High-Strength Concrete
High-Strength Concrete

by James A. Farny and William C. Panarese
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On the cover: Some recent high-rise buildings incorporating high-strength concrete are shown in silhouetted elevation. See Fig. 2 for building names, locations, dates of completion, and strength of concrete used.

First Edition print history
First printing 1994

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Printed in the United States of America

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Library of Congress Cataloging-in-Publication Data
Farny, James A., 1962-
High-strength concrete / by James A. Farny and William C. Panarese.
Includes bibliographical references.
ISBN 0-89312-127-4
1. High-strength concrete. I. Panarese, William C.
II. Portland Cement Association. III. Title. IV. Series:
Engineering bulletin (Skokie, Ill.)
TA440.F35 1993
620.1'36—dc20 93-31936
CIP

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Caution: Contact with wet (unhardened) concrete, mortar, cement, or cement mixtures can cause SKIN IRRITATION, SEVERE CHEMICAL BURNS, or SERIOUS EYE DAMAGE. Wear waterproof gloves, a long-sleeved shirt, full-length trousers, and proper eye protection when working with these materials. If you have to stand in wet concrete, use waterproof boots that are high enough to keep concrete from flowing into them. Wash wet concrete, mortar, cement, or cement mixtures from your skin immediately after contact. Indirect contact through clothing can be as serious as direct contact, so promptly rinse out wet concrete, mortar, cement, or cement mixtures from clothing. Seek immediate medical attention if you have persistent or severe discomfort.
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Preface

The twentieth century has brought about many technological advancements in all areas of life, including construction. High-strength concrete (HSC) is the current state-of-the-art in concrete construction. HSC is a truly efficient building material continually being pushed to ever-greater strengths and newer uses by leading professionals. And it is poised for even further development in the 21st century and beyond.

High-strength concrete as we know it today in the ready mix and precast industries is the result of ongoing research and development to optimize concrete ingredients, proportioning, mixing, placing, and quality control methods. For commercially available HSC, materials technology has perhaps out-paced available engineering information; accordingly, this publication has been developed to provide the most current available engineering data to concrete producers, specifiers, designers, contractors, and other users of HSC.

*High-Strength Concrete* was originally published as IS176T in 1971 by the Portland Cement Association; at the time it was an authorized reprint of a five-part series of articles authored by Sidney Fremdman and published in the October 1970-February 1971 issues of *Modern Concrete* magazine. In 1971, high-strength concrete was in its infancy. IS176T stated: “The ultimate limit of concrete strength at 90 days seems to be about 20,000 psi [138 MPa]. The practical and economical strength limit of ready mixed concrete that may be approached in the future seems to be about 11,000 psi [76 MPa] for normal-weight-aggregate concrete and 8000 psi [55 MPa] for structural-lightweight-aggregate concrete.” Today these projections have been realized and greatly exceeded; IS176T has been discontinued, rewritten, updated, and expanded into this major new engineering bulletin, *High-Strength Concrete*, EB114T.

EB114T includes such new information as the types, dosages, and uses of chemical and mineral admixtures; sample material proportions for typical HSC mixtures; detailed discussions of compressive strength, ultimate strength, and in-place strength—including drilled cores; strength comparisons between cylinders of various dimensions; greatly expanded discussions of topics such as modulus of elasticity and durability; and methods of developing optimal mixture proportions with available materials, to name just a few of the new additions to *High-Strength Concrete*.

Text layout is similar to the original publication; that is, a chapter is devoted to each of the logical sequential steps followed when designing, testing, or otherwise using high-strength concrete: Chapter 1—Introduction; Chapter 2—Materials; Chapter 3—Proportioning; Chapter 4—Realization (mixing, placing, quality control, etc.); Chapter 5—Properties; Chapter 6—General (applications, advantages, limitations, etc.); and Chapter 7—References. To aid the reader in locating information, a table of contents is included.

Over 35 tables, figures, and photos help describe the history, development, properties, and various projects that have used high-strength concrete. Current and future applications of HSC are discussed. All numerical values in the text, tables, and figures are presented in both U.S. customary and SI metric units (see “Metric Conversion” on page 3).

