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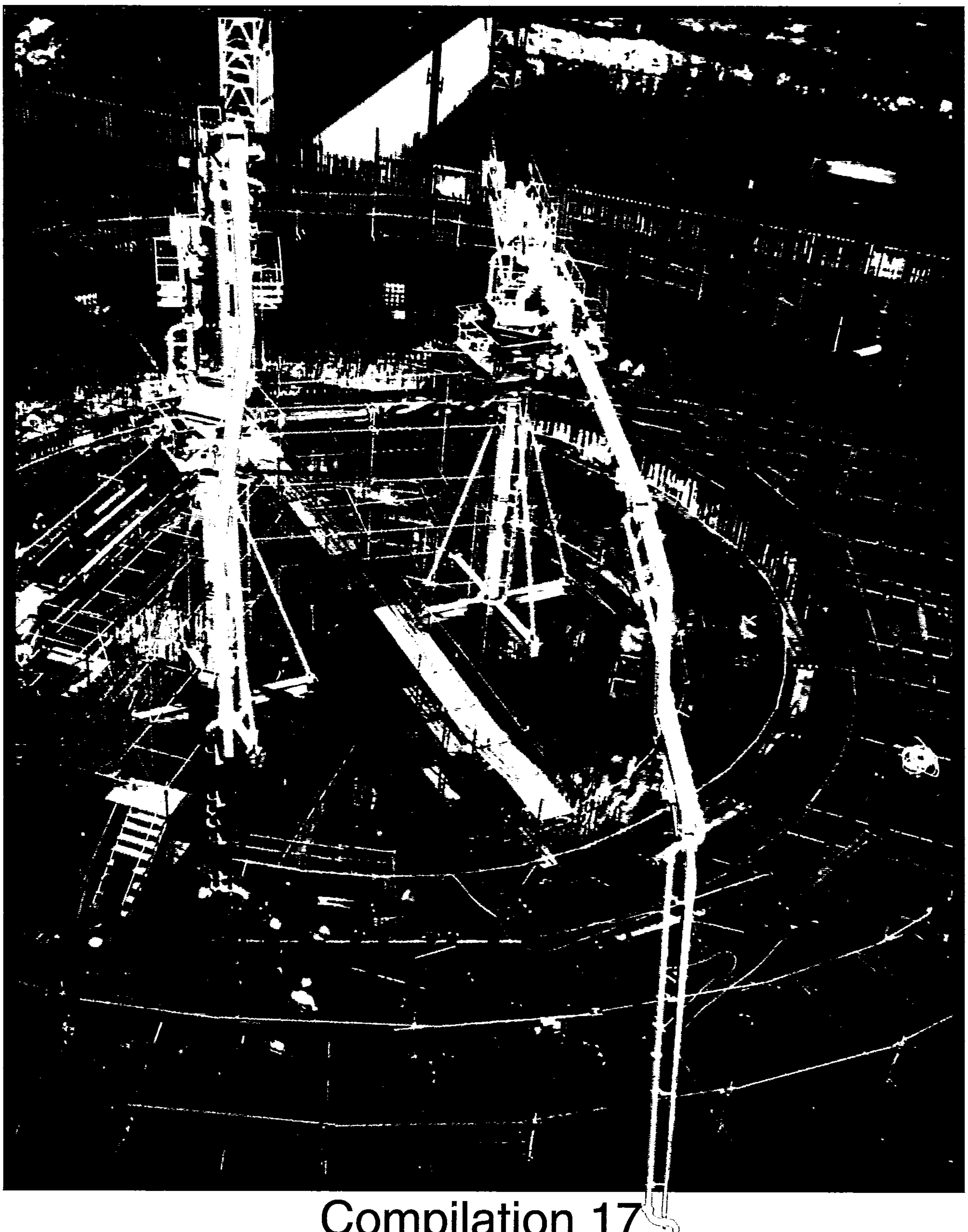
HIGH STRENGTH CONCRETE



Compilation 17

High Strength Concrete

ACI Compilation

Contents

Preface

ACI Compilations combine material previously published in Institute periodicals to provide compact and ready reference on specific topics. The material in a compilation does not necessarily represent the opinion of an ACI technical committee — only the opinions of the individual authors. However, the information presented here is considered to be a valuable resource for readers interested in the subject.

Kenneth L. Saucier

Chairman, ACI Committee 363

High Strength Concrete

On the cover: Automation, including robotic technology, is now a major factor in the construction industry, especially in nations like Japan. As shown in this photo, automatically controlled cranes are frequently used in placing concrete on jobs where large quantities are necessary.

