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Ultimax cement and nondestructive testing of high strength concrete

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ULTIMAX CEMENT AND NONDESTRUCTIVE TESTING OF HIGH STRENGTH CONCRETE

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ABSTRACT

ULTIMAX CEMENT AND NONDESTRUCTIVE TESTING OF HIGH STRENGTH CONCRETE

by Emma B. Aquino

This study is composed of two parts. The objective of the first part is to evaluate the physical properties of fresh and hardened concrete made with a new type of rapid hardening hydraulic cement commercially know as "Ultimax cement." The properties are compared with concrete containing ASTM Type I/II cement. The objective of the second part is to evaluate the use of the Windsor probe test to nondestructively determine the *in situ* compressive strength of normal and high strength concrete.

This study reveals that improved physical properties can be obtained when using Ultimax cement in concrete. The Windsor probe test was found capable of predicting the *in situ* compressive strength of normal and high strength concrete.

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Nomenclature

Organizations

ACI	American Concrete Institute
ASTM	American Society for Testing and Materials
PCA	Portland Cement Association

Units

lb/cyd	pounds per cubic yard
MPa	mega-pascal
pcf	pounds per cubic foot
psi	pounds per square inch

Abbreviations

HRWR	high-range water reducer
HSC	high strength concrete
SMF	sulfonated melamine formaldehyde (superplasticizer)
SNF	sulfonated naphthalene formaldehyde (superplasticizer)
WRA	water-reducing admixture

Symbols

A/cm	aggregate-to-cementitious materials ratio by weight
CA/FA	coarse aggregate-to-fine aggregate ratio by weight
Cov(X,Y)	covariance
E_c	modulus of elasticity of concrete, psi or MPa
f'_c	28-day compressive strength of concrete, psi or MPa
R	correlation coefficient
w/cm	water-to-cementitious materials ratio by weight
μ	mean
ν	coefficient of variation
σ	standard deviation

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Chapter 1

Introduction

1.1 Rapid Hardening Ultimax Cement and Nondestructive Testing of High Strength Concrete

Rapid hardening cement is useful in applications requiring rapid early strength development such as concrete repairs in roads and airport runways. Rapid hardening cements can also be used for smaller applications such as the installation of dividing walls, sealings in brick supports, sealings of inspection covers and manholes, door and window frames, moldings of window ledges, setting walls, and finishing facades. In this investigation, a new rapid hardening hydraulic cement commercially known as "Ultimax cement" was studied. The compressive strength, modulus of elasticity, splitting-tensile strength, bulk density, shrinkage, and expansion of concrete containing Ultimax cement were evaluated and compared with the properties of concrete containing ASTM Type I/II cement.

The use of high strength concrete in construction can result in a structure that requires a lesser volume of concrete than is required by a structure constructed with normal strength concrete. Many structures, especially high rise buildings, have been built using high strength concrete. In order to evaluate the *in situ* strength of the high strength concrete, nondestructive testing methods must be utilized. To date, nondestructive testing methods have not been evaluated for *in situ* testing of high strength concrete.

There are several methods used in nondestructive testing that have the potential to be utilized for high strength concrete testing including the penetration resistance method which is based on measuring the depth of penetration of steel probes into the surface of concrete. In this study, the most well known and widely used probe penetration technique, the Windsor probe test, will be used to conduct nondestructive testing on normal and high strength concrete.

1.2 Scope

In order to compare the physical properties of concrete made with Ultimax cement and ASTM Type I/II cement, twenty different concrete mixes were prepared with local aggregates and cement. Fifteen of these mixes were prepared with Ultimax cement while the other five were prepared with ASTM Type I/II cement. The concrete mixes were made with various water-to-cement ratios of 0.30, 0.35, 0.40, 0.45, and 0.50.

This research also investigates two types of probes for use in probe penetration testing of normal and high strength concrete. Specimens from eight mixes were tested to obtain compressive strength and probe penetration data. The exposed probe length was plotted against compressive strength to obtain correlation equations for both probe types.

1.3 Objectives

The main objectives of this investigation were:

(1) To study the properties of fresh and hardened concrete made with a new type of rapid hardening early strength cement commercially known as "Ultimax cement." Results will be compared with concrete made with ASTM Type I/II cement.

(2) To evaluate the Windsor probe test using two new types of probes for conducting nondestructive testing of concrete having high strengths up to 10,500 psi (70 MPa).

1.4 Thesis Outline

This thesis consists of six chapters. Chapter 1 introduces the investigations conducted. The scope, objectives, and outline of the research are also presented. Chapter 2 contains a review of high strength concrete. The concrete properties and constituents of high strength concrete are reviewed. The role of aggregates in high strength concrete is also discussed. Chapter 3 contains a review of the probe penetration resistance test used in this study. Chapter 4 describes the material investigation of concrete containing Ultimax cement. A comparison of the fresh and hardened properties of concrete containing Ultimax cement and concrete containing ASTM Type I/II cement is presented. Chapter 5 describes the experimental program used for finding a correlation between the compressive strength of normal and high strength concrete slabs and the depth of penetration of newly designed probes using the Windsor probe test. The test results of the experimental program are also presented in this chapter. Conclusions and future recommendations are presented in Chapter 6.

Chapter 2

Review of High Strength Concrete

2.1 Introduction

The definition of "high strength concrete" has been revised through the years. In the 1950s, 5000 psi (35 MPa) concrete was considered high strength. Today, 19,000 psi (130 MPa) concrete is being used in cast-in-place buildings. With each successive development and corresponding strength increase, this definition has changed. The exact point at which concrete can be classified as either "normal-strength" or "high-strength" cannot be determined. According to the American Concrete Institute (ACI), high strength concrete is defined as concrete with compressive strength over 6000 psi (40 MPa).(1) A strength classification system developed at the University of Illinois is shown in Table 2.1.

Table 2.1 Strength Classification of Concrete(2)

Parameter	Conventional concrete	High-strength concrete	Very-high-strength concrete	Ultra-high-strength concrete
Strength, psi (MPa)	< 7250 (50)	7250-14,500 (50-100)	14,500-21,750 (100-150)	> 21,750 (150)
Water-to-cement ratio	> 0.45	0.45-0.30	0.30-0.25	< 0.25
Chemical admixtures	Not necessary	WRA or HRWR*	HRWR*	HRWR*
Mineral admixtures	Not necessary	Fly ash	Silica fume**	Silica fume**
Permeability coefficient	$> 10^{-10}$	10^{-11}	10^{-12}	$< 10^{-13}$
Freeze-thaw protection	Needs air entrainment	Needs air entrainment	Needs air entrainment	No freezable water

* WRA = Water reducing admixture, HRWR = high-range water reducer.
** Also may contain fly ash.

High strength concrete (HSC) is used when a reduction in weight is needed or when smaller load-carrying elements are required. HSC allows for smaller vertical members which achieve more efficient floor plans. HSC has been proven to be an economical alternative by reducing the total volume of concrete, the amount of reinforcing steel required, and the amount of formwork needed, thereby reducing total costs. The number of applications of high strength concrete has increased as a result of developments in material technology and a demand for higher strength concrete. Some examples of concrete structures utilizing HSC are: Two Union Square in Seattle (1988) with strengths up to 19,000 psi (130 MPa), Gateway Tower in Seattle (1990) with strengths up to 17,000 psi (120 MPa), and 311 South Wacker Drive in Chicago (1989) with strengths up to 12,000 psi (80 MPa).

Another term which is used in technical literature when referring to high strength concrete is "high performance concrete." Some use these terms interchangeably, while others make a distinction between the two. According to the Portland Cement Association, high-strength concrete is a form of high performance concrete, but the inverse is not necessarily true.[2]

In 1979, American Concrete Institute Committee 363 was formed for the purpose of studying and reporting information on high-strength concrete. Its first document, the ACI 363R-84 State-of-the-Art Report on High Strength Concrete,[3] contains information about material selection, mixture proportions, mixing and placing, physical properties, structural design, economics and examples of applications. It was necessary for the Committee to define a range of concrete strengths for its activities. The Committee decided that its immediate concern would be concretes with compressive strengths of 6000 psi (40MPa) or greater, excluding concrete made with exotic materials or techniques such as polymer-impregnated concrete, epoxy concrete, or concrete with artificial normal and heavy weight aggregates.

2.2 Materials and Proportioning

High-strength concrete consists of the same basic ingredients as normal-strength concrete: cement, coarse and fine aggregate, and water. Its production is achieved by optimization of characteristics of the cementing medium, characteristics of the aggregate, proportions of the paste, paste-aggregate interaction, mixing, consolidating, curing, and testing procedures.[2]

The differences between high-strength concrete and normal concrete are that in high-strength concrete, entrained or entrapped air is reduced or removed, the addition of normal and high-range water-reducing admixtures or "superplasticizers" is mandatory to ensure workability at low water-to-cement ratios, and pozzolans are used to improve the paste by physical and chemical processes.[2] Fly ash replaced by weight of cementitious materials can increase strength up to 15,000 psi (100 MPa). To exceed this value, silica fume replaced by weight of cementitious materials is necessary for a uniform and dense cement paste. Only a minimum amount of space exists between the cement particles in the paste. This space is filled with the silica fume particles which are much finer. High strength is derived from chemical bonds created by the cement hydrates. Pozzolans combine with free lime in the paste to form a dense, uniform paste. For the best source of proportioning information, prestressed concrete plants, admixture suppliers, and ready mix suppliers for these materials should be consulted.

Slump is not used much as a control for HSC because slump is obtained with high-range water reducers (HRWR) and not extra water as in normal-strength concrete. The maximum value of the water-to-cement ratio in HSC should be strictly regulated, because it is very important in quality control. In addition, slump does not have much meaning for flowing concrete, and most HSC is flowing. Finally, a maximum coarse aggregate dry unit weight of 100 to 110 pcf must be specified.

2.2.1 Cement

Selection of cement should be based on strength tests of concretes at 28 and 90 days. The preferred cement is that which yields the highest compressive strength at 90 days. A high percentage of tricalcium silicate and a greater fineness are the best indicators of optimum performance in cements. Increased fineness is advantageous for obtaining high early strengths.

2.2.2 Paste

To achieve HSC, a cementitious materials content of 600 to 1000 lb/cyd should be used. Depending on desired strength, the exact amount can be determined. Higher cement efficiencies are obtained with smaller maximum aggregate sizes. Unit strength versus maximum aggregate size can be plotted to produce strength envelopes useful in determining the maximum aggregate size which would provide the most efficient use of cement (see Figure 2.1).

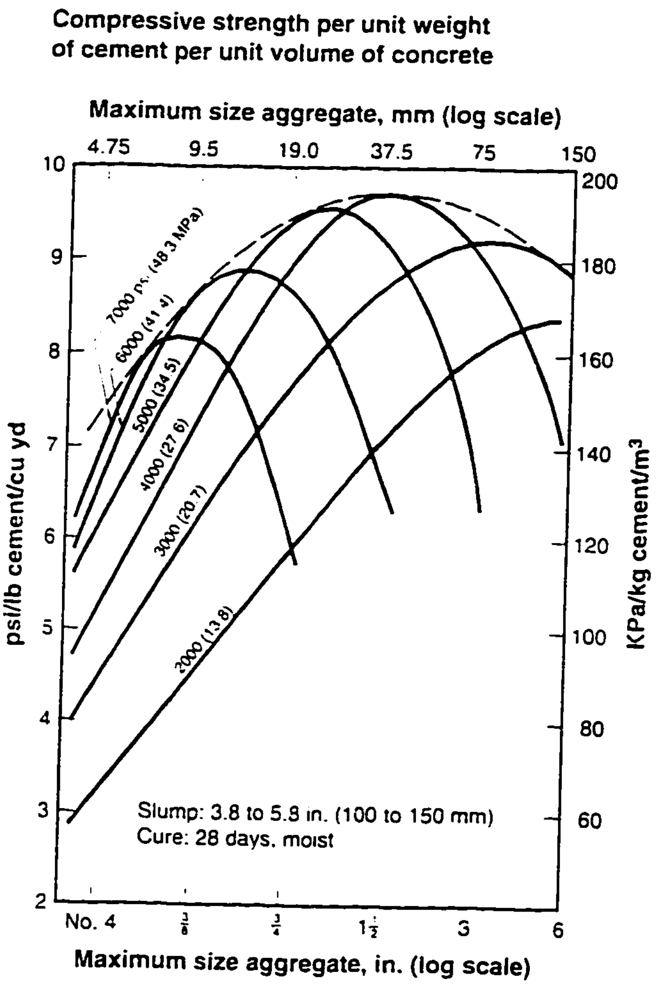

Figure 2.1: Strength efficiency of cement related to maximum aggregate size.(2)

Comparisons should be made between mixtures with equal slumps. ACI 211.4R[4] recommends a target slump of 1 to 2 in. (25 to 50 mm) for HSC before the HRWR is added, and a target slump of 2 to 4 in. (50 to100 mm) for HSC made without HRWR. Many HSC mixtures are proportioned to achieve flowing conditions or slumps in excess of 7 1/2 in. (190 mm) by adding HRWR in excess of that recommended by the manufacturer. As long as there is no segregation, flowing concrete for HSC is acceptable.

To ensure that pastes are as dense as possible, very low water-to-cement ratios are used. The lowest optimal water-to-cement ratio is approximately 0.22. The small amount of water in the mix combines chemically with the cement particles producing a low porosity paste.

The manner by which cement is proportioned is very important because it can have a great effect on the properties of the resulting material in its plastic and hardened state.

2.2.3 Aggregates

Concrete is comprised largely of aggregates; therefore, the characteristics of aggregates significantly influence the properties of the concrete. The strength of the cement paste in HSC is high enough to compete with the strength and other important properties of the aggregate. Aggregate strength, adhesion between the cement paste and aggregate, and absorption characteristics of the aggregate are all properties which could limit ultimate strength in HSC.

Optimum size of the coarse aggregate depends on the relative strength of the cement paste, cement-aggregate bond, and strength of aggregate particles. Trial batches provide the information needed to select the best aggregate for a concrete mix. Unlike in normal-strength concrete, large sizes of coarse aggregate reduce concrete strength in HSC. The use of small aggregates (3/8 to 3/4 in.) is usually sufficient to offset the higher mixing water demand. The net effect would be an increase in strength with a decrease in aggregate size.

In concretes of constant cement content and maximum aggregate size, compressive strength varies as a result of differences in mixing water requirements. The shape, texture, and coatings of the aggregate are responsible for differences in the mixing water requirements. Due to changes in aggregate shape and texture, mixing water requirements increase as void content of the aggregate increases.

In concretes of equal water-to-cement ratios, compressive strength varies with the use of different types of aggregate. Variability in the bonding between the paste and aggregate, and the strength of the aggregates are responsible for the strength variations. It is important to use hard and strong coarse aggregates such as fine-grained traprock, limestone, quartzite, or granite, in mixtures because they do not break down and produce fines during mixing. Since these aggregates have higher specific gravities and moderate absorption, strengths developed will be higher.

Fine aggregates provide a much larger surface area, therefore, the shape and texture of fine aggregates have a greater influence on the amount of mixing water required. Also, the bond of the paste to fine aggregate is less significant than the bond to coarse aggregate due to the larger surface area of fine aggregate. Maximizing the coarse-to-fine aggregate ratio results in the most efficient use of cementitious materials since all aggregates must be coated with the cement paste. Mixtures made with natural sand produce higher strengths than those made with manufactured sands due to particle shape and grading. Coarser fine aggregate is preferred because it has a lower water demand.

Since fine aggregate has a much larger surface area relative to its volume than does coarse aggregate, it has more influence on the amount of mixing water required and the properties of the paste. The shape and grading of fine aggregate as well as its proportion to the coarse aggregate will have direct impact on the requirements of a paste. Fine aggregate has a great influence on the amount of paste because more paste is required when more fine aggregate is used. In general, the best paste strength is produced by using the least sand required for the necessary workability.

Of all the components in a concrete mixture, coarse aggregate occupies the largest volume. The amount of coarse aggregate in a concrete mixture depends on the amount of fine aggregate. Concrete should be proportioned so that the paste coats all aggregates and fills all the voids between particles. Because HSC is a rich mixture (a mixture with a high cement content), the least amount of paste to coat all particles and fill all voids should be used.

2.2.4 Mixing Water

In terms of workability, a higher slump is desirable. A higher slump can be produced with the use of cool mixing water at 40°F instead of warm water at 70°F. If the volume of mixing water can be decreased with the use of cool mixing water, concrete strength will increase. This increase, however, may not be significant and thus the problems associated with obtaining cool mixing water might not be worth the effort.

2.2.5 Chemical Admixtures

The benefits of chemical admixtures in HSC have mandated their use. It is common to use a high-range water-reducing admixture or "superplasticizer" in combination with a water-reducing retarder.

The main components of water reducers or retarders are: salts of lignosulfonic acid, hydroxycarbolic acids, carbohydrates, and other compounds. Of these four, lignosulfonate-based compounds are the most widely used. Water requirements are reduced and concrete setting is retarded because these admixtures slow the rate of hydration of the cement for the first few hours. The most commonly used superplasticizers are the sulfonated melamine formaldehyde (SMF) and sulfonated naphthalene formaldehyde (SNF) based superplasticizers. They cause the cement to behave like a liquid by dispersing cement particles when the mixing water is added. In other words, the superplasticizers "plasticize" the paste.

Since air content within a concrete mix reduces compressive strength, no air-entraining agent is used in these concretes under normal conditions. Under saturated freezing-and-thawing conditions, however, air-entrained concrete must be used for improved durability.

Chemical admixtures should meet the requirements of ASTM C 494, Specifications for Chemical Admixtures for Concrete.[5] The amount of admixture that should be used is either the manufacturer recommended amount or the optimum amount determined by trial batches based on strength and workability.

Manufacturers of water-reducing admixtures (WRA) recommend dosages to produce specific results. When exceeding the recommended dosages, caution should be used. Excessive amounts of chemical admixtures have caused retardation of concrete setting time and reduced early strength.

The recommended dosage for superplasticizers is usually higher than for normal water-reducing admixtures.[2] Dosage for superplasticizers is measured as a percentage by weight of cement and is typically between 0.5% and 1.0%.

Water reducers affect concrete by variations in water reduction and degree of retardation. Changes in temperature, increases in cement fineness, and changes in aluminate content, soluble alkalies, and free lime all influence water reduction and retardation. The admixture must be compatible with the cement, as far as type and amount of calcium sulfate (gypsum) additive, and amount of soluble alkalies is concerned. Furthermore, slump loss is affected by the composition of the cement, composition of the admixture, rate of admixture use, and temperature of the concrete and surrounding air.

Water-reducing admixtures have their greatest impact if added at the end of mixing time of aggregates, cement, and total water. However, WRA should be added after 15 to 30 seconds of mixing the cement, aggregates, and one-half the water to assure uniform dispersion. The benefits of using WRA are more consistent concrete properties, lengthening of the setting time, and higher water reduction with a corresponding increase in compressive strength. Superplasticizers have their greatest impact on cement particles if added a few minutes after all other components have been thoroughly mixed.

2.2.6 Mineral Admixtures

Mineral admixtures are added to concrete before or during mixing to improve or change the plastic or hardened properties of the cement. Addition of mineral admixtures can be beneficial to the ultimate strength and durability of concrete. Mineral admixtures are classified as: cementitious materials, pozzolans, pozzolanic and cementitious materials, and nominally inert materials.(2) Pozzolans are the most important to the production of HSC. The two most commonly used pozzolans are fly ash and silica fume. Ground granulated blast-furnace slag is a cementitious material that is commonly used in Canada. The inert materials do not add more strength to the concrete, but they improve workability and reduce alkali-aggregate reactions.

By itself, a pozzolan possesses little or no cementitious value. As cement hydrates, it releases calcium hydroxide which reacts with water. This, in turn, causes the pozzolans to produce compounds possessing cementitious properties.

Fly ash is a by-product of the combustion of pulverized coal in electric power generating plants. Fly ash may cause a reduction in the water demand of the mixture because fly ash particles are rounded and smooth and help to lubricate the mix. Silica fume, also a pozzolan, is a by-product of the reduction of high-purity quartz with coal in electric arc furnaces. Like fly ash, it is an airborne material and has a spherical shape. Unlike fly ash, silica fume is extremely fine with a surface area of about 20,000 m^2/kg as compared to fly ash which has a surface area of about 300 to 500 m^2/kg. Silica fume is used in many high-strength concretes. It is always used in very- and ultra-high strength concretes. Silica fume improves concrete strength by modifying the binding paste both physically and chemically. Fly ash alone can help to achieve strengths up to 15,000 psi (100 MPa). For higher strengths, fly ash and silica fume or slag and silica fume are used.

Silica fume is added as an addition, as opposed to a replacement for cement. In general, silica fume dramatically increases the water demand of mixtures. However, for high-cement content mixes having water-to-cement ratios below 0.25 and incorporating superplasticizers, adding up to 10% silica fume as an admixture can actually lower the required dosage of superplasticizer and reduce the amount of time and energy required for thorough mixing.(6) Powdered silica fume is better than densified silica fume at reducing the amount of superplasticizer needed for workability.(6)

Part of the cement in high-performance concrete may be replaced by less costly materials such as fly ash or ground granulated blast-furnace slags, but with a loss in chemical reactivity. Use of these replacements allows a reduction in superplasticizer dosage. These replacements offer long-term strength gain that may offset some short-term loss in compressive strength.

2.3 Mixing and Placing

2.3.1 Mixing

Conventional procedures can be followed for the mixing of HSC. However, efficient mixing of high-strength concrete is more difficult than conventional concrete because of low water contents, high cement contents, and the absence of large coarse aggregate. Mixtures with high cement factors should be mixed longer. Two types of mixers that may be used are drum mixers and turbine mixers. Minimum mixing times for each should be determined by trial batches since the cohesive nature of HSC makes it adhere to mixer drums. Non-air-entrained mixtures with low-slump and small-sized aggregates may be sticky and difficult to mix. Special care should be taken to provide a homogeneous mix.

Low concrete temperatures provide the best workability due to the fact that the mixing water requirement, as well as, rate of slump loss increases with increased temperature. As the mixing water requirement is increased, the strength of the concrete is reduced. Ideally, the temperature of the mixing water and aggregates should be cooled to 40°F. Furthermore, temperature is not to exceed 75°F at the time the concrete is delivered to the forms.

The water-to-cement ratio should be strictly regulated. Water added should not exceed the maximum water-to-cementitious ratio prescribed. Though not recommended, second or third dosages of superplasticizer can be added after initial dosage to restore slump. Compressive strength is not adversely affected by this practice since strength gain is directly related to reduction in entrained air.

It is difficult to determine what causes slump loss. Many variables affect slump loss including initial slump value, type and amount of cement, type, amount, and time of addition of superplasticizer, humidity, temperature, mixing method, and presence of other admixtures. For this reason, optimization of placement, delivery, and coordination is preferable to modifying a mixture at a jobsite.

2.3.2 Placing

More care must be taken in placing high-strength concrete as opposed to normal-strength concrete. Preparations to transport, place, consolidate, and finish the concrete at the fastest possible rate should be made since workability time is reduced with HSC. An effective method of placing concrete is pumping because it allows a single input point as well as horizontal and vertical mobility.

Consolidation is important in achieving potential strength in HSC. After the concrete is placed in forms, it must be immediately vibrated. Care must be taken so that the concrete is not overly vibrated as this can result in segregation or loss of entrained air in cases where it is used. Since most HSC is flowing, however, it requires little vibration and contains little air.

2.3.3 Curing

The potential strength and durability of concrete will be fully developed if the concrete is properly cured for an adequate period of time. The chemical reaction between cement and water or "hydration" is responsible for the strength-producing properties of the cement paste. Time and favorable temperature and moisture conditions are required for hydration. In the beginning, hydration takes place rapidly. With time, it takes place more and more slowly and stops when the internal relative humidity of the concrete drops below 80%. The rate at which internal relative humidity decreases is very important in HSC. HSC continues to develop strength for a longer period of time than normal-strength concrete because relative humidity decreases more slowly in concretes of low water-to-cement ratios.

HSC is typically placed with water-to-cement ratios below the 0.40 required for (complete) hydration of cement.[7] Water curing is, therefore, the preferred method of curing during the first 24 hours because this method of curing provides the additional water needed. The ultimate degree of hydration is significantly reduced if moisture is not available. Water curing helps achieve more thorough hydration which leads to improved strength and surface quality. Moist curing up to as long as 28 to 90 days increases compressive strength. Fog spraying or sprinkling with spray nozzles are sufficient for water curing if immersion is not feasible. Burlap, cotton mats, rugs, and other coverings of wet absorbent materials will hold water on the surface. Sealing sheets or membranes are also acceptable for curing since they retain moisture without providing additional moisture.

To assure sufficient curing moisture for the interior of the concrete, saturated normal-weight aggregates should be used. This produces higher compressive strength in concretes with low water-to-cement ratios.[2]

2.3.4 Testing

Standard ASTM methods of sampling, molding, curing, and testing of cylinders should be followed.[8], [9], [10], [11] However, since most of these procedures were developed for testing normal-strength concrete, measures should be taken in addition to those required by existing standards.

Specimens may be cast in reusable steel molds or single-use plastic molds. Fresh concrete cast in cylinders should be finished very smooth, level, and parallel to the opposite end. After cylinders are molded, they must be covered with a plastic cap. Plastic bags and rubber bands may be used so that the surface is not distorted. Cylinders should be protected from loss of moisture at all times. The use of damp burlap prevents loss of moisture and helps to maintain a temperature of 60°F to 80°F. Storage at lower temperatures may increase 28-day strengths, but will decrease earlier age strengths. Normally, specimens are subjected to standard moist curing conditions after 24 hours.

The 4 x 8-in. (100 x 200-mm) cylinders are gaining acceptance as replacements for 6 x 12-in. (150 x 300-mm) cylinders. In Malhotra's 1976 study[12] on the effect of specimen size, he found that for development work, 4 x 8-in. (100 x 200-mm) cylinders are acceptable substitutes for 6 x 12-in. (150 x 300-mm) cylinders. In testing these smaller cylinders, it must be noted that smaller cylinders give slightly higher compressive strengths. Factors that influence measured compressive strength are specimen size and aspect ratio, preparation of the ends of the specimen, and size of the test machine's bearing block. Smaller cylinders offer many advantages among which are simplicity of fabrication, easier handling and transport, requirement of less storage space, economy, and utilization of smaller testing machines.

Capping of cylinders becomes more critical as strength of concrete increases. According to the PCA's publication, High-Strength Concrete,[2] sulfur capping compounds should be used for HSC and should be applied in a very thin uniform layer. A minimum waiting period of two hours between capping and testing must be strictly enforced. Capping may be eliminated if the ends of the cylinders are ground to required tolerances. It may be a good idea to eliminate capping due to the intrinsic strength limits of sulfur-based capping compounds. According to research by Burg and Ost,[13] surface grinding reduces skewness of data, standard deviations, and results in desired cone failures of compression specimens. Polymer pads may be used as an alternative to capping for concrete strengths up to 18,000 psi (125 MPa) if cylinder ends are smooth.

Bearing blocks on testing machines should be checked for planeness and alignment prior to testing. Cylinders should be properly centered in the machine and a protective screen or "cage" should be used to surround the cylinder. The operator should wear goggles, safety glasses, or a face shield.

The cylinders should be crushed to fracture. The appearance of a cylinder after testing may reveal inadequate capping. A cylinder should break into two conical sections with the caps intact. The capping material, planeness of caps, and machine bearing surfaces should be checked if the break is through the cap or the specimen splits vertically.

2.4 Properties

Physical properties which make HSC a desirable building material are: modulus of elasticity, drying shrinkage and creep, porosity, permeability, durability, corrosion resistance, thermal properties, adiabatic temperature, and bond to steel.

2.4.1 Strength

Concrete having compressive strengths of up to 20,000 psi (140 MPa) are now commercially available. According to research in progress,(14) strengths of 28,000 psi (190 MPa) will be achieved without using exotic aggregates, special processing, or special atmospheres and high casting pressures.

The limit of compressive strength appears to be 25,000 to 30,000 psi (170 to 210 MPa) at 90 days. However, exploratory work with special aggregates, special cements, or special processing has indicated that compressive strengths of 65,000 to 80,000 psi (450 to 550 MPa) are achievable.(13) Tensile strengths of normal-strength concrete are low and thus often ignored. However, with HSC, the tensile strengths are improved. HSC is more brittle than normal-strength concrete.

Small reductions in strength in HSC at later ages were reported by several HSC experts.[15] Minor strength regressions may be caused by self desiccation and surface drying which cause internal stresses and microcracking.

2.4.2 *In Situ* Strength

In situ compressive strength is usually lower than that of test cylinders. *Building Code Requirements for Structural Concrete*, ACI 318[16] states: "Concrete in an area represented by core tests shall be considered structurally adequate if the average of three cores is equal to at least 85% of f'_c and if no single core is less than 75% of f'_c." In HSC, minor imperfections such as entrapped air, micro-cracks and boundary conditions including cut aggregate and lack of total paste interlock of the near surface aggregate may contribute proportionately more to a lower strength in cores.[13] The study done by Burg and Ost did not find a significant strength difference between cores from the near surface of 4-ft (1220-mm) cubes and cores from the center. Early heat rise in the cube centers did not significantly affect core strengths. Cores from the bottom of the cubes had higher compressive strengths than those from the top due to consolidation and moisture movement. As *in situ* concrete ages, compressive strength is increasingly affected by loading history and relative humidity.

2.4.3 Modulus of Elasticity

Modulus of elasticity is the ratio of normal stress to strain for stresses below the proportional limit of a material. The modulus of elasticity is useful in determining deformation and stress distribution between concrete and steel in reinforced or prestressed members. A strain value of 0.003, as determined by ACI Committee 363,[1] satisfactorily represents experimental results for HSC.

Reinforced concrete may be efficiently designed because both concrete and steel yield or fail at the same load. Unreinforced concrete has some ductility which decreases with increasing concrete strength. The higher the strength of the concrete, the more brittle the concrete. In addition, faster rates of loading enhance the compressive strength and stiffness of concrete.

Modulus of elasticity of concrete, E_c, is dependent on the moduli of the paste and aggregate, and the relative amounts of the paste and aggregate. Different strengths and moduli of concrete are achieved by using different types and combinations of fine and coarse aggregate. E_c changes with variation in the modulus of elasticity of the paste and increased bonding with aggregates as curing continues. The general empirical relationship between strength and modulus of elasticity can be expressed with the following equation: $E_c = 40{,}000 * (f'_c)^{1/2} + 1.0 \times 10^6$ psi.[17] To determine the E_c, an extensometer is used to measure length and volume changes induced in the specimen by a load. The data obtained is used to plot stress-strain curves from which the E_c is determined.

The modulus of elasticity of the paste is a function of water-to-cement ratio and age. The lower the absorption of the aggregate, the higher the modulus of elasticity of the aggregate. This means, the greater the volume of paste per unit of aggregate, the lower the E_c will be. Concretes of similar strength, but made with different aggregates may have different moduli of elasticity because modulus of elasticity is affected by paste strength and aggregate type. Compressive strength alone is not a good indicator of modulus of elasticity of different concrete mixtures.(2) For a particular mixture, however, strength is a good indicator of the E_c. Furthermore, the modulus does not increase as rapidly with age as strength in HSC.

Burg and Ost(13) found that at equivalent strengths, E_c values were higher for moist-cured specimens than for air-cured specimens.

2.4.4 Drying Shrinkage and Creep

Drying shrinkage is a result of evaporation of chemically uncombined water. It can affect not only appearance, but performance. Creep is the dimensional change or increase in strain with time due to sustained stress. Effects of drying shrinkage and creep should be compensated for in structural designs. HSC members will experience lower creep than normal-strength members since specific creep (the measured creep strain divided by the applied stress) in HSC is 40 to 70% of specific creep in normal-strength concrete.

Parameters which affect drying shrinkage and creep are: size of the concrete element, cement paste content and characteristics, total water content, physical characteristics of the aggregate, environmental exposure conditions, ratio of volume-to-surface area, and amount of reinforcement.

The size of a member affects shrinkage and creep of concrete under drying conditions. The ultimate values of shrinkage and creep are smaller for larger members. More time is required to undergo dimensional changes in larger members.

Cement paste largely determines drying shrinkage and creep due to variations in chemical composition and fineness of the cement. These properties influence the rate of hydration and thus, the strength gain of concrete. Concrete strength at the time of loading affects the amount of creep. In the study by Burg and Ost,(13) specific creep was lowest for concretes with the highest compressive strengths. This trend is also observed in normal-strength concretes. Changes in water-to-cement ratio do not generally affect drying shrinkage.(18) Creep, however, increases with an increase in water-to-cement ratio.(18)

SMF superplasticizers increase drying shrinkage and creep by 10%. This increase is offset by the reduction in mixing water requirement allowed by superplasticizers, thus, superplasticized concretes experience approximately the same creep as reference concretes. Concrete made with fly ash tends to creep less than normal-strength concrete at ages later than 400 days. Low water content and improved strength achieved with the use of silica fume should result in decreases in the amount of creep over normal-strength concrete.

The purpose of aggregate in concrete is to minimize the paste content and restrain shrinkage and creep of the paste. Restraint of shrinkage and creep of the paste reduces overall shrinkage and creep of the concrete. The use of hard aggregates with high density, high modulus of elasticity, and moderate porosity or absorption, generally produces concrete with the lowest drying shrinkage and creep.

Humidity, temperature, and air circulation influence the rate of drying and the ultimate drying shrinkage and creep. Concrete exposed to a dry environment will have greater drying shrinkage and creep than concrete exposed to high humidities or subjected to a long moist-curing period.

Amount and rate of shrinkage and creep decrease as the ratio of volume-to-surface area of the member increases. Furthermore, the ultimate deformation decreases and the time required to reach ultimate deformation is lengthened with increased volume-to-surface area ratio. Burg and Ost(13) tested prisms in their study and found that the prisms having smaller volume-to-surface area ratios had higher overall shrinkage due to the faster rate of drying.

Shrinkage and creep is less in reinforced concrete as compared to plain concrete because steel reinforcement restricts drying shrinkage. The reduction in shrinkage and creep depends on the amount of reinforcement.

2.5 Summary

(1) The exact point at which concrete can be classified as either "normal-strength" or "high-strength" is vague. The American Concrete Institute defines high strength as compressive strength over 6000 psi (40 MPa).[1]

(2) High-strength concrete consists of the same basic ingredients as normal-strength concrete. The differences are that in high-strength concrete, entrained or entrapped air is reduced or removed, the addition of normal and high-range water-reducing admixtures or "superplasticizers" is mandatory to ensure workability at low water-to-cement ratios, and pozzolans are used to improve the paste by physical and chemical processes.[2]

(3) The production of high strength concrete is achieved by optimizing the characteristics of the cementing medium, characteristics of the aggregate, proportions of the paste, paste-aggregate interaction, mixing, consolidating, curing, and testing procedures.[2]

(4) Efficient mixing of high-strength concrete is more difficult than conventional concrete because of low water contents, high cement contents, and the absence of large coarse aggregate. Preparations to transport, place, consolidate, and finish the concrete at the fastest possible rate must be made since workability time is reduced with HSC.

(5) Physical properties which make HSC a desirable building material are: modulus of elasticity, drying shrinkage and creep, porosity, permeability, durability, corrosion resistance, thermal properties, adiabatic temperature, and bond to steel.

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Chapter 3

Review of the Probe Penetration Test

3.1 Introduction

Nondestructive testing is useful in identifying the quality of *in situ* concrete and in determining the relative strength of structural members. It is also useful in detecting areas where defects may exist. Nondestructive testing methods measure properties of concrete with which relative strength can be determined without testing specimens to failure. However, nondestructive test measurements are influenced by many variables such as aggregate type and size, age of concrete, moisture content, and mix proportions.[1] Therefore, the correlation between measured properties and relative strength is different for different concretes and must be adjusted for the particular concrete being tested.[2] There are several methods used in nondestructive testing including the penetration resistance methods.

Penetration resistance methods are based on the depth of penetration of a probe or a pin into concrete and are used for quality control and strength estimation of *in situ* concrete. The depth of penetration is a measure of the hardness or penetration resistance of the material which can be related to strength.

The most well known and widely used technique is the Windsor probe system which was introduced to the U.S. in the 1960s. The pin penetration test in Canada followed in the 1980s. This chapter focuses on the probe penetration test which is the method used in this study.

3.2 Probe Penetration Test System

The Windsor probe was advanced for penetration testing of laboratory and *in situ* concrete between 1964 and 1966. The technique was developed by the Port of New York Authority, New York, and the Windsor Machinery Co. in Connecticut.[3] It was designed to estimate the compressive strength of concrete by measuring the depth of penetration of probes driven into concrete by a powder-actuated driver. The probe penetration relates to some property of the concrete below the surface, making it possible to develop empirical correlations between compressive strength and probe penetration.

3.2.1 Description

The main equipment used in the Windsor probe testing system are a powder-actuated driver, hardened alloy-steel probes, loaded cartridges, and a depth gauge as shown in Figure 3.1. The standard probe has a tip with a conical point. The other end is threaded and screws into a driving head which fits snugly into the bore of the driver. The probe is driven into the concrete by firing of a powder charge. The power level can be decreased by pushing the probe further into the barrel.

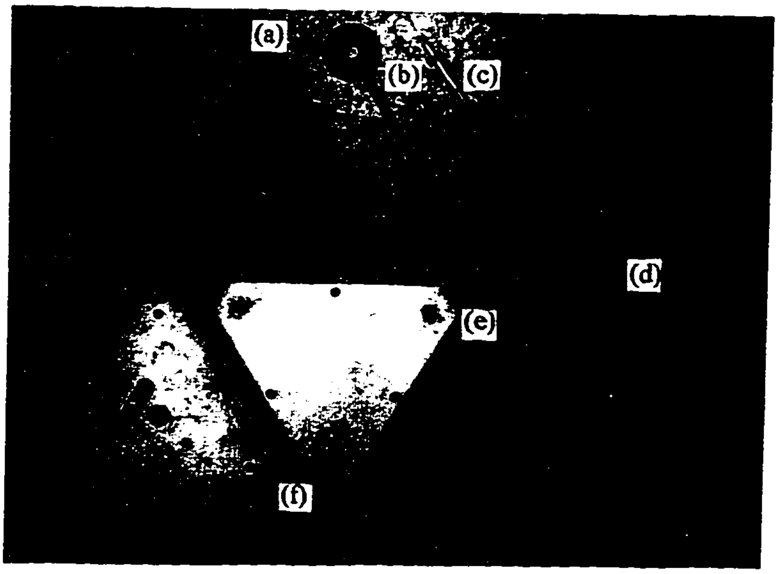

Figure 3.1: Equipment of the Windsor Probe Test

(a) triangular template
(b) single probe template
(c) hardened alloy-steel probe
(d) powder-actuated driver
(e) depth gauge
(f) mechanical averaging device

3.2.2 Method of Testing

The powder-actuated driver is used to drive probes into the concrete. Areas to be tested must have smooth surfaces. If flat surfaces are to be tested, three probes are driven into the concrete in a triangular pattern by means of a triangular template. A mechanical averaging device is used to measure the average exposed length of the three probes fired in a triangular pattern. If curved surfaces are to be tested, a single probe template is used and three probes are driven in three different locations. In both cases, the average value of exposed probe length is used to estimate the compressive strength of the concrete.

3.2.3 Correlation Procedure

The manufacturer of the Windsor probe test system has published tables relating exposed probe length to compressive strength.[5] Different values of compressive strength are given for each exposed length depending on the hardness of the aggregate. These tables are based on empirical relationships. However, studies conducted by Keiller[4] have found that these tables are not always satisfactory. It is, therefore, imperative that each user of the probe test system correlate probe test results with the type of concrete being used. The exposed probe length must be plotted against compressive strength and a curve or line fitted to the data by the method of least squares.

3.2.4 Mechanism of Concrete Failure

Penetration of the probe causes a cone-shaped fracture. Penetration below this fracture zone is largely resisted by the compression of the adjacent material. The manufacturer of the Windsor probe testing system claims that the probe test measures the compressibility of a localized area of concrete by creating a subsurface compaction bulb.[5] It is further claimed that the energy required to break pieces of aggregate is such a low percentage of the total energy of the driven probe, that the depth of penetration is not significantly affected.[5] Although there is no proof of these claims, it appears that the probe penetrations relate to some strength parameter below the surface of the concrete, which enables the establishment of empirical relationships between the depth of penetration and compressive strength.

3.2.5 Correlations Between Probe Test Results and Compressive Strength

Manufacturer's tables may give unsatisfactory results because factors, other than aggregate hardness, that affect probe penetration have not been considered. The largest influence on probe penetration comes from the coarse aggregate. The type and size of coarse aggregate have a significant effect on probe penetration.[6] Mixture proportions, moisture content, curing, and surface conditions are other parameters which may affect these correlations. Degree of carbonation may change the physical and chemical characteristics of the concrete. Age is also another significant parameter. The probe test may indicate higher strengths than actually exist in very old concrete due to microcracking between the aggregates and paste which affects compressive strength but does not affect probe penetration.[7] Other factors related to particular testing conditions need to be considered in using these correlation curves.

3.2.6 Variability

In general, within-batch variability of probe penetration tests can be attributed to operator and equipment errors, and the heterogeneous nature of concrete.[3] Operator error is generally minimal. Variations more likely result from the test equipment. For example, more accurate devices to measure exposed probe length could possibly reduce variations. The heterogeneous nature of the concrete is likely to be the major contributor to the variations in test results.

3.2.7 Variations in Estimated Strength Values

Uncertainty in estimated strength is a function of both the variability of the penetration measurements, and the degree of sensitivity of the penetration test in detecting small changes in strength.[3] It is necessary to use statistical procedures that take into account the variability of the penetration readings and the uncertainty of the correlation relationship.[8]

3.2.8 Use for Early Form Removal

By the late 1970s, the probe penetration test was probably the most widely used nondestructive method for the determination of safe stripping times.[9] The main advantage of this test is its great simplicity. Carette and Malhotra[10] concluded that the probe penetration test can estimate the early-age strength developments of concrete with a reasonable degree of accuracy and can be applied to determine safe stripping times for formwork removal.

3.2.9 Probe Penetration Versus Core Testing

The advantages of the probe penetration test should be judged against the precision of its test results.[3] Carette and Malhotra[10] found that at early ages, the probe penetration test results showed better correlation with standard cylinder strengths than with core strengths due to variations in the temperature history of the test slabs. The core test is the most reliable in estimating *in situ* strength since it is a direct measurement. However, it is possible to establish relationships between probe penetration and strength which are sufficiently accurate enough for probe testing to satisfactorily be substituted for core testing.

3.2.10 North American Survey on the Use of the Probe Penetration Test

In the early 1980s, a North American survey determined that the Windsor probe penetration technique was the second most often used method for *in situ* strength testing of concrete.[8] Methods including the rebound hammer, probe penetration, pullout, pulse velocity, maturity, and cast-in-place cylinder were considered. In terms of reliability, simplicity, accuracy, and economy, the probe test was given one of the best combined ratings.[3]

3.2.11 Advantages and Disadvantages

The advantages of the probe penetration test include the following:[3]

- Simple to operate.
- Requires little maintenance.
- Built-in safety feature that prevents accidental discharge of the probe.
- Speed and simplicity.
- Requires only one surface for the test.
- Correlation with concrete strength is affected by a relatively small number of variables.

The disadvantages of the probe penetration test include the following:[3]

- Must correlate probe test results with the particular type of concrete being used.
- Minimum size required of the concrete member to be tested.
- Minimum thickness required of members to be tested.
- Distance from reinforcement may affect depth of penetration.
- Uncertainty of estimated strength value is relatively large.

- Limitation to a certain range of strength (< 5800 psi or 40 MPa).
- Minor damage to concrete surfaces tested which need repair after the test is performed.

3.2.12 Standardization of the Probe Penetration Test

In 1972, the ASTM C 9 Committee initiated the development of a standard for penetration resistance techniques. A tentative test method covering their use was first issued in 1975.[3] A standard test method designated ASTM C 803 "Penetration Resistance of Hardened Concrete" was later issued in 1982 and the current edition of the standard test method was published in 1990.[11] The only equipment available that meets the ASTM C 803 requirements for probe penetration resistance methods is the Windsor probe test.

3.2.13 Limitations and Usefulness of Penetration Resistance Methods

Penetration resistance methods are hardness methods and should not be expected to yield absolute values of strength of concrete in a structure.[3] Penetration tests, however, are useful in determining relative strength in the same structure. Penetration tests may be used to estimate the strength of *in situ* concrete, but accurate correlations are required. Each user of the probe penetration test should prepare his own correlation curves for the specific type of concrete being tested since this test is sensitive to certain characteristics of aggregate. New correlations must be established if there is a change in the source of aggregates.

Although the probe penetration test is considered a nondestructive test, this is not exactly true. Upon penetration, the probe leaves minor damage on a small area with a 1/3-in. (8-mm) hole in the concrete. In mature concrete, the probe may also leave a fractured cone-shaped region, which may extend to the depth of penetration.

Standard probes made of AISI 4140 steel have a tendency to break at the threaded region when driven into concrete with compressive strengths above 3,000 psi (25 MPa). To solve this problem, various probe tips and various steels were tested. It was found that AISI 1045 steel probes with the standard probe tip and a rolled thread had the potential to satisfactorily evaluate concrete with compressive strengths above 3,000 psi (25 MPa). Figure 3.2 shows the standard probe and the proposed modified probe.

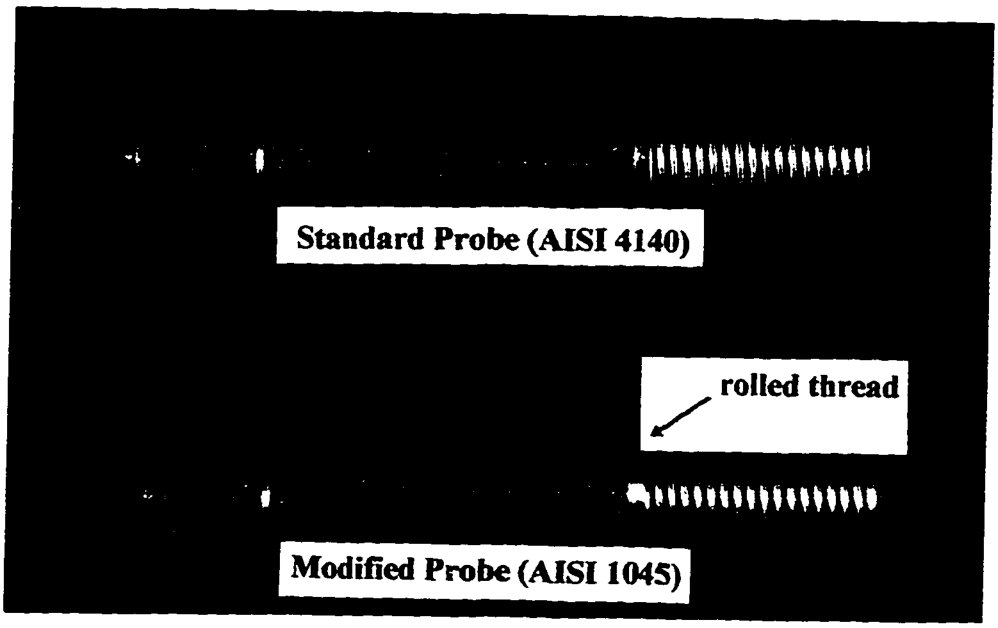

Figure 3.2: Standard Probe and Modified Probe

3.3 Summary

(1) Nondestructive testing methods are useful in identifying the quality of *in situ* concrete and in determining the relative strength of structural members. Nondestructive methods measure properties of concrete without testing specimens to failure. Nondestructive testing consists of several methods including the penetration resistance methods.

