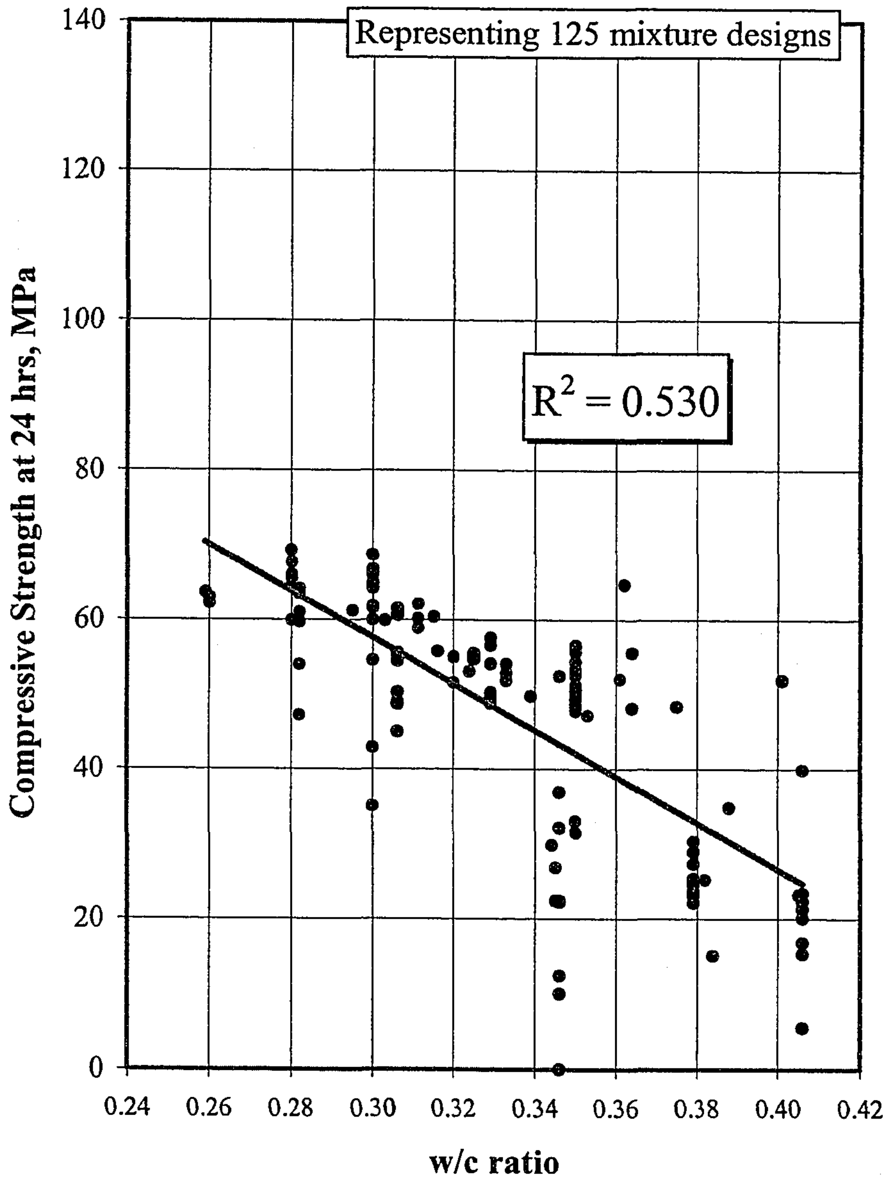


Figure 6.5. Concrete Strength & w/c (28 days)

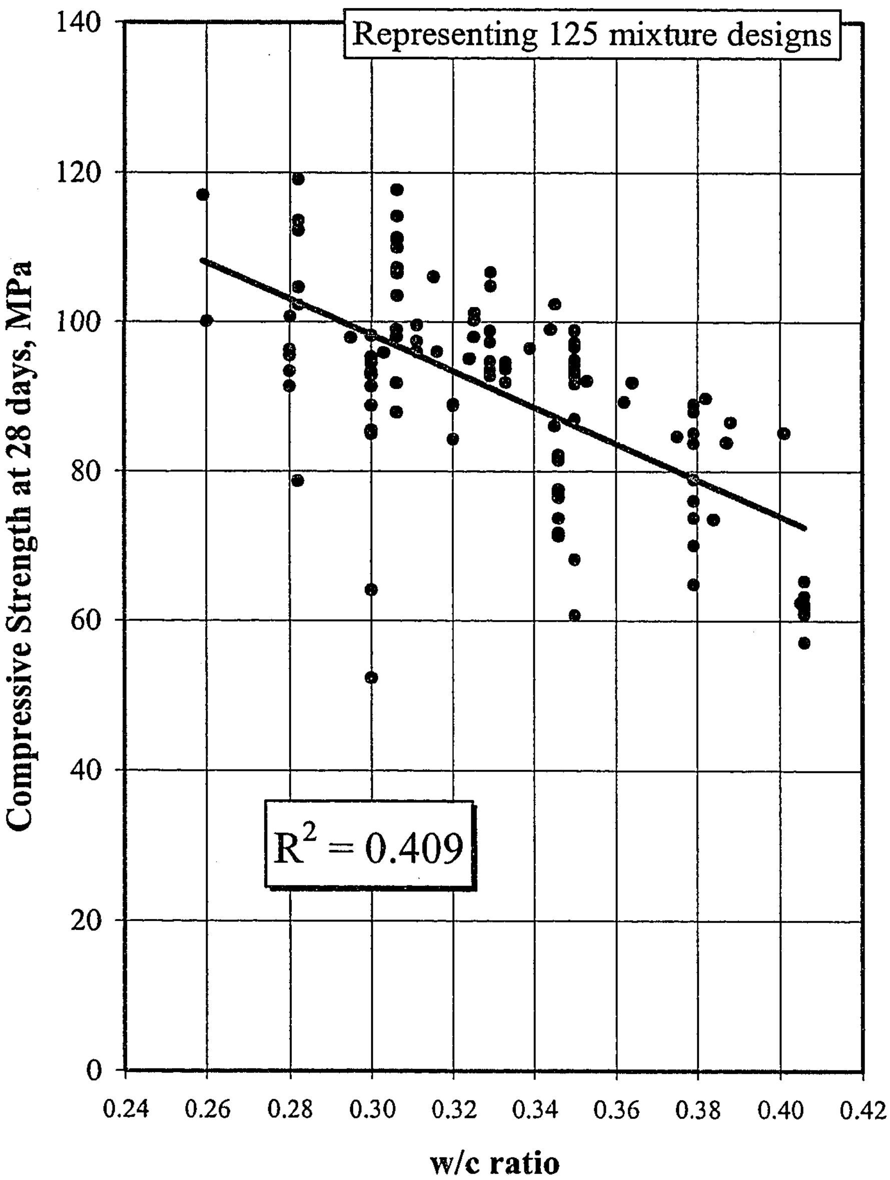
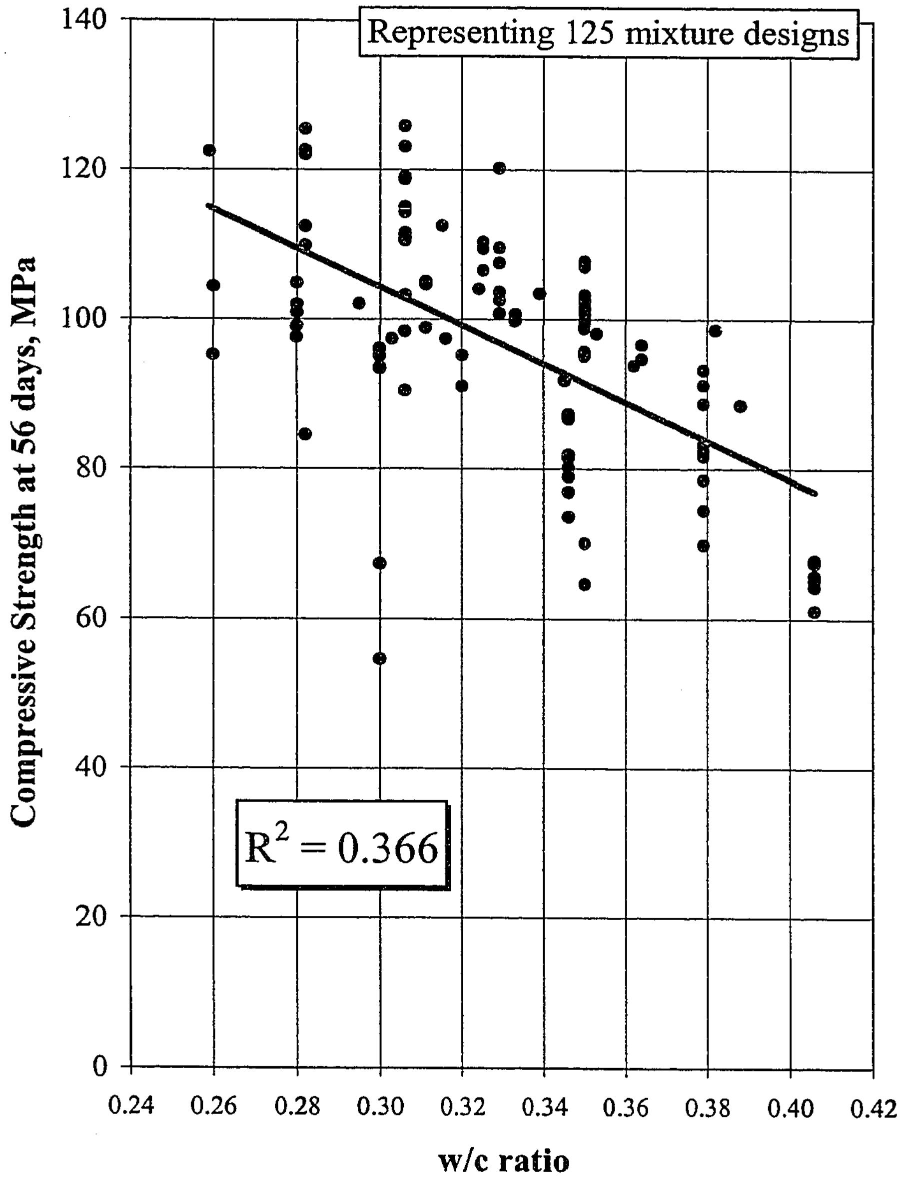


Figure 6.6. Concrete Strength & w/c (56 days)



A regression model to predict HPC strength would be helpful during trial batching efforts. Additionally, in the event of a batching error on the job, having a regression model might allow acceptance or rejection of a mixture with some confidence. The w/c was found more useful in predicting strength at an age of 1 day and the w/cm was better at 28 and 56 days. These results can be explained by the delayed pozzolanic activity of supplementary cementitious materials. Initially, cement hydration and the resulting calcium silicate hydrate is the principal source of strength in concrete. But as time progresses, the influence of supplementary cementitious materials becomes noticeable. Largely pozzolanic in composition, supplementary cementitious materials convert the weak calcium hydroxide released by cement hydration into calcium silicate hydrate.

A modified version of the w/cm has been suggested for improving the regression model.[4,5] A modified version of the w/cm would hope to specify the contribution over time of individual cementitious materials based on physical and chemical characteristics. Along the same idea, multiple linear regression models using both the w/cm and w/c as independent variables resulted in a better R^2 than the simple linear regression models. The multiple linear regression models explained up to 59.8% of the variability in the data.

6.6. Summary and Conclusions

The w/cm remains an essential, descriptive statistic for today's increasingly complex HPC mixtures. The w/c is also useful. A sample of 125 HPC mixtures of various materials and proportions was fitted with linear regression models relating compressive strength at ages of 1, 28 and 56 days to the w/cm and/or w/c. It was observed that strength generally increased as the w/cm or w/c was lowered. But linear regression models using a single independent variable, either the w/cm or w/c, failed to return a coefficient of determination, R^2, more than 0.535. It was learned that the w/c provides a stronger indication of strength at 1 day. By 28 and 56 days, because of pozzolanic activity, the w/cm becomes a better indication of strength. Multiple linear regression models using both the w/cm and w/c capture more of the variability in the data.

[1] ACI 211.4, "Guide for Selecting Proportions for High-Strength Concrete with Portland Cement and Fly Ash," *ACI Manual of Concrete Practice*, Part 1, American Concrete Institute, 1997.

[2] ACI 363, "State-of-the-Art Report on High Strength Concrete," *ACI Manual of Concrete Practice*, Part 1, American Concrete Institute, 1997.

[3] American Society for Testing and Materials, *Annual Book of ASTM Standards*, Vol. 4.01 and 4.02, 1995.

[4] Neville, A., "How Useful is the Water/Cement Ratio?" *Concrete International*, Vol. 21, No. 9, September 1999, pp. 69-70.

[5] Fidjestøl, P. and Kojundic, T., "High Performance Prefabricated Silica Fume Concrete for Infrastructure," *Proceedings of the PCI/FHWA International Symposium on High Performance Concrete*, New Orleans, Louisiana, 1997, pp. 159-171.

7. Heat Curing of HPC Containing *Type III* Cement

7.1. Introduction

In the manufacture of precast/prestressed concrete bridge beams, heat curing is regularly employed for accelerating strength gain. High early strength gain allows timely release of prestressing force and turnaround of casting beds, which helps productivity and keeps costs to a minimum. A production cycle of 24 hrs is typical.

With bridge beams, the precast/prestressed concrete industry is now encountering the need to achieve more than 60 MPa (8,700 psi) for stress release and up to 100 MPa (14,500 psi) for design purposes. These demanding compressive strength requirements are raising new questions about curing processes. How does high performance concrete (HPC), and in particular HPC designed with *Type III* cement, respond to heat curing? Is heat curing degrading to HPC designed with *Type III* cement?

This chapter describes a study in which a variety of HPC mixtures were examined under a number of heat curing schemes. The objective of the study was to determine how these mixtures respond to heat curing in terms of strength development.

7.2. Experimental Program

A variety of HPC mixtures were examined under a number of heat curing schemes to investigate the effect of curing on compressive strength at ages of 1, 28 and 56 days. The curing schemes are described in Table 3.17; a concise version is presented below. In the abbreviations for curing schemes, "S" is standard, "H" is heat, and "M" is moist.

Table 3.17. Curing Schemes

STANDARD	**S/M**	Cured at 23 °C (73.4 °F) and 50% relative humidity (RH) for the first 24 hrs, then moist cured (under water) at 23 °C (73.4 °F), as specified by ASTM C 192
MODERATE HEAT	**H1/M**	After 3 hr delay under standard conditions (23 °C and 50% RH) to reach initial set, cured at 42 °C (108 °F) for 21 hrs, then moist cured at 23 °C
	H2/M	Cured at 42 °C (108 °F) for first 24 hrs, then moist cured at 23 °C
	H3/M	Cured at about 30 °C (86 °F) for first 24 hrs, then moist cured at 23 °C
INTENSE HEAT	**H4/M**	After 3 hr delay under standard conditions (23 °C and 50% RH), steam cured to a peak of 71 °C (160 °F) for 21 hrs (temperature climbing at a rate of about 10 °C/hr (18 °F/hr)), then moist cured at 23 °C
	H5/M	After 6 hr delay under standard conditions (23 °C and 50% RH), cured at 60 °C (140 °F) for 18 hrs, then moist cured at 23 °C
	H6/M	After 4 hr delay under standard conditions (23 °C and 50% RH), cured at 60 °C (140 °F) for 14 hrs, returned to standard conditions for 6 hrs, then moist cured at 23 °C

Mixtures were evaluated under standard curing (S/M) in parallel with one or more of the six heat curing schemes. To accomplish this, concrete cylinders from a single mixture were divided into two or more sets, one set for standard curing and one or more sets for heat curing. One mixture was evaluated under multiple heat curing schemes. The heat curing schemes were classified as either moderate or intense based on peak temperature. These were intended to be representative of the heat curing processes typically employed in the manufacture of precast/prestressed concrete bridge beams.

The study involved 31 different HPC mixtures. All mixtures contained an ASTM C 150 *Type III* cement with tricalcium silicate (C_3S) content of 58.2%, dicalcium silicate (C_2S) content of 12.8%, tricalcium aluminate (C_3A) content of 10.7% and Blaine fineness of 5,490 cm^2/g. The water/cementitious material (w/cm) ratio of the mixtures ranged from 0.240 to 0.313. Cementitious material contents ranged from 400 to 750 kg/m^3 (674 to 1,260 lb/yd^3). Supplementary cementitious materials were employed in many of the mixtures as partial replacement of cement and included fly ash, silica fume and ground, granulated blast furnace slag. The ASTM C 618 *Class C* fly ash had a calcium oxide (CaO) content of 28.4% and pozzolanic activity index of 99%. Silica fume was available in slurry form. The ASTM C 989 *Grade 120* slag possessed both pozzolanic and cementitious properties. Replacement rates of supplementary cementitious materials ranged from 5% to 36%. All mixtures contained crushed limestone as coarse aggregate and natural river sand as fine aggregate as well as an ASTM C 494 *Type A* water reducing admixture and *Type A/F* superplasticizer. A summary of the mixture proportions is presented in Table 7.1 for "standard vs. moderate heat curing" and in Table 7.2 for "standard vs. intense heat curing." Mixtures are identified by number.

Table 7.1. Standard vs Moderate Heat Curing — Mixture Proportions & Testing Results

			8	7	9	6	5	4	3	2	1	15	13	27	28	94	96	95
Cementitious Materials		kg/m^3	400	450	475	500	550	600	650	700	750	600	500	500	550	593	593	652
Fly Ash		%	—	—	—	—	—	—	—	—	—	—	20	20	20	22	22	36
Silica Fume		%	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
Slag		%	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
w/cm			0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.30	0.28	0.30	0.28	0.28	0.28	0.31	0.29
Heat Curing			H1	H1	H1	H1	H1	H1	H1	H1	H1	H2	H2	H3	H3	H1	H1	H1
Compressive Strength at 1 day	Std	MPa	61.6	60.0	66.1	61.8	66.4	65.0	66.8	68.7	64.3	65.5	48.4	50.3	49.2	52.1	52.0	41.4
	Ht	MPa	57.8	58.3	66.9	63.4	63.6	61.1	61.5	66.6	66.2	63.2	48.6	56.6	57.7	61.6	53.0	47.2
	Diff	%	**(6.2)**	**(2.8)**	**1.2**	**2.6**	**(4.2)**	**(6.0)**	**(7.9)**	**(3.1)**	**3.0**	**(3.5)**	**0.4**	**12.5**	**17.3**	**18.2**	**1.9**	**14.0**
Compressive Strength at 28 days	Std	MPa	85.0	88.8	91.4	92.9	95.3	93.0	98.2	94.5	93.3	96.3	—	93.4	97.2	—	—	—
	Ht	MPa	77.5	78.8	87.5	84.4	83.3	84.1	87.4	93.4	91.1	88.3	—	94.4	92.9	—	—	—
	Diff	%	**(8.8)**	**(11.3)**	**(4.3)**	**(9.1)**	**(12.6)**	**(9.6)**	**(11.0)**	**(1.2)**	**(2.4)**	**(8.3)**	—	**1.1**	**(4.4)**	—	—	—

1 kg/m^3 = 1.686 lb/yd^3, 1 MPa = 145 psi

Table 7.2. Standard vs Intense Heat Curing — Mixture Proportions & Testing Results

			6	18	27	27	55	56	61	62	57	58	63	64	65	66	59	60
Cementitious Materials		kg/m^3	500	500	500	500	500	500	500	500	500	500	500	500	550	600	500	500
Fly Ash		%	—	—	20	20	—	—	—	—	10	10	10	10	10	10	—	—
Silica Fume		%	—	—	—	—	5	7.5	5	7.5	5	7.5	5	7.5	5	5	5	7.5
Slag		%	—	—	—	—	—	—	—	—	—	—	—	—	—	—	10	10
w/cm			0.30	0.28	0.28	0.28	0.30	0.30	0.28	0.28	0.28	0.28	0.26	0.26	0.26	0.24	0.30	0.30
Heat Curing			H5	H6	H4	H5	H5	H6	H6	H6	H6	H6	H6	H6	H6	H6	H6	H6
Compressive Strength at 1 day	Std	MPa	61.8	64.5	50.3	50.3	55.8	53.1	61.2	59.9	50.3	49.8	60.8	60.4	61.5	64.2	47.2	48.2
	Ht	MPa	59.4	60.0	59.6	58.2	67.0	56.2	70.3	63.2	76.1	72.9	70.4	65.7	71.9	74.8	67.2	50.6
	Diff	%	**(3.9)**	**(7.0)**	**18.5**	**15.7**	**20.1**	**5.8**	**14.9**	**5.5**	**51.3**	**46.4**	**15.8**	**8.8**	**16.9**	**16.5**	**42.4**	**5.0**
Compressive Strength at 28 days	Std	MPa	92.9	93.4	93.4	93.4	96.0	95.1	97.9	95.9	97.3	96.5	98.0	106.1	103.6	104.7	92.1	91.9
	Ht	MPa	80.7	74.0	65.3	78.2	73.5	63.8	68.4	71.6	87.5	83.4	85.9	68.2	95.9	95.5	71.6	61.1
	Diff	%	**(13.1)**	**(20.8)**	**(30.1)**	**(16.3)**	**(23.4)**	**(32.9)**	**(30.1)**	**(25.3)**	**(10.1)**	**(13.6)**	**(12.3)**	**(35.7)**	**(7.4)**	**(8.8)**	**(22.3)**	**(33.5)**
Compressive Strength at 56 days	Std	MPa	95.1	99.1	101.6	101.6	97.4	104.1	102.1	97.4	103.7	103.5	111.0	112.5	110.6	112.4	98.1	94.7
	Ht	MPa	83.4	76.8	73.5	82.8	74.2	64.9	68.9	68.8	77.5	87.8	81.0	75.1	93.0	93.3	68.6	55.2
	Diff	%	**(12.3)**	**(22.5)**	**(27.7)**	**(18.5)**	**(23.8)**	**(37.7)**	**(32.5)**	**(29.4)**	**(25.3)**	**(15.2)**	**(27.0)**	**(33.2)**	**(15.9)**	**(17.0)**	**(30.1)**	**(41.7)**

1 kg/m^3 = 1.686 lb/yd^3, 1 MPa = 145 psi

7.3. Experimental Procedures

Work was performed in the laboratory. Batching and testing procedures conformed to the applicable ASTM standards[1] except mixing time, which was often extended beyond the duration specified in ASTM C 192 and continued until the concrete appeared uniform.[2] Batch weights were adjusted for aggregate moisture.

Concrete cylinders were cast in 100 x 200 mm (4 x 8 in) plastic molds and consolidated by rodding. Cylinders were tested for compressive strength using neoprene pads seated in steel or aluminum rings. Tests followed the procedures of ASTM C 39 and were performed at ages of 1, 28 and 56 days. Three to five cylinders were tested at each age for each curing scheme under study; average results are reported.

Under standard curing (S/M), as described in Table 3.17, cylinders were cured at 23 °C (73.4 °F) and 50% relative humidity during the initial 24 hrs. Cylinders undergoing heat curing (other than H4/M) were placed into a water bath inside a tank and immersed up to the mold's rim. The tank was covered and enclosed with insulating material. The temperature of the water bath was regulated with a heating element. Under moderate heat curing (H1/M, H2/M, H3/M), the bath temperature was maintained at 42 °C (108 °F) or 30 °C (86 °F). With intense heat curing (H5/M, H6/M), the bath temperature was maintained at 60 °C (140 °F). Another method (H4/M) involved generating steam by boiling a pot of water inside the tank, with the temperature reaching 71 °C (160 °F). In most cases, heat curing commenced after a delay period of 3 to 6 hrs after casting to allow concrete to reach initial set. The various curing schemes differed only during the initial 24 hrs. At 24 hrs, molds were removed and thereafter, until tested, all cylinders were moist cured (under water) as specified by ASTM C 192 at a temperature of 23 °C (73.4 °F).

7.4. Experimental Results

A summary of the testing results is presented in Table 7.1 for "standard vs. moderate heat curing" and in Table 7.2 for "standard vs. intense heat curing." Compressive strength results are presented at various ages for both standard and heat curing together with the change, in percent, observed with heat curing relative to standard curing. Numbers in parenthesis indicate a negative response to heat curing relative to standard curing. Under standard curing, average compressive strength results of the 31 different HPC mixtures were 57.7 MPa (8,370 psi) at 1 day, 95.3 MPa (13,820 psi) at 28 days and 102.9 MPa (14,920 psi) at 56 days.

7.5. Analysis and Discussion of Results

Heat curing enhanced the early strength development of most HPC mixtures relative to standard curing. On average at 1 day, moderate heat curing increased strength development by 2.3% while intense heat curing increased strength development by 17.0%. Conversely, after 1 day, strength development was generally less with heat curing than with standard curing. At 28 days, moderate heat curing stunted strength development by 6.8%, on average. Intense heat curing, on average, stunted strength development by 20.7% at 28 days and by 25.8% at 56 days. The range of compressive strength results generally increased under heat curing.

For the purpose of analysis, mixtures were divided into five groups according to cementitious material composition:

- Cement only (those mixtures containing *Type III* cement exclusive of supplementary cementitious materials)
- With fly ash
- With silica fume
- With fly ash and silica fume
- With slag and silica fume

Compressive strength results of "standard vs. moderate heat curing" are illustrated in Figures 7.1 and 7.2 for ages of 1 and 28 days, respectively. Compressive strength results of "standard vs. intense heat curing" are illustrated in Figures 7.3, 7.4 and 7.5 for ages of 1, 28 and 56 days, respectively. In these figures, the strength with standard curing is measured on the abscissa and the strength with heat curing is measured on the ordinate for a single mixture. A main diagonal line represents an equal response to standard and heat curing. Other lines mark 20% and 40% above or below the main diagonal line to depict the influence of heat curing.

Different HPC mixtures responded differently to moderate heat curing. Moderate heat curing largely failed to enhance early strength development of the "cement only" mixtures, as portrayed in Figure 7.1. At 1 day, seven of ten "cement only" mixtures gained less strength with moderate heat curing than with standard curing. However, mixtures "with fly ash" were enhanced by moderate heat at 1 day. By 28 days, as portrayed in Figure 7.2, almost all mixtures achieved higher strength with standard curing.

Figure 7.1.
Standard vs. Moderate Heat Curing (1 day)

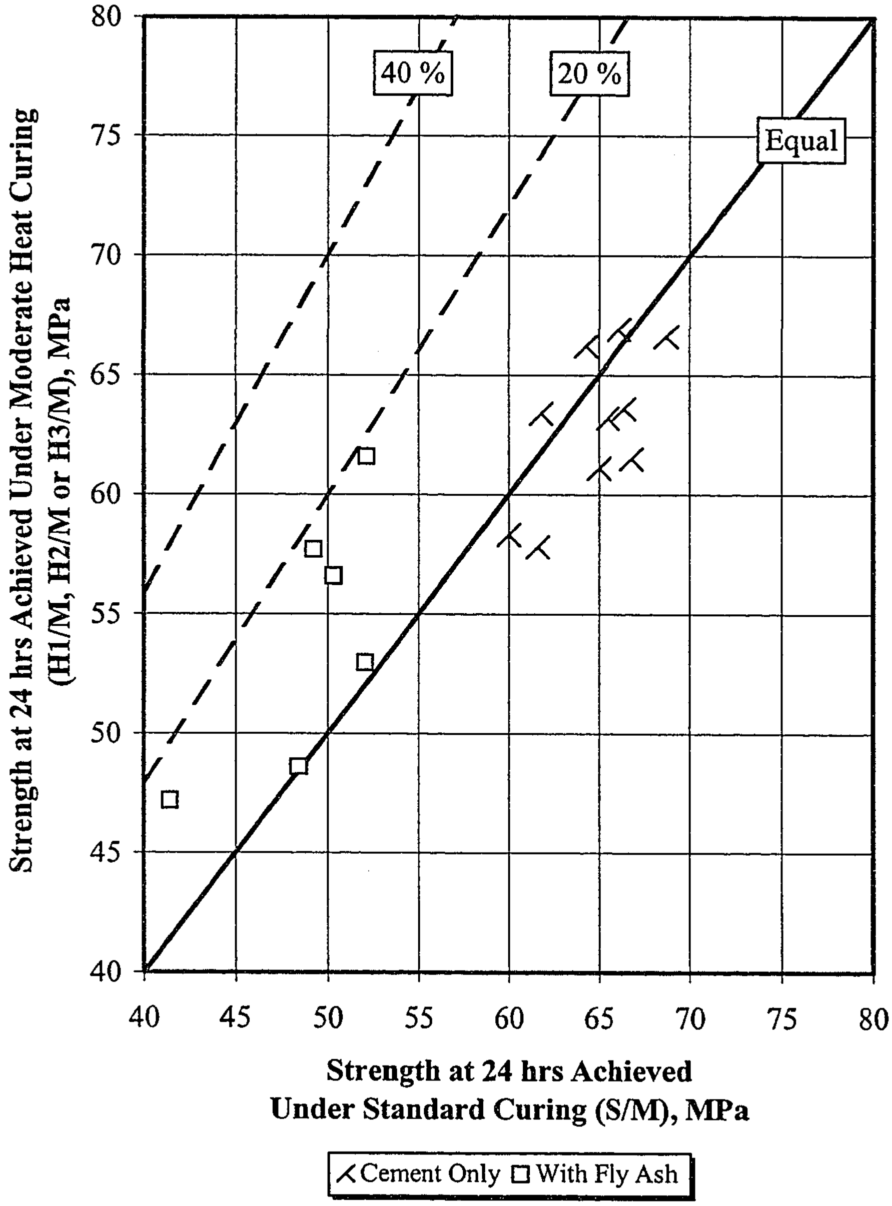


Figure 7.2.
Standard vs. Moderate Heat Curing (28 days)

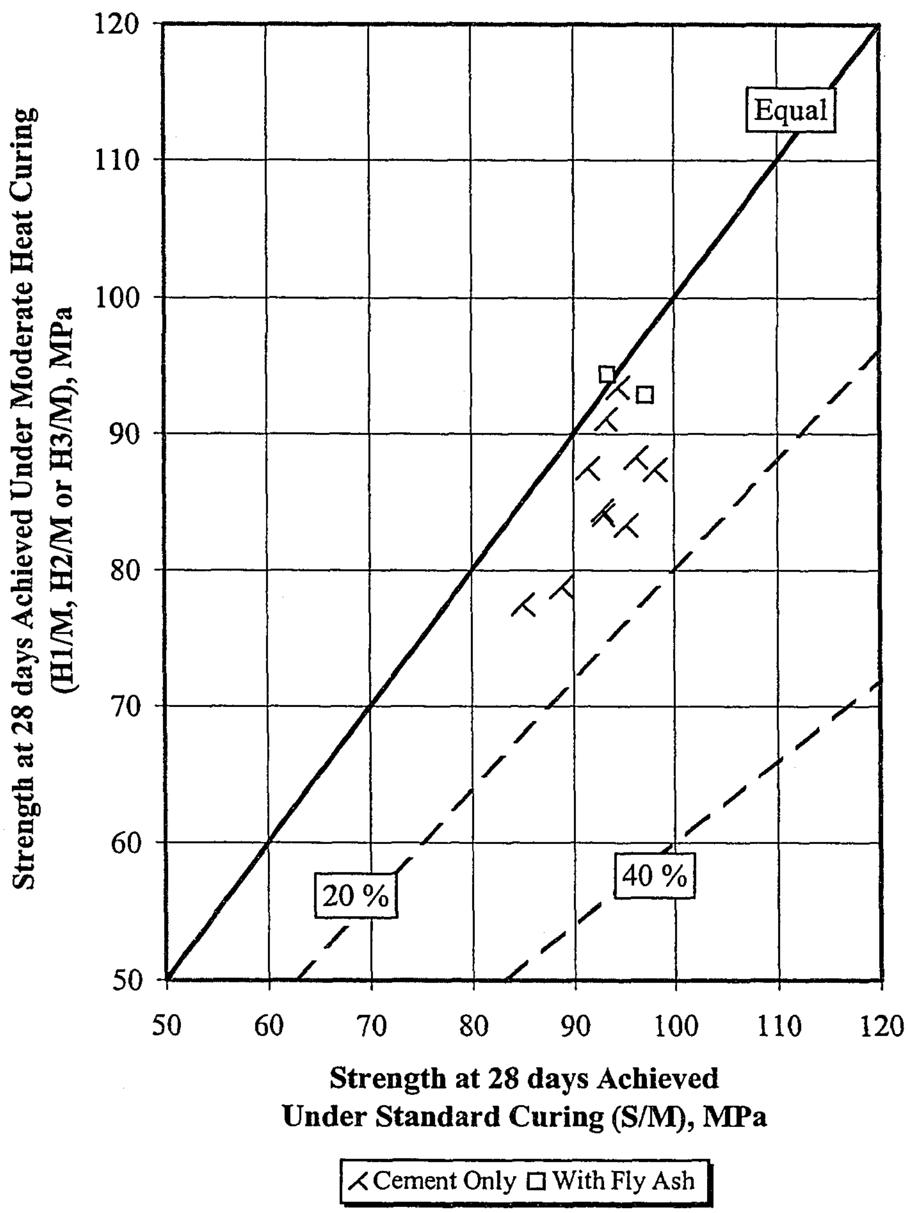


Figure 7.3.
Standard vs. Intense Heat Curing (1 day)

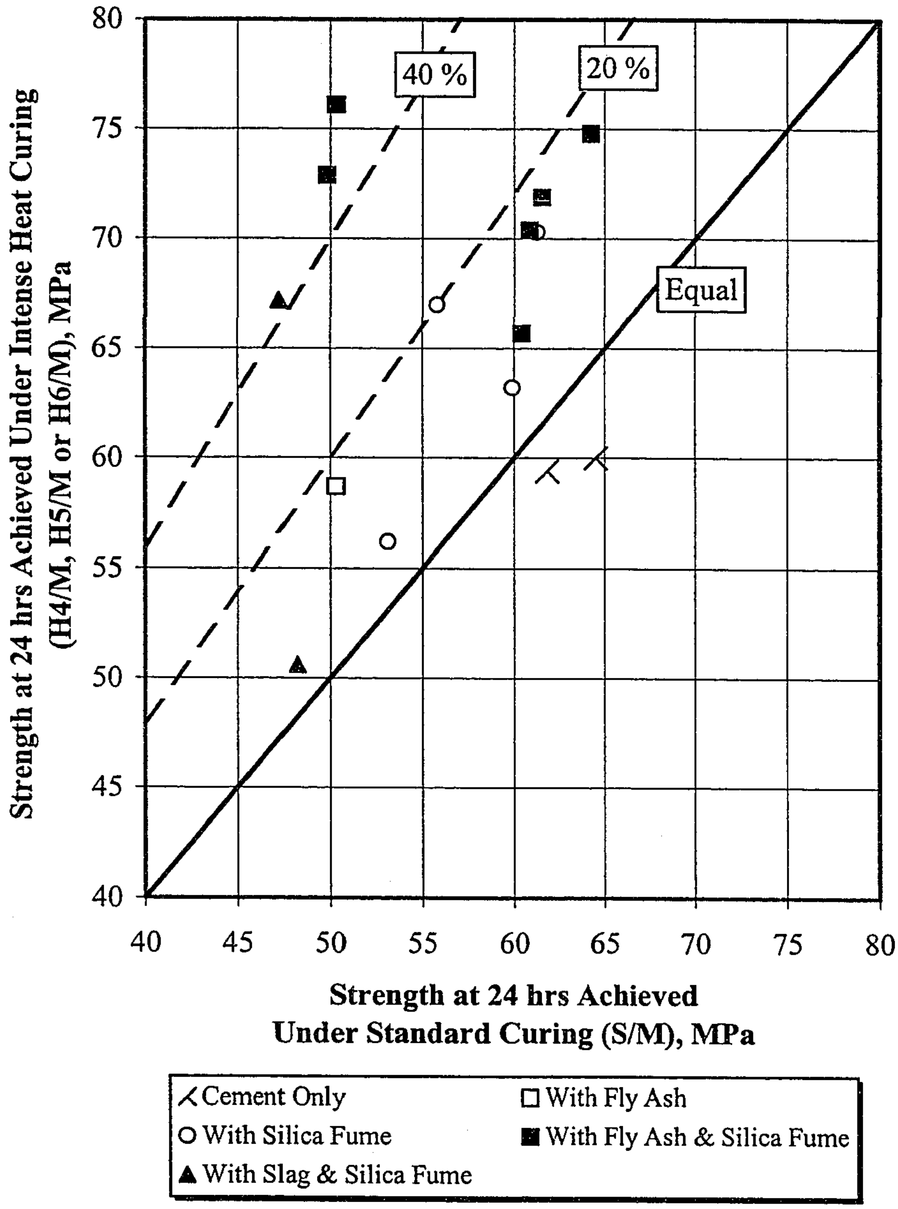


Figure 7.4.
Standard vs. Intense Heat Curing (28 days)

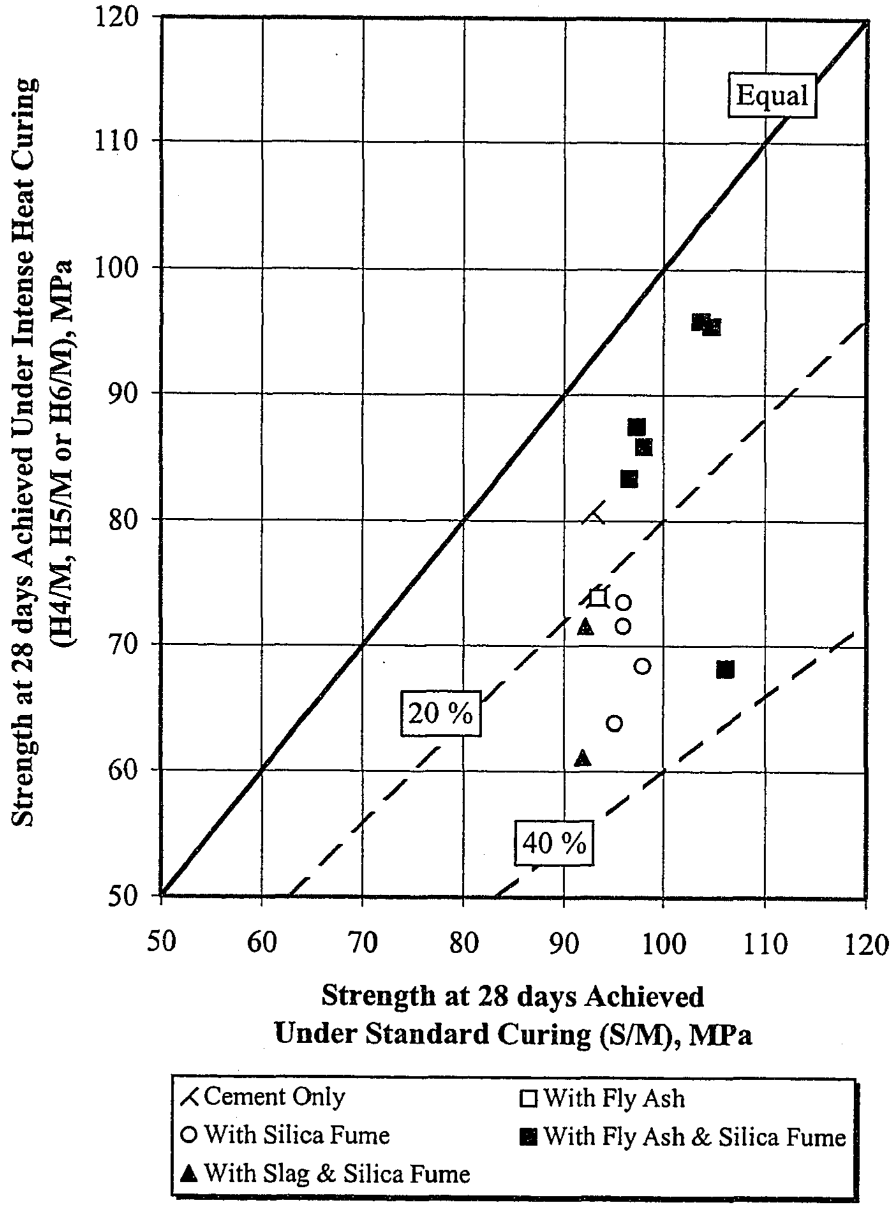
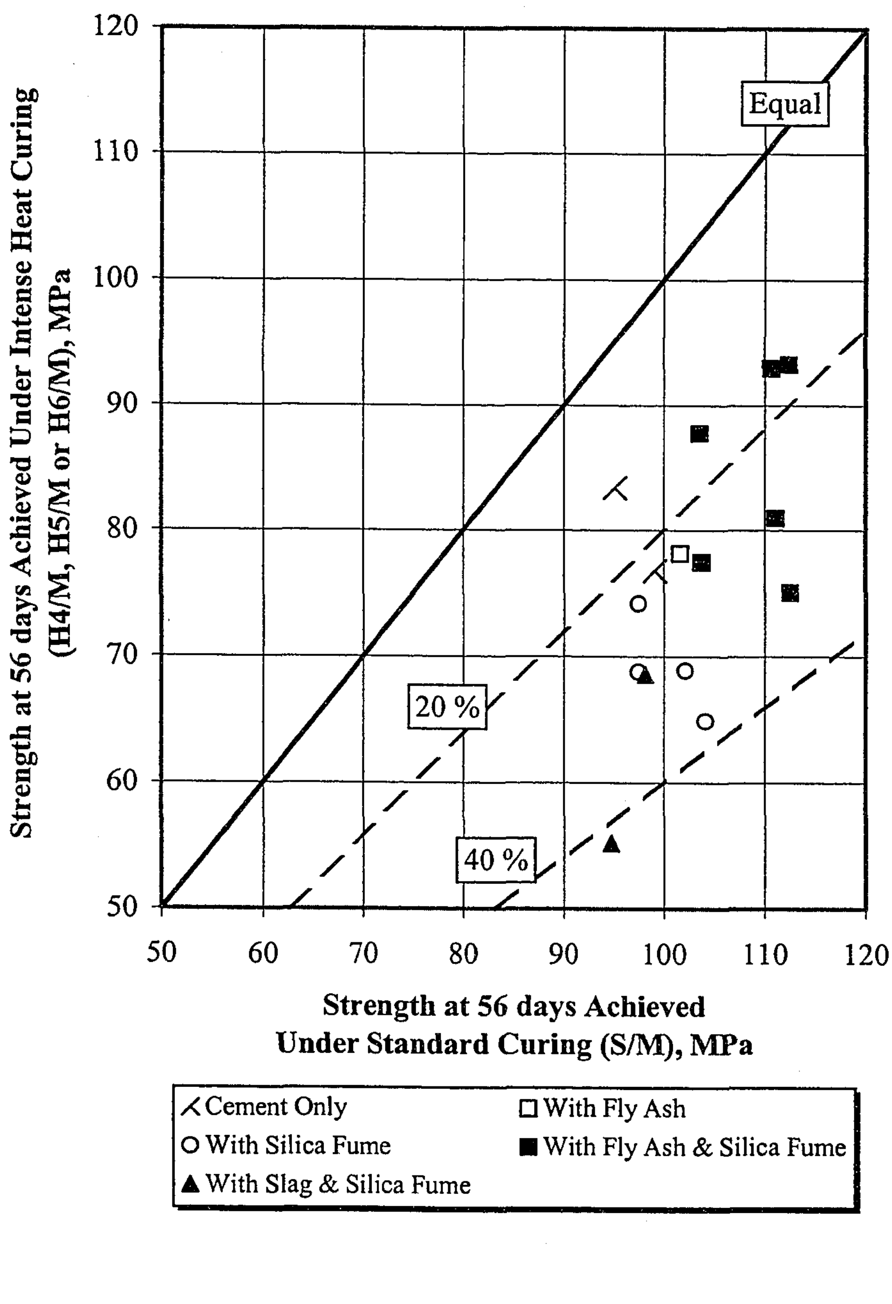


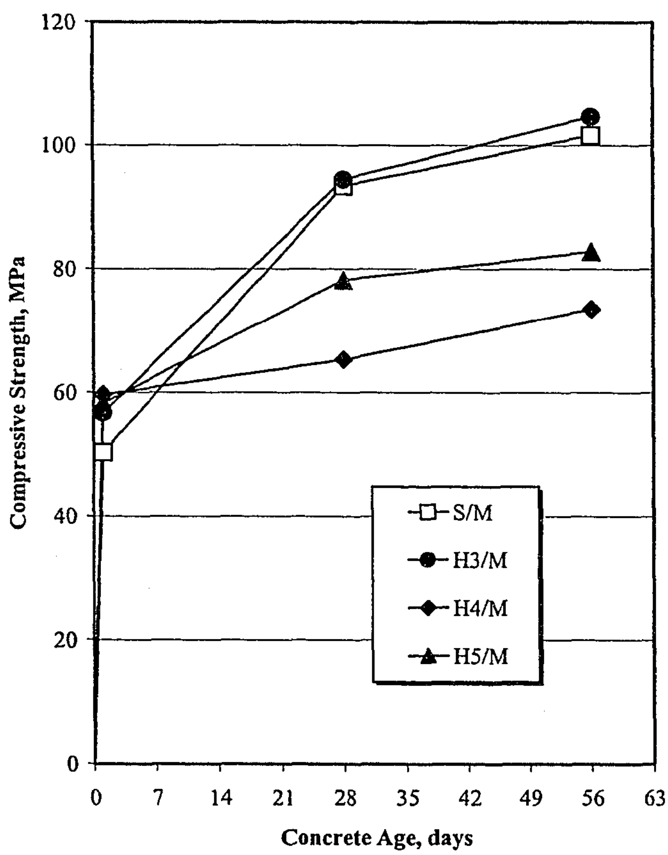
Figure 7.5.
Standard vs. Intense Heat Curing (56 days)



Different HPC mixtures responded differently to intense heat curing. Intense heat curing enhanced early strength development for those mixtures containing supplementary cementitious materials, as portrayed in Figure 7.3. In certain mixtures "with fly ash and silica fume" (57, 58) and "with slag and silica fume" (59) the improvement at 1 day from intense heat curing was more than 40%. Conversely, with the two "cement only" mixtures (6, 18), intense heat curing slightly impaired early strength development. By 28 and 56 days, as portrayed in Figures 7.4 and 7.5, intense heat curing was detrimental to strength development in all mixtures relative to standard curing. Intense heat curing caused strength retrogression between 28 and 56 days in certain mixtures "with silica fume" (62), "with fly ash and silica fume" (57, 63, 65, 66) and "with slag and silica fume" (59, 60). Strength retrogression under intense heat curing also occurred between 1 and 28 days in a mixture "with silica fume" (61).

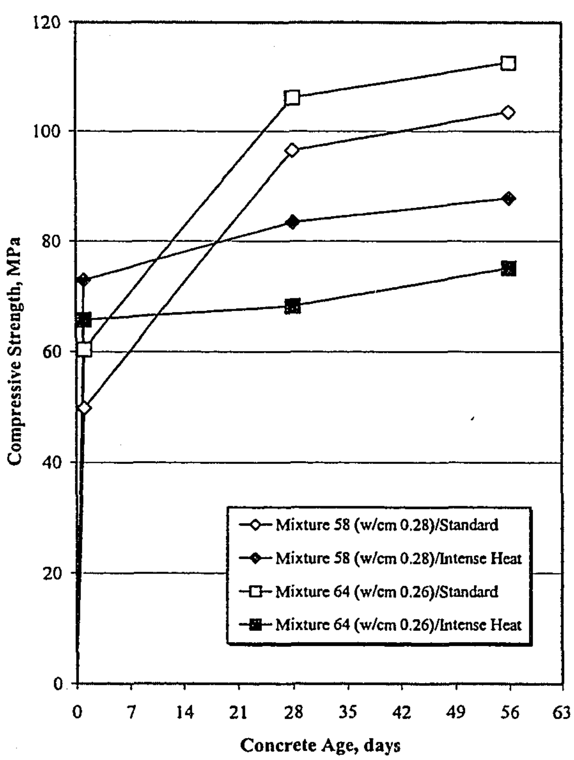
To directly compare curing schemes, a single mixture (27) was examined under three heat curing schemes, one moderate heat (H3/M) and two intense heat (H4/M and H5/M), along with standard curing. This mixture contained 500 kg/m^3 (843 lb/yd^3) of cementitious material, *Type III* cement with 20% fly ash replacement, at a w/cm of 0.28. Results are illustrated in Figure 7.6. At 1 day, heat curing was beneficial to strength development. The three heat curing schemes were almost identically effective and the order of the results corresponded with the peak temperatures. The heat curing scheme with the highest peak temperature (H4/M) also produced the highest strength at 1 day. At 28 and 56 days, intense heat curing was detrimental to strength development. Of the two intense heat curing schemes, H4/M was more damaging than H5/M. H4/M had a higher peak temperature (71 vs. 60 °C) and longer duration of heat (21 vs. 18 hrs) than H5/M. Moderate heat curing produced the best results at 28 and 56 days, slightly better than standard curing.

Figure 7.6.
A Single HPC Mixture Subjected to Multiple Curing Schemes



Two similar mixtures (58, 64) with w/cm's of 0.28 and 0.26 were examined under both standard and intense heat curing (H6/M). These mixtures contained 500 kg/m^3 (843 lb/yd^3) of cementitious material, *Type III* cement with 10% fly ash and 7.5% silica fume replacement. Results are illustrated in Figure 7.7. Under standard curing, the mixture with a w/cm of 0.26 (64) achieved higher strength than the mixture with a w/cm of 0.28 (58) at all ages, as expected given the lower w/cm. Conversely, under heat curing, the mixture with a w/cm of 0.28 (58) achieved higher strength at all ages. In this case, reducing the w/cm was detrimental to strength development under heat curing. The optimum w/cm may depend on the curing scheme.

Figure 7.7.
The Response of Similar HPC Mixtures to Heat Curing



Heat curing generally accelerated early strength development relative to standard curing but always at the expense of ultimate strength potential. Heat curing causes a rapid cement hydration, but the physical structure that grows is more porous and less complete. Under high temperature, the products of hydration build up quickly within the vicinity of cement particles and, with insufficient time available to disperse, subsequent hydration is hampered and porosity of the space between cement particles increases. Also associated with heat curing is the increased presence of very fine cracks caused by the thermal expansion of air bubbles.[3] Retrogression of strength may occur as a result and was observed in several of the HPC mixtures of this study.

Understanding the consequences of accelerating early strength gain with heat curing, it is clearly inadvisable to specify or to achieve early strength excessive to that required for release of prestressing force. The objective should be to meet, but not exceed, the strength requirements for release, thereby preserving the greatest possible strength gain after release.[4] Extending the production cycle beyond the typical 24 hrs may be necessary when a design requires exceptionally high strength.[5,6]

An interesting result of this study was that the "cement only" group of HPC mixtures generally achieved higher strength at 1 day under standard curing as opposed to heat curing. These results suggest that the heat of hydration was higher under standard curing. Concrete temperature during the early hydration period was not recorded, but another study recorded a temperature rise of 50 °C (90 °F) above an initial 23 °C (73.4

°F) within 100 x 200 mm (4 x 8 in) cylinders cured under adiabatic conditions.[7] (The other study's concrete had a compressive strength of 100 MPa at 28 days, similar to this study.) Under heat curing, it is believed that the bath effectively placed a ceiling on the temperature climb within these concrete cylinders.

In the view of some, heat curing of HPC may be an unnecessary expense.[8] A conclusion of Chapter 4, HPC naturally develops strength more rapidly than conventional concrete, particularly those HPC mixtures designed for use in precast/prestressed bridge beams.[9] These mixtures are commonly designed with *Type III* cement, w/cm's below 0.40 and cementitious material contents in excess of 500 kg/m^3 (843 lb/yd^3).

7.6. Summary and Conclusions

A variety of HPC mixtures were examined under a number of heat curing schemes in parallel with ASTM C 192 standard curing to investigate the effect of curing on compressive strength development. The heat curing schemes were classified as either moderate or intense based on peak temperature. These were intended to simulate the heat curing processes regularly employed in the manufacture of precast/prestressed concrete bridge beams. The study involved 31 different HPC mixtures, each containing *Type III* cement and many having partial replacement of cement with fly ash, silica fume and/or slag. The w/cm's of the HPC mixtures ranged from 0.24 to 0.31.