American Concrete Institute, Box 19150, Redford Station, Detroit, Michigan 48219

High-Strength Concrete

by H. G. Russell

"Imagine, for example, concrete with an available strength of 10,000 pounds per square inch. Smaller columns, thinner and lighter beams and slabs would at once result. Precast units, easy to handle, would be available. The present limiting heights of buildings, of spans of bridges would be at least double. A new basis of design, new codes and specifications would be required," said Professor S. C. Hollister, former Dean of Engineering at Cornell University during the ACI's 30th Annual Dinner in 1934.

As we all know, the "idle dreams" of Prof. Hollister have now been accomplished. We have 10,000 psi (69 MPa) compressive strength concrete readily available in many parts of North America and other major industrial nations. The development Prof. Hollister dreamed about has been accomplished over the years.

In the 1950s, we had 5000 psi (34 MPa) concrete. In the 1960s, we had the commercial use of 6000 and 7500 psi (41 and 52 MPa) concretes. In the early 1970s, we reached 9000 psi (62 MPa) concrete. And toward the end of the 1980s, we reached 20,000 psi (138 MPa) compressive strength concrete. As we look to the future and the year 2000, there is no doubt in my mind we will have a concrete with a compressive strength of at least 25,000 psi (172 MPa) and even 30,000 psi (207 MPa) produced commercially without using super-exotic materials.

The results of having these materials available will be just as Prof. Hollister predicted. Columns will become even smaller — to the point that we will begin to worry about the lateral stability of those members. Beams and slabs will become lighter, particularly in long-span structures such as cable-stayed bridges and prestressed girders. But, more importantly, we will see these materials used because of their enhanced performance characteristics.

In recent years, we have seen greater use of high-strength concrete in applications where durability is important — highway bridge decks, parking structures, industrial facilities, stilling basins, and offshore structures. Our next development is to combine the material characteristics with comparable structural performance so the two factors are used to their greatest advantage.

We will need to look constantly at the basis of our designs. Prof. Hollister said that new codes and specifications would be required, and as these higher strength materials have become available, it has been necessary to review our codes and specifications for their applicability to high-strength concretes.

In its report in 1988, ACI Committee 363, High Strength Concrete, identified numerous research needs for high-strength concrete, many of which were driven by a need for information with which to modify codes and specifications to accommodate new material characteristics. And we can't stop with the current research on 10,000 to 15,000 psi (69 to 103 MPa) concretes. We must look at the engineering characteristics of concretes with strengths of 15,000 to 25,000 psi (103 to 172 MPa) to validate or modify design methods.

As an industry, we have a great opportunity to capitalize on a material with strengths approaching those of structural steel; however, we have to advance in unison. At the present time, materials technology has outpaced engineering knowledge. Hopefully, this will change in the next few years and we will be able to pursue this opportunity before us.

To rephrase Prof. Hollister's dream, "Imagine concrete with a compressive strength of 30,000 psi (207 MPa). Smaller columns and lighter bridge girders will result. Taller buildings and longer span bridges will be built in concrete. Codes and specifications that support and include the use of these materials will be developed."

ACU Fellow **Henry G. Russell** is president of Construction Technology Laboratories, Inc., Skokie, Ill. He has authored numerous publications related to the structural design of reinforced and prestressed concrete. He is a Director of ACI and a member of ACI Committees 363, High Strength Concrete; 223, Expansive Cement Concrete; and 358, Concrete Guideways; and the Fellows Nominating Committee, Planning Committee, and International Activities Committee.

Expanding Applications
of Materials Technology

PCA Research on High-Strength Concrete

by Anthony E. Fiorato

Reviews Portland Cement Association-sponsored research on high-strength normal-weight concrete. This research has reflected construction-industry needs for technological information about high-strength concrete applications for prestressed members, building, and bridges, and in situations where durability rather than strength is the primary concern.

The development and use of high-strength concrete has been an evolutionary process. The objectives and direction of Portland Cement Association (PCA) research on high-strength concrete reflect this evolution.

The following review of PCA research was originally conceived as a convenient summary of one source of technical information on high-strength concrete. As work progressed, it was evident that this summary also provides a unique perspective on how developments in materials technology can meet changing needs of the construction industry.

Since this review is limited to PCA-sponsored research, it does not represent a comprehensive summary of the current state of the art. Many other organizations, researchers, and practitioners are involved in work on high-strength concrete, but their contributions are not reflected here. This review also is limited to normal-weight concretes, as developments in lightweight concrete technology require more space than can be given here.