(2) The Windsor probe test is a penetration resistance method designed to estimate the compressive strength of concrete by measuring the depth of penetration of probes driven into concrete by a powder-actuated driver.

(3) It is imperative that each user of the probe test system correlate probe test results with the type of concrete being tested since several factors affect probe penetration. Among these factors are the type and size of coarse aggregate, mixture proportions, moisture content, curing, surface conditions, degree of carbonation, and age.

(4) Standard probes made with AISI 4140 steel had problems in determining *in situ* strength above 3,000 psi (25MPa). A new probe made of AISI 1045 steel with a rolled thread was proposed for evaluation.

3.4 References

(1) Malhotra, V. M., "*In situ*/Nondestructive Testing of Concrete--A Global Review," *In Situ/Nondestructive Testing of Concrete*, SP-82, American Concrete Institute, Detroit, 1984, pp. 1-16.

(2) Nasser, K. W. and Al-Manaseer, A. A., "Comparison of Nondestructive Testers of Hardened Concrete," *ACI Materials Journal*, September 1987, pp. 374-380.

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(4) Keiller, A. P., "Assessing the Strength of In-Situ Concrete," *Concrete International*, ACI., February 1985, p.15

(5) Windsor Probe Test System, Inc, *Compressive Strength Testing of Concrete*, Elmwood, CT, 1970.

(6) Swamy, R. N., and Al-Hamed, A. H. M. S., *Evaluation of the Windsor Probe Test to Assess In-Situ Concrete Strength*, Proceedings of the Institute of Civil Engineering, Part 2, June 1984, p. 167.

(7) ACI Committee 207, "Practices for Evaluation of Concrete in Existing Massive Structures for Service Conditions," *ACI Manual of Concrete Practice*, American Concrete Institute, Detroit, MI, 1983.

(8) ACI Committee 228, "In-place methods for determination of strength of concrete," *ACI Materials Journal.*, 1988, p. 446.

(9) Bartos, M. J., "Testing Concrete In Place," *Civil Engineering*, 1979, p. 66.

(10) Carette, G. G. and Malhotra, V. M., *In-Situ Tests: Variability and Strength Prediction of Concrete at Early Ages*, Malhotra, V. M., Ed., American Concrete Institute, SP-82, 1984, p. 111.

(11) *1996 Annual Book of ASTM Standards*, "Standard Test Method for Penetration Resistance of Hardened Concrete," American Society for Testing and Materials, Philadelphia, V. 04.02 (C 803).

Chapter 4

Material Investigation of Concrete Containing Ultimax Cement

4.1 Introduction

This chapter describes the properties of concrete containing a new type of rapid hardening hydraulic cement commercially known as "Ultimax cement." Tests were conducted to evaluate the fresh and hardened properties of concrete made with Ultimax cement and concrete containing ASTM Type I/II Portland cement. These properties included the slump, compressive strength, modulus of elasticity, splitting-tensile strength, bulk density, shrinkage, and expansion.

4.2 Properties of Concrete Constituents

4.2.1 Cement

Two types of cement were used in this investigation, Ultimax cement, a new rapid hardening hydraulic cement, and ASTM Type I/II Portland cement. The chemical composition and physical properties of both cements are summarized in Table 4.1.

Table 4.1: Chemical Composition and Physical Properties of Ultimax and ASTM Type I/II Cements

Chemical Composition %	Ultimax Cement*	ASTM Type I/II Cement**	ASTM C 150 Specifications for Type I Cement	ASTM C 150 Specifications for Type II Cement
Silicon dioxide (SiO_2)	14.6	21.73	—	20.0 min
Aluminum oxide (Al_2O_3)	13.1	4.12	—	6.0 max
Ferric oxide (Fe_2O_3)	4.2	3.48	—	6.0 max
Calcium oxide (CaO)	48.9	63.75	—	—
Magnesium oxide (MgO)	1.2	1.72	6.0 max	6.0 max
Sulfur trioxide (SO_3)	11.6	2.59	3.0 max	3.0 max
Loss on ignition	3.86	1.33	3.0 max	3.0 max
Sodium oxide (Na_2O)	0.66	0.31	—	—
Potassium oxide (K_2O)	0.96	0.44	—	—
Equivalent alkalies ($Na_2O + 0.658K_2O$)	1.29	0.60	0.60 max	0.60 max
Insoluble residue	2.31	0.23	0.75 max	0.75 max
Compound Composition %* **				
Dicalcium silicate (C_2S)	—	21.31	—	—
Tricalcium silicate (C_3S)	—	54.34	—	—
Tricalcium aluminate (C_3A)	—	5.01	—	8.0 max
Sum of tricalcium silicate and tricalcium aluminate	—	59.35	—	58.0 max
Tertracalcium aluminoferrite (C_4AF)	—	10.60	—	—
Physical Properties				
Blaine fineness, m^2/kg	616	3772	160 min	160 min
No 325 fineness	85.0 % passing	92.7	—	—
Autoclave expansion, %	0.03	0.053	0.8 max	0.8 max
Setting time, Gilmore needles (min):				
Initial	31	133	60 min	60 min
Final	46	259	600 max	600 max
Setting time, Vicat (min):				
Initial	—	61	45 min	45 min
Final	—	169	375 max	375 max
Air content of mortar, volume %	18.6[#]	7.2	12 max	12 max
Compressive strength (psi) at:				
3 hours	3220	—	—	—
1 day	5080	1702	—	—
3 days	—	2969	1740 min	1450 min
7 days	—	3886	2760 min	2470 min
28 days	—	5517	4060 min	4060 min

* Chemical composition and physical data were provided by Ultimax Corporation in Huntington Beach, CA.
** Chemical composition and physical data were provided by RMC Lonestar in Davenport, CA.
*** Data not available for Ultimax cement
[#] Batched at 0.385 water-to-cement ratio

4.2.2 Aggregate

The coarse aggregate used in this study was composed of crushed granite. The maximum nominal size of the aggregate was 3/8 in. The aggregate was delivered from a granite crushing plant at two different dates during this investigation; therefore, two sieve analyses were performed in accordance to ASTM C 136[1] to determine the particle size distribution. The specific gravity and absorption of the coarse aggregate were determined in accordance to ASTM C 127.[2]

The fine aggregate was composed of crushed granite and had a fineness modulus ranging from 2.71 to 3.07. Two sieve analyses were performed in accordance to ASTM C 136.[1] The specific gravity and absorption of the fine aggregate were determined in accordance to ASTM C 128.[3]

The results of the sieve analyses and the physical properties of the aggregates are summarized in Tables 4.2 through 4.5. The sieve analyses are plotted in Figures 4.1 through 4.4. All data met ASTM C 33[4] specifications.

4.3 Mix Design

A total of twenty mixes were made to investigate the properties of concrete made with Ultimax cement and ASTM Type I/II cement. The concrete mixes were made with water-to-cement ratios of 0.30, 0.35, 0.40, 0.45, and 0.50.

Non-air-entrained concrete mixes were designed in accordance to the absolute volume method as described by the Portland Cement Association.[5] Fifteen mixes were

Table 4.2: Results of the First Sieve Analysis

3/8 in. Coarse Aggregate				Fine Aggregate			
ASTM C 33 Sieve Size	ASTM C 33 Lower Limit	ASTM C 33 Upper Limit	Cumulative Percentage Passing	ASTM C 33 Sieve Size	ASTM C 33 Lower Limit	ASTM C 33 Upper Limit	Cumulative Percentage Passing
1 in.	----	----	----	3/8 in.	100	100	100.00
3/4 in.	----	----	----	No. 4	95	100	100.00
1/2 in.	100	100	100.00	No. 8	80	100	90.91
3/8 in.	85	100	100.00	No. 16	50	85	63.64
No. 4	10	30	11.04	No. 30	25	60	40.00
No. 8	0	10	1.70	No. 50	10	30	21.82
pan	0	0	0.00	No. 100	2	10	12.73
				No. 200	----	----	7.27
				pan	0	0	0.00

Table 4.3: Physical Properties of the First Batch of Aggregate Delivered

3/8 in. Coarse Aggregate		Fine Aggregate	
Bulk specific gravity	2.64	Fineness Modulus	2.71
Bulk specific gravity (SSD)	2.72	Bulk specific gravity	2.18
Absorption	2.86%	Bulk specific gravity (SSD)	2.44
Total moisture content	2.88%	Absorption	1.37%
Unit weight	93.50 pcf	Total moisture content	0.70%

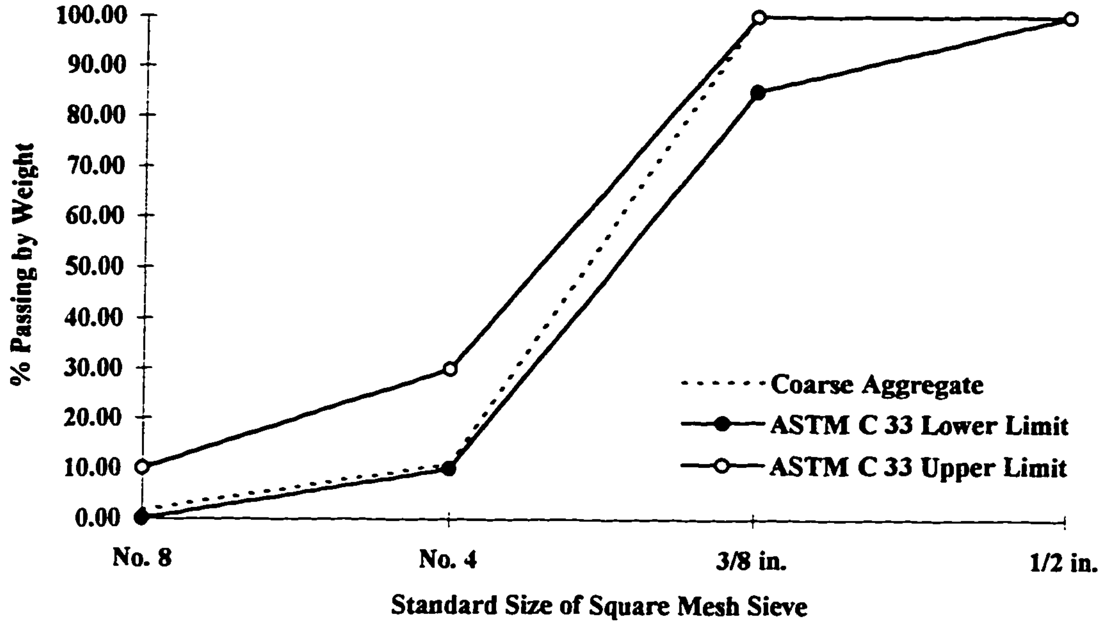


Figure 4.1: First Sieve Analysis for the 3/8 in. Coarse Aggregate

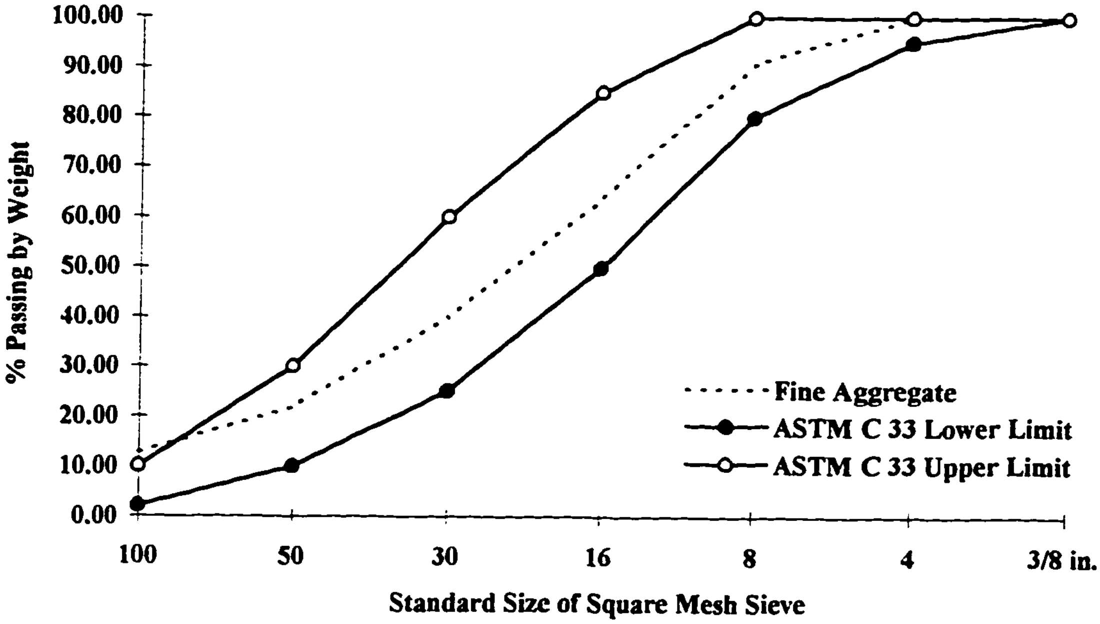


Figure 4.2: First Sieve Analysis for the Fine Aggregate

Table 4.4: Results of the Second Sieve Analysis

3/8 in. Coarse Aggregate				Fine Aggregate			
ASTM C 33 Sieve Size	ASTM C 33 Lower Limit	ASTM C 33 Upper Limit	Cumulative Percentage Passing	ASTM C 33 Sieve Size	ASTM C 33 Lower Limit	ASTM C 33 Upper Limit	Cumulative Percentage Passing
1 in.	----	----	----	3/8 in.	100	100	100.00
3/4 in.	----	----	----	No. 4	95	100	99.32
1/2 in.	100	100	100.00	No. 8	80	100	84.35
3/8 in.	85	100	100.00	No. 16	50	85	56.46
No. 4	10	30	17.33	No. 30	25	60	33.33
No. 8	0	10	4.83	No. 50	10	30	14.29
pan	0	0	0.00	No. 100	2	10	5.44
				No. 200	----	----	2.72
				pan	0	0	0.00

Table 4.5: Physical Properties of the Second Batch of Aggregate Delivered

3/8 in. Coarse Aggregate		Fine Aggregate	
Bulk specific gravity	2.71	Fineness Modulus	3.07
Bulk specific gravity (SSD)	2.77	Bulk specific gravity	2.44
Absorption	2.27%	Bulk specific gravity (SSD)	2.56
Total moisture content	2.01%	Absorption	5.26%
Unit weight	97.40 pcf	Total moisture content	6.16%

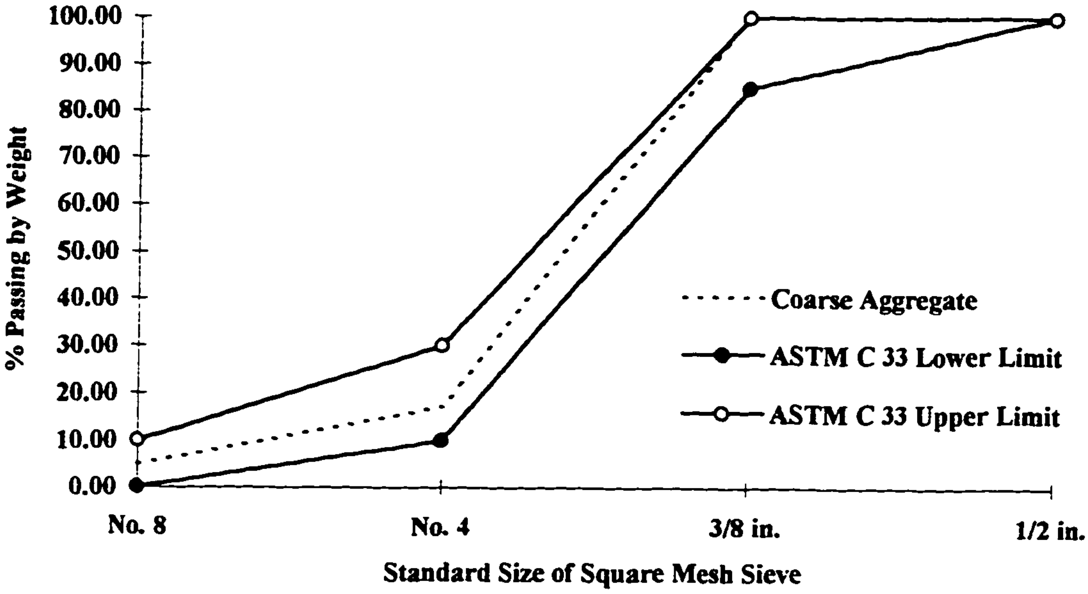


Figure 4.3: Second Sieve Analysis for the 3/8 in. Coarse Aggregate

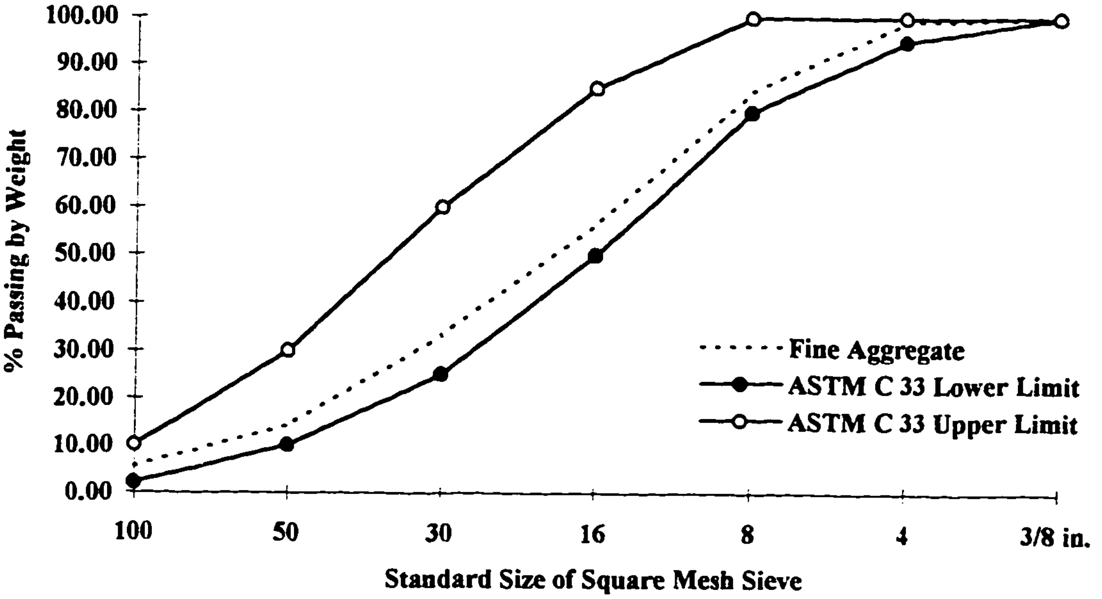


Figure 4.4: Second Sieve Analysis for the Fine Aggregate

made with Ultimax cement while the other five mixes were made with ASTM Type I/II cement. Tables 4.6 and 4.7 show the mix proportions for concrete made with Ultimax cement and concrete made with ASTM Type I/II cement. The majority of the mixes were mixed in more than one batch. The batches are indicated by the letters A, B, C, or D, next to the mix numbers.

4.4 Mixing Procedure

The following mixing procedure was used in this study to avoid false setting and gave the best results:

(1) Wet the mixer and drain the water.

(2) Add the coarse aggregate followed by the fine aggregate.

(3) Add the water until all aggregate is wet and uniformly mixed (approximately one-third the water).

(4) Add the cement alternately with the remaining water.

(5) Mix for three minutes after all components are added, let stand for two minutes, then mix for an additional three minutes.

4.5 Testing Program

The number and sizes of specimens cast from each mix are shown in Table 4.8. A maximum of thirty-six 4 x 8-in. (100 x 200-mm) cylinders, six 6 x 12-in. (150 x 300-mm) cylinders, and six 3 x 3 x 11 1/4-in. (76 x 76 x 285-mm) prisms were cast from each

Table 4.6: Mix Proportions Before Adjustments for Moisture Content and Absorption

Mix No.	*w/cm	**A/cm	***CA/FA	Fineness Modulus of Fine Aggregate	Volume of Coarse Aggregate Per Unit of Volume of Concrete	Mix Component: Water (lb/cyd)	Ultimax Cement (lb/cyd)	Portland Cement, Type I/II (lb/cyd)	3/8 in. Coarse Aggregate (lb/cyd)	Fine Aggregate (lb/cyd)
1A, 1B, 1C	0.35	3.02	0.77	2.71	0.47	315	900	0	1186	1540
1D	0.35	3.13	0.70	3.07	0.44	315	900	0	1157	1653
2A, 2B	0.40	3.49	0.74	2.71	0.47	320	800	0	1186	1603
2C	0.40	3.50	0.79	3.07	0.44	320	800	0	1157	1465
3A	0.45	4.12	0.70	2.71	0.47	315	700	0	1186	1694
3B	0.45	4.13	0.75	3.07	0.44	315	700	0	1157	1543
4A, 4B	0.50	5.01	0.65	2.71	0.47	300	600	0	1186	1825
4C	0.50	5.19	0.59	3.07	0.44	300	600	0	1157	1961
5A, 5B, 5C	0.30	2.07	0.97	2.71	0.47	350	1166	0	1186	1223
6A, 6B	0.30	2.18	0.93	2.71	0.47	340	1133	0	1186	1275
7A, 7B	0.30	2.29	0.89	2.71	0.47	330	1100	0	1186	1333
8A, 8B	0.30	2.41	0.86	2.71	0.47	320	1067	0	1186	1379
9A, 9B	0.30	2.54	0.83	2.71	0.47	310	1033	0	1186	1429
10A, 10B	0.30	2.67	0.80	2.71	0.47	300	1000	0	1186	1483
11A, 11B	0.50	4.18	0.72	2.71	0.47	340	680	0	1186	1647
12A, 12B	0.50	4.37	0.70	2.71	0.47	330	660	0	1186	1694
13A, 13B	0.50	4.57	0.68	2.71	0.47	320	640	0	1186	1744
14A, 14B	0.50	4.78	0.67	2.71	0.47	310	620	0	1186	1770
15A, 15B	0.50	5.25	0.64	2.71	0.47	290	580	0	1186	1853
16A, 16B#	0.40	1.58	1.32	3.07	0.44	515	0	1288	1157	877
17#	0.50	2.85	0.84	3.07	0.44	445	0	890	1157	1377
18#	0.30	0.62	14.06	3.07	0.44	600	0	2000	1157	82
19A, 19B#	0.45	2.08	1.05	3.07	0.44	490	0	1089	1157	1102
20A, 20B#	0.35	0.97	2.65	3.07	0.44	575	0	1643	1157	437

* *w/cm* = Water-to-cementitious materials ratio by weight
** *A/cm* = Aggregate-to-cementitious materials ratio by weight
*** CA/FA = Coarse aggregate-to-fine aggregate ratio by weight
\# Mixes containing ASTM Type I/II cement.

Table 4.7: Mix Proportions After Adjustments for Moisture Content and Absorption

Mix No.	Moisture Content		Absorption		Mix Component				
	Coarse Aggregate (%)	Fine Aggregate (%)	Coarse Aggregate (%)	Fine Aggregate (%)	Water (lb/cyd)	Ultimax Cement (lb/cyd)	Portland Cement, Type I/II (lb/cyd)	3/8 in. Coarse Aggregate (lb/cyd)	Fine Aggregate (lb/cyd)
1A, 1B, 1C	2.88	0.70	2.86	1.37	315	900	0	1221	1544
1D	2.01	6.16	2.27	5.26	315	900	0	1180	1758
2A, 2B	2.88	0.70	2.86	1.37	320	800	0	1221	1615
2C	2.01	6.96	2.86	1.37	320	800	0	1261	1668
3A	2.88	0.70	2.86	1.37	315	700	0	1221	1711
3B	2.01	6.96	2.86	5.26	315	700	0	1261	1770
4A, 4B	2.88	0.70	2.86	1.37	300	600	0	1221	1831
4C	2.01	6.16	2.27	5.26	300	600	0	1180	2075
5A, 5B, 5C	2.88	0.70	2.86	1.37	350	1166	0	1221	1236
6A, 6B	2.88	0.70	2.86	1.37	340	1133	0	1221	1288
7A, 7B	2.88	0.70	2.86	1.37	330	1100	0	1221	1341
8A, 8B	2.88	0.70	2.86	1.37	320	1067	0	1221	1393
9A, 9B	2.88	0.70	2.86	1.37	310	1033	0	1221	1445
10A, 10B	2.58	2.50	2.86	1.37	300	1000	0	1217	1498
11A, 11B	2.58	2.50	2.86	1.37	340	680	0	1217	1666
12A, 12B	2.58	2.50	2.86	1.37	330	660	0	1217	1707
13A, 13B	2.58	2.50	2.86	1.37	320	640	0	1217	1749
14A, 14B	0.00	6.99	2.86	1.37	310	620	0	1187	1790
15A, 15B	2.58	2.50	2.86	1.37	290	580	0	1217	1872
16A, 16B*	2.01	6.16	2.27	5.26	515	0	1288	1180	933
17*	2.01	6.16	2.27	5.26	445	0	890	1180	1466
18*	2.01	6.16	2.27	5.26	600	0	2000	1180	87
19A, 19B*	2.01	6.16	2.27	5.26	490	0	1089	1180	1172
20A, 20B*	2.01	6.16	2.27	5.26	575	0	1643	1180	463

* Mixes containing ASTM Type I/II cement.

Table 4.8: Mix Date, Quantity of Specimens, and Slump Measurements

Mix No.	*w/cm*	Cement Content (lb/cyd)	Mix Date (1997)	No. of Cylinders 4 x 8-in.	No. of Cylinders 6 x 12-in.	No. of Prisms*	Slump (in.)
1A	0.35	900	10-Jan	9	2	0	8 5/8
1B	0.35	900	10-Jan	9	3	0	—
1C	0.35	900	11-Jan	18	0	0	—
1D	0.35	900	18-Feb	0	1	6	8 1/2
2A	0.40	800	11-Jan	18	3	0	9 1/2
2B	0.40	800	11-Jan	18	2	0	—
2C	0.40	800	14-Feb	0	1	6	3 3/4**
3A	0.45	700	11-Jan	36	0	0	7 1/8
3B	0.45	700	15-Feb	0	6	6	7/8**
4A	0.50	600	13-Jan	18	3	0	4**
4B	0.50	600	13-Jan	18	3	0	—
4C	0.50	600	17-Feb	0	0	6	1/2
5A	0.30	1166	18-Jan	9	2	3	8 1/2
5B	0.30	1166	18-Jan	9	3	0	—
5C	0.30	1166	18-Jan	18	0	0	—
6A	0.30	1133	18-Jan	17	3	3	8 1/4
6B	0.30	1133	20-Jan	18	3	0	9
7A	0.30	1100	21-Jan	18	3	3	8 3/4
7B	0.30	1100	21-Jan	18	3	0	8 1/8
8A	0.30	1067	21-Jan	18	3	3	9
8B	0.30	1067	21-Jan	18	3	0	8 3/8
9A	0.30	1033	22-Jan	18	3	3	9 5/8
9B	0.30	1033	22-Jan	18	3	0	9 3/8
10A	0.30	1000	23-Jan	18	3	3	6 1/2
10B	0.30	1000	23-Jan	18	3	0	7 3/4
11A	0.50	680	24-Jan	18	3	3	9 1/2
11B	0.50	680	24-Jan	18	3	0	11
12A	0.50	660	25-Jan	18	3	3	9 5/8
12B	0.50	660	25-Jan	18	3	0	9 5/8
13A	0.50	640	25-Jan	18	3	3	10 1/8
13B	0.50	640	25-Jan	18	3	0	9 1/2
14A	0.50	620	30-Jan	18	3	3	1 5/8
14B	0.50	620	30-Jan	18	3	0	1 1/4
15A	0.50	580	28-Jan	18	3	3	—
15B	0.50	580	28-Jan	18	3	0	1/8
16A#	0.40	1288	19-Feb	3	0	0	9 1/4
16B#	0.40	1288	19-Feb	12	0	6	9 1/2
17#	0.50	890	20-Feb	15	0	6	3 3/8
18#	0.30	2000	21-Feb	15	0	6	5
19A#	0.45	1089	22-Feb	3	0	0	7 1/4
19B#	0.45	1089	22-Feb	12	0	3	8 1/8
20A#	0.35	1643	22-Feb	3	0	0	7 3/4
20B#	0.35	1643	22-Feb	12	0	3	7 1/4
Total:				614	89	81	

* Prism dimensions: 3 x 3 x 11 1/4 in.

** Value not used; out of norm.

Mixes containing ASTM Type I/II cement.

mix made with Ultimax cement. Fifteen 4 x 8-in. (100 x 200-mm) cylinders and a maximum of six prisms were cast from each mix made with ASTM Type I/II cement. The cylinders were cast in three layers and rodded with standard 5/8 in. rods as described in ASTM C 192.[6] The prisms were cast in two layers and rodded as described in ASTM C 157[7] and C 192.[6] The cylinders and prisms made with Ultimax cement were left to cure in a moist room for three hours, then stripped of their molds. The cylinders and 2 to 3 prisms from each mix were then placed in water tanks at 72° ± 2°F (22° ± 1°C) to cure for 28 days or until tested. The remaining 1 to 3 prism(s) were left to cure in air at a room temperature of 74°F (23°C). Since the concrete containing ASTM Type I/II cement required 1 day to completely harden, the specimens could not be stripped at 3 hours as were the specimens containing Ultimax cement. Instead, the cylinders and prisms made with ASTM Type I/II cement were left to cure in a moist room for 1 day before being stripped of their molds. The cylinders and 2 to 3 prisms were then placed in water tanks at 72° ± 2°F (22° ± 1°C) to cure for 28 days or until tested. The remaining 1 to 3 prism(s) were left to cure in air for 28 days at a room temperature of 74°F (23°C).

For each mix, the cone slump test was performed in accordance to ASTM C 143.[8] The slump data for the mixes are reported in Table 4.8.

The compressive strength of the concrete was determined in accordance to ASTM C 39.[9] Average strength data were reported at the ages of 6 hours, 1 day, 7 days, and 28 days for concrete containing Ultimax cement. Compressive strength data were obtained by testing a maximum of four 4 x 8-in. (100 x 200-mm) cylinders and three 6 x 12-in.

(150 x 300-mm) cylinders under uniaxial compression. Average compressive strength data for concrete containing ASTM Type I/II cement were reported at the ages of 1 day and 28 days by testing a maximum of three 4 x 8-in. (100 x 200-mm) cylinders.

The stress-strain curves were obtained from testing the 4 x 8-in. (100 x 200-mm) and 6 x 12-in. (150 x 300-mm) cylinders in accordance to ASTM C 469.[10] The cylinders were loaded uniaxially and corresponding longitudinal deformations were recorded at equal loading intervals. Longitudinal deformations were measured with a digital dial gauge connected to a digimatic mini-processor. The stress at each interval was calculated by dividing the load by the cross-sectional area of the cylinder tested. The strain was calculated by dividing the longitudinal deformation by the gage length of the cylinder tested. Stress-strain curves were then plotted and the slope of the curves in the linearly elastic region was calculated in accordance to ASTM C 469.[10] The slope of the stress-strain curve in the elastic region is equivalent to the modulus of elasticity of the cylinder tested.

Splitting-tensile strength was determined in accordance to ASTM C 496.[11] Average strength data were reported at the ages of 1 day and 28 days. Splitting-tensile strength data were obtained by testing four 4 x 8-in. (100 x 200-mm) cylinders and three 6 x 12-in. (150 x 300-mm) cylinders for concrete containing Ultimax cement. Splitting-tensile strength data for concrete containing ASTM Type I/II were obtained by testing a maximum of three 4 x 8-in. (100 x 200-mm) cylinders.

Shrinkage and expansion were determined in accordance to ASTM C 157.[7] Shrinkage and expansion data were reported at the following ages after stripping:

0 hours, 3 hours, 1 day, 3 days, 7 days, 14 days, 28 days, 56 days, and 90 days. Shrinkage and expansion data were obtained by testing a maximum of three 3 x 3 x 11 1/4-in. (76 x 76 x 285-mm) prisms for concrete containing Ultimax cement and concrete containing ASTM Type I/II cement.

4.6 Test Results and Discussion

4.6.1 Fresh Concrete Properties

The cone slump data for concrete containing Ultimax cement and ASTM Type I/II cement are summarized in Tables 4.8 and 4.9. Table 4.8 shows the slumps obtained by testing the mixes. In addition to the mix slumps, Table 4.9 includes the slumps obtained from testing smaller mixes made for the sole purpose of obtaining slump data. These smaller mixes were discarded after the slump data were obtained. The slump data for concrete containing Ultimax cement at different water-to-cement ratios of 0.25 to 0.50 is plotted in Figures 4.5 through 4.10. It can be observed from Figure 4.5 that zero slumps (slumps below 2 in.) were obtained for concrete having a water-to-cement ratio of 0.25. The slump for the water-to-cement ratios of 0.30 through 0.50 for the concrete made with Ultimax cement (Figures 4.6 through 4.10) was found to increase with increased cement content. In comparing Figures 4.6 through 4.10, it can be observed that, in general, lower cement contents were required to obtain workable concrete for mixes having higher water-to-cement ratios.

Table 4.9: Summary of Slump Data for Concrete Containing Ultimax Cement (in.)

w/cm	Cement Content (lb/cyd)	Mix No.	Mix Slump	Additional Slumps	Average Slump
0.25	1060	—	—	5/8	5/8
	1100	—	—	7/8	7/8
	1140	—	—	3/4	3/4
	1180	—	—	5/8	5/8
0.30	967	—	—	0	0
	983	—	—	2 1/4	2 1/4
	1000	10A	6 1/2	6 1/2	7
		10B	7 3/4	—	
	1033	9A	9 5/8	—	9 1/2
		9B	9 3/8	—	
	1067	8A	9	—	8 2/3
		8B	8 3/8	—	
	1100	7A	8 3/4	—	8 4/9
		7B	8 1/8	—	
	1133	6A	8 1/4	—	8 5/8
		6B	9	—	
	1166	5A	8 1/2	—	8 1/2
	1200	—	—	9 5/8	9 5/8
0.35	840	—	—	7/8	7/8
	857	—	—	1 1/5	1 1/5
	900	1A	8 5/8	2 1/2	7 1/4
		1D	8 1/2	9 3/8	
	940	—	—	8 1/2	8 1/2
	1070	—	—	9 1/2	9 1/2
	1140	—	—	10 7/8	10 1/4
			—	9 5/8	
	1200	—	—	7 1/2	7 1/2
0.40	750	—	—	1/8	1/8
	765	—	—	3 7/8	3 7/8
	780	—	—	8 3/8	8 3/8
	800	2A	9 1/2	—	9 1/2
	818	—	—	8 7/8	8 7/8
	840	—	—	9	9
	930	—	—	9 3/4	9 1/2
			—	9 1/4	
	1020	—	—	8 1/4	8 1/4
0.40	1110	—	—	10 3/8	10
		—	—	9 3/4	
	1200	—	—	9 7/8	9 7/8
0.45	644	—	—	3/8	3/8
	656	—	—	7/8	7/8
	678	—	—	5	5
	700	3A	7 1/8	7 1/2	7 1/3
	744	—	—	7 3/4	7 3/4
	789	—	—	7 3/8	7 3/8
	811	—	—	7 3/8	7 3/8
	900	—	—	5 1/4	5 4/5
		—	—	6 3/8	
	1000	—	—	8 3/4	8 3/4
	1100	—	—	8 1/2	8 3/8
		—	—	8 1/4	
	1200	—	—	8 3/4	8 3/4
0.50	580	15B	—	1/8	1/8
	590	—	—	1/8	1/8
	600	4C	—	1/2	1/2
	610	—	—	1/2	1/2
	620	14A	1 5/8	—	1 4/9
		14B	1 1/4		
	630	—	—	2	2
	640	13A	10 1/8	6 1/4	8 5/8
		13B	9 1/2		
	660	12A	9 5/8	8 7/8	9 3/8
		12B	9 5/8		
	680	11A	9 1/2	6 3/4	9
		11B	11		
	740	—	—	7 5/8	7 5/8
	800	—	—	8 1/8	8 1/8
	900	—	—	7 1/2	7 1/8
		—	—	6 3/4	
	1000	—	—	7 1/4	7 1/4
	1100	—	—	7 1/2	7 4/9
		—	—	7 3/8	
	1200	—	—	7 3/4	7 3/4

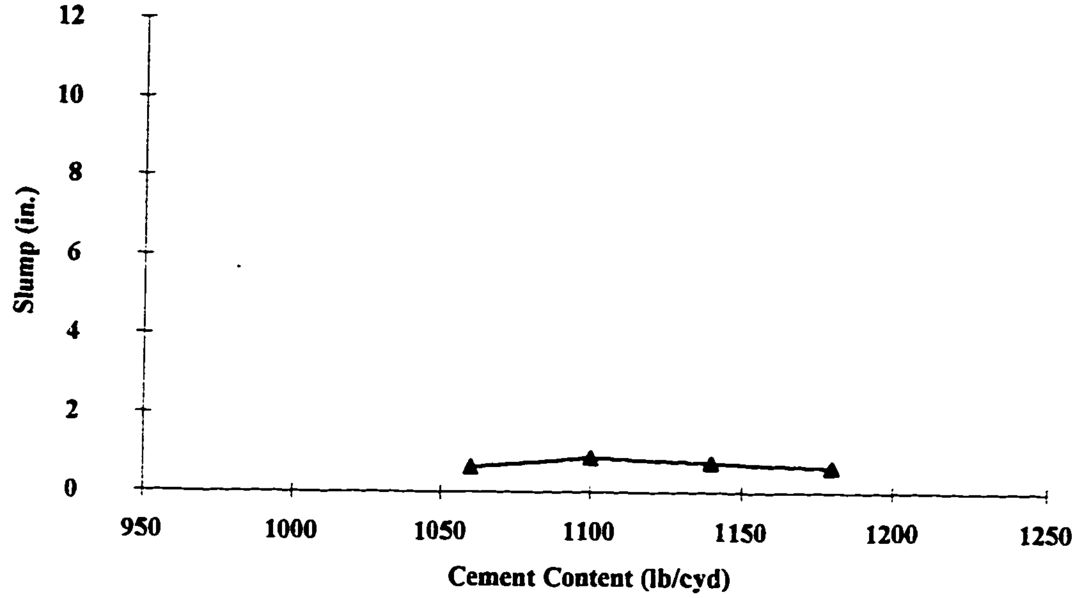


Figure 4.5: Slump of Concrete Containing Ultimax Cement Versus Cement Content (*w/cm* = 0.25)

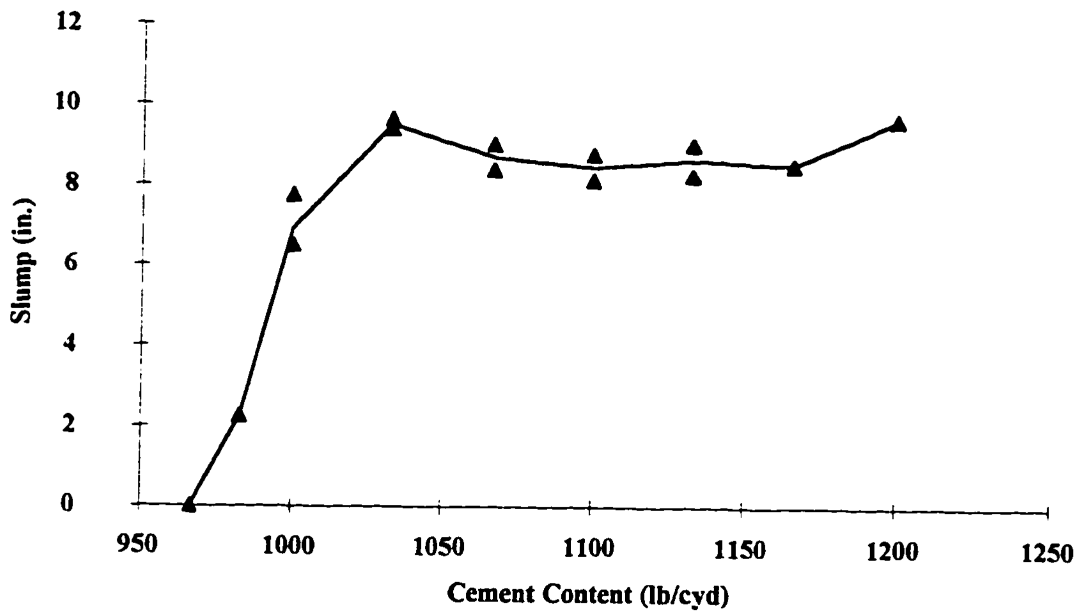


Figure 4.6: Slump of Concrete Containing Ultimax Cement Versus Cement Content (*w/cm* = 0.30)

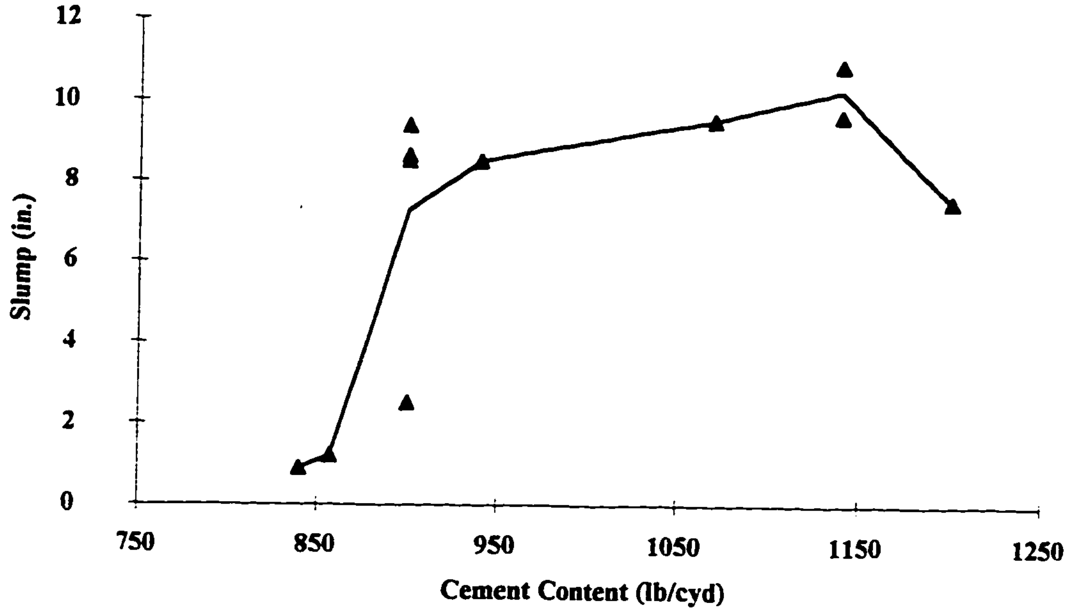


Figure 4.7: Slump of Concrete Containing Ultimax Cement Versus Cement Content (*w/cm* = 0.35)

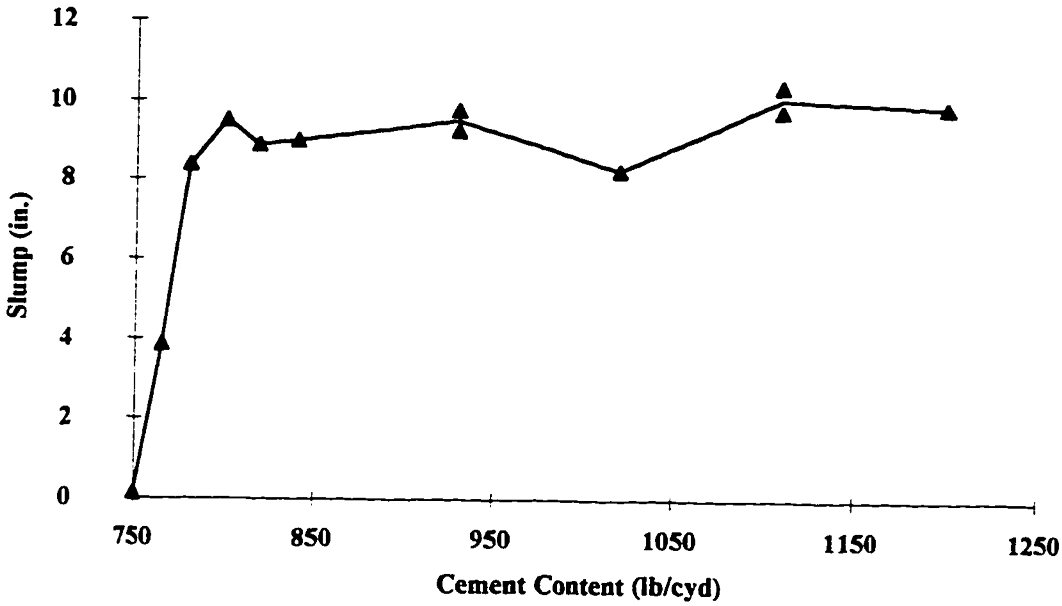


Figure 4.8: Slump of Concrete Containing Ultimax Cement Versus Cement Content (*w/cm* = 0.40)

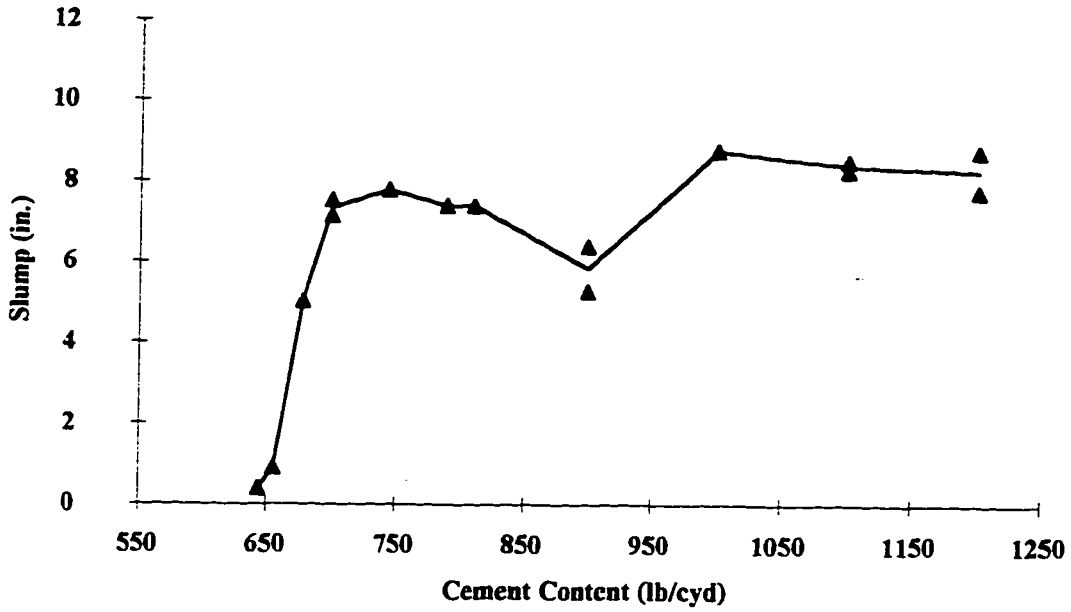


Figure 4.9: Slump of Concrete Containing Ultimax Cement Versus Cement Content (*w/cm* = 0.45)

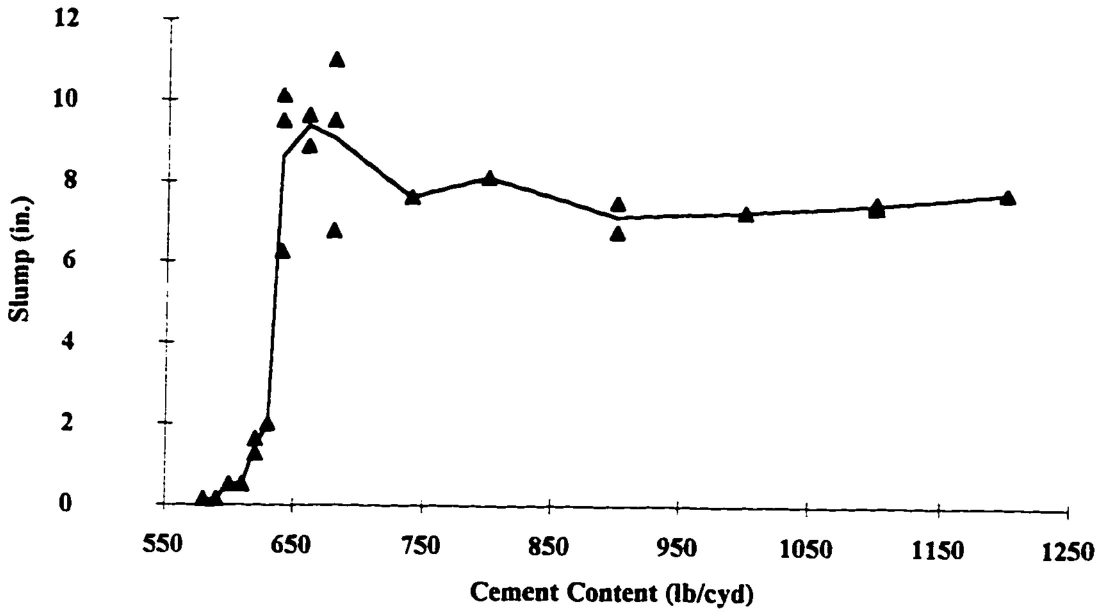


Figure 4.10: Slump of Concrete Containing Ultimax Cement Versus Cement Content (w/cm = 0.50)

Figures 4.11, 4.12, and Table 4.10 compare the concrete containing Ultimax cement with the concrete containing ASTM Type I/II cement. In order to obtain a reasonable comparison between the concrete containing Ultimax cement and concrete containing ASTM Type I/II cement, it was necessary to compare mixes having similar slumps at a given water-to-cement ratio (Figure 4.11). In order to achieve the comparable slumps shown in Figure 4.11, it was necessary to increase the cement content of the ASTM Type I/II cement at the different water-to-cement ratios. Figure 4.12 and Table 4.10 show the required cement contents for concrete containing Ultimax cement and concrete containing ASTM Type I/II cement. It can be observed that concrete containing Ultimax cement required cement contents of 600 to 1000 lb/cyd while concrete containing ASTM Type I/II cement required cement contents of 890 to 2000 lb/cyd to achieve similar slumps at given water-to-cement ratios. (Note: Cement contents above 1200 lb/cyd are unrealistic in real world applications. The comparison shows that Ultimax cement allows for larger slumps with reasonable cement content.) Table 4.10 also shows that the concrete containing ASTM Type I/II cement required a 48 to 100% higher cement content than concrete containing Ultimax cement depending on the water-to-cement ratio.