Under standard curing, average compressive strength results were 57.7 MPa (8,370 psi) at 1 day, 95.3 MPa (13,820 psi) at 28 days and 102.9 MPa (14,920 psi) at 56 days. Different mixtures responded differently to heat curing but, in general, heat curing was found damaging to ultimate strength potential and sometimes even failed to accelerate early strength development. In terms of strength development at 1 day, heat curing was beneficial to mixtures containing supplementary cementitious materials. However, mixtures with *Type III* cement exclusive of supplementary cementitious materials largely failed to benefit from heat curing at 1 day. Heat curing impaired strength development at 28 and 56 days relative to standard curing, and intense heat was found more damaging than moderate heat. By examining a single mixture under multiple curing schemes, moderate heat was found nearly as effective as intense heat for enhancing early strength development and without the negative consequences at 28 and 56 days. Additionally, lowering the w/cm, while beneficial to strength development under standard curing, was found to be detrimental under intense heat curing.

Speed of construction is an important consideration in the manufacture of precast/prestressed concrete bridge beams. Heat curing is regularly employed to accelerate early strength development. However, while heat curing may be useful in a business model that gives emphasis to rapid speed of construction, it may not always be pragmatic in a business model that gives emphasis to lifecycle costs.

[1] American Society for Testing and Materials, *Annual Book of ASTM Standards*, Vol. 4.01 and 4.02, 1995.
[2] ACI 318, *Building Code Requirements for Structural Concrete and Commentary*, American Concrete Institute, 1999.
[3] Neville, A. M., *Properties of Concrete*, Fourth Ed., John Wiley & Sons, Inc., 1996.
[4] Prussack, C., "Covington High Performance Concrete Bridge," *Proceedings of the PCI/FHWA International Symposium of High Performance Concrete*, New Orleans, Louisiana, 1997, pp. 515-520.
[5] Russell, H. G., "High Strength Concrete in Bridges — History and Challenges," *Proceedings of the PCI/FHWA International Symposium of High Performance Concrete*, New Orleans, Louisiana, 1997, pp. 27-38.
[6] Zia, P. and Hillmann, R. S., "Development of High Early Strength Concrete for Prestressed Concrete Applications," *North Carolina Department of Transportation in cooperation with the Federal Highway Administration*, June 1995.
[7] Khan, A. A., Cook, W. D. and Mitchell, D., "Thermal Properties and Transient Thermal Analysis of Structural Members during Hydration," *ACI Materials Journal*, Vol. 95, No. 3, May/June 1998, pp. 293-303.
[8] Huo, X. and Tadros, M. K., "Application of High Performance Concrete in Giles Road Bridge, Nebraska," *Proceedings of the PCI/FHWA International Symposium of High Performance Concrete*, New Orleans, Louisiana, 1997, pp. 646-656.
[9] Azimi, A. and Zia, P., "Research and Utilization of High Performance Concrete in North Carolina," *Proceedings of the PCI/FHWA International Symposium of High Performance Concrete*, New Orleans, Louisiana, 1997, pp. 635-645.

8. Designing HPC for Precast/Prestressed Bridge Beams

8.1. Introduction

High early strength is the concrete characteristic most desired in construction of precast/prestressed bridge beams, where productivity depends on timely release of prestressing force. The concrete strength required for release usually governs the mixture design.[1] But achieving high early strength alone is insufficient; other concrete characteristics are essential as well. The challenge unique to the precast/prestressed concrete industry is achieving high early strength in harmony with adequate workability and high ultimate strength. In construction of bridge beams, the industry is now encountering the need to achieve 60 MPa (8,700 psi) inside of 1 day and 100 MPa (14,500 psi) by 28 or 56 days as span and spacing continue to expand. Adequate workability is required for efficient placement and consolidation into narrow, congested sections. While not necessarily incompatible or conflicting, these performance requirements are increasingly at odds as the limits of high performance concrete (HPC) are pushed. When designing HPC to satisfy multiple performance objectives, it is helpful to survey all the options and to understand the benefits and the disadvantages of each.

8.2. Experimental Program

A study was performed to identify suitable materials and develop HPC mixtures for precast/prestressed bridge beams. Altogether, more than one hundred HPC mixtures were evaluated. Mixtures were designed on the basis of high early strength potential while providing adequate workability and long term strength development. Among the options for achieving high early strength, workability and high ultimate strength:

- Low water/cementitious material (w/cm) ratio
- Increased cement content
- Supplementary cementitious materials
- *Type III* cement
- Chemical admixtures — superplasticizer, air entraining admixture and corrosion inhibiting/strength accelerating admixture
- Heat curing

What follows is a discussion of these various options supported with experimental results from the *Mixture Proportion Study.*

8.3. Experimental Procedures

Work was performed in the laboratory. Batching and testing procedures conformed to the applicable ASTM standards[2] except mixing time, which was often extended beyond the duration specified in ASTM C 192 and continued until the concrete appeared uniform.[3] Batch weights were adjusted for aggregate moisture.

Concrete cylinders were cast in 100 x 200 mm (4 x 8 in) molds and consolidated by rodding. Cylinders were cured at 23 °C (73.4 °F) and 50% relative humidity during the initial 24 hrs. After 24 hrs and until tested, cylinders were moist cured (under water) at a temperature of 23 °C (73.4 °F) as specified by ASTM C 192.

Cylinders were tested for compressive strength at ages of 1, 28 and 56 days. Tests followed the procedures of ASTM C 39. Three to five cylinders were tested at each age. Many mixtures were batched multiple times to increase accuracy of the results. If batched more than once, the result was reported as an average of individual batch results. Complete testing results of the *Mixture Proportion Study* are included in Appendix E.

8.4. Experimental Results, Analysis and Discussion

Designing HPC to satisfy multiple performance objectives is an exercise of choosing among several options. In Table 8.1, the options for achieving high strength, workability and high ultimate strength are graded as beneficial or detrimental where appropriate. These grades reflect general guidelines and are based on the data of this research program and a synthesis of the literature.

Table 8.1. Options For Achieving High Strength & Workability

	HIGH EARLY STRENGTH GAIN	WORKABILITY	LONG TERM STRENGTH DEVELOPMENT
Low w/cm	△	▼	△
Increased Cement Content		△	
Supplementary Cementitious Materials		△	△
***Type III* Cement**	△	▼	▼
Superplasticizing Admixture	△	△	△
AE Admixture	▼	△	▼
CI/SA Admixture	△		△
Heat Curing	△		▼

△ Beneficial
▼ Detrimental

8.4.1. Low w/cm

The w/cm was identified as the most significant variable for producing HPC.[4] A low w/cm is beneficial to both early strength gain and ultimate strength potential. In Figure 8.1, simple linear regression models were created to describe the relationship between strength and w/cm. The regression lines represent the results from 125 HPC mixtures. These mixtures were designed with a variety of materials and proportions, with 94 of the mixtures containing *Type III* cement and w/cm's ranging from 0.406 to 0.220. The evidence suggests, at ages of 1, 28 and 56 days, that strength generally increases as the w/cm is lowered. Figure 8.1 is a summary of Figures 6.1, 6.2 and 6.3 and these results are presented in more detail in Chapter 6.

But how low a w/cm is too low? Or more precisely, is there a point when decreasing the w/cm fails to increase strength? Having a low w/cm may result in an incomplete cement hydration due to lack of water required for the process.[5] The theoretical minimum water/cement (w/c) ratio for complete cement hydration is about 0.20 to 0.40 depending on the physical and chemical characteristics of the cementitious materials and, in reality, on the effectiveness of chemical admixtures and mixing.[6,7] In HPC, ultimate strength potential may be limited by the amount of water available for hydration or by the intrinsic strength of the coarse aggregate.[6,8] Two similar HPC mixtures with w/cm's at very low levels are described in Table 8.2. Mixture 79 was designed with a w/cm of 0.24. Mixture 78 was designed with a w/cm of 0.22.

Compressive strength results are illustrated in Figure 8.2. In this case, lowering the w/cm from 0.24 to 0.22 enhanced strength at 1 day and, to a lesser extent, at 28 days. However, by 56 days both mixtures achieved nearly identical strength.

Results from the same 125 HPC mixtures as discussed earlier also demonstrate that the rate of early strength gain increases with lower w/cm. In Figure 8.3, regression models describe strength gain at 1 day relative to strength at 28 days and also strength gain at 56 days relative to strength at 28 days. In Figure 8.3, $\bar{f}_c$ is defined as the average measured compressive strength. Strength gain at 1 day was found to be as much as 60% of corresponding strength at 28 days. The lower w/cm and the proximity of the cement particles increases the rate of cement hydration.[6] In contrast, between 28 and 56 days, the rate of strength gain was found to be independent of w/cm. Across the range of w/cm's, a nearly identical rate of strength gain was observed between 28 and 56 days.

Reducing the w/cm is detrimental to workability. When working in summer, HPC mixtures designed with *Type III* cement at low w/cm's may be difficult to place, consolidate and finish. Workability requirements put a practical limit on how low the w/cm can be designed.

Figure 8.1. Concrete Strength & w/cm

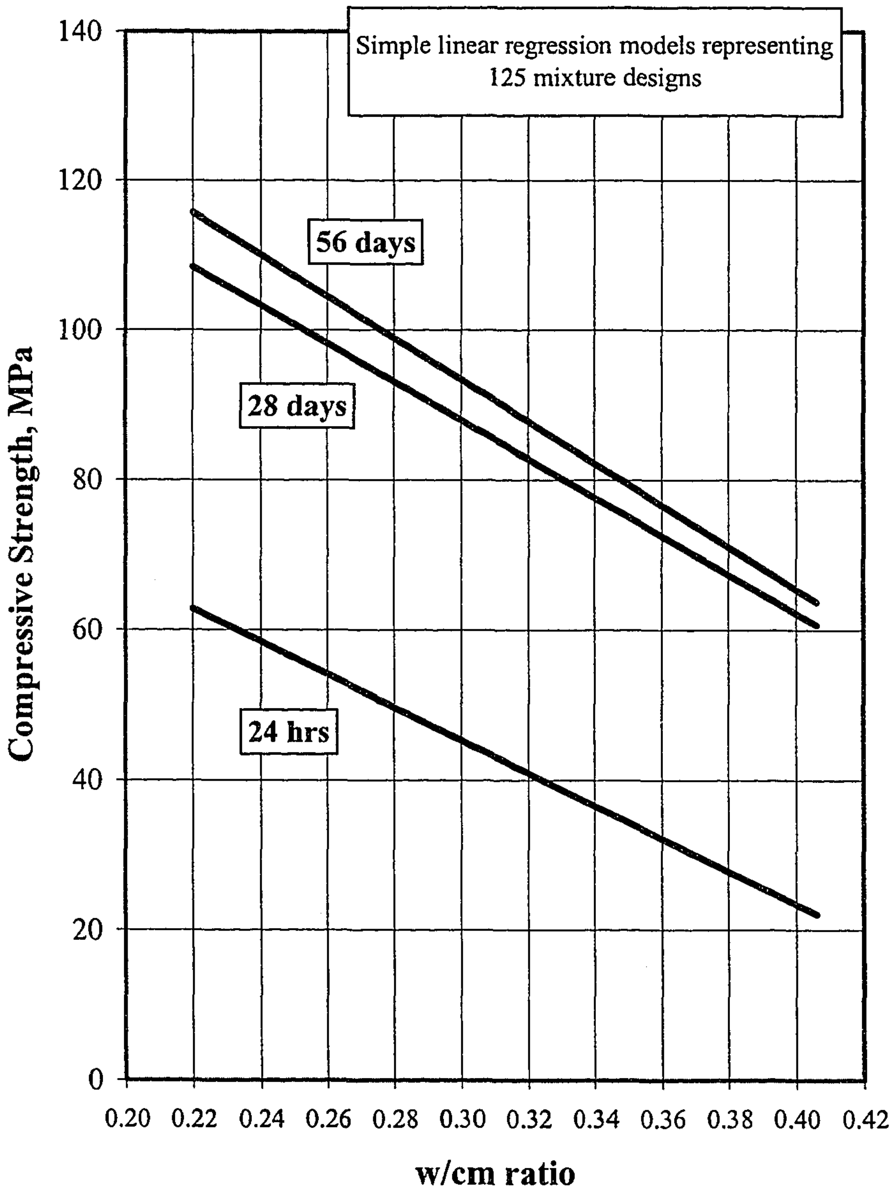


Table 8.2.
Lowering the w/cm to Extreme Levels —
Mixture Proportions and Testing Results

			79	78
Cement[a]		kg/m^3	510.0	510.0
Fly Ash[b]		kg/m^3	60.0	60.0
Silica Fume		kg/m^3	30.0	30.0
Coarse Aggregate[c]		kg/m^3	980.4	980.4
Fine Aggregate[d]		kg/m^3	701.5	733.0
Mixing Water		kg/m^3	138.3	126.3
WR Admixture[e]		L/m^3	1.80	1.80
HRWR Admixture[f]		L/m^3	7.80	7.80
w/cm			**0.240**	**0.220**
No. of Batches			2	1
Compressive Strength	1 d	MPa	54.0	63.7
	28 d	MPa	112.3	117.0
	56 d	MPa	122.0	122.4

[a] ASTM C 150 *Type III* cement with a C_3S content of 63.0%, C_2S content of 12.0% and Blaine fineness of 4,740 cm^2/g
[b] ASTM C 618 *Class C* fly ash having specific gravity of 2.65, calcium oxide (CaO) content of 28.4% and pozzolanic activity index of 99%
[c] Crushed limestone meeting the No. 8 grading requirements of ASTM C 33 and having a bulk specific gravity of 2.67 and absorption of 1.2% and DRUW of 1,623 kg/m^3
[d] Natural river sand having a bulk specific gravity of 2.63, absorption of 0.7% and fineness modulus of 2.47
[e] ASTM C 494 *Type A* water reducing admixture
[f] ASTM C 494 *Type F* superplasticizer

1 kg/m^3 = 1.686 lb/yd^3, 1 L/m^3 = 25.85 $floz/yd^3$, 1 MPa = 145 psi

Figure 8.2.
Lowering the w/cm to Extreme Levels

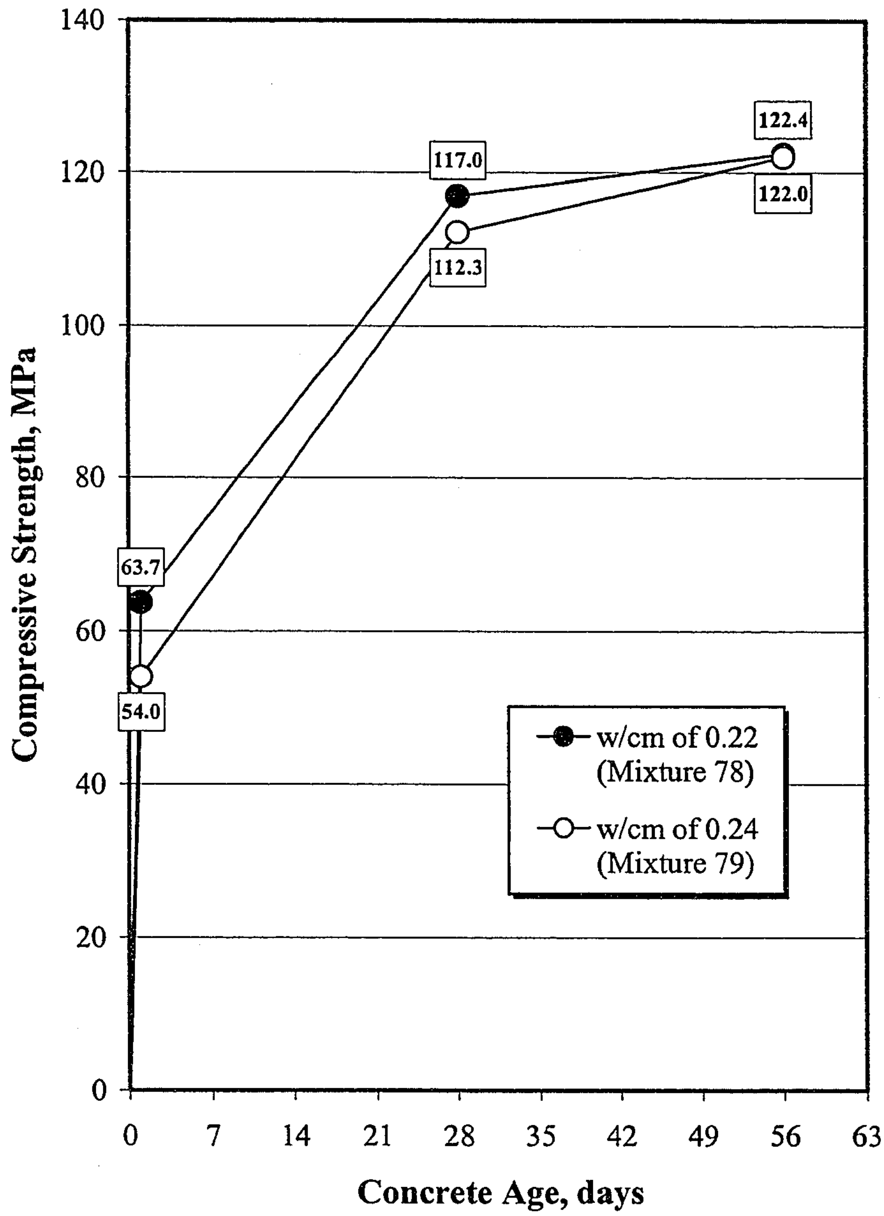
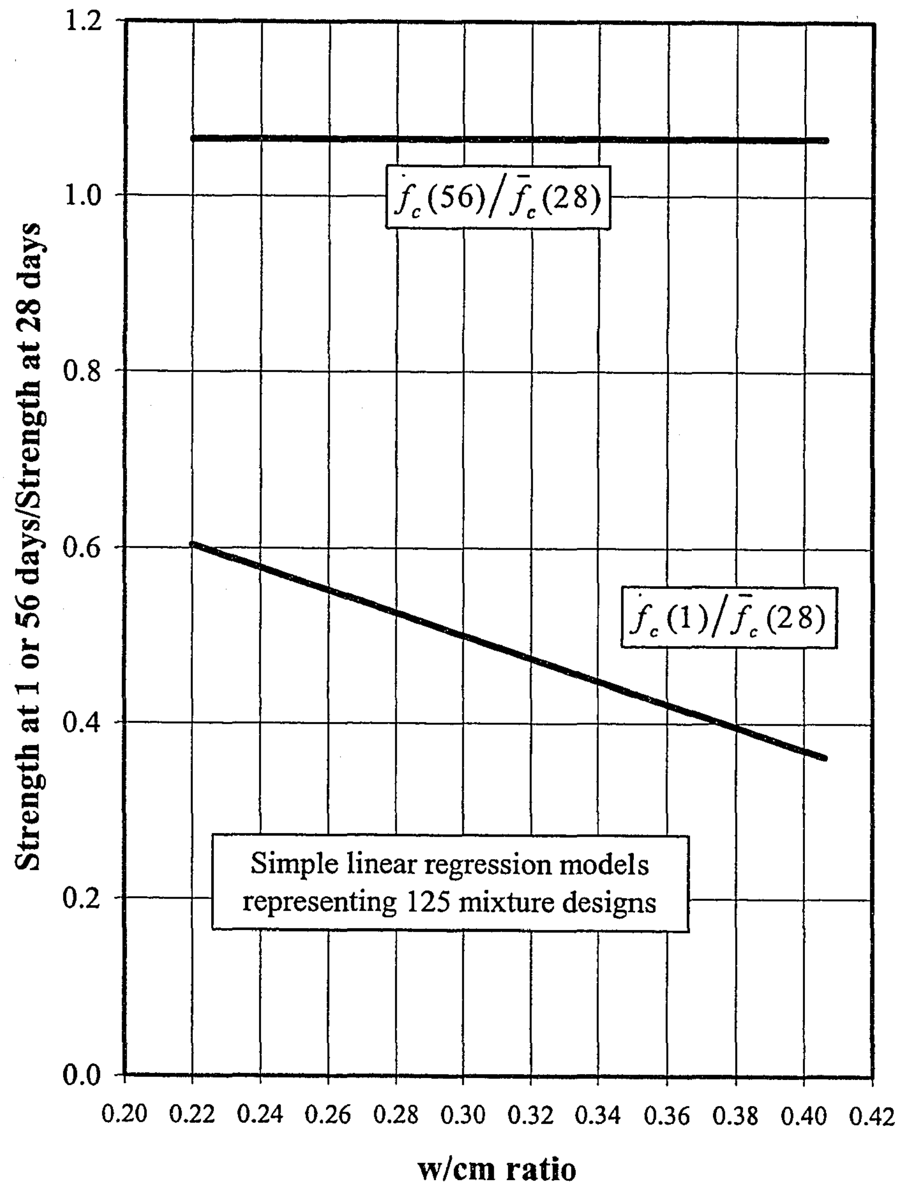


Figure 8.3.
Rate of Strength Gain & w/cm



8.4.2. Increased Cement Content

Increases of cement content at a constant w/cm do not necessarily influence compressive strength, in conventional concrete or in HPC.[6,9] Guidelines for concrete mixture design by both the Portland Cement Association and ACI 363 specify relationships between compressive strength and w/cm, but not compressive strength and cement content. But, one study of conventional concrete found that increases of cement content at a constant w/cm actually decreases strength.[10]

A series of HPC mixtures with a w/cm of 0.30 and *Type III* cement are presented in Table 8.3. Cement content of these mixtures ranged from 400 to 750 kg/m^3 (674 to 1,265 lb/yd^3). Slump and compressive strength results are illustrated in Figure 8.4. A strength plateau was reached at a cement content near 500 kg/m^3 (843 lb/yd^3). Beyond this point, increasing cement content did not significantly improve strength development, at 1 or 28 days. The modest increase in strength observed with increasing cement content might be attributed to an increase in the heat of hydration.

Increasing the cement content in an HPC mixture is often necessary for adequate workability. Slump measurements and a second order polynomial trendline are portrayed in Figure 8.4. Increasing cement content at the same w/cm was observed to enhance slump. Slump is an approximate measure of workability. Simply explained, more water is available for lubrication of the fresh concrete, especially after a superplasticizer is introduced. If slump of 150 mm (6 in) is desired for workability then, given these results, a mixture with a minimum of 500 kg/m^3 (843 lb/yd^3) cement is necessary. Sometimes in practice, an increase in the cement content is accompanied by a decrease in the w/cm at the same workability. It is advisable to increase cement content sparingly to avoid escalating the cost of the mixture as well as amplifying heat during curing and the danger of cracking.

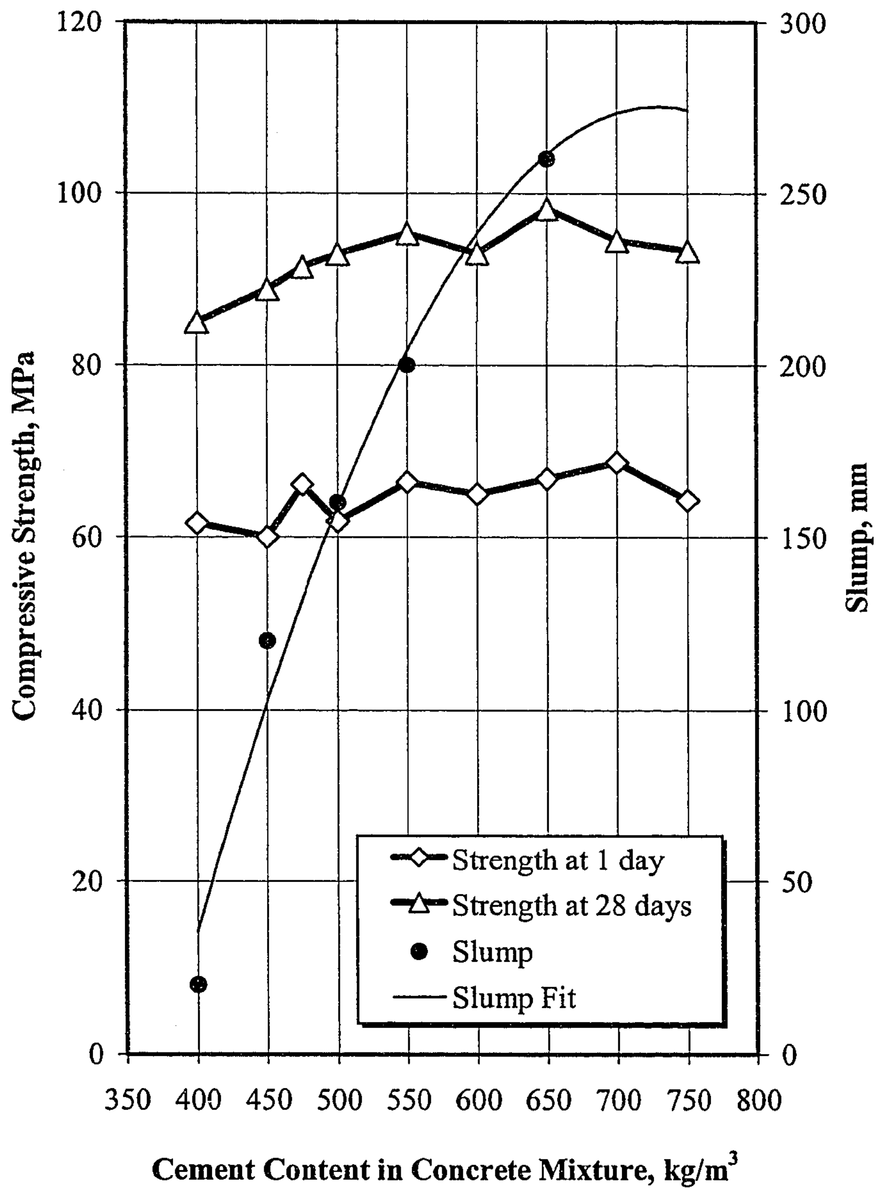
Table 8.3. Changing Cement Content with a Constant w/cm — Mixture Proportions and Testing Results

			8	7	9	6	5	4	3	2	1
Cement[a]		**kg/m^3**	**400.0**	**450.0**	**475.0**	**500.0**	**550.0**	**600.0**	**650.0**	**700.0**	**750.0**
Coarse Aggregate[b]		kg/m^3	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1
Fine Aggregate[c]		kg/m^3	875.3	793.4	751.7	711.4	629.4	547.5	464.2	383.5	300.0
Mixing Water		kg/m^3	116.0	130.5	138.0	145.0	159.5	174.0	189.0	203.0	218.0
WR Admixture[d]		L/m^3	1.20	1.35	1.43	1.50	1.65	1.80	1.95	2.10	2.25
HRWR Admixture[e]		L/m^3	5.20	5.85	6.18	6.50	7.15	7.80	8.45	9.10	9.75
w/cm			**0.300**	**0.300**	**0.300**	**0.300**	**0.300**	**0.300**	**0.300**	**0.300**	**0.300**
No. of Batches			1	2	4	3	1	1	1	1	1
Slump		mm	20	120	—	160	200	—	260	—	280
Compressive Strength	1 d	MPa	61.6	60.0	66.1	61.8	66.4	65.0	66.8	68.7	64.3
	28 d	MPa	85.0	88.8	91.4	92.9	95.3	93.0	98.2	94.5	93.3

[a] ASTM C 150 *Type III cement with a* C_3S *content of 58.2 %,* C_2S *content of 12.8 %* and Blaine fineness of 5,490 cm^2/g
[b] Crushed limestone meeting the No. 8 grading requirements of ASTM C 33 and having a bulk specific gravity of 2.67 and absorption of 1.2 % and DRUW of 1,623 kg/m^3
[c] Natural river sand having a bulk specific gravity of 2.63, absorption of 0.7 % and fineness modulus of 2.47
[d] ASTM C 494 *Type A* water reducing admixture
[e] ASTM C 494 *Type A/F* superplasticizer

1 kg/m^3 = 1.686 lb/yd^3, 1 L/m^3 = 25.85 $floz/yd^3$, 25.4 mm = 1 in, 1 MPa = 145 psi

Figure 8.4.
Changing Cement Content with a Constant w/cm



8.4.3. Supplementary Cementitious Materials

Supplementary cementitious materials such as fly ash are frequently employed in HPC mixtures. Partial replacement of cement with supplementary cementitious materials usually, but not always, improves workability. Supplementary cementitious materials enhance workability by moderating the temperature rise of fresh concrete. The spherical shape of fly ash particles also contributes to workability. Largely pozzolanic in composition, supplementary cementitious materials convert weak calcium hydroxide into strong calcium silicate hydrate, enhancing strength development.

Three similar mixtures are reported in Table 8.4. Mixture 14 was designed without fly ash. Mixture 36 was designed with 10% fly ash replacement. Mixture 28 was designed with 20% fly ash replacement. Compressive strength results are illustrated in Figure 8.5. Fly ash replacement was detrimental to early strength gain. Fly ash replacement of 20% curbed strength at 1 day more than fly ash replacement of 10%. However, heat curing may be offsetting in this respect. As presented in Chapter 7, HPC mixtures containing supplementary cementitious materials responded at 1 day to heat curing more positively than mixtures with *Type III* cement only. Both mixtures containing fly ash achieved higher strength at 28 and 56 days than the mixture without fly ash. At 28 days, the mixture with 10% fly ash was best and at 56 days the mixture with 20% fly ash was best.

Table 8.4.
Fly Ash Replacement Rate —
Mixture Proportions and Testing Results

			14	**36**	**28**
Cement[a]		**kg/m³**	**550.0**	**495.0**	**440.0**
Fly Ash[b]		**kg/m³**	**—**	**55.0**	**110.0**
Coarse Aggregate[c]		kg/m³	1,062.1	1,062.1	1,062.1
Fine Aggregate[d]		kg/m³	657.8	649.1	640.5
Mixing Water		kg/m³	148.7	148.7	148.7
WR Admixture[e]		L/m³	1.65	1.65	1.65
HRWR Admixture[f]		L/m³	7.15	7.15	7.15
w/cm			0.280	0.280	0.280
No. of Batches			1	1	1
Compressive Strength	1 d	MPa	67.7	60.2	49.2
	28 d	MPa	95.5	99.6	97.2
	56 d	MPa	100.9	105.1	107.8

[a] ASTM C 150 *Type III* cement with a C_3S content of 58.2%, C_2S content of 12.8% and Blaine fineness of 5,490 cm^2/g

[b] ASTM C 618 *Class C* fly ash having specific gravity of 2.65, calcium oxide (CaO) content of 28.4% and pozzolanic activity index of 99%

[c] Crushed limestone meeting the No. 8 grading requirements of ASTM C 33 and having a bulk specific gravity of 2.67 and absorption of 1.2% and DRUW of 1,623 kg/m^3

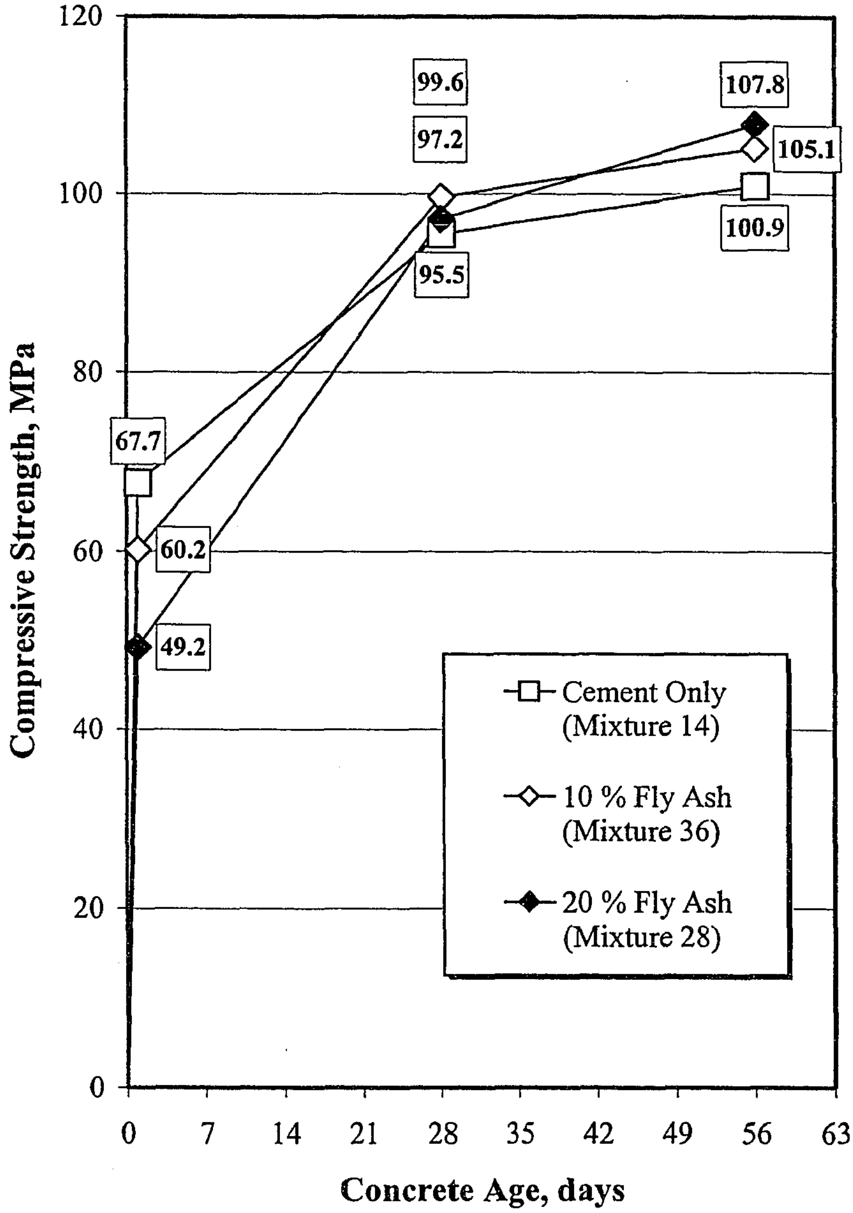
[d] Natural river sand having a bulk specific gravity of 2.63, absorption of 0.7% and fineness modulus of 2.47

[e] ASTM C 494 *Type A* water reducing admixture

[f] ASTM C 494 *Type A/F* superplasticizer

1 kg/m^3 = 1.686 lb/yd^3, 1 L/m^3 = 25.85 $floz/yd^3$, 1 MPa = 145 psi

Figure 8.5. Fly Ash Replacement Rate



8.4.4. *Type III* Cement

The precast/prestressing industry typically uses *Type III* cement. The physical and chemical characteristics of *Type III* cement produce relatively rapid hydration activity and early strength gain. Still, among *Type III* cements, there can be substantial differences. Two *Type III* cements, identified as C8 and C9, were compared in similar HPC mixtures, 66 and 79. Mixture proportions are reported in Table 8.5. Cement characteristics and compressive strength results are presented in Figure 8.6. Cement characteristics are also reported in Table 4.1. High tricalcium silicate (C_3S) and high fineness are beneficial to early strength gain. In this case, the mixture with C8, which had higher fineness but lower C_3S than C9, achieved higher strength at 1 day. The mixture with C9 achieved higher strength at 28 and 56 days.

HPC mixtures designed with *Type III* cement at low w/cm's can have harsh workability, especially when working in summer. *Type I* or *Type II* cements produce better workability than *Type III* cements, as presented in Chapter 4, and are possibly better for ultimate strength development. Increased quantities of dicalcium silicate (C_2S) are beneficial to ultimate strength development.

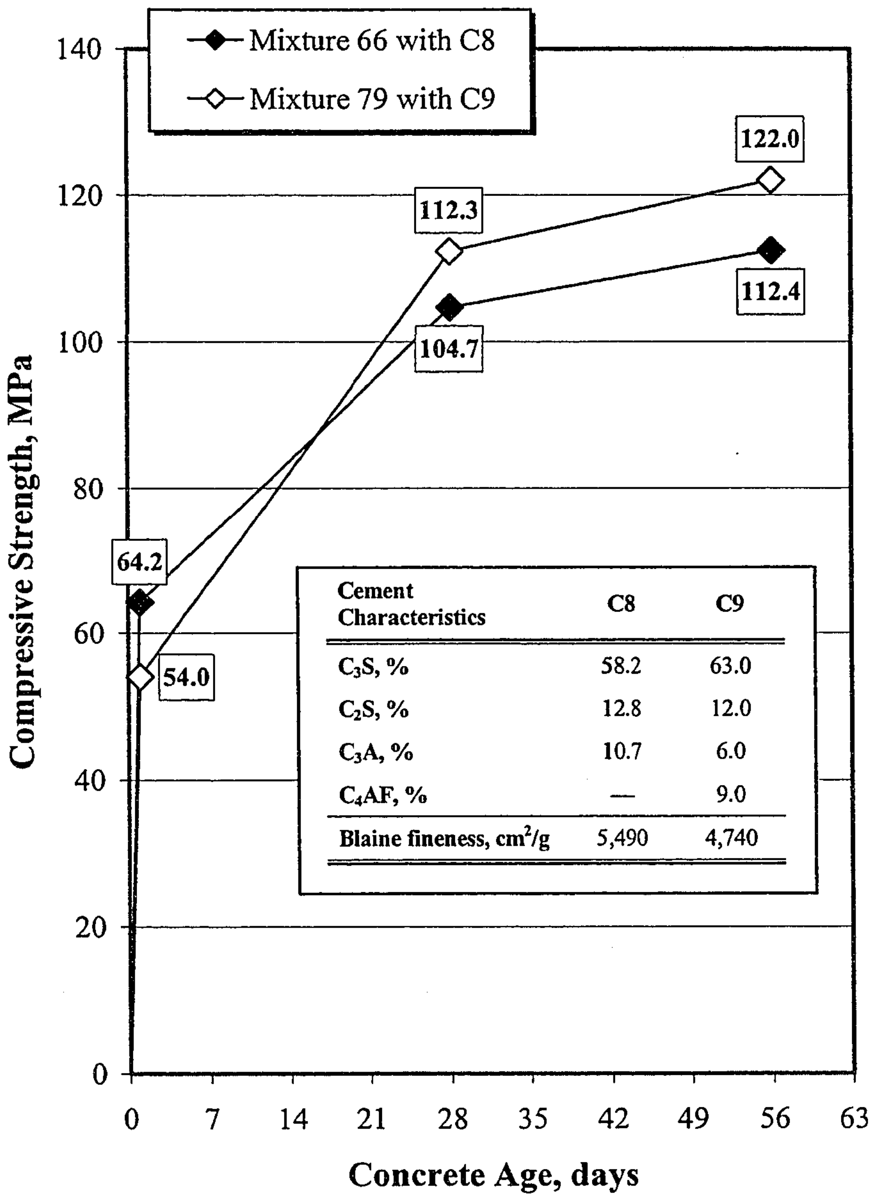
Table 8.5.
A Tale of Two *Type IIIs* —
Mixture Proportions and Testing Results

			66	**79**
Cement Source			**C8**	**C9**
Cement		kg/m^3	510.0	510.0
Fly Ash[a]		kg/m^3	60.0	60.0
Silica Fume		kg/m^3	30.0	30.0
Coarse Aggregate[b]		kg/m^3	1,062.1	980.4
Fine Aggregate[c]		kg/m^3	621.0	701.5
Mixing Water		kg/m^3	138.3	138.3
WR Admixture[d]		L/m^3	1.80	1.80
HRWR Admixture		L/m^3	7.80[e]	7.80[f]
w/cm			0.240	0.240
No. of Batches			1	2
Compressive Strength	1 d	MPa	64.2	54.0
	28 d	MPa	104.7	112.3
	56 d	MPa	112.4	122.0

[a] ASTM C 618 *Class C* fly ash having specific gravity of 2.65, calcium oxide (CaO) content of 28.4% and pozzolanic activity index of 99%
[b] Crushed limestone meeting the No. 8 grading requirements of ASTM C 33 and having a bulk specific gravity of 2.67 and absorption of 1.2% and DRUW of 1,623 kg/m^3
[c] Natural river sand having a bulk specific gravity of 2.63, absorption of 0.7% and fineness modulus of 2.47
[d] ASTM C 494 *Type A* water reducing admixture
[e] ASTM C 494 *Type A/F* superplasticizer
[f] ASTM C 494 *Type F* superplasticizer

1 kg/m^3 = 1.686 lb/yd^3, 1 L/m^3 = 25.85 $floz/yd^3$, 1 MPa = 145 psi

Figure 8.6. A Tale of Two *Type IIIs*



Cement Characteristics	C8	C9
C_3S, %	58.2	63.0
C_2S, %	12.8	12.0
C_3A, %	10.7	6.0
C_4AF, %	—	9.0
Blaine fineness, cm^2/g	5,490	4,740

8.4.5. Chemical Admixtures

Chemical admixtures are commonly employed in HPC mixtures. The most important of these in construction of precast/prestressed concrete bridge beams are superplasticizers, which are necessary for design of low w/cm's. As a rule, superplasticizers are necessary when the w/cm is below 0.40 to provide satisfactory workability.[6,11] Superplasticizers have a powerful dispersing effect on cement particles which facilitates an efficient hydration process and enhances strength development. The addition rate must be properly adjusted for different mixtures and conditions because superplasticizers can retard setting and early strength gain.

Superplasticizers have tremendous aptitude for increasing slump. Many trial mixtures without observable slump before addition of superplasticizer had slumps exceeding 230 mm (9 in) after addition and final mixing. Still, a superplasticizer has limitations; HPC mixtures can remain viscous or "sticky" and undergo rapid stiffening before adequate time for placement.

In situations where a concrete structural member will be exposed to cycles of freeze/thaw, an air entraining (AE) admixture is commonly specified in the interest of durability. Air entrainment is considered necessary for freeze/thaw resistance unless the w/cm is below 0.21 and compressive strength exceeds 138 MPa (20,000 psi).[12]

Three similar HPC mixtures are reported in Table 8.6. Mixture 6 was designed without air entrainment. Mixtures 50 and 49 contained an air entraining (AE) admixture that produced air contents of 6.7% and 8.6%, respectively. Compressive strength results are illustrated in Figure 8.7. Strength was reduced about 6.6% for every 1.0% increase in air content. It was observed that an AE admixture was beneficial to workability by creating countless tiny, discrete air bubbles in the fresh concrete. Slump increased from 150 mm (6 in) without air entrainment to 220 mm ($8^3/_4$ in) with air entrainment. By improving workability, use of an AE admixture can allow a reduction in the w/cm.

A corrosion inhibiting/strength accelerating (CI/SA) admixture containing calcium nitrite was found effective for enhancing strength gain, both at early ages and long term. As reported in Table 8.7, two HPC mixtures, 69 and 71, were compared to evaluate the effects of a CI/SA admixture. Compressive strength results are illustrated in Figure 8.8. The mixture containing the CI/SA admixture achieved higher strength at all ages. At 1 day, the CI/SA admixture improved strength by 8%. By 28 and 56 days, the improvement with the CI/SA admixture was 24% and 25%, respectively. The CI/SA admixture was not detrimental to workability, at least when adhering to the suggested additions rates. But too excessive an addition rate can cause rapid set, dramatically reducing the time available for placement, consolidation and finishing.[13] Precast/prestressing plants don't normally use accelerating admixtures during the summer.[14]

Table 8.6.
Strength Reduction Observed with Entrained Air — Mixture Proportions and Testing Results

			6	50	49
Cement[a]		kg/m³	500.0	500.0	500.0
Coarse Aggregate[b]		kg/m³	1,062.1	1,062.1	1,062.1
Fine Aggregate[c]		kg/m³	711.4	627.2	599.3
Mixing Water		kg/m³	145.0	142.5	141.6
WR Admixture[d]		L/m³	1.50	1.50	1.50
AE Admixture[e]		**L/m³**	—	**4.50**	**6.00**
HRWR Admixture[f]		L/m³	6.50	6.50	6.50
w/cm			0.300	0.300	0.300
No. of Batches			3	1	1
Unit Weight		kg/m³	2,422	2,284	2,225
Air Content		**%**	**2.1**	**6.7**	**8.6**
Slump		mm	150	220	220
Compressive Strength	1 d	MPa	61.8	42.9	35.0
	28 d	MPa	92.9	64.1	52.3
	56 d	MPa	95.1	67.4	54.6

[a] ASTM C 150 *Type III* cement with a C_3S content of 58.2%, C_2S content of 12.8% and Blaine fineness of 5,490 cm^2/g
[b] Crushed limestone meeting the No. 8 grading requirements of ASTM C 33 and having a bulk specific gravity of 2.67 and absorption of 1.2% and DRUW of 1,623 kg/m^3
[c] Natural river sand having a bulk specific gravity of 2.63, absorption of 0.7% and fineness modulus of 2.47
[d] ASTM C 494 *Type A* water reducing admixture
[e] ASTM C 260 air entraining admixture
[f] ASTM C 494 *Type A/F* superplasticizer

1 kg/m^3 = 1.686 lb/yd^3, 1 L/m^3 = 25.85 $floz/yd^3$, 25.4 mm = 1 in, 1 kg/m^3 = 0.06243 lb/ft^3, 1 MPa = 145 psi

Figure 8.7.
Strength Reduction Observed with Entrained Air

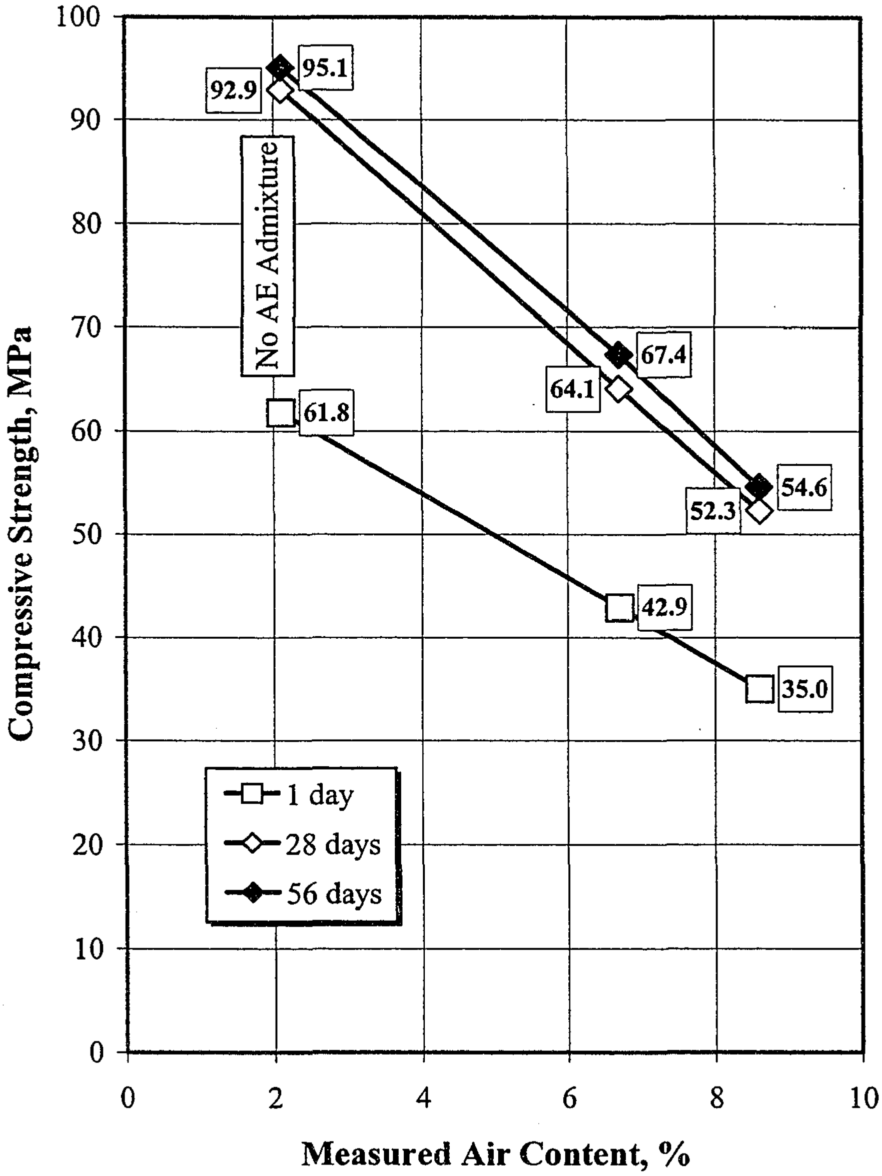


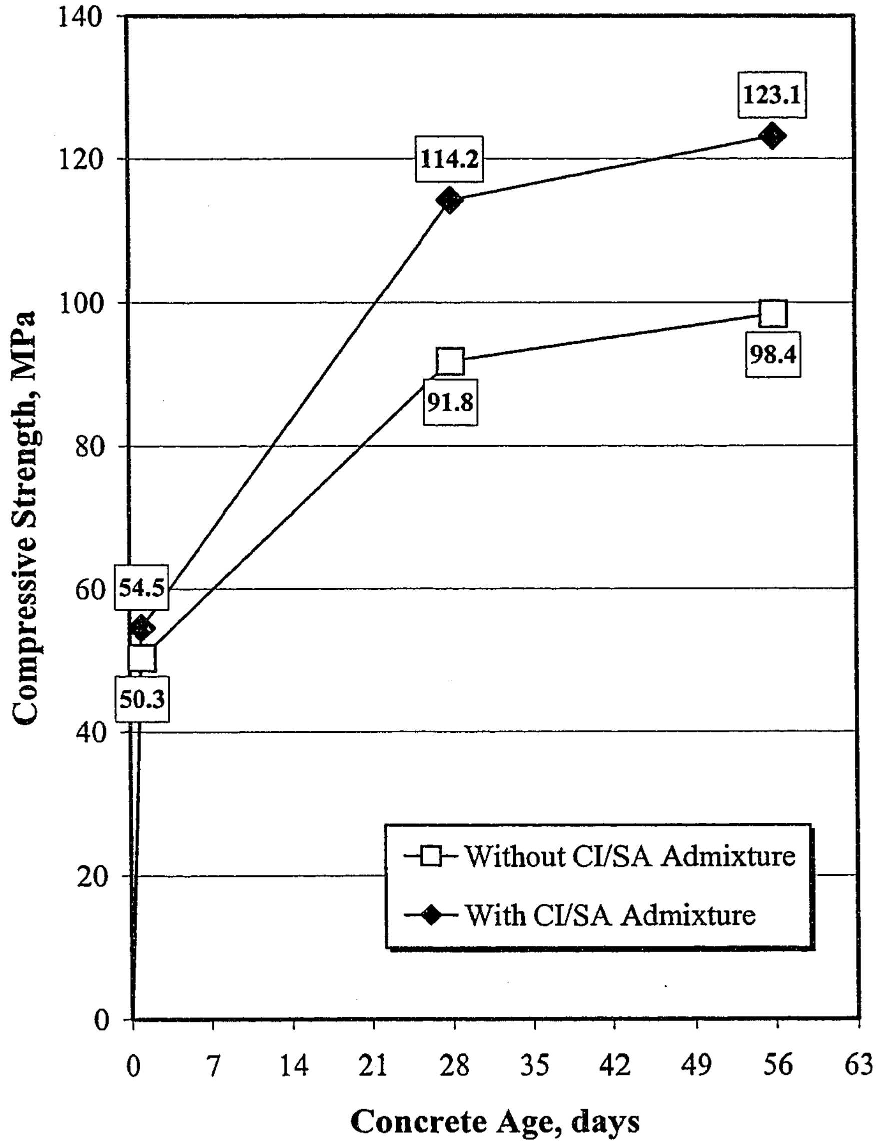
Table 8.7.
Strength Enhancement Observed with a Calcium Nitrite Solution — Mixture Proportions and Testing Results

			69	71
Cement[a]		kg/m³	510.0	510.0
Fly Ash[b]		kg/m³	60.0	60.0
Silica Fume		kg/m³	30.0	30.0
Coarse Aggregate[c]		kg/m³	980.4	980.4
Fine Aggregate[d]		kg/m³	673.9	656.0
Mixing Water		kg/m³	152.4	139.2
CI/SA Admixture[e]		**L/m³**	—	**20.0**
HRWR Admixture[f]		L/m³	6.00	6.00
w/cm			0.260	0.260
No. of Batches			1	1
	1 d	MPa	50.3	54.5
Compressive Strength	28 d	MPa	91.8	114.2
	56 d	MPa	98.4	123.1

[a] ASTM C 150 *Type III* cement with a C_3S content of 63.0%, C_2S content of 12.0% and Blaine fineness of 4,740 cm^2/g
[b] ASTM C 618 *Class C* fly ash having specific gravity of 2.65, calcium oxide (CaO) content of 28.4% and pozzolanic activity index of 99%
[c] Crushed limestone meeting the No. 8 grading requirements of ASTM C 33 and having a bulk specific gravity of 2.67 and absorption of 1.2% and DRUW of 1,623 kg/m^3
[d] Natural river sand having a bulk specific gravity of 2.63, absorption of 0.7% and fineness modulus of 2.47
[e] ASTM C 494 *Type C* corrosion inhibiting/strength accelerating admixture
[f] ASTM C 494 *Type F* superplasticizer

1 kg/m^3 = 1.686 lb/yd^3, 1 L/m^3 = 25.85 $floz/yd^3$, 1 MPa = 145 psi

Figure 8.8. Strength Enhancement Observed with a Calcium Nitrite Solution



8.4.6. Heat Curing

Heat curing has been employed by the precast/prestressing industry in construction of bridge beams to increase productivity. Heat curing spurs rapid hydration activity and may enhance early strength gain. However, as learned in Chapter 7, heat curing can also stunt ultimate strength development.