PCA is very heavily oriented toward applied, or "market driven" research; thus, work on high-strength concrete closely mirrors needs of the construction industry.

Needs of the prestressing industry led to some of the first applications of high-strength concrete, and the development of high-rise buildings was, and remains, a strong impetus for high-strength concrete research. The experience and technology gained from use of high-strength concrete in buildings has provided a base for such additional applications as bridges. Perhaps the most recent direction for high-strength concrete has been in applications where durability rather than strength is the primary design concern.

High-strength concrete for prestressed members

Early work on high-strength concrete was directed toward providing high early strengths for prestressing,[1,2] where relatively high-strength concretes are required even though the high later-age strengths may not be used.

Work by Klieger in the 1950s defined mix proportion characteristics, consolidation techniques, and curing conditions to develop one-day compressive strengths in excess of 2000 psi (13.8 MPa) for Type I cements and 4000 psi (27.6 MPa) for Type III cements.[1] Strengths at 28 days ranged from about 7500 to 8500 psi (51.7 to 58.6 MPa) for cylinders moist cured at room temperature. Mixes evaluated had water-cement ratios ranging from 0.29 to 0.41, with cement contents of 470 to 1128 lb/yd^3 (279 to 670 kg/m^3).

Accelerated curing at elevated temperatures provided one-day strengths up to 180 percent of those of equivalent moist-cured cylinders made from Type I cement. The mixes had very low slumps—less than 1.5 in. (38 mm)—and were made without the water reducers that are now common.

Based on his tests, Klieger recommended the following means for obtaining high-quality high early strength concrete:

- Use low water-cement ratio mixes.
- Use Type III cement.
- Use mechanical vibration to permit more aggregate per unit volume.
- Use saturated steam at atmospheric pressure at temperatures below the boiling point of water, together with insulation.
- Carefully control aggregate gradation, batch weights, mixing, compacting, and curing.
- Use water curing during early hours of hydration.

Keywords: **bridges; buildings; concrete durability; high-strength concretes;** prestressed concrete; reinforced concrete; **research;** structural design.

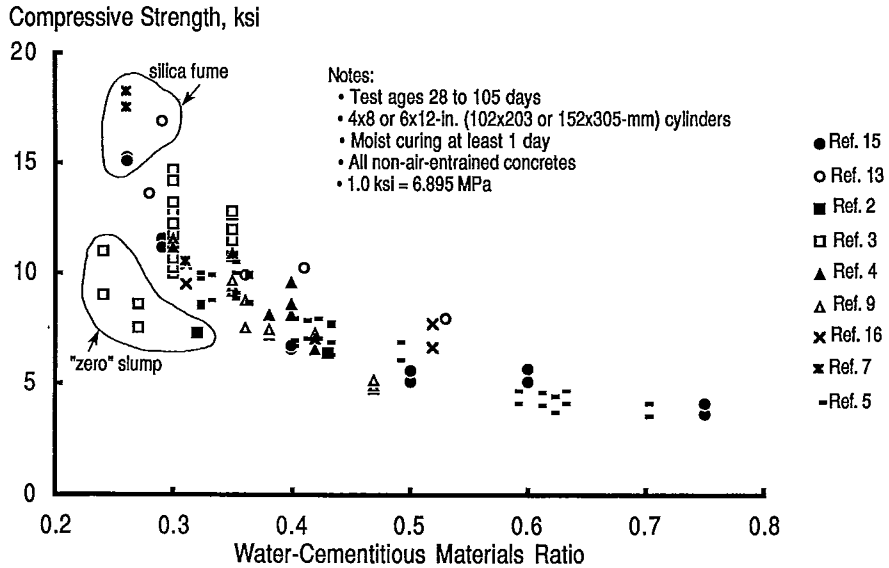


Fig. 1—Summary of strength data as a function of *w/c*.

Klieger also evaluated freeze-thaw and deicer-scaling resistance as well as creep and shrinkage characteristics of high early strength concretes for prestressing.[2] Air-entrained and nonair-entrained concretes with water-cement ratios from 0.30 to 0.50, cement contents from 564 to 799 lb/yd^3 (335 to 474 kg/m^3), and compressive strengths (28-day moist-cured) up to 7630 psi (52.6 MPa) were tested. For air-entrained concretes, air contents ranged from 2.2 to 3 percent for the higher cement content mixes to 3.9 to 6 percent for the lower cement content mixes.