4.6.2 Hardened Concrete Properties

The properties of hardened concrete including the compressive strength, modulus of elasticity, splitting-tensile strength, bulk density, shrinkage, and expansion are

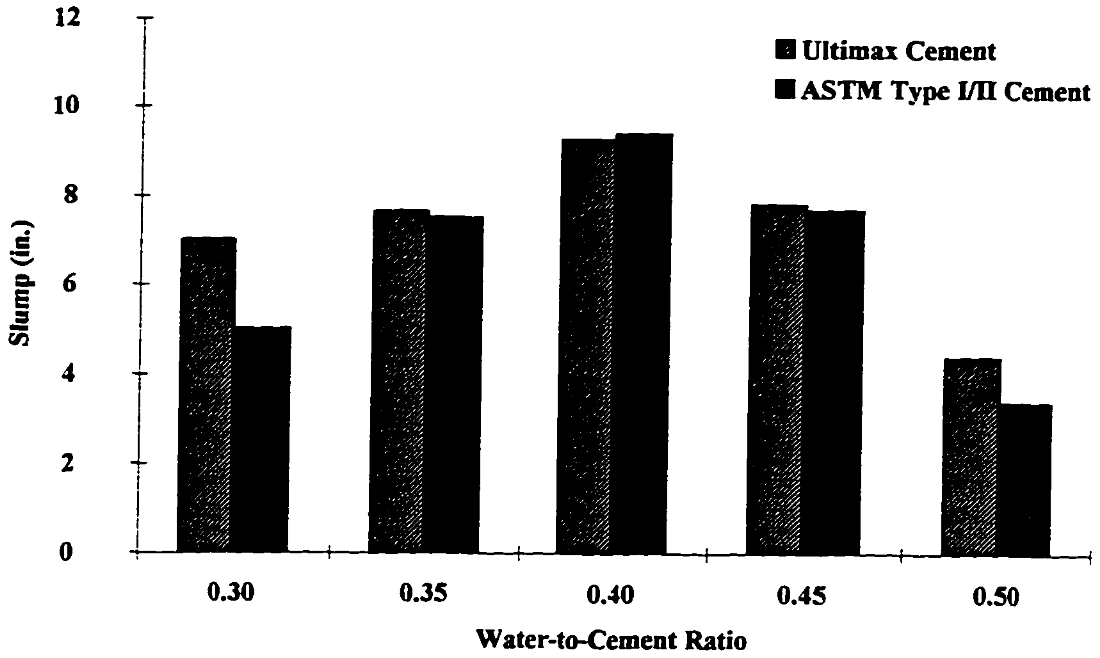


Figure 4.11: Average Slump Versus Water-to-Cement Ratio

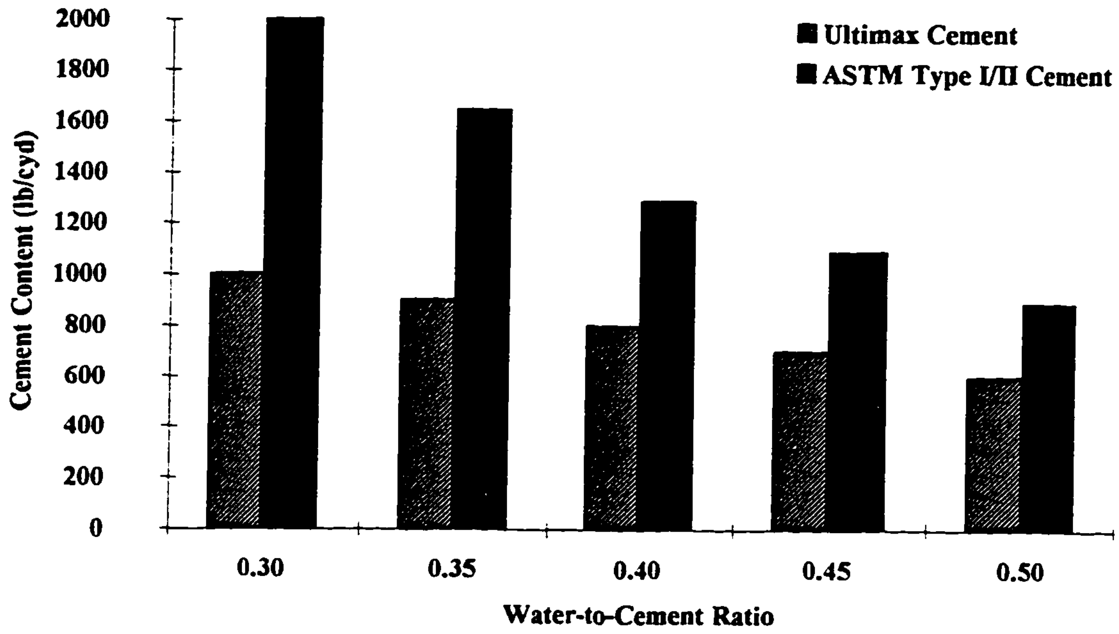


Figure 4.12: Cement Content Versus Water-to-Cement Ratio

Table 4.10: Comparison of Cement Contents of Concrete Containing Ultimax and ASTM Type I/II Cements

w/cm	Cement Content of Concrete Containing Ultimax Cement (lb/cyd)	Cement Content of Concrete Containing ASTM Type I/II Cement (lb/cyd)	Percent Increase of ASTM Type I/II Cement Content
0.30	1000	2000	100%
0.35	900	1643	83%
0.40	800	1288	61%
0.45	700	1089	56%
0.50	600	890	48%

summarized in Tables 4.11 through 4.24. The raw data including the stress-strain data are given in Appendices I-VI.

4.6.2.1 Compressive Strength

The compressive strength of concrete made with Ultimax cement at different water-to-cement ratios is shown in Figures 4.13, 4.14, and Table 4.11. Detailed raw data for individual cylinders are given in Appendix I (a) through I (c). In general, it can be observed from the figures that the compressive strength is decreasing with increased water-to-cement ratio. It can also be observed from Figure 4.13 that the compressive strength increases with age. Figure 4.14 compares the compressive strength of 4 x 8-in. (100 x 200-mm) cylinders with 6 x 12-in. (150 x 300-mm) cylinders at 28 days. The figure shows that the strengths obtained from the 4 x 8-in. (100 x 200-mm) cylinders were similar to those obtained from the 6 x 12-in. (150 x 300-mm) cylinders. The average

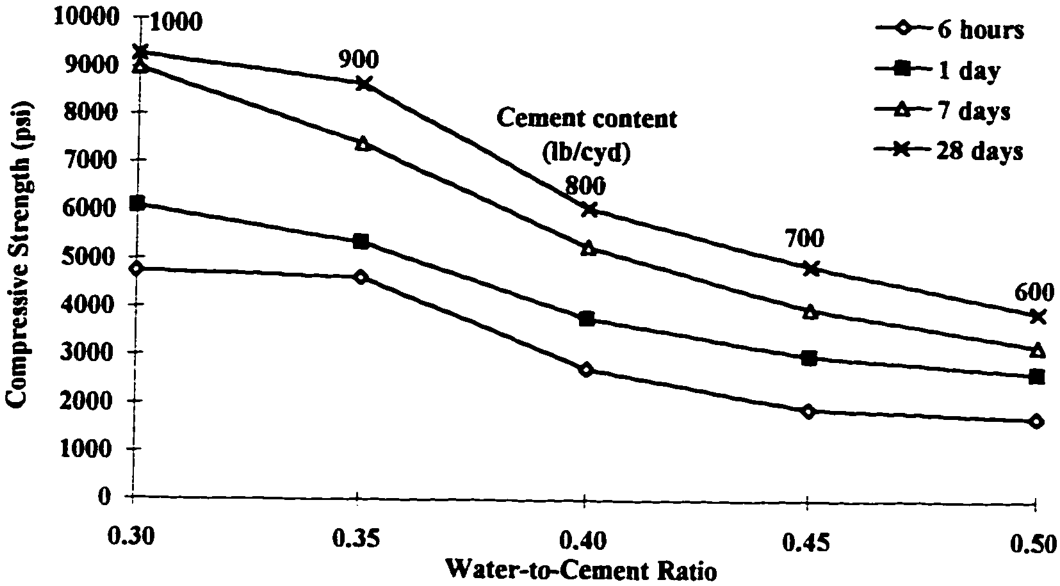


Figure 4.13: Compressive Strength of Concrete Containing Ultimax Cement Versus Water-to-Cement Ratio (4 x 8-in.)

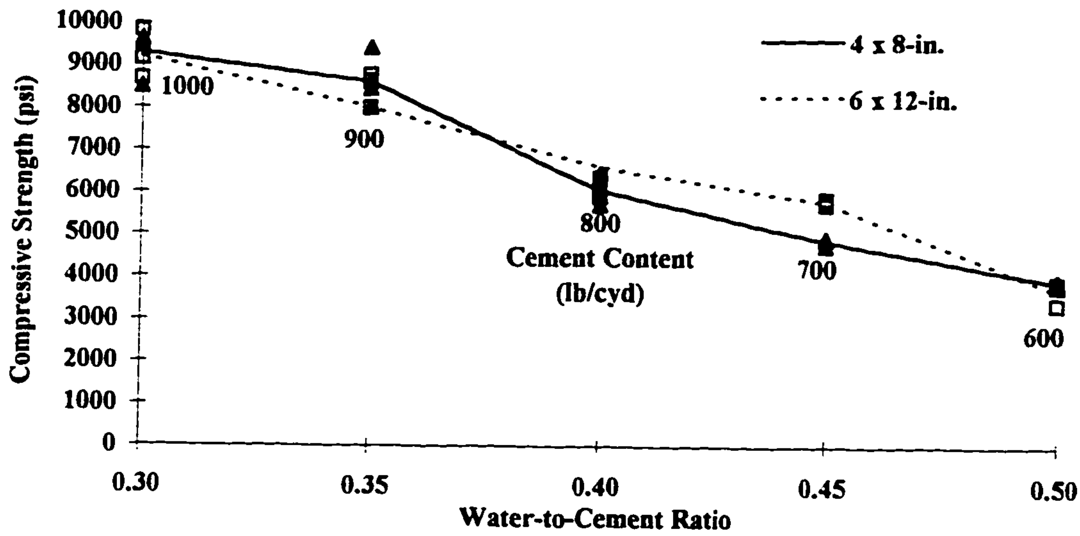


Figure 4.14: Compressive Strength of Concrete Containing Ultimax Cement Versus Water-to-Cement Ratio at 28 Days

Table 4.11: Compressive Strength Data of Concrete Containing Ultimax Cement at Different Ages

Age	Cylinder Size	*w/cm*	Cement Content (lb/cyd)	Compressive Strength (psi)				Average
6 hours	4 x 8-in.	0.30	1000	4794	4854	4612	-----	4753
		0.35	900	4416	4596	4834	-----	4615
		0.40	800	2725	2666	2785	-----	2725
		0.45	700	1970	1850	1910	-----	1910
		0.50	600	1751	1731	1731	-----	1738
1 day	4 x 8-in.	0.30	1000	6450	5710	5968	6197	6081
		0.35	900	7878	7003	3342	3143	5342
		0.40	800	3740	3860	3720	-----	3773
		0.45	700	3024	2964	2972	-----	2987
		0.50	600	2566	2730	2650	-----	2649
7 days	4 x 8-in.	0.30	1000	8893	8913	9132	-----	8979
		0.35	900	7440	7460	7202	-----	7367
		0.40	800	5371	5431	4974	-----	5259
		0.45	700	4019	3983	3919	-----	3974
		0.50	600	3263	3402	2944	-----	3203
28 days	4 x 8-in.	0.30	1000	9450	8475	9609	9549	9271
		0.35	900	9410	8455	7998	8614	8619
		0.40	800	6127	6476	5710	5899	6053
		0.45	700	4755	4944	4914	-----	4871
		0.50	600	3939	3820	3919	3919	3899
	6 x 12-in.	0.30	1000	9806	9134	8665	-----	9202
		0.35	900	8762	7997	7268	-----	8009
		0.40	800	6295	5915	7675	-----	6628
		0.45	700	5765	5721	5862	-----	5783
		0.50	600	3882	3811	3395	-----	3696

Table 4.12: Compressive Strength Data of Concrete Containing ASTM Type I/II Cement at Different Ages (4 x 8-in.)

Age	*w/cm*	Cement Content (lb/cyd)	Compressive Strength (psi)				Average
1 day	0.30	2000	4635	4615	4625	-----	4625
	0.35	1643	4128	3679	3610	-----	3806
	0.40	1288	2964	3207	3044	-----	3072
	0.45	1089	2582	2407	2459	-----	2483
	0.50	890	1950	2052	2109	-----	2037
28 days	0.30	2000	6056	7490	8017	-----	7188
	0.35	1643	8356	7321	7739	-----	7805
	0.40	1288	7353	7202	-----	-----	7278
	0.45	1089	6903	7142	7062	-----	7036
	0.50	890	6525	6356	5988	-----	6290

compressive strengths of the 4 x 8-in. (100 x 200-mm) concrete cylinders made with Ultimax cement ranged from 2650 to 6080 psi at 1 day and from 3900 to 9270 psi at 28 days (Table 4.11).

Table 4.12 shows the compressive strength data for concrete containing ASTM Type I/II cement. Detailed raw data for individual cylinders are given in Appendix I (d). It can be observed that the average compressive strengths of the 4 x 8-in. (100 x 200-mm) concrete cylinders made with ASTM Type I/II cement ranged from 2035 to 4625 psi at 1 day and from 6290 to 7805 psi at 28 days.

Figures 4.15 and 4.16 compare the average compressive strengths of concrete containing Ultimax cement with concrete containing ASTM Type I/II cement at 1 day and 28 days, respectively. In both figures this comparison was based on the assumption that concrete made with Ultimax cement and concrete made with ASTM Type I/II cement had a similar slump at a given water-to-cement ratio as was shown in Figure 4.11. It can also be observed from Figure 4.15 that the compressive strengths of concrete made with Ultimax cement at 1 day were higher than those of ASTM Type I/II at all water-to-cement ratios. At 28 days, as shown in Figure 4.16, the strength of concrete containing Ultimax cement was higher than the strength of concrete containing ASTM Type I/II cement at the lower water-to-cement ratios of 0.30 and 0.35. The opposite was true at the higher water-to-cement ratios of 0.40 to 0.50.

Table 4.13 shows the average compressive strengths of the two types of concrete and the percentage difference in strength. At 1 day, the compressive strengths of the

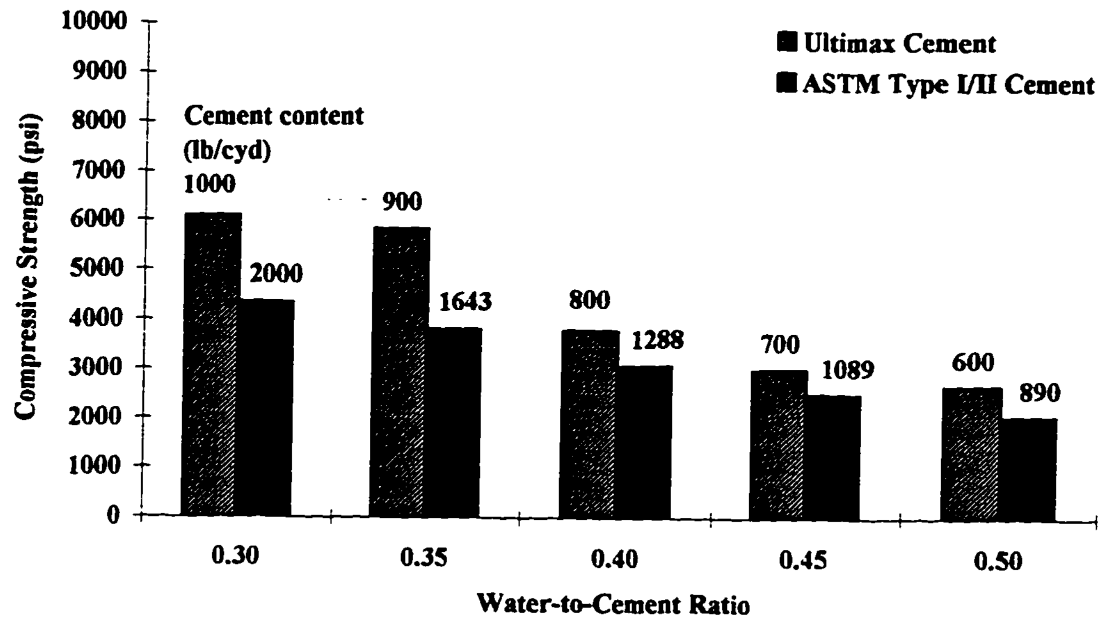


Figure 4.15: Compressive Strength at 1 Day Versus Water-to-Cement Ratio (4 x 8-in.)

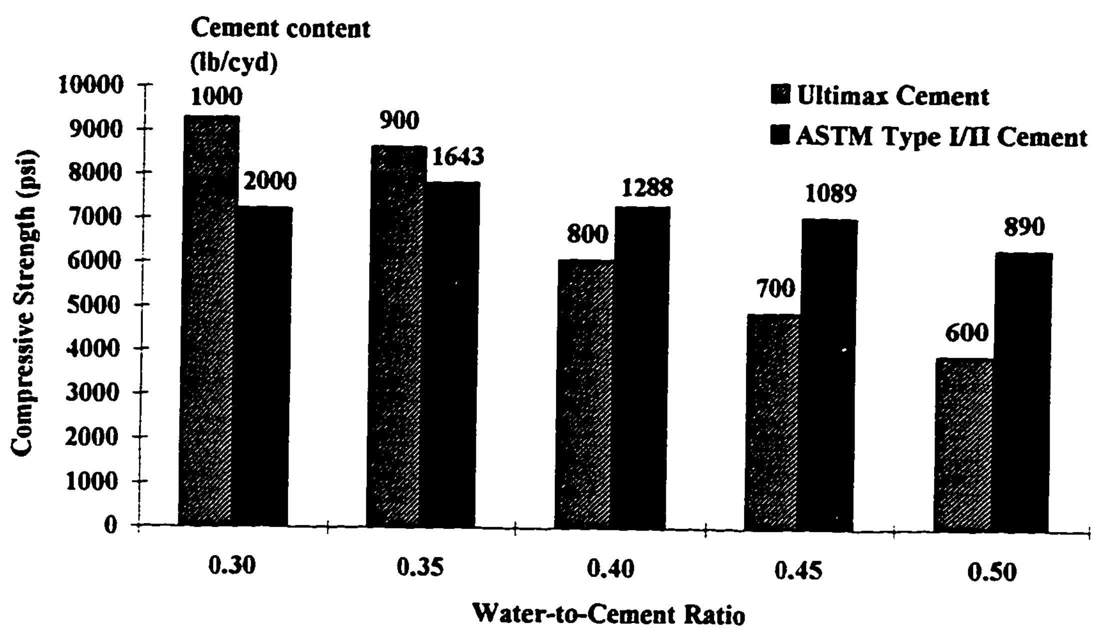


Figure 4.16: Compressive Strength at 28 Days Versus Water-to-Cement Ratio (4 x 8-in.)

concrete containing Ultimax cement were found to be 20 to 40% higher than those of concrete made with ASTM Type I/II cement. At 28 days, the compressive strengths of concrete made with Ultimax cement were found to be 10 to 29% higher at water-to-cement ratios of 0.30 and 0.35 and 17 to 38% lower at water-to-cement ratios of 0.40 to 0.50.

Table 4.13: Comparison of Compressive Strength of Concrete Containing Ultimax and ASTM Type I/II Cements (4 x 8-in.)

Age	*w/cm*	Average Compressive Strength (psi)		Percent Increase in Strength of Concrete Containing Ultimax Cement
		Ultimax Cement	ASTM Type I/II Cement	
1 day	0.30	6081	4625	31%
	0.35	5342	3806	40%
	0.40	3773	3072	23%
	0.45	2987	2483	20%
	0.50	2649	2037	30%
28 days	0.30	9271	7188	29%
	0.35	8619	7805	10%
	0.40	6053	7278	-17%
	0.45	4871	7036	-31%
	0.50	3899	6290	-38%

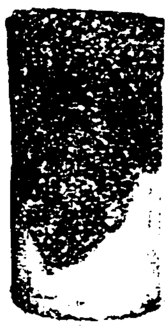
Figures 4.17 and 4.18 show a series of photographs that were taken after specimens made with Ultimax cement and ASTM Type I/II cement had failed underuniaxial compression. The concrete specimens made with Ultimax cement exhibited a brittle type of failure similar to concrete made with ASTM Type I/II cement.

w/cm = 0.30
Cement Content = 1000 (lb/cyd)

w/cm = 0.35
Cement Content = 900 (lb/cyd)

w/cm = 0.40
Cement Content = 800 (lb/cyd)

w/cm = 0.45
Cement Content = 700 (lb/cyd)



w/cm = 0.50
Cement Content = 600 (lb/cyd)

Figure 4.17: Compression Failure of Concrete Containing Ultimax Cement at Different Water-to-Cement Ratios

w/cm = 0.30

Cement Content = 2000 (lb/cyd)

w/cm = 0.35

Cement Content = 1643 (lb/cyd)

w/cm = 0.40

Cement Content = 1288 (lb/cyd)

w/cm = 0.45

Cement Content = 1089 (lb/cyd)

w/cm = 0.50

Cement Content = 890 (lb/cyd)

Figure 4.18: Compression Failure of Concrete Containing ASTM Type I/II Cement at Different Water-to-Cement Ratios

4.6.2.2 Modulus of Elasticity

The static modulus of elasticity of concrete made with Ultimax cement at different water-to-cement ratios is shown in Figures 4.19 and 4.20. It can be observed that the modulus of elasticity generally decreases with an increase in water-to-cement ratio. It can also be observed from Figure 4.19 that the modulus of elasticity increases with age. Figure 4.20 compares the modulus of elasticity for the 4 x 8-in. (100 x 200-mm) cylinders with that of the 6 x 12-in. (150 x 300-mm) cylinders at different water-to-cement ratios. In general, it can be observed that the 6 x 12-in. (150 x 300-in.) cylinders had a modulus of elasticity similar to that of the 4 x 8-in. (100 x 200-mm) cylinders.

Tables 4.14 and 4.15 summarize the static modulus of elasticity data for concrete made with Ultimax cement and concrete made with ASTM Type I/II cement. Detailed raw data for individual cylinders are given in Appendix II. The average static modulus of elasticity for the 4 x 8-in. (100 x 200-mm) cylinders made with Ultimax cement ranged from 2.4 x 10^6 psi to 3.6 x 10^6 psi at 1 day and from 3.6 x 10^6 psi to 4.6 x 10^6 psi at 28 days. The average static modulus of elasticity for the 6 x 12-in. (150 x 300-mm) cylinders made with Ultimax cement ranged from 2.9 x 10^6 psi to 4.0 x 10^6 psi at 28 days. The average static modulus of elasticity for the 4 x 8-in. (100 x 200-mm) cylinders made with ASTM Type I/II cement ranged from 1.8 x 10^6 psi to 2.6 x 10^6 psi at 1 day and from 3.2 x 10^6 psi to 2.0 x 10^6 psi at 28 days.

The static modulus of elasticity of concrete made with ASTM Type I/II cement is compared to that of concrete made with Ultimax cement at different water-to-cement

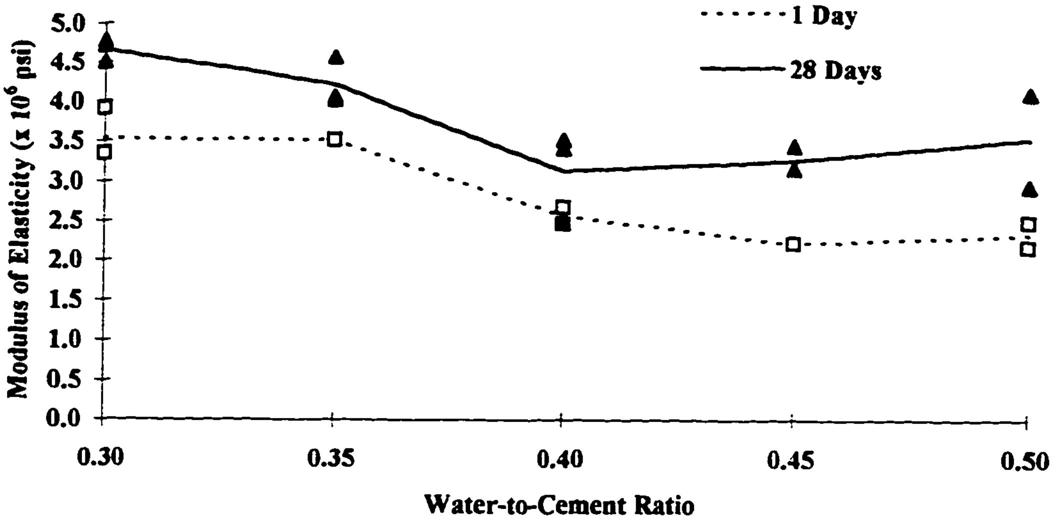


Figure 4.19: Static Modulus of Elasticity of Concrete Containing Ultimax Cement Versus Water-to-Cement Ratio (4 x 8-in.)

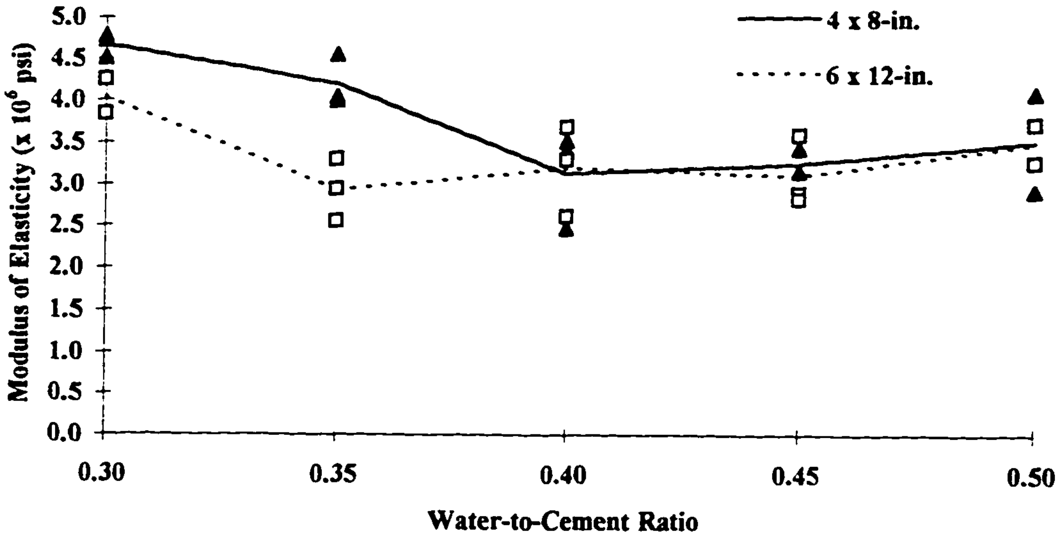


Figure 4.20: Static Modulus of Elasticity of Concrete Containing Ultimax Cement Versus Water-to-Cement Ratio at 28 Days

Table 4.14: Static Modulus of Elasticity Data of Concrete Containing Ultimax Cement at Different Ages

Age	Cylinder Size	*w/cm*	Cement Content (lb/cyd)	Modulus of Elasticity (10^6 psi)			Average
1 day	4 x 8-in.	0.30	1000	3.340	3.912	3.340	3.531
		0.35	900	3.504	----	----	3.504
		0.40	800	2.466	2.678	----	2.572
		0.45	700	2.220	2.220	----	2.220
		0.50	600	2.480	2.168	----	2.324
28 days	4 x 8-in.	0.30	1000	4.720	4.504	4.774	4.666
		0.35	900	4.046	4.004	4.548	4.199
		0.40	800	3.410	3.520	2.472	3.134
		0.45	700	3.168	3.168	3.442	3.259
		0.50	600	2.932	4.096	----	3.514
	6 x 12-in.	0.30	1000	4.244	3.835	----	4.040
		0.35	900	2.559	2.948	3.300	2.936
		0.40	800	2.618	3.694	3.300	3.204
		0.45	700	2.903	3.597	2.829	3.110
		0.50	600	3.726	3.274	----	3.500

Table 4.15: Static Modulus of Elasticity Data of Concrete Containing ASTM Type I/II Cement at Different Ages (4 x 8-in.)

Age	*w/cm*	Cement Content (lb/cyd)	Modulus of Elasticity (10^6 psi)			Average
1 day	0.30	2000	2.274	2.430	----	2.352
	0.35	1643	2.466	2.610	----	2.538
	0.40	1288	2.480	2.346	----	2.413
	0.45	1089	2.108	1.860	----	1.984
	0.50	890	1.874	1.888	----	1.881
28 days	0.30	2000	3.978	3.596	----	3.787
	0.35	1643	4.004	4.004	----	4.004
	0.40	1288	3.182	----	----	3.182
	0.45	1089	3.316	3.714	----	3.515
	0.50	890	3.644	3.410	----	3.527

ratios in Figures 4.21 and 4.22. It can be observed that the modulus of elasticity of concrete made with Ultimax cement and concrete made with ASTM Type I/II cement generally decreases with increased water-to-cement ratio. In general, the static modulus of elasticity at 28 days was similar for concrete made with Ultimax cement and concrete made with ASTM Type I/II cement especially at water-to-cement ratios above 0.35.

4.6.2.3 Stress-Strain Relationship

Figures 4.23 through 4.28 show the average stress-strain relationships for concrete made with Ultimax cement and ASTM Type I/II cement at different water-to-cement ratios. Detailed raw data for individual cylinders are given in Appendix III. It can be observed that the slope of the stress-strain curve in the elastic region generally decreases as the water-to-cement ratio is increased. This observation was the same for both the concrete containing Ultimax cement and the concrete containing ASTM Type I/II cement. Figure 4.28 compares the stress-strain curves of 4 x 8-in. (100 x 200-mm) concrete cylinders with those of 6 x 12-in. (150 x 300-mm) concrete cylinders containing Ultimax cement. In general, the stress-strain curves of the 6 x 12-in. (150 x 300-mm) cylinders were found to have similar slopes in the elastic region to those obtained from testing the 4 x 8 in. (100 x 200-mm) cylinders.

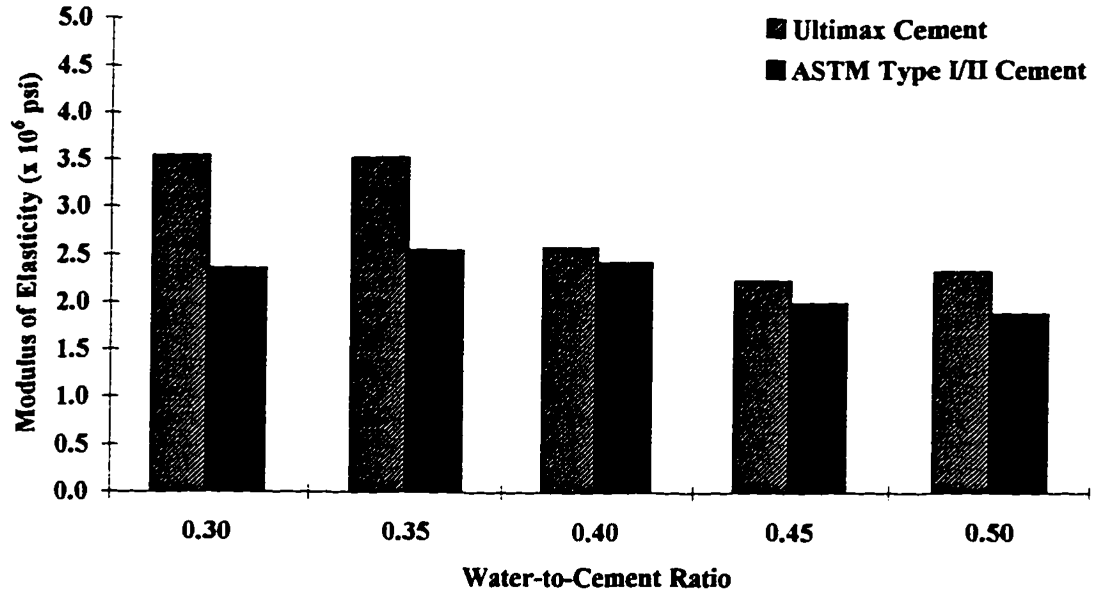


Figure 4.21: Static Modulus of Elasticity Versus Water-to-Cement Ratio at 1 Day (4 x 8-in.)

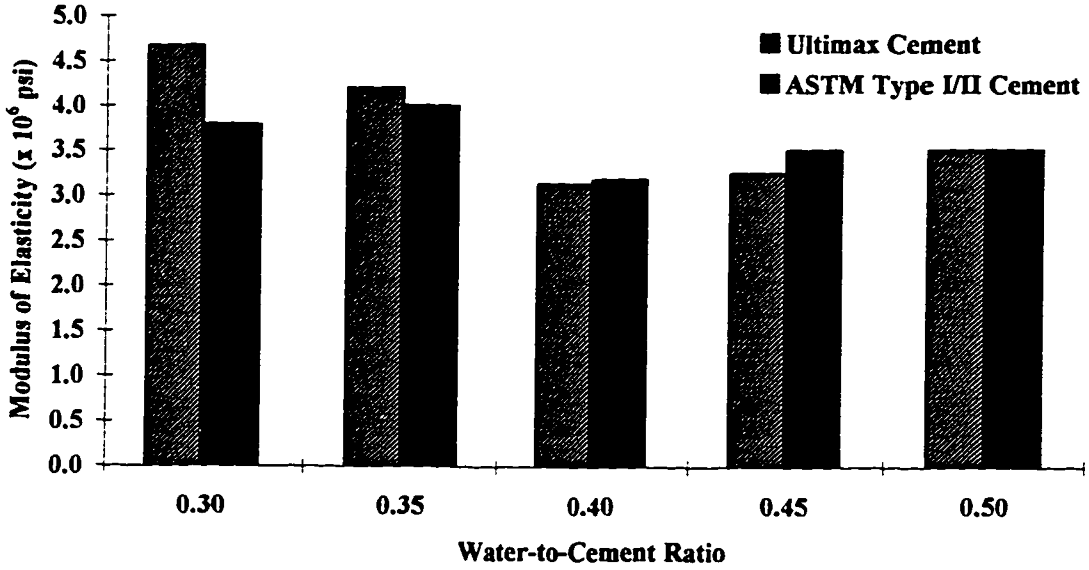


Figure 4.22: Static Modulus of Elasticity Versus Water-to-Cement Ratio at 28 Days (4 x 8-in.)

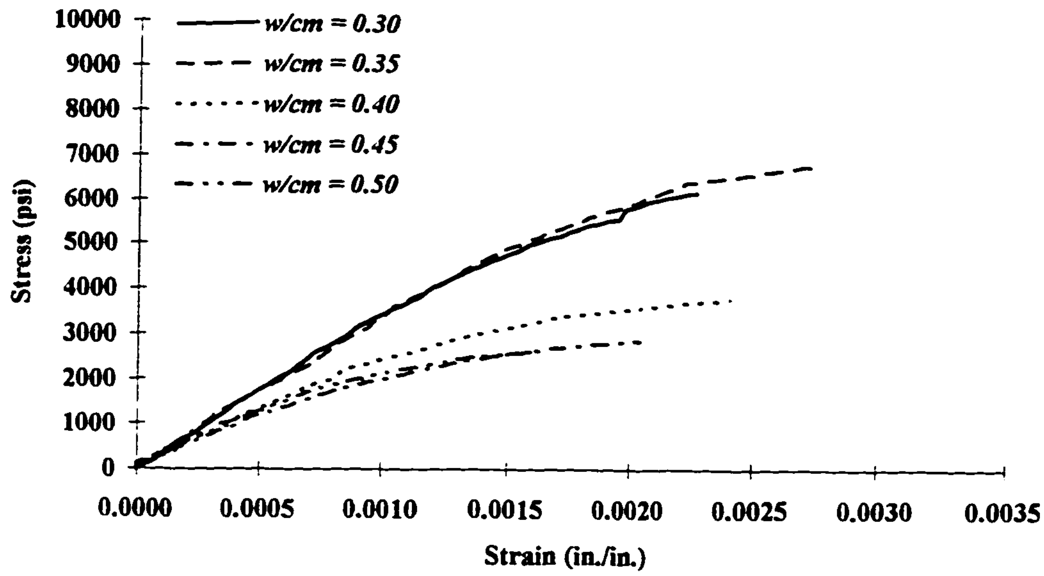


Figure 4.23: Stress-Strain Curves for Concrete Containing Ultimax Cement at 1 Day (4 x 8-in.)

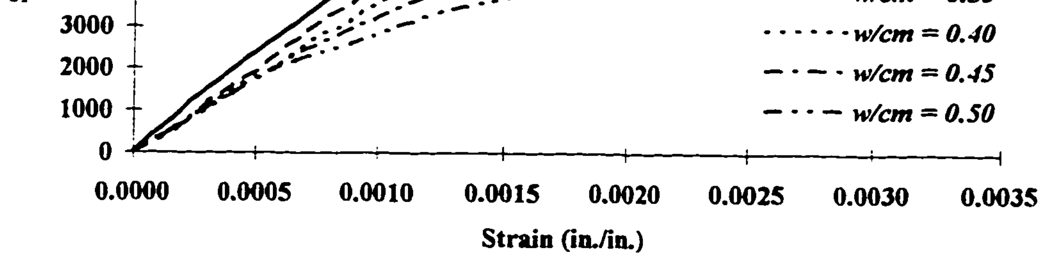


Figure 4.24: Stress-Strain Curves for Concrete Containing Ultimax Cement at 28 Days (4 x 8-in.)

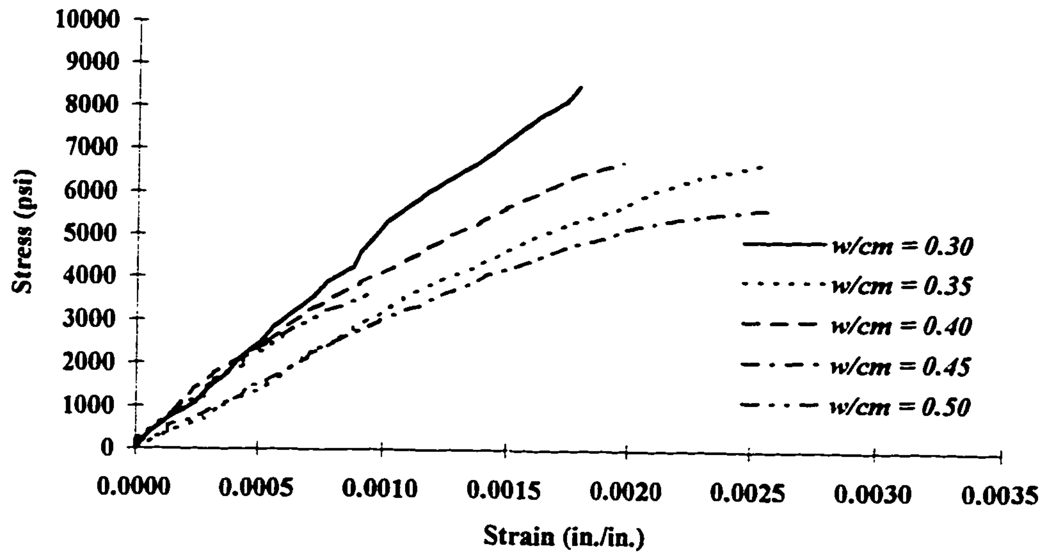


Figure 4.25: Stress-Strain Curves for Concrete Containing Ultimax Cement at 28 Days (6 x 12-in.)

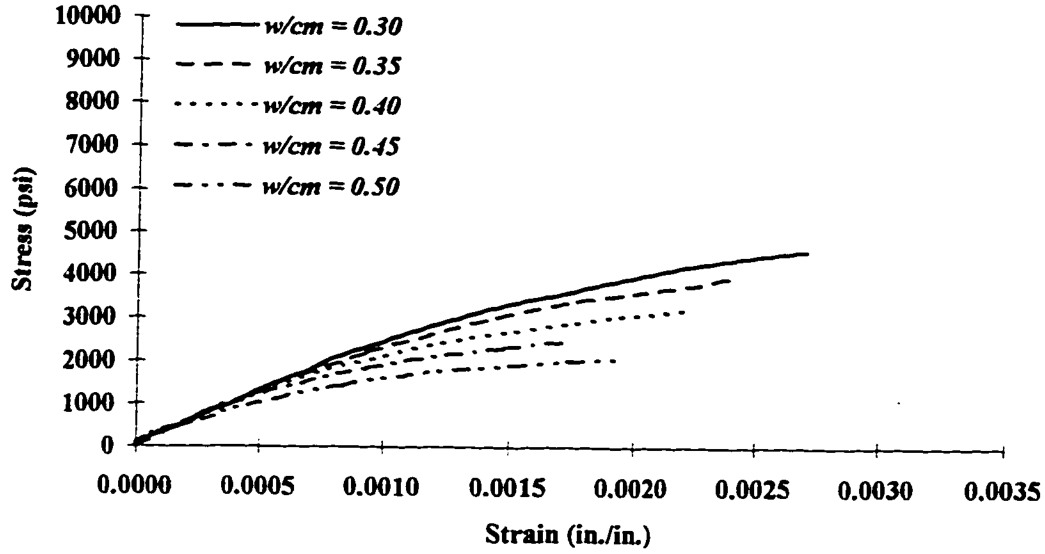


Figure 4.26: Stress-Strain Curves for Concrete Containing ASTM Type I/II Cement at 1 Day (4 x 8-in.)

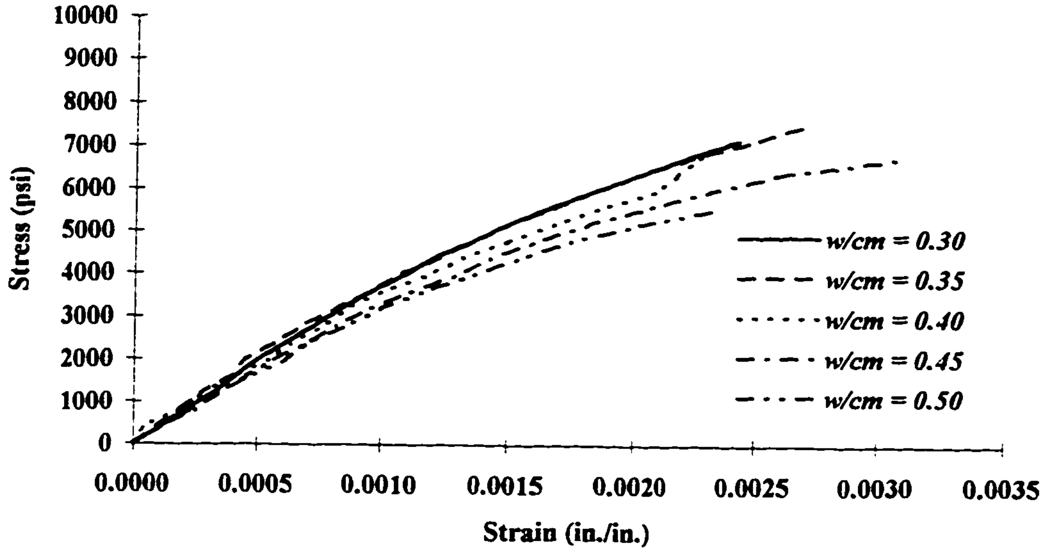


Figure 4.27: Stress-Strain Curves for Concrete Containing ASTM Type I/II Cement at 28 Days (4 x 8-in.)