8.5. Summary and Conclusions

Achieving high early strength in harmony with adequate workability and high ultimate strength is a challenge facing the precast/prestressing industry in construction of bridge beams. There are several options for elevating early strength gain. Among these options is design of a low w/cm and the use of *Type III* cement, certain chemical admixtures, and heat curing. Frequently, however, these options compromise workability or ultimate strength development.

Lowering the w/cm increases strength but is detrimental to workability. Also, lowering the w/cm increases the rate of early strength gain and, in 1 day, HPC mixtures can achieve up to 60% of 28 day strength under standard curing. Increasing cement content at a constant w/cm does not necessarily increase strength. Using a *Type III* cement at a w/cm of 0.30, a strength plateau was reached at a cement content near 500 kg/m^3 (843 lb/yd^3). However, increasing cement content at a constant w/cm enhances workability. Use of fly ash as a partial replacement of cement can enhance workability and ultimate strength development. HPC with fly ash and/or other supplementary cementitious materials has relatively slow early strength gain, but responds well to heat curing. *Type III* cement is typically employed in precast/prestressed concrete bridge beams where its high fineness enhances early strength gain. But in terms of workability and ultimate strength potential, *Type I* or *Type II* cements are preferable. A superplasticizing admixture is beneficial in all respects. An air entraining admixture, although beneficial to workability, substantially reduced strength. A corrosion inhibiting/strength accelerating admixture containing calcium nitrite was found beneficial to both early and ultimate strength and did not affect workability. Use of a CI/SA admixture increased strength more than 20% at 28 and 56 days. Finally, heat curing can enhance early strength gain in some HPC mixtures. But heat curing is always detrimental to ultimate strength development.

When designing an HPC mixture to satisfy multiple performance objectives, it is helpful to survey all the options and to understand how these are sometimes both beneficial and detrimental. Trial batching is necessary to determine the best mixture for the specific application.

[1] Russell, H. G., "High Strength Concrete in Bridges — History and Challenges," *Proceedings of the PCI/FHWA International Symposium of High Performance Concrete*, New Orleans, Louisiana, 1997, pp. 27-38.

[2] American Society for Testing and Materials, *Annual Book of ASTM Standards*, Vol. 4.01 and 4.02, 1995.

[3] ACI 318, *Building Code Requirements for Structural Concrete and Commentary*, American Concrete Institute, 1999.

[4] ACI 211.4, "Guide for Selecting Proportions for High-Strength Concrete with Portland Cement and Fly Ash," *ACI Manual of Concrete Practice*, Part 1, American Concrete Institute, 1997.

[5] Kaszynska, M., "Hydration Heat and Strength Development in High Performance Concrete, *Proceedings of the PCI/FHWA International Symposium of High Performance Concrete*, New Orleans, Louisiana, 1997, pp. 108-117.

[6] Kosmatka, S. H. and Panarese, W. C., *Design and Control of Concrete Mixtures*, 13th Ed., Portland Cement Association, Skokie, IL 1988.

[7] Aïtcin, P. C. and Neville, A., "High Performance Concrete Demystified," *Concrete International*, Vol. 15, No. 1, January 1993, pp. 21-26.

[8] deLarrard, F. and Belloc, A., "The Influence of Aggregate on the Compressive Strength of Normal and High Strength Concrete," *ACI Materials Journal*, Vol. 94, No. 5, September/October 1997, pp. 417-426.

[9] ACI 363, "State-of-the-Art Report on High Strength Concrete," *ACI Manual of Concrete Practice*, Part 1, American Concrete Institute, 1997.

[10] Popovics, S., "Analysis of Concrete Strength Versus Water/Cement Ratio Relationship," *ACI Materials Journal*, Vol. 87, No. 5, September 1990, pp. 517-529.

[11] Ralls, M. L., "Texas HPC Bridge Decks," *Concrete International*, Vol. 21, No. 2, February 1999, pp. 63-65.

[12] ACI 363.2, "Guide to Quality Control and Testing of High Strength Concrete," American Concrete Institute, 1998.

[13] Ramseyer, C., "Investigation of Very Early Strength Concrete with Low Shrinkage Properties," Thesis, University of Oklahoma, 1999.

[14] Zia, P. and Hillmann, R. S., "Development of High Early Strength Concrete for Prestressed Concrete Applications," *North Carolina Department of Transportation in cooperation with the Federal Highway Administration*, June 1995.

9. Repeatability and Normality of HPC Compressive Strength

9.1. Introduction

A study was performed to assess the batch-to-batch repeatability of high performance concrete (HPC) and also the normality of compressive strength results. Knowledge of the repeatability statistics is necessary to commercially implement HPC. Without knowledge of the repeatability statistics, use of HPC can be risky and uneconomical. Normality is a theoretical assumption in the calculation of required average compressive strength in the ACI 318 "Building Code Requirements for Structural Concrete and Commentary."[1] But it is unknown whether HPC compressive strength results follow a normal distribution or exhibit some skewness.

9.2. Experimental Program

Six HPC mixtures were batched multiple times to assess the batch-to-batch repeatability and also the normality of the compressive strength results. Mixtures C3/1, C3/2, and C8/2 were first introduced in the *Cement Study*. Mixture LIq was first introduced in the *Aggregate Study*. Mixtures 9 and 27 were designed as part of the *Mixture Proportion Study*. These mixtures were each batched four to six times. No other mixture in the research was batched more than three times with complete test data. Mixture proportions are presented in Table 9.1. Mixtures C3/1, C3/2, and LIq contained *Type I* cement, while mixtures C8/2, 9, and 27 contained *Type III* cement.

Mixtures LIq and 27 contained fly ash. The water/cementitious materials (w/cm) ratios of the mixtures ranged from 0.280 to 0.406. All mixtures contained limestone coarse aggregate and also a superplasticizing admixture.

9.3. Experimental Procedures

Work was performed in the laboratory. Batching and testing procedures conformed to the applicable ASTM standards[2] except mixing time, which was often extended beyond the duration specified in ASTM C 192. Mixing continued until the concrete appeared uniform. Batch weights were adjusted for aggregate moisture.

Fresh concrete temperature, slump and unit weight were measured on most batches. ASTM C 143 slump was measured after all mixing and discharge. Concrete cylinders for determining compressive strength were cast in 100 x 200 mm (4 x 8 in) plastic molds and consolidated by rodding. Cylinders were cured at 23 °C (73.4 °F) and 50% relative humidity during the initial 24 hrs. Molds were removed at 24 hrs and thereafter, until tested, cylinders were moist cured (under water) as specified by ASTM C 192 at a temperature of 23 °C (73.4 °F).

Cylinders were tested for compressive strength using neoprene pads seated in steel or aluminum rings. Tests followed the procedures of ASTM C 39 and were performed at ages of 1 and 28 days. Three to five cylinders were tested at each age.

Table 9.1.
Repeatability and Normality Study — Mixture Proportions

		C3/1	C3/2	C8/2	LIq	9	27
Cement	kg/m^3	385.5[a]	462.6[a]	462.6[b]	474.5[a]	475.0[b]	400.0[b]
Fly Ash[c]	kg/m^3	—	—	—	166.1	—	100.0
Coarse Aggregate	kg/m^3	1,053[d]	1,008[e]	1,008[e]	1,040[e]	1,062[e]	1,062[e]
Fine Aggregate[f]	kg/m^3	794.8	753.3	753.3	526.1	751.7	721.4
Mixing Water	kg/m^3	154.2	157.2	157.2	177.3	138.0	135.2
WR Admixture[g]	L/m^3	—	—	—	—	1.43	1.50
SR/WR Admixture[h]	L/m^3	0.77	0.89	0.89	1.25	—	—
HRWR Admixture[i]	L/m^3	3.02	4.18	4.18	2.92	6.18	6.50
w/cm		0.406	0.346	0.346	0.281	0.300	0.280
Calculated Unit Weight	kg/m^3	2,392	2,387	2,387	2,389	2,436	2,428

[a] ASTM C 150 *Type I* cement with a C_3S content of 54.4%, C_2S content of 18.4% and Blaine fineness of 3,390 cm^2/g

[b] ASTM C 150 *Type III* cement with a C_3S content of 58.2%, C_2S content of 12.8% and Blaine fineness of 5,490 cm^2/g

[c] ASTM C 618 *Class C* fly ash having specific gravity of 2.65, calcium oxide (CaO) content of 28.4% and pozzolanic activity index of 99%

[d] Crushed limestone meeting the No. 67 grading requirements of ASTM C 33 and having a bulk specific gravity of 2.67, absorption of 1.2% and DRUW of 1,621 kg/m^3

[e] Crushed limestone meeting the No. 8 grading requirements of ASTM C 33 and having a bulk specific gravity of 2.67, absorption of 1.2% and DRUW of 1,623 kg/m^3

[f] Natural river sand having a bulk specific gravity of 2.63, absorption of 0.7% and fineness modulus of 2.47

[g] ASTM C 494 *Type A* water reducing admixture

[h] ASTM C 494 *Type B/D* set retarding/water reducing admixture

[i] ASTM C 494 *Type A/F* superplasticizer

1 kg/m^3 = 1.686 lb/yd^3, 1 L/m^3 = 25.85 $floz/yd^3$, 1 kg/m^3 = 0.06243 lb/ft^3

9.4. Experimental Results

Individual batch results are presented in Table 9.2. Mixture LIq was batched six times. Mixtures C3/1 and C8/2 were batched five times each. Mixtures C3/2, 9, and 27 were batched four times each. In Table 9.2, the compressive strength values reported at 1 and 28 days were determined as an average result of the test cylinders. There were three to five test cylinders in an individual batch. Fresh concrete properties from the individual batches are also reported in Table 9.2 and include concrete temperature, slump and unit weight.

Fresh concrete temperatures ranged from 12.2 to 20.0 °C (54 to 68 °F) with mixture LIq and from 14.4 to 20.0 °C (58 to 68 °F) with mixture 27, which was typical of the variability in the data. Slumps ranged from 140 to 230 mm ($5^1/_2$ to 9 in) with mixture LIq and from 170 to 200 mm ($6^3/_4$ to 8 in) with mixture 27, which was also typical of the variability in the data. With a calculated unit weight of 2,389 kg/m^3 (149.1 lb/ft^3), the measured unit weights of mixture LIq ranged from 2,371 to 2,404 kg/m^3 (148.0 to 150.1 lb/ft^3). With a calculated unit weight of 2,428 kg/m^3 (151.6 lb/ft^3), the measured unit weights of mixture 27 ranged from 2,425 to 2,435 kg/m^3 (151.4 to 152.0 lb/ft^3). Measured unit weights were typically within 1% of calculated unit weights.

Table 9.2. Fresh Concrete Properties and Compressive Strength Results

			Individual Batches					
			A	B	C	D	E	F
C3/1	Concrete Temp.	°C	26.7	18.3	22.2	33.3	17.2	—
	Slump	mm	—	220	250	230	180	—
	Unit Weight	kg/m^3	2,425	2,408	—	2,455	2,388	—
	Strength at 1 d	MPa	25.1	23.8	20.4	18.7	23.3	—
	Strength at 28 d	MPa	63.9	64.7	53.2	58.7	64.7	—
C3/2	Concrete Temp.	°C	29.4	—	—	29.4	—	—
	Slump	mm	—	270	270	200	—	—
	Unit Weight	kg/m^3	2,416	2,423	2,376	2,417	—	—
	Strength at 1 d	MPa	39.1	35.1	32.7	40.6	—	—
	Strength at 28 d	MPa	81.4	82.7	78.8	83.1	—	—
C8/2	Concrete Temp.	°C	27.8	18.3	19.4	—	28.9	—
	Slump	mm	—	190	270	—	210	—
	Unit Weight	kg/m^3	2,385	2,399	2,396	—	2,423	—
	Strength at 1 d	MPa	37.4	61.1	56.7	52.6	54.5	—
	Strength at 28 d	MPa	71.0	86.8	88.4	83.1	81.7	—

T(°C) = 5/9[T(°F) – 32], 25.4 mm = 1 in, 1 kg/m^3 = 0.06243 lb/ft^3, 1 MPa = 145 psi

Table 9.2. Fresh Concrete Properties and Compressive Strength Results (Cont'd)

			Individual Batches					
			A	B	C	D	E	F
LIq	Concrete Temp.	°C	12.2	—	13.9	13.9	20.0	20.0
	Slump	mm	230	—	230	200	210	140
	Unit Weight	kg/m^3	2,371	—	2,404	2,403	2,385	2,396
	Strength at 1 d	MPa	28.1	29.3	27.4	26.5	23.4	28.8
	Strength at 28 d	MPa	86.6	88.2	87.2	83.3	80.0	85.3
9	Concrete Temp.	°C	25.0	28.9	28.1	22.2	—	—
	Slump	mm	—	—	—	170	—	—
	Unit Weight	kg/m^3	—	2,415	2,428	2,447	—	—
	Strength at 1 d	MPa	71.2	67.2	68.4	57.4	—	—
	Strength at 28 d	MPa	91.9	91.9	93.2	88.7	—	—
27	Concrete Temp.	°C	20.0	14.4	18.3	16.7	—	—
	Slump	mm	170	200	170	200	—	—
	Unit Weight	kg/m^3	2,435	—	2,425	2,432	—	—
	Strength at 1 d	MPa	51.1	48.6	51.8	49.7	—	—
	Strength at 28 d	MPa	97.6	96.3	92.0	91.2	—	—

T(°C) = 5/9[T(°F) – 32], 25.4 mm = 1 in, 1 kg/m^3 = 0.06243 lb/ft^3, 1 MPa = 145 psi

Final compressive strength results are reported in Table 9.3. Final compressive strength results were determined as an average of the individual batch results, not as an average of the individual test cylinders. Final compressive strength results ranged from 22.3 to 66.1 MPa (3,230 to 9,580 psi) at an age of 1 day and from 61.0 to 94.3 MPa (8,850 to 13,670 psi) at 28 days. The standard deviation and the coefficient of variation (CV), based on the individual batch results, are also reported in Table 9.3. The CV is the standard deviation expressed as a percent of the final compressive strength result. The CV is a measure of the batch-to-batch repeatability; a low CV is indicative of a high level of repeatability. At 1 day, the CV's ranged from 2.84% to 17.2%. At 28 days, the CV's ranged from 2.10% to 8.30%. With five of the six mixtures, the CV was lower at 28 days than at 1 day.

Table 9.3. Repeatability Statistics

			C3/1	C3/2	C8/2	LIq	9	27
No. of Batches			5	4	5	6	4	4
Average Compressive Strength	1 d	MPa	22.3	36.9	52.5	27.3	66.1	50.3
Standard Deviation	1 d	MPa	2.63	3.62	8.99	2.13	6.01	1.43
Coefficient of Variation	**1 d**	**%**	**11.8**	**9.83**	**17.2**	**7.83**	**9.09**	**2.84**
Average Compressive Strength	28 d	MPa	61.0	81.5	82.2	85.1	91.4	94.3
Standard Deviation	28 d	MPa	5.05	1.94	6.82	3.02	1.92	3.15
Coefficient of Variation	**28 d**	**%**	**8.27**	**2.38**	**8.30**	**3.55**	**2.10**	**3.34**

1 MPa = 145 psi

9.5. Analysis and Discussion of Results

9.5.1. Repeatability

The CV is a useful measure of batch-to-batch repeatability. Standards of repeatability based on the CV are recommended in ACI 363's "Guide to Quality Control and Testing of High Strength Concrete." These standards are presented in Table 9.4 and are applicable to concrete with a compressive strength in excess of 35 MPa (5,000 psi) and to tests performed at 28 days on laboratory trial batches. The repeatability is considered "excellent" when the CV is less than 3.5% and "very good" when the CV is between 3.5% and 4.5%. The repeatability is considered "poor" when the CV is more than 7.0%.

Table 9.4.
ACI 363's Repeatability Standards for Laboratory Trial Batches

CV, %	Standard
Under 3.5	"Excellent"
3.5 to 4.5	"Very Good"
4.5 to 5.5	"Good"
5.5 to 7.0	"Fair"
Over 7.0	"Poor"

At 28 days, the repeatability of mixtures C3/2, 9, and 27 was considered "excellent" according to the ACI 363 standards, while the repeatability of mixture LIq was considered "very good." Conversely, the repeatability of mixtures C3/1 and C8/2 was considered "poor." The standards are not applicable to tests performed at 1 day, but the repeatability of mixture 27 would be considered "excellent" at this age, while the repeatability of the remaining five mixtures would be considered "poor."

A strict quality assurance/quality control (QA/QC) program is necessary to uphold a high level of batch-to-batch repeatability. In this case, the QA/QC issues that were most likely to have contributed to the variability of the compressive strength results included:

- Variability of the properties of the constituent materials
- Inaccuracy in determining aggregate moisture contents and adjusting mixture proportions
- Inaccuracy in measuring batch quantities

The extent to which the different QA/QC issues influenced the variability in the data is unknown.

Fresh concrete temperature, slump, and unit weight are useful measures in a QA/QC program. Mixtures with high fresh concrete temperature could be expected to have high early strength development. An unusually low slump or high unit weight might be evidence of an unusually low w/cm, which can enhance strength development. However, the data gathered in this research does not suggest a relationship between these measures and compressive strength.

9.5.2. Normality

The relative frequency histogram is a method for assessing normality. If the data are approximately normal, the histogram will be mound shaped and symmetric about the mean. If the data exhibit some skewness, the histogram will be shifted in one direction. To construct a relative frequency histogram, the data range is divided into classes of equal width. The number of classes is arbitrary, but when the number of observations in a data set is less than 25, 5 or 6 classes are most descriptive. In this case, data sets with 15 to 19 observations (the results of the individual test cylinders) were divided into 6 classes. The class frequency is the number of observations falling within a specific class. The class relative frequency is the number of observations in a class divided by the total number of observations. The probability that an observation will fall within a specific class is equal to the relative frequency of that class. The probability that an observation will fall within one of two or more specific classes is equal to the sum of the respective relative frequencies.[3]

Data from mixtures LIq and 27 were used to construct relative frequency histograms. The results of the individual test cylinders from different batches were considered as one data set. Data necessary to construct the relative frequency histograms are presented in Tables 9.5, 9.6, 9.7, and 9.8. Tables 9.5 and 9.6 show the data range, class width, class interval, class number, class frequency, and class relative frequency for mixture LIq at 1 and 28 days, respectively. Tables 9.7 and 9.8 show similar information for mixture 27 at 1 and 28 days, respectively. The relative frequency histograms, typical of all of the mixtures, are illustrated in Figures 9.1, 9.2, 9.3, and 9.4.

In general, the compressive strength results can be described as normal, as illustrated in Figures 9.1, 9.2, 9.3, and 9.4. However, the data exhibits some skewness. With mixture LIq, at both 1 and 28 days, the highest relative frequency of test results fell within the fifth class, instead of the third or fourth classes as would be expected under a normal distribution. Another departure from normality appears in the first class. Mixture LIq at 1 and 28 days, as well as mixture 27 at 1 day, had greater relative frequencies in the first class than in the second class.

Table 9.5. Relative Frequency Histogram Data for Compressive Strength Results (Mixture LIq at 1 day)

Mixture	LIq
Age	1 day
Data Range	7.3 MPa
Class Width	1.3 MPa

Class Interval	Class Number	Class Frequency	Class Relative Frequency
22.5 to <23.8	1	2	0.111
23.8 to <25.1	2	1	0.056
25.1 to <26.4	3	1	0.056
26.4 to <27.7	4	4	0.222
27.7 to <29.0	5	7	0.389
29.0 to <30.3	6	3	0.167
		18	1.000

Figure 9.1. Relative Frequency Histogram for Compressive Strength Results (Mixture LIq at 1 day)

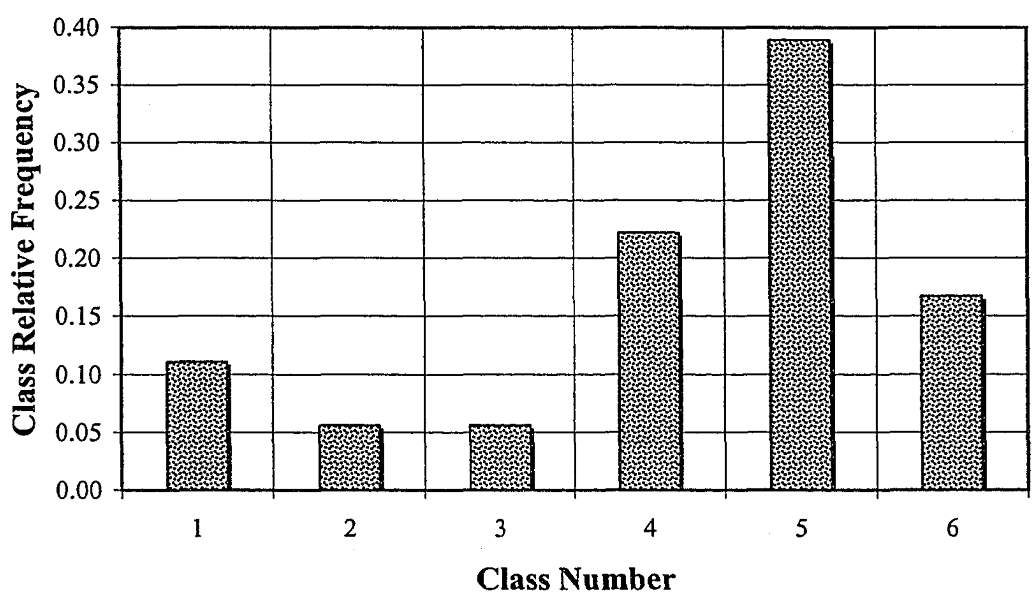


Table 9.6. Relative Frequency Histogram Data for Compressive Strength Results (Mixture LIq at 28 days)

Mixture	LIq		
Age	28 days		
Data Range	13.7 MPa		
Class Width	2.3 MPa		
Class Interval	Class Number	Class Frequency	Class Relative Frequency
76.9 to <79.2	1	2	0.105
79.2 to <81.5	2	1	0.053
81.5 to <83.8	3	2	0.105
83.8 to <86.1	4	5	0.263
86.1 to <88.4	5	7	0.368
88.4 to <90.7	6	2	0.105
		19	1.000

Figure 9.2. Relative Frequency Histogram for Compressive Strength Results (Mixture LIq at 28 days)

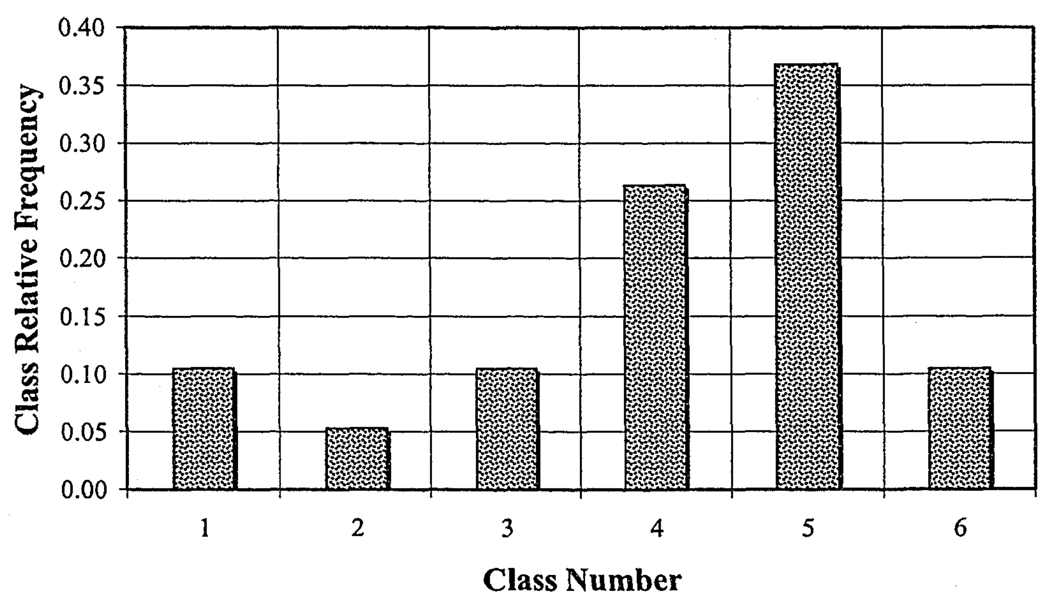


Table 9.7. Relative Frequency Histogram Data for Compressive Strength Results (Mixture 27 at 1 day)

Mixture	27		
Age	1 day		
Data Range	6.5 MPa		
Class Width	1.1 MPa		
Class Interval	Class Number	Class Frequency	Class Relative Frequency
46.8 to <47.9	1	2	0.133
47.9 to <49.0	2	1	0.067
49.0 to <50.1	3	3	0.200
50.1 to <51.2	4	5	0.333
51.2 to <52.3	5	3	0.200
52.3 to <53.4	6	1	0.067
		15	1.000

Figure 9.3. Relative Frequency Histogram for Compressive Strength Results (Mixture 27 at 1 day)

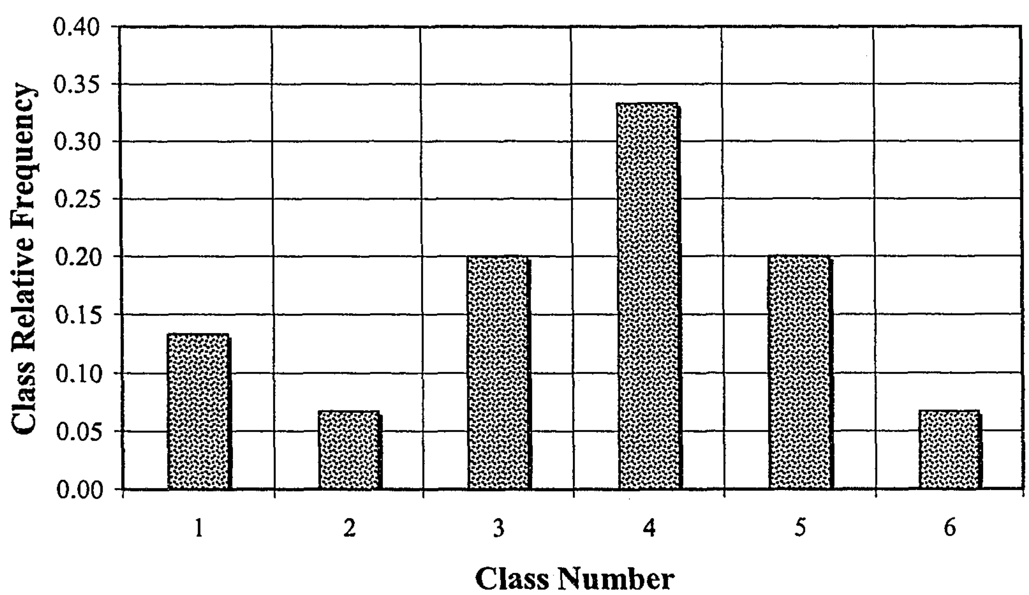
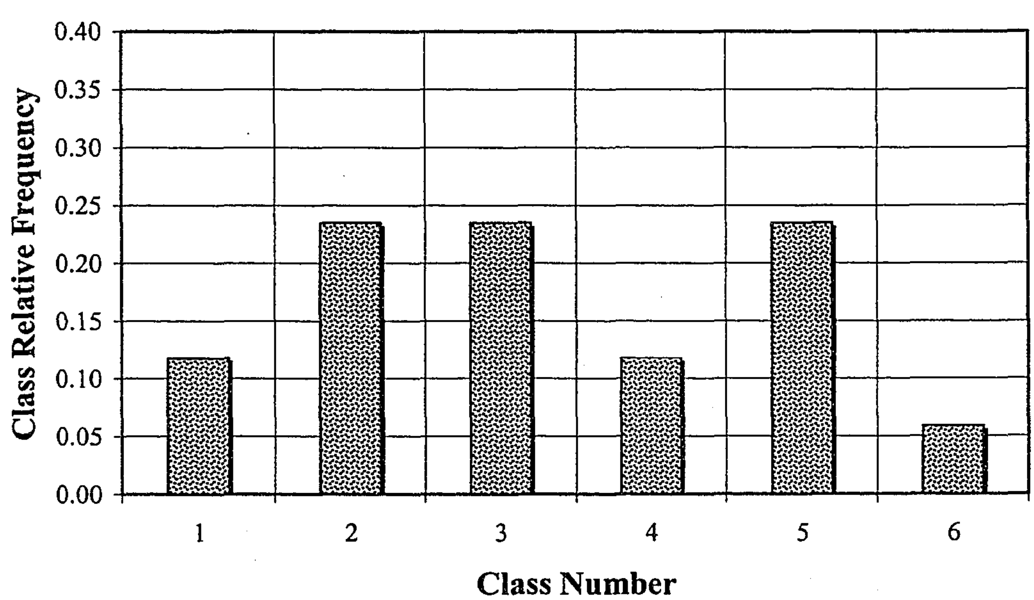


Table 9.8. Relative Frequency Histogram Data for Compressive Strength Results (Mixture 27 at 28 days)

Mixture	27
Age	28 days
Data Range	13.3 MPa
Class Width	2.3 MPa

Class Interval	Class Number	Class Frequency	Class Relative Frequency
87.8 to <90.1	1	2	0.118
90.1 to <92.4	2	4	0.235
92.4 to <94.7	3	4	0.235
94.7 to <97.0	4	2	0.118
97.0 to <99.3	5	4	0.235
99.3 to <101.6	6	1	0.059
		17	1.000

Figure 9.4. Relative Frequency Histogram for Compressive Strength Results (Mixture 27 at 28 days)



9.6. Conclusions

Six HPC mixtures were batched multiple times to assess the batch-to-batch repeatability and also the normality of the compressive strength results. The HPC mixtures had compressive strength values at 28 days between 61.0 to 94.3 MPa (8,850 to 13,670 psi). The coefficient of variation (CV) is a useful measure of the batch-to-batch repeatability; a low CV is indicative of a high level of repeatability. At 28 days, the CV's ranged from 2.10% to 8.30%. The repeatability of four of the mixtures was considered "excellent" or "very good" according to the ACI 363 standards, while the repeatability of the remaining two mixtures was considered "poor." With five of the six mixtures, the CV was lower at 28 days than at 1 day. One of the issues most likely to have contributed to the CV of the compressive strength results was the innacuracy of determining the aggregate moisture contents. The HPC compressive strength results generally followed a normal distribution. However, some irregularity was observed in the relative frequency histograms.

[1] ACI 318, *Building Code Requirements for Structural Concrete and Commentary*, American Concrete Institute, 1999.
[2] American Society for Testing and Materials, *Annual Book of ASTM Standards*, Vol. 4.01 and 4.02, 1995.
[3] Mendenhall, W. and Sincich, T., *Statistics for Engineering and the Sciences*, 4th Ed., Prentice Hall, 1995.

10. Bringing HPC from Laboratory to a Precast/Prestressing Plant

10.1. Introduction

Experience with high performance concrete (HPC) shows that in most cases laboratory trial batches exhibit strengths and other properties different from those achieved in production.[1] Recent studies have recommended a 15% allowance to account for the strength decrease from lab to field.[2,3] Even when conditions in the field are ideal, a strength reduction of 10% is believed to be realistic.[4]

An experimental program was conducted to investigate differences between HPC produced in laboratory and HPC produced at a precast/prestressing plant. Of specific interest were workability and compressive strength. It was also intended to identify quality control issues that could be at the root of possible inconsistencies between lab and plant results.

The "lab vs. plant" experimental program was not conceived at the outset, but rather evolved over time as difficulties were encountered with reproducibility and as more mixtures were tried. In all, seven HPC mixtures, initially evaluated in the laboratory, were selected for trial at a nearby precast/prestressing facility. The work described in this chapter moved forward after earlier efforts to assess the suitability of local materials and develop HPC mixture proportions.

10.2. Experimental Program

Seven HPC mixtures were selected for trial batching at a precast/prestressing plant. The mixtures were chosen from a group of more than one hundred mixture designs having cement and aggregates from Oklahoma and neighboring states. Each mixture was selected on the basis of its potential to meet early strength requirements while conserving adequate workability and long term strength development. Target compressive strengths were 60 MPa (8,700 psi) at 24 hrs and 100 MPa (14,500 psi) at 28 or 56 days. These strengths exceeded the previous best strengths in the Oklahoma region by more than 30%.

The seven mixture designs were batched at each location, first at the laboratory and then at the plant. Three different curing schemes were employed. Lab-batched cylinders for compressive strength testing were standard cured in conformance with ASTM C 192.[5] Plant-batched cylinders were divided into two sets for both ambient curing and heat curing.

The structure of the testing program into three series, lab/standard, plant/ambient and plant/heat, offers valuable information and encompasses the traditional scope of testing for technology transfer. However, by introducing two sources of variability, batching location and curing scheme, comparative analysis is in some ways limited.

Mixture proportions for the seven mixtures evaluated in this study are reported in Table 10.1. Mixture proportions were designed by the absolute volume method. The water fraction of chemical admixtures was included in the amount of mixing water. A similar adjustment was made when batching with silica fume, which came in slurry form.

All mixtures contained *Type III* cement at water/cementitious material (w/cm) ratios ranging from 0.26 to 0.30. Cementitious material contents for the mixtures ranged from 500 to 600 kg/m^3 (843 to 1,012 lb/yd^3). These fairly high cementitious material contents were necessary in order to provide sufficient mixing water for workability while maintaining such low w/cm's. Adequate workability was needed for concrete placement into a thin section with tight spacing of reinforcement. A combination of fly ash and silica fume was used in five of the seven mixtures.

All of the mixtures contained crushed limestone coarse aggregate. Several chemical admixtures were variously used, including conventional water reducing (WR), air entraining (AE), corrosion inhibiting/strength accelerating (CI/SA), and superplasticizing admixtures.

10.3. Experimental Procedures

Identical materials were used for parallel lab and plant mixtures. However, it was unavoidable that between batching location, lab and plant, there existed several key differences, including the following:

- Method of determining aggregate moisture
- Accuracy of measuring batch quantities
- Batch size
- Mixing machinery — type, capacity and speed
- Ambient conditions
- Temperature of materials before batching
- Fresh concrete temperature
- Handling of cylinders

Table 10.1. Mixture Proportions (SSD Aggregates)

		5	27	65	72	98	99	100
Cement[a]	kg/m^3	550.0	400.0	467.5	510.0	510.0	510.0	510.0
Fly Ash[b]	kg/m^3	—	100.0	55.0	60.0	60.0	60.0	60.0
Silica Fume	kg/m^3	—	—	27.5	30.0	30.0	30.0	30.0
Coarse Aggregate (CA)[c]	kg/m^3	1,062.1	1,062.1	1,062.1	980.4	980.4	980.4	980.4
Fine Aggregate (FA)[d]	kg/m^3	629.4	721.4	668.1	654.2	622.6	515.8	547.4
Mixing Water	kg/m^3	159.5	135.2	137.7	138.1	150.1	149.2	137.2
WR Admixture	L/m^3	1.65	1.50	1.65	1.80	1.80	1.80	1.80
AE Admixture	L/m^3	—	—	—	—	—	1.50	1.50
CI/SA Admixture	L/m^3	—	—	—	20.0	20.0	20.0	20.0
Superplasticizer[e]	L/m^3	7.15	6.50	7.15	6.00	6.00	6.00	6.00
w/cm		**0.300**	**0.280**	**0.260**	**0.260**	**0.280**	**0.280**	**0.260**
w/c		0.300	0.350	0.306	0.306	0.329	0.329	0.306
Cement Replacement	%	0	20	15	15	15	15	15
CA Content	%	65.4	65.4	65.4	60.4	60.4	60.4	60.4
Calculated Air Content	%	2.00	2.00	2.00	2.00	2.00	6.00	6.00
Calculated Unit Weight	kg/m^3	2,412	2,428	2,428	2,406	2,386	2,281	2,300

[a] All mixtures contain *Type III* cement from one of two sources (Mixtures 5, 27 and 65 have cement from the first source and mixtures 72, 98, 99 and 100 have cement from the second source)

[b] ASTM C 618 *Class C* fly ash having specific gravity of 2.65, calcium oxide (CaO) content of 28.4% and pozzolanic activity index of 99%

[c] Crushed limestone meeting the No. 8 grading requirements of ASTM C 33 and having a bulk specific gravity of 2.67, absorption of 1.2% and dry rodded unit weight of 1,623 kg/m^3

[d] Natural river sand having a bulk specific gravity of 2.63, absorption of 0.7% and fineness modulus of 2.47

[e] An ASTM C 494 *Type A/F* superplasticizer for the first three mixtures and a *Type F* superplasticizer for the following four mixtures

1 kg/m^3 = 1.686 lb/yd^3, 1 L/m^3 = 25.85 floz/yd^3

10.3.1. Batching and Testing

Batching and testing procedures generally conformed to the applicable ASTM standards.[5] Each mixture was batched once at each location, lab and plant, except for mixture 27, which was batched six times at the lab.

Corrections to batch weights were made to compensate for moisture in the aggregates. In the lab, moisture contents were determined and aggregates stored in sealed containers until batching. At the plant, coarse and fine aggregate samples were collected from stockpiles for moisture content determination prior to batching. Samples were extracted from the portion of the stockpile where aggregate for the next batch would likely come.

Mixing time was often extended beyond the ASTM specified duration and continued until the concrete appeared uniform.[6] The necessary time of mixing was influenced by the nature of the mixture, batch size, concrete temperature, and mixer efficiency.

Plant trial batching was performed during the summer months. Work usually proceeded in the heat of the afternoon and without the benefit of ice to chill the mixing water. These circumstances were dictated by the busy schedule at the commercial facility. As such, the practicality of the mixtures was tested under adverse conditions.

Lab batching, conversely, had the benefit of ice or heated mixing water for seasonal temperature control.

Slump, air content, unit weight and concrete temperature were measured within minutes after discharge from the mixer. Ambient conditions (air temperature and relative humidity) were also recorded.

Concrete cylinders were cast in 100 x 200 mm (4 x 8 in) plastic molds. All cylinders were consolidated by rodding and moved carefully to avoid skewing the shape or disturbing the concrete. At the plant, a brief truck transit was necessary for moving the newly finished cylinders across the yard to a curing location. Caps were fitted on cylinders undergoing ambient curing, to prevent evaporation. Work was completed within one hour of concrete discharge or before initial set.

Cylinders were tested for compressive strength using neoprene pads seated in steel or aluminum rings. Tests conformed to the procedures of ASTM C 39 and were performed at ages of 1, 28 and 56 days. In most cases, five cylinders were tested at each age. Testing machines at both the lab and plant were adequate for testing high strength concrete. Strength testing at 24 hrs was done at the batching location, either lab or plant. The remaining plant-batched cylinders were transported to the lab for subsequent curing and testing.

10.3.2. Curing Schemes

Three curing schemes were evaluated in this study: standard, ambient and heat. The three schemes differed only during the initial 24 hrs. After 24 hrs, all cylinders were moist cured (under water) as defined by ASTM C 192 at a temperature of 23 °C (73.4 °F) until tested.

Under lab/standard curing, cylinders were cured at 23 °C (73.4 °F) and 50% relative humidity (RH) during the initial 24 hrs. For plant/ambient curing, cylinders were placed under ambient conditions and protected under a tarp during the initial 24 hrs. Plant batching was performed in summer when Oklahoma normally experiences temperatures between 25 and 40 °C (77 to 104 °F) in a given day. Plant/heat curing represented the steam curing cycle that is regularly applied at the precast/prestressing facility. Concrete cylinders from the trial batch were placed next to the formwork of a production beam, under a tarp. After a delay of 2 to 4 hrs, intended for concrete to reach initial set, steam was applied. Temperature beneath the tarp climbed at a maximum rate of 22 °C/hr (40 °F/hr), reaching a peak of 60 to 65 °C (140 to 149 °F) for roughly 12 hrs. After steam was discontinued, the beams and cylinders remained undisturbed for another 2 to 6 hrs, until temperature under the tarp fell to within 10 °C (18 °F) of outside air and the labor force arrived. In order to facilitate simultaneous curing of test cylinders with production beams, trial batching at the plant usually began immediately after completion of a set of beams.

10.4. Observations of Batching and Quality Control Procedures at the Plant

A precast/prestressing plant in Oklahoma City assisted with the trial batching. In general, no effort was made to interfere with established batching or quality assurance/quality control procedures at the plant. However, in the interest of this study, one practice was discontinued. Normal procedures at the plant have mixing water and chemical admixture quantities subject to impromptu modification. An experienced individual orders the changes, sending instruction by way of hand signals to a colleague at the batch controls. Adjustments like these are pragmatic when working on hot, sunny days and with mixtures containing *Type III* cement at low w/cm's. Workability is a priority at the plant where the risk of a structural member being declared unfit because of improper placement and consolidation is well understood. Still, the impromptu modifications conflicted with the purpose of this study, which was to batch HPC mixtures exactly as originated in the lab.

10.4.1. Determining Aggregate Moisture Content

Determining aggregate moisture at the plant was accomplished with less certainty than at the lab. At the plant, the task was made difficult by the enormity of the aggregate supply and the nonuniformity and instability of moisture within the supply.

Aggregate samples were collected from stockpiles prior to batching. Moisture contents were determined by drying samples on a hot plate. This process required more than an hour. During this time, a number of developments could change the moisture of the aggregate stockpiles, thereby rendering the samples unrepresentative. For example, a sprinkler head, positioned to cool the coarse aggregate stockpiles, would get moved or inexplicably kick on or off. Brief thunderstorms rolled through bringing heavy rainfall. Trucks arrived with new aggregate, dumping the payload at the front of the enclosed stockpile where aggregate would likely be lifted for the next batch.

Moisture content tests were repeated after rain and after new material deliveries. Experience indicates that HPC mixtures designed with low w/cm's leave little latitude for error. Without accurate adjustment of batch weights, the moisture released or absorbed by the aggregates can undermine the properties of an HPC mixture.

10.4.2. Issues with Wet Coarse Aggregate and Silica Fume Pumping

Over the course of this study, it was learned to exercise discretion when batching coarse aggregate with unduly high moisture content. During one trial batch at the plant, coarse aggregate, wet several percent above absorption capacity, was moved from stockpile to a bin just prior to lunch break. The delay allowed free moisture to drain from the aggregate and out the bottom of the bin. By that time, mixture proportions were adjusted for the coarse aggregate moisture as sampled from the stockpile and work proceeded. As a result, the mixture turned out with scant workability and was discarded. Batching with wet fine aggregate is less of a concern. This is because fine aggregate can hold heavy moisture better than coarse aggregate. Experience shows that a free moisture content as high as 6% can be stable in fine aggregate.[7]

Pumping of silica fume slurry introduced another potential inaccuracy. At the start of work, the hose for pumping contained wash water from the previous cleanup. Flushing the hose with silica fume slurry prior to batching was necessary to remove the water and obtain a correct amount of silica fume. In a misguided attempt to save resources, adjustments were made to the mixing water and silica fume quantities based on an estimate of the volume and fill of the hose. This resulted in several botched efforts. Flushing the hose is minimally wasteful and only necessary for the first of successive batches.

10.4.3. Measures to Reduce Fresh Concrete Temperature

The precast/prestressing facility normally takes measures to curb fresh concrete temperatures during hot weather operations. Work is scheduled for the cool of early morning. Sprinkling of the coarse aggregate stockpiles helps reduce concrete temperatures. Additionally, as required, the plant uses crushed ice to chill the mixing water. However, going off site to purchase ice is inconvenient and, even so, satisfying the temperature specification during the height of an Oklahoma summer is uncertain. The plant now has plans for installation of a refrigeration unit. Establishing efficient and economical methods to reduce fresh concrete temperature is important since the rush of construction activity occurs during summer.

10.5. Experimental Results

Fresh concrete properties for both lab and plant batches are reported in Table 10.2. Measured slumps and fresh concrete temperatures are illustrated in Figure 10.1. Complete testing results are included in Appendix E.

Compressive strength results from lab batches cured under standard conditions, together with corresponding plant batches, these both ambient and heat cured, are reported in Table 10.3 and illustrated in Figures 10.2 and 10.3 for ages of 24 hrs and 28 days, respectively.

Table 10.2. Fresh Concrete Properties

			5	27	65	72	98	99	100
LABORATORY BATCHES	Concrete Temp.	°C	29.4	19.3	28.9	12.8	23.0	23.0	26.7
	Air Temp.	°C	38.9	24.2	—	7.8	—	—	—
	RH	%	35	65	—	43	—	—	—
	Slump	mm	200	180	80	240	270	280	250
	Measured Air Content	%	1.9	2.4	—	—	2.0	6.4	3.0
	Measured Unit Weight	kg/m^3	2,410	2,427	2,425	—	2,418	2,312	2,407
	Yield	m^3	1.00	1.00	1.00	—	0.99	0.99	0.96
PLANT BATCHES	Concrete Temp.	°C	34.4	35.0	33.9	30.0	34.4	35.0	32.8
	Air Temp.	°C	—	35.6	—	27.8	33.9	33.9	30.0
	RH	%	—	77	—	50	52	52	60
	Slump	mm	90	210	10	40	150	100	80
	Measured Air Content	%	3.5	1.8	4.0	2.4	4.5	6.1	4.3
	Measured Unit Weight	kg/m^3	2,412	2,450	2,425	2,444	2,344	2,261	2,373
	Yield	m^3	1.00	0.99	1.00	0.98	1.02	1.01	0.97

Fresh concrete properties for mixture 27 (lab) represent the averages from six batches
25.4 mm = 1 in, T(°C) = 5/9[T(°F) – 32], 1 kg/m^3 = 0.06243 lb/ft^3

Table 10.3. Measured Compressive Strengths

			5	27	65	72	98	99	100
1 day	**Lab/Standard**	MPa	**66.4**	**50.3**	**61.5**	**55.6**	**54.1**	**49.7**	**55.1**
	Plant/Ambient	MPa	54.1	41.1	61.2	41.9	29.5	36.7	45.7
	Plant/Heat	MPa	64.7	49.5	79.8	64.6	54.6	60.4	69.0
28 days	**Lab/Standard**	MPa	**95.3**	**93.4**	**103.6**	**117.7**	**106.7**	**98.8**	**107.3**
	Plant/Ambient	MPa	—	90.6	—	89.7	79.6	84.2	89.0
	Plant/Heat	MPa	75.0	86.3	74.0	84.8	81.2	82.9	87.1
56 days	**Lab/Standard**	MPa	—	**101.6**	**110.6**	**125.8**	**120.2**	**107.6**	**111.5**
	Plant/Ambient	MPa	—	96.6	—	94.9	88.4	87.8	93.7
	Plant/Heat	MPa	—	99.5	—	91.4	84.0	84.2	85.1

All mixtures were batched once except for mixture 27 (lab), which was batched six times with average results reported

1 MPa = 145 psi

10.6. Analysis and Discussion of Results

10.6.1. Workability

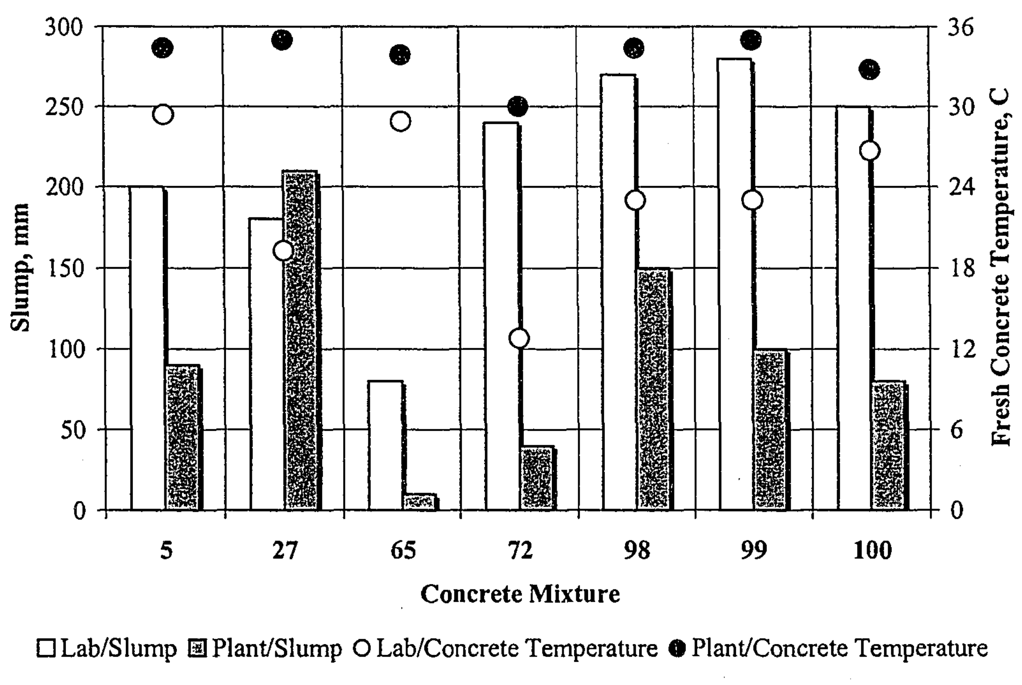
The mixtures selected for this study were largely geared for early strength development with *Type III* cement at low w/cm's, some even having a corrosion inhibiting/strength accelerating admixture. All these options for achieving high early strength innately work against workability. It was feared that workability problems could be encountered in the summer weather. Elevated temperatures stifle workability in two ways, by increasing the evaporation rate of moisture from fresh concrete and by accelerating cement hydration and setting.

Evaporation was clearly a concern. Given the concrete temperature, ambient temperature and relative humidity experienced when working at the plant, and assuming a wind velocity of 16 km/hr (10 mi/hr), the rate of evaporation, as estimated by the method of ACI 305,[8] was near 1 $kg/m^2/hr$ (0.2 $lb/ft^2/hr$). This is the level where precautions against plastic shrinkage cracking become necessary.

Working at the precast/prestressing plant under an afternoon sun and without the benefit of ice, fresh concrete temperatures exceeded that of counterpart lab batches every time. This is depicted in Figure 10.1. In fact, fresh concrete temperatures at the plant matched or exceeded 30 °C (86 °F), the maximum allowed by the Oklahoma DOT for highway projects.[9] Concrete delivered at temperatures outside specification limits is normally rejected. The resulting loss of workability, as indicated by the slump measurements, was sometimes dramatic. Six of the seven mixtures met reduced slump at the plant. Of these six, it was found that each increase of 1.67 °C (3.0 °F) in concrete temperature reduced the slump by an average of 25 mm (1 in).

A slump of 150 mm (6 in) was considered essential for prompt placement and effective consolidation. A slump of 200 mm (8 in) was preferred. Only two of the plant mixtures yielded the necessary slump. Compounding this problem, rapid stiffening of the mixture limited the time frame for placement and consolidation. Sometimes this window was as short as 15 minutes.