Among other conclusions, these tests indicated:

- All concretes required intentionally entrained air for a high degree of freeze-thaw and deicer-scale resistance.
- Concretes made with Type I and Type III cements were equally durable.
- Curing at elevated temperatures did not impair durability of air-entrained concretes provided some drying followed prior to exposure.
- Richer low water-cement ratio mixes showed lower creep strains than leaner higher water-cement ratio mixes.

High-strength concrete for buildings

Buildings have probably attracted the most attention of any application of high-strength concrete, and much of the work on development of high-strength concretes has been directed toward the need for such materials in high-rise structures. High-strength concrete is considered in design of buildings to achieve greater heights, to reduce column sections, and to provide greater stiffness.

Materials development

In 1973, Perenchio[3] reported on factors that affect production of high-strength concrete. He considered a number of mix proportioning variables including cement composition and fineness; water-cement ratio; curing; aggregate composition, size, and gradation; and admixtures. At water-cement ratios ranging from 0.22 to 0.35, the low-slump mixes tested reached 28-day compressive strengths (moist cured) up to 13,240 psi (91.3 MPa).

Within this fundamental program, the following findings were highlighted:

- Cement paste was a primary factor in obtaining high strengths. Cements with higher percentages of tricalcium silicate produced higher strength pastes. At equivalent water-cement ratios, finer cements produced higher early age strengths, but fineness was of little significance at later ages.
- The lowest water-cement ratios consistent with workable mixes provided the highest strengths.
- Provision of moist curing, particularly within the first 24 hours, was very important to strength development.
- Use of saturated aggregates provided an internal source of curing water.
- Smaller maximum aggregate sizes provided higher strength concretes.
- Aggregate properties of importance to producing high-strength concrete were strength, bonding potential, and absorption.

As an extension of the fundamental program, Perenchio and Klieger[4] reported on a study to evaluate some physical properties of high-strength concretes. Three aggregate combinations were used in zero-slump concretes prepared at water-cement ratios of 0.30, 0.35, and 0.40 by weight. Concretes were tested for compressive strength, modulus of elasticity, Poisson's ratio, creep, drying shrinkage, and resistance to freezing and thawing. Both air-entrained and nonair-entrained concretes were tested for freezing and thawing. Compressive strengths up to 11,580 psi (79.8 MPa) at 28 days (moist cured) were tested.

Significant conclusions from this investigation were:

- Compressive strength and modulus of elasticity increased with decreasing water-cement ratio.

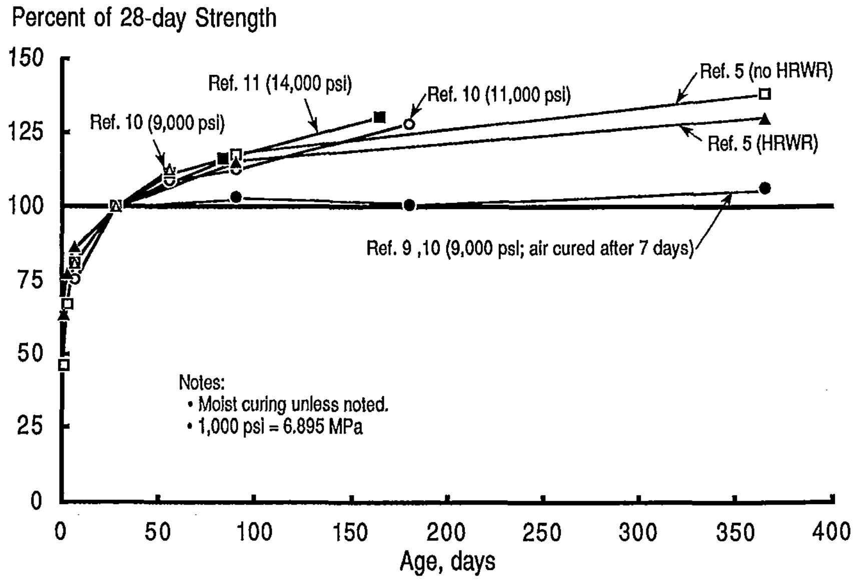


Fig. 2—Compressive strength development.

- Specific creep, in millionths per psi, decreased with decreasing water-cement ratio (increasing strength).
- Drying shrinkage was generally unaffected by change in water-cement ratio. Concretes with lower water-cement ratios appeared to require a longer drying period to reach equilibrium.
- Both air-entrained and nonair-entrained concretes had excellent freeze-thaw resistance. This was attributed to the low freezable water contents and increased tensile strengths of the low water-cement ratio mixes. It is also noted that these tests included a period of drying prior to freeze-thaw exposure.