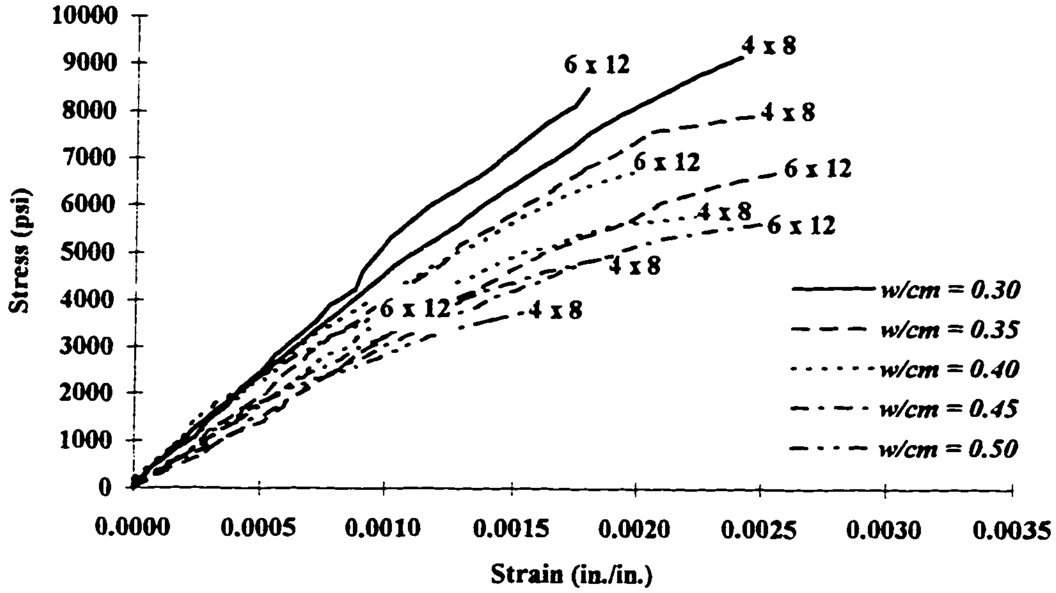


Figure 4.28: Stress-Strain Curves for Concrete Containing Ultimax Cement at 28 Days (4 x 8-in. and 6 x 12-in.)

4.6.2.4 Splitting-Tensile Strength

The splitting-tensile strengths of concrete made with Ultimax cement at different water-to-cement ratios are shown in Figures 4.29 and 4.30, and summarized in Tables 4.16 and 4.17. Detailed raw data for individual cylinders are given in Appendix IV (a) through (c). It can be observed from the figures that splitting-tensile strength decreases with increased water-to-cement ratio. It can also be observed from Figure 4.29 that the splitting-tensile strength increases with age. Figure 4.30 shows the splitting-tensile strengths of the 4 x 8-in. (100 x 200-mm) cylinders as compared to the 6 x 12-in. (150 x 300-mm) cylinders. The average splitting-tensile strength of the 4 x 8-in. (100 x 200-mm) cylinders made with Ultimax cement ranged from 245 to 495 psi at 1 day and from 385 to 705 psi at 28 days (Tables 4.16). In general, the splitting-tensile strengths of the 4 x 8-in. (100 x 200-mm) cylinders were 19 to 27% higher than those of the 6 x 12-in. (150 x 300-mm) cylinders (Table 4.17).

Table 4.18 shows the splitting-tensile strength data for concrete made with ASTM Type I/II cement. Detailed raw data for individual cylinders are given in Appendix IV (d). It can be observed from the table that the average splitting-tensile strength of the 4 x 8-in. (100 x 200-mm) cylinders made with ASTM Type I/II cement ranged from 310 to 471 psi at 1 day and from 560 to 650 psi at 28 days.

Figures 4.31 and 4.32 compare the average splitting-tensile strengths of concrete containing Ultimax cement at different water-to-cement ratios to those of concrete containing ASTM Type I/II cement at 1 day and 28 days, respectively. It can be observed that the splitting-tensile strength of both the concrete containing Ultimax cement and the

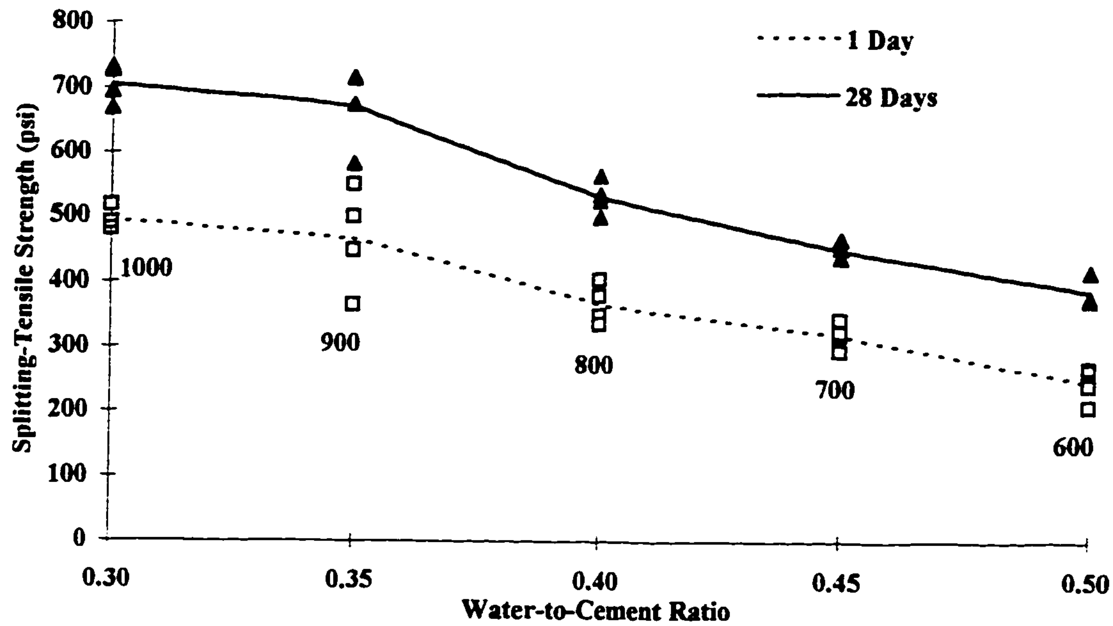


Figure 4.29: Splitting-Tensile Strength of Concrete Containing Ultimax Cement Versus Water-to-Cement Ratio (4 x 8-in.)

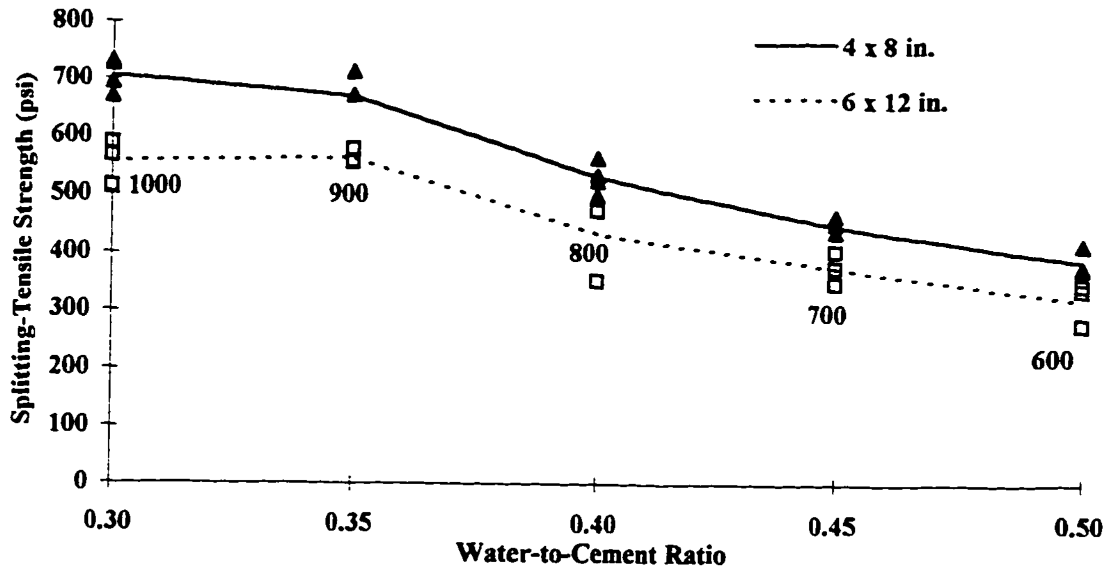


Figure 4.30: Splitting-Tensile Strength of Concrete Containing Ultimax Cement Versus Water-to-Cement Ratio at 28 Days

Table 4.16: Splitting-Tensile Strength Data of Concrete Containing Ultimax Cement at Different Ages

Age	Cylinder Size	w/cm	Cement Content (lb/cyd)	Splitting-Tensile Strength (psi)				Average
1 day	4 x 8-in.	0.30	1000	490	480	490	517	494
		0.35	900	497	364	447	547	464
		0.40	800	403	349	379	336	367
		0.45	700	343	293	318	323	320
		0.50	600	267	264	208	241	245
28 days	4 x 8-in.	0.30	1000	694	726	669	732	705
		0.35	900	579	714	671	712	669
		0.40	800	565	525	500	535	531
		0.45	700	438	465	438	453	448
		0.50	600	376	415	373	376	385
	6 x 12-in.	0.30	1000	514	588	566	----	556
		0.35	900	578	555	558	----	563
		0.40	800	352	473	474	----	433
		0.45	700	348	404	375	----	376
		0.50	600	344	336	275	----	318

Table 4.17: Comparison Between Splitting-Tensile Strength of 4 x 8-in. Concrete Cylinders and 6 x 12-in. Concrete Cylinders Containing Ultimax Cement

Age	w/cm	Average Splitting-Tensile Strength of Concrete Containing Ultimax Cement (psi)		Percent Increase in Strength of 4 x 8-in. Cylinders
		4 x 8-in.	6 x 12-in.	
28 days	0.30	705	556	27%
	0.35	669	563	19%
	0.40	531	433	23%
	0.45	448	376	19%
	0.50	385	318	21%

Table 4.18: Splitting-Tensile Strength Data of Concrete Containing ASTM Type I/II Cement at Different Ages (4 x 8-in.)

Age	w/cm	Cement Content (lb/cyd)	Splitting-Tensile Strength (psi)				Average
1 day	0.30	2000	475	445	493	----	471
	0.35	1643	440	450	424	----	438
	0.40	1288	376	418	433	----	409
	0.45	1089	341	304	333	----	326
	0.50	890	298	323	308	----	310
28 days	0.30	2000	679	639	632	----	650
	0.35	1643	613	671	622	----	635
	0.40	1288	624	592	----	----	608
	0.45	1089	647	657	624	----	642
	0.50	890	525	578	574	----	559

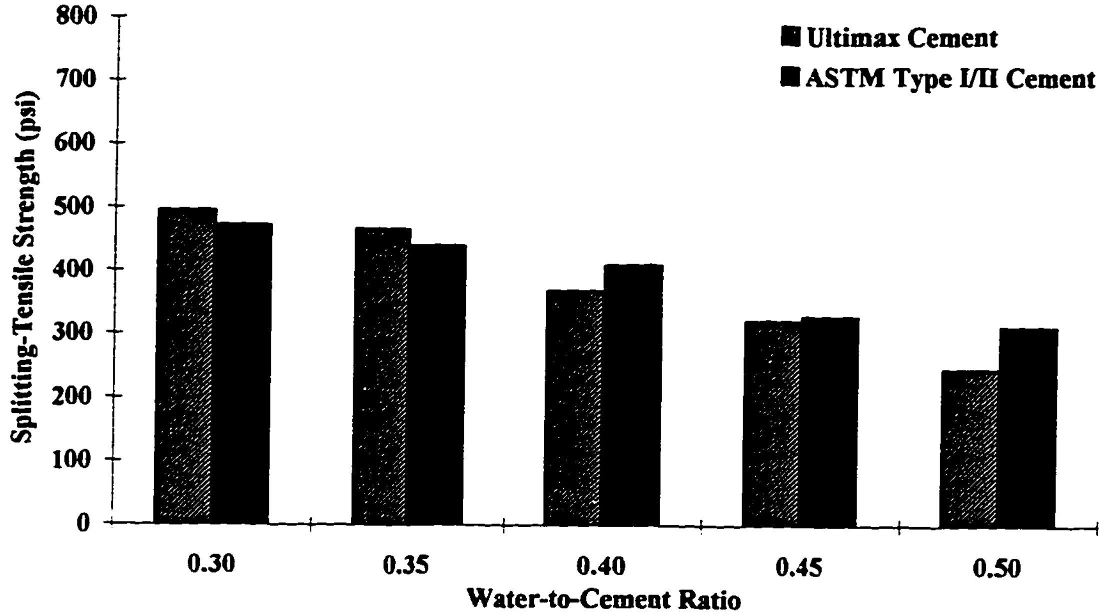


Figure 4.31: Splitting-Tensile Strength at 1 Day Versus Water-to-Cement Ratio (4 x 8-in.)

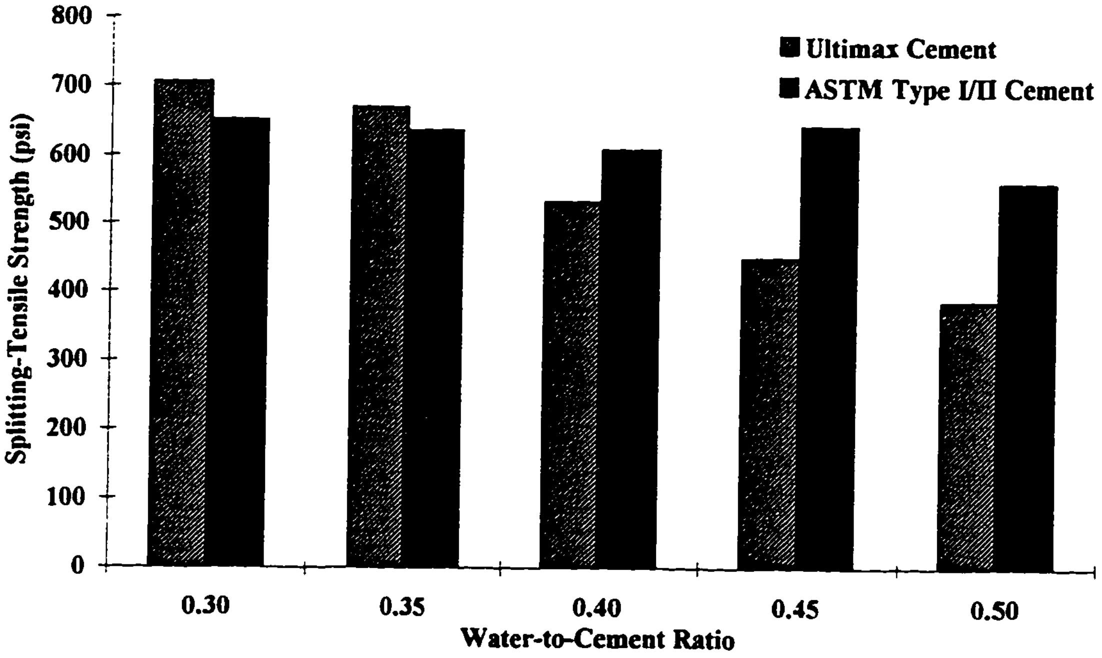


Figure 4.32: Splitting-Tensile Strength at 28 Days Versus Water-to-Cement Ratio (4x 8-in.)

concrete containing ASTM Type I/II cement generally decreases with increased water-to-cement ratio.

Table 4.19 compares the average splitting-tensile strengths of concrete made with Ultimax cement to concrete made with ASTM Type I/II cement and shows the percentage difference in strength. At 1 day, the concrete made with Ultimax cement had 5 to 6% higher splitting-tensile strengths at the lower water-to-cement ratios of 0.30 and 0.35, and 2 to 21% lower splitting-tensile strengths at the higher water-to-cement ratios of 0.40, 0.45, and 0.50. At 28 days, the concrete made with Ultimax cement had 5 to 8% higher splitting-tensile strengths at the lower water-to-cement ratios of 0.30 and 0.35 and 13 to 31% lower splitting-tensile strengths at the higher water-to-cement ratios of 0.40, 0.45, and 0.50.

Table 4.19: Comparison of Splitting-Tensile Strength of Concrete Containing Ultimax and ASTM Type I/II Cements (4 x 8-in.)

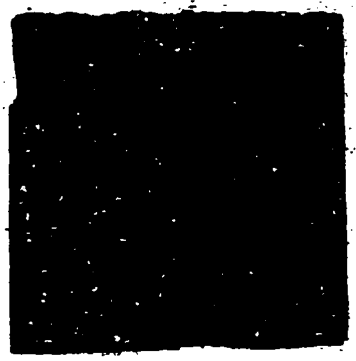
Age	*w/cm*	Average Splitting-Tensile Strength (psi) 4 x 8-in. Cylinders (psi)		Percent Increase in Strength of Concrete Containing Ultimax Cement
		Ultimax Cement	ASTM Type I/II Cement	
1 day	0.30	494	471	5%
	0.35	464	438	6%
	0.40	367	409	-10%
	0.45	320	326	-2%
	0.50	245	310	-21%
28 days	0.30	705	650	8%
	0.35	669	635	5%
	0.40	531	608	-13%
	0.45	448	642	-30%
	0.50	385	559	-31%

Figures 4.33 and 4.34 show a series of photographs that were taken after the specimens made with Ultimax cement and ASTM Type I/II cement had failed in tension. The concrete specimens made with Ultimax cement exhibited a similar type of brittle failure as specimens made with ASTM Type I/II cement.

4.6.2.5 Bulk Density

The bulk density of the concrete made with Ultimax cement at different water-to-cement ratios is shown in Figures 4.35, 4.36, and Table 4.20. Detailed raw data for individual cylinders are given in Appendix V (a) through (c). Figure 4.35 compares the bulk density at 1 day with the bulk density at 28 days. It can be observed that there was no significant difference in the bulk density of 4 x 8-in. (100 x 200-mm) concrete cylinders at 1 day and 28 days. Figure 4.36 compares the bulk density of 4 x 8-in. (100 x 200-mm) cylinders with the bulk density of 6 x 12-in. (150 x 300-mm) cylinders at 28 days and shows no significant difference. The bulk density of the 4 x 8-in. (100 x 200-mm) cylinders made with Ultimax cement ranged from 151 to 154 pcf at 1 day and from 152 to 154 pcf at 28 days (Table 4.20).

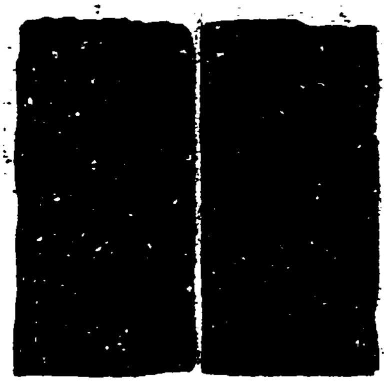
Table 4.21 shows the bulk density data for concrete made with ASTM Type I/II cement. Detailed raw data for individual cylinders are given in Appendix V (d). The average bulk density of the 4 x 8-in. (100 x 200-mm) cylinders made with ASTM Type I/II cement ranged 145 to 150 pcf at 1 day and from 147 to 150 pcf at 28 days.



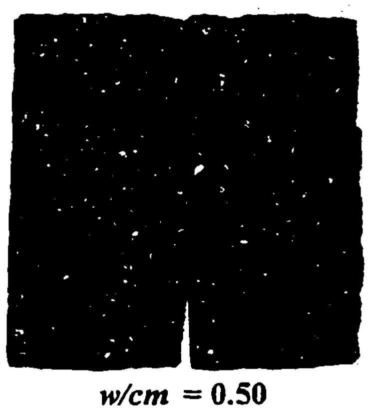
w/cm = 0.30
Cement Content = 1000 (lb/cyd)

w/cm = 0.35
Cement Content = 900 (lb/cyd)

w/cm = 0.40
Cement Content = 800 (lb/cyd)

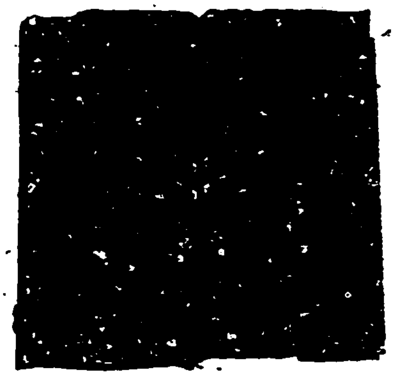


w/cm = 0.45
Cement Content = 700 (lb/cyd)



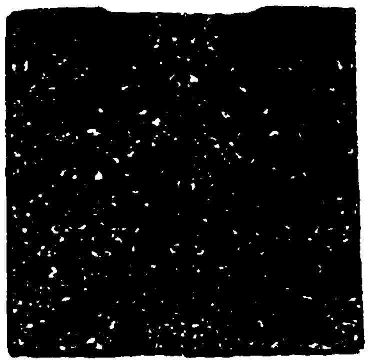
w/cm = 0.50
Cement Content = 600 (lb/cyd)

Figure 4.33: Splitting-Tensile Failure of Concrete Containing Ultimax Cement at Different Water-to-Cement Ratios



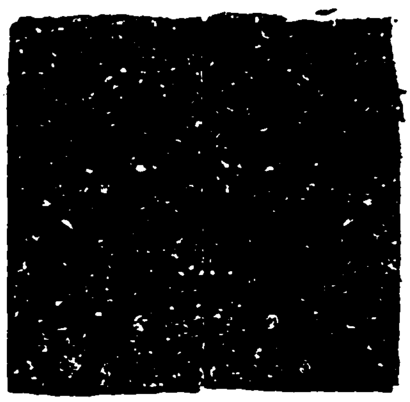
_w/cm_ = 0.30
Cement Content = 2000 (lb/cyd)

_w/cm_ = 0.35
Cement Content = 1643 (lb/cyd)



_w/cm_ = 0.40
Cement Content = 1288 (lb/cyd)

_w/cm_ = 0.45
Cement Content = 1089 (lb/cyd)



_w/cm_ = 0.50
Cement Content = 890 (lb/cyd)

Figure 4.34: Splitting-Tensile Failure of Concrete Containing ASTM Type I/II Cement at Different Water-to-Cement Ratios

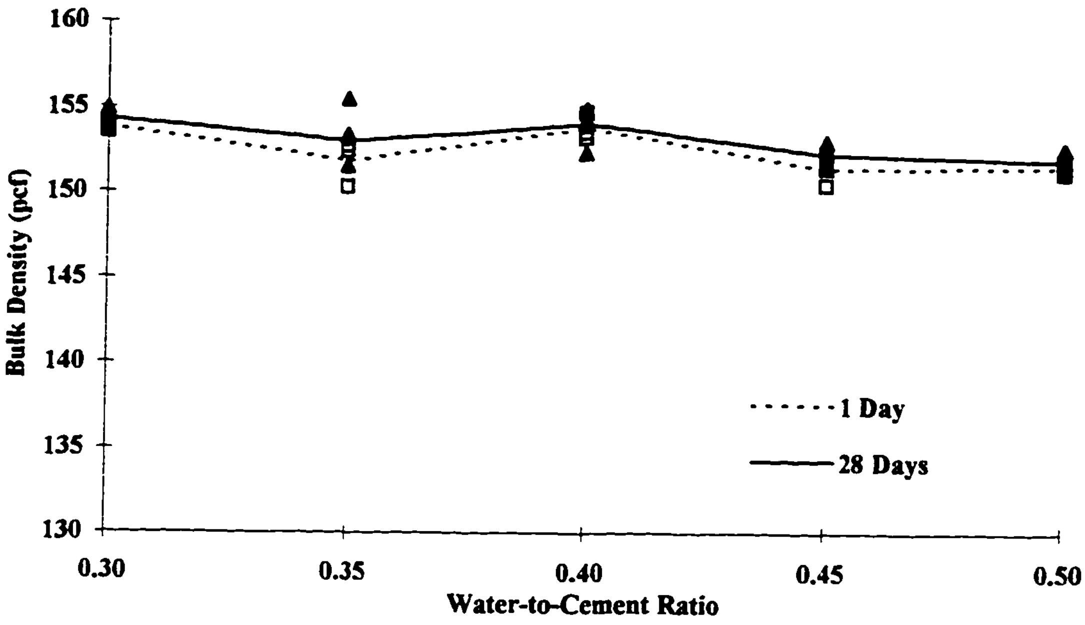


Figure 4.35: Bulk Density of Concrete Containing Ultimax Cement Versus Water-to-Cement Ratio (4 x 8-in.)

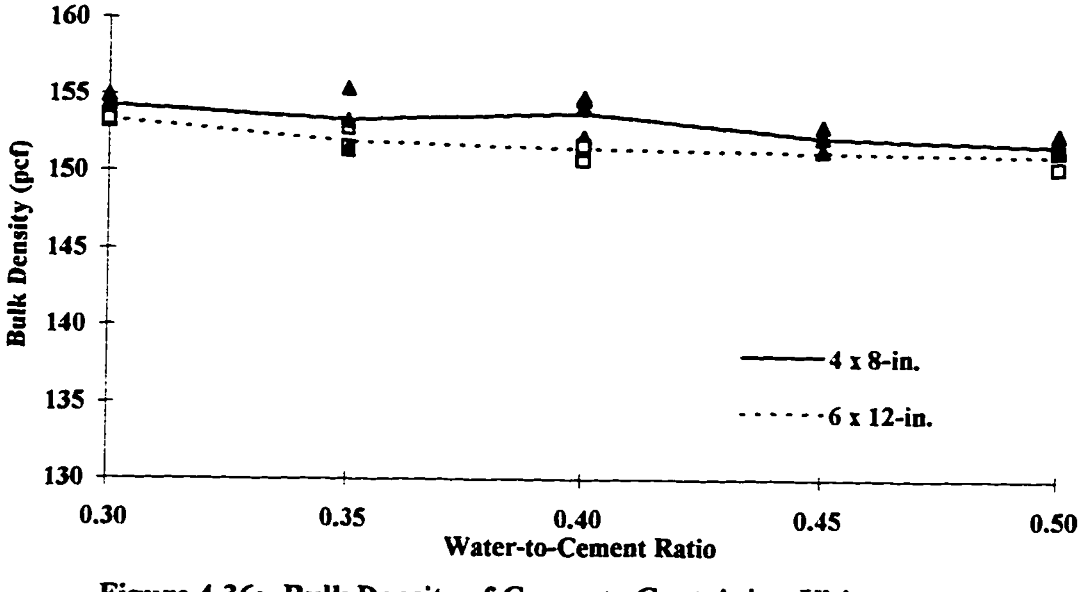


Figure 4.36: Bulk Density of Concrete Containing Ultimax Cement Versus Water-to-Cement Ratio at 28 Days

Table 4.20: Bulk Density Data of Concrete Containing Ultimax Cement at Different Ages

Age	Cylinder Size	w/cm	Cement Content (lb/cyd)	Bulk Density (pcf)				Average
1 day	4 x 8-in.	0.30	1000	154	154	154	154	154
		0.35	900	153	152	150	——	152
		0.40	800	153	155	154	——	154
		0.45	700	150	152	151	——	151
		0.50	600	151	151	152	——	151
28 days	4 x 8-in.	0.30	1000	154	155	154	154	154
		0.35	900	155	153	151	151	153
		0.40	800	154	155	152	155	154
		0.45	700	152	151	153	——	152
		0.50	600	151	151	153	152	152
	6 x 12-in.	0.30	1000	153	153	154	153	153
		0.35	900	151	152	153	——	152
		0.40	800	152	151	152	152	152
		0.45	700	——	——	——	——	151
		0.50	600	152	151	150	——	151

Table 4.21 Bulk Density Data of Concrete Containing ASTM Type I/II Cement at Different Ages (4 x 8-in.)

Age	w/cm	Cement Content (lb/cyd)	Bulk Density (pcf)				Average
1 day	0.30	2000	146	145	145	——	145
	0.35	1643	148	147	145	146	147
	0.40	1288	150	149	148	148	149
	0.45	1089	151	149	148	148	149
	0.50	890	150	150	149	——	150
28 days	0.30	2000	147	146	147	——	147
	0.35	1643	149	147	148	149	148
	0.40	1288	148	148	149	——	148
	0.45	1089	151	149	149	149	150
	0.50	890	150	150	150	150	150

Figures 4.37 and 4.38 show the average bulk density of concrete made with Ultimax cement as compared with that of ASTM Type I/II cement. It can be observed that the bulk density of the concrete made with Ultimax cement was higher than that of concrete made with ASTM Type I/II cement.

Table 4.22 shows the average bulk density of concrete made with Ultimax cement and concrete made with ASTM Type I/II cement and the percentage difference. At 1 day, the bulk density of concrete containing Ultimax cement was 1 to 6% higher than that of concrete containing ASTM Type I/II cement. At 28 days, the bulk density of concrete containing Ultimax cement was 1 to 5% higher than that of concrete containing ASTM Type I/II.

4.6.2.6 Shrinkage and Expansion

Shrinkage and expansion of concrete made with Ultimax cement are plotted versus age at different water-to-cement ratios in Figures 4.39 and 4.40. Detailed raw data for the individual specimens are given in Appendix VI (a) through VI (c). It can be observed from Figure 4.39 that there was a fluctuation in the shrinkage measurement for concrete made with Ultimax cement at early ages up to seven days. After seven days, the shrinkage became stable. At 28 days, the shrinkage reached values of 170×10^{-6} to 200×10^{-6} in./in. depending on the water-to-cement ratio. At 90 days, the shrinkage generally appeared to reach a flat plateau with values ranging from 277×10^{-6} to 390×10^{-6} in./in. depending on the water-to-cement ratio. It can be observed from Figure 4.40 that the specimens

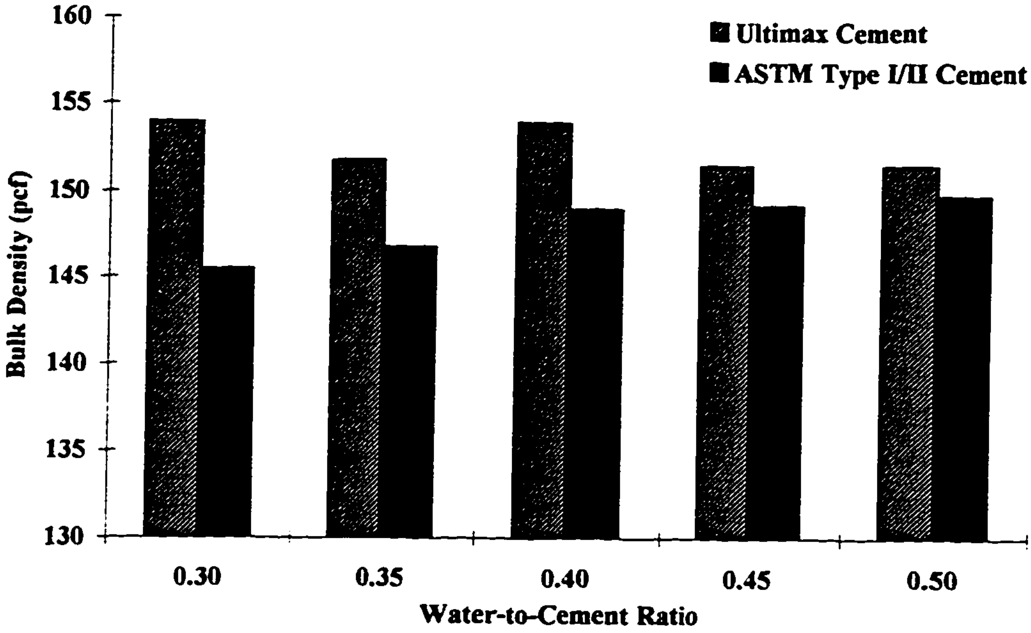


Figure 4.37: Bulk Density Versus Water-to-Cement Ratio at 1 Day (4 x 8-in.)

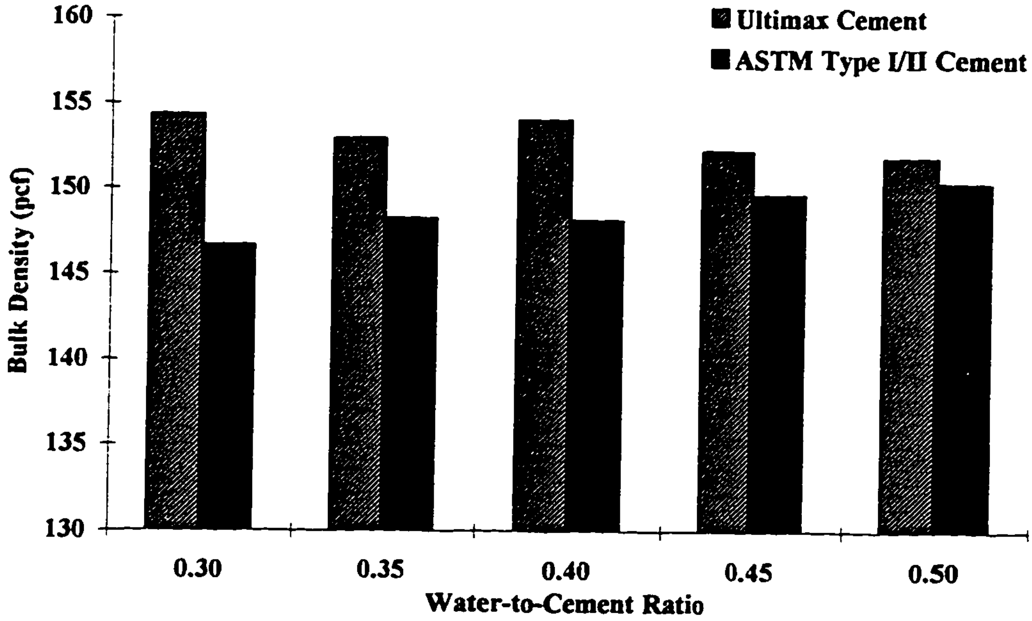


Figure 4.38: Bulk Density Versus Water-to-Cement Ratio at 28 Days (4 x 8-in.)

Table 4.22: Comparison of Bulk Density of Concrete Containing Ultimax and ASTM Type I/II Cements (4 x 8-in.)

Age	*w/cm*	Average Bulk Density (pcf)		Percent Increase in Bulk Density of Concrete Containing Ultimax Cement
		Ultimax Cement	ASTM Type I/II Cement	
1 day	0.30	154	145	6%
	0.35	152	147	3%
	0.40	154	149	3%
	0.45	151	149	1%
	0.50	151	150	1%
28 days	0.30	154	147	5%
	0.35	153	148	3%
	0.40	154	148	4%
	0.45	152	150	1%
	0.50	152	150	1%

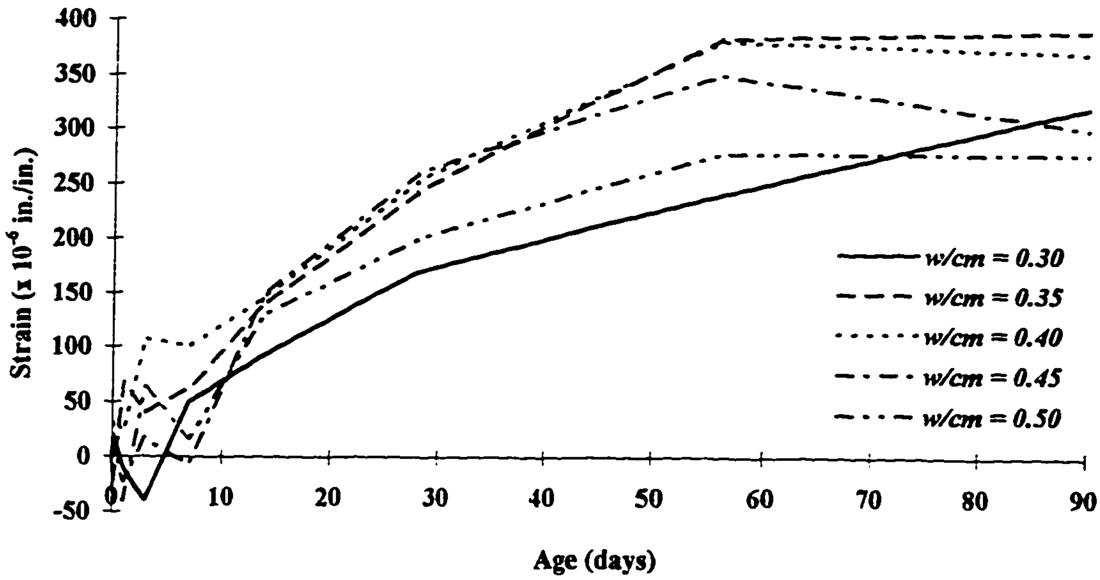


Figure 4.39: Shrinkage of Air-Dried Prisms Containing Ultimax Cement

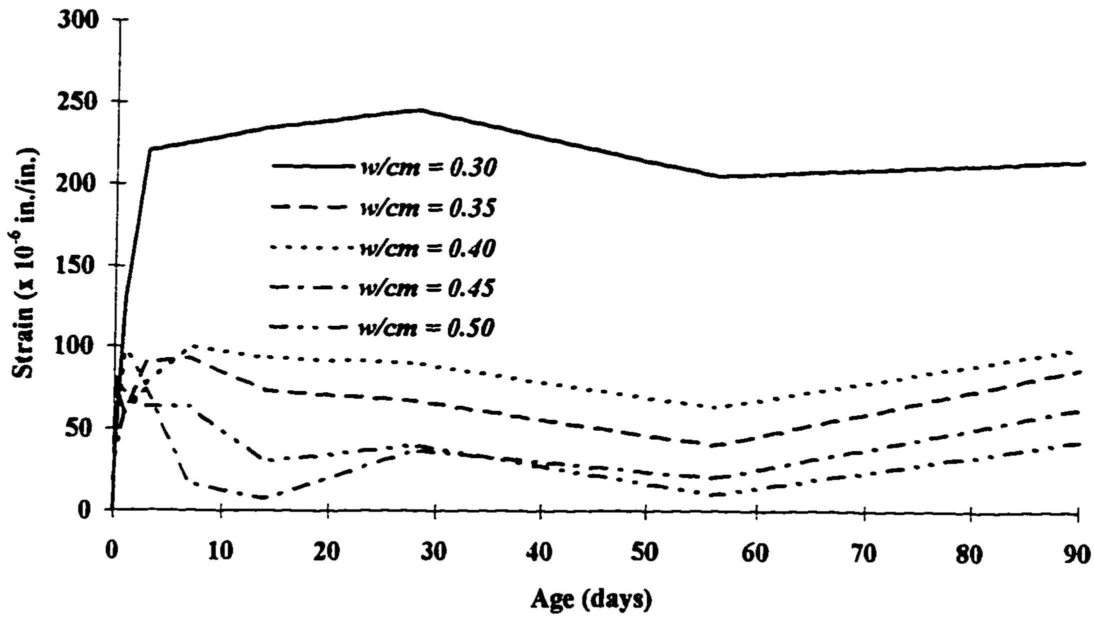


Figure 4.40: Expansion of Water-Cured Prisms Containing Ultimax Cement

reached ultimate expansion at 90 days. The expansion values up to 90 days did not exceed 100 x 10^{-6} in./in. for water-to-cement ratios between 0.35 and 0.50. At the water-to-cement ratio of 0.30, higher expansion values of 245 x 10^{-6} in/in. at 28 days and 215 x 10^{-6} in./in at 90 days were obtained.

Shrinkage and expansion of concrete made with ASTM Type I/II cement are plotted versus age at different water-to-cement ratios in Figures 4.41 and 4.42. Detailed raw data for the individual specimens are given in Appendix VI (d). It can be observed from Figure 4.41 that all air-dried specimens made with ASTM Type I/II cement exhibited a gradual increase in shrinkage. At 28 days, the shrinkage values varied from 690 x 10^{-6} to 757 x 10^{-6} in./in. depending on the water-to-cement ratio. At 90 days, the shrinkage values varied from 1047 x 10^{-6} to 1280 x 10^{-6} in./in. depending on the water-to-cement ratio. It can be observed from Figure 4.42 that a fluctuation in expansion measurement was observed at early ages up to 7 days. The expansion at 28 days varied from 70 x 10^{-6} to 170 x 10^{-6} in./in. depending on the water-to-cement ratio. The expansion at 90 days varied from 110 x 10^{-6} to 290 x 10^{-6} in./in. depending on the water-to-cement ratio.

Figure 4.43 and Table 4.23 compare the shrinkage of concrete specimens containing Ultimax cement with concrete specimens containing ASTM Type I/II cement at 28 days. It can be observed from Figure 4.43 that concrete containing Ultimax cement exhibited significantly less shrinkage than concrete containing ASTM Type I/II. Table

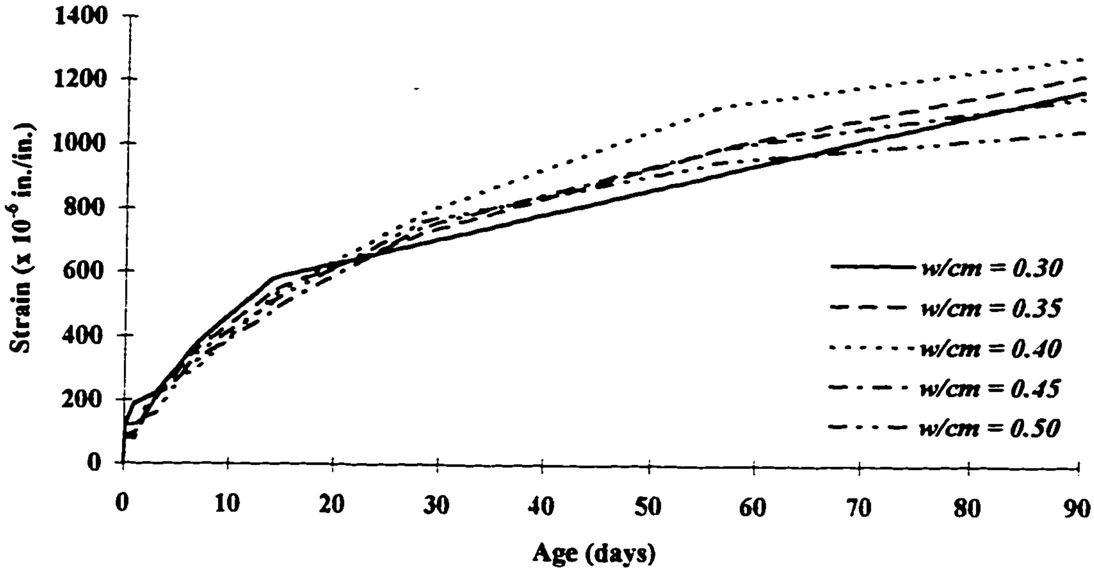


Figure 4.41: Shrinkage of Air-Dried Prisms Containing ASTM Type I/II Cement

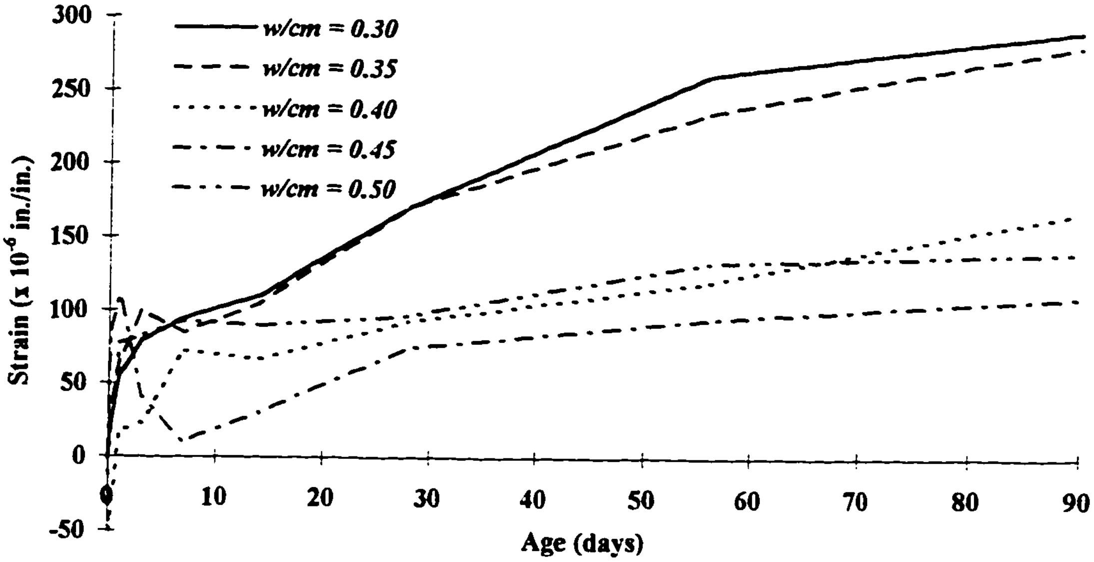


Figure 4.42: Expansion of Water-Cured Prisms Containing ASTM Type I/II Cement

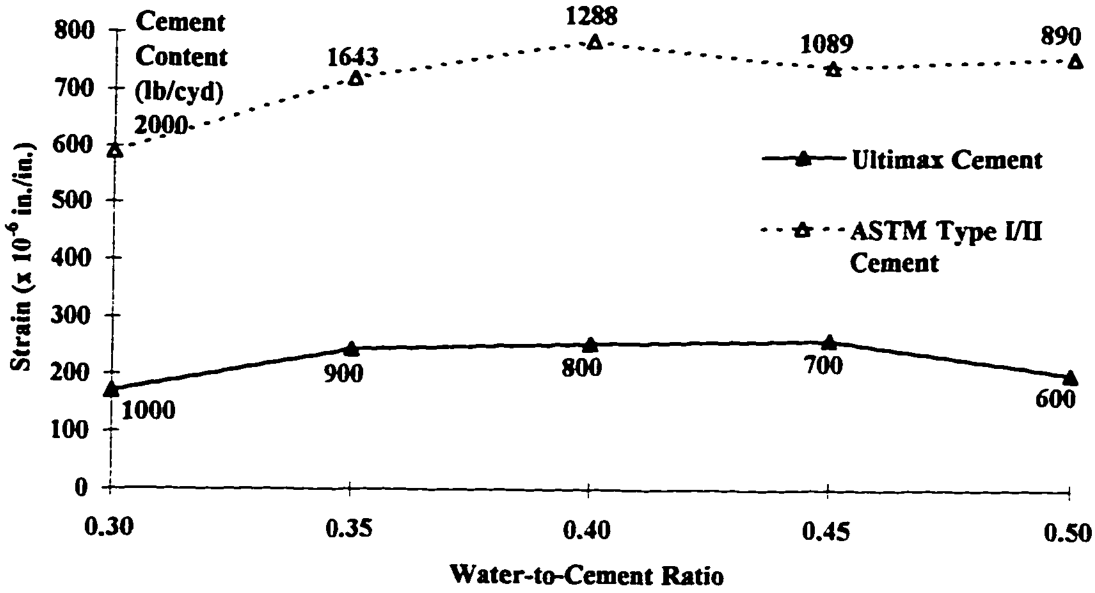


Figure 4.43: Shrinkage of Air-Dried Prisms Versus Water-to-Cement Ratio at 28 Days

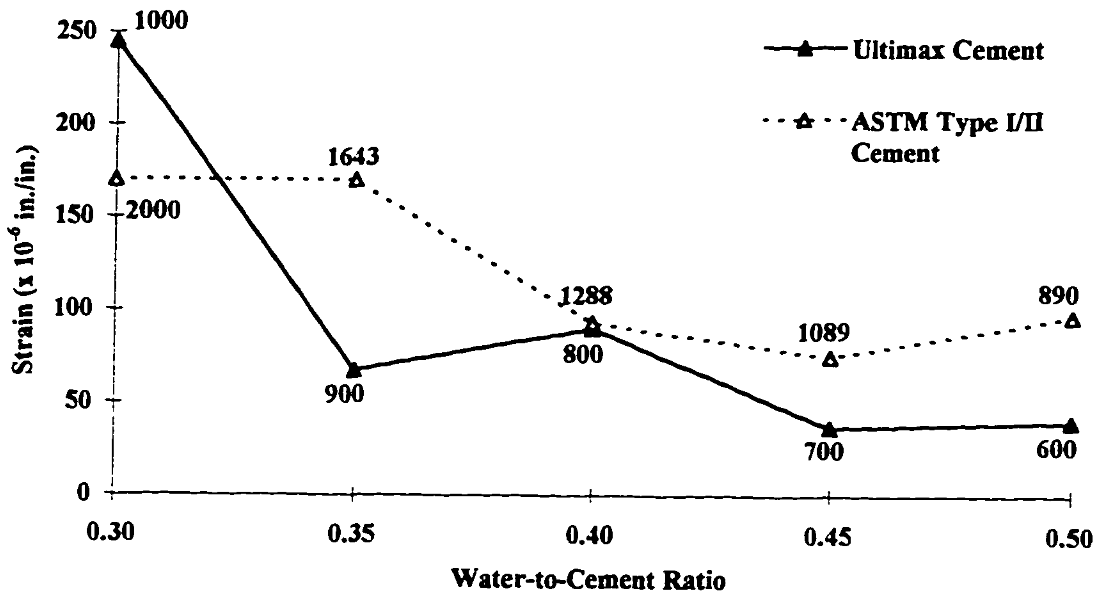


Figure 4.44: Expansion of Water-Cured Prisms Versus Water-to-Cement Ratio at 28 Days

4.23 shows that the concrete made with Ultimax cement exhibited 65 to 75% less shrinkage than concrete made with ASTM Type I/II cement.