Figure 10.1. Slump & Temperature



10.6.2. Early Strength Gain

Compressive strength results at 24 hrs for the three series of mixtures, lab/standard, plant/ambient and plant/heat are illustrated in Figure 10.2. Only two lab/standard mixtures achieved the target strength of 60 MPa (8,700 psi). It was anticipated that heat curing at the plant would make up the difference. Indeed, heat curing was generally advantageous to early strength gain. Five of the plant/heat mixtures reached 60 MPa (8,700 psi) at 24 hrs. Mixture 65 produced under plant/heat performed best at 24 hrs, achieving 79.8 MPa (11,570 psi). All seven plant/heat strengths exceeded corresponding plant/ambient strengths. However, plant/heat failed to exceed counterpart lab/standard on two instances, mixtures 5 and 27.

10.6.3. Strength Development

All plant/ambient and plant/heat mixtures, by ages of 28 and 56 days, achieved less strength than counterpart lab/standard mixtures. Figure 10.3 illustrates these results at 28 days.

Four of seven lab/standard mixtures achieved the 100 MPa (14,500 psi) target strength at 28 days. By 56 days, all of the lab/standard mixtures that were tested achieved the target strength. Yet only lab/standard mixture 65 satisfied both the early and ultimate strength targets. By contrast, all mixtures from the plant/ambient or plant/heat series failed to meet the 100 MPa target. Plant/heat mixture 27 was nearest, 99.5 MPa (14,430 psi) at 56 days, but was shy of the early age target, gaining only 49.5 MPa at 24 hrs.

Average strength development for the three series of mixtures is portrayed in Figure 10.4. Clearly, strength gain for the plant/heat series was stunted after 24 hrs. Best of the three series at 24 hrs, plant/heat confirmed the reduction in long term strength that is emblematic of heat curing. Two plant/heat mixtures even declined in measured strength.

Lab/standard mixtures demonstrate the best rate of strength development between 28 and 56 days, increasing strength by 8.0% on average. Plant/ambient and plant/heat strengths at 28 and 56 days are fairly similar, plant/ambient having rebounded from an early disadvantage. A test of hypothesis conducted by matched pairs, with 95% confidence, indicates that the differences observed between plant/ambient and plant/heat at these ages are statistically insignificant. On average at 28 days, plant/ambient mixtures achieved 83.2% of corresponding lab/standard results. Similarly, plant/heat mixtures achieved only 79.4% of corresponding lab/standard results.

Figure 10.2. Compressive Strength (1 day)

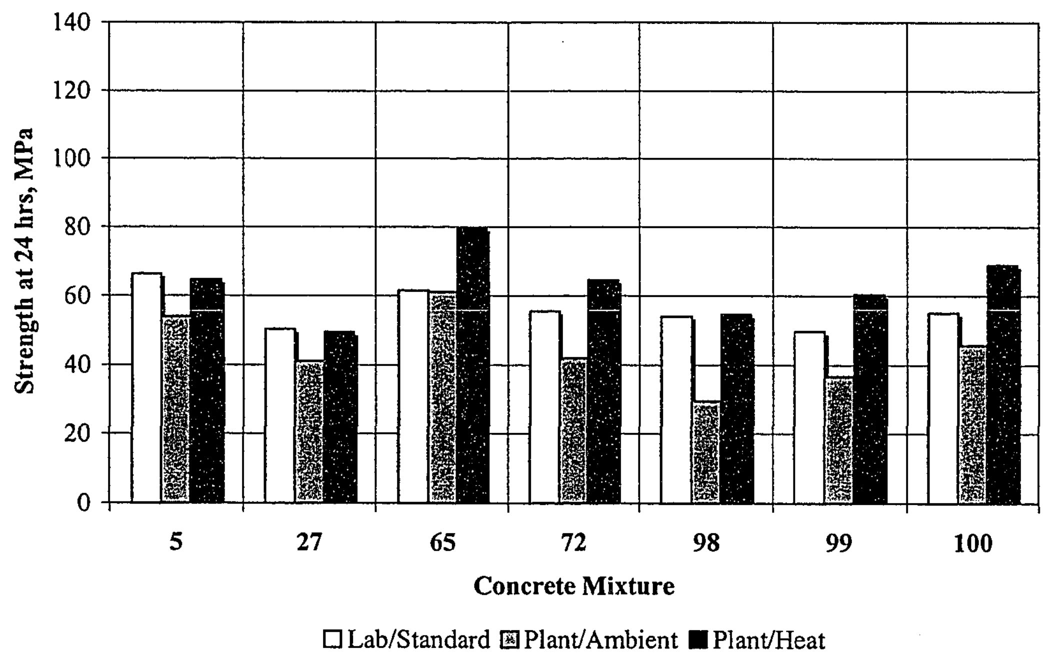


Figure 10.3. Compressive Strength (28 days)

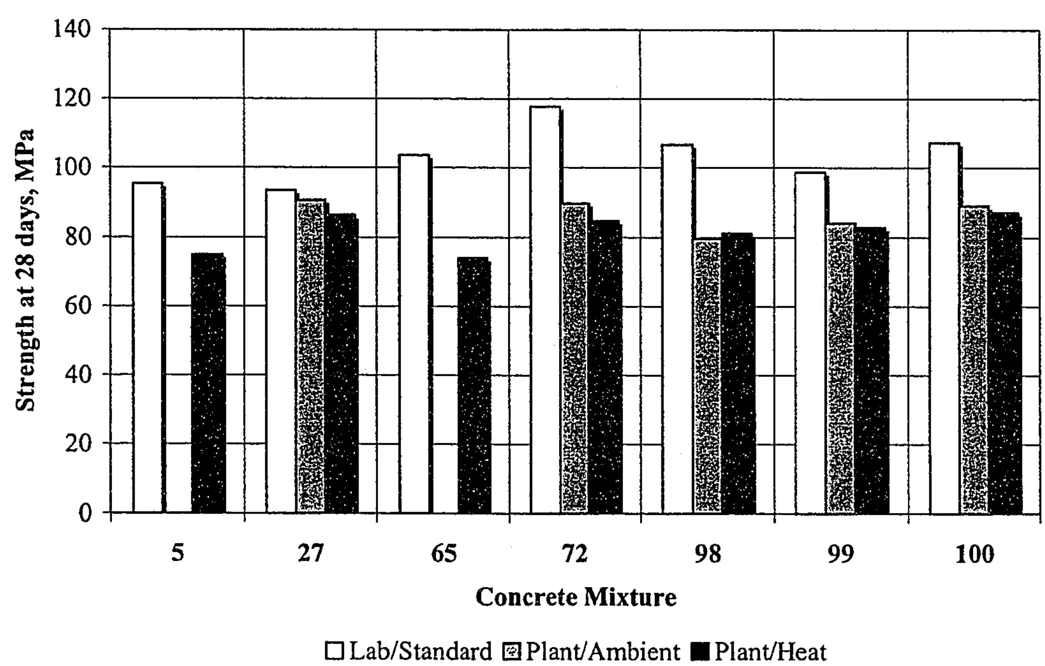
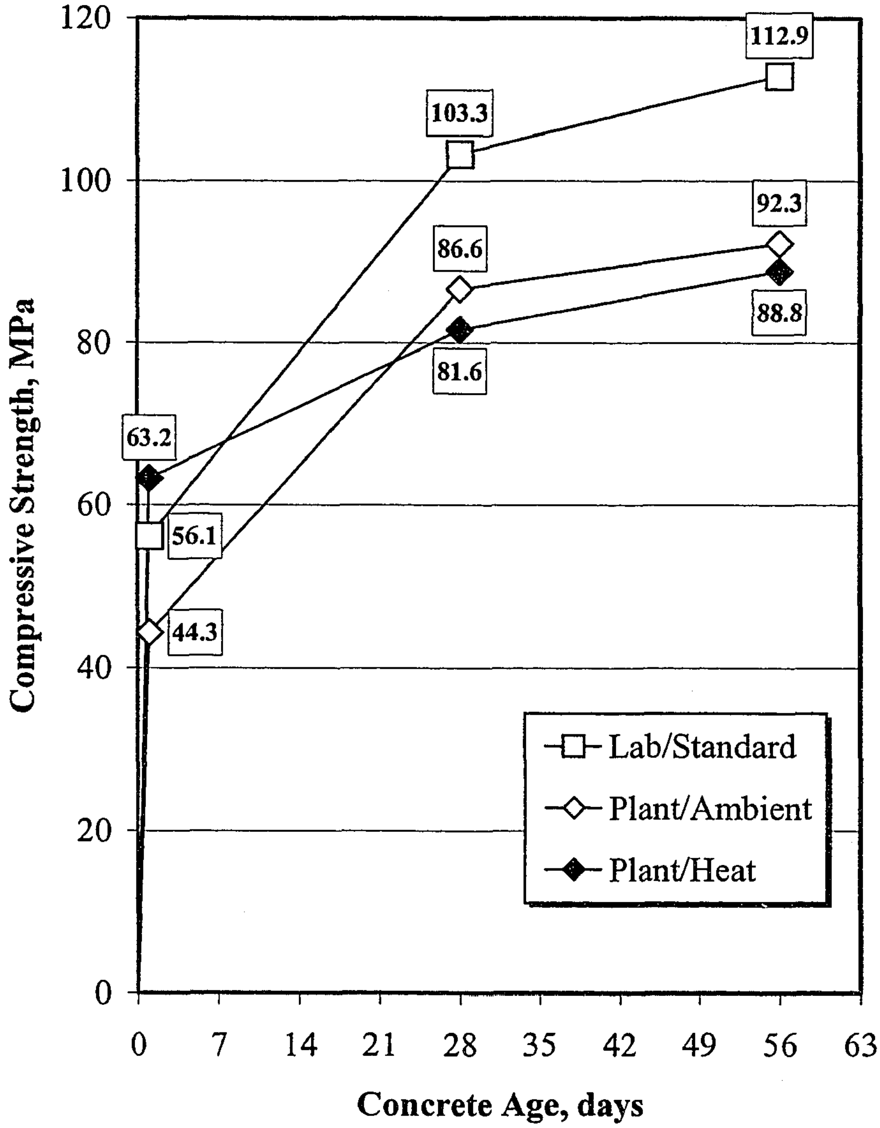


Figure 10.4.
Average Strength Development with Time



10.6.4. Statistical Concepts

ACI 363[1] suggests standards of quality control based on the coefficient of variation. The coefficient of variation is the standard deviation expressed as a percentage of the average compressive strength. The coefficient of variation is useful for describing the degree of control for a wide range of strength levels.

The within-test coefficient of variation was lowest for lab/standard testing. It was determined to be 2.7% on average. Plant/ambient and plant/heat within-test variations were similar to each other and both much higher than lab/standard, reaching 4.6% on average. The curing schemes, more than the discrepancies associated with batching location, are believed to have contributed to the greater within-test variation observed for the plant/ambient and plant/heat mixtures.

10.7. Conclusions

Advancing HPC technology from laboratory to a precast/prestressing facility presented a challenge because workability and compressive strength from lab-batched HPC were not readily reproduced at a plant. Tested at 28 days, plant-batched concrete (plant/ambient and plant/heat) achieved, on average, about 80% of corresponding lab/standard strengths. Moreover, the plant-batched concrete displayed greater within-test variation.

As expected, heat curing at the plant enhanced early strength gain. Mixtures from the plant/heat series generally achieved the best strength at 24 hrs and, when compared to ambient curing during the summer season, did not result in significant difference in ultimate strength.

A chief quality control concern at the precast/prestressing plant participating in this study was regulating the quantity of water in the mixture and batching the concrete as intended. The uncertainty of aggregate moisture made this difficult. Aggregate stockpiles were constantly in transition with daily arrival of new material, sprinkling to help reduce temperature, and rainfall. Understanding the configuration of the batching works is also necessary. It was learned to avoid batching coarse aggregates with excessive moisture and to flush the hose before dispensing silica fume slurry.

Summer temperatures experienced at the plant resulted in diminished workability, as indicated by slump. Because HPC workability can be very sensitive to concrete temperature, improved measures to reduce fresh concrete temperature are necessary.

Difficulties can arise when conveying new technology beyond the confines of the laboratory. Prior to application of HPC, trials at the intended commercial facility under anticipated working conditions are essential to verify concrete qualities. Adjustments to the mixture proportions may be necessary.

[1] ACI 363.2, *Guide to Quality Control and Testing of High-Strength Concrete*, American Concrete Institute, 1998.
[2] Ralls, M. L., "Texas HPC Bridge Decks," *Concrete International*, Vol. 21, No. 2, February 1999, pp. 63-65.
[3] Myers, J. J. and Carrasquillo, R. L., "Quality Control and Quality Assurance Program for Precast Plant Produced High Performance Concrete U-Beams," *Proceedings of the PCI/FHWA International Symposium on High Performance Concrete*, New Orleans, Louisiana, 1997, pp. 368-382.
[4] ACI 211.4, "Guide for Selecting Proportions for High-Strength Concrete with Portland Cement and Fly Ash," *ACI Manual of Concrete Practice*, Part 1, American Concrete Institute, 1997.
[5] American Society for Testing and Materials, *Annual Book of ASTM Standards*, Vols. 4.01 and 4.02, 1995.
[6] ACI 318, *Building Code Requirements for Structural Concrete and Commentary*, American Concrete Institute, 1999.
[7] ACI 304, "Guide for Measuring, Mixing, Transporting, and Placing Concrete," *ACI Manual of Concrete Practice*, Part 2, American Concrete Institute, 1999.
[8] ACI 305, "Hot Weather Concreting," *ACI Manual of Concrete Practice*, Part 2, American Concrete Institute, 1999.
[9] Oklahoma Department of Transportation, *Standard Specifications for Highway Construction*, 1996.

11. Conclusions & Suggestions for Additional Research

There exists the potential to produce high performance concrete (HPC) in Oklahoma using readily available constituents, local to Oklahoma or neighboring states. One likely application of HPC is in precast/prestressed bridge beams, where the benefits include structural efficiency, speed of construction and durability. HPC compressive strengths of 60 MPa (8,700 psi) at 1 day and 100 MPa (14,500 psi) at 28 or 56 days are attainable in Oklahoma.

11.1. Comparing Different Cements in HPC

Trial batching is necessary to assess the quality and suitability of constituent materials in concrete. Eight cements encompassing different types, manufacturers and plant locations were examined in two classes of HPC mixtures. The choice of cement influenced both the fresh and hardened properties of HPC. The results show that all cements appear suitable for producing HPC with these constituent materials and mixture proportions. Mixtures containing a *Type III* cement achieved the highest compressive strength at all ages tested, most significantly at early ages. The compressive strength results with *Type III* cement were statistically significant at 1 day on the basis of 95% confidence intervals, however, the differences observed between mixtures at 28 and 56 days were statistically insignificant. In other words, compressive strength differences among the mixtures were most pronounced at 1 day but diminished over time through 56 days. The wide range in early strength was to some extent due to the retarding effects of chemical admixtures. Superplasticizer addition rates should be adjusted for different cements to avoid an excessive delay in setting time. At 28 days, cement characteristics influenced splitting tensile strength more significantly than compressive strength and compressive strength more significantly than modulus of elasticity, a conclusion based on the coefficient of variation of the results. The applicability of the ACI prediction equations must be confirmed for different cements in HPC. ACI 209 underestimated the rate of compressive strength development at early ages. ACI 363 was mostly accurate within ±10% in describing splitting tensile strength, but overestimated the majority of the results. ACI 363 underestimated modulus of elasticity by more than 10% while ACI 318, extended beyond its valid range, underestimated most elastic moduli results. The relationship between elastic modulus and compressive strength was not apparent.

11.2. Comparing Different Aggregates in HPC

Trial batching is necessary to assess the quality and suitability of constituent materials in concrete. Four coarse aggregates quarried in Oklahoma, limestone, rhyolite, granite and river gravel, were evaluated in HPC mixtures in both a "quarry-acquired" and "standard" grading. The "quarry-acquired" approach allowed examination of the aggregates in a manner consistent with commercial production. The "standard" approach allowed examination of the type, shape and texture of aggregates independent of grading. The choice of coarse aggregate influenced both the fresh and hardened properties of HPC. On average, HPC mixtures achieved about 75 MPa (10,900 psi) compressive strength at 28 days. The range of compressive strength results expanded with age. The opposite tendency was observed in a similar study of different cements, where a wide range of compressive strengths resulted at an early age but narrowed with time. Together, these results indicate that, in HPC, cement selection was crucial to early strength gain while the choice of coarse aggregate was more important to ultimate strength development. In terms of compressive strength, limestone (best in "quarry-acquired" grading), granite (best in "standard" grading) and rhyolite — all crushed aggregates and angular in shape and rough in surface texture — demonstrate potential for use in HPC; the smooth and partially uncrushed river gravel aggregates have less potential. The maximum size of aggregate (MSA) influenced compressive strength, with smaller MSA better. However, on the basis of 95% confidence intervals, the compressive strength results at all ages were statistically similar. Granite aggregates produced relatively low splitting tensile strength and flexural strength but, conversely, provided high modulus of elasticity. ACI 363 was mostly accurate within ±10% in describing splitting tensile strength and underestimated flexural strength results, sometimes by more than 10%. ACI 363 underestimated modulus of elasticity by 10% or more while ACI 318, extended beyond its valid range, underestimated most elasticity results. The applicability of these empirical relationships must be confirmed for different coarse aggregates in HPC. Increasing the fineness modulus by introducing an intermediate aggregate did not enhance slump, as expected, but slightly increased compressive strength and splitting tensile strength.

11.3. The Utility of the w/cm and w/c for Predicting HPC Strength

The w/cm remains an essential, descriptive statistic for today's increasingly complex HPC mixtures. The w/c is also useful. A sample of 125 HPC mixtures of various materials and proportions was fitted with linear regression models relating compressive strength at ages of 1, 28 and 56 days to the w/cm and/or w/c. It was observed that strength generally increased as the w/cm or w/c was lowered. But linear regression models using a single independent variable, either the w/cm or w/c, failed to return a coefficient of determination, R^2, more than 0.535. It was learned that the w/c provides a stronger indication of strength at 1 day. By 28 and 56 days, because of pozzolanic activity, the w/cm becomes a better indication of strength. Multiple linear regression models using both the w/cm and w/c capture more of the variability in the data.

11.4. Heat Curing of HPC

A variety of HPC mixtures were examined under a number of heat curing schemes in parallel with ASTM C 192 standard curing to investigate the effect of curing on compressive strength development. The heat curing schemes were classified as either moderate or intense based on peak temperature. These were intended to simulate the heat curing processes regularly employed in the manufacture of precast/prestressed concrete bridge beams. The study involved 31 different HPC mixtures, each containing *Type III* cement and many having partial replacement of cement with fly ash, silica fume and/or slag. The w/cm's of the HPC mixtures ranged from 0.24 to 0.31.

Under standard curing, average compressive strength results were 57.7 MPa (8,370 psi) at 1 day, 95.3 MPa (13,820 psi) at 28 days and 102.9 MPa (14,920 psi) at 56 days. Different mixtures responded differently to heat curing but, in general, heat curing was found damaging to ultimate strength potential and sometimes even failed to accelerate early strength development. In terms of strength development at 1 day, heat curing was beneficial to mixtures containing supplementary cementitious materials. However, mixtures with *Type III* cement exclusive of supplementary cementitious materials largely failed to benefit from heat curing at 1 day. Heat curing impaired strength development at 28 and 56 days relative to standard curing, and intense heat was found more damaging than moderate heat. By examining a single mixture under multiple curing schemes, moderate heat was found nearly as effective as intense heat for enhancing early strength development and without the negative consequences at 28 and 56 days. Additionally, lowering the w/cm, while beneficial to strength development under standard curing, was found to be detrimental under intense heat curing.

Speed of construction is an important consideration in the manufacture of precast/prestressed concrete bridge beams. Heat curing is regularly employed to accelerate early strength development. However, while heat curing may be useful in a business model that gives emphasis to rapid speed of construction, it may not always be pragmatic in a business model that gives emphasis to lifecycle costs.

11.5. Designing HPC for Precast/Prestressed Beams

Achieving high early strength in harmony with adequate workability and high ultimate strength is a challenge facing the precast/prestressing industry in construction of bridge beams. There are several options for elevating early strength gain. Among these options is design of a low w/cm and the use of *Type III* cement, certain chemical admixtures, and heat curing. Frequently, however, these options compromise workability or ultimate strength development.

Lowering the w/cm increases strength but is detrimental to workability. Also, lowering the w/cm increases the rate of early strength gain and, in 1 day, HPC mixtures can achieve up to 60% of 28 day strength under standard curing. Increasing cement content at a constant w/cm does not necessarily increase strength. Using a *Type III* cement at a w/cm of 0.30, a strength plateau was reached at a cement content near 500 kg/m^3 (843 lb/yd^3). However, increasing cement content at a constant w/cm enhances workability. Use of fly ash as a partial replacement of cement can enhance workability and ultimate strength development. HPC with fly ash and/or other supplementary cementitious materials has relatively slow early strength gain, but responds well to heat curing. *Type III* cement is typically employed in precast/prestressed concrete bridge beams where its high fineness enhances early strength gain. But in terms of workability and ultimate strength potential, *Type I* or *Type II* cements are preferable. A superplasticizing admixture is beneficial in all respects. An air entraining admixture, although beneficial to workability, substantially reduced strength. A corrosion inhibiting/strength accelerating admixture containing calcium nitrite was found beneficial to both early and ultimate strength and did not affect workability. Use of a CI/SA admixture increased strength more than 20% at 28 and 56 days. Finally, heat curing can enhance early strength gain in some HPC mixtures. But heat curing is always detrimental to ultimate strength development.

When designing an HPC mixture to satisfy multiple performance objectives, it is helpful to survey all the options and to understand how these are sometimes both beneficial and detrimental. Trial batching is necessary to determine the best mixture for the specific application.

11.6. Repeatability and Normality of HPC Compressive Strength

Six HPC mixtures were batched multiple times to assess the batch-to-batch repeatability and also the normality of the compressive strength results. The HPC mixtures had compressive strength values at 28 days between 61.0 to 94.3 MPa (8,850 to 13,670 psi). The coefficient of variation (CV) is a useful measure of the batch-to-batch repeatability; a low CV is indicative of a high level of repeatability. At 28 days, the CV's ranged from 2.10% to 8.30%. The repeatability of four of the mixtures was considered "excellent" or "very good" according to the ACI 363 standards, while the repeatability of the remaining two mixtures was considered "poor." With five of the six mixtures, the CV was lower at 28 days than at 1 day. One of the issues most likely to have contributed to the CV of the compressive strength results was the innacuracy of determining the aggregate moisture contents. The HPC compressive strength results generally followed a normal distribution. However, some irregularity was observed in the relative frequency histograms.

11.7. Bringing HPC from Laboratory to a Precast/Prestressing Plant

Advancing HPC technology from laboratory to a precast/prestressing facility presented a challenge because workability and compressive strength from lab-batched HPC were not readily reproduced at a plant. Tested at 28 days, plant-batched concrete (plant/ambient and plant/heat) achieved, on average, about 80% of corresponding lab/standard strengths. Moreover, the plant-batched concrete displayed greater within-test variation.

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Difficulties can arise when conveying new technology beyond the confines of the laboratory. Prior to application of HPC, trials at the intended commercial facility under anticipated working conditions are essential to verify concrete qualities. Adjustments to the mixture proportions may be necessary.

11.8. Ideas for Additional Research

HPC is a new and rapidly evolving material and there are many unexplored avenues of research. Some potential titles of journal articles in the future:

- "Suggested Modifications to the ASTM Standards for Laboratory Batching and Testing of HPC" ASTM does not address several concerns, including aggregate moisture content during batching and the hardness of neoprene pads.
- "An Assessment of Current Quality Assurance/Quality Control Tests" The slump test is increasingly considered an imprecise measure of workability. How useful is the unit weight measurement? Does it correlate well with compressive strength? What new QA/QC tests are being introduced?
- "Variables Influencing the Aggregate/Paste Bond in HPC" Aggregate surface texture and cement chemistry are certainly two important variables. Other variables may include supplementary cementitious materials, w/cm, curing, and concrete age.
- "Designing HPC at Very Low w/cm's" Is it practical to design HPC with less water than required for complete cement hydration? The presence of unhydrated cement particles may thwart some types of corrosion.

- "A Life Cycle Cost Analysis Procedure for Precast/Prestressed Concrete Bridges" A collection of cost data on existing bridges would be useful.
- "Waste Materials With Potential for Use in HPC" One possibility is old concrete crushed and recycled as new aggregate.
- "Think Green, Think Concrete" How does HPC compare to other building materials in terms of environmental impact and sustainable development, and how might HPC's competitive position be improved?
- "HPC and Residential Homes" The thermal mass of concrete provides energy efficiency by reducing indoor temperature swings, among other benefits.

Appendix A. Glossary

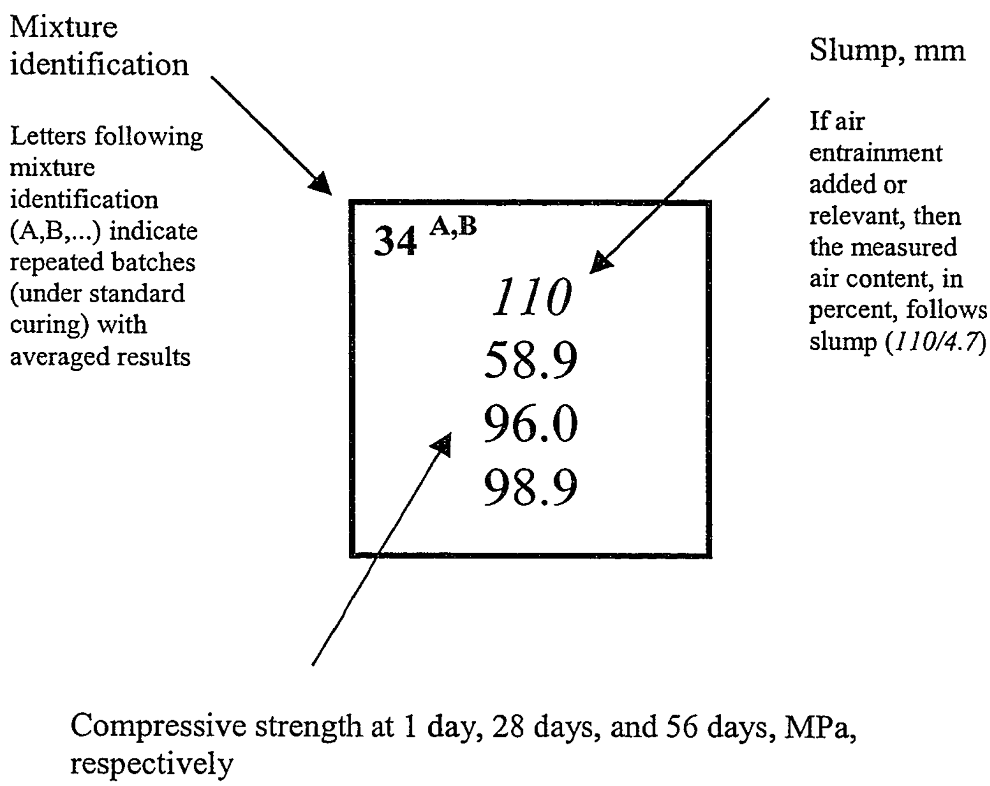
W_{AG_C}	Weight of aggregate after corrected for aggregate moisture
$W_{AG_{SSD}}$	Weight of SSD aggregate
AB_{AG}	Absorption of aggregate
MC_{AG}	Moisture content of aggregate at time of batching
W_{W_C}	Weight of water after corrected for aggregate moisture
W_W	Weight of water in a concrete mixture with SSD aggregates
$f_c^{'}$	Specified compressive strength of concrete
$\dot{f}_c$	Average measured compressive strength of concrete
$f_r^{'}$	Flexural strength (modulus of rupture) of concrete
$f_{sp}^{'}$	Splitting tensile strength of concrete
E_c	Modulus of elasticity of concrete
AC *I/II*	Ash Grove *Type I/II* cement from Chanute, KS; also designated C5
AC *III*	Ash Grove *Type III* cement from Chanute, KS; also designated C9
AE admixture	Air entraining admixture
AF *I*	Ash Grove *Type I* cement from Foreman, AR; also designated C4
AM *I*	Ash Grove *Type I* cement from Midlothian, TX; also designated C3
CA	Coarse aggregate
CI/SA admixture	Corrosion inhibiting/set accelerating admixture

DRUW	Dry rodded unit weight
DS	Natural river sand from Dolese Bros. Co., Dover, OK
FA	Fine aggregate
GAF	Grace Construction Products' *ADVA Flow* high range water reducer (superplasticizer) for ready mix concrete (ASTM C 494 *Type F*)
GD17	Grace Construction Products' *Daratard 17* set retarding/water reducing admixture (ASTM C 494 *Type B/D*)
GD19	Grace Construction Products' *Daracem 19* high range water reducing or superplasticizing admixture (ASTM C 494 *Type A/F*)
GDCI	Grace Construction Products' *DCI* corrosion inhibitor with secondary set and strength accelerating properties (ASTM C 494 *Type C*)
GDV	Grace Construction Products' *Daravair 1000* air entraining admixture (ASTM C 260)
GHC	Grace Construction Products' *WRDA with Hycol* water reducing admixture (ASTM C 494 *Type A*)
GNq GNs	Crushed granite from Meridian Aggregates Co., Snyder, OK with either of two gradings: "quarry-acquired" (which closely met the No. 7 grading requirements of ASTM C 33) or "standard"
GVq/GV7 GVs	Partially crushed sandstone river gravel from B & B Sand & Gravel, Broken Bow, OK with either of two gradings: "quarry-acquired" (which met the No. 7 grading requirements of ASTM C 33) or "standard"
HA *I*	Holnam *Type I* cement from Ada, OK; also designated C6
HA *II*	Holnam *Type II* cement from Ada, OK; also designated C7
HM *III*	Holnam *Type III* cement from Midlothian, TX; also designated C8
HPC	High performance concrete
HRWR admixture	High range water reducing admixture, often called superplasticizer

HSC	High strength concrete
IA	Intermediate aggregate
LIq/LI8 LIs LI67	Crushed limestone from Dolese Bros. Co., Davis or Richard Spur, OK with either of three gradings: "quarry-acquired" (which met the No. 8 grading requirements of ASTM C 33), "standard", or No. 67
LP *I*	Lonestar *Type I* cement from Pryor, OK; also designated C1
LP *I/II*	Lonestar *Type I/II* cement from Pryor, OK; also designated C2
LS	Limestone screenings, also called "washed shot," from Dolese Bros. Co., Davis, OK
RHq/RH7 RHs	Crushed rhyolite from Western Rock Products, Davis, OK with either of two gradings: "quarry-acquired" (which met the No. 7 grading requirements of ASTM C 33) or "standard"
SCM/TCM	The ratio of supplementary cementitious materials to total cementitious material by weight in a concrete mixture
SG	Specific gravity
SR/WR admixture	Set retarding/water reducing admixture
SSD aggregates	Saturated and surface dry aggregates
w/c	The ratio of water to cement by weight in a concrete mixture
w/cm	The ratio of water to cementitious material by weight in a concrete mixture
WR admixture	Water reducing admixture
Yield	The total weight of materials divided by the measured unit weight

Appendix B. Batching Matrices

BATCHING MATRICES
KEY



All results are from laboratory trial batching at the University of Oklahoma and standard cured 100 x 200 mm cylinders tested with neoprene pads

BATCHING MATRIX 1

		Class 1	Class 2
Cement	C1	C1/1 [A,B,C,D] *230* 23.4 57.1 61.1	C1/2 [A,B,C] *250* 32.1 71.8 77.0
	C2	C2/1 [A,B,C,D] *270* — 61.1 67.6	C2/2 [A,B,C] *260* — 76.5 81.5
	C3	C3/1 [A,B,C,D,E] *220* 22.3 61.0 65.8	C3/2 [A,B,C,D] *240* 36.9 81.5 86.7
	C4	C4/1 [A,B,C] *260* 20.1 63.3 67.9	C4/2 [A,B,C] *230* 22.2 77.1 80.2
	C5	C5/1 [A,B,C] *240* 21.3 61.8 67.5	C5/2 [A,B,C] *260* 12.4 77.6 81.9
	C6	C6/1 [A,B,C] *180* 15.3 62.3 65.2	C6/2 [A,B,C] *230* 22.4 73.7 79.0
	C7	C7/1 — 16.8 60.8 64.3	C7/2 — 10.0 71.3 73.7
	C8	C8/1 [A,B,C] *120* 39.9 65.3 —	C8/2 [A,B,C,D,E] *220* 52.5 82.2 87.3

BATCHING MATRIX 2

Aggregate Type		Quarry–Acquired Gradation	Standard Gradation
Aggregate Type	Limestone	LIq [A,B,C,D,E,F] *200* 27.3 85.1 91.2	LIs [A,B] *240* 23.3 73.8 78.6
	Rhyolite	RHq [A,B] *200* 28.9 76.0 81.7	RHs [A,B] *200* 25.3 78.9 83.3
	Granite	GNq [A,B] *260* 23.7 76.1 82.4	GNs [A,B] *220* 30.3 83.8 88.7
	River Gravel	GVq [A,B] *230* 22.1 64.9 70.0	GVs [A,B] *250* 24.6 70.1 74.6

All concrete mixtures designed with a w/cm of 0.281 and contain 640.6 kg/m^3 of cementitious material with 26% fly ash replacement

All mixtures contain Ash Grove/Midlothian *Type I* cement, natural sand, and Grace admixtures *Daratard 17* and *Daracem 19* — at a uniform addition rate

BATCHING MATRIX 3

	Fineness Modulus	
	2.5	**3.3**
First Mixture	**C3/1** A,B,C,D,E *220* 22.3 61.0 65.8	**C3/1 i** *200* 23.2 62.4 —
Second Mixture	**LIq** A,B,C,D,E,F *200* 27.3 85.1 91.2	**LIq i** *150* 23.1 89.0 —

The fineness modulus was increased by blending an intermediate size limestone aggregate with natural sand

BATCHING MATRIX 4

Cementitious Material Content, kg/m^3		Cement Only			10% Fly Ash		20% Fly Ash	
		w/cm **0.32**	w/cm **0.30**	w/cm **0.28**	w/cm **0.30**	w/cm **0.28**	w/cm **0.28**	w/cm **0.26**
	400	37 *60* 51.6 84.3 91.0	8 *20* 61.6 85.0 —				25 *10* 47.8 91.7 98.8	
	450	38 [A,B] *100* 55.1 88.8 95.2	7 [A,B] *120* 60.0 88.8 93.6				26 *100* 48.0 94.9 103.3	
	475		9 [A,B,C,D] — 66.1 91.4 96.1					
	500	39 *200* 55.0 89.0 95.2	6 [A,B,D] *160* 61.8 92.9 95.1	18 [A,B] *10* 64.5 93.4 99.1	33 *210* 51.9 91.9 99.8	34 [A,B] *110* 58.9 96.0 98.9	27 [B,C,D,E,F] *180* 50.3 93.4 101.6	32 *10* 55.5 100.2 110.4
	550		5 *200* 66.4 95.3 —	14 *110* 67.7 95.5 100.9	35 *220* 52.9 94.6 99.8	36 *100* 60.2 99.6 105.1	28 [B] *220* 49.2 97.2 107.8	31 *120* 55.1 98.0 106.6
	600		4 — 65.0 93.0 —	15 *150* 65.5 96.3 —			29 *250* 49.8 96.6 100.7	30 *190* 54.7 101.2 109.5
	650		3 *260* 66.8 98.2 —	16 *220* 66.1 95.5 97.6				
	700		2 — 68.7 94.5 —					
	750		1 — 64.3 93.3 —					

All concrete mixtures contain Holnam/Midlothian *Type III* cement, No. 8 graded limestone aggregate, natural sand, and Grace admixtures *WRDA with Hycol* and *Daracem 19*

BATCHING MATRIX 5

				w/cm **0.32**	w/cm **0.30**	w/cm **0.28**	w/cm **0.26**
Cement Only				39 *200* 55.0 89.0 95.2	6 [A,B,D] *160* 61.8 92.9 95.1	18 [A,B] *10* 64.5 93.4 99.1	
Fly Ash Replacement,%	**10**	**Silica Fume Replacement, %**	**0**		33 *210* 51.9 91.9 99.8	34 [A,B] *110* 58.9 96.0 98.9	
Fly Ash Replacement,%	**20**	**Silica Fume Replacement, %**	**0**			27 [B,C,D,E,F] *180* 50.3 93.4 101.6	32 *10* 55.5 100.2 110.4
Fly Ash Replacement,%	**0**	**Silica Fume Replacement, %**	**5**		55 *120* 55.8 96.0 97.4	61 *70* 61.2 97.9 102.1	
Fly Ash Replacement,%	**0**	**Silica Fume Replacement, %**	**7.5**		56 *110* 53.1 95.1 104.1	62 *70* 59.9 95.9 97.4	
Fly Ash Replacement,%	**0**	**Silica Fume Replacement, %**	**10**		54 [A,B] *80* 54.1 93.7 100.7		
Fly Ash Replacement,%	**10**	**Silica Fume Replacement, %**	**5**			57 *110* 50.3 97.3 103.7	63 *40* 60.8 98.0 111.0
Fly Ash Replacement,%	**10**	**Silica Fume Replacement, %**	**7.5**			58 *130* 49.8 96.5 103.5	64 *40* 60.4 106.1 112.5
GGBF Slag, %	**10**	**Silica Fume Replacement, %**	**5**		59 *150* 47.2 92.1 98.1		
GGBF Slag, %	**10**	**Silica Fume Replacement, %**	**7.5**		60 *160* 48.2 91.9 94.7		

All concrete mixtures designed with 500 kg/m^3 of cementitious material and contain Holnam/Midlothian *Type III* cement, No. 8 graded limestone aggregate, natural sand, and Grace admixtures *WRDA with Hycol* and *Daracem 19*

BATCHING MATRIX 6

Corrosion Inhibitor/Strength Accelerator Addition, L/m³	Water Reducer & Superplasticizer Addition, mL/100 kg of cementitious material	w/cm **0.28**	w/cm **0.26**	w/cm **0.24**	w/cm **0.22**
0	**0** **1,000**		69 *210* 50.3 91.8 98.4	70 *130* 59.7 102.3 109.9	
0	**300** **1,300**			79 A,B *230* 54.0 112.3 122.0	78 *10* 63.7 117.0 122.4
20	**300** **700**	77 *280* 48.8 104.9 109.6	82 *100* 60.6 111.1 118.7		
20	**0** **1,000**		71 *230* 54.5 114.2 123.1		
20	**300** **1,000**	98 *270* 54.1 106.7 120.2	72 *240* 55.6 117.7 125.8	73 *100* 63.5 119.1 125.4	
30	**390** **650**		81 *120* 49.0 110.0 115.0		
30	**300** **1,000**		74 *250* 54.7 111.3 119.0		
40	**300** **1,000**		75 — 54.9 106.6 114.3		
50	**300** **1,300**		76 *250* 48.7 99.0 103.3		

Concrete mixtures designed with 600 kg/m³ of cementitious material (10% fly ash and 5% silica fume replacement) and contain Ash Grove/Chanute *Type III* cement, No. 8 graded limestone aggregate, and natural sand; Grace admixtures: *WRDA with Hycol* water reducer, *ADVA Flow* superplasticizer, and *DCI* corrosion inhibitor/strength accelerator

BATCHING MATRIX 7

	Cementitious Material Content, kg/m³				
	500		550	600	
	w/cm **0.28**	w/cm **0.26**		w/cm **0.24**	w/cm **0.22**
Holnam/Midlothian ***Type III* Cement** CA Content: 65% Admixtures: GHC, GD19	**57** *110* 50.3 97.3 103.7	**63** *40* 60.8 98.0 111.0	**65** *80* 61.5 103.6 110.6	**66** *60* 64.2 104.7 112.4	
Ash Grove/Chanute ***Type III* Cement** CA Content: 60% Admixtures: GHC, GAF				**79** [A,B] *230* 54.0 112.3 122.0	**78** *10* 63.7 117.0 122.4

All mixtures have 10% fly ash and 5% silica fume replacement of cement

All mixtures contain No. 8 graded limestone aggregate, natural sand, and chemical admixtures

BATCHING MATRIX 8

		Water Reducer & Superplasticizer Addition, mL/100 kg of cement	
		300 **1,300**	**300** **2,000**
Cement Content, kg/m³	**500**	18 [A,B] *10* 64.5 93.4 99.1	24 [A,B] *210* 59.9 91.4 102.0
	550	14 *110* 67.7 95.5 100.9	10 *230* 69.3 100.7 104.9
	600	15 *150* 65.5 96.3 —	11 — 65.7 96.2 102.0

All concrete mixtures designed with a w/cm of 0.28

All mixtures contain Holnam/Midlothian *Type III* cement, No. 8 graded limestone aggregate, natural sand, and Grace admixtures *WRDA with Hycol* and *Daracem 19*

BATCHING MATRIX 9

Water Reducer & Superplasticizer Addition, mL/100 kg of cementitious material	Fly Ash Replacement, %			
	0	**10**	**15**	**20**
400 **900**		20 *10* 62.1 97.4 104.7	21 *70* 56.6 94.7 102.6	17 *60* 53.4 98.8 107.1
200 **1,100**			22 *70* 57.6 92.8 100.7	
200 **1,300**			23 *190* 54.2 93.6 100.8	
300 **1,300**	18 [A,B] *10* 64.5 93.4 99.1	34 [A,B] *110* 58.9 96.0 98.9		27 [B,C,D,E,F] *180* 50.3 93.4 101.6
300 **2,000**	24 [A,B] *210* 59.9 91.4 102.0			

All concrete mixtures designed with a w/cm of 0.28 and 500 kg/m^3 of cementitious material

All mixtures contain Holnam/Midlothian *Type III* cement, No. 8 graded limestone aggregate, natural sand, and Grace admixtures *WRDA with Hycol* and *Daracem 19*

BATCHING MATRIX 10

Addition of AEA, mL/100 kg of cementitious material		Cement Only w/cm 0.30	Cement Only w/cm 0.26	Fly Ash Replacement of 20% w/cm 0.28	Fly Ash Replacement of 20% w/cm 0.24
	0	6 [A,B,D] *160/2.1* 61.8 92.9 95.1		27 [B,C,D,E,F] *180/2.4* 50.3 93.4 101.6	
	900	50 *220/6.7* 42.9 64.1 67.4		41 *240/—* 33.0 68.2 70.2	
	1,200	49 *220/8.6* 35.0 52.3 54.6	51 *0/—* 63.0 — 95.2	40 *240/6.3* 31.5 60.7 64.7	42 *10/—* 54.6 85.5 93.4

All concrete mixtures designed with 500 kg/m^3 of cementitious material

All mixtures contain Holnam/Midlothian *Type III* cement, No. 8 graded limestone aggregate, natural sand, and Grace admixtures *WRDA with Hycol, Daracem 19*, and, as indicated, *Daravair 1000*

BATCHING MATRIX 11

Addition of AEA, mL/100 kg of cementitious material		w/cm **0.28**	w/cm **0.26**	w/cm **0.24**
	0	98 *270/2.0* 54.1 106.7 120.2	72 *240/—* 55.6 117.7 125.8	73 *100/—* 63.5 119.1 125.4
	250	99 *280/6.4* 49.7 98.8 107.6	100 *250/3.0* 55.1 107.3 111.5	101 *220/2.2* 61.0 113.6 122.6
	500		102 *260/6.1* 45.0 87.9 90.4	
	750			103 *190/8.0* 47.2 78.7 84.5

All concrete mixtures designed with 600 kg/m^3 of cementitious material and have 10% fly ash replacement and 5% silica fume replacement

All mixtures contain Ash Grove/Chanute *Type III* cement, No. 8 graded limestone aggregate, and natural sand

Grace admixtures: *WRDA with Hycol* water reducer, *ADVA Flow* superplasticizer, *DCI* corrosion inhibitor/strength accelerator, and, as indicated, *Daravair 1000* air entrainer

BATCHING MATRIX 12

Aggregate Type		Coarse Aggregate Content (Volume of dry rodded coarse aggregate per unit volume of concrete), %					
		50	**55**	**60**	**65**	**70**	**75**
Aggregate Type	**Limestone**	67 *210* 48.6 87.0 99.2	43 *140* 52.6 97.0 102.4	44 *150* 51.3 98.9 102.7	27 B,C,D,E,F *180* 50.3 93.4 101.6	45 A,B *190* 50.7 94.8 101.3	46 A,B *200* 48.3 92.8 95.1
	Rhyolite			53 *150* 54.4 93.0 99.8	48 *140* 55.7 94.3 95.4		
	Granite			52 *190* 56.6 92.7 95.7	47 *170* 56.3 96.8 100.6		

All concrete mixtures designed with a w/cm of 0.28 and contain 500 kg/m^3 of cementitious material with 20% fly ash replacement

All mixtures contain Holnam/Midlothian *Type III* cement, coarse aggregate in a quarry-acquired gradation, natural sand, and Grace admixtures *WRDA with Hycol* and *Daracem 19*

Appendix C. Constituent Materials

PRODUCT INFORMATION

Grace Specialty Admixtures

Product Reference and Information Index

The grid below cross-references general admixture applications with particular products. It provides a visual representation of admixture selections available to concrete designers. Readers are encouraged to become familiar with specific product expectations by reviewing product information and consulting local Grace Concrete Products representatives.

Key
- ● = Primary influence on application
- ○ = Secondary influence on application

PRODUCTS: Type	Grace Products	APPLICATIONS	ASTM DESIGNATION C
Accelerators	PolarSet	[illegible]	494 Type C
	Daraccel	[illegible]	494 Type C & E
Air Entraining Agents	Darex Series	[illegible]	260
	Daravair Series	[illegible]	260
Controlled Low Strength Materials	DaraFill	[illegible]	
Corrosion Inhibitors	DCI	[illegible]	494 Type C
	DCI S	[illegible]	494 Type C
Fibers	Grace MicroFiber	[illegible]	
	Grace Fibers	[illegible]	
	GRACE Structural Fibers	[illegible]	
Finish Enhancing/Mid Range Water Reducers	MIRA	[illegible]	494 Type A & D
	Daracem 50	[illegible]	494 Type A
	Daracem 55	[illegible]	494 Type A
	Daracem 65	[illegible]	494 Type A
Hydration Stabilizers	Recover	[illegible]	494 Type D
Microsilica	Force 10,000 S	[illegible]	1240
	Force 10,000 D	[illegible]	1240
Retarders	Daratard	[illegible]	494 Type B & D
Shrinkage Reducing Admixtures	Eclipse	[illegible]	
Superplasticizers/High Range Water Reducers	ADVA	[illegible]	494 Type F
	Daracem 19	[illegible]	494 Type F
	Daracem 100	[illegible]	494 Type A, F & G
	Daracem ML 330	[illegible]	494 Type A & F
	Daracem ML 500	[illegible]	494 Type A & F
Water Reducers	Darapel	[illegible]	
	WRDA	[illegible]	494 Type A & D

* 41.4 MPa Plus (6,000 psi Plus)

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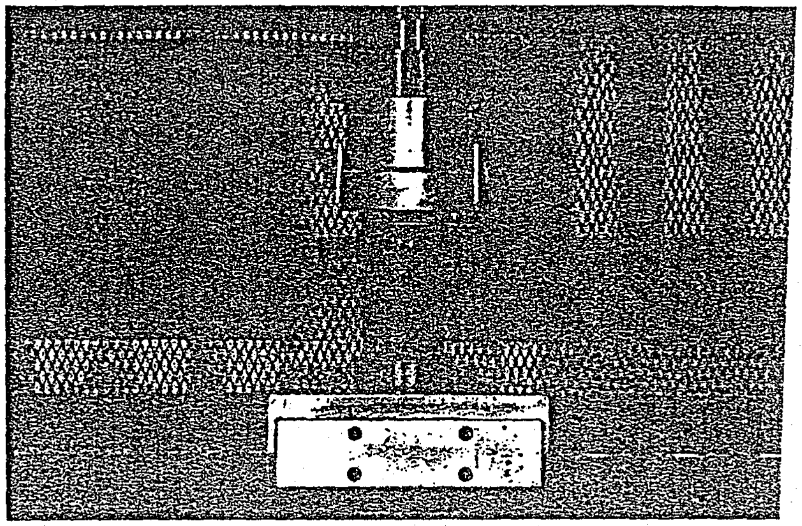
GRACE Construction Products

ODUCT INFORMATION

Force 10,000®

Microsilica, High Performance Concrete Admixture



Description

Force 10,000® is a microsilica-based liquid admixture designed to increase concrete compressive and flexural strengths, increase durability, reduce permeability and improve hydraulic abrasion-erosion resistance. Force 10,000 microsilica contains a minimum of 0.72 kg/L (6.0 lbs) of microsilica and weighs 1.39 ± .012 kg/L (11.6 ± 0.1 lbs/gal).

Uses

Force 10,000 microsilica can be used to consistently produce concrete with strengths of 41.4 MPa (6,000 psi) and higher in most instances with locally available materials and existing methods. It may also be used in precast and prestress applications where high early strengths are required.
The addition of Force 10,000 microsilica also produces concrete with increased watertightness and dramatically reduced permeability compared to conventional mixes. Reduced permeability is an important advantage in slowing the intrusion of chloride where corrosion of reinforcing steel is a potential problem. Examples are parking garages, bridge decks and concrete in a marine environment. Force 10,000 also enhances the durability of concrete against aggressive chemical attack and in hydraulic abrasion-erosion applications.

Chemical Action

Force 10,000 microsilica improves concrete through two mechanisms. The extremely fine microsilica particles are able to fill the microscopic voids between the cement particles, creating a less permeable structure. In addition, the microsilica reacts with the free calcium hydroxide within the concrete to form additional calcium silicate hydrate (glue), producing a tighter paste-to-aggregate bond.

Addition Rate

Force 10,000 microsilica dosage rates will vary based on the requirements of the application. Dosage rates should be calculated on percent microsilica per hundred weight of cement, or on pounds per cubic yard of concrete, as appropriate. Dosage rates will be as specified. If not specified, consult your Grace representative for your particular job needs.

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Compatibility with Other Admixtures

Force 10,000 microsilica is compatible with all conventional air-entraining agents, water reducers, superplasticizers, set retarders and DCI® corrosion inhibitor. Only non-chloride set accelerators, such as PolarSet®, may be used with Force 10,000 concrete. All admixtures must be added separately to assure their prescribed performance. Trial mixes and pretesting of concrete are recommended to optimize dosage rates, and ensure ultimate performance.

Concrete Mix

Force 10,000 microsilica can be used in either central or transit mix concrete production, and in mobile mixers. Force 10,000 microsilica may be used in conjunction with water-reducing admixtures (both normal and high range as approved by ASTM) to assure workability of the mix.

Force 10,000 microsilica does not affect concrete set times. When slump life extension is desired for transportation, finishing, etc, Force 10,000 may be used with an ASTM C 494, Type G, slump extending superplasticizer like Daracem® 100 as manufactured by Grace Construction Products, or approved equal.

Mix Water Reduction

Mix water adjustment is essential to account for the water in Force 10,000 and thus maintain the desired water/cement ratio. The mix water added at the batch plant must be reduced by 0.7 kg of water per Liter (5.8 lbs/gal) of Force 10,000 microsilica.

Finishing and Curing of Slabs

Force 10,000 concrete can be used in flatwork with little or no modification to the recommended practices outlined in ACI 302, "Guide for Concrete Floor and Slab Construction."

Force 10,000 microsilica will reduce the surface bleed water of concrete in large applications. ACI 308, "Standard Practice for Curing Concrete", must be followed to ensure that any problems that can occur due to decreased bleeding are minimized. Your Grace representative is available to review your particular job needs.

Preconstruction Trial Mix

It is strongly recommended that trial mixes be made several weeks before construction start up. This will allow the concrete producer an opportunity to determine the proper batching sequence and amounts of other admixtures needed in order to deliver the required concrete mix to the jobsite. A trial mix will also help determine whether the combination of concrete materials and construction practices will allow the concrete to meet a specified performance. Grace's broad experience with this product can help the concrete producer deliver a satisfactory product regardless of the mixture proportions. Contact your Grace salesman for help with trial mixes.