The work of Klieger and Perenchio was supplemented by an investigation of high-range water reducers (superplasticizers) reported by Whiting in 1979.[5] Although not specifically directed at high-strength concretes, the work included evaluation of concretes with water-cement ratios down to 0.32 and 28-day moist-cured compressive strengths up to 9100 psi (62.7 MPa). Nominal cement content for the high-strength concretes was 658 lb/yd^3 (391 kg/m^3). Slumps ranged from 1.7 to 3.2 in. (43 to 81 mm).

Results relevant to high-strength concrete were that low water-cement ratio mixes could be obtained effectively using high-range water reducers, which provided a means of achieving workability at low water contents. The high-range water reducers lowered net water contents from 10 to 20 percent. Efficiency of water reduction increased with increasing cement content.

Structural design

As work on materials progressed, it was evident that information was also needed to update design criteria for higher strength concretes. One of the first issues that needed to be resolved was the flexural stress distribution for ultimate strength design. In 1977, Kaar, Hanson, and Capell reported on an investigation of stress-versus-strain characteristics of high-strength concrete.[6]

Tests included normal-weight concretes with compressive strengths from 6500 to 14,850 psi (44.8 to 102.4 MPa). Three aggregates were used. Results included stress-versus-strain curves, flexural constants for design, and moduli of elasticity for all concretes tested.

A primary result of this investigation was to define constants for design of high-strength concrete flexural members. In particular, the value of the constant that defines the fraction of the neutral axis depth that can be used for the ACI Building Code[7] rectangular stress block depth was confirmed. This value is in Section 10.2.7.3 of the ACI Building Code.

A paper by Roller and Russell on the most recent research on structural design for high-strength concrete was directed toward gathering information on shear strength of beams with web reinforcement.* Beams made with nominal concrete strengths of 10,000 and 17,000 psi (69.0 and 117.2 MPa) were tested. Shear reinforcement ranged from the minimum amount required by ACI 318-83 to the maximum amount that can be assumed when calculating shear capacity.

Results of these tests indicate that for nonprestressed high-strength concrete members subject to shear and flexure only, minimum shear reinforcement must be increased with increased compressive strength. These results have confirmed proposed ACI Building Code revisions that would require increases in the minimum amount of web reinforcement for concretes with compressive strengths in excess of 10,000 psi (69.0 MPa).

Time-dependent deformations

In August 1966, a field investigation at Lake Point Tower, a 70-story, 645 ft (197 m) tall building in Chicago, was begun.[8] Objectives of the investigation were to measure deformations on what, at the time, was an unusually tall structure, to relate the field measurements to companion laboratory data and to develop methods to predict time-de-

*Roller, J. J., and Russell, H. G., "Shear Strength of High-Strength Concrete Beams with Web Reinforcement," in print.

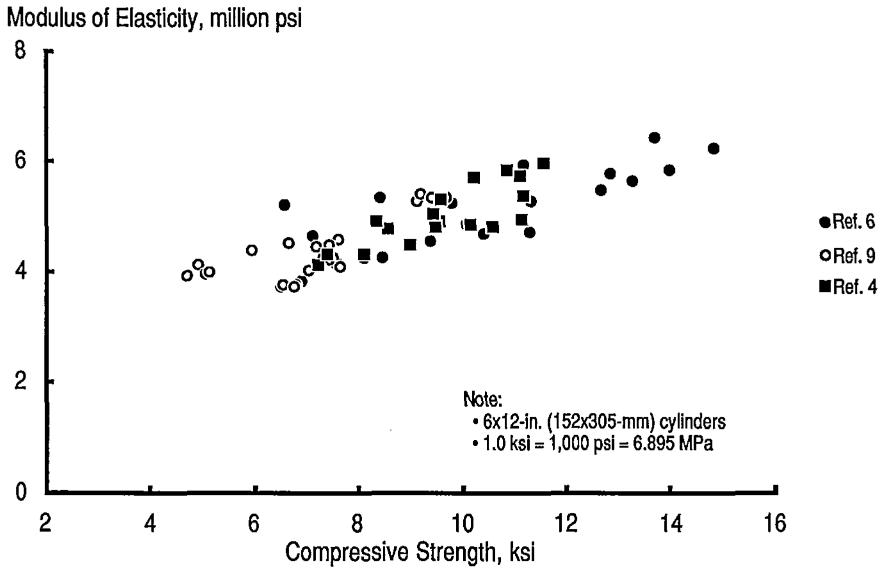


Fig. 3—Modulus of elasticity as a function of strength.

pendent deformations of the structure. Concrete design strengths ranged from 7500 to 3500 psi (51.7 to 24.1 MPa) over the height of the building.