Table 4.23: Comparison of Shrinkage and Expansion of Concrete Prisms Containing Ultimax and ASTM Type I/II Cements at 28 Days

w/cm	Average Shrinkage (x 10^{-6} in./in.)		Percent Decrease in Shrinkage of Concrete Containing Ultimax Cement
	Ultimax Cement	ASTM Type I/II Cement	
0.30	170	690	75%
0.35	243	720	66%
0.40	253	783	68%
0.45	260	740	65%
0.50	200	757	74%

w/cm	Average Expansion (x 10^{-6} in./in.)		Percent Decrease in Expansion of Concrete Containing Ultimax Cement
	Ultimax Cement	ASTM Type I/II Cement	
0.30	245	170	-44%
0.35	67	170	61%
0.40	90	93	3%
0.45	37	75	51%
0.50	40	97	59%

Figure 4.44 and Table 4.23 compare the expansion of concrete specimens containing Ultimax cement with concrete specimens containing ASTM Type I/II cement at 28 days. Figure 4.44 shows that, in general, specimens containing Ultimax cement expanded less when subjected to water-curing than specimens containing ASTM Type I/II cement. Table 4.23 shows that concrete made with Ultimax cement exhibited 44% more expansion at water-to-cement ratio of 0.30 and 3 to 61% less expansion at water-to-cement ratios of 0.35 to 0.50.

Figure 4.45 and Table 4.24 compare the shrinkage of concrete specimens containing Ultimax cement with concrete specimens containing ASTM Type I/II cement at 90 days. Similar to Figure 4.43, Figure 4.45 shows that concrete containing Ultimax cement exhibited significantly less shrinkage than concrete containing ASTM Type I/II. Table 4.24 shows that the concrete made with Ultimax cement exhibited 68 to 74% less shrinkage than concrete made with ASTM Type I/II cement at 90 days.

Figure 4.46 and Table 4.24 compare the expansion of concrete made with Ultimax cement with concrete made with ASTM Type I/II cement at 90 days. Figure 4.46 shows that all specimens containing Ultimax cement expanded less when subjected to water-curing than specimens containing ASTM Type I/II cement. Table 4.24 shows that concrete made with Ultimax cement exhibited 26 to 69% less expansion than concrete made with ASTM Type I/II cement.

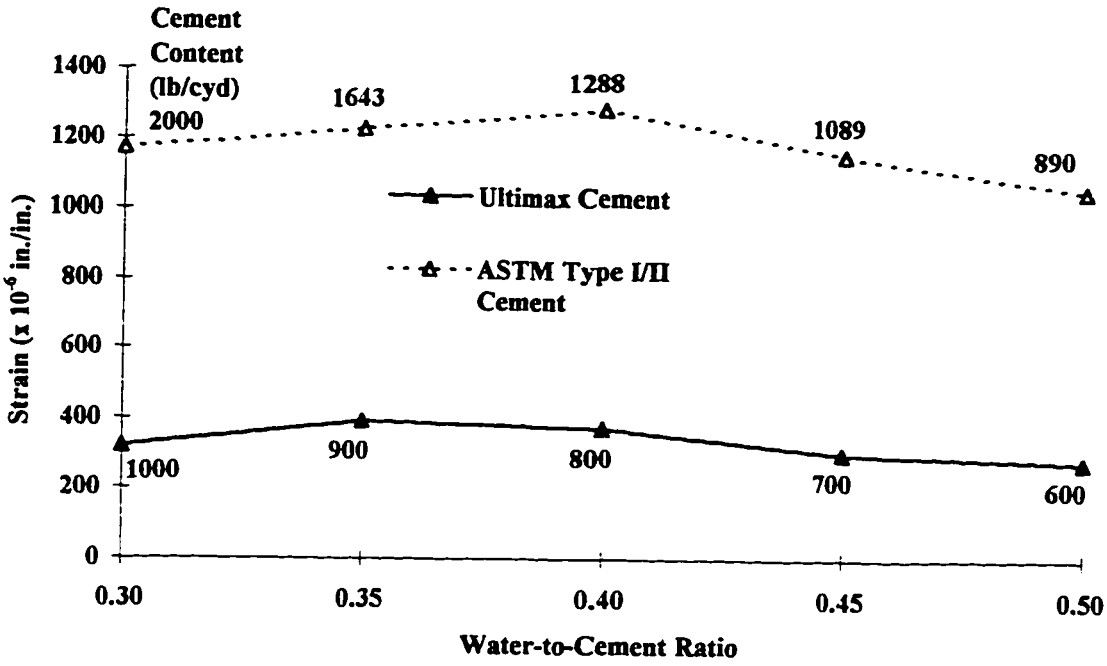


Figure 4.45: Shrinkage of Air-Dried Prisms Versus Water-to-cement Ratio at 90 Days

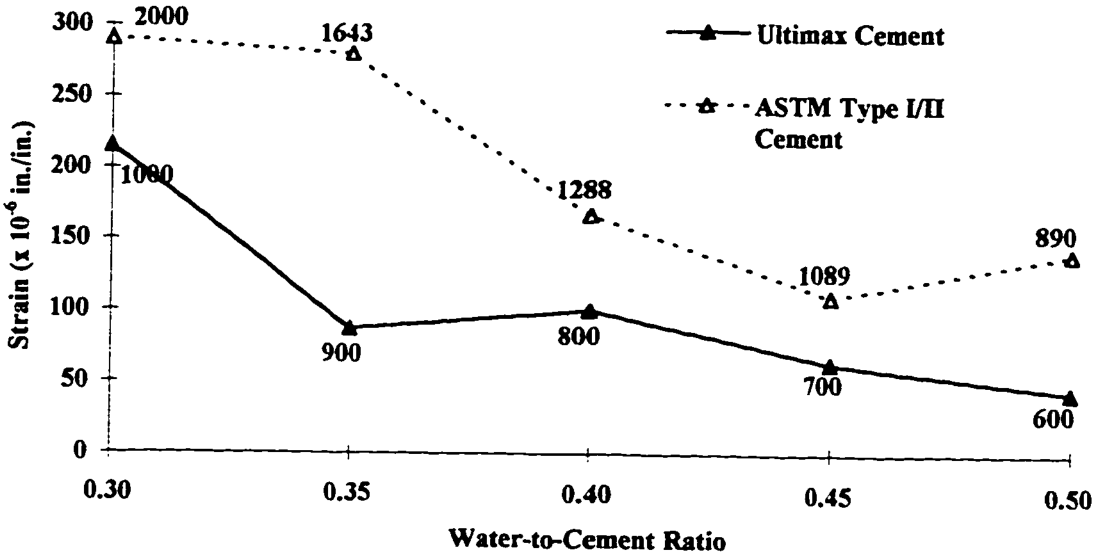


Figure 4.46: Expansion of Water-Cured Prisms Versus Water-to-Cement Ratio at 90 Days

Table 4.24: Comparison of Shrinkage and Expansion of Concrete Prisms Containing Ultimax and ASTM Type I/II Cements at 90 Days

w/cm	Average Shrinkage (x 10^{-6} in./in.)		Percent Decrease in Shrinkage of Concrete Containing Ultimax Cement
	Ultimax Cement	ASTM Type I/II Cement	
0.30	320	1170	73%
0.35	390	1220	68%
0.40	370	1280	71%
0.45	300	1150	74%
0.50	277	1047	74%

w/cm	Average Expansion (x 10^{-6} in./in.)		Percent Decrease in Expansion of Concrete Containing Ultimax Cement
	Ultimax Cement	ASTM Type I/II Cement	
0.30	215	290	26%
0.35	87	280	69%
0.40	100	167	40%
0.45	63	110	43%
0.50	43	140	69%

4.7 References

(1) *1996 Annual Book of ASTM Standards*, "Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates," American Society for Testing and Materials, Philadelphia, V. 04.02 (C 136).

(2) *1996 Annual Book of ASTM Standards*, "Standard Test Method for Specific Gravity and Absorption of Coarse Aggregate," American Society for Testing and Materials, Philadelphia, V. 04.02 (C 127).

(3) *1996 Annual Book of ASTM Standards*, "Standard Test Method for Specific Gravity and Absorption of Fine Aggregate," American Society for Testing and Materials, Philadelphia, V. 04.02 (C 128).

(4) *1996 Annual Book of ASTM Standards*, "Standard Specification for Concrete Aggregates," American Society for Testing and Materials, Philadelphia, V. 04.02 (C 33).

(5) *Design and Control of Concrete Mixtures*, 13th ed., Portland Cement Association, Skokie, Illinois, 1988.

(6) *1996 Annual Book of ASTM Standards*, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory," American Society for Testing and Materials, Philadelphia, V. 04.02 (C 192).

(7) *1996 Annual Book of ASTM Standards*, "Standard Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete," American Society for Testing and Materials, Philadelphia, V. 04.02 (C 157).

(8) *1996 Annual Book of ASTM Standards*, "Standard Test Method for Slump of Hydraulic Cement Concrete," American Society for Testing and Materials, Philadelphia, V. 04.02 (C 143).

(9) *1996 Annual Book of ASTM Standards*, "Standard Test Method Compressive Strength of Cylindrical Concrete Specimens," American Society for Testing and Materials, Philadelphia, V. 04.02 (C 39).

(10) *1996 Annual Book of ASTM Standards*, "Standard Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression," American Society for Testing and Materials, Philadelphia, V. 04.02 (C 469).

(11) *1996 Annual Book of ASTM Standards*, "Standard Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens," American Society for Testing and Materials, Philadelphia, V. 04.02 (C 496).

Chapter 5

Experimental Program and Test Results

5.1 Introduction

The Windsor probe test was used to nondestructively evaluate the *in situ* compressive strength of normal and high strength concrete slabs. The compressive strengths of the slabs were obtained by testing 4 x 8-in. (100 x 200-mm) cylinders which were subjected to uniaxial compression. The compressive strengths ranged from 2,200 to 10,500 psi (15 to 70 MPa). This research also investigates two probe types to determine the most suitable probe for the probe penetration testing of normal and high strength concrete by means of correlations between compressive strength and probe penetration. Statistical verification was used to determine the accuracy of the measurements.

The equipment and procedures used to perform the probe penetration tests are described in this chapter. In addition, specimen preparation is presented in detail. The test results include equations for lines fitted to the probe penetration data by various regression methods.

5.2 Experimental Program

5.2.1 Mix Design

In this study, tests were performed on eight concrete mixes using two types of cement. Mixes 1, 2, 3, and 6 were made with Ultimax rapid hardening hydraulic cement. The remaining mixes were made with Type III Portland cement. The mixes contained coarse aggregate consisting of crushed granite with a maximum nominal size ranging from 3/8 in. to 1 in. and fine aggregate with a fineness modulus varying between 2.7 and 3.0. All mixes except mix 6 contained a high-range water-reducing admixture or superplasticizer conforming to ASTM C 494[1] requirements for Type A and Type F admixtures. Silica fume was used in mixes 1 and 2. Mix details are given in Table 5.1. The chemical composition and physical properties of the Ultimax cement can be found in Table 4.1. The chemical composition and physical properties of the Type III Portland cement and silica fume can be found in Tables 5.2 and 5.3.

5.2.2 Mixing Procedure

The following mixing procedure was used for mixes 1 and 2:

(1) Wet the mixer and drain the water.

(2) Mix half the superplasticizer with half of the water.

(3) Add coarse aggregate to the mixer.

(4) Add water mixed with superplasticizer until all aggregate is wet.

Table 5.1: Mix Proportions Before Adjustments for Moisture Content and Absorption

Mix No.	*w/cm	**A/cm	***CA/FA	Fineness Modulus of Fine Aggregate	Volume of Coarse Aggregate Per Unit of Volume of Concrete	Mix Component								
						Water (lb/cyd)	Ultimax Cement (lb/cyd)	Portland Cement, Type III (lb/cyd)	Silica Fume (lb/cyd)	3/8 in. Coarse Aggregate (lb/cyd)	1 in. Coarse Aggregate (lb/cyd)	Fine Aggregate (lb/cyd)	Super-plasticizer (lb/cyd)	% Super-plasticizer
1	0.25	2.25	0.79	3.00	0.44	280	968	0	152	1117	0	1414	49.0	1.80
2	0.25	2.25	0.79	3.00	0.44	281	968	0	152	1117	0	1414	50.7	1.80
3	0.26	2.28	0.73	3.00	0.44	308	0	1167	0	1117	0	1530	97.3	3.28
4	0.38	1.96	0.93	2.70	0.44	480	0	1273	0	0	1200	1290	152.0	4.81
5	0.26	2.83	0.74	2.70	0.44	261	0	1000	0	0	1200	1622	84.9	3.38
6	0.30	2.41	0.86	2.71	0.47	320	1067	0	0	1186	0	1380	0.0	0.00
7	0.27	2.09	0.84	2.71	0.44	320	0	1167	0	1111	0	1323	164.9	5.56
8	0.27	2.09	0.84	2.71	0.44	319	0	1167	0	1111	0	1323	164.9	5.58

* *w/cm* = Water-to-cementitious materials ratio by weight

** *A/cm* = Aggregate-to-cementitious materials ratio by weight

*** CA/FA = Coarse aggregate-to-fine aggregate ratio by weight

Table 5.2: Chemical Composition and Physical Properties of ASTM Type III Cement

Chemical Composition %	ASTM Type III Cement*	ASTM C 150 Specifications for Type III Cement
Silicon dioxide (SiO_2)	21.08	—
Aluminum oxide (Al_2O_3)	5.01	—
Ferric oxide (Fe_2O_3)	1.34	—
Calcium oxide (CaO)	68.78	—
Magnesium oxide (MgO)	2.99	6.0 max
Sulfur trioxide (SO_3)	3.54	4.5 max
Loss on ignition	2.11	3.0 max
Equivalent alkalies ($Na_2O + 0.658K_2O$)	0.47	0.6 max
Insoluble residue	0.25	0.75 max
Compound Composition %		
Tricalcium silicate (C_3S)	54	—
Tricalcium aluminate (C_3A)	11	15 max
Physical Properties		
Blaine fineness, m^2/kg	598	—
Autoclave expansion, %	0.18	0.80 max
Normal Consistency, %	28.40	—
Setting time, Vicat (min):		
Initial	55	45 min
Final	—	375 max
Air content of mortar, volume %	7.7	12 max
Compressive strength (psi) at:		
1 day	3520	1740 min
3 days	5250	3480 min
7 days	6060	—
28 days	7060	—

* Chemical composition and physical data were provided by the California Portland Cement Company in Glendora, CA.

Table 5.3: Chemical Composition and Physical Properties of Silica Fume*

Chemical Composition	Percentage by Dry Mass
Silicon dioxide (SiO_2)	93.08
CL	0.19
Aluminum oxide (Al_2O_3)	1.17
Ferric oxide (Fe_2O_3)	0.19
Calcium oxide (CaO)	0.43
Magnesium oxide (MgO)	0.53
Sulfur trioxide (SO_3)	0.22
Sodium oxide (Na_2O)	0.42
Potassium oxide (K_2O)	1.18
Available alkalies	1.27
Carbon (C)	3.47
Loss on ignition	4.47
Physical Properties	
325 sieve retained (%)	3.44
Specific gravity	2.20
Density - Fluffy (pcf)	10.50
Moisture Content (%)	0.14

* Chemical composition and physical data were provided by Norchem Concrete Products Inc. in Fort Pierce, Florida.

(5) Add silica fume to the mixer.

(6) Add water mixed with superplasticizer until mixture is completely wet and all aggregate is coated with mixture.

(7) Add the cement alternately with remaining water until wet and uniform.

(8) Add the fine aggregate alternately with remaining water.

(9) Add remaining superplasticizer.

The mixing procedure for mixes 3 to 8 was basically the same except for the elimination of steps 5 and 6 since these mixes did not contain silica fume.

5.2.3 Preparation of Test Specimens

One 18 x 24 x 3 1/2-in. (460 x 610 x 90-mm) slab and a minimum of three 4 x 8-in. (100 x 200-mm) cylinders were cast from each mix for testing. The cylinders were rodded 25 times in three layers, while the slabs were rodded in two layers, one rodding for every 2 $in.^2$ (129 mm^2) of surface area as described in ASTM C 192.[2] All specimens were covered with plastic sheets after casting to minimize moisture loss. Cylinders and slabs cast from mixes 1, 2, and 6 were stripped the next day and cured in a moist room under standard conditions. Cylinders and slabs cast from mixes 3, 4, 5, 7, and 8 were stripped six days later when the concrete had completely hardened.

5.2.4 Equipment

The main equipment used in the penetration probe test are a powder-actuated driver, steel probes, loaded cartridges, and a depth gauge as shown in Figure 3.1. The two sets of probes were made of AISI 1045 steel. This type of steel was used instead of the AISI 4140 steel because the AISI 4140 steel had problems when used to test concrete having strengths above 3,000 psi (25MPa). One set of probes was baked for stress relief for 3 1/2 hours at 350°F while the other set was baked for 7 hours at 350°F. The probes baked for 3 1/2 hours had no identifying grooves and will hereafter be referred to as the "no-line" probes. The probes baked for 7 hours were marked with two identifying grooves on each probe and will be referred to as the "double-line" probes. The dimensions for both sets of probes are shown in Figure 5.1.

5.2.5 Testing

The specimens were tested at different ages as shown in Tables 5.4 and 5.5. For each age a minimum of one cylinder was tested for compressive strength and a minimum of one probe from each of the two sets was driven into the corresponding slab(s). The tests, as shown in Figure 5.2, were performed in accordance to ASTM C 803[3] specifications.

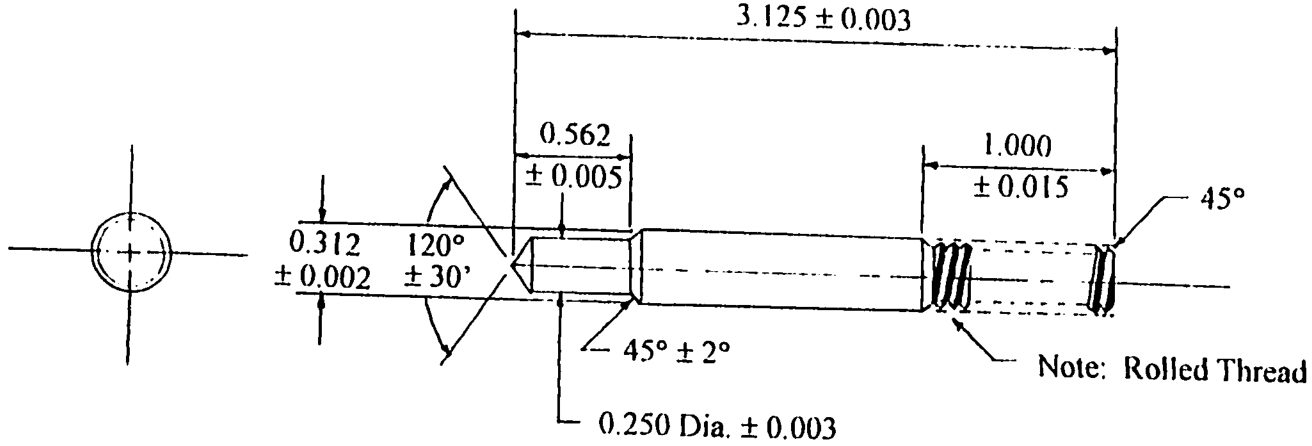


Figure 5.1: Probe Dimensions (in.)
(Courtesy James Instruments Inc. in Chicago, Illinois.)

Table 5.4: Compressive Strength and Exposed Probe Length Data for Different Probe Materials

Mix No.	Age (days)	Compressive Strength (psi)				Average Strength (psi)	Standard Deviation	Coefficient of Variation (%)	Exposed Probe Length (in.)								Combined Double-Line and No-Line Data	
									Double-Line Probe			Average Length	No-Line Probe			Average Length	Average Length	Standard Deviation
1	1	5153	5411	5511	----	5358	185	3.45	----	----	----	----	----	----	----	----	----	----
	8	4974	4496	----	----	4735	338*	7.14*	1.560	1.625	1.500	1.562	1.500	1.640	----	1.570	1.565	0.067
	15	5929	6486	7361	----	6208	394	6.34	1.650	1.775	1.575	1.667	1.600	1.763	----	1.682	1.673	0.092
	21	6247	6386	6028	----	6220	180	2.90	----	----	----	----	----	----	----	----	----	----
	28	7023	6963	6963	5813	6983	586	8.39	1.625	1.638	----	1.632	1.675	----	----	1.675	1.646	0.026
2	15	4695	4337	----	----	4516	253*	5.60*	1.435	1.494	----	1.465	1.588	1.523	----	1.556	1.510	0.064
	28	4755	----	----	----	4755	----	----	1.538	1.607	----	1.573	1.688	1.601	----	1.645	1.609	0.062
3	8	7361	7003	----	----	7182	253*	3.52*	1.974	1.875	----	1.925	1.925	1.875	----	1.900	1.912	0.047
	28	9092	----	----	----	9092	----	----	2.038	2.050	----	2.044	2.112	----	----	2.112	2.067	0.040
4	8	4357	4357	4906	----	4540	317	6.98	1.700	1.675	----	1.688	1.650	----	----	1.650	1.675	0.025
	15	6283	6207	6004	----	6165	144	2.34	2.225	2.088	----	2.157	1.712	----	----	1.712	2.008	0.266
	28	6923	6613	6446	----	6661	242	3.63	----	----	----	----	----	----	----	----	----	----
5	8	2268	2208	2248	----	2241	31	1.36	1.513	1.540	----	1.527	1.240	1.600	1.450	1.430	1.469	0.139
	15	3024	2785	2726	----	2845	158	5.55	1.275	----	----	1.275	----	----	----	----	1.275	----
6	1	7500	4755**	8256	----	6837	1842	26.95**	----	----	----	----	----	----	----	----	----	----
	8	9076	4663**	9434	----	7724	2657	34.40**	----	----	----	----	----	----	----	----	----	----
	21	9350	8813	9569	----	9244	389	4.21	----	----	----	----	----	----	----	----	----	----
	63	10882	10146	----	----	10514	520*	4.95*	2.038	----	----	2.038	2.113	2.013	----	2.063	2.055	0.052
	90	10464	----	----	----	10464	----	----	2.038	----	----	2.038	2.025	1.963	----	1.994	2.009	0.040
7	8	7918	7679	8356	----	7984	343	4.30	----	----	----	----	----	----	----	----	----	----
	21	8276	8081	----	----	8179	138*	1.69*	----	----	----	----	----	----	----	----	----	----
	63	10265	9951	----	----	10108	222*	2.20*	1.950	----	----	1.950	2.000	1.938	----	1.969	1.963	0.033
	90	10405	----	----	----	10405	----	----	2.175	----	----	2.175	2.075	2.000	----	2.038	2.083	0.088
8	8	9076	7361	7162	----	7866	1052	13.38	----	----	----	----	----	----	----	----	----	----
	21	7958	8137	----	----	8048	127*	1.57*	----	----	----	----	----	----	----	----	----	----

* Data is limited to two readings and this value is not a good indicator.

** Out of norm, but included in analysis.

Table 5.5: Compressive Strength and Embedded Probe Length Data for Different Probe Materials

Mix No.	Age (days)	Average Compressive Strength (psi)	Standard Deviation	Coefficient of Variation (%)	Embedded Probe Length (in.)								Combined Double-Line and No-Line Data		
					Double-Line Probe			Average Length	No-Line Probe			Average Length	Average Length	Standard Deviation	Coefficient of Variation (%)
1	1	5358	185	3.45	—	—	—	—	—	—	—	—	—	—	—
	8	4735	338*	7.14*	1.565	1.500	1.625	1.563	1.625	1.485	—	1.555	1.560	0.067	4.26
	15	6208	394	6.34	1.475	1.350	1.550	1.458	1.525	1.362	—	1.444	1.452	0.092	6.34
	21	6220	180	2.90	—	—	—	—	—	—	—	—	—	—	—
	28	6983	586	8.39	1.500	1.487	—	1.494	1.450	—	—	1.450	1.479	0.026	1.75
2	15	4516	253*	5.61*	1.690	1.631	—	1.661	1.537	1.602	—	1.570	1.615	0.064	3.94
	28	4755	—	—	1.587	1.518	—	1.553	1.437	1.524	—	1.481	1.517	0.062	4.06
3	8	7182	253*	3.52*	1.151	1.250	—	1.201	1.200	1.250	—	1.225	1.213	0.047	3.91
	28	9092	—	—	1.087	1.075	—	1.081	1.013	—	—	1.013	1.058	0.040	3.75
4	8	4540	317	6.98	1.425	1.450	—	1.438	1.475	—	—	1.475	1.450	0.025	1.72
	15	6165	144	2.34	0.900	1.037	—	0.969	1.413	—	—	1.413	1.117	0.266	23.79
	28	6661	242	3.63	—	—	—	—	—	—	—	—	—	—	—
5	8	2241	31	1.36	1.612	1.585	—	1.599	1.885	1.525	1.675	1.695	1.656	0.139	8.37
	15	2845	158	5.55	1.850	—	—	1.850	—	—	—	—	1.850	—	—
6	1	6837	1842	26.95**	—	—	—	—	—	—	—	—	—	—	—
	8	7724	2657	34.40**	—	—	—	—	—	—	—	—	—	—	—
	21	9244	389	4.21	—	—	—	—	—	—	—	—	—	—	—
	63	10514	520*	4.95*	1.087	—	—	1.087	1.012	1.112	—	1.062	1.070	0.052	4.86
	90	10464	—	—	1.087	—	—	1.087	1.100	1.162	—	1.131	1.116	0.040	3.59
7	8	7984	343	4.30	—	—	—	—	—	—	—	—	—	—	—
	21	8179	138*	1.69*	—	—	—	—	—	—	—	—	—	—	—
	63	10108	222*	2.20*	1.175	—	—	1.175	1.125	1.187	—	1.156	1.162	0.033	2.83
	90	10405	—	—	0.950	—	—	0.950	1.050	1.125	—	1.088	1.042	0.088	8.43
8	8	7866	1052	13.38	—	—	—	—	—	—	—	—	—	—	—
	21	8048	127*	1.57*	—	—	—	—	—	—	—	—	—	—	—

* Data is limited to two readings and this value is not a good indicator.

** Out of norm, but included in analysis.

Figure 5.2: The Windsor Probe Test

5.3 Test Results

5.3.1 Regression Analysis

The ultimate compressive strength for the concrete is plotted against the probe penetration in Figures 5.3 through 5.10. Regression analysis was carried out using linear, exponential, power, and logarithmic curves for the two sets of probes tested, as well as, the combined probe data. Correlation coefficients were obtained from each set of data. The equation used to calculate the correlation coefficient, R, is given in Appendix VII. Plots of the fitted curves are also shown in Figures 5.3 through 5.10.

The following equations were determined for the double-line, no-line, and combined probe data:

Table 5.6: Correlation Equations for Estimating Compressive Strength of Normal and High Strength Concrete*

Probe Type	Linear	Exponential	Power	Logarithmic
Double-line	$y = 7362x - 6610$ $R = 0.78$	$y = 663e^{1.24x}$ $R = 0.75$	$y = 1722x^{2.21}$ $R = 0.76$	$y = 13026Ln(x) - 882$ $R = 0.79$
No-line	$y = 11353x - 13215$ $R = 0.92$	$y = 216e^{1.90x}$ $R = 0.89$	$y = 989x^{3.26}$ $R = 0.90$	$y = 19282Ln(x) - 3959$ $R = 0.91$
Combined Data	$y = 9145x - 9525$ $R = 0.84$	$y = 406e^{1.53x}$ $R = 0.82$	$y = 1345x^{2.69}$ $R = 0.82$	$y = 15906Ln(x) - 2269$ $R = 0.84$

where y = compressive strength (psi)
x = exposed probe length (in.)
R = correlation coefficient

* Each equation and R were computed from the combined data of all 8 mixes.

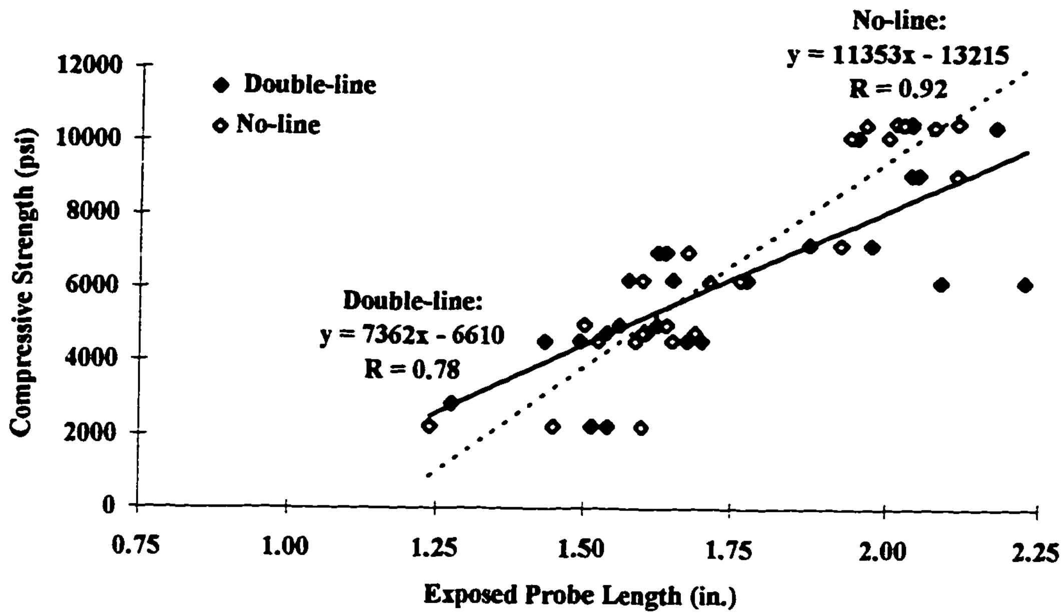


Figure 5.3: Compressive Strength Versus Exposed Probe Length (Linear Regression)

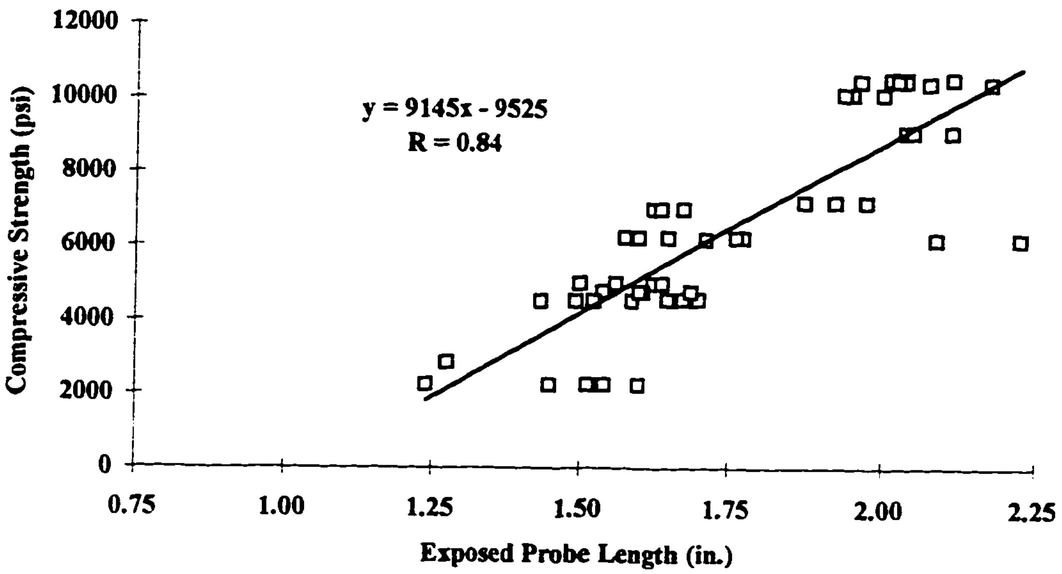


Figure 5.4: Compressive Strength Versus Combined Exposed Probe Length (Linear Regression)

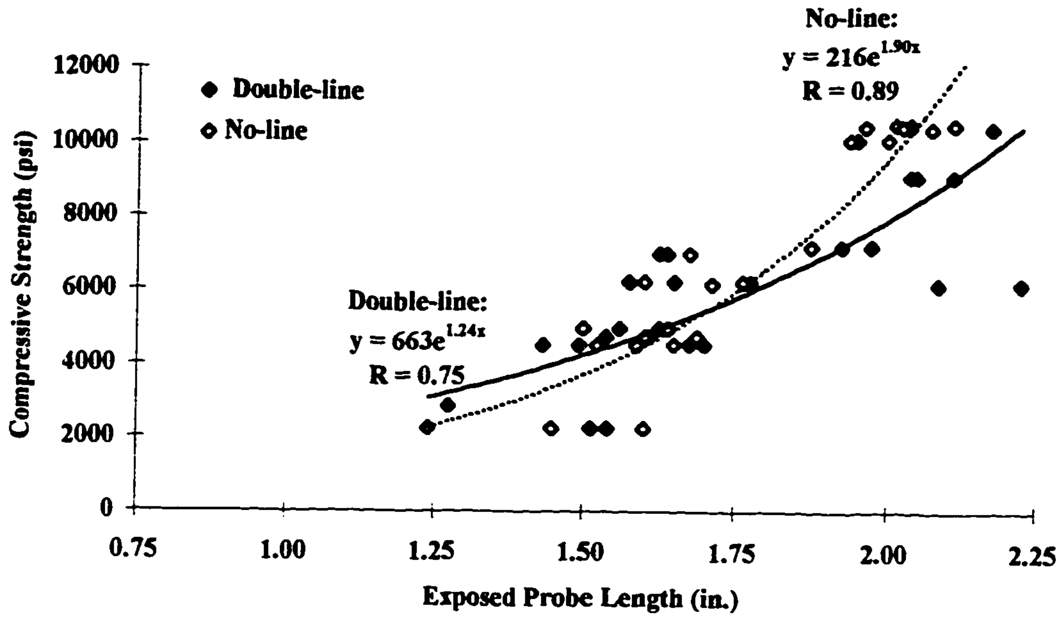


Figure 5.5: Compressive Strength Versus Exposed Probe Length (Exponential Regression)

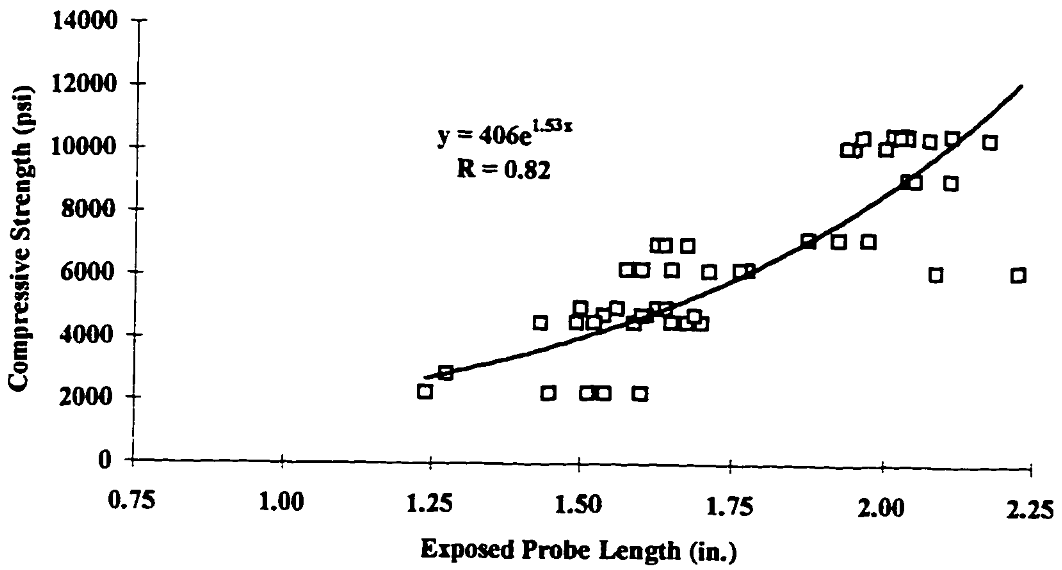


Figure 5.6: Compressive Strength Versus Combined Exposed Probe Length (Exponential Regression)

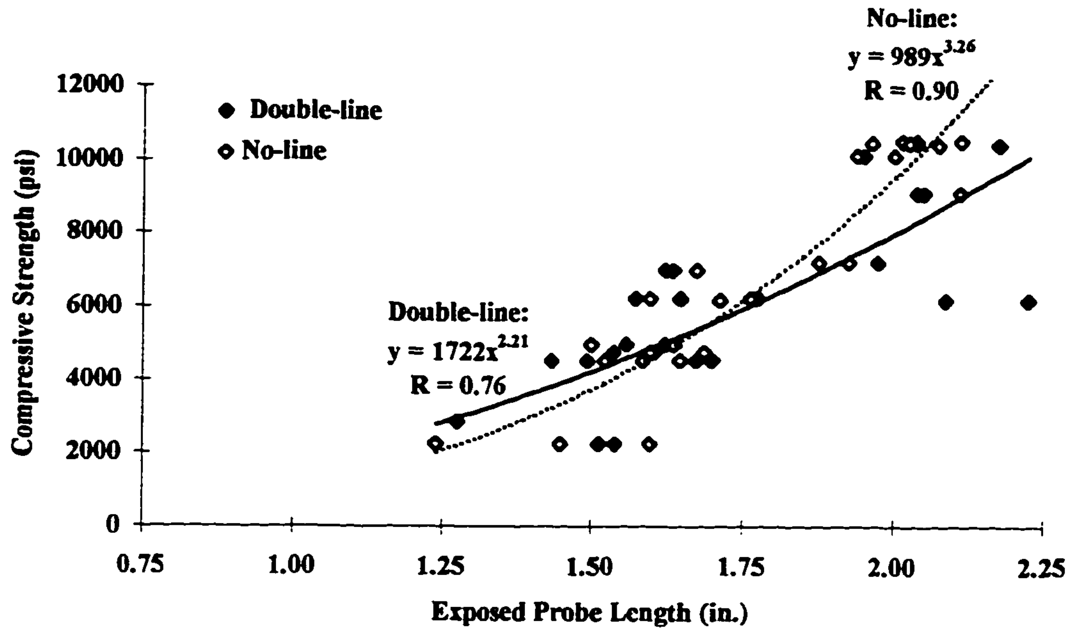


Figure 5.7: Compressive Strength Versus Exposed Probe Length (Power Regression)

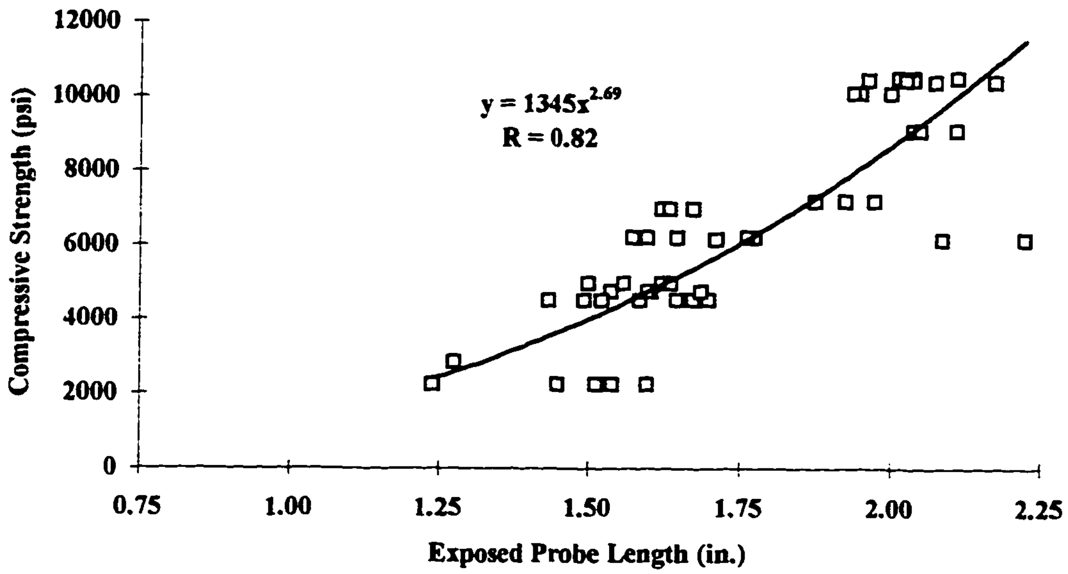


Figure 5.8: Compressive Strength Versus Combined Exposed Probe Length (Power Regression)

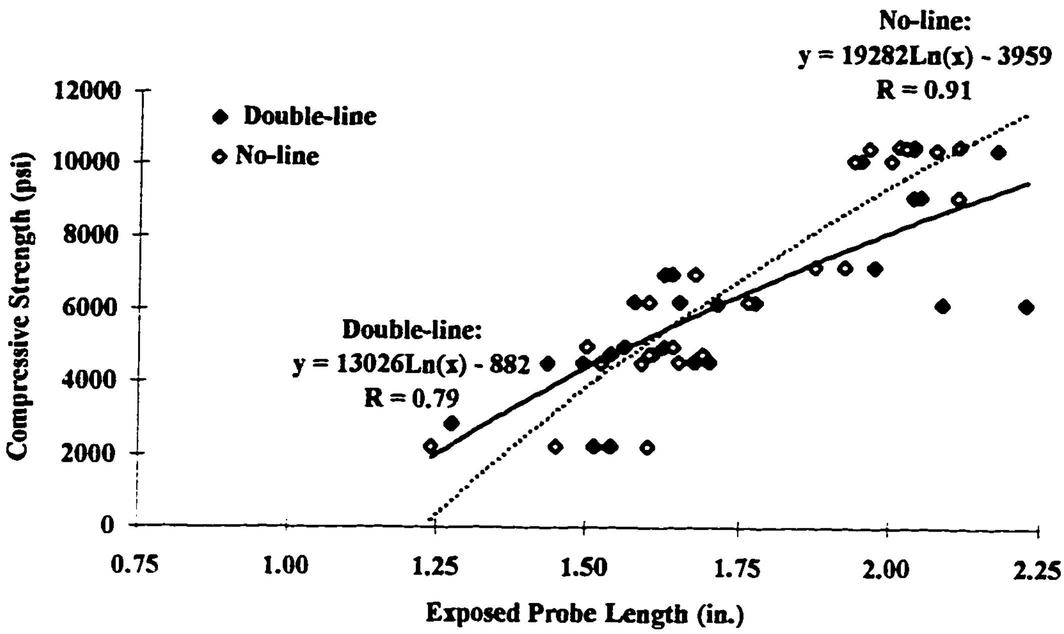


Figure 5.9: Compressive Strength Versus Exposed Probe Length (Logarithmic Regression)

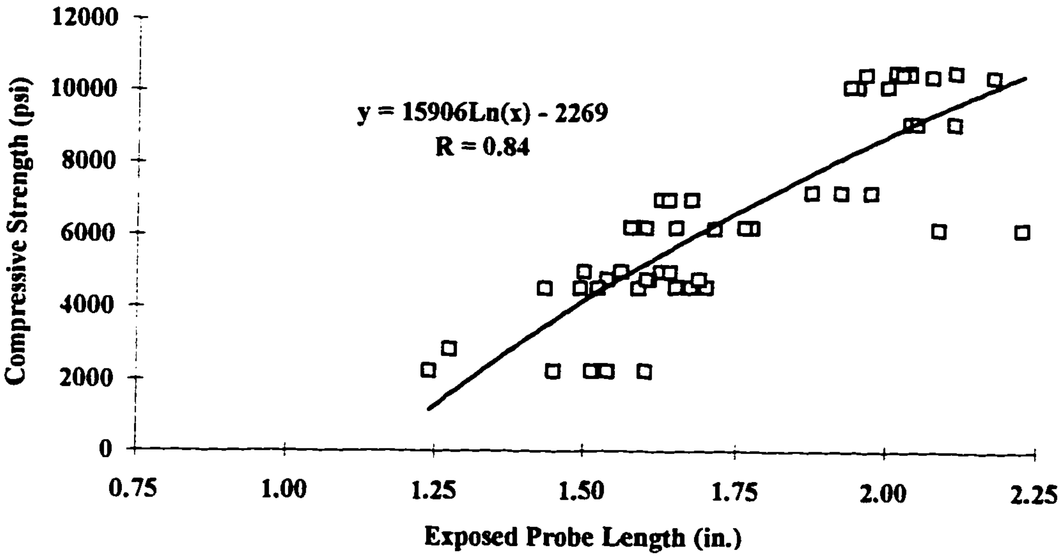


Figure 5.10: Compressive Strength Versus Combined Exposed Probe Length (Logarithmic Regression)

Table 5.6 shows the correlation coefficients obtained for the double-line, no-line, and combined probe data for each method of regression analysis. It can be observed that the best correlation coefficient in the case of the double-line probes was obtained for the logarithmic regression. Similarly, the best correlation coefficient for the no-line probes was obtained in the case of a linear regression. The best correlation coefficient for the combined probe data was obtained using both linear and logarithmic regressions.