Dispensing

Dispensing equipment for the liquid Force 10,000 will be provided by Grace Construction Products.

Packaging/Availability

Force 10,000 is available in bulk via Grace delivery vehicles. It is also available in 210 L (55 gal) drums.

Freezing Point

Force 10,000 will freeze at approximately 0 °C (32 °F). Care should be taken to prevent Force 10,000 from freezing, since once frozen the admixture is no longer usable.

Flammability

None.

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PRODUCT INFORMATION

DCI®

Corrosion Inhibitor ASTM C 494, Type C

Description

DCI® corrosion inhibitor is a liquid added to concrete during the batching process. It chemically inhibits the corrosive action of chlorides on reinforcing steel and prestressed strands in concrete. It also promotes strength development of the concrete while meeting ASTM C 494 requirements as a Type C admixture. One Liter of DCI weighs approximately 1.28 kg ± 0.01 kg (one gal of DCI weighs approximately 10.7 lb). DCI contains a minimum of 30% calcium nitrite.

Uses

DCI is recommended for all steel-reinforced, post tensioned and prestressed concrete that will come in contact with chlorides from deicing salts or a marine environment. Examples are parking garage decks and support structures, bridge decks and prestressed members, and structures in marine environments. It may also be used in concrete where chlorides are added during manufacture.

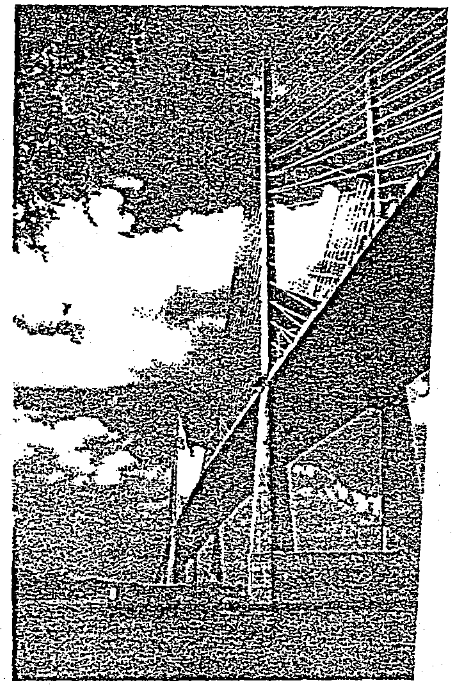
Chemical Inhibition of Corrosion

DCI corrosion inhibitor is a patented system containing calcium nitrite which interacts with the embedded steel in concrete to prevent salt attack. By chemically reacting with the reinforcing, a barrier is formed which prevents chloride penetration. Corrosion initiation is delayed and corrosion rates are kept under control. Once corrosion has been inhibited, physical disruption of the concrete due to rust formation will not occur.

When added to concrete in sufficient quantity as determined by the anticipated chloride ion content of the concrete over the design life of the structure, DCI maintains an active corrosion-controlling system within the concrete matrix.

Addition Rates

Recommended addition rates range from 10 to 30 L/m^3 (2.0 to 6.0 gal/yd^3). The level of corrosion protection increases in proportion to the dosage. The project specification will indicate the addition rate. In the absence of a specified dosage, or where needed to offset premixed chlorides, call your Grace admixture technical representative.



DCI also increases the early strength of a concrete mixture and may have an accelerating action on setting time. These effects become more pronounced as the addition rate rises. Control of setting time can be achieved with retarding admixtures (see Set Acceleration).

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Cement Compatibility

DCI corrosion inhibitor is compatible with all types of portland cement, and concretes containing pozzolans. However, due to the significant variation between cements, even the same type, may result in differences in cement response to DCI. This is especially true with respect to the effect on setting time, which also influences slump retention.

Mix Water Reduction

Mix water adjustment is essential to account for the water in DCI and thus maintain the desired water/cement ratio. The mix water added at the batch plant must therefore be reduced to compensate for the addition of the corrosion inhibitor. The adjustment factor is .84 kg of water per Liter (7.0 lb/gal) of DCI.

A high-range water reducer such as ADVA™, Daracem® 100 or Daracem 19 may be used to maintain workability in low water/cement ratio concrete.

Compatibility with Other Admixtures

DCI corrosion inhibitor can be used in concrete with other admixtures — including air-entraining admixtures, water reducers, superplasticizers, set-retarders and microsilica — without impeding their performance.

Each admixture must be added separately. Individually added, each will deliver exactly the results desired.

Set Acceleration

At all recommended addition rates, DCI corrosion inhibitor may accelerate concrete setting times, which may also aggravate slump loss. To extend the set time to a more normal duration, separately add a retarder such as Daratard® 17 or Daratard HC.

A retarder may not be necessary in cold weather. The full accelerating action of DCI may actually be desirable during the cool months of the year.

Air Entrainment

DCI corrosion inhibitor at the normal addition rates may moderately reduce the entrained air content. It may be necessary to increase the dosage of the air-entraining admixture to compensate. Project specifications for DCI generally will show requirements of $6\frac{1}{2} \pm 1\frac{1}{2}\%$ air in the plastic or fresh concrete.

Preconstruction Trial Mix

It is strongly recommended that trial mixes be made several weeks before construction start up. This will allow the concrete producer an opportunity to determine the proper batching sequence and amounts of other admixtures needed in order to deliver the required concrete mix to the jobsite. Due to the cement response variation and the strong acceleration potential of DCI, it is vital that set time and slump retention of the proposed mix be thoroughly tested and evaluated in the light of job requirements. Grace's broad experience with this product can help the concrete producer deliver satisfactory product regardless of the mixture proportions. Contact your Grace admixture salesman for help with trial mixes.

Finishing and Curing

Concrete containing DCI corrosion inhibitor finishes with standard tools and techniques. It is no different from any other air-entrained, low water/cement ratio mix in terms of finishability. Curing procedures must follow ACI 302 and ACI 308.

Packaging and Availability

DCI corrosion inhibitor is available in bulk quantities by Grace Construction Products metered systems, or, in 208 L (55 gal) drums.

Dispensing Equipment

A complete line of accurate dispensers is available. DCI may be introduced on the sand, in the water, at the beginning or the end of the batch cycle. Similar to all concrete admixtures, DCI should not come into contact with other admixtures prior to entering the concrete.

Freezing Point

DCI freezes at approximately -15°C (5°F), but its corrosion inhibition and strength gain properties are completely restored by thawing and thorough agitation.

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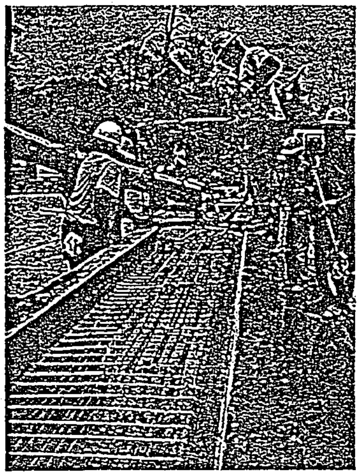
P R O D U C T   I N F O R M A T I O N

ADVA® Flow

Superplasticizer ASTM C 494, Type F



ADVA

Description

ADVA® Flow Superplasticizer is a high range water-reducing admixture. It is a liquid which has been formulated by the manufacturer for use as received. ADVA Flow Superplasticizer contains no added chloride. ADVA Flow Superplasticizer is formulated to comply with Standard Specification for Chemical Admixtures for Concrete, ASTM C 494, Type F. One liter weighs approximately 1.05 kg (8.7 lbs/gal).

Dispersion

ADVA Flow Superplasticizer is a superior dispersing admixture having a marked capacity to disperse the cement agglomerates normally found in a cement-water suspension. This capability exceeds that of normal water-reducing admixtures, resulting in lower dosages and better control.

Uses

ADVA Flow Superplasticizer produces concrete with extreme workability characteristics for high slump, flowing concrete. It also allows concrete to be produced with very low water/cement ratios at low or normal slumps.

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ADVA Flow Superplasticizer is ideal for use in any concrete where it is desired to keep the water/cement ratio to a minimum and still achieve the degree of workability necessary to provide easy placement and consolidation. ADVA Flow Superplasticizer will also fluidize concrete making it ideal for tremie concreting or other applications where high slumps are desired.

Advantages

1. ADVA Flow Superplasticizer is highly efficient, producing high slump concrete at very low dosage with no loss in strength.
2. ADVA Flow Superplasticizer is added to concrete mix water for rapid batching.
3. ADVA Flow Superplasticizer provides a superior combination of long slump life with near neutral set time.
4. ADVA Flow Superplasticizer concrete, even at high slump, exhibits no significant segregation in comparison to concrete without a superplasticizer at the same slump.
5. ADVA Flow Superplasticizer finishes easily without stickiness, tearing or spotty set characteristics.

Addition Rates

Addition rates of ADVA Flow Superplasticizer can vary with type of application, but will normally range from 195 to 650 mL/100 kg (3 to 10 fl oz/100 lbs) of cement. In most instances the addition of 195 to 325 mL/100 kg (3 to 5 fl oz/100 lbs) of cement will be sufficient. For best results, ADVA Flow Superplasticizer should be added to the initial mix water. At a given water/cement ratio, the slump required for placement can be controlled by varying the addition rate. Should job site conditions require using more than recommended addition rates, please consult your Grace Representative.

Compatibility

In concrete containing ADVA Flow Superplasticizer the use of an air-entraining agent (such as Daravair® 1000 or Darex® II AEA) is recommended to provide suitable air void parameters for resistance against freeze-thaw attack. Due to synergistic effects between ADVA Flow Superplasticizer and air-entraining agents, the quantity of air-entraining admixture added to concrete containing ADVA Flow Superplasticizer may be reduced. Please consult your Grace Representative for dosage guidance.

Most Type A water reducers or Type D water-reducing retarders are compatible with ADVA Flow Superplasticizer as long as they are separately added to the concrete. Caution should be exercised when using ADVA Flow Superplasticizer together with a retarder, as excessive retardation can occur if the admixture dosages are too high. Pre-testing of the concrete should be performed to optimize dosages and addition times of these admixtures. The admixtures should not contact each other before they enter the concrete.

Packaging

ADVA Flow Superplasticizer is available in bulk, delivered by metered tank trucks, in 1250 L (330 gal) disposable totes, and in 208 L (55 gal) drums. ADVA Flow Superplasticizer contains no flammable ingredients.

It will begin to freeze at approximately 0°C (32°F), but will return to full strength after thawing and thorough agitation.

In storage, and for proper dispensing, ADVA Flow Superplasticizer should be maintained at temperatures above 0°C (32°F).

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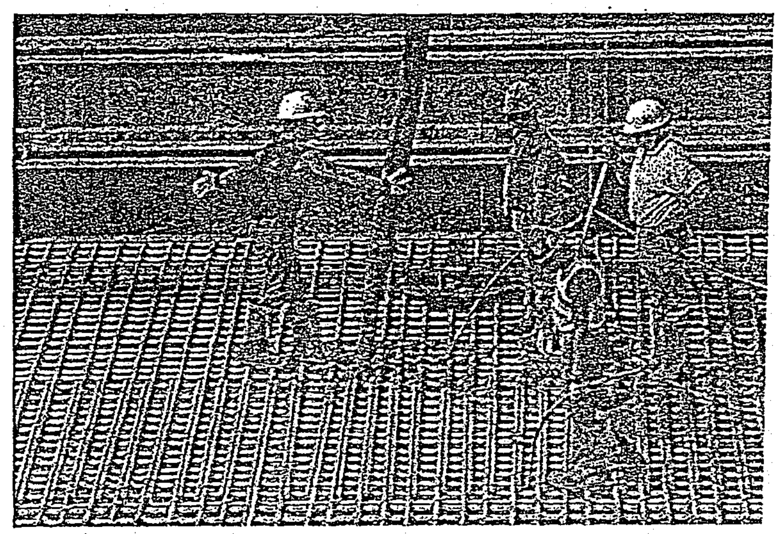
PRODUCT INFORMATION

Daracem® 19

Superplasticizer ASTM C 494, Type A and Type F; ASTM C 1017, Type I



Description

Daracem® 19 is a high range water reducer, commonly referred to as a superplasticizer. It is an aqueous solution of a modified naphthalene sulfonate. It is a low viscosity liquid which has been formulated by the manufacturer for use as received. Daracem 19 contains no added chloride. Daracem 19 is formulated to comply with specifications for Chemical Admixtures for Concrete, ASTM Designation C 494 as a Type A and Type F admixture; C1017 as a Type I admixture.

One Liter of Daracem 19 weighs approximately 1.2 kg (10 lbs/gal).

Dispersion

Daracem 19 is a superior dispersing admixture having a marked capacity to disperse the cement agglomerates normally found in a cement-water suspension. The capability of Daracem 19, in this respect, exceeds that of normal water-reducing admixtures.

Uses

Daracem 19 produces concrete with extremely workable characteristics referred to as high slump, flowing concrete. Daracem 19 also allows concrete to be produced with very low water/cement ratios at low or normal slumps.

Daracem 19 is ideal for use in prestress, precast, bridge deck or any concrete where it is desired to keep the water/cement ratio to a minimum and still achieve the degree of workability necessary to provide easy placement and consolidation. Daracem 19 will also fluidize concrete making it ideal for tremie concreting or other applications where high slumps are desired.

Advantages

1. Daracem 19 can produce high slump flowable concrete at no loss in strength.
2. Daracem 19 can produce low water/cement ratio concrete and therefore, high strengths.
3. Daracem 19, in prestress/precast work, can be used to substantially reduce or eliminate the high energy requirements of external heat for accelerated curing.

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4. Daracem 19 concrete produced with Type I cement may be substituted for normal concrete produced with Type III cement to achieve early release strengths.
5. Daracem 19 concrete, even at high slump, exhibits no significant segregation in comparison to concrete without a superplasticizer at the same slump.
6. Daracem 19 aids in rapid discharge of concrete from truck mixers thereby reducing on the job time and improving mixer utilization.

Addition Rates

Addition rates of Daracem 19 can vary with type of application, but will normally range from 390 to 1300 mL/100 kg (6 to 20 fl oz/100 lbs) of cement. In most instances the addition of 650 to 1040 mL/100 kg (10 to 16 fl oz/100 lbs) of cement will be sufficient. At a given water/cement ratio, the slump required for placement can be controlled by varying the addition rate. Should job site conditions require using more than recommended addition rates, please consult your Grace Representative.

Compatibility with Other Admixtures

In concrete containing Daracem 19, the use of an air-entraining agent (such as Daravair® or Darex® II AEA) is recommended to provide suitable air void parameters for resistance against freeze-thaw attack.

Most Type A water reducers or Type D water-reducing retarders are compatible with Daracem 19 as long as they are separately added to the concrete. Pretesting of the concrete should be performed to optimize dosages and addition times of these admixtures. Caution should be exercised when using Daracem 19 together with a retarder, as excessive retardation can occur if the admixture dosages are too high.

Pretesting of the concrete should be performed to determine dosages and addition times of these admixtures. The admixtures should not contact each othe. before they enter the concrete.

Packaging

Daracem 19 is available in bulk, delivered by metered tank trucks, and in 210 L (55 gal) drums. Daracem 19 contains no flammable ingredients.

It will begin to freeze at approximately 0°C (32°F), but will return to full strength after thawing and thorough agitation.

In storage, and for proper dispensing, Daracem 19 should be maintained at temperatures above 0°C (32°F).

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PRODUCT INFORMATION

WRDA® with HYCOL®

Water-Reducing Admixture ASTM C 494, Type A

Description

WRDA® with HYCOL® water-reducing admixture is an aqueous solution of complex organic compounds, one of which is HYCOL, a patented portland cement hydration control agent. WRDA with HYCOL water-reducing admixture is a ready to use low viscosity liquid which is factory premixed in exact proportions to minimize handling, eliminate mistakes and guesswork. One Liter weighs approximately 1.15 kg (1 gal weighs 9.6 lb). WRDA with HYCOL contains no calcium chloride.

Uses

WRDA with HYCOL produces a concrete with lower water content (typically 8 to 10% reduction), greater plasticity and higher strength. It is used in ready mix plants, block and concrete products plants, in lightweight and prestressed work . . . wherever concrete is produced. It is also used by contractors in field equipment such as job site plants and pavers.

Advantages

Most calcium-chloride-free water-reducing admixtures on the market today produce some significant degree of set retardation. Minimal extension of setting time has been experienced in field concrete containing WRDA with HYCOL. Under closely controlled laboratory conditions, the retardation observed with the addition of 3 fl oz of WRDA with HYCOL per 100 lb (190 mL/100 kg) of cement is in the range of 15 to 20 minutes, well within the limit of the accuracy of the method of test. It is through the action of the patented HYdration COntroL (HYCOL) agent in the admixture that its effect on the setting time of concrete is reduced to an insignificant degree.

The use of WRDA with HYCOL produces a plastic concrete that is more workable, easier to place, more pumpable, and has better finishability than plain or other admixtured concrete. In the hardened state, WRDA with HYCOL concrete has higher compressive and flexural strengths at all ages than untreated or conventionally admixtured concrete.

The greater degree of plasticity achieved, compared with conventional water-reducing admixtures, allows improved finishability.

Hydration Control

HYCOL acts to optimize the rate and degree of hydration of the portland cement in the concrete. This optimization gives concrete strength advantages at all ages without appreciably altering its setting time.

WRDA with HYCOL also acts as a dispersing agent and lessens the natural interparticle attraction between cement grains in water. This reduces their tendency to clump together, making the mix more workable, placeable and finishable with less water.

The combination of water reduction and controlled hydration by HYCOL optimizes the rate of formation of the gel, the paste or binder that "glues" the concrete aggregates together. This controlled rate of gel formation adds to the water retention and internal cohesiveness of the mix, reducing the bleeding and segregation while increasing or improving the workability, placeability and finishability of concrete.

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Finishability

Finishers have stated that the cement paste, or mortar, in WRDA with HYCOL admixtured concrete has improved trowelability. The influence of WRDA with HYCOL on the finishability of lean mixes has been particularly noticeable. Floating and troweling, by machine or hand, easily imparts a smooth, close tolerance surface with less machine time and labor.

Addition Rate

Excellent results are obtained using addition rates of 3 to 6 fl oz of WRDA with HYCOL per 100 lb (190 to 375 mL/100 kg) of cement. In some cases it may be necessary to slightly modify the addition rate due to variations in cement, aggregate or other job conditions.

Dispensing Equipment

A complete line of accurate dispensing equipment is available. WRDA with HYCOL may be introduced to the mix on the sand or in the water.

Compatibility with Other Admixtures

WRDA with HYCOL is compatible in concrete with all air entrainers such as Daravair® or Darex® air-entraining admixtures. Due to a synergistic effect of WRDA with HYCOL, the quantity of air entrainer admixtured in concrete may be reduced by about 25%. EACH ADMIXTURE SHOULD BE ADDED SEPARATELY. While WRDA with HYCOL contains no calcium chloride, it is compatible with calcium chloride in concrete mixes. Again, each should be added separately.

Packaging

WRDA with HYCOL is available in bulk, delivered by metered tank trucks, and 210 L (55 gal) drums. WRDA with HYCOL contains no flammable ingredients. IT WILL FREEZE AT ABOUT -2°C (28°F), BUT WILL RETURN TO FULL STRENGTH AFTER THAWING AND THOROUGH AGITATION.

Architects' Specification for Concrete Water-reducing Admixture

Concrete shall be designed in accordance with ACI Standard Recommended Practice for Selecting Proportions for Concrete ACI 211.1.

The water-reducing admixture shall be WRDA with HYCOL, as manufactured by Grace Construction Products, or equal. The admixture shall not contain calcium chloride. It shall be used in strict accordance with the manufacturer's recommendations. The admixture shall comply with ASTM Designation C 494, Type A water-reducing admixtures. Certification of compliance shall be made available upon request.

The admixture shall be considered as part of the total water. The admixture shall be delivered as a ready to use liquid product and shall require no mixing at the batching plant or job site.

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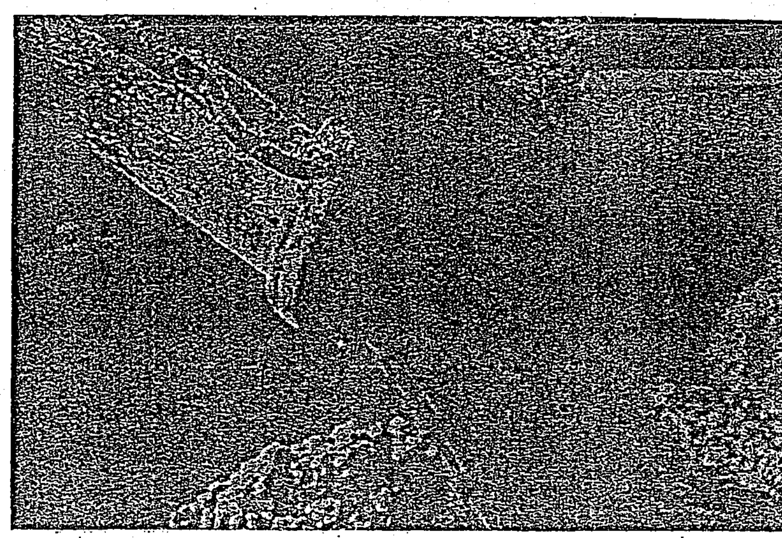
PRODUCT INFORMATION

Daravair® 1000

Air-Entraining Admixture ASTM C 260; AASHTO M 154

Description

Daravair® 1000 is a liquid air-entraining admixture that provides freeze-thaw resistance, yield control, and finishability performance across the full range of concrete mix designs. Daravair 1000 is a clean, light-orange product designed to generate specification-quality air systems. Based on a high-grade saponified rosin formulation, Daravair 1000 is chemically similar to vinsol-based products, but with increased purity and supply dependability.



Uses

Daravair 1000 air-entraining admixture may be used wherever the purposeful entrainment of air is required by concrete specifications. Formulated to perform across the entire spectrum of production mixes, Daravair 1000 generates quality, freeze-thaw resistant air systems in concrete conditions that include the following:

- Low Slump
- Paving
- Central Mix
- Extruded Slip Form
- Mixes Containing Hot Water and Accelerators
- Precast
- High Cement Factor
- Fly Ash and Slag
- Superplasticizers
- Manufactured Sands

Air-Entraining Action

Air is incorporated into the concrete by the mechanics of mixing and stabilized into millions of discrete semi-microscopic bubbles in the presence of a specifically designed air-entraining admixture such as Daravair 1000. These air bubbles act much like flexible ball bearings increasing the mobility, or plasticity and workability of the concrete. This can permit a reduction in mixing water with no loss of slump. Placeability is improved. Bleeding, plastic shrinkage and segregation are minimized.

Through the purposeful entrainment of air, Daravair 1000 markedly increases the durability of concrete to severe exposures particularly to freezing and thawing. It has also demonstrated a remarkable ability to impart resistance to the action of frost and deicing salts as well as sulfate, sea and alkaline waters.

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Compatibility with Other Admixtures

Daravair 1000 air-entraining admixture is fully effective and compatible in concrete with other admixtures. EACH ADMIXTURE, HOWEVER, SHOULD BE ADDED TO THE CONCRETE SEPARATELY.

Addition Rate

There is no standard addition rate for Daravair 1000 air-entraining admixture. The amount to be used will depend upon the amount of air required for job conditions, usually in the range of 4 to 8%. Typical factors which might influence the amount of air-entraining admixture required are, temperature, cement, sand gradation, and the use of extra fine materials such as fly ash and microsilica. Typical Daravair 1000 addition rates range from 50 to 200 mL/100 kg (¾ to 3 fl oz/100 lbs) of cement.

The air-entraining capacity of Daravair 1000 is usually increased when other concrete admixtures are contained in the concrete, particularly water-reducing admixtures and water-reducing retarders. This may allow up to a two-thirds reduction in the amount of Daravair 1000 required.

Mix Adjustment

Entrained air will increase the volume of the concrete making it necessary to adjust the mix proportions to maintain the cement factor and yield. This may be accomplished by a reduction in water requirement and aggregate content.

Dispensing Equipment

A complete line of accurate automatic dispensing equipment is available. These dispensers can be located to discharge into the water line, the mixer, or on the sand.

Packaging

Daravair 1000 air-entraining admixture is available in bulk, delivered by metered tank trucks and in 210 L (55 gal) drums. Daravair 1000 contains no flammable ingredients. Daravair 1000 will freeze at about -1°C (30°F) but its air-entraining properties are completely restored by thawing and thorough mechanical agitation.

Architects' Specifications

Concrete shall be air entrained concrete, containing 4 to 8% entrained air. The air contents in the concrete shall be determined by the pressure method (ASTM Designation C 231) or volumetric method (ASTM Designation C 173). The air-entraining admixture shall be a completely neutralized rosin solution, such as Daravair 1000, as manufactured by Grace Construction Products, or equal, and comply with standard specification for air-entraining admixtures (ASTM Designation C 260). The air-entraining admixture shall be added at the concrete mixer or batching plant at approximately 50 to 200 mL/100 kg (¾ to 3 fl oz/100 lbs) of cement, or in such quantities as to give the specified air contents.

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PRODUCT INFORMATION

Daratard® 17

Initial Set Retarder ASTM C 494, Type B and Type D

Description

Daratard® 17 admixture is a ready-to-use aqueous solution of hydroxylated organic compounds. Ingredients are factory premixed in exact proportions to minimize handling, eliminate mistakes and guesswork. 1.17 kg weighs approximately 1 L (1 gal/10.2 lb).

Uses

Daratard 17 retards the initial and final set of concrete. At the usual addition rate of 195 mL/ 100 kg (3 fl oz/100 lb) cement it will extend the initial setting time of portland cement concrete by 2 to 3 hours at 21°C (70°F). Daratard 17 is used wherever a delay in setting time will insure sufficient delivery, placement, vibration or compaction time, such as in:

- Hot Weather Concreting
- Transit Mix Concrete
- Prestressed Concrete

Daratard 17 is also used in special applications, as in bridge decks where it extends plastic characteristics of the concrete until progressive deflection resulting from increasing loads is completed.

Water-Reducing Properties

Along with set retardation, Daratard 17 provides water-reduction (typically 8 to 10%) in a concrete mix. This water-reducing action of Daratard 17 produces greater plasticity and workability in the fresh concrete and the strength and permeability of the hardened concrete are measurably improved. Daratard 17 is designed for use on jobs where high temperatures or extended setting times are the prime factors. It is recommended only when the primary purpose is to delay and control the setting time of concrete. When time and temperature are not major considerations, Grace Construction Product's water-reducing admixtures such as WRDA® with HYCOL® should be used.

Compatibility with Other Admixtures

Daratard 17 is compatible in concrete with all commercial air-entraining admixtures, such as Daravair®. Due to the slight air-

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entraining properties of Daratard 17, itself, the addition rate of Daravair may be reduced by about 25%. Each admixture should be added separately.

Addition Rates

Addition rates for Daratard 17 will range from 130 to 520 mL/100 kg (2 to 8 fl oz/100 lb) of cement. The amount to be used will depend upon the degree of retardation required under job conditions. Longer setting times or higher temperatures will require higher addition rates. Conversely, the addition rate will be lower for shorter extensions of time.

Dispensing Equipment

A complete line of accurate, automatic dispensing equipment is available. Daratard 17 may be introduced to the mix with the sand or with the water.

Packaging

Daratard 17 is available in bulk, delivered by metered tank trucks, and 210 L (55 gal) drums. It contains no flammable ingredients. **Daratard 17 will freeze at about -2°C (28°F), but will return to full strength after thawing and thorough agitation.**

Architects' Specification for Concrete Retarding Admixture

Concrete shall be designed in accordance with ACI Standard Recommended Practice for Selecting Proportions for Concrete (ACI 211.1).

The set-retarding/water-reducing admixture shall comply with ASTM Designation C 494, Type D admixture, and shall be Daratard 17, as manufactured by Grace Construction Products, or equal. Certification of compliance shall be made available on request. It shall be used in strict accordance with the manufacturer's recommendations.

The addition rate shall be adjusted to produce the specified retardation of the concrete mix at all temperatures.

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Appendix D. Cement and Aggregate Studies

Section	Property	Unit	C1/1[A]	C1/1[B]	C1/1[C]	C1/1[D]	C2/1[A]	C2/1[B]
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	385.5	385.5	385.5	385.5	385.5	385.5
	Fly Ash	kg/m³						
	Silica Fume	kg/m³						
	GGBF Slag	kg/m³						
	Coarse Aggregate	kg/m³	1,052.8	1,052.8	1,052.8	1,052.8	1,052.8	1,052.8
	Intermediate Aggregate	kg/m³						
	Fine Aggregate	kg/m³	794.8	794.8	794.8	794.8	794.8	794.8
	Mixing Water	kg/m³	154.2	154.2	154.2	154.2	154.2	154.2
	WR Admixture	L/m³						
	SR/WR Admixture	L/m³	0.77	0.77	0.77	0.77	0.77	0.77
	AE Admixture	L/m³						
	CI/SA Admixture	L/m³						
	HRWR Admixture	L/m³	3.02	3.02	3.02	3.02	3.02	3.02
MATERIALS	Cement Brand & Type		LP *I*	LP *I*	LP *I*	LP *I*	LP *I/II*	LP *I/II*
	Fly Ash							
	Silica Fume							
	GGBF Slag							
	CA Type & Grading		LI67	LI67	LI67	LI67	LI67	LI67
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m³	1,621	1,621	1,621	1,621	1,621	1,621
	IA Type							
	IA SG							
	IA Absorption	%						
	IA Fineness Modulus							
	FA Type		DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture							
	SR/WR Admixture		GD17	GD17	GD17	GD17	GD17	GD17
	AE Admixture							
	CI/SA Admixture							
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.406	0.406	0.406	0.406	0.406	0.406
	w/c		0.406	0.406	0.406	0.406	0.406	0.406
	SCM/TCM	%	0	0	0	0	0	0
	CA Content	%	64.9	64.9	64.9	64.9	64.9	64.9
	CA/FA		1.32	1.32	1.32	1.32	1.32	1.32
	Calculated Air Content	%	2.31	2.31	2.31	2.31	2.31	2.31
	Calculated Unit Weight	kg/m³	2,392	2,392	2,392	2,392	2,392	2,392
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	15.6	19.4	23.3	26.7	23.9	26.1
	Air Temp.	C		21.1	18.9	30.0		27.8
	RH	%		37	86	49		46
	Initial Slump	mm	110	20	30	20	60	40
	Final Slump	mm		210	250	230		280
	Measured Air Content	%	2.3	2.6	1.5	1.8	1.6	0.3
	Measured Unit Weight	kg/m³	2,361	2,390	2,421	2,423	2,424	2,456
	Yield	m³	1.01	1.00	0.99	0.99	0.99	0.97

			$C2/1^C$	$C2/1^D$	$C3/1^A$	$C3/1^B$	$C3/1^C$	$C3/1^D$
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m^3	385.5	385.5	385.5	385.5	385.5	385.5
	Fly Ash	kg/m^3						
	Silica Fume	kg/m^3						
	GGBF Slag	kg/m^3						
	Coarse Aggregate	kg/m^3	1,052.8	1,052.8	1,052.8	1,052.8	1,052.8	1,052.8
	Intermediate Aggregate	kg/m^3						
	Fine Aggregate	kg/m^3	794.8	794.8	794.8	794.8	794.8	794.8
	Mixing Water	kg/m^3	154.2	154.2	154.2	154.2	154.2	154.2
	WR Admixture	L/m^3						
	SR/WR Admixture	L/m^3	0.77	0.77	0.77	0.77	0.77	0.77
	AE Admixture	L/m^3						
	CI/SA Admixture	L/m^3						
	HRWR Admixture	L/m^3	3.02	3.02	3.02	3.02	3.02	3.02
MATERIALS	Cement Brand & Type		LP *I/II*	LP *I/II*	AM *I*	AM *I*	AM *I*	AM *I*
	Fly Ash							
	Silica Fume							
	GGBF Slag							
	CA Type & Grading		LI67	LI67	LI67	LI67	LI67	LI67
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m^3	1,621	1,621	1,621	1,621	1,621	1,621
	IA Type							
	IA SG							
	IA Absorption	%						
	IA Fineness Modulus							
	FA Type		DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture							
	SR/WR Admixture		GD17	GD17	GD17	GD17	GD17	GD17
	AE Admixture							
	CI/SA Admixture							
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.406	0.406	0.406	0.406	0.406	0.406
	w/c		0.406	0.406	0.406	0.406	0.406	0.406
	SCM/TCM	%	0	0	0	0	0	0
	CA Content	%	64.9	64.9	64.9	64.9	64.9	64.9
	CA/FA		1.32	1.32	1.32	1.32	1.32	1.32
	Calculated Air Content	%	2.31	2.31	2.31	2.31	2.31	2.31
	Calculated Unit Weight	kg/m^3	2,392	2,392	2,392	2,392	2,392	2,392
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	25.6		26.7	18.3	22.2	33.3
	Air Temp.	C	24.4	30.6		21.1		41.1
	RH	%	54	49		35		50
	Initial Slump	mm	30	30	40	20	60	40
	Final Slump	mm	270	270		220	250	230
	Measured Air Content	%	0.5	1.0	2.7	2.1		1.6
	Measured Unit Weight	kg/m^3	2,442	2,430	2,425	2,408		2,455
	Yield	m^3	0.98	0.98	0.99	0.99		0.97

			C3/1[E]	C3/1 i	C4/1[A]	C4/1[B]	C4/1[C]	C5/1[A]
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	385.5	385.5	385.5	385.5	385.5	385.5
	Fly Ash	kg/m³						
	Silica Fume	kg/m³						
	GGBF Slag	kg/m³						
	Coarse Aggregate	kg/m³	1,052.8	1,052.8	1,052.8	1,052.8	1,052.8	1,052.8
	Intermediate Aggregate	kg/m³		285.3				
	Fine Aggregate	kg/m³	794.8	509.5	794.8	794.8	794.8	794.8
	Mixing Water	kg/m³	154.2	154.2	154.2	154.2	154.2	154.2
	WR Admixture	L/m³						
	SR/WR Admixture	L/m³	0.77	0.77	0.77	0.77	0.77	0.77
	AE Admixture	L/m³						
	CI/SA Admixture	L/m³						
	HRWR Admixture	L/m³	3.02	3.02	3.02	3.02	3.02	3.02
MATERIALS	Cement Brand & Type		AM *I*	AM *I*	AF *I*	AF *I*	AF *I*	AC *I/II*
	Fly Ash							
	Silica Fume							
	GGBF Slag							
	CA Type & Grading		LI67	LI67	LI67	LI67	LI67	LI67
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m³	1,621	1,621	1,621	1,621	1,621	1,621
	IA Type			LS				
	IA SG			2.67				
	IA Absorption	%		1.0				
	IA Fineness Modulus			4.7				
	FA Type		DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture							
	SR/WR Admixture		GD17	GD17	GD17	GD17	GD17	GD17
	AE Admixture							
	CI/SA Admixture							
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.406	0.406	0.406	0.406	0.406	0.406
	w/c		0.406	0.406	0.406	0.406	0.406	0.406
	SCM/TCM	%	0	0	0	0	0	0
	CA Content	%	64.9	64.9	64.9	64.9	64.9	64.9
	CA/FA		1.32	2.07	1.32	1.32	1.32	1.32
	Calculated Air Content	%	2.31	2.47	2.31	2.31	2.31	2.31
	Calculated Unit Weight	kg/m³	2,392	2,392	2,392	2,392	2,392	2,392
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	17.2	16.1	26.7	25.6	25.6	32.2
	Air Temp.	C	14.4	15.6		25.0	24.4	
	RH	%	35	31		55	55	
	Initial Slump	mm	10	30	40	30	10	30
	Final Slump	mm	180	200		260	260	
	Measured Air Content	%	3.0	3.4	2.0	1.3	1.1	2.0
	Measured Unit Weight	kg/m³	2,388	2,388	2,435	2,419	2,441	2,430
	Yield	m³	1.00	1.00	0.98	0.99	0.98	0.98

			C5/1[B]	C5/1[C]	C6/1[A]	C6/1[B]	C6/1[C]	C7/1
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	385.5	385.5	385.5	385.5	385.5	385.5
	Fly Ash	kg/m³						
	Silica Fume	kg/m³						
	GGBF Slag	kg/m³						
	Coarse Aggregate	kg/m³	1,052.8	1,052.8	1,052.8	1,052.8	1,052.8	1,052.8
	Intermediate Aggregate	kg/m³						
	Fine Aggregate	kg/m³	794.8	794.8	794.8	794.8	794.8	794.8
	Mixing Water	kg/m³	154.2	154.2	154.2	154.2	154.2	154.2
	WR Admixture	L/m³						
	SR/WR Admixture	L/m³	0.77	0.77	0.77	0.77	0.77	0.77
	AE Admixture	L/m³						
	CI/SA Admixture	L/m³						
	HRWR Admixture	L/m³	3.02	3.02	3.02	3.02	3.02	3.02
MATERIALS	Cement Brand & Type		AC *I/II*	AC *I/II*	HA *I*	HA *I*	HA *I*	HA *II*
	Fly Ash							
	Silica Fume							
	GGBF Slag							
	CA Type & Grading		LI67	LI67	LI67	LI67	LI67	LI67
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m³	1,621	1,621	1,621	1,621	1,621	1,621
	IA Type							
	IA SG							
	IA Absorption	%						
	IA Fineness Modulus							
	FA Type		DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture							
	SR/WR Admixture		GD17	GD17	GD17	GD17	GD17	GD17
	AE Admixture							
	CI/SA Admixture							
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.406	0.406	0.406	0.406	0.406	0.406
	w/c		0.406	0.406	0.406	0.406	0.406	0.406
	SCM/TCM	%	0	0	0	0	0	0
	CA Content	%	64.9	64.9	64.9	64.9	64.9	64.9
	CA/FA		1.32	1.32	1.32	1.32	1.32	1.32
	Calculated Air Content	%	2.31	2.31	2.31	2.31	2.31	2.31
	Calculated Unit Weight	kg/m³	2,392	2,392	2,392	2,392	2,392	2,392
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	18.9	18.9	13.9	17.8	17.8	31.1
	Air Temp.	C	15.6	16.1		18.9	17.8	
	RH	%	88	90		53	54	
	Initial Slump	mm	30	50	40	10	10	60
	Final Slump	mm	220	270		180	180	
	Measured Air Content	%	1.6	1.5	2.0	1.9	2.5	2.0
	Measured Unit Weight	kg/m³	2,406	2,403	2,427	2,420	2,407	2,444
	Yield	m³	0.99	1.00	0.99	0.99	0.99	0.98

			C8/1[A]	C8/1[B]	C8/1[C]	C1/2[A]	C1/2[B]	C1/2[C]
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	385.5	385.5	385.5	462.6	462.6	462.6
	Fly Ash	kg/m³						
	Silica Fume	kg/m³						
	GGBF Slag	kg/m³						
	Coarse Aggregate	kg/m³	1,052.8	1,052.8	1,052.8	1,008.3	1,008.3	1,008.3
	Intermediate Aggregate	kg/m³						
	Fine Aggregate	kg/m³	794.8	794.8	794.8	753.3	753.3	753.3
	Mixing Water	kg/m³	154.2	154.2	154.2	157.2	157.2	157.2
	WR Admixture	L/m³						
	SR/WR Admixture	L/m³	0.77	0.77	0.77	0.89	0.89	0.89
	AE Admixture	L/m³						
	CI/SA Admixture	L/m³						
	HRWR Admixture	L/m³	3.02	3.02	3.02	4.18	4.18	4.18
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	HM *III*	LP *I*	LP *I*	LP *I*
	Fly Ash							
	Silica Fume							
	GGBF Slag							
	CA Type & Grading		LI67	LI67	LI67	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m³	1,621	1,621	1,621	1,623	1,623	1,623
	IA Type							
	IA SG							
	IA Absorption	%						
	IA Fineness Modulus							
	FA Type		DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture							
	SR/WR Admixture		GD17	GD17	GD17	GD17	GD17	GD17
	AE Admixture							
	CI/SA Admixture							
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.406	0.406	0.406	0.346	0.346	0.346
	w/c		0.406	0.406	0.406	0.346	0.346	0.346
	SCM/TCM	%	0	0	0	0	0	0
	CA Content	%	64.9	64.9	64.9	62.1	62.1	62.1
	CA/FA		1.32	1.32	1.32	1.34	1.34	1.34
	Calculated Air Content	%	2.31	2.31	2.31	2.68	2.68	2.68
	Calculated Unit Weight	kg/m³	2,392	2,392	2,392	2,387	2,387	2,387
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	8.9	25.0	25.6	27.8	21.7	22.2
	Air Temp.	C		23.3	23.3		22.2	21.1
	RH	%		63	62		75	77
	Initial Slump	mm	30	0	10	10	0	0
	Final Slump	mm		120			250	250
	Measured Air Content	%	2.5	1.9	2.1	2.2	2.7	2.7
	Measured Unit Weight	kg/m³	2,385	2,420	2,427	2,395	2,378	2,373
	Yield	m³	1.00	0.99	0.99	1.00	1.00	1.01

			C2/2[A]	C2/2[B]	C2/2[C]	C3/2[A]	C3/2[B]	C3/2[C]
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m^3	462.6	462.6	462.6	462.6	462.6	462.6
	Fly Ash	kg/m^3						
	Silica Fume	kg/m^3						
	GGBF Slag	kg/m^3						
	Coarse Aggregate	kg/m^3	1,008.3	1,008.3	1,008.3	1,008.3	1,008.3	1,008.3
	Intermediate Aggregate	kg/m^3						
	Fine Aggregate	kg/m^3	753.3	753.3	753.3	753.3	753.3	753.3
	Mixing Water	kg/m^3	157.2	157.2	157.2	157.2	157.2	157.2
	WR Admixture	L/m^3						
	SR/WR Admixture	L/m^3	0.89	0.89	0.89	0.89	0.89	0.89
	AE Admixture	L/m^3						
	CI/SA Admixture	L/m^3						
	HRWR Admixture	L/m^3	4.18	4.18	4.18	4.18	4.18	4.18
MATERIALS	Cement Brand & Type		LP *I/II*	LP *I/II*	LP *I/II*	AM *I*	AM *I*	AM *I*
	Fly Ash							
	Silica Fume							
	GGBF Slag							
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m^3	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type							
	IA SG							
	IA Absorption	%						
	IA Fineness Modulus							
	FA Type		DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture							
	SR/WR Admixture		GD17	GD17	GD17	GD17	GD17	GD17
	AE Admixture							
	CI/SA Admixture							
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.346	0.346	0.346	0.346	0.346	0.346
	w/c		0.346	0.346	0.346	0.346	0.346	0.346
	SCM/TCM	%	0	0	0	0	0	0
	CA Content	%	62.1	62.1	62.1	62.1	62.1	62.1
	CA/FA		1.34	1.34	1.34	1.34	1.34	1.34
	Calculated Air Content	%	2.68	2.68	2.68	2.68	2.68	2.68
	Calculated Unit Weight	kg/m^3	2,387	2,387	2,387	2,387	2,387	2,387
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	29.4		30.0	29.4		
	Air Temp.	C		35.0	37.8		22.2	18.3
	RH	%		49	45		33	37
	Initial Slump	mm	10	10	40	10	0	0
	Final Slump	mm		260	270		270	270
	Measured Air Content	%	1.6	1.2	1.7	2.3	1.5	1.4
	Measured Unit Weight	kg/m^3	2,380	2,446	2,448	2,416	2,423	2,376
	Yield	m^3	1.00	0.98	0.98	0.99	0.99	1.00

			C3/2^{D}	C4/2^{A}	C4/2^{B}	C4/2^{C}	C5/2^{A}	C5/2^{B}
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m^3	462.6	462.6	462.6	462.6	462.6	462.6
	Fly Ash	kg/m^3						
	Silica Fume	kg/m^3						
	GGBF Slag	kg/m^3						
	Coarse Aggregate	kg/m^3	1,008.3	1,008.3	1,008.3	1,008.3	1,008.3	1,008.3
	Intermediate Aggregate	kg/m^3						
	Fine Aggregate	kg/m^3	753.3	753.3	753.3	753.3	753.3	753.3
	Mixing Water	kg/m^3	157.2	157.2	157.2	157.2	157.2	157.2
	WR Admixture	L/m^3						
	SR/WR Admixture	L/m^3	0.89	0.89	0.89	0.89	0.89	0.89
	AE Admixture	L/m^3						
	CI/SA Admixture	L/m^3						
	HRWR Admixture	L/m^3	4.18	4.18	4.18	4.18	4.18	4.18
MATERIALS	Cement Brand & Type		AM *I*	AF *I*	AF *I*	AF *I*	AC *I/II*	AC *I/II*
	Fly Ash							
	Silica Fume							
	GGBF Slag							
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m^3	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type							
	IA SG							
	IA Absorption	%						
	IA Fineness Modulus							
	FA Type		DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture							
	SR/WR Admixture		GD17	GD17	GD17	GD17	GD17	GD17
	AE Admixture							
	CI/SA Admixture							
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.346	0.346	0.346	0.346	0.346	0.346
	w/c		0.346	0.346	0.346	0.346	0.346	0.346
	SCM/TCM	%	0	0	0	0	0	0
	CA Content	%	62.1	62.1	62.1	62.1	62.1	62.1
	CA/FA		1.34	1.34	1.34	1.34	1.34	1.34
	Calculated Air Content	%	2.68	2.68	2.68	2.68	2.68	2.68
	Calculated Unit Weight	kg/m^3	2,387	2,387	2,387	2,387	2,387	2,387
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	29.4	29.4	18.3	18.3	23.9	28.9
	Air Temp.	C	30.0		17.8	17.8		29.4
	RH	%	53		64	59		40
	Initial Slump	mm	0	10	0	0	10	0
	Final Slump	mm	200		250	220		260
	Measured Air Content	%	2.4	3.0			2.0	
	Measured Unit Weight	kg/m^3	2,417	2,398	2,426	2,434	2,408	2,460
	Yield	m^3	0.99	1.00	0.98	0.98	0.99	0.97

			C5/2[C]	C6/2[A]	C6/2[B]	C6/2[C]	C7/2	C8/2[A]
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	462.6	462.6	462.6	462.6	462.6	462.6
	Fly Ash	kg/m³						
	Silica Fume	kg/m³						
	GGBF Slag	kg/m³						
	Coarse Aggregate	kg/m³	1,008.3	1,008.3	1,008.3	1,008.3	1,008.3	1,008.3
	Intermediate Aggregate	kg/m³						
	Fine Aggregate	kg/m³	753.3	753.3	753.3	753.3	753.3	753.3
	Mixing Water	kg/m³	157.2	157.2	157.2	157.2	157.2	157.2
	WR Admixture	L/m³						
	SR/WR Admixture	L/m³	0.89	0.89	0.89	0.89	0.89	0.89
	AE Admixture	L/m³						
	CI/SA Admixture	L/m³						
	HRWR Admixture	L/m³	4.18	4.18	4.18	4.18	4.18	4.18
MATERIALS	Cement Brand & Type		AC *I/III*	HA *I*	HA *I*	HA *I*	HA *II*	HM *III*
	Fly Ash							
	Silica Fume							
	GGBF Slag							
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m³	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type							
	IA SG							
	IA Absorption	%						
	IA Fineness Modulus							
	FA Type		DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture							
	SR/WR Admixture		GD17	GD17	GD17	GD17	GD17	GD17
	AE Admixture							
	CI/SA Admixture							
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.346	0.346	0.346	0.346	0.346	0.346
	w/c		0.346	0.346	0.346	0.346	0.346	0.346
	SCM/TCM	%	0	0	0	0	0	0
	CA Content	%	62.1	62.1	62.1	62.1	62.1	62.1
	CA/FA		1.34	1.34	1.34	1.34	1.34	1.34
	Calculated Air Content	%	2.68	2.68	2.68	2.68	2.68	2.68
	Calculated Unit Weight	kg/m³	2,387	2,387	2,387	2,387	2,387	2,387
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	28.3	31.1	18.3	20.0	26.7	27.8
	Air Temp.	C	29.4		23.3	21.1		
	RH	%	38		30	36		
	Initial Slump	mm	0	30	0	0	10	10
	Final Slump	mm	260		240	220		
	Measured Air Content	%		2.0	2.7	2.7	1.3	2.0
	Measured Unit Weight	kg/m³	2,461	2,406	2,388	2,399	2,422	2,385
	Yield	m³	0.97	0.99	1.00	1.00	0.99	1.00

			C8/2^{B}	C8/2^{C}	C8/2^{D}	C8/2^{E}
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m^3	462.6	462.6	462.6	462.6
	Fly Ash	kg/m^3				
	Silica Fume	kg/m^3				
	GGBF Slag	kg/m^3				
	Coarse Aggregate	kg/m^3	1,008.3	1,008.3	1,008.3	1,008.3
	Intermediate Aggregate	kg/m^3				
	Fine Aggregate	kg/m^3	753.3	753.3	753.3	753.3
	Mixing Water	kg/m^3	157.2	157.2	157.2	157.2
	WR Admixture	L/m^3				
	SR/WR Admixture	L/m^3	0.89	0.89	0.89	0.89
	AE Admixture	L/m^3				
	CI/SA Admixture	L/m^3				
	HRWR Admixture	L/m^3	4.18	4.18	4.18	4.18
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	HM *III*	HM *III*
	Fly Ash					
	Silica Fume					
	GGBF Slag					
	CA Type & Grading		LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2
	CA DRUW	kg/m^3	1,623	1,623	1,623	1,623
	IA Type					
	IA SG					
	IA Absorption	%				
	IA Fineness Modulus					
	FA Type		DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5
	WR Admixture					
	SR/WR Admixture		GD17	GD17	GD17	GD17
	AE Admixture					
	CI/SA Admixture					
	HRWR Admixture		GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.346	0.346	0.346	0.346
	w/c		0.346	0.346	0.346	0.346
	SCM/TCM	%	0	0	0	0
	CA Content	%	62.1	62.1	62.1	62.1
	CA/FA		1.34	1.34	1.34	1.34
	Calculated Air Content	%	2.68	2.68	2.68	2.68
	Calculated Unit Weight	kg/m^3	2,387	2,387	2,387	2,387
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	18.3	19.4		28.9
	Air Temp.	C	21.1	20.0	23.3	40.0
	RH	%	26	31	80	52
	Initial Slump	mm	0	0		0
	Final Slump	mm	190	270		210
	Measured Air Content	%	2.5	1.9		2.1
	Measured Unit Weight	kg/m^3	2,399	2,396		2,423
	Yield	m^3	1.00	1.00		0.99

		Unit	LIq^A	LIq^B	LIq^C	LIq^D	LIq^E	LIq^F
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m^3	474.5	474.5	474.5	474.5	474.5	474.5
	Fly Ash	kg/m^3	166.1	166.1	166.1	166.1	166.1	166.1
	Silica Fume	kg/m^3						
	GGBF Slag	kg/m^3						
	Coarse Aggregate	kg/m^3	1,039.7	1,039.7	1,039.7	1,039.7	1,039.7	1,039.7
	Intermediate Aggregate	kg/m^3						
	Fine Aggregate	kg/m^3	526.1	526.1	526.1	526.1	526.1	526.1
	Mixing Water	kg/m^3	177.3	177.3	177.3	177.3	177.3	177.3
	WR Admixture	L/m^3						
	SR/WR Admixture	L/m^3	1.25	1.25	1.25	1.25	1.25	1.25
	AE Admixture	L/m^3						
	CI/SA Admixture	L/m^3						
	HRWR Admixture	L/m^3	2.92	2.92	2.92	2.92	2.92	2.92
MATERIALS	Cement Brand & Type		AM *I*	AM *I*	AM *I*	AM *I*	AM *I*	AM *I*
	Fly Ash		Cl C	Cl C	Cl C	Cl C	Cl C	Cl C
	Silica Fume							
	GGBF Slag							
	CA Type & Grading		LIq	LIq	LIq	LIq	LIq	LIq
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m^3	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type							
	IA SG							
	IA Absorption	%						
	IA Fineness Modulus							
	FA Type		DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture							
	SR/WR Admixture		GD17	GD17	GD17	GD17	GD17	GD17
	AE Admixture							
	CI/SA Admixture							
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.281	0.281	0.281	0.281	0.281	0.281
	w/c		0.379	0.379	0.379	0.379	0.379	0.379
	SCM/TCM	%	25.9	25.9	25.9	25.9	25.9	25.9
	CA Content	%	64.1	64.1	64.1	64.1	64.1	64.1
	CA/FA		1.98	1.98	1.98	1.98	1.98	1.98
	Calculated Air Content	%	1.58	1.58	1.58	1.58	1.58	1.58
	Calculated Unit Weight	kg/m^3	2,389	2,389	2,389	2,389	2,389	2,389
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	12.2		13.9	13.9	20.0	20.0
	Air Temp.	C	13.3				13.9	14.4
	RH	%					73	98
	Initial Slump	mm	50		30	10	40	30
	Final Slump	mm	230		230	200	210	140
	Measured Air Content	%	3.0		2.1	2.2		
	Measured Unit Weight	kg/m^3	2,371		2,404	2,403	2,385	2,396
	Yield	m^3	1.01		0.99	0.99	1.00	1.00