The Lake Point Tower investigation demonstrated that it is possible to obtain reliable field measurements on a multistory structure during and after construction. It also identified the significant effects of creep and shrinkage on total deformations. Differential shortening between columns and core walls was found to increase uniformly from the first story to the midheight of the building, and then to remain relatively constant. An analytical procedure for calculation of deformations was presented that showed satisfactory agreement between calculated and measured deformations.

Subsequent to the work on Lake Point Tower, a combined laboratory and field investigation was undertaken of the time-dependent deformations of columns and walls in Water Tower Place, a 76-story, 859 ft (262 m) tall reinforced concrete building in Chicago.[9]

Laboratory tests were conducted on concretes obtained in the field to measure compressive strength, modulus of elasticity, coefficient of thermal expansion, creep, and shrinkage. Field measurements were made to evaluate vertical shortening of individual members and relative vertical displacements at selected floor levels during and after construction of the building. Concrete design strengths ranged from 9000 psi (62.1 MPa) at the lower levels to 4000 psi (27.6 MPa) at the top of the building.

In addition to providing properties of high-strength concrete used in an actual structure, the Water Tower Place investigation extended the base of essential information on short- and long-term building deformations. Based on construction records that defined loading histories on instrumented columns and walls and on laboratory data on elastic properties, creep, and shrinkage, time-dependent shortening was calculated. These calculations accounted for load history, column and wall sizes, amount of reinforcement, and concrete properties. Calculated shortening compared well with measured values.

This work provided a quantitative basis for dealing with time-dependent movements in high-rise buildings and has since been extended to other buildings.[10,11] In addition, a new publication provides an update to the Water Tower Place investigation and documents measurements continued for about 13 years after start of construction.[12]

Fire endurance

Another issue related to high-strength concrete structures that has been addressed in recent research is fire endurance. Fire tests were performed on reinforced 3 x 3 x 0.33 ft (914 x 914 x 101 mm) slab specimens fabricated from conventional and high-strength concrete mixes, with and without silica fume.[13] Commercially supplied concretes with water-cement ratios ranging from 0.28 to 0.53, with 56-day compressive strengths from 6990 to 17,490 psi (48.2 to 120.6 MPa) were used.

Specimens were fire tested for four hours and monitored for temperature rise and physical integrity. Fire endurances of all specimens were not significantly different. None of the specimens exhibited spalling of exposed surfaces.

Summary of selected properties

Fig. 1 summarizes compressive strength test results as a function of water-cementitious materials ratio from previously discussed references and from projects that will be described later. This figure confirms what by now is obvious: strength increases with decreasing water-cement ratio. However, the changes that have occurred in mix proportions over time are not directly evident.

The advent of conventional and high-range water reducers has permitted production of very low water-cement ratio concretes that are extremely workable. Supplementary cementitious materials (fly ash, slag, and silica fume) have been effective additions to cement in producing high-strength concretes. Silica fume, in particular, has been used in combination with high-range water reducers to increase achievable strength levels at very low water-cementitious materials ratios (Fig. 1).

Fig. 2 illustrates compressive strength development of high-strength concretes. For moist-cured specimens, strengths at 56 days are about 10 percent greater than 28-day strengths. Strengths at 90 days are about 15 percent greater than 28-day strengths. Mixes shown contain cement only or cement and fly ash.

While it is inappropriate to generalize such results, they do provide an overall indication of potential for strength gain at later ages. In addition, the effect of curing is evident from the curve shown for air-cured specimens, where only marginal strength increases were achieved after 28 days.

Fig. 3 summarizes modulus of elasticity test results as a function of compressive strength. These data confirm the increased stiffness obtained at higher strength levels.

High-strength concrete for bridges

Much of the work on high-strength concrete buildings has direct applicability to bridges. Generally, design requirements and economics have not yet led to the use of the same strength levels in bridges as are used in some buildings. However, there has been a growing recognition of the availability of high-strength concretes by the bridge design community. High-strength concretes are being considered to reduce dead weights (smaller sections), to permit longer spans or fewer girders for equivalent loading, and to provide improved durability.