Double-line, no-line, and combined probe data were analyzed to determine which of these produced the most consistent readings of exposed probe length. Of the three sets of data analyzed, the no-line probe data produced the highest correlation coefficient of 0.92. Therefore, the linear regression for the no-line probe data produced an equation that was the best fit to the data. This implies that the no-line probes produced the most consistent readings of exposed probe length.

5.3.2 Statistical Analysis

Tables 5.7 and 5.8 summarize the analysis of the probe data and the compressive strength data, respectively, for all eight mixes. The equations used to calculate standard deviation and coefficient of variation are given in Appendix VII. The values shown in these Tables 5.7 and 5.8 were used to plot Figure 5.11 which shows the coefficient of variation obtained at a given age for the double-line data, no-line data, combined probe data, and the uniaxial compression test. The uniaxial compression test showed a decrease in coefficient of variation with an increase in age. The double-line probes and the

Table 5.7: Analysis of Probe Data*

		Embedded Probe Length (in.)				
		Age (days)				
		8	15	28	63	90
Probe Type	AISI 1045 steel (baked for 7 hours) "Double-Line"	1.565	1.475	1.500	----	----
		1.500	1.350	1.487	----	----
		1.625	1.550	1.587	----	----
		1.151	1.690	1.518	----	----
		1.250	1.631	1.087	----	----
		1.425	0.900	1.075	----	----
		1.450	1.037	----	----	----
		1.612	1.850	----	----	----
		1.585	----	----	----	----
	AISI 1045 steel (baked for 3 1/2 hours) "No-Line"	1.625	1.525	1.450	1.012	1.100
		1.485	1.362	1.437	1.112	1.162
		1.200	1.537	1.524	1.125	1.050
		1.250	1.602	1.013	1.187	1.125
		1.475	1.413	----	----	----
		1.885	----	----	----	----
		1.525	----	----	----	----
		1.675	----	----	----	----
Average Embedded Probe Length	Double-Line	1.463	1.435	1.376	----	----
	No-Line	1.515	1.488	1.356	1.109	1.109
	Combined	1.487	1.456	1.368	1.109	1.109
Standard Deviation	Double-Line	0.166	0.326	0.231	----	----
	No-Line	0.223	0.098	0.232	0.072	0.047
	Combined	0.190	0.256	0.218	0.072	0.047
Coefficient of Variation (%)	Double-Line	11.3	22.7	16.8	----	----
	No-Line	14.7	6.6	17.1	6.5	4.2
	Combined	12.8	17.6	16.0	6.5	4.2

* Data is from all mixes combined.

Table 5.8: Analysis of Compressive Strength Data*

	Age (days)				
	8	15	28	63	90
Compressive Strength (psi)	4974	5929	7023	10882	10464
	4496	6486	6963	10146	10405
	7361	7361	6963	10265	----
	7003	4695	4755	9951	----
	4357	4337	9092	----	----
	4906	6283	6923	----	----
	2268	6207	6613	----	----
	2208	6004	6446	----	----
	2248	3024	----	----	----
	9076	2785	----	----	----
	4663	2726	----	----	----
	9434	----	----	----	----
	7918	----	----	----	----
	7679	----	----	----	----
	8356	----	----	----	----
	9076	----	----	----	----
	7361	----	----	----	----
	7162	----	----	----	----
Average	6141	5076	6847	10311	10435
Standard Deviation	2424	1649	1177	402	42**
Coefficient of Variation (%)	39.5	32.5	17.2	3.9	0.4**

* Data is from all mixes combined.
** Data is limited and this value is not a good indicator.

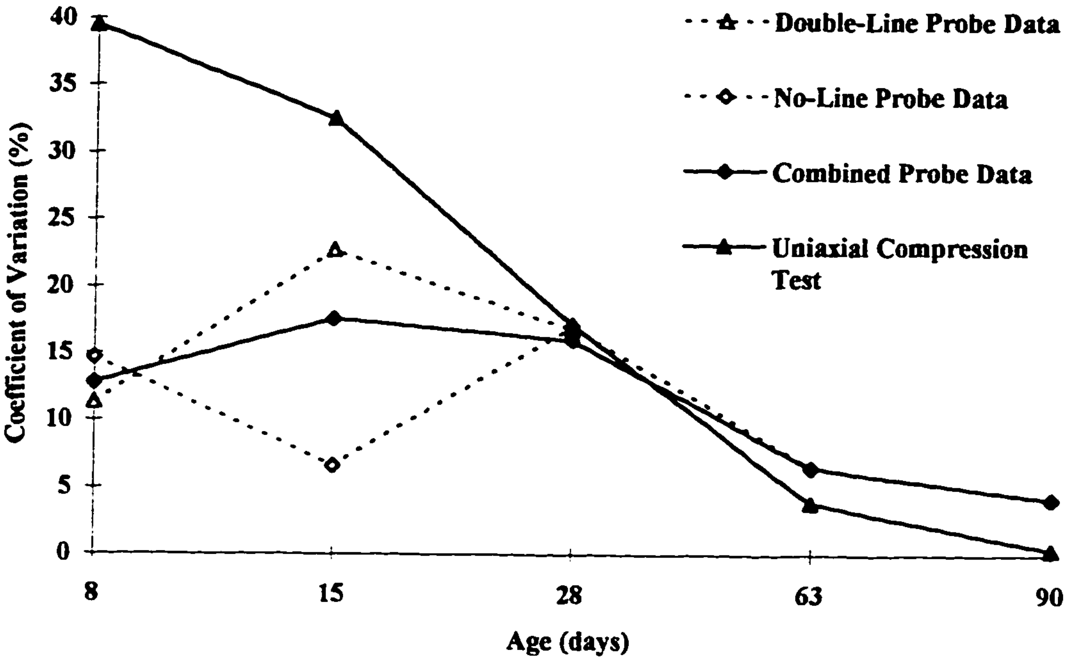


Figure 5.11: Coefficient of Variation Versus Age

combined probe data showed a slight increase in coefficient of variation up to 15 days. The coefficient of variation then decreases up to 90 days. The coefficient of variation of the no-line probe data fluctuated with the age of the concrete. All data showed a possible sensitivity to age. The uniaxial compression test, double-line probe data, and combined probe data showed a general decreasing trend in the coefficient of variation with age, while no trend could be established for the no-line probe data.

Figures 5.12 and 5.13, respectively, show the standard deviation and coefficient of variation of the combined probe data at various compressive strengths. It can be observed from Figure 5.12 that the standard deviation of the combined probe data did not exceed 0.14 in. at any compressive strength. It can also be observed from Figure 5.13 that the coefficient of variation for all compressive strengths was below 9%. The coefficient of variation was within acceptable practical limits.

Figures 5.14 and 5.15, respectively, show the standard deviation and coefficient of variation of the uniaxial compression test at various compressive strengths. It can be observed from Figure 5.14 that the standard deviation was below 3000 psi. In general, the standard deviation of the majority of the mixes did not exceed 1000 psi. It can also be observed from Figure 5.15 that the coefficient of variation, in the worst case, did not exceed 35%, and the majority of the points fell below 10%. The coefficient of variation was within acceptable practical limits.

In general, low coefficients of variation were obtained for the Windsor probe data and the compressive strength data indicating that the Windsor probe test can be used

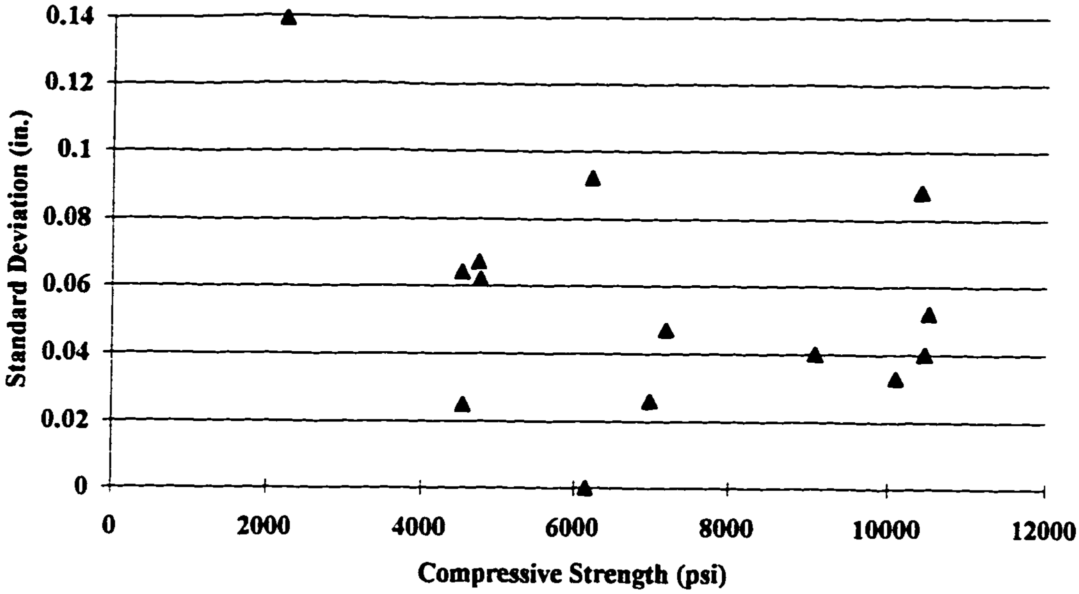


Figure 5.12: Standard Deviation of Combined Embedded Probe Length Versus Compressive Strength

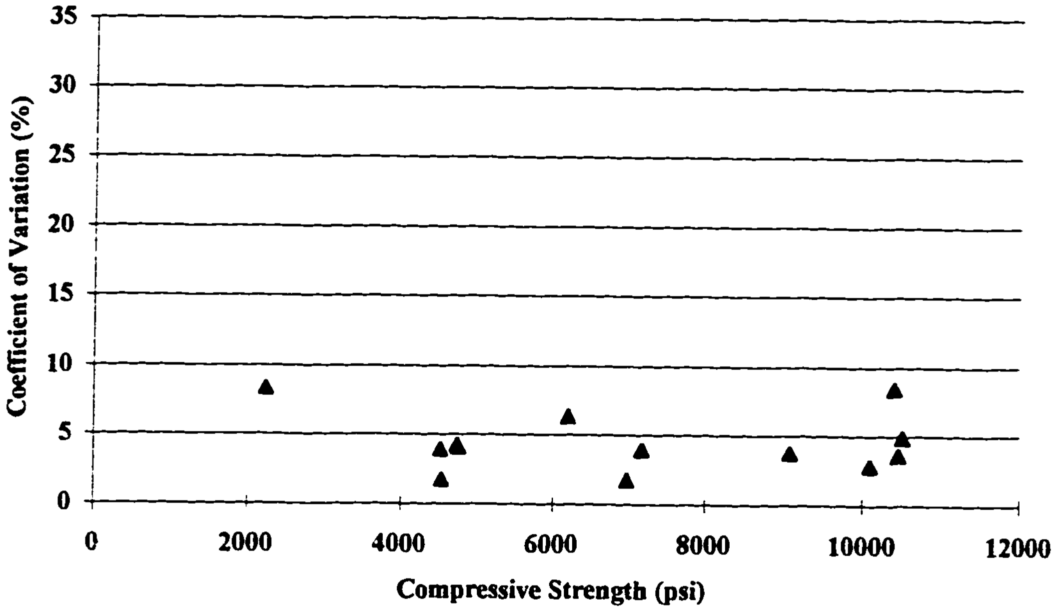


Figure 5.13: Coefficient of Variation of Combined Embedded Probe Length Versus Compressive Strength

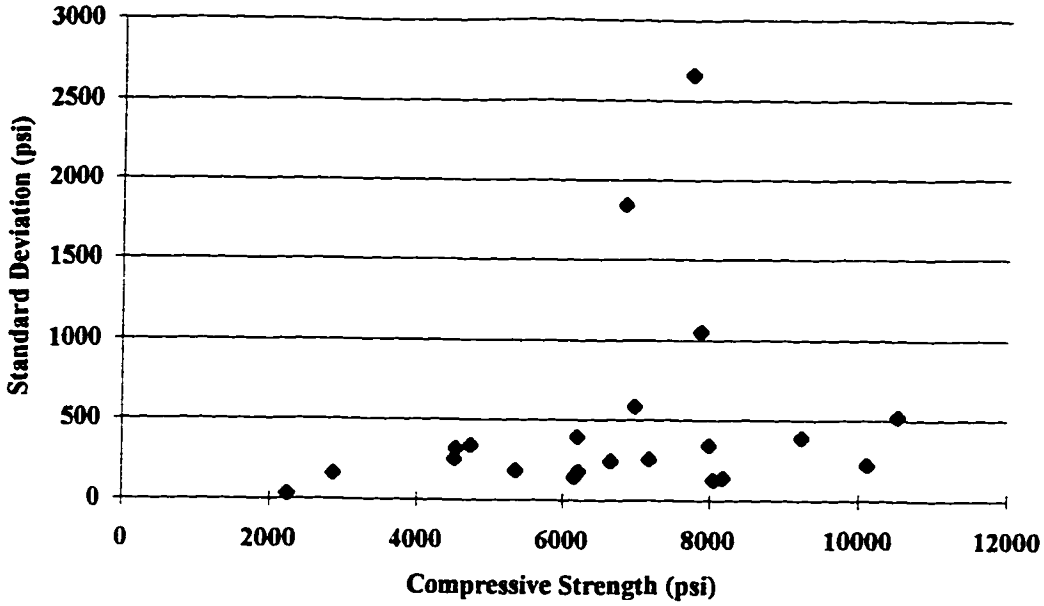


Figure 5:14: Standard Deviation of Uniaxial Compression Test Versus Compressive Strength

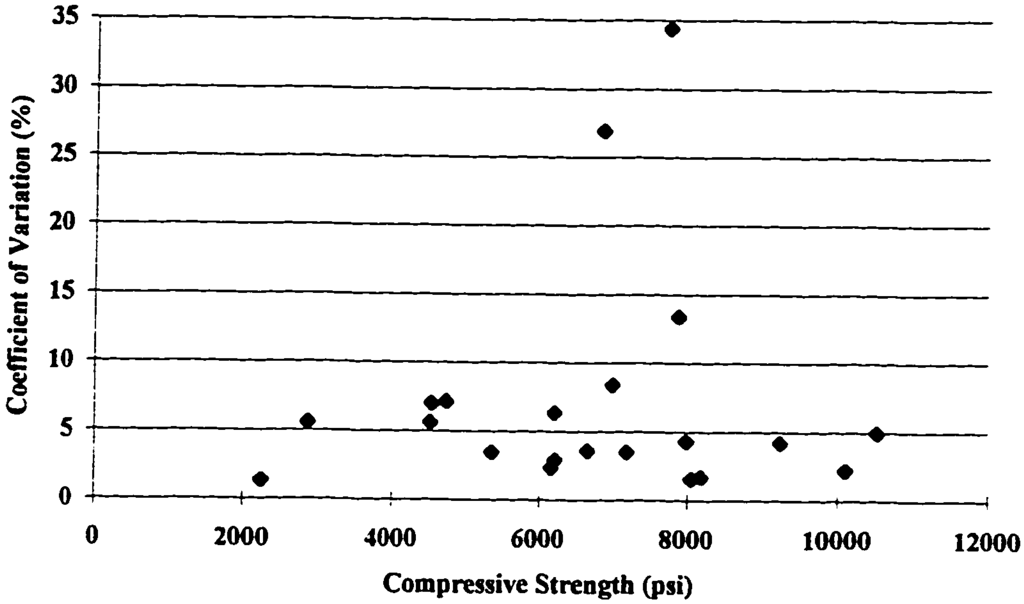


Figure 5.15: Coefficient of Variation of Uniaxial Compression Test Versus Compressive Strength

reliably to establish trends to predict the ultimate compressive strength of concrete up to 10,500 psi (70 MPa).

5.4 References

(1) *1996 Annual Book of ASTM Standards*, "Standard Specification for Chemical Admixtures for Concrete," American Society for Testing and Materials, Philadelphia, V. 04.02 (C 494).

(2) *1996 Annual Book of ASTM Standards*, "Standard Practice for Making and Curing Concrete Test Specimens in the Laboratory," American Society for Testing and Materials, Philadelphia, V. 04.02 (C 192).

(3) *1996 Annual Book of ASTM Standards*, "Standard Test Method for Penetration Resistance of Hardened Concrete," American Society for Testing and Materials, Philadelphia, V. 04.02 (C 803).

Chapter 6

Conclusions and Future Recommendations

6.1 Conclusions

6.1.1 Ultimax Cement Versus ASTM Type I/II Cement

Concrete containing Ultimax cement exhibited improved properties when compared with concrete containing ASTM Type I/II cement. The following conclusions can be drawn on the use of Ultimax cement as compared to ASTM Type I/II cement.

(1) The slump for concrete containing Ultimax cement at a given water-to-cement ratio was found to increase with increased cement content. In general, lower cement contents were required to obtain workable concrete for mixes having higher water-to-cement ratios.

(2) In order to achieve a slump with concrete containing ASTM Type I/II cement that was comparable to concrete containing Ultimax cement at a given water-to-cement ratio, a higher cement content was required. The cement content required of concrete containing ASTM Type I/II cement ranged from 890 to 2000 lb/cyd while the cement content of concrete containing Ultimax cement ranged from 600 to 1000 lb/cyd. Concrete containing ASTM Type I/II cement required about 48 to 100%

higher cement content than concrete containing Ultimax cement. The use of Ultimax cement could be advantageous since lower cement content than conventional concrete is required to achieve similar slump, however, cost comparison must be considered.

(3) The compressive strength of concrete made with Ultimax cement generally decreases with an increase in water-to-cement ratio. The strengths obtained from the 4 x 8-in. (100 x 200-mm) cylinders were similar to those obtained from the 6 x 12-in. (150 x 300-mm) cylinders.

(4) The compressive strengths of the 4 x 8-in. (100 x 200-mm) cylinders made with Ultimax cement at 1 day ranged from 2650 to 6080 psi and were found to be 20 to 40% higher than those of concrete made with ASTM Type I/II cement.

(5) At 28 days, the compressive strengths of the 4 x 8-in. (100 x 200-mm) cylinders made with Ultimax cement ranged from 3900 to 9270 psi and were 10 to 28% higher at water-to-cement ratios of 0.30 and 0.35. On the contrary, the compressive strengths of the 4 x 8-in. (100 x 200-mm) cylinders made with Ultimax cement were 17 to 38% lower at water-to-cement ratios of 0.40 to 0.50 than those of concrete made with ASTM Type I/II cement.

(6) The modulus of elasticity of concrete containing Ultimax cement generally decreases with an increase in water-to-cement ratio. The modulus of elasticity of the 4 x 8-in. (100 x 200-mm) cylinders made with Ultimax cement ranged from 2.4×10^6 psi to 3.6×10^6 psi at 1 day and from 3.6×10^6 psi to 4.6×10^6 psi at 28 days. In general, the 6 x 12-in. (150 x 300-mm) cylinders containing Ultimax cement had a modulus of elasticity similar to that of the 4 x 8-in. (100 x 200-mm) cylinders.

(7) The modulus of elasticity of concrete containing Ultimax cement and concrete containing ASTM Type I/II cement was similar for concrete made with both types of cement and generally decreases with an increase in water-to-cement ratio and.

(8) The slope of the stress-strain curve in the elastic region generally decreases as the water-to-cement ratio is increased for concrete containing Ultimax cement and concrete containing ASTM Type I/II cement. In general, the stress-strain curves of the 6 x 12-in. (150 x 300-mm) concrete cylinders made with Ultimax cement were found to have similar slopes in the elastic region to those obtained from testing the 4 x 8-in. (100 x 200-mm) cylinders.

(9) The splitting-tensile strength of concrete made with Ultimax cement decreases with an increase in water-to-cement ratio. At 28 days, the splitting-tensile strengths of the 4 x 8-in. (100 x 200-mm) cylinders containing Ultimax cement were 21 to 27 %

higher than those of the 6 x 12-in. (150 x 300-mm) cylinders. The splitting-tensile strengths of the 6 x 12-in. (150 x 300-mm) cylinders ranged from 320 psi to 560 psi.

(10) At 1 day, the splitting-tensile strengths of the 4 x 8-in. (100 x 200-mm) cylinders made with Ultimax cement ranged from 245 to 494 psi and were 5 to 6% higher than those of concrete containing ASTM Type I/II cement at the water-to-cement ratios of 0.30 and 0.35. On the contrary, the splitting-tensile strengths of the 4 x 8-in. (100 x 200-mm) cylinders made with Ultimax cement were 2 to 21% lower than those of concrete containing ASTM Type I/II cement at the water-to-cement ratios of 0.40 to 0.50.

(11) At 28 days, the splitting-tensile strengths of concrete containing Ultimax cement ranged from 385 to 705 psi and were 5 to 8% higher than those of concrete containing ASTM Type I/II cement at water-to-cement ratios of 0.30 and 0.35. However, the splitting-tensile strengths of concrete containing Ultimax cement were 13 to 31% lower than those of concrete containing ASTM Type I/II cement at the water-to-cement ratios of 0.40 to 0.50.

(12) The bulk density of the 4 x 8-in. (100 x 200-mm) cylinders made with concrete containing Ultimax cement was similar to that of the 6 x 12-in. (150 x 300-mm) cylinders. At 1 day, the bulk density of concrete made with Ultimax cement ranged from 151 to 154 psi and was 1 to 6% higher than the bulk density of concrete

containing ASTM Type I/II cement. At 28 days, the bulk density of concrete made with Ultimax cement ranged from 152 to 154 psi and was 1 to 5% higher than the bulk density of concrete containing ASTM Type I/II cement.

(13) The shrinkage of concrete specimens made with Ultimax cement fluctuated at early ages up to seven days, after which the shrinkage became stable. At 28 days, the shrinkage reached values of 170 x 10^{-6} to 200 x 10^{-6} in./in. depending on the water-to-cement ratio. At 90 days, the shrinkage generally appeared to reach a flat plateau with values ranging from 277 x 10^{-6} to 390 x 10^{-6} in./in. depending on the water-to-cement ratio. The expansion values up to 90 days did not exceed 100 x 10^{-6} in./in. for water-to-cement ratios between 0.35 and 0.50. At the water-to-cement ratio of 0.30, higher expansion values of 245 x 10^{-6} in/in. and 215 x 10^{-6} in./in were obtained at 28 days and 90 days, respectively.

(14) At 28 days, the shrinkage values of concrete specimens containing ASTM Type I/II cement varied from 690 x 10^{-6} to 757 x 10^{-6} in./in. depending on the water-to-cement ratio. At 90 days, the shrinkage values varied from 1047 x 10^{-6} to 1280 x 10^{-6} in./in. depending on the water-to-cement ratio. A fluctuation in expansion measurement was observed at early ages up to 7 days. The expansion at 28 days varied from 70 x 10^{-6} to 170 x 10^{-6} in./in. depending on the water-to-cement ratio.

The expansion at 90 days varied from 110 x 10^{-6} to 290 x 10^{-6} in./in. depending on the water-to-cement ratio.

(15) At 28 days, concrete made with Ultimax cement exhibited 65 to 75% less shrinkage than concrete made with ASTM Type I/II. Concrete made with Ultimax cement exhibited 44% more expansion at water-to-cement ratio of 0.30 and 3 to 61% less expansion at water-to-cement ratios of 0.35 to 0.50.

(16) At 90 days, concrete made with Ultimax cement exhibited 68 to 74% less shrinkage than concrete made with ASTM Type I/II cement. Concrete made with Ultimax cement exhibited 26 to 69% less expansion than concrete made with ASTM Type I/II cement.

6.1.2 Probe Penetration Test

(1) The standard probes made of AISI 4140 steel were not satisfactory for testing concrete with strengths above 3000 psi (25 MPa). The modified AISI 1045 steel probes were satisfactorily used to predict *in situ* concrete strengths up to 10,500 psi (70 MPa).

(2) Linear, exponential, power, and logarithmic relationships were established to estimate the ultimate compressive strength of normal and high strength concrete. These equations are as follows:

Probe Type	Linear	Exponential	Power	Logarithmic
Double-line	$y = 7362x - 6610$ $R = 0.78$	$y = 663e^{1.24x}$ $R = 0.75$	$y = 1722x^{2.21}$ $R = 0.76$	$y = 13026Ln(x) - 882$ $R = 0.79$
No-line	$y = 11353x - 13215$ $R = 0.92$	$y = 216e^{1.90x}$ $R = 0.89$	$y = 989x^{3.26}$ $R = 0.90$	$y = 19282Ln(x) - 3959$ $R = 0.91$
Combined	$y = 9145x - 9525$ $R = 0.84$	$y = 407e^{1.53x}$ $R = 0.82$	$y = 1345x^{2.69}$ $R = 0.82$	$y = 15906Ln(x) - 2269$ $R = 0.84$

where y = compressive strength (psi)
x = exposed probe length (in.)
R = correlation coefficient

(3) A logarithmic regression was found to be the most satisfactory for the double-line probe data giving a correlation coefficient of 0.79. A linear regression was found to be the most satisfactory for the no-line probe data giving a correlation coefficient of 0.92. Both linear and logarithmic regressions were found to be the most satisfactory for the combined probe data giving a correlation coefficient of 0.84.

(4) Of the three sets of data analyzed, the no-line probes (baked for stress relief for 3 1/2 hours) produced the highest correlation coefficient of 0.92. This implies that the no-line probes produced the most consistent readings of exposed probe length.

(5) Plots of standard deviation and coefficient of variation of the combined probe data versus compressive strength revealed that the coefficient of variation was within acceptable practical limits. The standard deviation of the combined probe data did not exceed 0.14 and the coefficient of variation was below 9% for all compressive strengths.

(6) Plots of standard deviation and coefficient of variation of the uniaxial compression test versus compressive strength revealed that the coefficient of variation was within acceptable practical limits. The coefficient of variation for the majority of the points fell below 10%. The standard deviation for the majority of the points did not exceed 1000 psi.

(7) In general, coefficients of variation below 10% were obtained for the Windsor probe data and the compressive strength data indicating that the Windsor probe test can be used reliably to establish trends to predict the ultimate compressive strength of concrete up to 10,500 psi (70 MPa).

6.2 Future Recommendations

The basic properties of concrete containing Ultimax rapid hardening hydraulic cement have been studied in this investigation. Future studies on the addition of silica fume at different percentages, use of different aggregate sizes, addition of superplasticizers, and the effect of air entrainment should be conducted to determine the performance of concrete containing Ultimax cement. In addition, durability issues such as freeze-thaw resistance and permeability should be evaluated.

This study has established linear, exponential, power, and logarithmic relationships to estimate the ultimate compressive strength of *in situ* normal and high strength concrete by means of the Windsor probe test. Research should be done to evaluate the performance of the Windsor probe test using the AISI 1045 steel probes baked for stress relief for 3 1/2 hours and 7 hours on concrete with compressive strengths above 10,500 psi (70 MPa).

Appendix I (a): Compressive Strength Data of Concrete Containing Ultimax Cement (*w/cm* = 0.30)

Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Compressive Strength (psi)		
1000	10A	6 hr	4 x 8	4794	4854	----
		1 day	4 x 8	6450	5710	----
		7 days	4 x 8	8893	----	----
		28 days	4 x 8	9450	8475	----
			6 x 12	9806	----	----
	10B	6 hr	4 x 8	4612	----	----
		1 day	4 x 8	5968	6197	----
		7 days	4 x 8	8913	9132	----
		28 days	4 x 8	9609	9549	----
			6 x 12	9134	8665	----
1033	9A	6 hr	4 x 8	----	----	----
		1 day	4 x 8	6306	6257	----
		7 days	4 x 8	9132	7600	----
		28 days	4 x 8	9108	8913	----
			6 x 12	8311	----	----
	9B	6 hr	4 x 8	4695	4775	4775
		1 day	4 x 8	5759	5740	----
		7 days	4 x 8	7222	----	----
		28 days	4 x 8	8554	8330	----
			6 x 12	8806	8842	----
1067	8A	6 hr	4 x 8	----	----	----
		1 day	4 x 8	----	----	----
		7 days	4 x 8	8574	8196	----
		28 days	4 x 8	9231	9211	----
			6 x 12	8541	8435	----
	8B	6 hr	4 x 8	4934	4775	5097
		1 day	4 x 8	5328	5819	6157
		7 days	4 x 8	8554	----	----
		28 days	4 x 8	10385	9275	----
			6 x 12	----	----	----
1100	7A	6 hr	4 x 8	4635	5093	4978
		1 day	4 x 8	----	----	----
		7 days	4 x 8	8515	8196	----
		28 days	4 x 8	9410	8789	----
			6 x 12	8612	8347	----
	7B	6 hr	4 x 8	----	----	----
		1 day	4 x 8	6135	6326	6177
		7 days	4 x 8	8316	----	----
		28 days	4 x 8	7719	----	----
			6 x 12	9594	----	----

Appendix I (a): Compressive Strength Data of Concrete Containing Ultimax Cement (*w/cm* = 0.30)

Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Compressive Strength (psi)		
1133	6A	6 hr	4 x 8	—	—	—
		1 day	4 x 8	7222	7261	7679
		7 days	4 x 8	8972	8813	—
		28 days	4 x 8	11081	10007	—
			6 x 12	9470	10349	—
	6B	6 hr	4 x 8	4874	5272	4934
		1 day	4 x 8	8932	—	—
		7 days	4 x 8	—	—	—
		28 days	4 x 8	8921	9529	—
			6 x 12	9408	—	—
1166	5A	6 hr	4 x 8	6068	5698	6092
		1 day	4 x 8	—	—	—
		7 days	4 x 8	8455	—	—
		28 days	4 x 8	9808	—	—
			6 x 12	9461	—	—
	5B	6 hr	4 x 8	—	—	—
		1 day	4 x 8	—	—	—
		7 days	4 x 8	8336	—	—
		28 days	4 x 8	9211	8634	—
			6 x 12	8948		—
	5C	6 hr	4 x 8	—	—	—
		1 day	4 x 8	5690	5899	5839
		7 days	4 x 8	7341	—	—
		28 days	4 x 8	8435	—	—
			6 x 12	—	—	—

Appendix I (b): Compressive Strength Data of Concrete Containing Ultimax Cement (*w/cm* = 0.35-0.45)

w/cm	Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Compressive Strength (psi)		
0.35	900	1A	6 hr	4 x 8	4416	4596	—
			1 day	4 x 8	7003	3143	—
			7 days	4 x 8	—	—	—
			28 days	4 x 8	—	—	—
				6 x 12	—	—	—
		1B	6 hr	4 x 8	4834	—	—
			1 day	4 x 8	7878	3342	—
			7 days	4 x 8	—	—	—
			28 days	4 x 8	9410	—	—
				6 x 12	—	—	—
		1C	6 hr	4 x 8	—	—	—
			1 day	4 x 8	—	—	—
			7 days	4 x 8	7440	7460	7202
			28 days	4 x 8	8455	7998	8614
				6 x 12	—	—	—
		1D	6 hr	4 x 8	—	—	—
			1 day	4 x 8	—	—	—
			7 days	4 x 8	—	—	—
			28 days	4 x 8	—	—	—
				6 x 12	7268	6989	7012
0.40	800	2A	6 hr	4 x 8	—	—	—
			1 day	4 x 8	—	—	—
			7 days	4 x 8	5371	5431	4974
			28 days	4 x 8	6127	6476	—
				6 x 12	—	—	—
		2B	6 hr	4 x 8	2725	2666	2785
			1 day	4 x 8	3740	3860	3720
			7 days	4 x 8	—	—	—
			28 days	4 x 8	5710	5899	—
				6 x 12	—	—	—
		2C	6 hr	4 x 8	—	—	—
			1 day	4 x 8	—	—	—
			7 days	4 x 8	—	—	—
			28 days	4 x 8	—	—	—
				6 x 12	7675	7300	6888
0.45	700	3A	6 hr	4 x 8	1970	1850	1910
			1 day	4 x 8	3024	2964	2972
			7 days	4 x 8	4019	3983	3919
			28 days	4 x 8	4755	4944	4914
				6 x 12	—	—	—
		3B	6 hr	4 x 8	—	—	—
			1 day	4 x 8	—	—	—
			7 days	4 x 8	—	—	—
			28 days	4 x 8	—	—	—
				6 x 12	5765	5721	5862

Appendix I (c): Compressive Strength Data of Concrete Containing Ultimax Cement (*w/cm* = 0.50)

Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Compressive Strength (psi)		
580	15A	6 hr	4 x 8	696.3	795.8	----
		1 day	4 x 8	1094	1198	----
		7 days	4 x 8	1910	----	----
		28 days	4 x 8	2328	2367	----
			6 x 12	3498	----	----
	15B	6 hr	4 x 8	736.1	----	----
		1 day	4 x 8	1068	1188	----
		7 days	4 x 8	1999	1900	----
		28 days	4 x 8	2102	2463	----
			6 x 12	2467	2443	----
600	4A	6 hr	4 x 8	1751	1731	1731
		1 day	4 x 8	2566	2730	2650
		7 days	4 x 8	3263	3402	----
		28 days	4 x 8	3939	3820	----
			6 x 12	3882	----	----
	4B	6 hr	4 x 8	----	----	----
		1 day	4 x 8	----	----	----
		7 days	4 x 8	2944	----	----
		28 days	4 x 8	3919	3919	----
			6 x 12	3811	3395	----
620	14A	6 hr	4 x 8	1015	1104	----
		1 day	4 x 8	2119	2421	----
		7 days	4 x 8	4357	----	----
		28 days	4 x 8	4914	5033	----
			6 x 12	4978	----	----
	14B	6 hr	4 x 8	1313		----
		1 day	4 x 8	2471	2741	----
		7 days	4 x 8	4586	4546	----
		28 days	4 x 8	4739	4690	----
			6 x 12	5544	5579	----
640	13A	6 hr	4 x 8	855.4	----	----
		1 day	4 x 8	1601	1492	----
		7 days	4 x 8	2755	2676	----
		28 days	4 x 8	3382	3253	----
			6 x 12	3263	3333	----
	13B	6 hr	4 x 8	875.4	805.7	----
		1 day	4 x 8	1552	1596	----
		7 days	4 x 8	2636	----	----
		28 days	4 x 8	3136	3127	----
			6 x 12	3165	----	----

Appendix I (c): Compressive Strength Data of Concrete Containing Ultimax Cement (*w/cm* = 0.50)

Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Compressive Strength (psi)		
660	12A	6 hr	4 x 8	855.4	895.2	----
		1 day	4 x 8	1472	1564	----
		7 days	4 x 8	2924	2844	----
		28 days	4 x 8	3064	2590	----
			6 x 12	3033	----	----
	12B	6 hr	4 x 8	736.1	----	----
		1 day	4 x 8	1466	1500	----
		7 days	4 x 8	2447	2487	2596
		28 days	4 x 8	3280	2960	----
			6 x 12	3165	3310	----
680	11A	6 hr	4 x 8	1293	1214	----
		1 day	4 x 8	1890	2025	----
		7 days	4 x 8	2805	----	----
		28 days	4 x 8	3760	3549	----
			6 x 12	3855		----
	11B	6 hr	4 x 8	1194	----	----
		1 day	4 x 8	2129	2029	----
		7 days	4 x 8	2924	2844	----
		28 days	4 x 8	3621	3863	----
			6 x 12	3687	3882	----

Appendix I (d): Compressive Strength Data of Concrete Containing ASTM Type I/II Cement (*w/cm* = 0.30-0.50)

w/cm	Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Compressive Strength (psi)		
0.30	2000	18	1 day	4 x 8	4635	4615	4625
			28 days	4 x 8	6056	7490	8017
0.35	1643	20A	1 day	4 x 8	4128	----	----
			28 days	4 x 8	8356	----	----
		20B	1 day	4 x 8	3879	3810	----
			28 days	4 x 8	7321	7739	----
0.40	1288	16A	1 day	4 x 8	2964	----	----
			7 days	4 x 8	4886	----	----
			28 days	4 x 8	----	----	----
		16B	1 day	4 x 8	3207	3044	----
			7 days	4 x 8	4894	4874	----
			28 days	4 x 8	7353	7202	----
0.45	1089	19A	1 day	4 x 8	2582	----	----
			28 days	4 x 8	6903	----	----
		19B	1 day	4 x 8	2407	2459	----
			28 days	4 x 8	7142	7062	----
0.50	890	17	1 day	4 x 8	1950	2052	2109
			28 days	4 x 8	6525	6386	5988

Appendix II (a): Modulus of Elasticity of Concrete Containing Ultimax Cement (w/cm = 0.30)

Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Modulus of Elasticity ($\times 10^6$ psi)		
1000	10A	1 day	4 x 8	3.340	-----	-----
		28 days	4 x 8	4.720	-----	-----
			6 x 12	-----	-----	-----
	10B	1 day	4 x 8	3.912	3.340	-----
		28 days	4 x 8	4.504	4.774	-----
			6 x 12	4.244	3.835	-----
1033	9A	1 day	4 x 8	3.260	-----	-----
		28 days	4 x 8	4.548	-----	-----
			6 x 12	4.222	-----	-----
	9B	1 day	4 x 8	3.520	3.260	-----
		28 days	4 x 8	4.244	4.264	-----
			6 x 12	3.772	3.772	-----
1067	8A	1 day	4 x 8	-----	-----	-----
		28 days	4 x 8	4.046	-----	-----
			6 x 12	4.797	4.197	-----
	8B	1 day	4 x 8	3.872	3.824	3.586
		28 days	4 x 8	4.774	4.774	-----
			6 x 12	4.222	-----	-----
1100	7A	1 day	4 x 8	-----	-----	-----
		28 days	4 x 8	4.004	-----	-----
			6 x 12	4.751	4.222	4.244
	7B	1 day	4 x 8	3.340	3.586	-----
		28 days	4 x 8	4.548	-----	-----
			6 x 12	-----	-----	-----
1133	6A	1 day	4 x 8	3.978	3.978	-----
		28 days	4 x 8	4.082	-----	-----
			6 x 12	4.161	3.966	-----
	6B	1 day	4 x 8	-----	-----	-----
		28 days	4 x 8	4.046	4.046	-----
			6 x 12	4.244	-----	-----
1166	5A	1 day	4 x 8	-----	-----	-----
		28 days	4 x 8	-----	-----	-----
			6 x 12	4.797	-----	-----
	5B	1 day	4 x 8	-----	-----	-----
		28 days	4 x 8	4.264	4.860	-----
			6 x 12	3.408	-----	-----
	5C	1 day	4 x 8	3.126	3.126	3.340
		28 days	4 x 8	4.252	-----	-----
			6 x 12	-----	-----	-----

Appendix II (b): Modulus of Elasticity Data of Concrete Containing Ultimax Cement (*w/cm* = 0.35-0.45)

w/cm	Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Modulus of Elasticity (x 10^6 psi)		
0.35	900	1A	1 day	4 x 8	----	----	----
			28 days	4 x 8	----	----	----
				6 x 12	----	----	----
		1B	1 day	4 x 8	3.504	----	----
			28 days	4 x 8	4.046	----	----
				6 x 12	----	----	----
		1C	1 day	4 x 8	----	----	----
			28 days	4 x 8	4.004	4.548	----
				6 x 12	----	----	----
		1D	1 day	4 x 8	----	----	----
			28 days	4 x 8	----	----	----
				6 x 12	2.559	2.948	3.300
0.40	800	2A	1 day	4 x 8	----	----	----
			28 days	4 x 8	3.410	----	----
				6 x 12	----	----	----
		2B	1 day	4 x 8	2.466	2.678	----
			28 days	4 x 8	3.520	2.472	----
				6 x 12	----	----	----
		2C	1 day	4 x 8	----	----	----
			28 days	4 x 8	----	----	----
				6 x 12	2.618	3.694	3.300
0.45	700	3A	1 day	4 x 8	2.220	2.220	----
			28 days	4 x 8	3.168	3.168	3.442
				6 x 12	----	----	----
		3B	1 day	4 x 8	----	----	----
			28 days	4 x 8	----	----	----
				6 x 12	2.903	3.597	2.829

Appendix II (c): Modulus of Elasticity Data of Concrete Containing Ultimax Cement (*w/cm* = 0.50)

Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Modulus of Elasticity ($\times 10^6$ psi)		
580	15A	1 day	4 x 8	2.052	----	----
		28 days	4 x 8	2.428	----	----
			6 x 12	2.292	----	----
	15B	1 day	4 x 8	1.276	1.432	----
		28 days	4 x 8	1.912	2.342	----
			6 x 12	1.967	1.768	----
600	4A	1 day	4 x 8	2.480	2.168	----
		28 days	4 x 8	2.932	----	----
			6 x 12	3.726	----	----
	4B	1 day	4 x 8	----	----	----
		28 days	4 x 8	4.096	----	----
			6 x 12	3.274	----	----
620	14A	1 day	4 x 8	2.068	----	----
		28 days	4 x 8	4.132	----	----
			6 x 12	4.040	----	----
	14B	1 day	4 x 8	2.342	2.342	----
		28 days	4 x 8	4.136	4.162	----
			6 x 12	3.467	3.120	----
640	13A	1 day	4 x 8	1.888	----	----
		28 days	4 x 8	2.480	----	----
			6 x 12	3.721	2.080	----
	13B	1 day	4 x 8	1.888	1.912	----
		28 days	4 x 8	2.480	2.480	----
			6 x 12	2.795	----	----
660	12A	1 day	4 x 8	1.888	----	----
		28 days	4 x 8	2.698	----	----
			6 x 12	----	----	----
	12B	1 day	4 x 8	1.592	1.908	----
		28 days	4 x 8	2.894	2.342	----
			6 x 12	3.274	3.031	----
680	11A	1 day	4 x 8	1.874	----	----
		28 days	4 x 8	2.960	----	----
			6 x 12	2.467	----	----
	11B	1 day	4 x 8	2.228	2.228	----
		28 days	4 x 8	3.332	----	----
			6 x 12	2.467	2.526	----

Appendix II (d): Modulus of Elasticity Data of Concrete Containing ASTM Type I/II Cement (*w/cm* = 0.30-0.50)

w/cm	Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Modulus of Elasticity ($\times 10^6$ psi)		
0.30	2000	18	1 day	4 x 8	2.274	2.430	----
			28 days	4 x 8	3.978	3.596	----
0.35	1643	20A	1 day	4 x 8	2.466	----	----
			28 days	4 x 8	4.004	----	----
		20B	1 day	4 x 8	2.610	----	----
			28 days	4 x 8	4.004	----	----
0.40	1288	16A	1 day	4 x 8	2.480	----	----
			28 days	4 x 8	----	----	----
		16B	1 day	4 x 8	2.346	----	----
			28 days	4 x 8	3.182	----	----
0.45	1089	19A	1 day	4 x 8	2.108	----	----
			28 days	4 x 8	----	----	----
		19B	1 day	4 x 8	1.860	----	----
			28 days	4 x 8	3.316	3.714	----
0.50	890	17	1 day	4 x 8	1.874	1.888	----
			28 days	4 x 8	3.644	3.410	----

Appendix III (a): Stress-Strain Data of Concrete Containing Ultimax Cement (*w/cm* = 0.30)

Mix No. 10
Cement Content = 1000 lb/cyd
Age: 1 Day (4 x 8-in.)

Mix 10A		Mix 10B		Mix 10B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0
0.00009	199	0.00009	199	0.00005	199
0.00014	398	0.00009	398	0.00014	398
0.00018	597	0.00014	597	0.00018	597
0.00027	796	0.00023	796	0.00023	796
0.00032	995	0.00027	995	0.00027	995
0.00036	1194	0.00032	1194	0.00036	1194
0.00041	1393	0.00036	1393	0.00041	1393
0.00050	1592	0.00041	1592	0.00045	1592
0.00055	1791	0.00050	1791	0.00050	1791
0.00059	1989	0.00055	1989	0.00059	1989
0.00068	2188	0.00059	2188	0.00064	2188
0.00073	2387	0.00064	2387	0.00068	2387
0.00077	2586	0.00068	2586	0.00073	2586
0.00086	2785	0.00077	2785	0.00077	2785
0.00091	2984	0.00082	2984	0.00086	2984
0.00095	3183	0.00086	3183	0.00091	3183
0.00105	3382	0.00091	3382	0.00100	3382
0.00114	3581	0.00100	3581	0.00105	3581
0.00118	3780	0.00109	3780	0.00114	3780
0.00123	3979	0.00114	3979	0.00118	3979
0.00132	4178	0.00118	4178	0.00127	4178
0.00141	4377	0.00127	4377	0.00132	4377
0.00150	4576	0.00136	4576	0.00141	4576
0.00159	4775	0.00145	4775	0.00150	4775
0.00168	4974	0.00150	4974	0.00159	4974
0.00182	5173	0.00164	5173	0.00168	5173
0.00191	5372	0.00173	5372	0.00177	5372
0.00214	5571	0.00186	5571	0.00186	5571
		0.00200	5770	0.00195	5770
				0.00209	5968
				0.00227	6167

Appendix III (a): Stress-Strain Data of Concrete Containing Ultimax Cement (w/cm = 0.30)

Mix No. 10
Cement Content = 1000 lb/cyd
Age: 28 Days

4 x 8-in.						6 x 12-in.					
Mix 10A		Mix 10B		Mix 10B		Mix 10A		Mix 10B		Mix 10B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00005	398	0.00009	398	0.00009	398	0.00000	354	0.00008	354	0.00008	354
0.00014	796	0.00018	796	0.00014	796	0.00008	707	0.00016	707	0.00016	707
0.00018	1194	0.00027	1194	0.00023	1194	0.00016	1061	0.00024	1061	0.00032	1061
0.00027	1592	0.00036	1592	0.00036	1592	0.00016	1415	0.00032	1415	0.00040	1415
0.00036	1989	0.00045	1989	0.00045	1989	0.00024	1768	0.00040	1768	0.00048	1768
0.00045	2387	0.00055	2387	0.00055	2387	0.00024	2122	0.00048	2122	0.00056	2122
0.00055	2785	0.00064	2785	0.00064	2785	0.00032	2476	0.00056	2476	0.00064	2476
0.00064	3183	0.00073	3183	0.00068	3183	0.00032	2829	0.00064	2829	0.00072	2829
0.00073	3581	0.00082	3581	0.00077	3581	0.00040	3183	0.00072	3183	0.00080	3183
0.00082	3979	0.00091	3979	0.00086	3979	0.00048	3537	0.00080	3537	0.00088	3537
0.00091	4377	0.00100	4377	0.00095	4377	0.00048	3891	0.00088	3891	0.00096	3891
0.00100	4775	0.00109	4775	0.00109	4775	0.00056	4244	0.00096	4244	0.00112	4244
0.00114	5173	0.00118	5173	0.00177	5173	0.00056	4598	0.00096	4598	0.00120	4598
0.00123	5571	0.00132	5571	0.00259	5571	0.00064	4952	0.00096	4952	0.00128	4952
0.00132	5968	0.00141	5968	0.00327	5968	0.00064	5305	0.00104	5305	0.00136	5305
0.00145	6366	0.00150	6366	0.00405	6366	0.00072	5659	0.00104	5659	0.00152	5659
0.00155	6764	0.00164	6764	0.00473	6764	0.00080	6013	0.00112	6013	0.00160	6013
0.00168	7162	0.00173	7162	0.00536	7162	0.00096	6366	0.00120	6366	0.00168	6366
0.00177	7560	0.00182	7560	0.00591	7560	0.00104	6720	0.00128	6720	0.00184	6720
0.00191	7958	0.00195	7958	0.00659	7958	0.00112	7074	0.00136	7074	0.00192	7074
0.00214	8356	0.00205	8356	0.00714	8356	0.00112	7427	0.00144	7427	0.00208	7427
		0.00223	8754	0.00785	8754	0.00120	7781	0.00152	7781	0.00216	7781
		0.00241	9152	0.00864	9152	0.00128	8135	0.00160	8135	0.00232	8135
						0.00120	8488	0.00168	8488	0.00248	8488
						0.00120	8842	0.00184	8842		
						0.00112	9196				

Appendix III (a): Stress-Strain Data of Concrete Containing Ultimax Cement (*w/cm* = 0.30)

Mix No. 9
Cement Content = 1033 lb/cyd
Age: 1 Day (4 x 8-in.)