			LIq i	LIs^A	LIs^B	RHq^A	RHq^B	RHs^A
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m^3	474.5	474.5	474.5	474.5	474.5	474.5
	Fly Ash	kg/m^3	166.1	166.1	166.1	166.1	166.1	166.1
	Silica Fume	kg/m^3						
	GGBF Slag	kg/m^3						
	Coarse Aggregate	kg/m^3	1,039.7	1,014.2	1,014.2	973.3	973.3	962.0
	Intermediate Aggregate	kg/m^3	189.2					
	Fine Aggregate	kg/m^3	336.9	551.0	551.0	605.6	605.6	616.8
	Mixing Water	kg/m^3	177.3	177.3	177.3	177.3	177.3	177.3
	WR Admixture	L/m^3						
	SR/WR Admixture	L/m^3	1.25	1.25	1.25	1.25	1.25	1.25
	AE Admixture	L/m^3						
	CI/SA Admixture	L/m^3						
	HRWR Admixture	L/m^3	2.92	2.92	2.92	2.92	2.92	2.92
MATERIALS	Cement Brand & Type		AM *I*	AM *I*	AM *I*	AM *I*	AM *I*	AM *I*
	Fly Ash		Cl C	Cl C	Cl C	Cl C	Cl C	Cl C
	Silica Fume							
	GGBF Slag							
	CA Type & Grading		LIq	LIs	LIs	RHq	RHq	RHs
	CA SG		2.67	2.67	2.67	2.71	2.71	2.71
	CA Absorption	%	1.2	1.2	1.2	1.4	1.4	1.4
	CA DRUW	kg/m^3	1,623	1,605	1,605	1,525	1,525	1,525
	IA Type		LS					
	IA SG		2.67					
	IA Absorption	%	1.0					
	IA Fineness Modulus		4.7					
	FA Type		DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture							
	SR/WR Admixture		GD17	GD17	GD17	GD17	GD17	GD17
	AE Admixture							
	CI/SA Admixture							
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.281	0.281	0.281	0.281	0.281	0.281
	w/c		0.379	0.379	0.379	0.379	0.379	0.379
	SCM/TCM	%	25.9	25.9	25.9	25.9	25.9	25.9
	CA Content	%	64.1	63.2	63.2	63.8	63.8	63.1
	CA/FA		3.09	1.84	1.84	1.61	1.61	1.56
	Calculated Air Content	%	1.69	1.59	1.59	1.58	1.58	1.57
	Calculated Unit Weight	kg/m^3	2,389	2,388	2,388	2,402	2,402	2,402
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	20.0	18.3	17.2	18.9	18.9	16.7
	Air Temp.	C	16.7					
	RH	%	94					
	Initial Slump	mm	20	50	60	20	10	30
	Final Slump	mm	150	240	240	230	180	180
	Measured Air Content	%		2.1	2.0	1.8	2.0	1.8
	Measured Unit Weight	kg/m^3	2,399	2,368	2,329	2,419	2,424	2,427
	Yield	m^3	1.00	1.01	1.03	0.99	0.99	0.99

			RHs^B	GNq^A	GNq^B	GNs^A	GNs^B
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	474.5	474.5	474.5	474.5	474.5
	Fly Ash	kg/m³	166.1	166.1	166.1	166.1	166.1
	Silica Fume	kg/m³					
	GGBF Slag	kg/m³					
	Coarse Aggregate	kg/m³	962.0	957.3	957.3	970.3	970.3
	Intermediate Aggregate	kg/m³					
	Fine Aggregate	kg/m³	616.8	589.6	589.6	576.5	576.5
	Mixing Water	kg/m³	177.3	177.3	177.3	177.3	177.3
	WR Admixture	L/m³					
	SR/WR Admixture	L/m³	1.25	1.25	1.25	1.25	1.25
	AE Admixture	L/m³					
	CI/SA Admixture	L/m³					
	HRWR Admixture	L/m³	2.92	2.92	2.92	2.92	2.92
MATERIALS	Cement Brand & Type		AM *I*	AM *I*	AM *I*	AM *I*	AM *I*
	Fly Ash		Cl C	Cl C	Cl C	Cl C	Cl C
	Silica Fume						
	GGBF Slag						
	CA Type & Grading		RHs	GNq	GNq	GNs	GNs
	CA SG		2.71	2.62	2.62	2.62	2.62
	CA Absorption	%	1.4	0.5	0.5	0.5	0.5
	CA DRUW	kg/m³	1,525	1,538	1,538	1,525	1,525
	IA Type						
	IA SG						
	IA Absorption	%					
	IA Fineness Modulus						
	FA Type		DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5
	WR Admixture						
	SR/WR Admixture		GD17	GD17	GD17	GD17	GD17
	AE Admixture						
	CI/SA Admixture						
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.281	0.281	0.281	0.281	0.281
	w/c		0.379	0.379	0.379	0.379	0.379
	SCM/TCM	%	25.9	25.9	25.9	25.9	25.9
	CA Content	%	63.1	62.2	62.2	63.6	63.6
	CA/FA		1.56	1.62	1.62	1.68	1.68
	Calculated Air Content	%	1.57	1.57	1.57	1.57	1.57
	Calculated Unit Weight	kg/m³	2,402	2,370	2,370	2,370	2,370
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	18.3	16.7	14.4	17.8	18.9
	Air Temp.	C					
	RH	%					
	Initial Slump	mm	40	20	110	30	40
	Final Slump	mm	220	260		220	230
	Measured Air Content	%	2.0	1.9	1.8	1.3	1.5
	Measured Unit Weight	kg/m³	2,412	2,384	2,374	2,409	2,396
	Yield	m³	1.00	0.99	1.00	0.98	0.99

			GVq[A]	GVq[B]	GVs[A]	GVs[B]
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	474.5	474.5	474.5	474.5
	Fly Ash	kg/m³	166.1	166.1	166.1	166.1
	Silica Fume	kg/m³				
	GGBF Slag	kg/m³				
	Coarse Aggregate	kg/m³	1,038.6	1,038.6	1,026.1	1,026.1
	Intermediate Aggregate	kg/m³				
	Fine Aggregate	kg/m³	495.8	495.8	508.3	508.3
	Mixing Water	kg/m³	177.3	177.3	177.3	177.3
	WR Admixture	L/m³				
	SR/WR Admixture	L/m³	1.25	1.25	1.25	1.25
	AE Admixture	L/m³				
	CI/SA Admixture	L/m³				
	HRWR Admixture	L/m³	2.92	2.92	2.92	2.92
MATERIALS	Cement Brand & Type		AM *I*	AM *I*	AM *I*	AM *I*
	Fly Ash		Cl C	Cl C	Cl C	Cl C
	Silica Fume					
	GGBF Slag					
	CA Type & Grading		GVq	GVq	GVs	GVs
	CA SG		2.59	2.59	2.59	2.59
	CA Absorption	%	1.3	1.3	1.3	1.3
	CA DRUW	kg/m³	1,644	1,644	1,624	1,624
	IA Type					
	IA SG					
	IA Absorption	%				
	IA Fineness Modulus					
	FA Type		DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5
	WR Admixture					
	SR/WR Admixture		GD17	GD17	GD17	GD17
	AE Admixture					
	CI/SA Admixture					
	HRWR Admixture		GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.281	0.281	0.281	0.281
	w/c		0.379	0.379	0.379	0.379
	SCM/TCM	%	25.9	25.9	25.9	25.9
	CA Content	%	63.2	63.2	63.2	63.2
	CA/FA		2.09	2.09	2.02	2.02
	Calculated Air Content	%	1.57	1.57	1.58	1.58
	Calculated Unit Weight	kg/m³	2,357	2,357	2,357	2,357
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	17.8	17.8	16.7	16.1
	Air Temp.	C				
	RH	%				
	Initial Slump	mm	150	100	70	70
	Final Slump	mm	230	240	250	250
	Measured Air Content	%	1.7	1.8	1.8	1.9
	Measured Unit Weight	kg/m³	2,347	2,342	2,326	2,343
	Yield	m³	1.00	1.01	1.01	1.01

		C1/1[A]	C1/1[B]	C1/1[C]	C1/1[D]	C2/1[A]	C2/1[B]	C2/1[C]	C2/1[D]
Curing Cylinder Diam & End Prep		S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N
Compressive Strength at 18 hrs	MPa								
Average	MPa								
s	MPa								
Compressive Strength at 24 hrs	MPa	20.3 21.4 21.4	23.0 22.1 26.8 24.8	24.4 25.3 24.6	24.1 23.5 23.2	22.0 22.0 22.0	0.0	0.0	0.0
Average	MPa	21.0	24.2	24.8	23.6	22.0	0.0	0.0	0.0
s	MPa	0.64	2.08	0.47	0.46	0.00			
Compressive Strength at 3 days	MPa	36.2 35.6 35.4	43.5 43.6 42.6	43.0 42.8 42.9	44.6 45.5 44.8	38.4 37.3 37.3	36.0 35.6 35.8	29.8 33.5 31.0	41.6 44.8 41.3
Average	MPa	35.7	43.2	42.9	45.0	37.7	35.8	31.4	42.6
s	MPa	0.42	0.55	0.10	0.47	0.64	0.20	1.89	1.94
Compressive Strength at 7 days	MPa	43.4 43.4 43.4	51.8 50.3 47.8	49.2 48.3 48.1	50.8 50.5 51.8	46.1 45.0 45.0	55.7 51.7 50.9	51.6 50.4 50.6	48.8 50.7 48.7
Average	MPa	43.4	50.0	48.5	51.0	45.4	52.8	50.9	49.4
s	MPa	0.00	2.02	0.59	0.68	0.64	2.57	0.64	1.13
Compressive Strength at 28 days	MPa	47.9 50.4 49.6	60.8 61.3 61.7	54.2 56.1 57.1	61.8 61.1 62.4	55.4 57.9 57.7	63.0 63.9 66.8	58.2 59.6 67.5	62.6 60.3 60.5
Average	MPa	49.3	61.3	55.8	61.8	57.0	64.6	61.8	61.1
s	MPa	1.28	0.45	1.47	0.65	1.39	1.99	5.01	1.27
Compressive Strength at 56 days	MPa	52.7 52.6 53.6	65.8 66.3 64.0	62.5 59.8 61.4	67.1 64.9 62.0	60.9 62.8 61.0	67.7 68.8 69.0	67.6 72.3 67.3	68.3 75.7 69.0
Average	MPa	53.0	65.4	61.2	64.7	61.6	68.5	69.1	71.0
s	MPa	0.55	1.21	1.36	2.56	1.07	0.70	2.80	4.09

		C3/1[A]	C3/1[B]	C3/1[C]	C3/1[D]	C3/1[E]	C3/1 i	C4/1[A]	C4/1[B]
Curing Cylinder Diam & End Prep		S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N
Compressive Strength at 18 hrs	MPa								
Average	MPa								
s	MPa								
Compressive Strength at 24 hrs	MPa	25.6 25.0 24.7	23.9 24.0 23.5	20.5 20.4 20.3	19.3 18.9 18.0	23.5 22.5 23.9	22.8 23.5 23.2	29.8 31.0 29.3	14.7 16.7 17.3
Average	MPa	25.1	23.8	20.4	18.7	23.3	23.2	30.0	16.2
s	MPa	0.46	0.26	0.10	0.67	0.72	0.35	0.87	1.36
Compressive Strength at 3 days	MPa	47.1 49.0 47.4	45.6 46.0 46.4	37.6 38.6 38.0	40.4 40.1 37.7	46.5 46.6 47.3 46.7	43.0 46.2 41.2	47.5 47.8 48.5	41.6 45.4 45.5
Average	MPa	47.8	46.0	38.1	39.4	46.8	43.5	47.9	44.2
s	MPa	1.02	0.40	0.50	1.48	0.36	2.53	0.51	2.22
Compressive Strength at 7 days	MPa	55.3 54.3 54.8	53.2 53.7 53.5	43.6 48.5 43.7	47.4 45.5 46.8	60.7 63.7 62.8 61.0	59.5 59.0 58.4 56.6	56.6 58.7 57.1	49.6 52.7
Average	MPa	54.8	53.5	45.3	46.6	62.1	58.4	57.5	51.2
s	MPa	0.50	0.25	2.80	0.97	1.44	1.27	1.10	2.19
Compressive Strength at 28 days	MPa	64.8 64.9 62.1	66.0 64.3 63.8	53.2 53.0 53.4	60.5 58.8 56.9	63.3 63.3 65.0 67.1	63.8 62.3 61.3 62.1	64.5 64.7 63.8	61.8 65.2 61.4
Average	MPa	63.9	64.7	53.2	58.7	64.7	62.4	64.3	62.8
s	MPa	1.59	1.15	0.20	1.80	1.80	1.04	0.47	2.09
Compressive Strength at 56 days	MPa	69.4 69.9 67.9	68.4 70.1 70.2	57.8 58.4 59.7				69.1 69.9 69.1	
Average	MPa	69.1	69.6	58.6				69.4	
s	MPa	1.04	1.01	0.97				0.46	

		C4/1^C	C5/1^A	C5/1^B	C5/1^C	C6/1^A	C6/1^B	C6/1^C	C7/1
Curing Cylinder Diam & End Prep		S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N
Compressive Strength at 18 hrs	MPa								
Average	MPa								
s	MPa								
Compressive Strength at 24 hrs	MPa	13.4 14.5	25.0 26.5 26.7	19.2 20.5 20.8	17.1 18.5 16.9	16.5 17.6 16.5	13.3 14.2 14.6	15.5 14.8 14.7	16.7 15.5 18.3
Average	MPa	14.0	26.1	20.2	17.5	16.9	14.0	15.0	16.8
s	MPa	0.78	0.93	0.85	0.87	0.64	0.67	0.44	1.40
Compressive Strength at 3 days	MPa	45.3 47.2 45.3	46.7 46.8 46.4	42.4 43.6 43.2	43.8 43.1 40.6	41.2 42.3 40.6	43.0 43.0 44.1	44.1 43.2 43.2	41.3 41.9 41.6
Average	MPa	45.9	46.6	43.1	42.5	41.4	43.4	43.5	41.6
s	MPa	1.10	0.21	0.61	1.68	0.86	0.64	0.52	0.30
Compressive Strength at 7 days	MPa	56.1 52.6 56.1	51.2 54.3 51.5	47.8 51.9 49.5	48.6 48.1 50.3	49.4 49.9 49.9	51.6 53.5 53.6	52.0 52.8 53.2	49.8 50.9 50.6
Average	MPa	54.9	52.3	49.7	49.0	49.7	52.9	52.7	50.4
s	MPa	2.02	1.71	2.06	1.15	0.29	1.13	0.61	0.57
Compressive Strength at 28 days	MPa	58.5 63.5 66.5	63.3 63.4 64.2	61.8 61.3 60.3	61.8 61.4 58.9	59.3 59.7 59.5	61.7 65.2 64.3	62.7 62.2 66.6	61.0 59.8 61.5
Average	MPa	62.8	63.6	61.1	60.7	59.5	63.7	63.8	60.8
s	MPa	4.04	0.49	0.76	1.57	0.20	1.82	2.41	0.87
Compressive Strength at 56 days	MPa	65.7 67.2 66.1	67.7 69.0 68.5	65.9 68.6 69.1	64.3 67.3 66.6	62.3 61.5 60.6	69.2 66.7 65.3	66.3 66.3 68.7	65.8 64.0 63.0
Average	MPa	66.3	68.4	67.9	66.1	61.5	67.1	67.1	64.3
s	MPa	0.78	0.66	1.72	1.57	0.85	1.98	1.39	1.42

		C8/1A	C8/1B	C8/1C	C1/2A	C1/2B	C1/2C	C2/2A	C2/2B
Curing Cylinder Diam & End Prep		S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N
Compressive Strength at 18 hrs	MPa								
Average	MPa								
s	MPa								
Compressive Strength at 24 hrs	MPa	33.5 35.7 34.6	41.7 41.1 42.6	43.2 42.5 44.0	34.0 33.4 34.1	28.5 31.6 29.3	32.9 34.2 31.0	0.0	0.0
Average	MPa	34.6	41.8	43.2	33.8	29.8	32.7	0.0	0.0
s	MPa	1.10	0.75	0.75	0.38	1.61	1.61		
Compressive Strength at 3 days	MPa	49.4 50.5 49.4	51.0 49.6 49.6	52.1 50.9 50.8	54.4 55.8 54.2			42.8 41.4 42.3	50.5 52.5 53.3
Average	MPa	49.8	50.1	51.3	54.8			42.2	52.1
s	MPa	0.64	0.81	0.72	0.87			0.71	1.44
Compressive Strength at 7 days	MPa	54.3 53.2 54.3	59.0 60.9 58.6	58.0 59.6 57.6	64.2 62.6 62.4	59.8 60.7 61.0	61.3 60.4 61.4	56.1 53.8 55.8	65.6 67.6 65.9
Average	MPa	53.9	59.5	58.4	63.1	60.5	61.0	55.2	66.4
s	MPa	0.64	1.23	1.06	0.99	0.62	0.55	1.25	1.08
Compressive Strength at 28 days	MPa	66.2 61.2 63.6	63.3 64.9 64.9	68.4 67.4 67.7	72.2 72.0 69.8	70.9 70.7 72.5	72.0 74.3 72.0	63.9 63.8 65.1	83.8 83.9 83.9
Average	MPa	63.7	64.4	67.8	71.3	71.4	72.8	64.3	83.9
s	MPa	2.50	0.92	0.51	1.33	0.99	1.33	0.72	0.06
Compressive Strength at 56 days	MPa	63.2 66.5 64.9			76.0 76.7 74.6	75.4 78.8 75.9	78.6 77.4 79.6	70.0 68.7 67.8	86.1 88.5 88.2
Average	MPa	64.9			75.8	76.7	78.5	68.8	87.6
s	MPa	1.65			1.07	1.84	1.10	1.11	1.31

		C2/2^C	C3/2^A	C3/2^B	C3/2^C	C3/2^D	C4/2^A	C4/2^B	C4/2^C
Curing Cylinder Diam & End Prep		S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N
Compressive Strength at 18 hrs	MPa								
Average	MPa								
s	MPa								
Compressive Strength at 24 hrs	MPa	0.0	40.1 38.5 38.8	35.1 36.3 33.9	31.8 33.9 32.4	39.5 41.2 41.2	22.2 22.2 23.0	23.2 21.9 24.6	21.1 20.4 20.9
Average	MPa	0.0	39.1	35.1	32.7	40.6	22.5	23.2	20.8
s	MPa		0.85	1.20	1.08	0.98	0.46	1.35	0.36
Compressive Strength at 3 days	MPa	51.3 51.2 51.5	59.6 61.0 61.7	60.7 59.0 61.2	55.9 56.5 54.5	63.2 62.9 62.5	52.5 52.3 51.6	56.7 59.0 58.6	56.8 60.2 58.9
Average	MPa	51.3	60.8	60.3	55.6	62.9	52.1	58.1	58.6
s	MPa	0.15	1.07	1.15	1.03	0.35	0.47	1.23	1.72
Compressive Strength at 7 days	MPa	65.8 66.6 67.2	69.2 69.0 70.6	70.6 70.3 70.2	66.2 62.8 65.3	70.2 70.2 71.5 72.6	59.7 58.8 59.2	68.3 66.0 68.9	66.5 67.5 69.0
Average	MPa	66.5	69.6	70.4	64.8	71.1	59.2	67.7	67.7
s	MPa	0.70	0.87	0.21	1.76	1.16	0.45	1.53	1.26
Compressive Strength at 28 days	MPa	83.6 80.8 79.2	80.8 80.8 82.7	83.7 83.2 81.1	79.5 77.6 79.2	83.4 83.1 82.7	69.6 70.5 69.1	81.1 81.9 78.3	80.7 83.2 80.1
Average	MPa	81.2	81.4	82.7	78.8	83.1	69.7	80.4	81.3
s	MPa	2.23	1.10	1.38	1.02	0.35	0.71	1.89	1.64
Compressive Strength at 56 days	MPa	85.9 87.8 90.6	85.5 88.6 86.4	88.2 90.3 89.7	83.9 83.8	86.9 91.1 82.3	72.8 72.4 72.8	83.9 85.6 83.7	82.5 84.6
Average	MPa	88.1	86.8	89.4	83.9	86.8	72.7	84.4	83.6
s	MPa	2.36	1.59	1.08	0.07	4.40	0.23	1.04	1.48

		$C5/2^A$	$C5/2^B$	$C5/2^C$	$C6/2^A$	$C6/2^B$	$C6/2^C$	C7/2	$C8/2^A$
Curing Cylinder Diam & End Prep		S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N
Compressive Strength at 18 hrs	MPa								
Average	MPa								
s	MPa								
Compressive Strength at 24 hrs	MPa	18.1 18.2 18.4	11.3 12.1 11.3	7.5 7.0 7.5	23.6 22.6 23.5	19.4 20.9 21.7	22.9 23.8 23.1	10.0 9.5 10.5	37.4 37.4 37.4
Average	MPa	18.2	11.6	7.3	23.2	20.7	23.3	10.0	37.4
s	MPa	0.15	0.46	0.29	0.55	1.17	0.47	0.50	0.00
Compressive Strength at 3 days	MPa	55.2 55.8 55.5	61.0 56.4 59.0	59.5 59.8 58.1	51.3 51.8 50.9	50.6 51.3	50.2 49.1 50.4	46.4 47.5 47.2	55.1 55.6 55.4
Average	MPa	55.5	58.8	59.1	51.3	51.0	49.9	47.0	55.4
s	MPa	0.30	2.31	0.91	0.45	0.49	0.70	0.57	0.25
Compressive Strength at 7 days	MPa	63.6 62.9 63.3	67.3 63.6 67.4	70.2 70.5 74.3	64.5 61.6 64.4	61.8 61.2 61.3	60.7 60.7 61.0	61.0 60.4 60.7	62.0 61.8 62.8
Average	MPa	63.3	66.1	71.7	63.5	61.4	60.8	60.7	62.2
s	MPa	0.35	2.17	2.29	1.65	0.32	0.17	0.30	0.53
Compressive Strength at 28 days	MPa	73.0 72.8 72.8	80.0 80.0 78.9	79.5 80.8 80.6	72.2 71.5 73.2	76.1 74.6 75.7	73.4 73.8 72.6	72.3 71.7 70.0	70.5 70.7 71.7
Average	MPa	72.9	79.6	80.3	72.3	75.5	73.3	71.3	71.0
s	MPa	0.12	0.64	0.70	0.85	0.78	0.61	1.19	0.64
Compressive Strength at 56 days	MPa	78.0 77.9 80.0	85.3 87.0 84.2	79.2 83.0 82.5	76.5 76.5 75.9	81.3 81.4 77.4	79.2 81.3 81.3	74.5 73.3 73.3	77.8 76.4 76.3
Average	MPa	78.6	85.5	81.6	76.3	80.0	80.6	73.7	76.8
s	MPa	1.18	1.41	2.06	0.35	2.28	1.21	0.69	0.84

		C8/2[B]	C8/2[C]	C8/2[D]	C8/2[E]
Curing Cylinder Diam & End Prep		S/M 100N	S/M 100N	S/M 100N	S/M 100N
Compressive Strength at 18 hrs	MPa				
Average	MPa				
s	MPa				
Compressive Strength at 24 hrs	MPa	59.3 61.2 62.9	57.7 56.6 55.7	53.2 54.4 50.3	53.8 54.5 55.1
Average	MPa	61.1	56.7	52.6	54.5
s	MPa	1.80	1.00	2.11	0.65
Compressive Strength at 3 days	MPa	69.7 72.1 72.6	69.2 69.4 70.5	64.3 63.8 65.7	66.0 65.8 65.7
Average	MPa	71.5	69.7	64.6	65.8
s	MPa	1.55	0.70	0.98	0.15
Compressive Strength at 7 days	MPa	78.4 79.3 77.8	75.7 77.0 76.6	69.9 71.2 71.8	73.7 72.5 71.0
Average	MPa	78.5	76.4	71.0	72.4
s	MPa	0.75	0.67	0.97	1.35
Compressive Strength at 28 days	MPa	85.6 86.9 87.9	88.4 89.3 87.4	83.3 83.4 82.7	80.9 81.3 83.0
Average	MPa	86.8	88.4	83.1	81.7
s	MPa	1.15	0.95	0.38	1.12
Compressive Strength at 56 days	MPa	93.0 92.2 90.6	93.2 93.5 93.1		
Average	MPa	91.9	93.3		
s	MPa	1.22	0.21		

		LIq[A]	LIq[B]	LIq[C]	LIq[D]	LIq[E]	LIq[F]	LIq i	LIs[A]
Curing Cylinder Diam & End Prep		S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N
Compressive Strength at 18 hrs	MPa								
Average	MPa								
s	MPa								
Compressive Strength at 24 hrs	MPa	27.2 28.4 28.8	28.8 29.9 29.1	27.8 27.7 26.6	25.3 27.2 27.1	22.6 24.2 23.4	29.1 28.7 28.7	22.9 23.6 22.9	23.2 23.4 25.3
Average	MPa	28.1	29.3	27.4	26.5	23.4	28.8	23.1	24.0
s	MPa	0.83	0.57	0.67	1.07	0.80	0.23	0.40	1.16
Compressive Strength at 3 days	MPa	60.3 61.0 62.9	62.5 63.1 61.9	57.7 59.3 59.1	52.6 56.8 55.9	54.4 54.3 56.4	57.9 59.9 56.5	60.6 60.9 62.6	50.5 52.1 53.3
Average	MPa	61.4	62.5	58.7	55.1	55.0	58.1	61.4	52.0
s	MPa	1.35	0.60	0.87	2.21	1.18	1.71	1.08	1.40
Compressive Strength at 7 days	MPa	74.2 73.3 73.7	71.4 73.4 72.3	69.8 69.7 73.6	67.3 67.4 72.0	68.9 70.3 68.7	70.5 71.7 74.7 74.9	75.4 71.9 73.9 72.8	58.8 63.6 63.2
Average	MPa	73.7	72.4	71.0	68.9	69.3	73.0	73.5	61.9
s	MPa	0.45	1.00	2.22	2.69	0.87	2.19	1.51	2.66
Compressive Strength at 28 days	MPa	86.7 86.6 86.6	90.6 87.4 86.7	87.3 88.4 85.8	83.3 88.1 78.4	82.0 81.2 76.9	86.0 85.0 84.8 85.2	88.9 90.1 88.3 88.6	76.0 75.2 79.7
Average	MPa	86.6	88.2	87.2	83.3	80.0	85.3	89.0	77.0
s	MPa	0.06	2.08	1.31	4.85	2.74	0.53	0.79	2.40
Compressive Strength at 56 days	MPa	94.3 94.4	92.3 90.8 93.1 95.5	92.4 94.2 95.6	88.0 88.4 88.1	86.7 85.9 86.4			78.2 88.4
Average	MPa	94.4	92.9	94.1	88.2	86.3			83.3
s	MPa	0.07	1.96	1.60	0.21	0.40			7.21

		LIs^B	RHq^A	RHq^B	RHs^A	RHs^B	GNq^A	GNq^B	GNs^A
Curing Cylinder Diam & End Prep		S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N
Compressive Strength at 18 hrs	MPa								
Average	MPa								
s	MPa								
Compressive Strength at 24 hrs	MPa	21.8 23.2 22.9	27.1 30.4 28.2	28.5 29.5 29.2	23.9 26.2 23.9	25.2 26.8 25.8	23.7 24.6 26.0	21.8 22.7 23.2	30.5 32.8 31.7
Average	MPa	22.6	28.6	29.1	24.7	25.9	24.8	22.6	31.7
s	MPa	0.74	1.68	0.51	1.33	0.81	1.16	0.71	1.15
Compressive Strength at 3 days	MPa	44.6 46.9 50.0	51.5 51.4 53.8	48.9 51.7 51.5	50.5 54.6 52.6	54.0 54.1 50.0	51.8 52.3 51.8	53.7 54.4 55.0	55.4 58.7 56.9
Average	MPa	47.2	52.2	50.7	52.6	52.7	52.0	54.4	57.0
s	MPa	2.71	1.36	1.56	2.05	2.34	0.29	0.65	1.65
Compressive Strength at 7 days	MPa	59.8 55.1 58.3	65.1 67.9 64.2	60.4 59.5 58.8	63.6 65.2 63.0	63.3 64.5 65.8	63.3 62.4 62.2	62.2 60.8 61.1	68.3 69.5 72.5
Average	MPa	57.7	65.7	59.6	63.9	64.5	62.6	61.4	70.1
s	MPa	2.40	1.93	0.80	1.14	1.25	0.59	0.74	2.16
Compressive Strength at 28 days	MPa	71.9 69.9 70.1	77.9 80.3 81.1	69.8 73.0 73.8	80.9 76.6 77.2	81.0 79.0 78.4	75.6 76.3 78.3	75.7 74.4 76.3	85.0 87.1 87.5
Average	MPa	70.6	79.8	72.2	78.2	79.5	76.7	75.5	86.5
s	MPa	1.10	1.67	2.12	2.33	1.36	1.40	0.97	1.34
Compressive Strength at 56 days	MPa	73.3 72.7 75.4	86.6	77.8 75.8	82.6 86.5 82.8	81.4 81.9 84.2	84.4 80.8 84.4	83.4 80.3 80.8	89.4 89.1 93.4
Average	MPa	73.8	86.6	76.8	84.0	82.5	83.2	81.5	90.6
s	MPa	1.42		1.41	2.20	1.49	2.08	1.66	2.40

		GNs^B	GVq^A	GVq^B	GVs^A	GVs^B
Curing Cylinder Diam & End Prep		S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N
Compressive Strength at 18 hrs	MPa					
Average	MPa					
s	MPa					
Compressive Strength at 24 hrs	MPa	29.3 28.1 29.0	22.4 24.3 22.0	19.6 21.7 22.7	22.4 22.5 23.9	26.3 26.8 25.9
Average	MPa	28.8	22.9	21.3	22.9	26.3
s	MPa	0.62	1.23	1.58	0.84	0.45
Compressive Strength at 3 days	MPa	53.6 55.1 57.5	44.0 45.4 42.5	43.4 43.3 44.3	46.3 45.9 45.9	45.0 48.2 47.6
Average	MPa	55.4	44.0	43.7	46.0	46.9
s	MPa	1.97	1.45	0.55	0.23	1.70
Compressive Strength at 7 days	MPa	67.5 68.9 67.6	51.4 50.0 51.5	53.2 51.5 53.1	56.5 55.6 57.5	56.6 56.5 57.3
Average	MPa	68.0	51.0	52.6	56.5	56.8
s	MPa	0.78	0.84	0.95	0.95	0.44
Compressive Strength at 28 days	MPa	81.6 80.7 80.7	61.9 67.7 66.8	64.4 63.8 64.7	71.0 70.3 69.9	71.8 68.2 69.3
Average	MPa	81.0	65.5	64.3	70.4	69.8
s	MPa	0.52	3.12	0.46	0.56	1.84
Compressive Strength at 56 days	MPa	87.3 85.4 87.4	68.9 72.9 69.0	69.6	74.8 75.3 73.6	
Average	MPa	86.7	70.3	69.6	74.6	
s	MPa	1.13	2.28		0.87	

		C1/1^A	C1/1^B	C1/1^C	C1/1^D	C2/1^A	C2/1^B	C2/1^C	C2/1^D
Curing		S/M	S/M	S/M	S/M	S/M	S/M	S/M	S/M
Splitting Tensile Strength at 28 days	MPa	3.47 3.76 3.44	4.32 4.81 4.74	4.29 3.97 4.59	4.13 4.46 4.46	4.76 3.99 4.16	4.44 4.44 5.10	4.10 4.15 5.06	4.20 4.57 4.46
Average	MPa	3.56	4.62	4.28	4.35	4.30	4.66	4.44	4.41
s	MPa	0.18	0.27	0.31	0.19	0.40	0.38	0.54	0.19
MOR at 28 days	MPa	4.84 4.97 4.89				5.60 5.29 5.57			
Average	MPa	4.90				5.49			
s	MPa	0.07				0.17			
Modulus of Elasticity at 7 days	GPa								
Average	GPa								
s	GPa								
Modulus of Elasticity at 28 days	GPa	40.8 40.6 40.5	41.4 41.0 41.1 41.1	41.1 40.8 40.6 41.5	43.1 42.7	36.5 36.4	43.1 43.2	44.3 44.3 45.8 47.7	43.0 42.9
Average	GPa	40.6	41.2	41.0	42.9	36.5	43.2	45.5	43.0
s	GPa	0.15	0.17	0.39	0.28	0.07	0.07	1.61	0.07
Length Change at 3 days	με						40 30	40 30	80 90
Average	με						35	35	85
Length Change at 7 days	με		80 80	100 110	100 90	150 130 100	160 150	170 140	140 150
Average	με		80	105	95	127	155	155	145
Length Change at 28 days	με		180 180	170 180	160 160	230 200 230	280 250	280 240	260 280
Average	με		180	175	160	220	265	260	270
Length Change at 56 days	με		290 290	280 310	320 360	300 250 320	280 250	280 240	
Average	με		290	295	340	290	265	260	

		C3/1^{A}	C3/1^{B}	C3/1^{C}	C3/1^{D}	C3/1^{E}	C3/1 i	C4/1^{A}	C4/1^{B}
Curing		S/M	S/M	S/M	S/M	S/M	S/M	S/M	S/M
Splitting Tensile	MPa	4.50	4.84	4.95	4.53	4.99	5.43	4.77	4.35
Strength		4.31	4.38	4.43	4.84	4.31	4.72	4.38	4.19
at 28 days		4.60	4.79	4.26		5.57	5.52	4.47	3.66
Average	MPa	4.47	4.67	4.55	4.69	4.96	5.22	4.54	4.07
s	MPa	0.15	0.25	0.36	0.22	0.63	0.44	0.20	0.36
MOR	MPa	6.67						6.84	
at 28 days		6.38						6.52	
		5.92						6.52	
Average	MPa	6.32						6.63	
s	MPa	0.38						0.18	
Modulus of	GPa								
Elasticity									
at 7 days									
Average	GPa								
s	GPa								
Modulus of	GPa	43.7	42.7	42.8	44.0			43.5	47.6
Elasticity		42.4	42.7	42.3	44.2			42.3	47.6
at 28 days		42.3	42.2	42.8	48.2			41.5	45.1
			42.2	42.8	46.8				45.3
Average	GPa	42.8	42.5	42.7	45.8			42.4	46.4
s	GPa	0.78	0.29	0.25	2.05			1.01	1.39
Length Change	με		70	120	60				100
at 3 days			70	120					100
Average	με		70	120	60				100
Length Change	με	120	150	180	130			70	180
at 7 days		100	150	180				70	200
		180						90	
Average	με	133	150	180	130			77	190
Length Change	με	210	280	300	290			210	280
at 28 days		170	260	300				210	310
		270						230	
Average	με	217	270	300	290			217	295
Length Change	με	220	330	360				220	290
at 56 days		230	290	360				210	320
		290						250	
Average	με	247	310	360				227	305

		C4/1[C]	C5/1[A]	C5/1[B]	C5/1[C]	C6/1[A]	C6/1[B]	C6/1[C]	C7/1
Curing		S/M	S/M	S/M	S/M	S/M	S/M	S/M	S/M
Splitting Tensile Strength at 28 days	MPa	4.26 4.39 4.76	4.34 4.56 4.53	4.07 4.18 5.15	4.62 4.50 4.07	4.18 3.88 4.58	4.55 4.49 4.24	4.21 4.24 4.28	4.39 4.51 4.61
Average	MPa	4.47	4.48	4.47	4.40	4.21	4.43	4.24	4.50
s	MPa	0.26	0.12	0.59	0.29	0.35	0.16	0.04	0.11
MOR at 28 days	MPa		6.75 7.01 6.75			6.52 6.32 6.38			5.55 5.92 5.80
Average	MPa		6.84			6.41			5.76
s	MPa		0.15			0.10			0.19
Modulus of Elasticity at 7 days	GPa								
Average	GPa								
s	GPa								
Modulus of Elasticity at 28 days	GPa	45.4 45.6 42.8 43.0	42.2 41.5 42.2	43.1 42.8 44.9 44.9	42.4 42.0 42.7 42.4	40.2 41.4 41.4	43.7 43.3 42.8 43.0	41.9 42.9 42.5 42.6	40.9 42.0 41.3
Average	GPa	44.2	42.0	43.9	42.4	41.0	43.2	42.5	41.4
s	GPa	1.51	0.40	1.13	0.29	0.69	0.39	0.42	0.56
Length Change at 3 days	με	110 110		80 90	80 80		90 80	100 110	
Average	με	110		85	80		85	105	
Length Change at 7 days	με	200 220	80 120 120	120 140	140 130	70 90 60	190 170	190 200	130 190 140
Average	με	210	107	130	135	73	180	195	153
Length Change at 28 days	με	320 320	170 260 250	280 290	290 290	310 220 190	340 300	340 350	360 380 350
Average	με	320	227	285	290	240	320	345	363
Length Change at 56 days	με	320 330	240 300 310	280 290	300 300		370 330	360 370	
Average	με	325	283	285	300		350	365	

		$C8/1^{A}$	$C8/1^{B}$	$C8/1^{C}$	$C1/2^{A}$	$C1/2^{B}$	$C1/2^{C}$	$C2/2^{A}$	$C2/2^{B}$
Curing		S/M	S/M	S/M	S/M	S/M	S/M	S/M	S/M
Splitting Tensile	MPa	4.40	5.32	5.41	5.01	5.76	4.49	5.10	5.49
Strength		3.99	4.72	4.28	4.84	5.22	4.15	5.08	4.72
at 28 days		4.24	5.06	5.46	5.46	5.04	5.38	4.69	5.04
Average	MPa	4.21	5.03	5.05	5.10	5.34	4.67	4.96	5.08
s	MPa	0.21	0.30	0.67	0.32	0.37	0.64	0.23	0.39
MOR	MPa	6.64			7.96			6.98	
at 28 days		6.58			7.96			6.41	
		7.16			8.33			6.64	
Average	MPa	6.79			8.08			6.68	
s	MPa	0.32			0.21			0.29	
Modulus of	GPa								
Elasticity									
at 7 days									
Average	GPa								
s	GPa								
Modulus of	GPa	39.9	43.9	42.6	41.9	41.7	41.5	39.5	44.0
Elasticity		41.2	43.8	43.0	41.0	41.4	41.8	39.0	44.2
at 28 days		42.4	43.9	43.1	40.0	42.0	41.6	39.1	44.0
			43.8	42.8		42.0	41.5		43.8
Average	GPa	41.2	43.9	42.9	41.0	41.8	41.6	39.2	44.0
s	GPa	1.25	0.06	0.22	0.95	0.29	0.14	0.26	0.16
Length Change	με		70	90					90
at 3 days			70	90					90
Average	με		70	90					90
Length Change	με	180	140	160		270	300		190
at 7 days		160	130	160		260	280		180
		150							
Average	με	163	135	160		265	290		185
Length Change	με		230	240		490	530	360	310
at 28 days			230	250		490	510	300	310
								360	
Average	με		230	245		490	520	340	310
Length Change	με		330	290		560	610	450	380
at 56 days			300	310		560	580	370	370
								400	
Average	με		315	300		560	595	407	375

		$C2/2^C$	$C3/2^A$	$C3/2^B$	$C3/2^C$	$C3/2^D$	$C4/2^A$	$C4/2^B$	$C4/2^C$
Curing		S/M	S/M	S/M	S/M	S/M	S/M	S/M	S/M
Splitting Tensile Strength at 28 days	MPa	4.75 4.56 4.53	4.60 4.65 4.73	5.30 5.44 4.25	5.89 5.05 5.56	6.08 4.98 4.84	5.12 5.08 4.72	5.47 5.60 6.02	4.37 5.01 5.90
Average	MPa	4.61	4.66	5.00	5.50	5.30	4.97	5.70	5.09
s	MPa	0.12	0.07	0.65	0.42	0.68	0.22	0.29	0.77
MOR at 28 days	MPa		7.76 7.21 7.50				7.93 7.70 7.56		
Average	MPa		7.49				7.73		
s	MPa		0.28				0.19		
Modulus of Elasticity at 7 days	GPa								
Average	GPa								
s	GPa								
Modulus of Elasticity at 28 days	GPa	44.9 44.9 44.5 44.3	42.7 42.4 41.9	43.4 43.1 44.5 44.6	43.0 43.3 42.7 42.8	41.6 42.4	44.5 42.8 42.6	44.6 44.7 41.7 41.9	45.0 45.1 44.2 44.2
Average	GPa	44.7	42.3	43.9	43.0	42.0	43.3	43.2	44.6
s	GPa	0.30	0.40	0.76	0.26	0.57	1.04	1.65	0.49
Length Change at 3 days	με	60 30		40 60	70 60	60 60		120 110	130 120
Average	με	45		50	65	60		115	125
Length Change at 7 days	με	170 140		130 160	180 180	140 140	150 190 260	200 190	220 210
Average	με	155		145	180	140	200	195	215
Length Change at 28 days	με	260 250		290 360	400 390	290 290	300 310 370	340 340	360 330
Average	με	255		325	395	290	327	340	345
Length Change at 56 days	με	340 340		350 420	470 450	300 320	350 350 430	390 390	400 370
Average	με	340		385	460	310	377	390	385

		C5/2A	C5/2B	C5/2C	C6/2A	C6/2B	C6/2C	C7/2	C8/2A
Curing		S/M	S/M	S/M	S/M	S/M	S/M	S/M	S/M
Splitting Tensile	MPa	4.36	4.82	4.80	3.98	4.56	4.59	4.69	5.41
Strength		4.87	4.86	5.33	4.02	4.27	5.10	4.54	5.00
at 28 days		3.99	5.90	5.56	3.92	4.64	4.46	5.05	5.35
Average	MPa	4.41	5.19	5.23	3.97	4.49	4.72	4.76	5.25
s	MPa	0.44	0.61	0.39	0.05	0.19	0.34	0.26	0.22
MOR	MPa	7.56			8.33			8.22	7.44
at 28 days		7.79			7.39			8.13	7.18
		7.21			7.76			7.64	7.50
Average	MPa	7.52			7.83			8.00	7.37
s	MPa	0.29			0.47			0.31	0.17
Modulus of Elasticity at 7 days	GPa								
Average	GPa								
s	GPa								
Modulus of	GPa	42.8	44.8	44.6	39.3	42.7	42.2	40.9	37.6
Elasticity		41.8	44.7	44.6	39.3	42.5	42.4	40.7	37.1
at 28 days		41.8	44.5	44.5	39.3	42.1	42.7	43.8	38.9
			44.3	45.1		42.0	42.6		
Average	GPa	42.1	44.6	44.7	39.3	42.3	42.5	41.8	37.9
s	GPa	0.58	0.22	0.27	0.00	0.33	0.22	1.73	0.93
Length Change	με		150	150					
at 3 days			170	160					
Average	με		160	155					
Length Change	με		220	220	200			80	
at 7 days			240	240	160			90	
					150			140	
Average	με		230	230	170			103	
Length Change	με	430	390	380	320			280	
at 28 days		420	390	390	300			250	
		300			240			320	
Average	με	383	390	385	287			283	
Length Change	με	540			580			310	
at 56 days		530			560			260	
		420			540			350	
Average	με	497			560			307	

		C8/2[B]	C8/2[C]	C8/2[D]	C8/2[E]
Curing		S/M	S/M	S/M	S/M
Splitting Tensile Strength at 28 days	MPa	5.68 6.35 5.98	6.29 5.93 6.41	5.69 5.13 5.70	6.06 5.10 5.47
Average	MPa	6.00	6.21	5.51	5.54
s	MPa	0.34	0.25	0.33	0.48
MOR at 28 days	MPa				
Average	MPa				
s	MPa				
Modulus of Elasticity at 7 days	GPa				
Average	GPa				
s	GPa				
Modulus of Elasticity at 28 days	GPa	45.4 45.2 45.0 44.9	44.3 44.0 45.5 45.4	42.6 42.1 41.4 41.3	42.1 42.3 43.2 43.5
Average	GPa	45.1	44.8	41.9	42.8
s	GPa	0.22	0.76	0.61	0.68
Length Change at 3 days	$\mu\varepsilon$	100 100	110 100		150 140
Average	$\mu\varepsilon$	100	105		145
Length Change at 7 days	$\mu\varepsilon$	170 170	190 170		
Average	$\mu\varepsilon$	170	180		
Length Change at 28 days	$\mu\varepsilon$	340 330	350 330		
Average	$\mu\varepsilon$	335	340		
Length Change at 56 days	$\mu\varepsilon$	390 370	390 390		
Average	$\mu\varepsilon$	380	390		

		LIq^A	LIq^B	LIq^C	LIq^D	LIq^E	LIq^F	LIq i	LIs^A
Curing		S/M	S/M	S/M	S/M	S/M	S/M	S/M	S/M
Splitting Tensile Strength at 28 days	MPa	6.31 6.59	6.57 6.23 6.94	6.83 6.26 6.06	5.46 6.30 5.89	4.64 4.44 5.10	6.64 5.93 4.97	6.31 6.39 6.04	5.97 4.62 4.27
Average	MPa	6.45	6.58	6.38	5.88	4.73	5.85	6.25	4.95
s	MPa	0.20	0.36	0.40	0.42	0.34	0.84	0.18	0.90
MOR at 28 days	MPa			8.66 9.04	9.62 9.18				8.91 9.69
Average	MPa			8.85	9.40				9.30
s	MPa			0.27	0.31				0.55
Modulus of Elasticity at 7 days	GPa			41.4 39.5	40.8 40.5				40.6 40.6
Average	GPa			40.5	40.7				40.6
s	GPa			1.34	0.21				0.00
Modulus of Elasticity at 28 days	GPa			42.2 42.5	41.3 42.3				43.4 43.4
Average	GPa			42.4	41.8				43.4
s	GPa			0.21	0.71				0.00
Length Change at 3 days	$\mu\varepsilon$								
Average	$\mu\varepsilon$								
Length Change at 7 days	$\mu\varepsilon$								
Average	$\mu\varepsilon$								
Length Change at 28 days	$\mu\varepsilon$								
Average	$\mu\varepsilon$								
Length Change at 56 days	$\mu\varepsilon$								
Average	$\mu\varepsilon$								

		LIs^B	RHq^A	RHq^B	RHs^A	RHs^B	GNq^A	GNq^B	GNs^A
Curing		S/M	S/M	S/M	S/M	S/M	S/M	S/M	S/M
Splitting Tensile Strength at 28 days	MPa	5.23 5.19 4.88	6.07 5.94 5.30	5.74 5.86 5.80	5.57 5.02 5.41	5.46 5.74 6.31	4.72 5.00 5.19	4.64 5.32 4.53	5.41 4.83 5.41
Average	MPa	5.10	5.77	5.80	5.33	5.84	4.97	4.83	5.22
s	MPa	0.19	0.41	0.06	0.28	0.43	0.24	0.43	0.33
MOR at 28 days	MPa	8.93 9.19	9.55 9.47	8.84 8.84	9.21 8.54	9.75 9.62	9.25 8.60	8.51 7.84	9.19 8.41
Average	MPa	9.06	9.51	8.84	8.88	9.69	8.93	8.18	8.80
s	MPa	0.18	0.06	0.00	0.47	0.09	0.46	0.47	0.55
Modulus of Elasticity at 7 days	GPa	37.8 40.7	41.4 41.6 40.5 40.0	40.3 40.7	39.3 39.6	38.0 37.8 40.1 40.5	41.8 42.6	38.8 39.4	40.7 39.9
Average	GPa	39.3	40.9	40.5	39.5	39.1	42.2	39.1	40.3
s	GPa	2.05	0.75	0.28	0.21	1.40	0.57	0.42	0.57
Modulus of Elasticity at 28 days	GPa	43.3 43.8	43.0 43.1 42.4 42.1	41.2 41.5 40.6 40.7	40.0 40.2 42.6 42.4	43.1 42.7 42.5 42.2	43.9 45.5	37.4 43.6	45.4 44.4
Average	GPa	43.6	42.7	41.0	41.3	42.6	44.7	40.5	44.9
s	GPa	0.35	0.48	0.42	1.39	0.38	1.13	4.38	0.71
Length Change at 3 days	με								
Average	με								
Length Change at 7 days	με								
Average	με								
Length Change at 28 days	με								
Average	με								
Length Change at 56 days	με								
Average	με								

		GNs[B]	GVq[A]	GVq[B]	GVs[A]	GVs[B]
Curing		S/M	S/M	S/M	S/M	S/M
Splitting Tensile	MPa	4.99	5.30	5.52	5.57	5.02
Strength		4.91	4.86	5.49	4.97	5.27
at 28 days		4.69	5.21	5.35	5.43	5.27
Average	MPa	4.86	5.12	5.45	5.32	5.19
s	MPa	0.16	0.23	0.09	0.31	0.14
MOR	MPa	8.79	7.86	8.26	8.50	9.04
at 28 days		8.34	7.53	8.34	9.63	8.85
Average	MPa	8.57	7.70	8.30	9.07	8.95
s	MPa	0.32	0.23	0.06	0.80	0.13
Modulus of	GPa	40.2	34.0	34.7	37.2	35.5
Elasticity		40.2	35.1	34.6	38.1	34.8
at 7 days						
Average	GPa	40.2	34.6	34.7	37.7	35.2
s	GPa	0.00	0.78	0.07	0.64	0.49
Modulus of	GPa	43.8	36.5	38.5	40.6	38.1
Elasticity		43.2	36.4	36.8	40.1	39.9
at 28 days						
Average	GPa	43.5	36.5	37.7	40.4	39.0
s	GPa	0.42	0.07	1.20	0.35	1.27
Length Change	με					
at 3 days						
Average	με					
Length Change	με					
at 7 days						
Average	με					
Length Change	με					
at 28 days						
Average	με					
Length Change	με					
at 56 days						
Average	με					