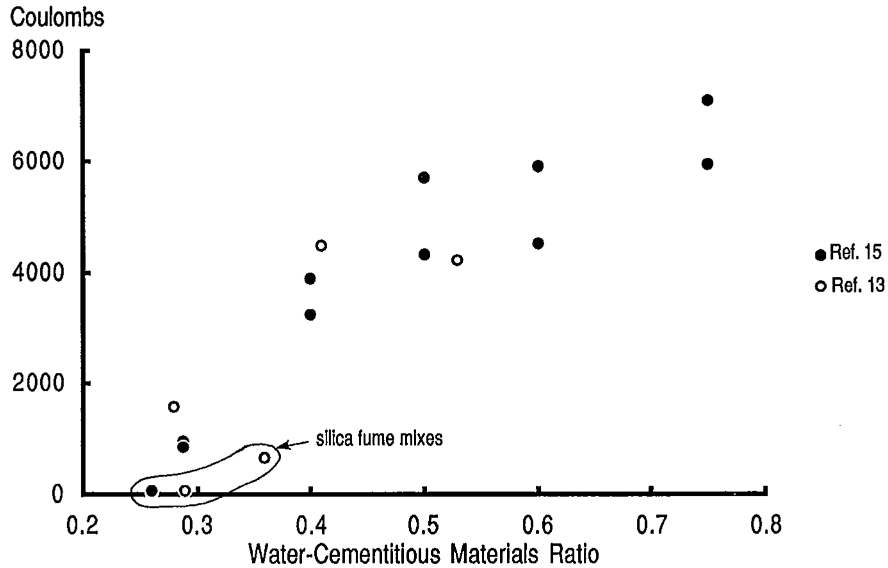


Fig. 4—Rapid chloride permeability test results.

In a study sponsored by the Federal Highway Administration, which is summarized in Reference 14, a limited investigation was made on the effect of concrete strength on span lengths. For standard precast prestressed bridge girders, increasing concrete compressive strength from 5000 to 7000 psi (34.5 to 48.3 MPa) increased span capabilities of AASHTO girders by about 15 percent.

High-strength concrete for durability

An interesting and relatively recent development has been the use of high-strength concretes where durability rather than strength is the primary design criteria. Durability of structures takes many forms, including resistance to corrosion, freezing and thawing, deicing chemicals, alkali-aggregate reactivity, chemical attack, sulfate attack, abrasion, and combination effects.

Permeability

One of the most important characteristics of durable concrete is low permeability. Low water-cement ratio, high-strength concretes have very low permeabilities relative to conventional strength concretes.

One of the problems in evaluating permeability is the difficulty of measurements for low water-cement ratio concretes. Whiting reported on a program to compare test procedures for permeability and to establish effects of mix design variables, materials, and curing on permeability of selected concrete mixes.[15]

Test procedures included conventional steady-state flow tests for air and water permeability, rapid chloride permeability, helium porosity, and volume of permeable voids. Concretes tested had water-cement ratios ranging from 0.26 to 0.75, cement contents from 413 to 750 lb/yd^3 (245 to 445 kg/m^3), and slumps from 3.5 to 4.9 in. (89 to 124 mm). Some mixes included silica fume and high-range water reducers. Curing included a 7-day moist cure as well as simulation of cases with minimal curing. Compressive strengths ranged from 4120 to 15,100 psi (28.4 to 104.1 MPa) at 90 days (7-day moist cure).

Findings from this study:

- Confirmed the strong influence of water-cement ratio on permeability
- Confirmed the importance of adequate curing to achieve lower permeabilities, particularly at higher water-cement ratios
- Demonstrated that at water-cement ratios less than 0.3, especially when silica fume was used, concretes were virtually impermeable to water and chloride ions
- Demonstrated that rapid test procedures such as the rapid chloride permeability test (AASHTO T-277) and volume of permeable voids (ASTM C 642) can be used