Mix 9A		Mix 9B		Mix 9B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0
0.00005	199	0.00005	199	0.00005	199
0.00009	398	0.00009	398	0.00009	398
0.00018	597	0.00014	597	0.00018	597
0.00023	796	0.00023	796	0.00023	796
0.00027	995	0.00027	995	0.00027	995
0.00032	1194	0.00032	1194	0.00036	1194
0.00041	1393	0.00041	1393	0.00041	1393
0.00045	1592	0.00045	1592	0.00045	1592
0.00050	1791	0.00050	1791	0.00050	1791
0.00055	1989	0.00055	1989	0.00059	1989
0.00064	2188	0.00059	2188	0.00064	2188
0.00068	2387	0.00068	2387	0.00068	2387
0.00073	2586	0.00073	2586	0.00073	2586
0.00077	2785	0.00077	2785	0.00082	2785
0.00082	2984	0.00082	2984	0.00086	2984
0.00091	3183	0.00091	3183	0.00091	3183
0.00095	3382	0.00100	3382	0.00100	3382
0.00105	3581	0.00105	3581	0.00109	3581
0.00109	3780	0.00114	3780	0.00114	3780
0.00114	3979	0.00118	3979	0.00118	3979
0.00123	4178	0.00127	4178	0.00127	4178
0.00132	4377	0.00136	4377	0.00136	4377
0.00136	4576	0.00145	4576	0.00145	4576
0.00145	4775	0.00155	4775	0.00155	4775
0.00150	4974	0.00164	4974	0.00164	4974
0.00159	5173	0.00177	5173	0.00177	5173
0.00173	5372	0.00191	5372	0.00186	5372
0.00182	5571	0.00209	5571	0.00205	5571

Appendix III (a): Stress-Strain Data of Concrete Containing Ultimax Cement (w/cm = 0.30)

Mix No. 9
Cement Content = 1033 lb/cyd
Age: 28 Days

4 x 8-in.						6 x 12-in.					
Mix 9A		Mix 9B		Mix 9B		Mix 9A		Mix 9B		Mix 9B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00009	398	0.00014	398	0.00014	398	0.00008	354	0.00000	354	0.00008	354
0.00023	796	0.00023	796	0.00018	796	0.00016	707	0.00016	707	0.00016	707
0.00027	1194	0.00032	1194	0.00027	1194	0.00024	1061	0.00024	1061	0.00032	1061
0.00036	1592	0.00041	1592	0.00036	1592	0.00032	1415	0.00032	1415	0.00040	1415
0.00045	1989	0.00050	1989	0.00045	1989	0.00040	1768	0.00040	1768	0.00048	1768
0.00055	2387	0.00059	2387	0.00059	2387	0.00048	2122	0.00056	2122	0.00048	2122
0.00064	2785	0.00068	2785	0.00068	2785	0.00056	2476	0.00064	2476	0.00064	2476
0.00073	3183	0.00077	3183	0.00077	3183	0.00064	2829	0.00072	2829	0.00072	2829
0.00082	3581	0.00086	3581	0.00086	3581	0.00072	3183	0.00080	3183	0.00080	3183
0.00091	3979	0.00095	3979	0.00095	3979	0.00080	3537	0.00088	3537	0.00080	3537
0.00100	4377	0.00105	4377	0.00105	4377	0.00096	3891	0.00104	3891	0.00088	3891
0.00114	4775	0.00114	4775	0.00114	4775	0.00104	4244	0.00112	4244	0.00096	4244
0.00123	5173	0.00118	5173	0.00127	5173	0.00112	4598	0.00128	4598	0.00104	4598
0.00132	5571	0.00132	5571	0.00136	5571	0.00120	4952	0.00136	4952	0.00112	4952
0.00145	5968	0.00141	5968	0.00145	5968	0.00136	5305	0.00152	5305	0.00128	5305
0.00159	6366	0.00155	6366	0.00155	6366	0.00144	5659	0.00168	5659	0.00136	5659
0.00168	6764	0.00164	6764	0.00168	6764	0.00152	6013	0.00176	6013	0.00144	6013
0.00186	7162	0.00177	7162	0.00182	7162	0.00168	6366	0.00192	6366	0.00152	6366
0.00195	7560	0.00191	7560	0.00195	7560	0.00184	6720	0.00208	6720	0.00160	6720
0.00214	7958	0.00205	7958	0.00209	7958	0.00200	7074	0.00224	7074	0.00176	7074
0.00230	8356	0.00223	8356	0.00218	8356	0.00208	7427	0.00240	7427	0.00184	7427
				0.00191	8754	0.00232	7781	0.00272	7781	0.00200	7781
						0.00256	8135	0.00312	8135	0.00216	8135

Appendix III (a): Stress-Strain Data of Concrete Containing Ultimax Cement (w/cm = 0.30)

Mix No. 8
Cement Content = 1067 lb/cyd
Age: 1 Day (4 x 8-in.)

Mix 8A		Mix 8B		Mix 8B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0
0.00005	199	0.00000	199	0.00005	199
0.00009	398	0.00005	398	0.00009	398
0.00014	597	0.00009	597	0.00014	597
0.00018	796	0.00018	796	0.00018	796
0.00023	995	0.00023	995	0.00027	995
0.00032	1194	0.00027	1194	0.00032	1194
0.00036	1393	0.00032	1393	0.00036	1393
0.00041	1592	0.00036	1592	0.00041	1592
0.00045	1791	0.00041	1791	0.00045	1791
0.00050	1989	0.00045	1989	0.00055	1989
0.00055	2188	0.00050	2188	0.00059	2188
0.00059	2387	0.00055	2387	0.00064	2387
0.00064	2586	0.00059	2586	0.00068	2586
0.00073	2785	0.00068	2785	0.00073	2785
0.00077	2984	0.00073	2984	0.00082	2984
0.00082	3183	0.00077	3183	0.00091	3183
0.00091	3382	0.00082	3382	0.00095	3382
0.00095	3581	0.00091	3581	0.00100	3581
0.00100	3780	0.00095	3780	0.00109	3780
0.00105	3979	0.00100	3979	0.00114	3979
0.00114	4178	0.00109	4178	0.00123	4178
0.00118	4377	0.00114	4377	0.00127	4377
0.00127	4576	0.00123	4576	0.00132	4576
0.00132	4775	0.00132	4775	0.00141	4775
0.00141	4974	0.00136	4974	0.00150	4974
0.00150	5173	0.00145	5173	0.00159	5173
0.00159	5372	0.00155	5372	0.00168	5372
0.00168	5571	0.00164	5571	0.00177	5571
0.00186	5770	0.00173	5770	0.00186	5770
		0.00182	5968	0.00200	5968
		0.00195	6167		

Appendix III (a): Stress-Strain Data of Concrete Containing Ultimax Cement (w/cm = 0.30)

Mix No. 8
Cement Content = 1067 lb/cyd
Age: 28 Days

4 x 8-in.						6 x 12-in.					
Mix 8A		Mix 8B		Mix 8B		Mix 8A		Mix 8A		Mix 8B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00014	398	0.00009	398	0.00009	398	0.00000	354	0.00000	354	0.00008	354
0.00023	796	0.00014	796	0.00018	796	0.00008	707	0.00008	707	0.00016	707
0.00032	1194	0.00023	1194	0.00023	1194	0.00016	1061	0.00016	1061	0.00024	1061
0.00041	1592	0.00032	1592	0.00032	1592	0.00024	1415	0.00024	1415	0.00032	1415
0.00050	1989	0.00041	1989	0.00041	1989	0.00032	1768	0.00032	1768	0.00040	1768
0.00059	2387	0.00050	2387	0.00050	2387	0.00032	2122	0.00040	2122	0.00048	2122
0.00068	2785	0.00059	2785	0.00059	2785	0.00040	2476	0.00048	2476	0.00056	2476
0.00077	3183	0.00068	3183	0.00068	3183	0.00048	2829	0.00056	2829	0.00064	2829
0.00091	3581	0.00077	3581	0.00077	3581	0.00056	3183	0.00064	3183	0.00072	3183
0.00100	3979	0.00086	3979	0.00086	3979	0.00064	3537	0.00064	3537	0.00080	3537
0.00109	4377	0.00091	4377	0.00091	4377	0.00072	3891	0.00072	3891	0.00088	3891
0.00118	4775	0.00182	4775	0.00105	4775	0.00080	4244	0.00080	4244	0.00096	4244
0.00127	5173	0.00509	5173	0.00109	5173	0.00080	4598	0.00080	4598	0.00104	4598
0.00136	5571	0.00595	5571	0.00123	5571	0.00096	4952	0.00088	4952	0.00120	4952
0.00150	5968	0.00614	5968	0.00132	5968	0.00096	5305	0.00096	5305	0.00128	5305
0.00159	6366	0.00655	6366	0.00141	6366	0.00104	5659	0.00104	5659	0.00144	5659
0.00168	6764	0.00673	6764	0.00155	6764	0.00120	6013	0.00104	6013	0.00152	6013
0.00182	7162	0.00705	7162	0.00164	7162	0.00128	6366	0.00112	6366	0.00160	6366
0.00191	7560	0.00741	7560	0.00173	7560	0.00128	6720	0.00120	6720	0.00176	6720
0.00205	7958	0.00777	7958	0.00186	7958	0.00144	7074	0.00128	7074	0.00184	7074
0.00223	8356	0.00818	8356	0.00200	8356	0.00152	7427	0.00128	7427	0.00192	7427
0.00236	8754	0.00859	8754	0.00218	8754	0.00160	7781	0.00048	7781	0.00208	7781
		0.00900	9152	0.00236	9152	0.00168	8135	0.00040	8135		
						0.00144	8488				

Appendix III (a): Stress-Strain Data of Concrete Containing Ultimax Cement (*w/cm* = 0.30)

Mix No. 7
Cement Content = 1100 lb/cyd
Age: 1 Day (4 x 8-in.)

Mix 7B		Mix 7B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0
0.00005	199	0.00005	199
0.00014	398	0.00009	398
0.00018	597	0.00014	597
0.00023	796	0.00018	796
0.00027	995	0.00023	995
0.00032	1194	0.00032	1194
0.00041	1393	0.00036	1393
0.00045	1592	0.00041	1592
0.00050	1791	0.00050	1791
0.00055	1989	0.00055	1989
0.00059	2188	0.00059	2188
0.00068	2387	0.00064	2387
0.00073	2586	0.00068	2586
0.00077	2785	0.00077	2785
0.00086	2984	0.00082	2984
0.00095	3183	0.00086	3183
0.00105	3382	0.00095	3382
0.00109	3581	0.00105	3581
0.00118	3780	0.00109	3780
0.00127	3979	0.00114	3979
0.00136	4178	0.00123	4178
0.00150	4377	0.00132	4377
0.00159	4576	0.00136	4576
0.00173	4775	0.00145	4775
0.00182	4974	0.00155	4974
0.00195	5173	0.00164	5173
0.00205	5372	0.00173	5372
0.00218	5571	0.00182	5571
0.00232	5770	0.00191	5770
		0.00205	5968
		0.00223	6167

Appendix III (a): Stress-Strain Data of Concrete Containing Ultimax Cement (*w/cm* = 0.30)

Mix No. 7
Cement Content = 1100 lb/cyd
Age: 28 Days

4 x 8-in.				6 x 12-in.					
Mix 7A		Mix 7B		Mix 7A		Mix 7A		Mix 7B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00009	398	0.00009	398	0.00008	354	0.00008	354	0.00008	354
0.00023	796	0.00018	796	0.00016	707	0.00016	707	0.00016	707
0.00032	1194	0.00027	1194	0.00024	1061	0.00024	1061	0.00024	1061
0.00041	1592	0.00041	1592	0.00032	1415	0.00032	1415	0.00032	1415
0.00050	1989	0.00050	1989	0.00040	1768	0.00040	1768	0.00040	1768
0.00064	2387	0.00055	2387	0.00048	2122	0.00048	2122	0.00048	2122
0.00073	2785	0.00064	2785	0.00056	2476	0.00056	2476	0.00056	2476
0.00082	3183	0.00073	3183	0.00064	2829	0.00064	2829	0.00064	2829
0.00091	3581	0.00077	3581	0.00072	3183	0.00072	3183	0.00072	3183
0.00100	3979	0.00086	3979	0.00072	3537	0.00080	3537	0.00080	3537
0.00109	4377	0.00100	4377	0.00080	3891	0.00088	3891	0.00088	3891
0.00123	4775	0.00109	4775	0.00088	4244	0.00096	4244	0.00096	4244
0.00132	5173	0.00118	5173	0.00096	4598	0.00104	4598	0.00104	4598
0.00145	5571	0.00132	5571	0.00104	4952	0.00112	4952	0.00112	4952
0.00159	5968	0.00145	5968	0.00112	5305	0.00120	5305	0.00128	5305
0.00173	6366	0.00159	6366	0.00128	5659	0.00128	5659	0.00136	5659
0.00186	6764	0.00168	6764	0.00136	6013	0.00136	6013	0.00144	6013
0.00200	7162	0.00186	7162	0.00144	6366	0.00144	6366	0.00152	6366
0.00214	7560	0.00209	7560	0.00152	6720	0.00160	6720	0.00160	6720
0.00223	7958			0.00168	7074	0.00160	7074	0.00176	7074
0.00245	8356			0.00176	7427	0.00168	7427	0.00184	7427
				0.00192	7781	0.00208	7781	0.00200	7781
				0.00216	8135	0.00216	8135	0.00208	8135
				0.00224	8488			0.00224	8488
								0.00240	8842

Appendix III (a): Stress-Strain Data of Concrete Containing Ultimax Cement (*w/cm* = 0.30)

Mix No. 6
Cement Content = 1133 lb/cyd
Age: 1 Day (4 x 8-in.)

Mix 6A		Mix 6A	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0
0.00014	398	0.00014	398
0.00023	796	0.00023	796
0.00032	1194	0.00032	1194
0.00045	1592	0.00045	1592
0.00055	1989	0.00050	1989
0.00064	2387	0.00064	2387
0.00073	2785	0.00073	2785
0.00082	3183	0.00082	3183
0.00095	3581	0.00095	3581
0.00105	3979	0.00109	3979
0.00118	4377	0.00118	4377
0.00132	4775	0.00132	4775
0.00145	5173	0.00145	5173
0.00164	5571	0.00159	5571
0.00177	5968	0.00173	5968
0.00200	6366	0.00195	6366
0.00223	6764	0.00218	6764

Appendix III (a): Stress-Strain Data of Concrete Containing Ultimax Cement (w/cm = 0.30)

Mix No. 6
Cement Content = 1133 lb/cyd
Age: 28 Days

4 x 8-in.						6 x 12-in.					
Mix 6A		Mix 6B		Mix 6B		Mix 6A		Mix 6A		Mix 6B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00009	398	0.00009	398	0.00009	398	0.00000	531	0.00016	531	0.00008	531
0.00018	796	0.00023	796	0.00023	796	0.00000	1061	0.00032	1061	0.00016	1061
0.00032	1194	0.00032	1194	0.00032	1194	0.00008	1592	0.00048	1592	0.00032	1592
0.00041	1592	0.00041	1592	0.00041	1592	0.00024	2122	0.00056	2122	0.00040	2122
0.00055	1989	0.00050	1989	0.00055	1989	0.00032	2653	0.00072	2653	0.00056	2653
0.00059	2387	0.00064	2387	0.00064	2387	0.00048	3183	0.00088	3183	0.00064	3183
0.00068	2785	0.00073	2785	0.00073	2785	0.00056	3714	0.00104	3714	0.00080	3714
0.00082	3183	0.00082	3183	0.00082	3183	0.00072	4244	0.00112	4244	0.00088	4244
0.00091	3581	0.00091	3581	0.00091	3581	0.00080	4775	0.00128	4775	0.00104	4775
0.00100	3979	0.00100	3979	0.00105	3979	0.00096	5305	0.00144	5305	0.00120	5305
0.00109	4377	0.00109	4377	0.00114	4377	0.00104	5836	0.00160	5836	0.00128	5836
0.00123	4775	0.00118	4775	0.00123	4775	0.00120	6366	0.00168	6366	0.00144	6366
0.00136	5173	0.00132	5173	0.00132	5173	0.00136	6897	0.00192	6897	0.00136	6897
0.00155	5571	0.00145	5571	0.00150	5571	0.00152	7427	0.00208	7427	0.00152	7427
0.00168	5968	0.00155	5968	0.00168	5968	0.00168	7958	0.00224	7958	0.00168	7958
0.00182	6366	0.00168	6366	0.00191	6366	0.00184	8488	0.00248	8488	0.00184	8488
0.00200	6764	0.00182	6764	0.00209	6764	0.00208	9019	0.00264	9019	0.00192	9019
0.00214	7162	0.00195	7162	0.00227	7162			0.00288	9549		
0.00227	7560	0.00209	7560	0.00236	7560			0.00320	10080		
0.00245	7958	0.00223	7958	0.00255	7958						
0.00236	8356	0.00236	8356	0.00273	8356						
0.00250	8754	0.00255	8754	0.00286	8754						
0.00259	9152			0.00314	9152						
0.00268	9550										
0.00291	9947										

Appendix III (a): Stress-Strain Data of Concrete Containing Ultimax Cement (*w/cm* = 0.30)

Mix No. 5
Cement Content = 1166 lb/cyd
Age: 1 Day (4 x 8-in.)

Mix 5C		Mix 5C		Mix 5C	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0
0.00005	199	0.00005	199	0.00005	199
0.00014	398	0.00009	398	0.00009	398
0.00018	597	0.00018	597	0.00014	597
0.00023	796	0.00023	796	0.00023	796
0.00032	995	0.00032	995	0.00027	995
0.00036	1194	0.00036	1194	0.00032	1194
0.00041	1393	0.00041	1393	0.00041	1393
0.00050	1592	0.00050	1592	0.00045	1592
0.00055	1791	0.00055	1791	0.00050	1791
0.00059	1989	0.00059	1989	0.00059	1989
0.00068	2188	0.00068	2188	0.00064	2188
0.00073	2387	0.00073	2387	0.00068	2387
0.00077	2586	0.00077	2586	0.00077	2586
0.00086	2785	0.00086	2785	0.00082	2785
0.00091	2984	0.00091	2984	0.00086	2984
0.00100	3183	0.00100	3183	0.00095	3183
0.00105	3382	0.00105	3382	0.00105	3382
0.00114	3581	0.00114	3581	0.00109	3581
0.00118	3780	0.00123	3780	0.00118	3780
0.00127	3979	0.00127	3979	0.00123	3979
0.00132	4178	0.00136	4178	0.00132	4178
0.00141	4377	0.00145	4377	0.00141	4377
0.00155	4576	0.00155	4576	0.00150	4576
0.00168	4775	0.00168	4775	0.00159	4775
0.00182	4974	0.00177	4974	0.00168	4974
0.00195	5173	0.00191	5173	0.00182	5173
0.00214	5372	0.00205	5372	0.00195	5372
0.00232	5571	0.00218	5571	0.00209	5571
0.00259	5770	0.00245	5770	0.00236	5770

Appendix III (a): Stress-Strain Data of Concrete Containing Ultimax Cement (*w/cm* = 0.30)

Mix No. 5
Cement Content = 1166 lb/cyd
Age: 28 Days

4 x 8-in.						6 x 12-in.			
Mix 5B		Mix 5B		Mix 5C		Mix 5A		Mix 5B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00009	398	0.00014	398	0.00000	398	0.00000	354	0.00008	354
0.00018	796	0.00023	796	0.00014	796	0.00008	707	0.00016	707
0.00027	1194	0.00032	1194	0.00023	1194	0.00016	1061	0.00032	1061
0.00041	1592	0.00036	1592	0.00036	1592	0.00024	1415	0.00040	1415
0.00050	1989	0.00045	1989	0.00041	1989	0.00032	1768	0.00048	1768
0.00059	2387	0.00055	2387	0.00050	2387	0.00040	2122	0.00056	2122
0.00068	2785	0.00059	2785	0.00059	2785	0.00040	2476	0.00064	2476
0.00077	3183	0.00068	3183	0.00068	3183	0.00048	2829	0.00072	2829
0.00086	3581	0.00073	3581	0.00082	3581	0.00056	3183	0.00088	3183
0.00100	3979	0.00082	3979	0.00091	3979	0.00064	3537	0.00096	3537
0.00109	4377	0.00086	4377	0.00100	4377	0.00072	3891	0.00104	3891
0.00118	4775	0.00095	4775	0.00109	4775	0.00080	4244	0.00112	4244
0.00132	5173	0.00168	5173	0.00118	5173	0.00088	4598	0.00120	4598
0.00141	5571	0.00314	5571	0.00127	5571	0.00096	4952	0.00128	4952
0.00150	5968	0.00359	5968	0.00136	5968	0.00104	5305	0.00136	5305
0.00164	6366	0.00395	6366	0.00150	6366	0.00112	5659	0.00144	5659
0.00173	6764	0.00450	6764	0.00164	6764	0.00120	6013	0.00152	6013
0.00191	7162	0.00482	7162	0.00177	7162	0.00128	6366	0.00160	6366
0.00200	7560	0.00527	7560	0.00191	7560	0.00136	6720	0.00168	6720
0.00214	7958	0.00586	7958	0.00205	7958	0.00144	7074	0.00184	7074
0.00227	8356	0.00645	8356			0.00160	7427	0.00192	7427
0.00245	8754					0.00168	7781	0.00208	7781
						0.00184	8135	0.00216	8135
						0.00192	8488		
						0.00200	8842		
						0.00216	9196		

Appendix III (b): Stress-Strain Data of Concrete Containing Ultimax Cement

Mix No. 1
***w/cm* = 0.35**
Cement Content = 900 lb/cyd
Age: 1 Day (4 x 8-in.)

Mix 1B	
Strain (in./in.)	Stress (psi)
0.00000	0
0.00014	398
0.00023	796
0.00032	1194
0.00045	1592
0.00059	1989
0.00073	2387
0.00082	2785
0.00095	3183
0.00105	3581
0.00118	3979
0.00132	4377
0.00145	4775
0.00164	5173
0.00182	5571
0.00205	5968
0.00223	6366
0.00273	6764

Appendix III (b): Stress-Strain Data of Concrete Containing Ultimax Cement

Mix No. 1
w/cm = 0.35
Cement Content = 900 lb/cyd
Age: 28 Days

4 x 8-in.						6 x 12-in.					
Mix 1B		Mix 1B		Mix 1C		Mix 1D		Mix 1D		Mix 1D	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00014	398	0.00014	398	0.00009	398	0.00016	354	0.00008	354	0.00008	354
0.00023	796	0.00023	796	0.00023	796	0.00032	707	0.00016	707	0.00024	707
0.00032	1194	0.00032	1194	0.00027	1194	0.00040	1061	0.00024	1061	0.00032	1061
0.00041	1592	0.00045	1592	0.00036	1592	0.00056	1415	0.00032	1415	0.00048	1415
0.00050	1989	0.00055	1989	0.00050	1989	0.00064	1768	0.00048	1768	0.00056	1768
0.00059	2387	0.00064	2387	0.00055	2387	0.00072	2122	0.00056	2122	0.00064	2122
0.00068	2785	0.00073	2785	0.00064	2785	0.00088	2476	0.00064	2476	0.00072	2476
0.00077	3183	0.00082	3183	0.00073	3183	0.00096	2829	0.00072	2829	0.00080	2829
0.00091	3581	0.00095	3581	0.00082	3581	0.00104	3183	0.00088	3183	0.00096	3183
0.00100	3979	0.00105	3979	0.00091	3979	0.00112	3537	0.00096	3537	0.00104	3537
0.00114	4377	0.00114	4377	0.00105	4377	0.00128	3891	0.00104	3891	0.00112	3891
0.00123	4775	0.00127	4775	0.00114	4775	0.00144	4244	0.00120	4244	0.00128	4244
0.00132	5173	0.00132	5173	0.00123	5173	0.00152	4598	0.00136	4598	0.00144	4598
0.00145	5571	0.00145	5571	0.00136	5571	0.00168	4952	0.00152	4952	0.00152	4952
0.00159	5968	0.00155	5968	0.00145	5968	0.00184	5305	0.00160	5305	0.00168	5305
0.00173	6366	0.00164	6366	0.00159	6366	0.00200	5659	0.00184	5659	0.00192	5659
0.00182	6764	0.00177	6764	0.00173	6764	0.00208	6013	0.00200	6013	0.00208	6013
0.00195	7162	0.00191	7162	0.00191	7162	0.00232	6366	0.00224	6366	0.00224	6366
0.00209	7560	0.00205	7560	0.00200	7560	0.00256	6720	0.00272	6720	0.00256	6720
0.00227	7958	0.00300	7958	0.00223	7958	0.00328	7074				
0.00241	8356			0.00250	8356						
0.00264	8754										

Appendix III (b): Stress-Strain Data of Concrete Containing Ultimax Cement

Mix No. 2
***w/cm* = 0.40**
Cement Content = 800 lb/cyd
Age: 1 Day (4 x 8-in.)

Mix 2B		Mix 2B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0
0.00005	199	0.00009	199
0.00014	398	0.00018	398
0.00018	597	0.00023	597
0.00027	796	0.00032	796
0.00036	995	0.00041	995
0.00041	1194	0.00045	1194
0.00050	1393	0.00055	1393
0.00059	1592	0.00064	1592
0.00068	1791	0.00068	1791
0.00077	1989	0.00082	1989
0.00082	2188	0.00086	2188
0.00095	2387	0.00100	2387
0.00109	2586	0.00114	2586
0.00123	2785	0.00123	2785
0.00136	2984	0.00136	2984
0.00155	3183	0.00155	3183
0.00168	3382	0.00173	3382
0.00195	3581	0.00214	3581
0.00241	3780		

Appendix III (b): Stress-Strain Data of Concrete Containing Ultimax Cement

Mix No. 2
w/cm = 0.40
Cement Content = 800 lb/cyd
Age: 28 Days

4 x 8-in.						6 x 12-in.					
Mix 1A		Mix 2B		Mix 2B		Mix 2C		Mix 2C		Mix 2C	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00005	199	0.00005	199	0.00005	199	0.00000	354	0.00008	354	0.00008	354
0.00014	398	0.00009	398	0.00009	398	0.00000	707	0.00016	707	0.00024	707
0.00018	597	0.00018	597	0.00014	597	0.00000	1061	0.00024	1061	0.00032	1061
0.00023	796	0.00023	796	0.00018	796	0.00000	1415	0.00032	1415	0.00040	1415
0.00027	995	0.00027	995	0.00023	995	0.00000	1768	0.00048	1768	0.00048	1768
0.00032	1194	0.00032	1194	0.00032	1194	0.00008	2122	0.00056	2122	0.00064	2122
0.00041	1393	0.00036	1393	0.00032	1393	0.00024	2476	0.00064	2476	0.00072	2476
0.00045	1592	0.00041	1592	0.00041	1592	0.00032	2829	0.00072	2829	0.00080	2829
0.00050	1791	0.00050	1791	0.00045	1791	0.00040	3183	0.00080	3183	0.00088	3183
0.00059	1989	0.00055	1989	0.00064	1989	0.00056	3537	0.00088	3537	0.00096	3537
0.00064	2188	0.00059	2188	0.00077	2188	0.00064	3891	0.00096	3891	0.00112	3891
0.00068	2387	0.00064	2387	0.00091	2387	0.00080	4244	0.00112	4244	0.00120	4244
0.00073	2586	0.00068	2586	0.00109	2586	0.00088	4598	0.00120	4598	0.00136	4598
0.00077	2785	0.00073	2785	0.00123	2785	0.00104	4952	0.00128	4952	0.00144	4952
0.00086	2984	0.00082	2984	0.00145	2984	0.00120	5305	0.00136	5305	0.00160	5305
0.00091	3183	0.00086	3183	0.00173	3183	0.00128	5659	0.00152	5659	0.00168	5659
0.00095	3382	0.00091	3382	0.00191	3382	0.00144	6013	0.00160	6013	0.00184	6013
0.00100	3581	0.00100	3581	0.00223	3581	0.00160	6366	0.00168	6366	0.00200	6366
0.00109	3780	0.00105	3780	0.00245	3780	0.00184	6720	0.00184	6720	0.00224	6720
0.00118	3979	0.00109	3979	0.00277	3979	0.00208	7074	0.00192	7074		
0.00123	4178	0.00118	4178	0.00314	4178						
0.00132	4377	0.00123	4377	0.00368	4377						
0.00141	4576	0.00132	4576	0.00423	4576						
0.00145	4775	0.00141	4775	0.00468	4775						
0.00155	4974	0.00150	4974	0.00527	4974						
0.00173	5173	0.00159	5173	0.00618	5173						
0.00182	5372	0.00168	5372	0.00682	5372						
0.00200	5571	0.00177	5571	0.00768	5571						
0.00223	5770			0.00836	5770						
0.00245	5968										
0.00273	6167										
0.00314	6366										

Appendix III (b): Stress-Strain Data of Concrete Containing Ultimax Cement

Mix No. 3
***w/cm* = 0.45**
Cement Content = 700 lb/cyd
Age: 1 Day (4 x 8-in.)

Mix 3A		Mix 3A	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0
0.00005	159	0.00005	159
0.00009	318	0.00009	318
0.00018	477	0.00018	477
0.00027	637	0.00023	637
0.00032	796	0.00032	796
0.00041	955	0.00041	955
0.00045	1114	0.00045	1114
0.00055	1273	0.00055	1273
0.00064	1432	0.00064	1432
0.00073	1592	0.00073	1592
0.00082	1751	0.00082	1751
0.00091	1910	0.00095	1910
0.00105	2069	0.00109	2069
0.00114	2228	0.00123	2228
0.00127	2387	0.00136	2387
0.00145	2547	0.00155	2547
0.00168	2706	0.00173	2706
0.00200	2865	0.00209	2865

Appendix III (b): Stress-Strain Data of Concrete Containing Ultimax Cement

Mix No. 3
w/cm = 0.45
Cement Content = 700 lb/cyd
Age: 28 Days

4 x 8-in.						6 x 12-in.					
Mix 3A		Mix 3A		Mix 3A		Mix 3B		Mix 3B		Mix 3B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00005	199	0.00005	199	0.00005	199	0.00000	177	0.00008	177	0.00000	177
0.00009	398	0.00014	398	0.00009	398	0.00008	354	0.00016	354	0.00016	354
0.00014	597	0.00018	597	0.00018	597	0.00008	531	0.00016	531	0.00016	531
0.00023	796	0.00023	796	0.00023	796	0.00016	707	0.00024	707	0.00032	707
0.00027	995	0.00032	995	0.00027	995	0.00024	884	0.00032	884	0.00032	884
0.00032	1194	0.00036	1194	0.00032	1194	0.00032	1061	0.00040	1061	0.00040	1061
0.00041	1393	0.00041	1393	0.00041	1393	0.00040	1238	0.00040	1238	0.00048	1238
0.00045	1592	0.00045	1592	0.00045	1592	0.00040	1415	0.00048	1415	0.00048	1415
0.00050	1791	0.00055	1791	0.00050	1791	0.00048	1592	0.00056	1592	0.00056	1592
0.00059	1989	0.00059	1989	0.00055	1989	0.00056	1768	0.00056	1768	0.00064	1768
0.00064	2188	0.00064	2188	0.00059	2188	0.00056	1945	0.00064	1945	0.00072	1945
0.00068	2387	0.00068	2387	0.00068	2387	0.00064	2122	0.00064	2122	0.00080	2122
0.00077	2586	0.00077	2586	0.00073	2586	0.00072	2299	0.00064	2299	0.00080	2299
0.00082	2785	0.00086	2785	0.00082	2785	0.00080	2476	0.00072	2476	0.00088	2476
0.00091	2984	0.00091	2984	0.00086	2984	0.00088	2653	0.00072	2653	0.00096	2653
0.00100	3183	0.00100	3183	0.00095	3183	0.00096	2829	0.00080	2829	0.00104	2829
0.00105	3382	0.00105	3382	0.00105	3382	0.00096	3006	0.00088	3006	0.00112	3006
0.00114	3581	0.00114	3581	0.00109	3581	0.00104	3183	0.00096	3183	0.00120	3183
0.00123	3780	0.00123	3780	0.00118	3780	0.00112	3360	0.00104	3360	0.00128	3360
0.00132	3979	0.00127	3979	0.00127	3979	0.00120	3537	0.00104	3537	0.00136	3537
0.00136	4178	0.00136	4178	0.00136	4178	0.00128	3714	0.00112	3714	0.00144	3714
0.00150	4377	0.00150	4377	0.00150	4377	0.00136	3891	0.00120	3891	0.00152	3891
0.00164	4576	0.00159	4576	0.00159	4576	0.00136	4067	0.00128	4067	0.00160	4067
0.00182	4775	0.00173	4775	0.00173	4775	0.00144	4244	0.00136	4244	0.00176	4244
				0.00191	4974	0.00152	4421	0.00144	4421	0.00184	4421
						0.00160	4598	0.00152	4598	0.00192	4598
						0.00168	4775	0.00160	4775	0.00200	4775
						0.00176	4952	0.00176	4952	0.00216	4952
						0.00184	5128	0.00184	5128	0.00224	5128
						0.00192	5305	0.00200	5305	0.00240	5305
						0.00200	5482	0.00232	5482	0.00256	5482
						0.00208	5659	0.00256	5659	0.00304	5659

Appendix III (c): Stress-Strain Data of Concrete Containing Ultimax Cement (w/cm = 0.50)

Mix No. 15
Cement Content = 580 lb/cyd
Age: 1 Day (4 x 8-in.)

Mix 15A		Mix 15B		Mix 15B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0
0.00000	40	0.00000	40	0.00000	40
0.00005	80	0.00005	80	0.00005	80
0.00005	119	0.00005	119	0.00005	119
0.00005	159	0.00009	159	0.00009	159
0.00009	199	0.00014	199	0.00009	199
0.00009	239	0.00014	239	0.00014	239
0.00014	279	0.00018	279	0.00014	279
0.00014	318	0.00018	318	0.00018	318
0.00014	358	0.00023	358	0.00018	358
0.00018	398	0.00023	398	0.00023	398
0.00018	438	0.00027	438	0.00023	438
0.00018	477	0.00027	477	0.00027	477
0.00023	517	0.00032	517	0.00027	517
0.00027	557	0.00036	557	0.00032	557
0.00027	597	0.00036	597	0.00032	597
0.00032	637	0.00041	637	0.00036	637
0.00032	676	0.00045	676	0.00041	676
0.00036	716	0.00050	716	0.00041	716
0.00036	756	0.00050	756	0.00045	756
0.00041	796	0.00055	796	0.00050	796
0.00045	836	0.00059	836	0.00050	836
0.00045	875	0.00064	875	0.00055	875
0.00050	915	0.00073	915	0.00059	915
0.00055	955	0.00082	955	0.00064	955
0.00059	995	0.00091	995	0.00068	995
0.00064	1035	0.00114	1035	0.00077	1035
0.00068	1074			0.00082	1074
0.00073	1114			0.00095	1114
0.00082	1154			0.00114	1154
0.00109	1194				

Appendix III (c): Stress-Strain Data of Concrete Containing Ultimax Cement (*w/cm* = 0.50)

Mix No. 15
Cement Content = 580 lb/cyd
Age: 28 Days

4 x 8-in.						6 x 12-in.					
Mix 15A		Mix 15B		Mix 15B		Mix 15A		Mix 15B		Mix 15B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00000	80	0.00000	80	0.00000	80	0.00000	88	0.00000	88	0.00000	88
0.00000	159	0.00000	159	0.00005	159	0.00000	177	0.00000	177	0.00008	177
0.00005	239	0.00005	239	0.00009	239	0.00008	265	0.00000	265	0.00008	265
0.00009	318	0.00005	318	0.00009	318	0.00008	354	0.00008	354	0.00008	354
0.00009	398	0.00009	398	0.00014	398	0.00016	442	0.00008	442	0.00016	442
0.00014	477	0.00014	477	0.00018	477	0.00016	531	0.00016	531	0.00016	531
0.00018	557	0.00018	557	0.00018	557	0.00024	619	0.00016	619	0.00024	619
0.00018	637	0.00018	637	0.00023	637	0.00024	707	0.00016	707	0.00024	707
0.00023	716	0.00023	716	0.00027	716	0.00024	796	0.00024	796	0.00032	796
0.00027	796	0.00027	796	0.00027	796	0.00032	884	0.00032	884	0.00032	884
0.00027	875	0.00027	875	0.00032	875	0.00032	973	0.00032	973	0.00040	973
0.00032	955	0.00032	955	0.00036	955	0.00040	1061	0.00040	1061	0.00040	1061
0.00032	1035	0.00036	1035	0.00041	1035	0.00040	1149	0.00040	1149	0.00040	1149
0.00036	1114	0.00041	1114	0.00041	1114	0.00048	1238	0.00048	1238	0.00048	1238
0.00041	1194	0.00041	1194	0.00045	1194	0.00048	1326	0.00048	1326	0.00048	1326
0.00041	1273	0.00045	1273	0.00050	1273	0.00056	1415	0.00056	1415	0.00048	1415
0.00045	1353	0.00050	1353	0.00050	1353	0.00056	1503	0.00064	1503	0.00056	1503
0.00050	1432	0.00055	1432	0.00055	1432	0.00064	1592	0.00064	1592	0.00064	1592
0.00055	1512	0.00059	1512	0.00059	1512	0.00064	1680	0.00072	1680	0.00064	1680
0.00059	1592	0.00064	1592	0.00064	1592	0.00072	1768	0.00072	1768	0.00072	1768
0.00059	1671	0.00068	1671	0.00064	1671	0.00080	1857	0.00080	1857	0.00072	1857
0.00068	1751	0.00073	1751	0.00068	1751	0.00080	1945	0.00088	1945	0.00080	1945
0.00073	1830	0.00077	1830	0.00073	1830	0.00088	2034	0.00096	2034	0.00088	2034
0.00077	1910	0.00086	1910	0.00077	1910	0.00096	2122	0.00104	2122	0.00088	2122
0.00082	1989	0.00086	1989	0.00082	1989	0.00104	2211	0.00120	2211	0.00096	2211
0.00086	2069	0.00095	2069	0.00091	2069	0.00120	2299	0.00128	2299	0.00104	2299
0.00095	2149			0.00095	2149	0.00136	2387	0.00152	2387	0.00120	2387
0.00105	2228			0.00100	2228	0.00168	2476				
0.00118	2308			0.00109	2308						
				0.00118	2387						
				0.00141	2467						

Appendix III (c): Stress-Strain Data of Concrete Containing Ultimax Cement (*w/cm* = 0.50)

Mix No. 4
Cement Content = 600 lb/cyd
Age: 1 Day (4 x 8-in.)

Mix 4A		Mix 4A	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0
0.00000	119	0.00000	119
0.00009	239	0.00005	239
0.00009	358	0.00009	358
0.00014	477	0.00014	477
0.00023	597	0.00018	597
0.00027	716	0.00023	716
0.00032	836	0.00032	836
0.00036	955	0.00032	955
0.00041	1074	0.00041	1074
0.00045	1194	0.00045	1194
0.00055	1313	0.00050	1313
0.00059	1432	0.00055	1432
0.00064	1552	0.00064	1552
0.00068	1671	0.00068	1671
0.00077	1791	0.00073	1791
0.00086	1910	0.00082	1910
0.00095	2029	0.00091	2029
0.00105	2149	0.00100	2149
0.00118	2268	0.00109	2268
0.00127	2387	0.00123	2387
0.00145	2507	0.00132	2507
0.00168	2626	0.00155	2626

Appendix III (c): Stress-Strain Data of Concrete Containing Ultimax Cement (*w/cm* = 0.50)

Mix No. 4
Cement Content = 600 lb/cyd
Age: 28 Days

4 x 8-in.				6 x 12-in.			
Mix 4A		Mix 4B		Mix 4A		Mix 4B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.	Stress (psi)	Strain (in./in.	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00005	199	0.00005	199	0.00000	177	0.00000	177
0.00014	398	0.00009	398	0.00000	354	0.00008	354
0.00018	597	0.00018	597	0.00008	531	0.00008	531
0.00023	796	0.00023	796	0.00008	707	0.00016	707
0.00032	995	0.00027	995	0.00016	884	0.00016	884
0.00036	1194	0.00032	1194	0.00016	1061	0.00024	1061
0.00045	1393	0.00036	1393	0.00024	1238	0.00032	1238
0.00050	1592	0.00036	1592	0.00024	1415	0.00032	1415
0.00059	1791	0.00041	1791	0.00032	1592	0.00032	1592
0.00068	1989	0.00045	1989	0.00032	1768	0.00040	1768
0.00073	2188	0.00059	2188	0.00040	1945	0.00048	1945
0.00082	2387	0.00073	2387	0.00040	2122	0.00048	2122
0.00091	2586	0.00086	2586	0.00048	2299	0.00056	2299
0.00100	2785	0.00095	2785	0.00056	2476	0.00056	2476
0.00109	2984	0.00105	2984	0.00056	2653	0.00064	2653
0.00123	3183	0.00109	3183	0.00064	2829	0.00064	2829
0.00136	3382	0.00114	3382	0.00072	3006	0.00072	3006
0.00159	3581	0.00123	3581	0.00072	3183	0.00080	3183
0.00177	3780	0.00136	3780	0.00080	3360	0.00088	3360
				0.00088	3537	0.00096	3537
				0.00088	3714	0.00104	3714

Appendix III (c): Stress-Strain Data of Concrete Containing Ultimax Cement (*w/cm* = 0.50)

Mix No. 14
Cement Content = 620 lb/cyd
Age: 1 Day (4 x 8-in.)

Mix 14A		Mix 14B		Mix 14B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0
0.00005	80	0.00005	80	0.00000	80
0.00005	159	0.00005	159	0.00005	159
0.00009	239	0.00009	239	0.00005	239
0.00014	318	0.00014	318	0.00009	318
0.00018	398	0.00014	398	0.00014	398
0.00018	477	0.00018	477	0.00014	477
0.00023	557	0.00018	557	0.00018	557
0.00027	637	0.00023	637	0.00023	637
0.00027	716	0.00027	716	0.00023	716
0.00032	796	0.00032	796	0.00027	796
0.00036	875	0.00032	875	0.00032	875
0.00041	955	0.00036	955	0.00032	955
0.00045	1035	0.00041	1035	0.00036	1035
0.00050	1114	0.00045	1114	0.00041	1114
0.00050	1194	0.00045	1194	0.00045	1194
0.00055	1273	0.00050	1273	0.00050	1273
0.00059	1353	0.00055	1353	0.00055	1353
0.00064	1432	0.00059	1432	0.00059	1432
0.00068	1512	0.00064	1512	0.00059	1512
0.00073	1592	0.00068	1592	0.00064	1592
0.00077	1671	0.00073	1671	0.00068	1671
0.00086	1751	0.00077	1751	0.00073	1751
0.00091	1830	0.00082	1830	0.00077	1830
0.00095	1910	0.00086	1910	0.00082	1910
0.00105	1989	0.00091	1989	0.00086	1989
0.00109	2069	0.00100	2069	0.00095	2069
0.00118	2149	0.00105	2149	0.00095	2149
0.00127	2228	0.00109	2228	0.00105	2228
0.00141	2308	0.00118	2308	0.00114	2308
0.00164	2387	0.00127	2387	0.00118	2387
		0.00141	2467	0.00127	2467
				0.00136	2547
				0.00145	2626
				0.00164	2706

Appendix III (c): Stress-Strain Data of Concrete Containing Ultimax Cement (*w/cm* = 0.50)

Mix No. 14
Cement Content = 620 lb/cyd
Age: 28 Days

4 x 8-in.						6 x 12-in.					
Mix 14A		Mix 14B		Mix 14B		Mix 14A		Mix 14B		Mix 14B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00005	199	0.00005	199	0.00000	199	0.00000	177	0.00000	177	0.00000	177
0.00005	398	0.00009	398	0.00009	398	0.00008	354	0.00008	354	0.00008	354
0.00009	597	0.00014	597	0.00009	597	0.00008	531	0.00016	531	0.00008	531
0.00009	796	0.00018	796	0.00014	796	0.00016	707	0.00016	707	0.00016	707
0.00014	995	0.00023	995	0.00018	995	0.00016	884	0.00024	884	0.00016	884
0.00023	1194	0.00027	1194	0.00023	1194	0.00024	1061	0.00032	1061	0.00024	1061
0.00023	1393	0.00032	1393	0.00027	1393	0.00024	1238	0.00032	1238	0.00032	1238
0.00032	1592	0.00036	1592	0.00032	1592	0.00032	1415	0.00040	1415	0.00032	1415
0.00032	1791	0.00041	1791	0.00036	1791	0.00032	1592	0.00048	1592	0.00040	1592
0.00041	1989	0.00045	1989	0.00045	1989	0.00040	1768	0.00048	1768	0.00048	1768
0.00045	2188	0.00055	2188	0.00050	2188	0.00040	1945	0.00056	1945	0.00048	1945
0.00050	2387	0.00059	2387	0.00055	2387	0.00048	2122	0.00056	2122	0.00056	2122
0.00059	2586	0.00068	2586	0.00059	2586	0.00048	2299	0.00064	2299	0.00064	2299
0.00064	2785	0.00073	2785	0.00068	2785	0.00056	2476	0.00072	2476	0.00064	2476
0.00068	2984	0.00077	2984	0.00073	2984	0.00064	2653	0.00080	2653	0.00072	2653
0.00077	3183	0.00082	3183	0.00077	3183	0.00064	2829	0.00080	2829	0.00080	2829
0.00082	3382	0.00091	3382	0.00082	3382	0.00072	3006	0.00088	3006	0.00080	3006
0.00095	3581	0.00105	3581	0.00091	3581	0.00072	3183	0.00096	3183	0.00088	3183
0.00100	3780	0.00114	3780	0.00100	3780	0.00080	3360	0.00104	3360	0.00088	3360
0.00109	3979	0.00127	3979	0.00105	3979	0.00088	3537	0.00112	3537	0.00096	3537
0.00118	4178	0.00141	4178	0.00109	4178	0.00088	3714	0.00120	3714	0.00104	3714
0.00127	4377	0.00155	4377	0.00118	4377	0.00096	3891	0.00128	3891	0.00104	3891
0.00136	4576	0.00168	4576	0.00127	4576	0.00104	4067	0.00136	4067	0.00112	4067
0.00150	4775			0.00141	4775	0.00112	4244	0.00144	4244	0.00120	4244
0.00173	4974					0.00120	4421	0.00152	4421	0.00128	4421
						0.00128	4598	0.00160	4598	0.00136	4598
						0.00136	4775	0.00168	4775	0.00144	4775
								0.00184	4952	0.00160	4952
								0.00200	5128	0.00168	5128
								0.00216	5305	0.00184	5305

Appendix III (c): Stress-Strain Data of Concrete Containing Ultimax Cement (*w/cm* = 0.50)

Mix No. 13
Cement Content = 640 lb/cyd
Age: 1 Day (4 x 8-in.)