Appendix E. Mixture Proportion Study and Plant Batching

			1	2	3	4	5	6^{A}	6^{B}
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m^3	750.0	700.0	650.0	600.0	550.0	500.0	500.0
	Fly Ash	kg/m^3							
	Silica Fume	kg/m^3							
	GGBF Slag	kg/m^3							
	Coarse Aggregate	kg/m^3	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1
	Intermediate Aggregate	kg/m^3							
	Fine Aggregate	kg/m^3	300.0	383.5	464.2	547.5	629.4	711.4	711.4
	Mixing Water	kg/m^3	218.0	203.0	189.0	174.0	159.5	145.0	145.0
	WR Admixture	L/m^3	2.25	2.10	1.95	1.80	1.65	1.50	1.50
	SR/WR Admixture	L/m^3							
	AE Admixture	L/m^3							
	CI/SA Admixture	L/m^3							
	HRWR Admixture	L/m^3	9.75	9.10	8.45	7.80	7.15	6.50	6.50
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*
	Fly Ash								
	Silica Fume								
	GGBF Slag								
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m^3	1,623	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC	GHC	GHC	GHC	GHC	GHC	GHC
	SR/WR Admixture								
	AE Admixture								
	CI/SA Admixture								
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.300	0.300	0.300	0.300	0.300	0.300	0.300
	w/c		0.300	0.300	0.300	0.300	0.300	0.300	0.300
	SCM/TCM	%	0	0	0	0	0	0	0
	CA Content	%	65.4	65.4	65.4	65.4	65.4	65.4	65.4
	CA/FA		3.54	2.77	2.29	1.94	1.69	1.49	1.49
	Calculated Air Content	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Calculated Unit Weight	kg/m^3	2,345	2,362	2,378	2,395	2,412	2,428	2,428
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	21.1	27.8	30.0	26.7	29.4	28.3	13.3
	Air Temp.	C	32.8	38.3	35.6	37.8	38.9	36.7	
	RH	%	63	46	50	45	35	36	
	Initial Slump	mm							
	Final Slump	mm			260		200	190	100
	Measured Air Content	%		0.9			1.9	2.2	
	Measured Unit Weight	kg/m^3		2,387		2,414	2,410	2,414	2,423
	Yield	m^3		0.99		0.99	1.00	1.01	1.00

			6^C	6^D	7^A	7^B	8	9^A	9^B
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	500.0	500.0	450.0	450.0	400.0	475.0	475.0
	Fly Ash	kg/m³							
	Silica Fume	kg/m³							
	GGBF Slag	kg/m³							
	Coarse Aggregate	kg/m³	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1
	Intermediate Aggregate	kg/m³							
	Fine Aggregate	kg/m³	711.4	711.4	793.4	793.4	875.3	751.7	751.7
	Mixing Water	kg/m³	145.0	145.0	130.5	130.5	116.0	138.0	138.0
	WR Admixture	L/m³	1.50	1.50	1.35	1.35	1.20	1.43	1.43
	SR/WR Admixture	L/m³							
	AE Admixture	L/m³							
	CI/SA Admixture	L/m³							
	HRWR Admixture	L/m³	6.50	6.50	5.85	5.85	5.20	6.18	6.18
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*
	Fly Ash								
	Silica Fume								
	GGBF Slag								
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m³	1,623	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC	GHC	GHC	GHC	GHC	GHC	GHC
	SR/WR Admixture								
	AE Admixture								
	CI/SA Admixture								
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.300	0.300	0.300	0.300	0.300	0.300	0.300
	w/c		0.300	0.300	0.300	0.300	0.300	0.300	0.300
	SCM/TCM	%	0	0	0	0	0	0	0
	CA Content	%	65.4	65.4	65.4	65.4	65.4	65.4	65.4
	CA/FA		1.49	1.49	1.34	1.34	1.21	1.41	1.41
	Calculated Air Content	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Calculated Unit Weight	kg/m³	2,428	2,428	2,445	2,445	2,461	2,436	2,436
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	17.8	16.1		20.8	27.5	25.0	28.9
	Air Temp.	C			30.6	32.2	37.8	35.0	37.2
	RH	%			90	49	47	60	48
	Initial Slump	mm							
	Final Slump	mm	190	150	150	100	20	0	0
	Measured Air Content	%	2.2	1.9	2.9		2.9		2.9
	Measured Unit Weight	kg/m³	2,424	2,428	2,407	2,441	2,426		2,415
	Yield	m³	1.00	1.00	1.02	1.00	1.01		1.01

			9[C]	9[D]	10	11	12	13[A]	13[B]
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m^3	475.0	475.0	550.0	600.0	360.0	400.0	400.0
	Fly Ash	kg/m^3					90.0	100.0	100.0
	Silica Fume	kg/m^3							
	GGBF Slag	kg/m^3							
	Coarse Aggregate	kg/m^3	1,062.1	1,062.1	1,062.1	1,062.1	1,184.7	1,062.1	1,062.1
	Intermediate Aggregate	kg/m^3							
	Fine Aggregate	kg/m^3	751.7	751.7	653.7	574.0	658.2	698.3	698.3
	Mixing Water	kg/m^3	138.0	138.0	146.4	159.7	130.8	147.1	147.1
	WR Admixture	L/m^3	1.43	1.43	1.65	1.80	2.00	0.98	0.98
	SR/WR Admixture	L/m^3							
	AE Admixture	L/m^3							
	CI/SA Admixture	L/m^3							
	HRWR Admixture	L/m^3	6.18	6.18	11.00	12.00	5.00	3.91	3.91
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*
	Fly Ash						Cl C	Cl C	Cl C
	Silica Fume								
	GGBF Slag								
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m^3	1,623	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC	GHC	GHC	GHC	GHC	GHC	GHC
	SR/WR Admixture								
	AE Admixture								
	CI/SA Admixture								
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.300	0.300	0.280	0.280	0.300	0.300	0.300
	w/c		0.300	0.300	0.280	0.280	0.375	0.375	0.375
	SCM/TCM	%	0	0	0	0	20	20	20
	CA Content	%	65.4	65.4	65.4	65.4	73.0	65.4	65.4
	CA/FA		1.41	1.41	1.62	1.85	1.80	1.52	1.52
	Calculated Air Content	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Calculated Unit Weight	kg/m^3	2,436	2,436	2,427	2,412	2,432	2,413	2,413
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	28.1	22.2	26.1	26.7	28.3	22.2	25.3
	Air Temp.	C	38.3	32.2	32.2	34.4	33.9	22.2	28.9
	RH	%	50	55	51	52	46	98	77
	Initial Slump	mm							
	Final Slump	mm	0	170	230		110	90	60
	Measured Air Content	%	2.2		2.3	1.3		2.0	
	Measured Unit Weight	kg/m^3	2,428	2,447	2,407	2,412	2,444	2,406	2,406
	Yield	m^3	1.00	1.00	1.01	1.00	1.00	1.00	1.00

Section	Property	Unit	14	15	16	17	18[A]	18[B]	19
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	550.0	600.0	650.0	400.0	500.0	500.0	440.0
	Fly Ash	kg/m³				100.0			110.0
	Silica Fume	kg/m³							
	GGBF Slag	kg/m³							
	Coarse Aggregate	kg/m³	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1
	Intermediate Aggregate	kg/m³							
	Fine Aggregate	kg/m³	657.8	578.2	498.8	723.0	737.1	737.1	642.2
	Mixing Water	kg/m³	148.7	162.3	175.8	136.1	135.2	135.2	149.7
	WR Admixture	L/m³	1.65	1.80	1.95	2.00	1.50	1.50	2.20
	SR/WR Admixture	L/m³							
	AE Admixture	L/m³							
	CI/SA Admixture	L/m³							
	HRWR Admixture	L/m³	7.15	7.80	8.45	4.50	6.50	6.50	4.95
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*
	Fly Ash					Cl C			Cl C
	Silica Fume								
	GGBF Slag								
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m³	1,623	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC	GHC	GHC	GHC	GHC	GHC	GHC
	SR/WR Admixture								
	AE Admixture								
	CI/SA Admixture								
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.280	0.280	0.280	0.280	0.280	0.280	0.280
	w/c		0.280	0.280	0.280	0.350	0.280	0.280	0.350
	SCM/TCM	%	0	0	0	20	0	0	20
	CA Content	%	65.4	65.4	65.4	65.4	65.4	65.4	65.4
	CA/FA		1.61	1.84	2.13	1.47	1.44	1.44	1.65
	Calculated Air Content	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Calculated Unit Weight	kg/m³	2,429	2,414	2,399	2,429	2,444	2,444	2,413
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	19.4	20.3	26.7	24.2	25.8	26.7	22.8
	Air Temp.	C	18.9	22.2	31.7	28.9	31.1		31.7
	RH	%	95	78	65	62	62		51
	Initial Slump	mm							
	Final Slump	mm	110	150	220	60	20	0	140
	Measured Air Content	%							
	Measured Unit Weight	kg/m³	2,405	2,422	2,406	2,425	2,424		2,426
	Yield	m³	1.01	1.00	1.00	1.00	1.01		0.99

			20	21	22	23	24A	24B	25
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m^3	450.0	425.0	425.0	425.0	500.0	500.0	320.0
	Fly Ash	kg/m^3	50.0	75.0	75.0	75.0			80.0
	Silica Fume	kg/m^3							
	GGBF Slag	kg/m^3							
	Coarse Aggregate	kg/m^3	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1
	Intermediate Aggregate	kg/m^3							
	Fine Aggregate	kg/m^3	730.8	726.9	726.9	725.9	733.5	733.5	883.2
	Mixing Water	kg/m^3	136.1	136.1	136.1	135.5	133.1	133.1	108.2
	WR Admixture	L/m^3	2.00	2.00	1.00	1.00	1.50	1.50	1.20
	SR/WR Admixture	L/m^3							
	AE Admixture	L/m^3							
	CI/SA Admixture	L/m^3							
	HRWR Admixture	L/m^3	4.50	4.50	5.50	6.50	10.00	10.00	5.20
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*
	Fly Ash		Cl C	Cl C	Cl C	Cl C			Cl C
	Silica Fume								
	GGBF Slag								
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m^3	1,623	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC	GHC	GHC	GHC	GHC	GHC	GHC
	SR/WR Admixture								
	AE Admixture								
	CI/SA Admixture								
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.280	0.280	0.280	0.280	0.280	0.280	0.280
	w/c		0.311	0.329	0.329	0.329	0.280	0.280	0.350
	SCM/TCM	%	10	15	15	15	0	0	20
	CA Content	%	65.4	65.4	65.4	65.4	65.4	65.4	65.4
	CA/FA		1.45	1.46	1.46	1.46	1.45	1.45	1.20
	Calculated Air Content	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Calculated Unit Weight	kg/m^3	2,437	2,433	2,433	2,433	2,443	2,443	2,461
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	22.8	22.8	23.9	25.0	24.7	26.7	26.1
	Air Temp.	C	32.2	35.0	35.0	34.4	34.4		35.6
	RH	%	45	50	56	50	49		46
	Initial Slump	mm							
	Final Slump	mm	10	70	70	190	220	200	10
	Measured Air Content	%							
	Measured Unit Weight	kg/m^3	2,433	2,429	2,433	2,439	2,443		2,446
	Yield	m^3	1.00	1.00	1.00	1.00	1.00		1.01

			26	27^A	27^B	27^C	27^D	27^E	27^F
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m^3	360.0	400.0	400.0	400.0	400.0	400.0	400.0
	Fly Ash	kg/m^3	90.0	100.0	100.0	100.0	100.0	100.0	100.0
	Silica Fume	kg/m^3							
	GGBF Slag	kg/m^3							
	Coarse Aggregate	kg/m^3	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1
	Intermediate Aggregate	kg/m^3							
	Fine Aggregate	kg/m^3	802.3	721.4	721.4	721.4	721.4	721.4	721.4
	Mixing Water	kg/m^3	121.7	135.2	135.2	135.2	135.2	135.2	135.2
	WR Admixture	L/m^3	1.35	1.50	1.50	1.50	1.50	1.50	1.50
	SR/WR Admixture	L/m^3							
	AE Admixture	L/m^3							
	CI/SA Admixture	L/m^3							
	HRWR Admixture	L/m^3	5.85	6.50	6.50	6.50	6.50	6.50	6.50
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*
	Fly Ash		Cl C	Cl C	Cl C	Cl C	Cl C	Cl C	Cl C
	Silica Fume								
	GGBF Slag								
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m^3	1,623	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC	GHC	GHC	GHC	GHC	GHC	GHC
	SR/WR Admixture								
	AE Admixture								
	CI/SA Admixture								
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.280	0.280	0.280	0.280	0.280	0.280	0.280
	w/c		0.350	0.350	0.350	0.350	0.350	0.350	0.350
	SCM/TCM	%	20	20	20	20	20	20	20
	CA Content	%	65.4	65.4	65.4	65.4	65.4	65.4	65.4
	CA/FA		1.32	1.47	1.47	1.47	1.47	1.47	1.47
	Calculated Air Content	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Calculated Unit Weight	kg/m^3	2,445	2,428	2,428	2,428	2,428	2,428	2,428
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	24.7	22.8	20.0	14.4	18.3	16.7	23.3
	Air Temp.	C	35.0	22.8	29.4	8.3			36.1
	RH	%	46	89	38	92			42
	Initial Slump	mm							
	Final Slump	mm	100	180	170	200	170	200	200
	Measured Air Content	%					2.4	2.4	
	Measured Unit Weight	kg/m^3	2,448	2,447	2,435		2,425	2,432	2,398
	Yield	m^3	1.00	0.99	1.00		1.00	1.00	1.01

Section	Property	Unit	28^A	28^B	29	30	31	32	33
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	440.0	440.0	480.0	480.0	440.0	400.0	450.0
	Fly Ash	kg/m³	110.0	110.0	120.0	120.0	110.0	100.0	50.0
	Silica Fume	kg/m³							
	GGBF Slag	kg/m³							
	Coarse Aggregate	kg/m³	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1
	Intermediate Aggregate	kg/m³							
	Fine Aggregate	kg/m³	640.5	640.5	559.3	590.8	669.4	747.7	703.0
	Mixing Water	kg/m³	148.7	148.7	162.3	150.3	137.7	125.2	145.2
	WR Admixture	L/m³	1.65	1.65	1.80	1.80	1.65	1.50	1.50
	SR/WR Admixture	L/m³							
	AE Admixture	L/m³							
	CI/SA Admixture	L/m³							
	HRWR Admixture	L/m³	7.15	7.15	7.80	7.80	7.15	6.50	6.50
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*
	Fly Ash		Cl C	Cl C	Cl C	Cl C	Cl C	Cl C	Cl C
	Silica Fume								
	GGBF Slag								
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m³	1,623	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC	GHC	GHC	GHC	GHC	GHC	GHC
	SR/WR Admixture								
	AE Admixture								
	CI/SA Admixture								
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.280	0.280	0.280	0.260	0.260	0.260	0.300
	w/c		0.350	0.350	0.350	0.325	0.325	0.325	0.333
	SCM/TCM	%	20	20	20	20	20	20	10
	CA Content	%	65.4	65.4	65.4	65.4	65.4	65.4	65.4
	CA/FA		1.66	1.66	1.90	1.80	1.59	1.42	1.51
	Calculated Air Content	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Calculated Unit Weight	kg/m³	2,412	2,412	2,395	2,415	2,430	2,445	2,420
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	22.5	22.8	19.4	19.7	22.8	23.3	22.2
	Air Temp.	C	25.6	28.9	18.9	18.9	31.7	28.9	23.3
	RH	%	82	51	96	81	29		88
	Initial Slump	mm							
	Final Slump	mm	230	220	250	190	120	10	210
	Measured Air Content	%							
	Measured Unit Weight	kg/m³	2,427	2,424	2,425	2,430	2,433	2,429	2,426
	Yield	m³	0.99	0.99	0.99	0.99	1.00	1.01	1.00

			34^{A}	34^{B}	35	36	37	38^{A}	38^{B}
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m^3	450.0	450.0	495.0	495.0	400.0	450.0	450.0
	Fly Ash	kg/m^3	50.0	50.0	55.0	55.0			
	Silica Fume	kg/m^3							
	GGBF Slag	kg/m^3							
	Coarse Aggregate	kg/m^3	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1
	Intermediate Aggregate	kg/m^3							
	Fine Aggregate	kg/m^3	729.3	729.3	620.2	649.1	853.8	769.2	769.2
	Mixing Water	kg/m^3	135.2	135.2	159.7	148.7	124.2	139.7	139.7
	WR Admixture	L/m^3	1.50	1.50	1.65	1.65	1.20	1.35	1.35
	SR/WR Admixture	L/m^3							
	AE Admixture	L/m^3							
	CI/SA Admixture	L/m^3							
	HRWR Admixture	L/m^3	6.50	6.50	7.15	7.15	5.20	5.85	5.85
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*
	Fly Ash		Cl C	Cl C	Cl C	Cl C			
	Silica Fume								
	GGBF Slag								
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m^3	1,623	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC	GHC	GHC	GHC	GHC	GHC	GHC
	SR/WR Admixture								
	AE Admixture								
	CI/SA Admixture								
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.280	0.280	0.300	0.280	0.320	0.320	0.320
	w/c		0.311	0.311	0.333	0.311	0.320	0.320	0.320
	SCM/TCM	%	10	10	10	10	0	0	0
	CA Content	%	65.4	65.4	65.4	65.4	65.4	65.4	65.4
	CA/FA		1.46	1.46	1.71	1.64	1.24	1.38	1.38
	Calculated Air Content	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Calculated Unit Weight	kg/m^3	2,436	2,436	2,403	2,420	2,448	2,430	2,430
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	24.4	15.0	22.2	17.8	15.0	20.0	17.8
	Air Temp.	C	27.2		18.9	13.3	12.8	17.2	17.2
	RH	%	78		68	52	44	72	39
	Initial Slump	mm							
	Final Slump	mm	150	80	220	100	60	70	130
	Measured Air Content	%							
	Measured Unit Weight	kg/m^3	2,419	2,425	2,431	2,417	2,423	2,421	2,427
	Yield	m^3	1.01	1.00	0.99	1.00	1.01	1.00	1.00

Section	Property	Unit	39	40	41	42	43	44	45[A]
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	500.0	400.0	400.0	400.0	400.0	400.0	400.0
	Fly Ash	kg/m³		100.0	100.0	100.0	100.0	100.0	100.0
	Silica Fume	kg/m³							
	GGBF Slag	kg/m³							
	Coarse Aggregate	kg/m³	1,062.1	1,062.1	1,062.1	1,062.1	898.7	980.4	1,143.8
	Intermediate Aggregate	kg/m³							
	Fine Aggregate	kg/m³	684.5	609.9	637.7	662.5	882.3	801.8	640.9
	Mixing Water	kg/m³	155.2	131.6	132.5	111.6	135.2	135.2	135.2
	WR Admixture	L/m³	1.50	1.50	1.50	1.50	1.50	1.50	1.50
	SR/WR Admixture	L/m³							
	AE Admixture	L/m³		6.00	4.50	6.00			
	CI/SA Admixture	L/m³							
	HRWR Admixture	L/m³	6.50	6.50	6.50	6.50	6.50	6.50	6.50
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*
	Fly Ash			Cl C	Cl C	Cl C	Cl C	Cl C	Cl C
	Silica Fume								
	GGBF Slag								
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m³	1,623	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC	GHC	GHC	GHC	GHC	GHC	GHC
	SR/WR Admixture								
	AE Admixture			GDV	GDV	GDV			
	CI/SA Admixture								
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.320	0.280	0.280	0.240	0.280	0.280	0.280
	w/c		0.320	0.350	0.350	0.300	0.350	0.350	0.350
	SCM/TCM	%	0	20	20	20	20	20	20
	CA Content	%	65.4	65.4	65.4	65.4	55.4	60.4	70.5
	CA/FA		1.55	1.74	1.67	1.60	1.02	1.22	1.78
	Calculated Air Content	%	2.00	6.00	5.00	6.00	2.00	2.00	2.00
	Calculated Unit Weight	kg/m³	2,411	2,320	2,347	2,353	2,426	2,427	2,430
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	23.9	17.2	18.3	18.3	18.9	16.7	18.9
	Air Temp.	C	23.9	16.1					
	RH	%	55	50					
	Initial Slump	mm							
	Final Slump	mm	200	240	240	10	140	150	200
	Measured Air Content	%		6.3				2.2	1.4
	Measured Unit Weight	kg/m³	2,418	2,264	2,282	2,402	2,408	2,421	2,435
	Yield	m³	1.00	1.02	1.03	0.98	1.01	1.00	1.00

Section	Property	Unit	45^B	46^A	46^B	47	48	49	50
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	400.0	400.0	400.0	400.0	400.0	500.0	500.0
	Fly Ash	kg/m³	100.0	100.0	100.0	100.0	100.0		
	Silica Fume	kg/m³							
	GGBF Slag	kg/m³							
	Coarse Aggregate	kg/m³	1,143.8	1,225.5	1,225.5	1,004.3	1,004.9	1,062.1	1,062.1
	Intermediate Aggregate	kg/m³							
	Fine Aggregate	kg/m³	640.9	560.4	560.4	751.7	781.4	599.3	627.2
	Mixing Water	kg/m³	135.2	135.2	135.2	135.2	135.2	141.6	142.5
	WR Admixture	L/m³	1.50	1.50	1.50	1.50	1.50	1.50	1.50
	SR/WR Admixture	L/m³							
	AE Admixture	L/m³						6.00	4.50
	CI/SA Admixture	L/m³							
	HRWR Admixture	L/m³	6.50	6.50	6.50	6.50	6.50	6.50	6.50
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*
	Fly Ash		Cl C	Cl C	Cl C	Cl C	Cl C		
	Silica Fume								
	GGBF Slag								
	CA Type & Grading		LI8	LI8	LI8	GNq	RH7	LI8	LI8
	CA SG		2.67	2.67	2.67	2.62	2.71	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	0.5	1.4	1.2	1.2
	CA DRUW	kg/m³	1,623	1,623	1,623	1,538	1,525	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC	GHC	GHC	GHC	GHC	GHC	GHC
	SR/WR Admixture								
	AE Admixture							GDV	GDV
	CI/SA Admixture								
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.280	0.280	0.280	0.280	0.280	0.300	0.300
	w/c		0.350	0.350	0.350	0.350	0.350	0.300	0.300
	SCM/TCM	%	20	20	20	20	20	0	0
	CA Content	%	70.5	75.5	75.5	65.3	65.9	65.4	65.4
	CA/FA		1.78	2.19	2.19	1.34	1.29	1.77	1.69
	Calculated Air Content	%	2.00	2.00	2.00	2.29	2.42	6.00	5.00
	Calculated Unit Weight	kg/m³	2,430	2,431	2,431	2,401	2,431	2,320	2,347
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	23.3	17.8	18.3	18.9	16.7	18.3	17.2
	Air Temp.	C	35.6						
	RH	%	40						
	Initial Slump	mm							
	Final Slump	mm	170	200	200	170	140	220	220
	Measured Air Content	%		2.1	1.7	2.6	2.5	8.6	6.7
	Measured Unit Weight	kg/m³		2,423	2,438	2,396	2,424	2,225	2,284
	Yield	m³		1.00	1.00	1.00	1.00	1.04	1.03

Section	Property	Unit	51	52	53	54^A	54^B	55	56
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	500.0	400.0	400.0	450.0	450.0	475.0	462.5
	Fly Ash	kg/m³		100.0	100.0				
	Silica Fume	kg/m³				50.0	50.0	25.0	37.5
	GGBF Slag	kg/m³							
	Coarse Aggregate	kg/m³	1,062.1	927.0	927.6	1,062.1	1,062.1	1,062.1	1,062.1
	Intermediate Aggregate	kg/m³							
	Fine Aggregate	kg/m³	651.9	829.9	857.3	692.8	692.8	701.8	697.3
	Mixing Water	kg/m³	121.6	135.2	135.2	145.2	145.2	145.2	145.2
	WR Admixture	L/m³	1.50	1.50	1.50	1.50	1.50	1.50	1.50
	SR/WR Admixture	L/m³							
	AE Admixture	L/m³	6.00						
	CI/SA Admixture	L/m³							
	HRWR Admixture	L/m³	6.50	6.50	6.50	6.50	6.50	6.50	6.50
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*
	Fly Ash			Cl C	Cl C				
	Silica Fume					GF10	GF10	GF10	GF10
	GGBF Slag								
	CA Type & Grading		LI8	GNq	RH7	LI8	LI8	LI8	LI8
	CA SG		2.67	2.62	2.71	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	0.5	1.4	1.2	1.2	1.2	1.2
	CA DRUW	kg/m³	1,623	1,538	1,525	1,623	1,623	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC	GHC	GHC	GHC	GHC	GHC	GHC
	SR/WR Admixture								
	AE Admixture		GDV						
	CI/SA Admixture								
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.260	0.280	0.280	0.300	0.300	0.300	0.300
	w/c		0.260	0.350	0.350	0.333	0.333	0.316	0.324
	SCM/TCM	%	0	20	20	10	10	5	7.5
	CA Content	%	65.4	60.3	60.8	65.4	65.4	65.4	65.4
	CA/FA		1.63	1.12	1.08	1.53	1.53	1.51	1.52
	Calculated Air Content	%	6.00	2.27	2.38	2.00	2.00	2.00	2.00
	Calculated Unit Weight	kg/m³	2,352	2,402	2,430	2,410	2,410	2,419	2,414
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	18.3	18.3	19.4	23.9	23.9	22.8	28.3
	Air Temp.	C							
	RH	%							
	Initial Slump	mm							
	Final Slump	mm	0	190	150	80	80	120	110
	Measured Air Content	%		2.8	2.8	1.8	1.7	1.6	1.8
	Measured Unit Weight	kg/m³	2,427	2,389	2,435	2,411	2,405	2,415	2,428
	Yield	m³	0.97	1.01	1.00	1.00	1.00	1.00	0.99

			57	58	59	60	61	62	63
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	425.0	412.5	425.0	412.5	475.0	462.5	425.0
	Fly Ash	kg/m³	50.0	50.0					50.0
	Silica Fume	kg/m³	25.0	37.5	25.0	37.5	25.0	37.5	25.0
	GGBF Slag	kg/m³			50.0	50.0			
	Coarse Aggregate	kg/m³	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1	1,062.1
	Intermediate Aggregate	kg/m³							
	Fine Aggregate	kg/m³	720.3	715.8	698.2	693.7	728.1	723.6	746.5
	Mixing Water	kg/m³	135.2	135.2	145.2	145.2	135.2	135.2	125.2
	WR Admixture	L/m³	1.50	1.50	1.50	1.50	1.50	1.50	1.50
	SR/WR Admixture	L/m³							
	AE Admixture	L/m³							
	CI/SA Admixture	L/m³							
	HRWR Admixture	L/m³	6.50	6.50	6.50	6.50	6.50	6.50	6.50
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*	HM *III*
	Fly Ash		Cl C	Cl C					Cl C
	Silica Fume		GF10	GF10	GF10	GF10	GF10	GF10	GF10
	GGBF Slag				Gr 120	Gr 120			
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m³	1,623	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC	GHC	GHC	GHC	GHC	GHC	GHC
	SR/WR Admixture								
	AE Admixture								
	CI/SA Admixture								
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.280	0.280	0.300	0.300	0.280	0.280	0.260
	w/c		0.329	0.339	0.353	0.364	0.295	0.303	0.306
	SCM/TCM	%	15	17.5	15	17.5	5	7.5	15
	CA Content	%	65.4	65.4	65.4	65.4	65.4	65.4	65.4
	CA/FA		1.47	1.48	1.52	1.53	1.46	1.47	1.42
	Calculated Air Content	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Calculated Unit Weight	kg/m³	2,427	2,423	2,415	2,411	2,435	2,431	2,443
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	25.6	23.9	20.0	19.4	24.4	23.3	18.9
	Air Temp.	C							
	RH	%							
	Initial Slump	mm							
	Final Slump	mm	110	130	150	160	70	70	40
	Measured Air Content	%	2.1						
	Measured Unit Weight	kg/m³	2,417	2,399	2,421	2,407	2,434	2,423	2,433
	Yield	m³	1.00	1.01	1.00	1.00	1.00	1.00	1.00

			64	65	66	67	68	69	70
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m^3	412.5	467.5	510.0	400.0	450.0	510.0	510.0
	Fly Ash	kg/m^3	50.0	55.0	60.0	100.0	50.0	60.0	60.0
	Silica Fume	kg/m^3	37.5	27.5	30.0			30.0	30.0
	GGBF Slag	kg/m^3							
	Coarse Aggregate	kg/m^3	1,062.1	1,062.1	1,062.1	817.0	1,062.1	980.4	980.4
	Intermediate Aggregate	kg/m^3							
	Fine Aggregate	kg/m^3	742.0	668.1	621.0	962.8	751.9	673.9	705.4
	Mixing Water	kg/m^3	125.2	137.7	138.3	135.2	123.1	152.4	140.4
	WR Admixture	L/m^3	1.50	1.65	1.80	1.50	1.50		
	SR/WR Admixture	L/m^3							
	AE Admixture	L/m^3							
	CI/SA Admixture	L/m^3							
	HRWR Admixture	L/m^3	6.50	7.15	7.80	6.50	10.00	6.00	6.00
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	HM *III*	HM *III*	AC *III*	AC *III*	AC *III*
	Fly Ash		Cl C	Cl C	Cl C	Cl C	Cl C	Cl C	Cl C
	Silica Fume		GF10	GF10	GF10			GF10	GF10
	GGBF Slag								
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m^3	1,623	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC	GHC	GHC	GHC	GHC		
	SR/WR Admixture								
	AE Admixture								
	CI/SA Admixture								
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GAF	GAF
MIX DESCRIPTION	w/cm		0.260	0.260	0.240	0.280	0.260	0.260	0.240
	w/c		0.315	0.306	0.282	0.350	0.289	0.306	0.282
	SCM/TCM	%	17.5	15	15	20	10	15	15
	CA Content	%	65.4	65.4	65.4	50.3	65.4	60.4	60.4
	CA/FA		1.43	1.59	1.71	0.85	1.41	1.45	1.39
	Calculated Air Content	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Calculated Unit Weight	kg/m^3	2,439	2,428	2,433	2,425	2,451	2,414	2,433
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	18.9	28.9	28.9	26.7	25.0	21.1	18.9
	Air Temp.	C				35.6	38.3	18.9	17.8
	RH	%				40	45	68	78
	Initial Slump	mm							
	Final Slump	mm	40	80	60	210	210	210	130
	Measured Air Content	%							
	Measured Unit Weight	kg/m^3	2,427	2,425	2,426	2,375			
	Yield	m^3	1.00	1.00	1.00	1.02			

			71	72	73	74	75	76	77
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m^3	510.0	510.0	510.0	510.0	510.0	510.0	510.0
	Fly Ash	kg/m^3	60.0	60.0	60.0	60.0	60.0	60.0	60.0
	Silica Fume	kg/m^3	30.0	30.0	30.0	30.0	30.0	30.0	30.0
	GGBF Slag	kg/m^3							
	Coarse Aggregate	kg/m^3	980.4	980.4	980.4	980.4	980.4	980.4	980.4
	Intermediate Aggregate	kg/m^3							
	Fine Aggregate	kg/m^3	656.0	654.2	685.7	645.2	636.3	625.2	624.4
	Mixing Water	kg/m^3	139.2	138.1	126.1	131.5	124.9	117.3	151.2
	WR Admixture	L/m^3		1.80	1.80	1.80	1.80	1.80	1.80
	SR/WR Admixture	L/m^3							
	AE Admixture	L/m^3							
	CI/SA Admixture	L/m^3	20.0	20.0	20.0	30.0	40.0	50.0	20.0
	HRWR Admixture	L/m^3	6.00	6.00	6.00	6.00	6.00	7.80	4.20
MATERIALS	Cement Brand & Type		AC *III*	AC *III*	AC *III*	AC *III*	AC *III*	AC *III*	AC *III*
	Fly Ash		Cl C	Cl C	Cl C	Cl C	Cl C	Cl C	Cl C
	Silica Fume		GF10	GF10	GF10	GF10	GF10	GF10	GF10
	GGBF Slag								
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m^3	1,623	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture			GHC	GHC	GHC	GHC	GHC	GHC
	SR/WR Admixture								
	AE Admixture								
	CI/SA Admixture		GDCI	GDCI	GDCI	GDCI	GDCI	GDCI	GDCI
	HRWR Admixture		GAF	GAF	GAF	GAF	GAF	GAF	GAF
MIX DESCRIPTION	w/cm		0.260	0.260	0.240	0.260	0.260	0.260	0.280
	w/c		0.306	0.306	0.282	0.306	0.306	0.306	0.329
	SCM/TCM	%	15	15	15	15	15	15	15
	CA Content	%	60.4	60.4	60.4	60.4	60.4	60.4	60.4
	CA/FA		1.49	1.50	1.43	1.52	1.54	1.57	1.57
	Calculated Air Content	%	2.00	2.00	2.00	2.00	2.00	2.00	2.00
	Calculated Unit Weight	kg/m^3	2,407	2,406	2,426	2,402	2,399	2,394	2,387
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	17.8	12.8	18.3		20.0		15.6
	Air Temp.	C	20.0	7.8	15.6	17.2	15.6	14.4	12.2
	RH	%	80	43	30	32	39	44	42
	Initial Slump	mm							
	Final Slump	mm	230	240	100	250		250	280
	Measured Air Content	%							
	Measured Unit Weight	kg/m^3							
	Yield	m^3							

Section	Property	Unit	78	79^A	79^B	80	81	82	83
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	510.0	510.0	510.0	593.1	504.1	510.0	474.5
	Fly Ash	kg/m³	60.0	60.0	60.0		59.3	60.0	118.6
	Silica Fume	kg/m³	30.0	30.0	30.0		29.7	30.0	
	GGBF Slag	kg/m³							
	Coarse Aggregate	kg/m³	980.4	980.4	980.4	1,062.1	980.4	980.4	1,008.3
	Intermediate Aggregate	kg/m³							
	Fine Aggregate	kg/m³	733.0	701.5	701.5	597.3	657.8	656.0	622.8
	Mixing Water	kg/m³	126.3	138.3	138.3	130.9	130.9	139.2	166.1
	WR Admixture	L/m³	1.80	1.80	1.80	2.32	2.32	1.80	
	SR/WR Admixture	L/m³							0.89
	AE Admixture	L/m³							
	CI/SA Admixture	L/m³				29.7	29.7	20.0	
	HRWR Admixture	L/m³	7.80	7.80	7.80	3.87	3.87	4.20	8.36
MATERIALS	Cement Brand & Type		AC *III*	AC *III*	AC *III*	AC *III*	AC *III*	AC *III*	HM *III*
	Fly Ash		Cl C	Cl C	Cl C		Cl C	Cl C	Cl C
	Silica Fume		GF10	GF10	GF10		GF10	GF10	
	GGBF Slag								
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m³	1,623	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC	GHC	GHC	GHC	GHC	GHC	
	SR/WR Admixture								GD17
	AE Admixture								
	CI/SA Admixture					GDCI	GDCI	GDCI	
	HRWR Admixture		GAF	GAF	GAF	GAF	GAF	GAF	GD19
MIX DESCRIPTION	w/cm		0.220	0.240	0.240	0.260	0.260	0.260	0.289
	w/c		0.259	0.282	0.282	0.260	0.306	0.306	0.362
	SCM/TCM	%	15	15	15	0	15	15	20
	CA Content	%	60.4	60.4	60.4	65.4	60.4	60.4	62.1
	CA/FA		1.34	1.40	1.40	1.78	1.49	1.49	1.62
	Calculated Air Content	%	2.00	2.00	2.00	2.00	2.00	2.00	1.48
	Calculated Unit Weight	kg/m³	2,451	2,432	2,432	2,426	2,405	2,407	2,401
FRESH CONCRETE PROPERTIES	Concrete Temp.	C		10.0		18.3	19.4		32.2
	Air Temp.	C	14.4	7.8	23.3		19.4	23.3	
	RH	%	37	64	41		22	41	
	Initial Slump	mm							0
	Final Slump	mm	10		230	40	120	100	130
	Measured Air Content	%							
	Measured Unit Weight	kg/m³							
	Yield	m³							

			84	85	86	87	88	89	90
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	474.5	474.5	474.5	474.5	474.5	474.5	474.5
	Fly Ash	kg/m³	118.6	166.1	166.1	166.1	166.1	166.1	166.1
	Silica Fume	kg/m³							
	GGBF Slag	kg/m³							
	Coarse Aggregate	kg/m³	1,008.3	1,029.1	1,029.1	1,029.1	1,029.1	1,067.6	1,067.6
	Intermediate Aggregate	kg/m³							
	Fine Aggregate	kg/m³	622.8	521.9	521.9	521.9	521.9	521.9	521.9
	Mixing Water	kg/m³	166.1	177.9	177.9	177.9	177.9	160.1	160.1
	WR Admixture	L/m³							
	SR/WR Admixture	L/m³	1.16	1.25	2.09	1.25	1.25	1.25	1.25
	AE Admixture	L/m³							
	CI/SA Admixture	L/m³							
	HRWR Admixture	L/m³	9.67	9.19	7.10	5.85	4.18	4.18	5.01
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	AM *I*	AM *I*	AM *I*	AM *I*	AM *I*
	Fly Ash		Cl C	Cl C	Cl C	Cl C	Cl C	Cl C	Cl C
	Silica Fume								
	GGBF Slag								
	CA Type & Grading		LI8	LI67	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m³	1,623	1,621	1,623	1,623	1,623	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture								
	SR/WR Admixture		GD17	GD17	GD17	GD17	GD17	GD17	GD17
	AE Admixture								
	CI/SA Admixture								
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.291	0.287	0.286	0.284	0.283	0.255	0.256
	w/c		0.364	0.388	0.387	0.384	0.382	0.344	0.345
	SCM/TCM	%	20	25.9	25.9	25.9	25.9	25.9	25.9
	CA Content	%	62.1	63.5	63.4	63.4	63.4	65.8	65.8
	CA/FA		1.62	1.97	1.97	1.97	1.97	2.05	2.05
	Calculated Air Content	%	1.32	1.45	1.57	1.78	1.95	2.29	2.20
	Calculated Unit Weight	kg/m³	2,403	2,382	2,381	2,378	2,376	2,397	2,398
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	29.4	28.9	25.0	30.6	23.9		
	Air Temp.	C							
	RH	%							
	Initial Slump	mm	0	0	70	20	40		0
	Final Slump	mm	230	230	230	230	230		230
	Measured Air Content	%		1.3	0.9	0.5	1.0		
	Measured Unit Weight	kg/m³		2,430	2,419	2,430	2,395		
	Yield	m³		0.98	0.98	0.98	0.99		

			91A	91B	92A	92B	92C	93	94
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	474.5	474.5	474.5	474.5	474.5	474.5	462.6
	Fly Ash	kg/m³	166.1	166.1	166.1	166.1	166.1	166.1	130.5
	Silica Fume	kg/m³							
	GGBF Slag	kg/m³							
	Coarse Aggregate	kg/m³	1,008.3	1,008.3	1,039.7	1,039.7	1,039.7	1,039.7	1,008.3
	Intermediate Aggregate	kg/m³							
	Fine Aggregate	kg/m³	581.3	581.3	526.1	526.1	526.1	526.1	652.4
	Mixing Water	kg/m³	160.1	160.1	177.3	177.3	177.3	187.4	163.1
	WR Admixture	L/m³						1.38	2.67
	SR/WR Admixture	L/m³	1.25	1.25	1.25	1.25	1.25		
	AE Admixture	L/m³							
	CI/SA Admixture	L/m³							
	HRWR Admixture	L/m³	5.01	5.01	2.92	2.92	2.92	3.58	4.18
MATERIALS	Cement Brand & Type		AM *I*	AM *I*	AM *I*	AM *I*	AM *I*	HM *III*	HM *III*
	Fly Ash		Cl C	Cl C	Cl C	Cl C	Cl C	Cl C	Cl C
	Silica Fume								
	GGBF Slag								
	CA Type & Grading		RH7	RH7	LI67	LI67	LI67	LI8	LI8
	CA SG		2.71	2.71	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.4	1.4	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m³	1,525	1,525	1,621	1,621	1,621	1,623	1,623
	IA Type								
	IA SG								
	IA Absorption	%							
	IA Fineness Modulus								
	FA Type		DS	DS	DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5	2.5	2.5
	WR Admixture							GHC	GHC
	SR/WR Admixture		GD17	GD17	GD17	GD17	GD17		
	AE Admixture								
	CI/SA Admixture								
	HRWR Admixture		GD19	GD19	GD19	GD19	GD19	GD19	GD19
MIX DESCRIPTION	w/cm		0.256	0.256	0.281	0.281	0.281	0.297	0.282
	w/c		0.345	0.345	0.379	0.379	0.379	0.401	0.361
	SCM/TCM	%	25.9	25.9	25.9	25.9	25.9	25.9	22
	CA Content	%	66.1	66.1	64.1	64.1	64.1	64.1	62.1
	CA/FA		1.73	1.73	1.98	1.98	1.98	1.98	1.55
	Calculated Air Content	%	2.72	2.72	1.58	1.58	1.58	0.49	0.82
	Calculated Unit Weight	kg/m³	2,398	2,398	2,389	2,389	2,389	2,400	2,425
FRESH CONCRETE PROPERTIES	Concrete Temp.	C						27.8	33.3
	Air Temp.	C						23.9	31.7
	RH	%						63	64
	Initial Slump	mm	0	0					
	Final Slump	mm	230	230					260
	Measured Air Content	%							
	Measured Unit Weight	kg/m³							
	Yield	m³							

			95	96	98	99	100	101	102
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	415.2	462.6	510.0	510.0	510.0	510.0	510.0
	Fly Ash	kg/m³	237.2	130.5	60.0	60.0	60.0	60.0	60.0
	Silica Fume	kg/m³			30.0	30.0	30.0	30.0	30.0
	GGBF Slag	kg/m³							
	Coarse Aggregate	kg/m³	919.3	1,067.6	980.4	980.4	980.4	980.4	980.4
	Intermediate Aggregate	kg/m³		533.8					
	Fine Aggregate	kg/m³	593.1		622.6	515.8	547.4	578.9	545.8
	Mixing Water	kg/m³	184.5	180.9	150.1	149.2	137.2	125.2	136.3
	WR Admixture	L/m³	2.67	1.55	1.80	1.80	1.80	1.80	1.80
	SR/WR Admixture	L/m³							
	AE Admixture	L/m³				1.50	1.50	1.50	3.00
	CI/SA Admixture	L/m³			20.0	20.0	20.0	20.0	20.0
	HRWR Admixture	L/m³	4.31	6.19	6.00	6.00	6.00	6.00	6.00
MATERIALS	Cement Brand & Type		HM *III*	HM *III*	AC *III*	AC *III*	AC *III*	AC *III*	AC *III*
	Fly Ash		Cl C	Cl C	Cl C	Cl C	Cl C	Cl C	Cl C
	Silica Fume				GF10	GF10	GF10	GF10	GF10
	GGBF Slag								
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m³	1,623	1,623	1,623	1,623	1,623	1,623	1,623
	IA Type			LS					
	IA SG			2.67					
	IA Absorption	%		1.0					
	IA Fineness Modulus			4.7					
	FA Type		DS		DS	DS	DS	DS	DS
	FA SG		2.63		2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7		0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5		2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC	GHC	GHC	GHC	GHC	GHC	GHC
	SR/WR Admixture								
	AE Admixture					GDV	GDV	GDV	GDV
	CI/SA Admixture				GDCI	GDCI	GDCI	GDCI	GDCI
	HRWR Admixture		GD19	GD19	GAF	GAF	GAF	GAF	GAF
MIX DESCRIPTION	w/cm		0.289	0.313	0.280	0.280	0.260	0.240	0.260
	w/c		0.454	0.401	0.329	0.329	0.306	0.282	0.306
	SCM/TCM	%	36.4	22	15	15	15	15	15
	CA Content	%	56.6	65.8	60.4	60.4	60.4	60.4	60.4
	CA/FA		1.55		1.57	1.90	1.79	1.69	1.80
	Calculated Air Content	%	1.74	1.55	2.00	6.00	6.00	6.00	6.00
	Calculated Unit Weight	kg/m³	2,358	2,385	2,386	2,281	2,300	2,320	2,299
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	30.6	31.1	23.0	23.0	26.7	26.7	25.0
	Air Temp.	C	29.4						22.2
	RH	%	47						87
	Initial Slump	mm							
	Final Slump	mm			270	280	250	220	260
	Measured Air Content	%			2.0	6.4	3.0	2.2	6.1
	Measured Unit Weight	kg/m³			2,418	2,312	2,407		2,346
	Yield	m³			0.99	0.99	0.96		0.98

Section	Property	Unit	103	P/P 5	P/P 27	P/P 65	P/P 72
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m^3	510.0	550.0	400.0	467.5	510.0
	Fly Ash	kg/m^3	60.0		100.0	55.0	60.0
	Silica Fume	kg/m^3	30.0			27.5	30.0
	GGBF Slag	kg/m^3					
	Coarse Aggregate	kg/m^3	980.4	1,062.1	1,062.1	1,062.1	980.4
	Intermediate Aggregate	kg/m^3					
	Fine Aggregate	kg/m^3	575.8	629.4	721.4	668.1	654.2
	Mixing Water	kg/m^3	123.4	159.5	135.2	137.7	138.1
	WR Admixture	L/m^3	1.80				1.80
	SR/WR Admixture	L/m^3		1.65	1.50	1.65	
	AE Admixture	L/m^3	4.50				
	CI/SA Admixture	L/m^3	20.0				20.0
	HRWR Admixture	L/m^3	6.00	7.15	6.50	7.15	6.00
MATERIALS	Cement Brand & Type		AC *III*	HM *III*	HM *III*	HM *III*	AC *III*
	Fly Ash		Cl C		Cl C	Cl C	Cl C
	Silica Fume		GF10			GF10	GF10
	GGBF Slag						
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m^3	1,623	1,623	1,623	1,623	1,623
	IA Type						
	IA SG						
	IA Absorption	%					
	IA Fineness Modulus						
	FA Type		DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC				GHC
	SR/WR Admixture			GD17	GD17	GD17	
	AE Admixture		GDV				
	CI/SA Admixture		GDCI				GDCI
	HRWR Admixture		GAF	GD19	GD19	GD19	GAF
MIX DESCRIPTION	w/cm		0.240	0.300	0.280	0.260	0.260
	w/c		0.282	0.300	0.350	0.306	0.306
	SCM/TCM	%	15	0	20	15	15
	CA Content	%	60.4	65.4	65.4	65.4	60.4
	CA/FA		1.70	1.69	1.47	1.59	1.50
	Calculated Air Content	%	6.00	2.00	2.00	2.00	2.00
	Calculated Unit Weight	kg/m^3	2,318	2,412	2,428	2,428	2,406
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	26.1	34.4	35.0	33.9	30.0
	Air Temp.	C	21.7		35.6		27.8
	RH	%	92		77		50
	Initial Slump	mm					
	Final Slump	mm	190	90	210	10	40
	Measured Air Content	%	8.0	3.5	1.8	4.0	2.4
	Measured Unit Weight	kg/m^3	2,266	2,412	2,450	2,425	2,444
	Yield	m^3	1.02	1.00	0.99	1.00	0.98

			P/P 97	P/P 98	P/P 99	P/P 100	P/P 104
MIX PROPORTIONS (SSD AGGREGATES) FOR ONE CUBIC METER OF CONCRETE	Cement	kg/m³	510.0	510.0	510.0	510.0	510.0
	Fly Ash	kg/m³	60.0	60.0	60.0	60.0	60.0
	Silica Fume	kg/m³	30.0	30.0	30.0	30.0	30.0
	GGBF Slag	kg/m³					
	Coarse Aggregate	kg/m³	980.4	980.4	980.4	980.4	980.4
	Intermediate Aggregate	kg/m³					
	Fine Aggregate	kg/m³	701.5	622.6	515.8	547.4	622.6
	Mixing Water	kg/m³	153.1	150.1	149.2	137.2	161.7
	WR Admixture	L/m³	1.80	1.80	1.80	1.80	1.80
	SR/WR Admixture	L/m³					
	AE Admixture	L/m³			1.50	1.50	
	CI/SA Admixture	L/m³		20.0	20.0	20.0	20.0
	HRWR Admixture	L/m³	8.80	6.00	6.00	6.00	6.00
MATERIALS	Cement Brand & Type		AC *III*	AC *III*	AC *III*	AC *III*	AC *III*
	Fly Ash		Cl C	Cl C	Cl C	Cl C	Cl C
	Silica Fume		GF10	GF10	GF10	GF10	GF10
	GGBF Slag						
	CA Type & Grading		LI8	LI8	LI8	LI8	LI8
	CA SG		2.67	2.67	2.67	2.67	2.67
	CA Absorption	%	1.2	1.2	1.2	1.2	1.2
	CA DRUW	kg/m³	1,623	1,623	1,623	1,623	1,623
	IA Type						
	IA SG						
	IA Absorption	%					
	IA Fineness Modulus						
	FA Type		DS	DS	DS	DS	DS
	FA SG		2.63	2.63	2.63	2.63	2.63
	FA Absorption	%	0.7	0.7	0.7	0.7	0.7
	FA Fineness Modulus		2.5	2.5	2.5	2.5	2.5
	WR Admixture		GHC	GHC	GHC	GHC	GHC
	SR/WR Admixture						
	AE Admixture				GDV	GDV	
	CI/SA Admixture			GDCI	GDCI	GDCI	GDCI
	HRWR Admixture		GAF	GAF	GAF	GAF	GAF
MIX DESCRIPTION	w/cm		0.266	0.280	0.280	0.260	0.299
	w/c		0.313	0.329	0.329	0.306	0.352
	SCM/TCM	%	15	15	15	15	15
	CA Content	%	60.4	60.4	60.4	60.4	60.4
	CA/FA		1.40	1.57	1.90	1.79	1.57
	Calculated Air Content	%	0.42	2.00	6.00	6.00	0.84
	Calculated Unit Weight	kg/m³	2,448	2,386	2,281	2,300	2,398
FRESH CONCRETE PROPERTIES	Concrete Temp.	C	29.4	34.4	35.0	32.8	31.7
	Air Temp.	C	27.8	33.9	33.9	30.0	30.0
	RH	%	45	52	52	60	60
	Initial Slump	mm					
	Final Slump	mm	190	150	100	80	290
	Measured Air Content	%	2.4	4.5	6.1	4.3	
	Measured Unit Weight	kg/m³	2,418	2,344	2,261	2,373	2,412
	Yield	m³	1.01	1.02	1.01	0.97	0.99

		1		2		3		4		5	
Curing		S/M	H1/M	S/M	H1/M	S/M	H1/M	S/M	H1/M	S/M	H1/M
Cylinder Diam & End		100N	100N	100N	100N	100N	100N	100N	100N	100N	100N
Compressive	MPa	64.2	62.2	64.7	63.7	64.6	61.7	61.2	60.4	59.6	61.0
Strength		63.3	62.8	65.2	62.2	62.4	60.8	65.1	59.4	62.8	61.5
at 18 hrs		61.5	62.9	65.5	64.1	61.6	60.9	62.2	59.2	62.6	62.7
Average	MPa	63.0	62.6	65.1	63.3	62.9	61.1	62.8	59.7	61.7	61.7
s	MPa	1.37	0.38	0.40	1.00	1.55	0.49	2.03	0.64	1.79	0.87
Compressive	MPa	63.6	65.2	69.9	66.7	66.6	60.1	65.3	60.4	67.0	63.4
Strength		64.4	65.7	69.1	66.8	66.9	61.4	65.6	62.2	66.4	61.4
at 24 hrs		64.8	67.6	67.2	66.2		62.9	64.1	60.7	65.8	63.7
				68.5							66.0
Average	MPa	64.3	66.2	68.7	66.6	66.8	61.5	65.0	61.1	66.4	63.6
s	MPa	0.61	1.27	1.14	0.32	0.21	1.40	0.79	0.96	0.60	1.88
Compressive	MPa										
Strength											
at 3 days											
Average	MPa										
s	MPa										
Compressive	MPa										
Strength											
at 7 days											
Average	MPa										
s	MPa										
Compressive	MPa	90.2	93.2	93.7	95.2	98.4	87.3	93.0	83.6	97.3	84.6
Strength		95.6	91.4	94.1	91.6	98.9	85.4	93.0	85.8	96.2	82.3
at 28 days		94.2	90.0	95.8		97.3	88.2	93.1	82.8	92.5	83.1
			89.9				88.5				
Average	MPa	93.3	91.1	94.5	93.4	98.2	87.4	93.0	84.1	95.3	83.3
s	MPa	2.80	1.54	1.12	2.55	0.82	1.40	0.06	1.55	2.51	1.17
Compressive	MPa										
Strength											
at 56 days											
Average	MPa										
s	MPa										