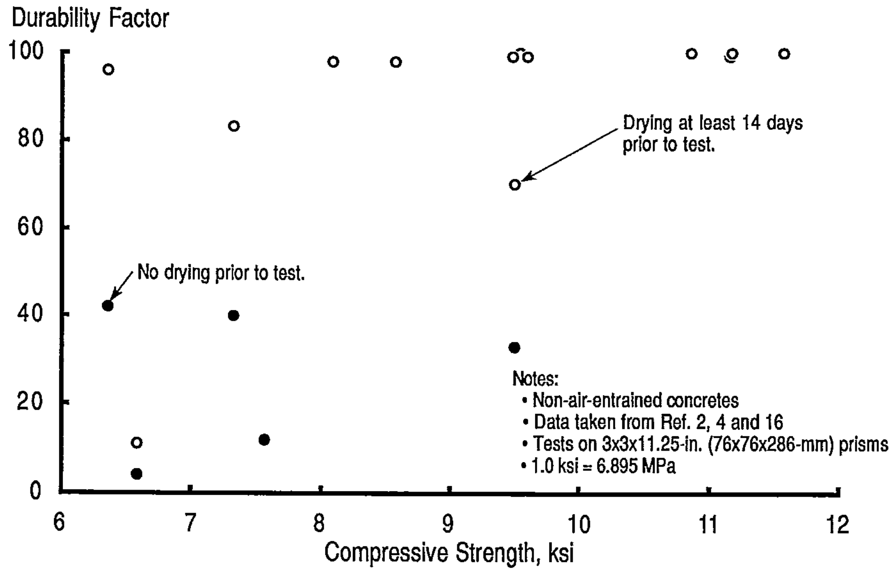


Fig. 5—Freeze-thaw test results

to estimate permeability in lieu of flow testing

Fig. 4 summarizes results of rapid chloride permeability measurements as reported in References 13 and 15. The reduction in permeability at lower water-cement ratios is readily evident. The addition of silica fume resulted in even greater reductions in permeability than would be anticipated based solely on water-cement ratio.

Freeze-thaw resistance

With many applications of high-strength concrete, freeze-thaw durability is not an issue because the concrete is used in elements that are not subject to freezing in a saturated condition. However, high-strength concretes are being used increasingly in elements such as parking or bridge decks and girders that are subject to severe freeze-thaw environments.

An important aspect related to freeze-thaw durability of high-strength concretes is entrained-air requirements. Addition of entrained air is not compatible with achieving high strengths; therefore, from the viewpoint of strength alone, it is preferable to minimize entrained air. The issue becomes whether the low permeabilities (lower probability of containing freezable water) and higher tensile strengths of high-strength concrete mixes offset the need for entrained air.

Several of the previously discussed investigations included tests on freezing and thawing and on deicer scaling. In addition to those investigations, a program was undertaken to address freeze-thaw durability specifically.[16]

The work included concretes with nominal 28-day compressive strengths of 6000, 8000, and 10,000 psi (41.4, 55.2, and 69.0 MPa) produced using representative commercial mixes with water reducers, high-range water reducers, and fly ash. Air contents were varied from no entrained air to 3 to 4 percent, 4 to 6 percent, and 7 to 9 percent by volume. Durability tests included rapid freezing and thawing in tap water and application of deicing agents. Some specimens were placed into testing immediately after moist curing for 28 days, while others were moist cured for 7 days and air dried for 21 days prior to exposure to freeze-thaw cycles.

The following findings were obtained from the tests:

- All nonair-entrained concretes performed poorly, regardless of curing, in both freeze-thaw and deicer-scaling tests.
- All air-entrained concretes performed satisfactorily when exposed to freezing and thawing in tap water. The only evidence of deterioration was weight loss (minor surface scaling), which decreased as nominal strength levels increased.
- For strength and air-content levels tested, the 8000 and 10,000 psi (55.2 and 69.0 MPa) concretes exhibited severe scaling in deicer tests, regardless of curing. The 6000 psi (41.4 MPa) concretes at recommended air-content levels performed satisfactorily.

Data on freeze-thaw tests reported in References 2, 4, and 16 all have indicated that air-entrained concretes perform well; however, results for nonair-entrained concretes appear inconsistent. Fig. 5 summarizes results of tests in terms of the durability factor as a function of compressive strength for nonair-entrained mixes. For this comparison, the durability factor was based on 300 cycles or the number of cycles at 60 percent of the original dynamic modulus, whichever was reached first.[2]

Results are divided into those in which there was no drying prior to freeze-thaw testing (solid circles) and those where at least 14 days of drying were permitted (hollow circles). The common thread in these results appears to be the level of drying after initial moist curing. Where drying was permitted, concretes generally performed better. This likely is related to the reduction of potentially freezable water during hydration and drying and to the ability of low-permeability concretes to resist resaturation under freeze-thaw conditions.

Because of uncertainties in initial curing and drying under actual field exposure conditions, the use of air entrainment is still recommended even in high-strength concretes where they are exposed to potential freezing and thawing under saturated conditions.

Data on deicer-scaling tests in References 2 and 16 indicate that nonair-entrained concretes exhibited severe scaling irrespective of strength level or conditions of curing (drying prior to test). Curi-