Mix 13A		Mix 13B		Mix 13B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0
0.00005	80	0.00005	80	0.00000	80
0.00009	159	0.00009	159	0.00005	159
0.00014	239	0.00014	239	0.00009	239
0.00014	318	0.00014	318	0.00014	318
0.00018	398	0.00018	398	0.00014	398
0.00023	477	0.00023	477	0.00018	477
0.00027	557	0.00027	557	0.00023	557
0.00032	637	0.00032	637	0.00027	637
0.00036	716	0.00036	716	0.00032	716
0.00041	796	0.00041	796	0.00036	796
0.00045	875	0.00045	875	0.00041	875
0.00050	955	0.00050	955	0.00045	955
0.00055	1035	0.00055	1035	0.00055	1035
0.00059	1114	0.00064	1114	0.00059	1114
0.00064	1194	0.00068	1194	0.00064	1194
0.00073	1273	0.00077	1273	0.00068	1273
0.00086	1353	0.00086	1353	0.00073	1353
0.00100	1432	0.00091	1432	0.00082	1432
0.00168	1512	0.00205	1512	0.00091	1512
		0.00282	1592	0.00114	1592
				0.00155	1671

Appendix III (c): Stress-Strain Data of Concrete Containing Ultimax Cement (*w/cm* = 0.50)

Mix No. 13
Cement Content = 640 lb/cyd
Age: 28 Days

4 x 8-in.						6 x 12-in.					
Mix 13A		Mix 13B		Mix 13B		Mix 13A		Mix 13A		Mix 13B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00000	159	0.00000	159	0.00000	159	0.00008	177	0.00000	177	0.00000	177
0.00005	318	0.00005	318	0.00005	318	0.00008	354	0.00016	354	0.00000	354
0.00009	477	0.00009	477	0.00009	477	0.00008	531	0.00024	531	0.00000	531
0.00014	637	0.00018	637	0.00014	637	0.00016	707	0.00024	707	0.00008	707
0.00018	796	0.00023	796	0.00023	796	0.00016	884	0.00040	884	0.00016	884
0.00027	955	0.00027	955	0.00023	955	0.00016	1061	0.00048	1061	0.00016	1061
0.00032	1114	0.00032	1114	0.00032	1114	0.00024	1238	0.00056	1238	0.00024	1238
0.00041	1273	0.00041	1273	0.00036	1273	0.00032	1415	0.00056	1415	0.00032	1415
0.00055	1432	0.00045	1432	0.00041	1432	0.00032	1592	0.00064	1592	0.00040	1592
0.00059	1592	0.00055	1592	0.00045	1592	0.00040	1768	0.00072	1768	0.00040	1768
0.00068	1751	0.00059	1751	0.00050	1751	0.00048	1945	0.00080	1945	0.00048	1945
0.00077	1910	0.00068	1910	0.00055	1910	0.00048	2122	0.00088	2122	0.00048	2122
0.00073	2069	0.00073	2069	0.00055	2069	0.00056	2299	0.00096	2299	0.00056	2299
0.00068	2228	0.00082	2228	0.00059	2228	0.00064	2476	0.00104	2476	0.00064	2476
0.00068	2387	0.00091	2387	0.00059	2387	0.00072	2653	0.00120	2653	0.00072	2653
0.00073	2547	0.00100	2547	0.00073	2547	0.00080	2829	0.00128	2829	0.00072	2829
0.00077	2706	0.00109	2706	0.00091	2706	0.00088	3006	0.00136	3006	0.00080	3006
0.00082	2865	0.00123	2865	0.00109	2865	0.00096	3183	0.00160	3183	0.00056	3183
0.00095	3024	0.00136	3024	0.00127	3024						
0.00109	3183			0.00145	3183						

Appendix III (c): Stress-Strain Data of Concrete Containing Ultimax Cement (*w/cm* = 0.50)

Mix No. 12
Cement Content = 660 lb/cyd
Age: 1 Day (4 x 8-in.)

Mix 12A		Mix 12B		Mix 12B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0
0.00005	80	0.00005	80	0.00005	80
0.00009	159	0.00005	159	0.00009	159
0.00014	239	0.00009	239	0.00009	239
0.00018	318	0.00014	318	0.00014	318
0.00018	398	0.00018	398	0.00018	398
0.00023	477	0.00023	477	0.00023	477
0.00027	557	0.00027	557	0.00027	557
0.00032	637	0.00032	637	0.00032	637
0.00036	716	0.00036	716	0.00036	716
0.00041	796	0.00041	796	0.00045	796
0.00045	875	0.00045	875	0.00050	875
0.00050	955	0.00050	955	0.00059	955
0.00055	1035	0.00059	1035	0.00064	1035
0.00059	1114	0.00068	1114	0.00073	1114
0.00068	1194	0.00073	1194	0.00086	1194
0.00073	1273	0.00082	1273	0.00105	1273
0.00082	1353	0.00100	1353	0.00109	1353
0.00095	1432	0.00118	1432	0.00118	1432
0.00109	1512				

Appendix III (c): Stress-Strain Data of Concrete Containing Ultimax Cement (w/cm = 0.50)

Mix No. 12
Cement Content = 660 lb/cyd
Age: 28 Days

4 x 8-in.						6 x 12-in.			
Mix 12A		Mix 12B		Mix 12B		Mix 12B		Mix 12B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00005	159	0.00005	159	0.00000	159	0.00000	177	0.00008	177
0.00009	318	0.00009	318	0.00005	318	0.00008	354	0.00016	354
0.00014	477	0.00014	477	0.00014	477	0.00016	531	0.00016	531
0.00023	637	0.00023	637	0.00018	637	0.00016	707	0.00024	707
0.00027	796	0.00027	796	0.00023	796	0.00024	884	0.00032	884
0.00032	955	0.00032	955	0.00032	955	0.00032	1061	0.00032	1061
0.00036	1114	0.00036	1114	0.00036	1114	0.00032	1238	0.00040	1238
0.00041	1273	0.00041	1273	0.00041	1273	0.00040	1415	0.00048	1415
0.00050	1432	0.00050	1432	0.00050	1432	0.00048	1592	0.00056	1592
0.00055	1592	0.00055	1592	0.00055	1592	0.00056	1768	0.00064	1768
0.00059	1751	0.00059	1751	0.00059	1751	0.00056	1945	0.00072	1945
0.00068	1910	0.00068	1910	0.00068	1910	0.00064	2122	0.00080	2122
0.00077	2069	0.00073	2069	0.00077	2069	0.00072	2299	0.00088	2299
0.00086	2228	0.00082	2228	0.00082	2228	0.00080	2476	0.00096	2476
0.00095	2387	0.00086	2387	0.00091	2387	0.00088	2653	0.00112	2653
0.00105	2547	0.00095	2547	0.00105	2547	0.00096	2829	0.00120	2829
		0.00105	2706	0.00114	2706	0.00112	3006	0.00136	3006
		0.00118	2865	0.00127	2865	0.00136	3183	0.00160	3183
		0.00132	3024						
		0.00136	3183						
		0.00159	3342						

Appendix III (c): Stress-Strain Data of Concrete Containing Utimax Cement (*w/cm* = 0.50)

Mix No. 11
Cement Content = 680 lb/cyd
Age: 1 Day (4 x 8-in.)

Mix 11A		Mix 11B		Mix 11B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0
0.00005	80	0.00000	80	0.00000	80
0.00005	159	0.00000	159	0.00000	159
0.00009	239	0.00005	239	0.00005	239
0.00014	318	0.00009	318	0.00009	318
0.00018	398	0.00009	398	0.00009	398
0.00023	477	0.00014	477	0.00014	477
0.00027	557	0.00018	557	0.00018	557
0.00027	637	0.00018	637	0.00018	637
0.00032	716	0.00023	716	0.00023	716
0.00036	796	0.00027	796	0.00027	796
0.00036	875	0.00032	875	0.00027	875
0.00041	955	0.00036	955	0.00032	955
0.00045	1035	0.00036	1035	0.00036	1035
0.00050	1114	0.00041	1114	0.00041	1114
0.00059	1194	0.00045	1194	0.00045	1194
0.00064	1273	0.00050	1273	0.00050	1273
0.00064	1353	0.00055	1353	0.00055	1353
0.00073	1432	0.00064	1432	0.00059	1432
0.00077	1512	0.00068	1512	0.00064	1512
0.00082	1592	0.00073	1592	0.00073	1592
0.00091	1671	0.00077	1671	0.00077	1671
0.00100	1751	0.00086	1751	0.00082	1751
0.00109	1830	0.00095	1830	0.00091	1830
0.00118	1910	0.00105	1910	0.00100	1910
0.00136	1989	0.00118	1989	0.00159	1989
		0.00132	2069		

Appendix III (c): Stress-Strain Data of Concrete Containing Ultimax Cement (*w/cm* = 0.50)

Mix No. 11
Cement Content = 680 lb/cyd
Age: 28 Days

4 x 8-in.				6 x 12-in.					
Mix 11A		Mix 11B		Mix 11A		Mix 11B		Mix 11B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00005	159	0.00005	159	0.00000	177	0.00008	177	0.00000	177
0.00009	318	0.00009	318	0.00008	354	0.00008	354	0.00008	354
0.00014	477	0.00014	477	0.00016	531	0.00016	531	0.00008	531
0.00018	637	0.00018	637	0.00024	707	0.00024	707	0.00016	707
0.00027	796	0.00023	796	0.00032	884	0.00024	884	0.00024	884
0.00027	955	0.00027	955	0.00032	1061	0.00032	1061	0.00024	1061
0.00032	1114	0.00032	1114	0.00040	1238	0.00040	1238	0.00032	1238
0.00036	1273	0.00036	1273	0.00048	1415	0.00048	1415	0.00040	1415
0.00045	1432	0.00041	1432	0.00048	1592	0.00048	1592	0.00040	1592
0.00059	1592	0.00045	1592	0.00056	1768	0.00056	1768	0.00048	1768
0.00091	1751	0.00050	1751	0.00064	1945	0.00064	1945	0.00056	1945
0.00118	1910	0.00055	1910	0.00072	2122	0.00072	2122	0.00064	2122
0.00123	2069	0.00064	2069	0.00080	2299	0.00072	2299	0.00064	2299
0.00127	2228	0.00068	2228	0.00080	2476	0.00080	2476	0.00072	2476
0.00136	2387	0.00073	2387	0.00088	2653	0.00088	2653	0.00080	2653
0.00150	2547	0.00082	2547	0.00088	2829	0.00096	2829	0.00088	2829
0.00168	2706	0.00086	2706	0.00096	3006	0.00104	3006	0.00096	3006
0.00182	2865	0.00095	2865	0.00112	3183	0.00112	3183	0.00104	3183
0.00195	3024	0.00100	3024	0.00120	3360	0.00120	3360	0.00112	3360
0.00214	3183	0.00109	3183	0.00136	3537	0.00128	3537	0.00120	3537
0.00232	3342	0.00118	3342	0.00152	3714			0.00136	3714
0.00259	3502	0.00127	3502						
		0.00141	3661						
		0.00159	3820						

Appendix III (d): Stress-Strain Data of Concrete Containing ASTM Type I/II Cement

Mix No. 18
***w/cm* = 0.30**
Cement Content = 2000 lb/cyd

1 Day				28 Days					
Cylinder 1		Cylinder 2		Cylinder 1				Cylinder 2	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00136	4974	0.00000	0
0.00005	199	0.00005	199	0.00005	199	0.00145	5173	0.00014	398
0.00014	398	0.00014	398	0.00009	398	0.00155	5372	0.00023	796
0.00023	597	0.00023	597	0.00014	597	0.00159	5571	0.00036	1194
0.00027	796	0.00027	796	0.00018	796	0.00168	5770	0.00045	1592
0.00041	995	0.00036	995	0.00023	995	0.00177	5968	0.00055	1989
0.00045	1194	0.00045	1194	0.00027	1194	0.00186	6167	0.00068	2387
0.00055	1393	0.00050	1393	0.00032	1393	0.00195	6366	0.00077	2785
0.00064	1592	0.00059	1592	0.00036	1592	0.00200	6565	0.00091	3183
0.00073	1791	0.00068	1791	0.00041	1791	0.00214	6764	0.00100	3581
0.00077	1989	0.00077	1989	0.00045	1989	0.00223	6963	0.00114	3979
0.00091	2188	0.00082	2188	0.00050	2188	0.00232	7162	0.00127	4377
0.00100	2387	0.00095	2387	0.00055	2387	0.00245	7361	0.00141	4775
0.00109	2586	0.00105	2586	0.00059	2586			0.00155	5173
0.00123	2785	0.00114	2785	0.00068	2785			0.00173	5571
0.00132	2984	0.00127	2984	0.00073	2984			0.00191	5968
0.00145	3183	0.00136	3183	0.00077	3183			0.00209	6366
0.00159	3382	0.00150	3382	0.00082	3382			0.00232	6764
0.00177	3581	0.00168	3581	0.00091	3581			0.00255	7162
0.00191	3780	0.00182	3780	0.00095	3780			0.00277	7560
0.00209	3979	0.00195	3979	0.00105	3979				
0.00227	4178	0.00214	4178	0.00109	4178				
0.00250	4377	0.00232	4377	0.00114	4377				
0.00282	4576	0.00259	4576	0.00123	4576				
				0.00132	4775				

Appendix III (d): Stress-Strain Data of Concrete Containing ASTM Type I/II Cement

Mix No. 20A, 20B
***w/cm* = 0.35**
Cement Content = 1643 lb/cyd

1 Day				28 Days			
Mix 20A		Mix 20B		Mix 20A		Mix 20B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00005	199	0.00009	199	0.00009	398	0.00009	398
0.00009	398	0.00014	398	0.00018	796	0.00018	796
0.00018	597	0.00023	597	0.00027	1194	0.00027	1194
0.00027	796	0.00032	796	0.00041	1592	0.00036	1592
0.00036	995	0.00041	995	0.00050	1989	0.00041	1989
0.00045	1194	0.00050	1194	0.00059	2387	0.00055	2387
0.00050	1393	0.00059	1393	0.00068	2785	0.00068	2785
0.00059	1592	0.00064	1592	0.00082	3183	0.00082	3183
0.00068	1791	0.00077	1791	0.00095	3581	0.00095	3581
0.00082	1989	0.00086	1989	0.00105	3979	0.00109	3979
0.00091	2188	0.00095	2188	0.00123	4377	0.00123	4377
0.00100	2387	0.00109	2387	0.00136	4775	0.00136	4775
0.00114	2586	0.00123	2586	0.00150	5173	0.00150	5173
0.00127	2785	0.00132	2785	0.00168	5571	0.00168	5571
0.00141	2984	0.00145	2984	0.00182	5968	0.00186	5968
0.00159	3183	0.00159	3183	0.00200	6366	0.00205	6366
0.00173	3382	0.00177	3382	0.00223	6764	0.00227	6764
0.00195	3581	0.00205	3581	0.00245	7162	0.00255	7162
0.00218	3780	0.00236	3780	0.00264	7560	0.00282	7560
0.00241	3979			0.00291	7958		

Appendix III (d): Stress-Strain Data of Concrete Containing ASTM Type I/II Cement

Mix No. 16A, 16B
***w/cm* = 0.40**
Cement Content = 1288 lb/cyd

1 Day				28 Days	
Mix 16A		Mix 16B		Mix 16B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0
0.00005	159	0.00000	159	0.00005	398
0.00009	318	0.00009	318	0.00018	796
0.00014	477	0.00018	477	0.00027	1194
0.00023	637	0.00023	637	0.00041	1592
0.00027	796	0.00027	796	0.00055	1989
0.00032	955	0.00036	955	0.00064	2387
0.00041	1114	0.00045	1114	0.00077	2785
0.00045	1273	0.00050	1273	0.00086	3183
0.00055	1432	0.00059	1432	0.00100	3581
0.00064	1592	0.00068	1592	0.00118	3979
0.00073	1751	0.00077	1751	0.00132	4377
0.00082	1910	0.00086	1910	0.00150	4775
0.00095	2069	0.00100	2069	0.00168	5173
0.00105	2228	0.00109	2228	0.00186	5571
0.00118	2387	0.00123	2387	0.00209	5968
0.00132	2547	0.00136	2547	0.00218	6366
0.00150	2706	0.00155	2706	0.00227	6764
0.00173	2865	0.00173	2865	0.00241	7162
		0.00191	3024		

Appendix III (d): Stress-Strain Data of Concrete Containing ASTM Type I/II Cement

Mix No. 19A, 19B
w/cm = 0.45
Cement Content = 1089 lb/cyd

1 Day								28 Days			
Mix 19A				Mix 19B				Mix 19B		Mix 19B	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00095	1989	0.00000	0	0.00118	1989	0.00000	0	0.00000	0
0.00000	80	0.00100	2069	0.00000	80	0.00132	2069	0.00014	398	0.00009	398
0.00000	159	0.00109	2149	0.00005	159	0.00141	2149	0.00027	796	0.00023	796
0.00005	239	0.00118	2228	0.00005	239	0.00155	2228	0.00036	1194	0.00032	1194
0.00005	318	0.00127	2308	0.00009	318	0.00168	2308	0.00045	1592	0.00045	1592
0.00009	398	0.00136	2387	0.00014	398	0.00182	2387	0.00059	1989	0.00055	1989
0.00014	477	0.00145	2467	0.00018	477	0.00200	2467	0.00077	2387	0.00064	2387
0.00014	557	0.00159	2547	0.00023	557			0.00086	2785	0.00077	2785
0.00018	637			0.00027	637			0.00100	3183	0.00091	3183
0.00023	716			0.00027	716			0.00118	3581	0.00105	3581
0.00027	796			0.00032	796			0.00136	3979	0.00123	3979
0.00027	875			0.00036	875			0.00150	4377	0.00136	4377
0.00032	955			0.00041	955			0.00168	4775	0.00155	4775
0.00036	1035			0.00045	1035			0.00191	5173	0.00173	5173
0.00041	1114			0.00050	1114			0.00214	5571	0.00195	5571
0.00041	1194			0.00055	1194			0.00241	5968	0.00223	5968
0.00045	1273			0.00059	1273			0.00273	6366	0.00245	6366
0.00050	1353			0.00064	1353			0.00327	6764	0.00291	6764
0.00055	1432			0.00073	1432						
0.00059	1512			0.00077	1512						
0.00064	1592			0.00082	1592						
0.00068	1671			0.00091	1671						
0.00077	1751			0.00095	1751						
0.00082	1830			0.00105	1830						
0.00086	1910			0.00114	1910						

Appendix III (d): Stress-Strain Data of Concrete Containing ASTM Type I/II Cement

Mix No. 17
***w/cm* = 0.50**
Cement Content = 890 lb/cyd

1 Day				28 Days			
Cylinder 1		Cylinder 2		Cylinder 1		Cylinder 2	
Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)	Strain (in./in.)	Stress (psi)
0.00000	0	0.00000	0	0.00000	0	0.00000	0
0.00000	80	0.00000	80	0.00009	398	0.00014	398
0.00005	159	0.00000	159	0.00023	796	0.00023	796
0.00009	239	0.00005	239	0.00032	1194	0.00036	1194
0.00014	318	0.00009	318	0.00045	1592	0.00050	1592
0.00014	398	0.00014	398	0.00059	1989	0.00064	1989
0.00018	477	0.00018	477	0.00068	2387	0.00073	2387
0.00023	557	0.00023	557	0.00086	2785	0.00086	2785
0.00027	637	0.00027	637	0.00100	3183	0.00100	3183
0.00032	716	0.00032	716	0.00114	3581	0.00118	3581
0.00036	796	0.00032	796	0.00136	3979	0.00136	3979
0.00041	875	0.00036	875	0.00155	4377	0.00155	4377
0.00045	955	0.00045	955	0.00173	4775	0.00177	4775
0.00050	1035	0.00050	1035	0.00200	5173	0.00205	5173
0.00059	1114	0.00055	1114	0.00232	5571	0.00241	5571
0.00064	1194	0.00059	1194	0.00264	5968		
0.00068	1273	0.00064	1273	0.00318	6366		
0.00077	1353	0.00073	1353				
0.00086	1432	0.00082	1432				
0.00091	1512	0.00086	1512				
0.00100	1592	0.00095	1592				
0.00114	1671	0.00105	1671				
0.00123	1751	0.00114	1751				
0.00141	1830	0.00127	1830				
0.00159	1910	0.00141	1910				
0.00186	1989	0.00159	1989				
		0.00195	2069				

Appendix IV (a): Splitting-Tensile Strength Data of Concrete Containing Ultimax Cement (*w/cm* = 0.30)

Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Splitting-Tensile Strength (psi)			
		1 day	4 x 8	490.0	480.0	——	——
	10A	28 days	4 x 8	693.8	726.1	——	——
1000			6 x 12	513.7	588.0	——	——
		1 day	4 x 8	490.0	517.0	——	——
	10B	28 days	4 x 8	668.9	731.6	——	——
			6 x 12	565.9	——	——	——
		1 day	4 x 8	514.8	547.1	——	——
	9A	28 days	4 x 8	703.8	733.6	——	——
1033			6 x 12	569.9	574.7	——	——
		1 day	4 x 8	509.8	544.6	——	——
	9B	28 days	4 x 8	611.8	636.6	——	——
			6 x 12	470.8	——	——	——
		1 day	4 x 8	——	——	——	——
	8A	28 days	4 x 8	740.1	768.4	——	——
1067			6 x 12	485.9	——	——	——
		1 day	4 x 8	599.3	497.4	484.9	514.8
	8B	28 days	4 x 8	756.0	686.4	——	——
			6 x 12	526.1	640.2	——	——
		1 day	4 x 8	——	——	——	——
	7A	28 days	4 x 8	675.9	722.7	——	——
1100			6 x 12	476.6	——	——	——
		1 day	4 x 8	547.1	514.8	519.7	504.8
	7B	28 days	4 x 8	627.7	716.2	——	——
			6 x 12	508.4	532.7	——	——
		1 day	4 x 8	572.0	514.8	527.2	490.0
	6A	28 days	4 x 8	788.3	681.4	——	——
1133			6 x 12	508.4	——	——	——
		1 day	4 x 8	——	——	——	——
	6B	28 days	4 x 8	607.8	718.7	——	——
			6 x 12	638.8	635.7	——	——
		1 day	4 x 8	——	——	——	——
	5A	28 days	4 x 8	636.6	763.4	——	——
			6 x 12	526.1	——	——	——
		1 day	4 x 8	——	——	——	——
1166	5B	28 days	4 x 8	696.3	——	——	——
			6 x 12	574.3	638.8	——	——
		1 day	4 x 8	482.4	480.0	467.5	502.3
	5C	28 days	4 x 8	——	——	——	——
			6 x 12	——	——	——	——

Appendix IV (b): Splitting-Tensile Strength Data of Concrete Containing Ultimax Cement (*w/cm* = 0.35-0.45)

w/cm	Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Splitting-Tensile Strength (psi)			
0.35	900	1A	1 day	4 x 8	497.4	364.1	----	----
			28 days	4 x 8	579.4	----	----	----
				6 x 12	578.0	----	----	----
		1B	1 day	4 x 8	446.6	547.1	----	----
			28 days	4 x 8	713.7		----	----
				6 x 12	554.8	557.5	----	----
		1C	1 day	4 x 8			----	----
			28 days	4 x 8	671.4	712.2	----	----
				6 x 12	----	----	----	----
		1D	1 day	4 x 8	----	----	----	----
			28 days	4 x 8	----	----	----	----
				6 x 12	----	----	----	----
0.40	800	2A	1 day	4 x 8	----	----	----	----
			28 days	4 x 8	564.5	524.7	----	----
				6 x 12	351.5	473.0	----	----
		2B	1 day	4 x 8	403.4	348.6	378.5	335.7
			28 days	4 x 8	499.8	534.7	----	----
				6 x 12	474.1	----	----	----
		2C	1 day	4 x 8	----	----	----	----
			28 days	4 x 8	----	----	----	----
				6 x 12	----	----	----	----
0.45	700	3A	1 day	4 x 8	343.2	293.4	318.3	323.3
			28 days	4 x 8	437.7	465.0	437.7	452.6
				6 x 12	----	----	----	----
		3B	1 day	4 x 8	----	----	----	----
			28 days	4 x 8	----	----	----	----
				6 x 12	390.0	390.0	390.0	----

Appendix IV (c): Splitting-Tensile Strength Data of Concrete Containing Ultimax Cement (*w/cm* = 0.50)

Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Splitting-Tensile Strength (psi)			
580	15A	1 day	4 x 8	144.2	141.2	----	----
		28 days	4 x 8	291.0	308.4	----	----
			6 x 12	265.2	236.5	----	----
	15B	1 day	4 x 8	139.3	149.2	----	----
		28 days	4 x 8	298.4	291.0	----	----
			6 x 12	247.1	----	----	----
600	4A	1 day	4 x 8	266.6	263.6	207.9	240.7
		28 days	4 x 8	375.5	415.3	----	----
			6 x 12	344.4	335.6	----	----
	4B	1 day	4 x 8	----	----	----	----
		28 days	4 x 8	373.0	375.5	----	----
			6 x 12	275.2	----	----	----
620	14A	1 day	4 x 8	278.5	274.5	----	----
		28 days	4 x 8	473.5	465.0	----	----
			6 x 12	442.5	424.4	----	----
	14B	1 day	4 x 8	321.3	309.4	----	----
		28 days	4 x 8	492.4	482.4	----	----
			6 x 12	415.6		----	----
640	13A	1 day	4 x 8	191.5	211.4	----	----
		28 days	4 x 8	348.2	360.6	----	----
			6 x 12	333.8	----	----	----
	13B	1 day	4 x 8	218.8	196.4	----	----
		28 days	4 x 8	412.8	363.1	----	----
			6 x 12	358.1	340.4	----	----
660	12A	1 day	4 x 8	191.5	201.4	----	----
		28 days	4 x 8	363.1	355.6	----	----
			6 x 12	366.9	322.7	----	----
	12B	1 day	4 x 8	201.4	186.5	----	----
		28 days	4 x 8	375.5	370.5	----	----
			6 x 12	426.6	----	----	----
680	11A	1 day	4 x 8	243.7	241.2	----	----
		28 days	4 x 8	392.9	392.9	----	----
			6 x 12	298.4	311.2	----	----
	11B	1 day	4 x 8	261.1	271.1	----	----
		28 days	4 x 8	380.5	383.0	----	----
			6 x 12	378.0	----	----	----

Appendix IV (d): Splitting-Tensile Strength Data of Concrete Containing ASTM Type I/II Cement (*w/cm* = 0.30-0.50)

w/cm	Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Splitting-Tensile Strength (psi)		
0.30	2000	18	1 day	4 x 8	475.0	445.1	493.4
			28 days	4 x 8	678.9	639.1	631.6
0.35	1643	20A	1 day	4 x 8	440.2	----	----
			28 days	4 x 8	----	----	----
		20B	1 day	4 x 8	450.1	423.8	----
			28 days	4 x 8	612.7	671.4	621.7
0.40	1288	16A	1 day	4 x 8	375.5	----	----
			28 days	4 x 8	----	----	----
		16B	1 day	4 x 8	417.8	432.7	----
			28 days	4 x 8	624.2	591.8	----
0.45	1089	19A	1 day	4 x 8	340.7	----	----
			28 days	4 x 8	----	----	----
		19B	1 day	4 x 8	304.4	333.2	----
			28 days	4 x 8	646.6	656.5	624.2
0.50	890	17	1 day	4 x 8	298.4	323.3	308.4
			28 days	4 x 8	524.7	577.9	574.4

Appendix V (a): Bulk Density Data of Concrete Containing Ultimax Cement (*w/cm* = 0.30)

Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Bulk Density (pcf)		
1000	10A	1 day	4 x 8	153.5	154.0	----
		28 days	4 x 8	154.0	154.9	----
			6 x 12	153.3	153.2	----
	10B	1 day	4 x 8	153.7	154.2	----
		28 days	4 x 8	154.4	153.8	----
			6 x 12	153.6	153.3	----
1033	9A	1 day	4 x 8	151.8	152.3	----
		28 days	4 x 8	152.3	152.3	----
			6 x 12	151.6	151.4	----
	9B	1 day	4 x 8	152.3	----	----
		28 days	4 x 8	152.1	152.8	----
			6 x 12	152.4	152.2	----
1067	8A	1 day	4 x 8	----	----	----
		28 days	4 x 8	152.5	152.5	----
			6 x 12	151.2	151.6	----
	8B	1 day	4 x 8	152.8	152.5	151.4
		28 days	4 x 8	153.7	154.0	----
			6 x 12	151.6	149.2	----
1100	7A	1 day	4 x 8	----	----	----
		28 days	4 x 8	153.0	151.8	----
			6 x 12	151.9	151.0	----
	7B	1 day	4 x 8	153.0	152.3	153.0
		28 days	4 x 8	153.2	153.8	----
			6 x 12	151.9	151.6	----
1133	6A	1 day	4 x 8	150.2	150.9	152.8
		28 days	4 x 8	154.5	152.5	----
			6 x 12	151.2	151.5	----
	6B	1 day	4 x 8	----	----	----
		28 days	4 x 8	152.1	152.8	----
			6 x 12	150.1	150.4	----
1166	5A	1 day	4 x 8	----	----	----
		28 days	4 x 8	152.1	151.8	----
			6 x 12	150.6	151.1	----
	5B	1 day	4 x 8	----	----	----
		28 days	4 x 8	152.3	----	----
			6 x 12	150.5	150.5	----
	5C	1 day	4 x 8	151.3	151.4	151.6
		28 days	4 x 8	152.5	----	----
			6 x 12	----	----	----

Appendix V (b): Bulk Density Data of Concrete Containing Ultimax Cement (*w/cm* = 0.35-0.45)

w/cm	Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Bulk Density (pcf)		
0.35	900	1A	1 day	4 x 8	----	----	----
			28 days	4 x 8	155.4	----	----
				6 x 12	151.4	----	----
		1B	1 day	4 x 8	----	----	----
			28 days	4 x 8	153.3	151.4	----
				6 x 12	151.6	152.8	----
		1C	1 day	4 x 8	152.6	152.3	150.2
			28 days	4 x 8	151.4	----	----
				6 x 12	----	----	----
		1D	1 day	4 x 8	----	----	----
			28 days	4 x 8	----	----	----
				6 x 12			
0.40	800	2A	1 day	4 x 8	153.2	154.7	153.5
			28 days	4 x 8	154.2	154.9	----
				6 x 12	152.0	150.8	----
		2B	1 day	4 x 8	----	----	----
			28 days	4 x 8	152.3	154.7	----
				6 x 12	151.5	151.7	----
		2C	1 day	4 x 8	----	----	----
			28 days	4 x 8	----	----	----
				6 x 12	153.8	154.2	153.8
0.45	700	3A	1 day	4 x 8	150.4	152.3	151.4
			28 days	4 x 8	152.3	151.4	153.0
				6 x 12	----	----	----
		3B	1 day	4 x 8	----	----	----
			28 days	4 x 8	----	----	----
				6 x 12	153.4	152.0	152.9

Appendix V (c): Bulk Density Data of Concrete Containing Ultimax Cement (*w/cm* = 0.50)

Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Bulk Density (pcf)		
580	15A	1 day	4 x 8	150.2	150.2	----
		28 days	4 x 8	151.8	151.1	----
			6 x 12	150.0	151.1	----
	15B	1 day	4 x 8	148.9	150.2	----
		28 days	4 x 8	150.2	150.7	----
			6 x 12	149.3	150.0	----
600	4A	1 day	4 x 8	151.1	151.3	151.8
		28 days	4 x 8	151.4	151.4	----
			6 x 12	151.6	151.4	----
	4B	1 day	4 x 8	----	----	----
		28 days	4 x 8	152.5	151.8	----
			6 x 12	150.3		----
620	14A	1 day	4 x 8	153.5	152..6	----
		28 days	4 x 8	152.8	151.8	----
			6 x 12	152.0	152.2	----
	14B	1 day	4 x 8	151.4	153.3	----
		28 days	4 x 8	153.7	152.6	----
			6 x 12	152.8	152.7	----
640	13A	1 day	4 x 8	152.1	151.4	----
		28 days	4 x 8	151.4	151.9	----
			6 x 12	150.8	----	----
	13B	1 day	4 x 8	150.9	151.3	----
		28 days	4 x 8	151.8	150.7	----
			6 x 12	149.6	149.8	----
660	12A	1 day	4 x 8	150.2	150.7	----
		28 days	4 x 8	151.6	151.1	----
			6 x 12	149.4	150.2	----
	12B	1 day	4 x 8	150.7	150.2	----
		28 days	4 x 8	152.1	151.8	----
			6 x 12	150.7	----	----
680	11A	1 day	4 x 8	151.6	151.9	----
		28 days	4 x 8	150.2	150.7	----
			6 x 12	149.7	149.4	----
	11B	1 day	4 x 8	151.6	151.3	----
		28 days	4 x 8	152.3	153.0	----
			6 x 12	150.6	150.3	----

Appendix V (d): Bulk Density of Concrete Containing ASTM Type I/II Cement (*w/cm* = 0.30-0.50)

w/cm	Cement Content (lb/cyd)	Mix No.	Age	Cylinder Size (in.)	Bulk Density (pcf)		
0.30	2000	18	1 day	4 x 8	145.6	145.2	145.4
			28 days	4 x 8	147.0	146.1	146.6
0.35	1643	20A	1 day	4 x 8	148.2	----	----
			28 days	4 x 8	148.8	----	----
		20B	1 day	4 x 8	146.6	146.4	146.4
			28 days	4 x 8	147.3	148.0	148.5
0.40	1288	16A	1 day	4 x 8	149.7	149.4	----
			28 days	4 x 8	----	----	----
		16B	1 day	4 x 8	147.6	147.5	----
			28 days	4 x 8	147.6	148.0	148.7
0.45	1089	19A	1 day	4 x 8	150.7	----	----
			28 days	4 x 8	151.3	----	----
		19B	1 day	4 x 8	148.5	148.0	148.0
			28 days	4 x 8	149.2	149.0	148.8
0.50	890	17	1 day	4 x 8	149.7	150.1	149.4
			28 days	4 x 8	150.4	150.2	150.4

Appendix VI (a): Shrinkage and Expansion Data of Concrete Containing Ultimax Cement (*w/cm* = 0.30)

Cement Content (lb/cyd)	Mix No.	Age (days)	Shrinkage (x 10^{-6} in./in.)			
			Air-dried (Shrinkage)	Water-cured (Expansion)		Average Expansion
		0	0	0	0	0
		0.125 (3 hr)	20	-30	-40	-35
		1	-10	-110	-150	-130
		3	-40	-220	-220	-220
1000	10A	7	50	-220	-230	-225
		14	—	—	—	—
		28	170	-250	-240	-245
		56	240	-180	-230	-205
		90	320	-210	-220	-215
		0	0	0	0	0
		0.125 (3 hr)	0	-40	-10	-25
		1	-40	-100	-90	-95
		3	-30	-130	-150	-140
1033	9A	7	-20	-160	-170	-165
		14	60	-160	-180	-170
		28	140	-190	-220	-205
		56	260	-260	-260	-260
		90	320	-350	-340	-345
		0	0	0	0	0
		0.125 (3 hr)	80	50	60	55
		1	80	-50	-60	-55
		3	110	-110	-110	-110
1067	8A	7	70	-170	-140	-155
		14	120	-140	-150	-145
		28	250	-170	-220	-195
		56	350	-240	-40	-140
		90	400	-360	-340	-350
		0	0	0	0	0
		0.125 (3 hr)	80	60	50	55
		1	80	-60	-30	-45
		3	90	-110	-70	-90
1100	7A	7	60	-170	-140	-155
		14	100	-170	-120	-145
		28	210	-190	-140	-165
		56	290	-160	-130	-145
		90	330	-210	-180	-195
		0	0	0	0	0
		0.125 (3 hr)	80	-20	-50	-35
		1	10	-100	-100	-100
		3	40	-120	-110	-115
1133	6A	7	70	-160	-150	-155
		14	80	-170	-170	-170
		28	240	-200	-180	-190
		56	350	-210	-200	-205
		90	460	-330	-330	-330
		0	0	0	0	0
		0.125 (3 hr)	60	20	10	15
		1	30	-90	-70	-80
		3	10	-90	-90	-90
1166	5A	7	30	-140	-120	-130
		14	80	-170	-150	-160
		28	190	-170	-90	-130
		56	250	-170	-140	-155
		90	350	-230	-200	-215

Appendix VI (b): Shrinkage and Expansion Data of Concrete Containing Ultimax Cement (*w/cm* = 0.35-0.45)

w/c	Cement Content (lb/cyd)	Mix No	Age (days)	Shrinkage (x 10^{4} in./in.) Air-dried (Shrinkage)			Average Shrinkage	Water-cured (Expansion)			Average Expansion
0.35	900	1D	0	0	0	0	0	0	0	0	0
			0.125 (3 hr)	-10	-30	-30	-23	-90	-20	-120	-77
			1	80	50	70	67	-70	-30	-80	-60
			3	70	20	30	40	-100	-70	-100	-90
			7	70	40	80	63	-100	-70	-110	-93
			14	150	110	160	140	-80	-60	-80	-73
			28	260	220	250	243	-70	-50	-80	-67
			56	410	360	380	383	-50	-20	-50	-40
			90	410	370	390	390	-110	-70	-80	-87
0.4	800	2C	0	0	0	0	0	0	0	0	0
			0.125 (3 hr)	20	50	30	33	-60	-70	10	-40
			1	30	50	-10	23	-110	-100	-80	-97
			3	100	110	110	107	-50	-80	-100	-77
			7	80	110	110	100	-90	-110	-100	-100
			14	120	160	160	147	-70	-110	-100	-93
			28	220	300	240	253	-70	-100	-100	-90
			56	350	410	380	380	-40	-80	-70	-63
			90	340	400	370	370	-90	-100	-110	-100
0.45	700	3A	0	0	0	0	0	0	0	0	0
			0.125 (3 hr)	-120	50	100	10	-20	-50	-30	-33
			1	-120	-10	60	-23	-100	-20	-60	-60
			3	-50	20	80	17	-100	-40	-80	-73
			7	130	140	-290	-7	0	0	-50	-17
			14	30	160	260	150	-20	10	-10	-7
			28	190	250	340	260	-30	-70	-10	-37
			56	280	340	430	350	0	-40	-20	-20
			90	180	310	410	300	-50	-90	-50	-63

Appendix VI (c): Shrinkage and Expansion Data of Concrete Containing Ultimax Cement (*w/cm* = 0.50)

Cement Content (lb/cyd)	Mix No.	Age (days)	Shrinkage (x 10^{-6} in./in.) Air-dried (Shrinkage)			Average Shrinkage	Water-cured (Expansion)			Average Expansion
580	15A	0	0	—	—	0	0	0	—	0
		0.125 (3 hr)	30	—	—	30	-30	-70	—	-50
		1	40	—	—	40	10	-90	—	-40
		3	170	—	—	170	70	-70	—	0
		7	160	—	—	160	20	-110	—	-45
		14	190	—	—	190	20	-100	—	-40
		28	280	—	—	280	30	-110	—	-40
		56	310	—	—	310	70	-80	—	-5
		90	380	—	—	380	60	-50	—	5
600	4C	0	0	0	0	0	0	0	0	0
		0.125 (3 hr)	-80	-20	-30	-43	-70	-80	-90	-80
		1	-70	0	-50	-40	-40	-70	-110	-73
		3	30	100	60	63	-10	-80	-100	-63
		7	-10	30	30	17	-20	-80	-90	-63
		14	80	160	150	130	10	-50	-50	-30
		28	140	230	230	200	0	-50	-70	-40
		56	230	320	280	277	20	20	-70	-10
		90	220	310	300	277	0	-60	-70	-43
620	14A	0	0	—	—	0	0	0	—	0
		0.125 (3 hr)	40	—	—	40	-10	-70	—	-40
		1	10	—	—	10	-140	-200	—	-170
		3	30	—	—	30	-190	-240	—	-215
		7	60	—	—	60	-170	-270	—	-220
		14	90	—	—	90	-200	-280	—	-240
		28	160	—	—	160	-210	-310	—	-260
		56	220	—	—	220	-280	-270	—	-275
		90	270	—	—	270	-180	-280	—	-230
640	13A	0	0	—	—	0	0	0	—	0
		0.125 (3 hr)	30	—	—	30	10	0	—	5
		1	20	—	—	20	-50	-70	—	-60
		3	10	—	—	10	-90	-50	—	-70
		7	20	—	—	20	-130	-90	—	-110
		14	150	—	—	150	-80	-60	—	-70
		28	230	—	—	230	-100	-40	—	-70
		56	260	—	—	260	-100	-60	—	-80
		90	320	—	—	320	-80	-40	—	-60
660	12A	0	0	—	—	0	0	0	—	0
		0.125 (3 hr)	30	—	—	30	-80	-80	—	-80
		1	20	—	—	20	-190	-200	—	-195
		3	20	—	—	20	-250	-240	—	-245
		7	20	—	—	20	-260	-260	—	-260
		14	130	—	—	130	-240	-230	—	-235
		28	220	—	—	220	-260	-260	—	-260
		56	240	—	—	240	-260	-270	—	-265
		90	310	—	—	310	-210	-220	—	-215
680	11A	0	0	—	—	0	0	0	—	0
		0.125 (3 hr)	30	—	—	30	-50	-50	—	-50
		1	10	—	—	10	-100	-100	—	-100
		3	-10	—	—	-10	-150	-120	—	-135
		7	30	—	—	30	-140	-120	—	-130
		14	70	—	—	70	-150	-90	—	-120
		28	120	—	—	120	-150	-130	—	-140
		56	290	—	—	290	-190	-90	—	-140
		90	290	—	—	290	-140	-70	—	-105

Appendix VI (d): Shrinkage and Expansion Data of Concrete Containing ASTM Type I/II Cement (*w/cm* = 0.30-0.50)

w/cm	Cement Content (lb/cyd)	Mix No.	Age (days)	Shrinkage (x 10^{-6} in./in.) Air-dried (Shrinkage)			Average Shrinkage	Water-cured (Expansion)			Average Expansion
0.30	2000	18	0	0	—	—	0	0	0	—	0
			0.125 (3 hr)	120	—	—	120	-30	0	—	-15
			1	190	—	—	190	-50	-60	—	-55
			3	220	—	—	220	-80	-80	—	-80
			7	380	—	—	380	-100	-90	—	-95
			14	580	—	—	580	-120	-100	—	-110
			28	690	—	—	690	-180	-160	—	-170
			56	910	—	—	910	-280	-240	—	-260
			90	1170	—	—	1170	-310	-270	—	-290
0.35	1643	20B	0	0	—	—	0	0	0	—	0
			0.125 (3 hr)	80	—	—	80	-30	-20	—	-25
			1	100	—	—	100	-80	-50	—	-65
			3	210	—	—	210	-110	-90	—	-100
			7	360	—	—	360	-90	-80	—	-85
			14	540	—	—	540	-120	-90	—	-105
			28	720	—	—	720	-170	-170	—	-170
			56	990	—	—	990	-240	-230	—	-235
			90	1220	—	—	1220	-280	-280	—	-280
0.40	1288	16B	0	0	0	0	0	0	0	0	0
			0.125 (3 hr)	130	150	100	127	70	50	30	50
			1	100	150	90	113	-10	10	-50	-17
			3	230	300	160	230	10	-40	-40	-23
			7	300	290	310	300	-50	-80	-90	-73
			14	530	510	530	523	-50	-70	-80	-67
			28	800	750	800	783	-80	-100	-100	-93
			56	1150	1080	1130	1120	-90	-130	-140	-120
			90	1300	1240	1300	1280	-150	-170	-180	-167
0.45	1089	19B	0	0	—	—	0	0	0	—	0
			0.125 (3 hr)	80	—	—	80	0	-170	—	-85
			1	80	—	—	80	-40	-180	—	-110
			3	200	—	—	200	-70	-10	—	-40
			7	330	—	—	330	-40	20	—	-10
			14	480	—	—	480	-70	10	—	-30
			28	740	—	—	740	-110	-40	—	-75
			56	990	—	—	990	-130	-60	—	-95
			90	1150	—	—	1150	-140	-80	—	-110
0.50	890	17	0	0	0	0	0	0	0	0	0
			0.125 (3 hr)	30	80	90	67	-40	20	0	-7
			1	110	120	140	123	-100	-30	-100	-77
			3	160	170	160	163	-100	-70	-80	-83
			7	360	350	330	347	-120	-70	-90	-93
			14	490	520	510	507	-120	-70	-80	-90
			28	770	750	750	757	-120	-60	-110	-97
			56	960	940	950	950	-170	-100	-130	-133
			90	1040	1040	1060	1047	-170	-120	-130	-140

Appendix VII: Equations for Statistical Analysis

$$\text{mean, } \mu_x = (\Sigma x)/n$$

The standard deviation, σ, is a measure of how widely values are from the average value (the mean).

$$\sigma_x^2 = \frac{n\Sigma x^2 - (\Sigma x)^2}{n(n - 1)}$$

$$\sigma_x = (\sigma_x^2)^{1/2}$$

The coefficient of variation, ν, is used to compare the relative dispersion of more than one kind of data.

$$\nu = \sigma/\mu$$

The covariance, *Cov (X, Y)*, is the average of the products of deviation for each data point pair. It is used to determine the relationship between two data sets.

$$Cov(X, Y) = \frac{\Sigma(x - \mu_x)(y - \mu_y)}{n}$$

The correlation coefficient, R, is used to determine the relationship between two properties.

$$R = \frac{Cov(X, Y)}{\sigma_x \sigma_y}$$