		6^A		6^B	6^C	6^D		7^A		7^B
Curing		S/M	H1/M	S/M	H5/M	S/M	H5/M	S/M	H1/M	S/M
Cylinder Diam & End		100N	100N	100N	100N	100N	100N	100N	100N	100N
Compressive	MPa	62.5	59.4					55.3	54.1	
Strength		64.4	60.2					53.6	56.0	
at 18 hrs			60.7					58.4	53.3	
Average	MPa	63.5	60.1					55.8	54.5	
s	MPa	1.34	0.66					2.43	1.39	
Compressive	MPa	66.7	64.2	60.6	57.7	55.5	58.7	64.6	57.7	57.7
Strength		70.4	61.0	58.6	56.7	55.1	63.7	61.8	58.9	57.5
at 24 hrs		65.4	63.9	58.5	58.8	58.0	61.8	60.7	58.2	57.3
			64.6	63.8	58.4	61.4	59.4	63.0		
Average	MPa	67.5	63.4	60.4	57.9	57.5	60.9	62.5	58.3	57.5
s	MPa	2.59	1.64	2.48	0.92	2.90	2.29	1.67	0.60	0.20
Compressive	MPa									
Strength										
at 3 days										
Average	MPa									
s	MPa									
Compressive	MPa									
Strength										
at 7 days										
Average	MPa									
s	MPa									
Compressive	MPa	98.2	85.0	91.0	78.8	91.6	84.1	90.5	77.6	87.3
Strength		91.4	85.0	92.1	78.8	87.2	81.1	88.9	79.5	89.6
at 28 days		95.1	83.2	94.6	81.0	91.2	81.7	87.9	79.4	88.6
				94.8	77.4	93.1				87.7
										89.1
Average	MPa	94.9	84.4	93.1	79.0	90.8	82.3	89.1	78.8	88.5
s	MPa	3.40	1.04	1.88	1.49	2.52	1.59	1.31	1.07	0.96
Compressive	MPa			93.2	83.0	95.0	77.5			92.2
Strength				94.9	81.3	93.2	87.7			94.3
at 56 days				97.1	81.5		89.2			93.1
				99.0	81.8					93.3
					82.3					95.1
Average	MPa			96.1	82.0	94.1	84.8			93.6
s	MPa			2.53	0.68	1.27	6.37			1.12

		8		9^A		9^B	9^C	9^D	10	11	12
Curing		S/M	H1/M	S/M	H1/M	S/M	S/M	S/M	S/M	S/M	H2/A
Cylinder Diam & End		100N	100N	100N	100N	100N	100N	100N	100N	100N	100N
Compressive	MPa	54.9	56.4	64.8	62.9	58.8	59.6		58.6	53.9	
Strength		57.8	55.2	66.4	62.3	63.3	61.7		59.0	57.5	
at 18 hrs		54.3	55.0	69.7	63.6	65.3	59.3		59.6	55.6	
						61.7	62.1			55.9	
						63.8					
Average	MPa	55.7	55.5	67.0	62.9	62.6	60.7		59.1	55.7	
s	MPa	1.87	0.76	2.50	0.65	2.47	1.43		0.50	1.48	
Compressive	MPa	63.0	56.0	69.5	65.5	66.4	68.3	58.4	67.9	66.0	55.1
Strength		60.4	58.7	71.7	68.0	66.6	68.3	57.5	70.7	64.5	56.0
at 24 hrs		60.7	58.4	69.5	66.1	67.2	67.3	56.3	68.7	63.3	56.8
		62.1	58.1	74.0	67.9	68.4	70.2	56.2	68.8	67.6	
						67.5	68.0	58.8	70.5	67.3	
Average	MPa	61.6	57.8	71.2	66.9	67.2	68.4	57.4	69.3	65.7	56.0
s	MPa	1.22	1.22	2.15	1.27	0.79	1.08	1.18	1.22	1.83	0.85
Compressive	MPa									77.5	
Strength										79.2	
at 3 days										76.8	
Average	MPa									77.8	
s	MPa									1.23	
Compressive	MPa										
Strength											
at 7 days											
Average	MPa										
s	MPa										
Compressive	MPa	87.0	78.4	92.9	87.4	92.2	93.6	88.2	100.1	96.3	
Strength		84.5	77.4	91.9	87.7	92.6	92.7	89.4	101.2	95.4	
at 28 days		83.4	76.6	90.9	87.5	90.8		89.6		97.0	
								87.5			
Average	MPa	85.0	77.5	91.9	87.5	91.9	93.2	88.7	100.7	96.2	
s	MPa	1.84	0.90	1.00	0.15	0.95	0.64	1.00	0.78	0.80	
Compressive	MPa							96.4	104.9	99.9	
Strength								96.0		103.4	
at 56 days								94.7		103.3	
								97.4		101.3	
Average	MPa							96.1	104.9	102.0	
s	MPa							1.12		1.69	

		13^A	13^B		14	15			16	17	18^A
Curing		H2/A	S/M	H2/A	S/M	S/M	H1/M	H2/M	S/M	S/M	S/M
Cylinder Diam & End		100N	100N	100N	100N	100N	100N	100N	100N	100N	100N
Compressive	MPa		42.0	46.4	61.8	59.8	60.4	59.6	56.5	44.8	
Strength			44.2	47.5	62.1	62.9	59.7	60.0	59.2	42.5	
at 18 hrs			45.1	43.9	62.6	62.6	58.5	61.6	57.1	44.4	
					61.3	62.2				45.0	
Average	MPa		43.8	45.9	62.0	61.9	59.5	60.4	57.6	44.2	
s	MPa		1.59	1.84	0.54	1.41	0.96	1.06	1.42	1.14	
Compressive	MPa	46.8	49.0	47.9	67.7	65.3	60.0	64.2	65.4	52.4	67.9
Strength		46.5	47.6	52.0	66.6	63.9	61.0	62.5	65.2	54.4	68.1
at 24 hrs		46.8	48.6	48.4	66.9	67.3	62.7	64.0	64.7	53.5	64.9
				53.2	68.7		64.4	66.5	67.5	53.2	65.7
					68.4				67.9		
Average	MPa	46.7	48.4	50.4	67.7	65.5	62.0	64.3	66.1	53.4	66.7
s	MPa	0.17	0.72	2.62	0.91	1.71	1.94	1.65	1.45	0.83	1.59
Compressive	MPa										
Strength											
at 3 days											
Average	MPa										
s	MPa										
Compressive	MPa										
Strength											
at 7 days											
Average	MPa										
s	MPa										
Compressive	MPa	70.2	85.0	67.5	96.3	94.4	88.7	88.2	95.6	96.3	97.4
Strength		61.5	88.0	59.1	93.6	99.1	87.2	89.0	95.6	99.3	97.3
at 28 days		65.3	83.9	59.6	96.1	95.3	87.5	89.2	95.4	100.7	102.7
			81.8		96.0					98.7	95.3
Average	MPa	65.7	84.7	62.1	95.5	96.3	87.8	88.8	95.5	98.8	98.2
s	MPa	4.36	2.58	4.71	1.27	2.49	0.79	0.53	0.12	1.84	3.17
Compressive	MPa				99.9				98.1	105.7	103.2
Strength					101.9				96.9	106.9	105.6
at 56 days									98.6	107.4	101.7
									96.9	108.4	99.8
Average	MPa				100.9				97.6	107.1	102.6
s	MPa				1.41				0.86	1.12	2.45

		18^{B}		19	20	21	22	23	24^{A}	24^{B}	25
Curing Cylinder Diam & End		S/M 100N	H6/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N
Compressive Strength at 18 hrs	MPa	59.0 59.0	54.9 56.2	43.2 41.0 42.6 42.5							
Average	MPa	59.0	55.6	42.3							
s	MPa	0.00	0.92	0.94							
Compressive Strength at 24 hrs	MPa	58.9 62.3 66.2 62.7 61.2	56.2 60.4 64.3 58.9	52.5 52.6 52.2 53.6	61.5 63.1 61.6 62.0	56.7 56.3 57.0 56.4	58.4 56.7 56.8 58.3	53.5 54.0 55.2 54.2	58.8 60.1 59.8 60.0	62.8 59.6 57.4 59.8 60.2	48.1 45.9 48.7 48.6
Average	MPa	62.3	60.0	52.7	62.1	56.6	57.6	54.2	59.7	60.0	47.8
s	MPa	2.65	3.38	0.61	0.73	0.32	0.93	0.71	0.60	1.93	1.31
Compressive Strength at 3 days	MPa										
Average	MPa										
s	MPa										
Compressive Strength at 7 days	MPa									75.1 71.0 68.3 73.6 75.0	
Average	MPa									72.6	
s	MPa									2.92	
Compressive Strength at 28 days	MPa	88.9 90.2 86.8	74.1 76.3 71.6	100.1 97.8 97.2 100.4	94.5 96.5 99.2 99.2	96.4 94.3 93.6 94.5	90.5 94.1 93.7	92.2 90.2 95.1 96.8	96.4 93.7 94.2 96.0	91.5 85.7 89.8 84.6 86.6	93.3 89.4 92.8 91.2
Average	MPa	88.6	74.0	98.9	97.4	94.7	92.8	93.6	95.1	87.6	91.7
s	MPa	1.72	2.35	1.61	2.29	1.20	1.97	2.94	1.33	2.90	1.76
Compressive Strength at 56 days	MPa	99.8 96.8 89.9	68.3 81.4 80.6		100.4 104.4 105.6 108.4	105.1 99.6 106.3 99.5	99.2 101.6 101.2	100.9 99.7 100.4 102.2	99.8 105.1 101.8 105.0	103.1 100.0 102.2 102.3 97.8	96.7 102.1 97.0 99.2
Average	MPa	95.5	76.8		104.7	102.6	100.7	100.8	102.9	101.1	98.8
s	MPa	5.08	7.34		3.32	3.58	1.29	1.06	2.59	2.16	2.50

		26	27^{A}	27^{B}	27^{C}		27^{D}		27^{E}	
Curing		S/M	H3/M	S/M	S/M	H4/M	S/M	H5/M	S/M	H5/M
Cylinder Diam & End		100N	100N	100N	100N	100N	100N	100N	100N	100N
Compressive Strength at 18 hrs	MPa									
Average	MPa									
s	MPa									
Compressive Strength at 24 hrs	MPa	48.6	55.4	50.8	47.7	65.1	52.0	56.4	51.0	57.5
		47.8	57.2	51.6	48.2	59.7	50.2	58.3	51.6	59.5
		47.6	56.0	50.8	49.2	59.2	53.3	60.2	46.8	57.5
			57.6	51.0	49.2	54.4		57.1	49.5	58.9
Average	MPa	48.0	56.6	51.1	48.6	59.6	51.8	58.0	49.7	58.4
s	MPa	0.53	1.02	0.38	0.75	4.38	1.56	1.66	2.14	1.01
Compressive Strength at 3 days	MPa									
Average	MPa									
s	MPa									
Compressive Strength at 7 days	MPa									
Average	MPa									
s	MPa									
Compressive Strength at 28 days	MPa	91.5	96.3	94.2	94.1	66.8	92.3	79.3	90.2	80.1
		93.3	95.8	97.5	95.1	58.0	91.7	77.5	88.0	76.4
		96.4	91.8	101.3	97.3	58.6	94.8	77.6	94.2	78.3
		98.2	93.6	97.2	98.7	77.6	89.2	77.4	90.8	
									93.0	
Average	MPa	94.9	94.4	97.6	96.3	65.3	92.0	78.0	91.2	78.3
s	MPa	3.01	2.08	2.91	2.08	9.16	2.30	0.90	2.43	1.85
Compressive Strength at 56 days	MPa	100.6	105.3	102.6	95.8	70.3			99.2	85.2
		101.8	103.9	105.7	99.7	72.7				84.3
		106.7	104.3	105.2	103.6	76.3				78.9
		103.9	104.9	105.1	103.9	74.6				
Average	MPa	103.3	104.6	104.7	100.8	73.5			99.2	82.8
s	MPa	2.67	0.62	1.39	3.81	2.58				3.41

		27[F]		28[A]	28[B]	29	30	31	32	33
Curing		S/M	S/M	H3/M	S/M	S/M	S/M	S/M	S/M	S/M
Cylinder Diam & End		100N	150S	100N	100N	100N	100N	100N	100N	100N
Compressive Strength at 18 hrs	MPa									
Average	MPa									
s	MPa									
Compressive Strength at 24 hrs	MPa			57.8 58.2 57.1	49.5 49.9 48.2	49.9 49.4 48.6 51.1	54.5 55.1 54.4 54.6	56.5 53.9 55.2 54.9	54.6 54.9 56.3 56.0	52.5 51.0 52.0 51.9
Average	MPa			57.7	49.2	49.8	54.7	55.1	55.5	51.9
s	MPa			0.56	0.89	1.05	0.31	1.07	0.83	0.62
Compressive Strength at 3 days	MPa									
Average	MPa									
s	MPa									
Compressive Strength at 7 days	MPa									
Average	MPa									
s	MPa									
Compressive Strength at 28 days	MPa	91.9 89.6 88.5	85.1	93.6 91.7 91.5 94.7	94.5 98.8 96.3 99.0	96.1 96.2 96.4 97.6	98.4 101.6 102.1 102.7	97.1 96.9 98.9 99.2	97.8 101.0 99.6 102.2	91.3 91.6 92.1 92.7
Average	MPa	90.0	85.1	92.9	97.2	96.6	101.2	98.0	100.2	91.9
s	MPa	1.73		1.54	2.15	0.69	1.92	1.19	1.89	0.61
Compressive Strength at 56 days	MPa			102.4 102.3 103.7 101.1	104.0 107.5 109.9 109.7	101.4 101.8 100.6 99.0	106.6 113.4 108.5 109.6	106.7 108.1 104.8 106.6	111.3 109.2 109.3 111.6	98.9 99.5 101.1
Average	MPa			102.4	107.8	100.7	109.5	106.6	110.4	99.8
s	MPa			1.06	2.74	1.24	2.87	1.35	1.28	1.14

	34A	34B	35	36	37	38A	38B	39	40	41
Curing Cylinder Diam & End	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N
Compressive Strength at 18 hrs MPa										
Average MPa										
s MPa										
Compressive Strength at 24 hrs MPa	54.9 56.6 55.7 57.1	61.0 60.5 63.0 61.9	52.1 53.3 53.2 53.0	60.1 59.9 59.2 61.6	51.7 51.5 50.8 52.5	56.1 55.2 56.3 56.3	53.4 54.3 54.9 54.2	52.8 54.7 55.4 55.5 56.6	31.1 31.6 31.9	32.1 33.5 33.8 32.6
Average MPa	56.1	61.6	52.9	60.2	51.6	56.0	54.2	55.0	31.5	33.0
s MPa	0.97	1.10	0.55	1.01	0.70	0.53	0.62	1.41	0.40	0.79
Compressive Strength at 3 days MPa										
Average MPa										
s MPa										
Compressive Strength at 7 days MPa										
Average MPa										
s MPa										
Compressive Strength at 28 days MPa	94.0 95.7 94.0 95.9	95.1 100.2 95.7 97.0	93.1 95.1 94.5 95.8	99.8 99.7 99.5 99.4	81.9 84.9 85.2 85.2	89.0 89.4 89.6 90.2	88.5 85.8 90.0 87.6	88.5 90.1 89.0 88.3	61.0 62.4 59.8 59.7	66.3 68.3 68.3 69.9
Average MPa	94.9	97.0	94.6	99.6	84.3	89.6	88.0	89.0	60.7	68.2
s MPa	1.04	2.28	1.15	0.18	1.61	0.50	1.76	0.81	1.26	1.47
Compressive Strength at 56 days MPa	99.0 101.9 102.9 101.0	92.4 93.9 97.8 102.0	97.2 100.0 100.8 101.3	103.8 105.1 104.8 106.5	86.8 92.1 92.1 93.0	95.3 90.8 97.7 97.7	93.4 95.3 95.3 95.6	95.3 94.4 95.8	65.1 64.6 64.0 65.1	70.4 71.9 71.1 67.2
Average MPa	101.2	96.5	99.8	105.1	91.0	95.4	94.9	95.2	64.7	70.2
s MPa	1.66	4.30	1.83	1.12	2.83	3.25	1.01	0.71	0.52	2.06

		42	43	44	45^A	45^B	46^A	46^B	47	48	49
Curing Cylinder Diam & End		S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N
Compressive Strength at 18 hrs	MPa										
Average	MPa										
s	MPa										
Compressive Strength at 24 hrs	MPa	50.5 54.7 57.2 55.9	52.6 51.8 54.2 51.6	52.2 51.6 49.7 51.8	51.2 52.1 53.5 54.6	49.0 48.0 49.6 47.2	48.7 50.0 50.8 51.4	45.5 48.8 46.6 44.8	57.1 56.5 55.3	55.1 55.4 56.0 56.3	35.9 33.7 33.4 36.8
Average	MPa	54.6	52.6	51.3	52.9	48.5	50.2	46.4	56.3	55.7	35.0
s	MPa	2.90	1.18	1.11	1.50	1.06	1.17	1.75	0.92	0.55	1.66
Compressive Strength at 3 days	MPa										
Average	MPa										
s	MPa										
Compressive Strength at 7 days	MPa										
Average	MPa										
s	MPa										
Compressive Strength at 28 days	MPa	81.3 83.6 88.6 88.6	99.3 93.5 97.0 101.0 94.3	98.0 98.2 97.8 103.5 97.1	97.9 99.1 97.2 99.5 96.5	94.7 90.3 92.6 92.4 87.7	97.4 96.8 95.6 101.5	90.2 83.3 85.4 92.9 87.1	93.1 99.4 97.2 97.9 96.5	92.4 91.9 96.2 94.9 96.3	50.0 52.9 51.0 55.1
Average	MPa	85.5	97.0	98.9	98.0	91.5	97.8	87.8	96.8	94.3	52.3
s	MPa	3.67	3.19	2.59	1.26	2.65	2.56	3.82	2.34	2.08	2.25
Compressive Strength at 56 days	MPa	95.5 92.7 93.6 91.7	99.7 102.2 102.3 105.2	100.4 102.6 102.9 104.9	98.9 103.2	93.5 104.6 105.6 103.6 99.6	100.7 97.8 101.4	86.9 93.8 89.9	98.8 98.7 105.0 100.0	98.3 96.8 92.1 94.5	51.4 55.1 52.8 59.2
Average	MPa	93.4	102.4	102.7	101.1	101.4	100.0	90.2	100.6	95.4	54.6
s	MPa	1.62	2.25	1.84	3.04	4.96	1.91	3.46	2.98	2.71	3.41

		50	51	52	53	54^{A}	54^{B}	55	
Curing Cylinder Diam & End		S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	H5/M 100N
Compressive Strength at 18 hrs	MPa								
Average	MPa								
s	MPa								
Compressive Strength at 24 hrs	MPa	44.2 41.7 41.8 43.9	62.3 61.1 64.6 63.8	56.1 58.2 57.3 54.7	53.9 54.7 54.0 54.8	53.0 51.9 54.3 55.6	56.0 54.9 50.2 57.0 54.1	54.6 56.1 56.8	70.0 67.5 65.2 65.3
Average	MPa	42.9	63.0	56.6	54.4	53.7	54.4	55.8	67.0
s	MPa	1.33	1.56	1.52	0.47	1.60	2.61	1.12	2.26
Compressive Strength at 3 days	MPa								
Average	MPa								
s	MPa								
Compressive Strength at 7 days	MPa					79.2 73.5 78.5	78.3 72.4 78.6	79.5 79.1	66.6 69.9
Average	MPa					77.1	76.4	79.3	68.3
s	MPa					3.11	3.50	0.28	2.33
Compressive Strength at 28 days	MPa	61.7 68.3 64.6 61.7		93.0 100.1 91.8 88.7 89.8	95.2 89.7 93.8 92.8 93.3	95.0 83.9 97.8 93.6 92.9	91.7 95.2 99.0 92.9	95.1 91.3 98.5 99.1	70.8 76.0 74.6 72.5
Average	MPa	64.1		92.7	93.0	92.6	94.7	96.0	73.5
s	MPa	3.13		4.47	2.03	5.23	3.21	3.59	2.29
Compressive Strength at 56 days	MPa	66.1 68.4 66.9 68.3	94.4 93.4 95.8 96.4 96.0	95.6 100.2 96.4 90.6	100.1 97.8 97.2 104.0	105.5 98.0 98.8 96.1	99.0 107.6 99.3 101.1	94.7 98.5 99.0	70.3 78.0
Average	MPa	67.4	95.2	95.7	99.8	99.6	101.8	97.4	74.2
s	MPa	1.12	1.26	3.95	3.08	4.09	4.01	2.35	5.44

		56		57		58		59	
Curing		S/M	H6/M	S/M	H6/M	S/M	H6/M	S/M	H6/M
Cylinder Diam & End		100N	100N	100N	100N	100N	100N	100N	100N
Compressive	MPa	46.4	54.4	45.1	68.7	44.3	67.8	39.5	64.5
Strength		47.9	53.0	45.7	72.5	44.8	70.5	43.2	64.3
at 18 hrs									
Average	MPa	47.2	53.7	45.4	70.6	44.6	69.2	41.4	64.4
s	MPa	1.06	0.99	0.42	2.69	0.35	1.91	2.62	0.14
Compressive	MPa	52.4	55.7	53.7	77.3	47.2	72.0	49.7	69.0
Strength		53.4	60.1	48.8	76.1	54.2	71.4	43.2	67.2
at 24 hrs		53.6	52.8	48.5	71.4	48.1	75.4	48.6	65.4
					79.6				
Average	MPa	53.1	56.2	50.3	76.1	49.8	72.9	47.2	67.2
s	MPa	0.64	3.68	2.92	3.45	3.81	2.16	3.48	1.80
Compressive	MPa								
Strength									
at 3 days									
Average	MPa								
s	MPa								
Compressive	MPa	78.9	61.7	79.1	78.9	79.0	76.6	72.3	76.2
Strength		78.9	60.0	78.1	82.0	80.6		71.6	75.0
at 7 days									
Average	MPa	78.9	60.9	78.6	80.5	79.8	76.6	72.0	75.6
s	MPa	0.00	1.20	0.71	2.19	1.13		0.49	0.85
Compressive	MPa	99.8	58.9	96.3	86.5	93.0	85.9	94.3	82.6
Strength		92.1	67.5	102.6	89.1	98.1	86.9	89.8	64.4
at 28 days		93.4	64.9	93.0	86.8	98.4	77.4		67.8
Average	MPa	95.1	63.8	97.3	87.5	96.5	83.4	92.1	71.6
s	MPa	4.12	4.41	4.88	1.42	3.03	5.22	3.18	9.68
Compressive	MPa	104.4	64.3	102.1	77.5	99.7	88.0	92.7	68.6
Strength		103.7	65.5	105.2		107.3	87.5	97.2	
at 56 days								104.4	
Average	MPa	104.1	64.9	103.7	77.5	103.5	87.8	98.1	68.6
s	MPa	0.49	0.85	2.19		5.37	0.35	5.90	

		60		61		62		63		64	
Curing Cylinder Diam & End		S/M 100N	H6/M 100N	S/M 100N	H6/M 100N	S/M 100N	H6/M 100N	S/M 100N	H6/M 100N	S/M 100N	H6/M 100N
Compressive Strength at 18 hrs	MPa	44.2 42.0	51.0 53.2	49.8 53.3	56.8 57.5	50.8 51.0	61.0 61.7	50.3 55.3	61.4 63.3	51.2 50.4	66.2 61.1
Average	MPa	43.1	52.1	51.6	57.2	50.9	61.4	52.8	62.4	50.8	63.7
s	MPa	1.56	1.56	2.47	0.49	0.14	0.49	3.54	1.34	0.57	3.61
Compressive Strength at 24 hrs	MPa	44.6 50.3 49.7	53.9 52.9 44.6 50.9	60.4 64.0 59.1 61.1	75.3 71.6 71.1 63.0	59.3 62.5 56.0 61.6	65.5 62.2 62.8 62.4	60.2 59.3 62.5 61.1	80.3 69.5 66.4 65.5	57.0 63.4 59.5 61.6	62.1 67.1 67.9
Average	MPa	48.2	50.6	61.2	70.3	59.9	63.2	60.8	70.4	60.4	65.7
s	MPa	3.13	4.17	2.07	5.18	2.90	1.54	1.36	6.80	2.76	3.14
Compressive Strength at 3 days	MPa										
Average	MPa										
s	MPa										
Compressive Strength at 7 days	MPa	72.7 73.5	59.2 58.9	81.0 78.1	61.7 67.8	79.8 81.5	63.3 63.2	82.9 83.4	70.5 69.9	80.4 77.4	67.5 68.2
Average	MPa	73.1	59.1	79.6	64.8	80.7	63.3	83.2	70.2	78.9	67.9
s	MPa	0.57	0.21	2.05	4.31	1.20	0.07	0.35	0.42	2.12	0.49
Compressive Strength at 28 days	MPa	92.9 93.8 89.1	62.5 59.6	100.1 94.3 99.2	66.2 66.6 72.5	93.6 91.8 102.4	70.9 72.2	96.7 93.9 103.4	81.1 90.7	103.8 108.0 106.8 105.9	69.5 66.8
Average	MPa	91.9	61.1	97.9	68.4	95.9	71.6	98.0	85.9	106.1	68.2
s	MPa	2.49	2.05	3.12	3.53	5.67	0.92	4.88	6.79	1.77	1.91
Compressive Strength at 56 days	MPa	96.9 92.5	60.0 50.3	105.3 99.2 101.8	68.9	98.8 99.0 94.5	68.8	107.6 111.9 113.6	79.8 82.2	112.0 112.9	72.1 78.0
Average	MPa	94.7	55.2	102.1	68.9	97.4	68.8	111.0	81.0	112.5	75.1
s	MPa	3.11	6.86	3.06		2.54		3.09	1.70	0.64	4.17

		65		66		67	68	69	70	71	72
Curing		S/M	H6/M	S/M	H6/M	S/M	S/M	S/M	S/M	S/M	S/M
Cylinder Diam & End		100N	100N	100N	100N	100N	100N	100N	100N	100N	100N
Compressive	MPa	59.3	62.0	58.0							
Strength		55.3	62.1	56.9							
at 18 hrs											
Average	MPa	57.3	62.1	57.5							
s	MPa	2.83	0.07	0.78							
Compressive	MPa	58.4	75.1	66.3	77.3	47.9	0.0	49.3	62.1	53.0	56.2
Strength		63.2	71.5	65.9	72.2	47.4		53.0	57.8	55.0	56.1
at 24 hrs		60.4	70.6	60.6		47.1		45.9	60.3	53.9	57.8
		64.1	70.2	63.4		52.0		51.5	59.0	56.0	53.5
		61.4		64.7		48.8		51.7	59.1	54.8	54.5
Average	MPa	61.5	71.9	64.2	74.8	48.6	0.0	50.3	59.7	54.5	55.6
s	MPa	2.26	2.23	2.30	3.61	1.99		2.79	1.63	1.14	1.66
Compressive	MPa										
Strength											
at 3 days											
Average	MPa										
s	MPa										
Compressive	MPa	79.6	76.9	86.3				82.9	92.0	94.3	90.4
Strength		82.1	81.8	79.1				86.6	78.5	94.1	91.0
at 7 days									75.7		
Average	MPa	80.9	79.4	82.7				84.8	82.1	94.2	90.7
s	MPa	1.77	3.46	5.09				2.62	8.72	0.14	0.42
Compressive	MPa	104.3	95.1	99.5	99.6	88.2	51.9	96.5	105.9	109.1	117.8
Strength		107.0	96.6	109.5	91.0	87.9	44.6	90.5	101.7	112.7	111.8
at 28 days		101.0		110.1	96.0	85.1	47.1	89.4	101.3	110.5	118.1
		102.3		107.4		86.8	54.0	94.0	99.6	118.4	120.2
		103.2		96.9		87.0	53.6	88.6	102.9	120.3	120.4
Average	MPa	103.6	95.9	104.7	95.5	87.0	50.2	91.8	102.3	114.2	117.7
s	MPa	2.27	1.06	6.07	4.32	1.21	4.18	3.34	2.34	4.92	3.48
Compressive	MPa	108.7	92.0	105.6	93.3	104.2		93.9	95.5	120.1	124.7
Strength		109.1	94.0	113.8		97.0		91.7	119.0	119.8	128.0
at 56 days		113.4		119.1		99.2		99.1	115.3	120.6	124.5
		111.1		111.2		98.3		109.0		128.7	125.8
						97.4				126.5	
Average	MPa	110.6	93.0	112.4	93.3	99.2		98.4	109.9	123.1	125.8
s	MPa	2.16	1.41	5.61		2.91		7.70	12.64	4.15	1.61

		73	74	75	76	77	78	79[A]	79[B]	80	81
Curing Cylinder Diam & End		S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N
Compressive Strength at 18 hrs	MPa										
Average	MPa										
s	MPa										
Compressive Strength at 24 hrs	MPa	63.6	55.6	54.6	49.2	46.7	63.2	53.4	51.4	60.5	48.0
		62.8	53.5	54.9	48.1	49.2	63.8	52.8	52.2	61.3	48.6
		63.7	54.3	57.0	49.0	50.8	63.3	55.7	53.3	63.5	49.1
		64.5	57.1	53.0	48.7	49.5	64.0	54.8	55.3	63.5	49.9
		63.0	53.0	54.9	48.7	47.8	64.2	54.5	56.3	62.2	49.6
Average	MPa	63.5	54.7	54.9	48.7	48.8	63.7	54.2	53.7	62.2	49.0
s	MPa	0.67	1.66	1.42	0.42	1.59	0.44	1.15	2.06	1.33	0.76
Compressive Strength at 3 days	MPa										
Average	MPa										
s	MPa										
Compressive Strength at 7 days	MPa	95.2	85.1	83.4	70.4	86.7	92.8			82.9	
		97.4	86.0	83.7	74.0	81.3	86.7			86.5	
										92.6	
Average	MPa	96.3	85.6	83.6	72.2	84.0	89.8			87.3	
s	MPa	1.56	0.64	0.21	2.55	3.82	4.31			4.90	
Compressive Strength at 28 days	MPa	113.8	112.2	107.0	100.8	109.3	119.8	112.0	114.3	101.0	116.0
		120.5	112.3	106.4	101.3	107.5	116.7	112.2	117.0	103.5	110.0
		120.8	108.4	105.8	101.0	103.4	118.5	107.1	109.2	97.8	109.0
		121.1	112.3	107.2	97.6	99.2	113.0	112.0	111.7	97.9	107.1
					94.2			116.0	110.9		108.1
Average	MPa	119.1	111.3	106.6	99.0	104.9	117.0	111.9	112.6	100.1	110.0
s	MPa	3.51	1.93	0.63	3.06	4.50	2.95	3.16	3.06	2.74	3.50
Compressive Strength at 56 days	MPa	126.7	110.6	111.2	102.5	108.6	116.4	114.8	125.2	100.3	113.4
		126.8	118.0	113.4	102.8	108.0	121.2	114.6	127.3	101.1	113.7
		125.2	122.5	115.8	107.0	109.6	126.1	117.8	128.0	111.8	117.3
		120.0	121.0	114.9	101.7	110.8	120.9	118.9	129.5		114.4
		128.5	123.0	116.3	102.4	110.8	127.6	119.8	124.2		116.3
Average	MPa	125.4	119.0	114.3	103.3	109.6	122.4	117.2	126.8	104.4	115.0
s	MPa	3.26	5.09	2.06	2.12	1.27	4.48	2.37	2.14	6.42	1.70

		82	83	84	85	86	87	88	89	90	91[A]
Curing Cylinder Diam & End		S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N	S/M 100N
Compressive Strength at 18 hrs	MPa										
Average	MPa										
s	MPa										
Compressive Strength at 24 hrs	MPa	58.9 60.5 59.3 63.6 60.9	63.7 66.2 64.4	56.3 52.7 57.7	34.4 34.5 35.6		14.4 15.2 15.7	23.9 26.3 25.3	29.1 30.3 30.1	23.5 21.0 22.7	26.8 27.4 28.3
Average	MPa	60.6	64.8	55.6	34.8		15.1	25.2	29.8	22.4	27.5
s	MPa	1.85	1.29	2.58	0.67		0.66	1.21	0.64	1.28	0.75
Compressive Strength at 3 days	MPa		73.5 73.4 71.6	75.1 71.9 69.3		46.2 46.7 46.7	43.7 46.4 46.7	67.7 66.8 66.6	65.3 66.8 66.7	67.9 67.8 69.5	56.5 56.9 57.1
Average	MPa		72.8	72.1		46.5	45.6	67.0	66.3	68.4	56.8
s	MPa		1.07	2.91		0.29	1.65	0.59	0.84	0.95	0.31
Compressive Strength at 7 days	MPa		81.1 79.8 79.4		73.5 71.9 64.6	71.7 70.4 69.1	76.4 66.2 73.0		78.5 82.1 83.1	78.9 86.2 81.5	70.8 73.9 70.4
Average	MPa		80.1		70.0	70.4	71.9		81.2	82.2	71.7
s	MPa		0.89		4.74	1.30	5.19		2.42	3.70	1.92
Compressive Strength at 28 days	MPa	111.4 107.8 111.2 111.7 113.6	90.0 87.7 90.1		87.0 86.1	83.4 86.0 82.3	71.6 77.9 71.2	88.2 89.7 91.5	97.9 100.5 98.7	104.3 99.1 103.9	83.4 85.4 82.0
Average	MPa	111.1	89.3		86.6	83.9	73.6	89.8	99.0	102.4	83.6
s	MPa	2.10	1.36		0.64	1.90	3.76	1.65	1.33	2.89	1.71
Compressive Strength at 56 days	MPa	116.1 118.7 120.4 115.1 123.3	93.4 96.6 91.5	96.6 97.0 96.2	92.3 84.7			96.1 100.8 98.8			93.6 92.7 90.9
Average	MPa	118.7	93.8	96.6	88.5			98.6			92.4
s	MPa	3.31	2.58	0.40	5.37			2.36			1.37

		91^B	92^A		92^B		92^C		93
Curing		S/M	S/M	S/M	S/M	S/M	S/M	S/M	S/M
Cylinder Diam & End		100N	100N	100S	100N	100S	100N	100S	100N
Compressive Strength at 18 hrs	MPa								
Average	MPa								
s	MPa								
Compressive Strength at 24 hrs	MPa	25.5 26.5 25.9	21.9 24.5 24.3		26.1 26.3 28.0		27.8 25.4 24.4		52.7 51.0 50.8 53.2
Average	MPa	26.0	23.6		26.8		25.9		51.9
s	MPa	0.50	1.45		1.04		1.75		1.20
Compressive Strength at 3 days	MPa	56.1 53.9 53.4	55.5 57.8 55.7		56.3 57.9 57.3		57.5 55.4 59.0		
Average	MPa	54.5	56.3		57.2		57.3		
s	MPa	1.44	1.27		0.81		1.81		
Compressive Strength at 7 days	MPa	64.3 62.1 70.9	69.3 69.5 65.5	68.4 64.2 65.7	72.9 70.7 72.2	69.5 64.2	69.5 72.2 74.1	65.5 66.1 68.7	75.5 75.7 77.7 72.7
Average	MPa	65.8	68.1	66.1	71.9	66.9	71.9	66.8	75.4
s	MPa	4.58	2.25	2.13	1.12	3.75	2.31	1.70	2.06
Compressive Strength at 28 days	MPa	86.3 90.4 89.1	89.9 85.6 88.6		88.6 88.0 91.8		86.2 87.4 85.6		87.2 88.0 80.4
Average	MPa	88.6	88.0		89.5		86.4		85.2
s	MPa	2.10	2.21		2.04		0.92		4.18
Compressive Strength at 56 days	MPa	89.0 90.0 94.5	88.9 92.8 94.1		90.8 94.2 95.5		94.2 92.8 96.0		
Average	MPa	91.2	91.9		93.5		94.3		
s	MPa	2.93	2.71		2.43		1.60		

		94		95		96		98	99	100
Curing Cylinder Diam & End		S/M 100N	H1/M 100N	S/M 100N	H1/M 100N	S/M 100N	H1/M 100N	S/M 100N	S/M 100N	S/M 100N
Compressive Strength at 18 hrs	MPa									
Average	MPa									
s	MPa									
Compressive Strength at 24 hrs	MPa	52.2 51.8 52.2	61.8 59.6 63.3	37.3 43.7 43.3	46.6 50.1 45.0	52.3 52.1 51.5	52.4 53.2 53.4	52.2 54.8 53.2 55.1 55.2	48.1 49.4 48.7 51.4 51.0	53.3 56.8 55.6 54.2 55.6
Average	MPa	52.1	61.6	41.4	47.2	52.0	53.0	54.1	49.7	55.1
s	MPa	0.23	1.86	3.59	2.61	0.42	0.53	1.33	1.43	1.36
Compressive Strength at 3 days	MPa									
Average	MPa									
s	MPa									
Compressive Strength at 7 days	MPa	85.8 83.7 84.9	86.6 85.5 87.9	71.8 68.0 68.5	65.5 65.9 65.2					
Average	MPa	84.8	86.7	69.4	65.5					
s	MPa	1.05	1.20	2.06	0.35					
Compressive Strength at 28 days	MPa							106.9 107.8 102.7 105.8 110.4	93.4 96.8 101.5 103.6	103.6 101.4 105.6 114.1 111.6
Average	MPa							106.7	98.8	107.3
s	MPa							2.82	4.60	5.39
Compressive Strength at 56 days	MPa							120.5 115.8 118.8 119.8 126.1	107.1 106.0 108.5 109.5 106.8	109.5 107.2 110.3 112.5 118.2
Average	MPa							120.2	107.6	111.5
s	MPa							3.75	1.40	4.18

		101	102	103	P/P 5			P/P 27				
Curing		S/M	S/M	S/M	A/M	H7/M	H7/M	A/M	H7/M	A/M	A/M	H7/M
Cylinder Diam & End		100N	100N	100N	100N	100N	150N	100N	100N	100S	150S	150S
Compressive Strength at 18 hrs	MPa											
Average	MPa											
s	MPa											
Compressive Strength	MPa	61.6	47.4	48.4	53.9	68.9	57.7	44.4	51.9			
at 24 hrs		62.5	46.0	45.5	55.2	66.5	59.1	39.2	48.1			
		57.9	45.0	47.3	53.3	58.9	60.5	37.8	48.4			
		63.6	39.4	47.4		64.5		42.4				
		59.4	47.3					41.9				
Average	MPa	61.0	45.0	47.2	54.1	64.7	59.1	41.1	49.5			
s	MPa	2.32	3.29	1.21	0.97	4.26	1.40	2.63	2.11			
Compressive Strength	MPa						59.8					
at 3 days							63.4					
Average	MPa						61.6					
s	MPa						2.55					
Compressive Strength at 7 days	MPa											
Average	MPa											
s	MPa											
Compressive Strength	MPa	109.1	85.5	71.7		76.3		96.2	86.3	71.9	77.0	70.2
at 28 days		108.5	91.6	74.0		72.8		85.0		73.6	76.1	67.8
		121.4	86.8	81.9		65.7				78.0	78.7	
		112.9	89.3	84.4		77.8						
		116.2	86.3	81.5		82.3						
Average	MPa	113.6	87.9	78.7		75.0		90.6	86.3	74.5	77.3	69.0
s	MPa	5.35	2.51	5.51		6.21		7.92		3.15	1.32	1.70
Compressive Strength	MPa	122.7	93.5	82.2				106.4	97.7			
at 56 days		124.9	94.9	87.5				89.3	101.3			
		118.0	84.3	90.9				100.8				
		124.8	88.9	85.3				92.3				
		122.6		76.5				94.0				
Average	MPa	122.6	90.4	84.5				96.6	99.5			
s	MPa	2.80	4.81	5.47				6.93	2.55			

		P/P 65		P/P 72		P/P 97		P/P 98	
Curing Cylinder Diam & End		A/M 100N	H7/M 100N	A/M 100N	H7/M 100N	A/M 100N	H7/M 100N	A/M 100N	H7/M 100N
Compressive Strength at 18 hrs	MPa			41.5 39.0	68.5 62.0	12.3 12.0	60.7 43.1		
Average	MPa			40.3	65.3	12.2	51.9		
s	MPa			1.77	4.60	0.21	12.45		
Compressive Strength at 24 hrs	MPa	62.5 59.7 61.3	80.3 78.3 80.8	40.7 42.2 40.6 41.8 44.4	68.3 65.2 65.3 65.2 58.8	25.2 25.2 25.6 25.7 26.5	63.3 59.7 52.9 66.1	29.0 28.7 27.8 29.6 32.4	55.7 54.4 53.2 56.8 52.8
Average	MPa	61.2	79.8	41.9	64.6	25.6	60.5	29.5	54.6
s	MPa	1.40	1.32	1.54	3.48	0.53	5.70	1.75	1.68
Compressive Strength at 3 days	MPa								
Average	MPa								
s	MPa								
Compressive Strength at 7 days	MPa		60.5 79.8						
Average	MPa		70.2						
s	MPa		13.65						
Compressive Strength at 28 days	MPa		73.1 78.1 67.5 77.1	89.4 90.4 84.3 92.9 91.7	88.2 85.6 79.3 86.6 84.1	106.7 106.5 100.9 107.2 102.2	87.2 82.8 87.9 86.0	75.1 80.3 85.0 78.1 79.3	85.1 83.7 76.3 79.2 81.9
Average	MPa		74.0	89.7	84.8	104.7	86.0	79.6	81.2
s	MPa		4.81	3.32	3.40	2.92	2.26	3.61	3.53
Compressive Strength at 56 days	MPa			90.9 96.1 92.7 98.7 96.2	95.3 92.7 90.0 95.1 84.0	108.8 110.5 106.7 103.9 112.4	91.9	90.5 98.6 90.8 78.9 83.4	84.1 88.4 79.0 86.4 82.1
Average	MPa			94.9	91.4	108.5	91.9	88.4	84.0
s	MPa			3.10	4.67	3.30		7.57	3.67

		P/P 99		P/P 100		P/P 104	
Curing		A/M	H7/M	A/M	H7/M	A/M	H7/M
Cylinder Diam & End		100N	100N	100N	100N	100N	100N
Compressive Strength at 18 hrs	MPa						
Average	MPa						
s	MPa						
Compressive Strength at 24 hrs	MPa	37.4	61.9	44.9	65.5	32.2	53.3
		37.8	59.2	47.2	68.6	31.3	55.1
		33.8	58.1	45.1	69.8	33.7	55.8
		37.1	59.8	45.4	69.2	32.1	
		37.2	62.8	45.9	71.7	33.6	
Average	MPa	36.7	60.4	45.7	69.0	32.6	54.7
s	MPa	1.62	1.94	0.92	2.26	1.04	1.29
Compressive Strength at 3 days	MPa						
Average	MPa						
s	MPa						
Compressive Strength at 7 days	MPa						
Average	MPa						
s	MPa						
Compressive Strength at 28 days	MPa	79.3	82.6	86.6	85.6	80.9	74.8
		88.3	84.8	95.0	83.9	83.2	78.1
		88.9	80.0	86.0	88.2	86.4	77.1
		80.4	89.8	85.6	87.8	78.7	79.9
		84.3	77.5	91.7	90.0	84.5	74.6
Average	MPa	84.2	82.9	89.0	87.1	82.7	76.9
s	MPa	4.40	4.71	4.17	2.38	3.02	2.25
Compressive Strength at 56 days	MPa	86.7	79.3	94.0	89.0	99.2	77.9
		81.6	82.4	94.7	83.7	87.3	84.8
		90.5	89.0	94.1	86.6	87.3	80.2
		91.6	92.2	93.3	84.1	87.5	76.9
		88.5	78.2	92.3	82.3	88.8	77.8
Average	MPa	87.8	84.2	93.7	85.1	90.0	79.5
s	MPa	3.93	6.13	0.92	2.66	5.17	3.19

		6^C	27^E	27^F	43	44	45^A	45^B
Curing		H5/M	S/M	S/M	S/M	S/M	S/M	S/M
Splitting Tensile Strength at 28 days	MPa			3.37 4.48 4.92				
Average	MPa			4.26				
s	MPa			0.80				
MOR at 28 days	MPa			10.48 10.38				
Average	MPa			10.43				
s	MPa			0.07				
Modulus of Elasticity at 1 day	GPa							
Average	GPa							
s	GPa							
Modulus of Elasticity at 28 days	GPa	45.0 45.5 46.4 46.1	48.3 48.6 46.8 47.0		47.7 47.8 47.6 47.6	48.4 48.7	48.3 48.2 48.2 48.4	47.3 47.3 46.2 46.2
Average	GPa	45.8	47.7		47.7	48.6	48.3	46.8
s	GPa	0.62	0.91		0.10	0.21	0.10	0.64
Length Change at 3 days	με			140 130	90 100	100 110		150 140
Average	με			135	95	105		145
Length Change at 7 days	με			210 200	160 150	140 180		230 220
Average	με			205	155	160		225
Length Change at 28 days	με			280 280	260 280	240 270		300 290
Average	με			280	270	255		295
Length Change at 56 days	με			330 330	310 340	300 330		360 340
Average	με			330	325	315		350

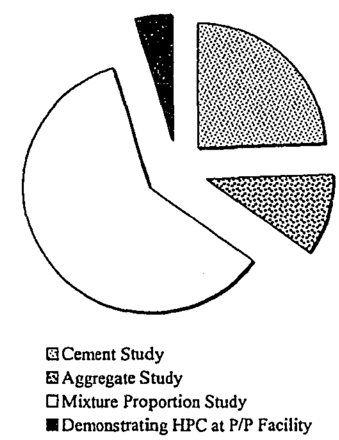
		46A	46B	47	48	52	53	67	79B
Curing		S/M	S/M	S/M	S/M	S/M	S/M	S/M	S/M
Splitting Tensile Strength at 28 days	MPa								
Average	MPa								
s	MPa								
MOR at 28 days	MPa								
Average	MPa								
s	MPa								
Modulus of Elasticity at 1 day	GPa		41.2 41.3	38.5 38.6 38.8 38.9	38.4 38.6 38.4 38.8	38.8 39.1 38.2 38.3	39.5 39.2 39.9 40.3		
Average	GPa		41.3	38.7	38.6	38.6	39.7		
s	GPa		0.07	0.18	0.19	0.42	0.48		
Modulus of Elasticity at 28 days	GPa	47.8 47.8 47.9 48.3	47.7 48.2 48.0 48.0	46.9 47.1 46.3 46.3	48.6 48.7 46.9 47.0	47.4 47.3 47.9 47.8	47.8 47.5 47.8 47.5	46.6 47.0 48.5 48.5	50.3 50.2 49.3 49.2
Average	GPa	48.0	48.0	46.7	47.8	47.6	47.7	47.7	49.8
s	GPa	0.24	0.21	0.41	0.98	0.29	0.17	0.99	0.58
Length Change at 3 days	με	80 70	70 80	90 90	100 100	80 70	130 120	130 130	
Average	με	75	75	90	100	75	125	130	
Length Change at 7 days	με	150 140	140 140	150 160	170 170	140 130	230 210	220 220	
Average	με	145	140	155	170	135	220	220	
Length Change at 28 days	με	250 220	230 220	210 220	300 290	230 210	360 350	320 310	
Average	με	235	225	215	295	220	355	315	
Length Change at 56 days	με	270 240	230 220	240 240	370 360	250 230	410 390	390 360	
Average	με	255	225	240	365	240	400	375	

		82	P/P 5	P/P 27	P/P 65	P/P 98	
Curing		S/M	H7/M	A/M	H7/M	A/M	H7/M
Splitting Tensile	MPa			5.37			
Strength				4.96			
at 28 days				3.29			
				4.27			
Average	MPa			4.47			
s	MPa			0.91			
MOR	MPa			11.38	7.78		
at 28 days				9.93	8.35		
				10.22	8.54		
Average	MPa			10.51	8.22		
s	MPa			0.77	0.40		
Modulus of	GPa						
Elasticity							
at 1 day							
Average	GPa						
s	GPa						
Modulus of	GPa	49.1	44.1			38.0	40.0
Elasticity		49.4	44.2			38.1	39.9
at 28 days		49.4	44.0			39.1	40.2
		49.1	44.4			39.4	39.8
Average	GPa	49.3	44.2			38.7	40.0
s	GPa	0.17	0.17			0.70	0.17
Length Change	με			100			
at 3 days				100			
				110			
Average	με			103			
Length Change	με			180			
at 7 days				180			
				200			
Average	με			187			
Length Change	με		290	250			
at 28 days			290	250			
			300	270			
Average	με		293	257			
Length Change	με		390	290			
at 56 days			380	290			
			400	320			
Average	με		390	300			

		P/P 99		P/P 100		P/P 104	
Curing		A/M	H7/M	A/M	H7/M	A/M	H7/M
Splitting Tensile Strength at 28 days	MPa						
Average	MPa						
s	MPa						
MOR at 28 days	MPa						
Average	MPa						
s	MPa						
Modulus of Elasticity at 1 day	GPa						
Average	GPa						
s	GPa						
Modulus of Elasticity at 28 days	GPa	38.8	37.6	39.4	45.3	39.1	37.5
		38.7	37.3	39.5	45.1	39.6	36.9
		36.7	39.4	42.4	38.4	37.5	35.1
		36.4	39.5	42.7	38.3	37.7	35.8
Average	GPa	37.7	38.5	41.0	41.8	38.5	36.3
s	GPa	1.28	1.16	1.79	3.96	1.03	1.08
Length Change at 3 days	με						
Average	με						
Length Change at 7 days	με						
Average	με						
Length Change at 28 days	με						
Average	με						
Length Change at 56 days	με						
Average	με						

Appendix F. Dissertation by the Numbers

130	Number of HPC mixture designs
76%	Mixtures designed with *Type III* cement
69%	Mixtures designed with supplementary cementitious materials
27%	Mixtures with heat curing parallel to standard curing
200	Number of HPC trial batches at the lab (see figure)
15.0 m^3 ($19.6\ yd^3$)	Estimated quantity of concrete batched at lab, based on an average of $0.075\ m^3$/batch
9	Number of HPC trial batches at precast/prestressing facility
2	Number of model precast/prestressed bridge beams constructed
3,193	Number of concrete cylinders tested for compressive strength



65.1 MPa (9,440 psi)	Best compressive strength at 18 hrs under standard curing (Mixture 2)
69.3 MPa (10,050 psi)	Best compressive strength at 24 hrs under standard curing (Mixture 10)
76.1 MPa (11,030 psi)	Best compressive strength at 24 hrs under heat curing (Mixture 57)
119.1 MPa (17,270 psi)	Best compressive strength at 28 days under standard curing (Mixture 73)
90.0 MPa (13,050 psi)	Average compressive strength at 28 days under standard curing
88%	Mixtures with compressive strength exceeding 69.0 MPa (10,000 psi) at 28 days under standard curing
125.8 MPa (18,240 psi)	Best compressive strength at 56 days under standard curing (Mixture 72)
6.0 MPa (870 psi)	Best splitting tensile strength at 28 days under standard curing (Mixture LIq)
10.4 MPa (1,510 psi)	Best MOR at 28 days under standard curing (Mixture 27)
49.8 GPa (7,220 ksi)	Best elastic modulus at 28 days under standard curing (Mixture 79)
240 $\mu\varepsilon$	Lowest measured shrinkage at 56 days under standard curing (Mixtures 46, 47 and 52)

Appendix G. Unit Conversions for Concrete Materials

SI units were employed in the text, tables and figures. U.S. customary units were provided secondary in the text for convenience.

MIXTURE PROPORTIONS & BATCHING

$1\ kg/m^3 = 1.686\ lb/yd^3$

$1\ kg = 2.205\ lb$

$0.765\ m^3 = 1\ yd^3 = 27\ ft^3$

ADMIXTURES

$1\ L/m^3 = 25.85\ floz/yd^3$

$4.951\ L/m^3 = 1\ gal/yd^3$

65.2 mL/100 kg = 1 floz/100 lb

$1\ m^3 = 1{,}000\ L$

3.785 L = 1 gal = 128 floz

FRESH CONCRETE PROPERTIES

25.4 mm = 1 in

$T(°C) = 5/9[T(°F) - 32]$

$1\ kg/m^3 = 0.06243\ lb/ft^3$

MECHANICAL PROPERTIES

1 MPa = 145 psi

1 GPa = 145 ksi

UNIT WEIGHT OF WATER

$1\ kg/L = 1{,}000\ kg/m^3 = 8.345\ lb/gal = 62.43\ lb/ft^3$