Some notable individuals in the cement and concrete industry have provided valuable assistance in the writing and publishing of this text. A special thanks to Michael Pistilli, Technical Director, Quality Assurance, Prairie Group, Bridgeview, Illinois; Henry G. Russell, Vice President, Consulting Services, Construction Technology Laboratories, Inc., Skokie, Illinois; and Ron Burg, Director, Materials Technology, CTL. Mr. Russell also is presently the chairman of ACI Committee 363, High-Strength Concrete, and Mr. Burg is one of the authors of a recent joint industry study, *Engineering Properties of Commercially Available High-Strength Concretes*, which we have drawn from extensively in updating this publication. This acknowledgment does not necessarily imply approval of the text by these individuals since final editorial prerogatives have necessarily been exercised by the Portland Cement Association.

The authors have tried to make this text a concise and current treatise on the subject of high-strength concrete. As there is always room for improvement, readers are encouraged to submit comments which will be carefully considered for use in improving future printings and editions of this publication.
Fig. 1. At 969 ft (295 m) and 71 stories, Chicago’s 311 South Wacker Drive (right) was the tallest concrete building in the world when completed in 1989, utilizing concrete with compressive strengths of up to 12,000 psi (83 MPa). The black steel-framed structure (left) is Sears Tower, the world’s tallest building. Photo: George Lambros, courtesy of Kohn Pedersen Fox Associates PC.
CHAPTER 1

Introduction

Not until the 1900's did engineers and materials technologists become involved in optimizing the strength of concrete, though concrete has been used throughout history as a building material. With each successive development and corresponding strength increase, the definition of "high strength" was revised. Of course, there is no exact point of separation between "normal-strength" and "high-strength" concrete. According to the American Concrete Institute, high strength is defined as that over 6000 psi (41 MPa) compressive strength. This value was adopted by ACI in 1984, but is not yet hard and fast, because ACI recognizes that the definition of high-strength varies on a geographical basis. Prof. J. Francis Young of the University of Illinois at Champaign-Urbana has developed a strength classification system that, though not yet adopted by a recognized authority, is a helpful tool for describing high-strength concretes (see Table 1).

A versatile material, high-strength concrete (HSC) possesses desirable properties other than high strength. The most dramatic and memorable applications stem from this aspect, however, as high-rise buildings like 311 South Wacker Drive (see Fig. 1) create striking visual impressions. This structure, at 969 ft (295 m), was the world’s tallest concrete building when completed in 1989, utilizing concrete with strengths of up to 12,000 psi (83 MPa).

HSC is specified where reduced weight is important or where architectural considerations require smaller load-carrying elements. In high-rise buildings, HSC helps to achieve more efficient floor plans through smaller vertical members and has also often proven to be the most economical alternative by reducing both the total volume of concrete and the amount of steel required for a load-bearing member. Also, formwork is a large portion of the cost of constructing a column; smaller column sizes reduce the amount of formwork needed and result in further cost savings.

Structural lightweight concrete—not necessarily high-strength—is well-suited to many special applications. This material, typically at strengths around 3500 psi (24 MPa), has found extensive use for constructing the floors of high-rise buildings.

The two properties that best characterize high-strength lightweight concrete (HSLWC) are its high strength and relatively low density. Like HSC, its

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Table 1. Strength Classification of Concrete

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Conventional concrete</th>
<th>High-strength concrete</th>
<th>Very-high-strength concrete</th>
<th>Ultra-high-strength concrete</th>
</tr>
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<tbody>
<tr>
<td>Strength, MPa (psi)</td>
<td>&lt; 50 (7250)</td>
<td>50-100 (7250-14,500)</td>
<td>100-150 (14,500-21,750)</td>
<td>&gt; 150 (21,750)</td>
</tr>
<tr>
<td>Water-cement ratio</td>
<td>&gt; 0.45</td>
<td>0.45-0.30</td>
<td>0.30-0.25</td>
<td>&lt; 0.25</td>
</tr>
<tr>
<td>Chemical admixtures</td>
<td>Not necessary</td>
<td>WRA/HRWR*</td>
<td>HRWR*</td>
<td>HRWR*</td>
</tr>
<tr>
<td>Mineral admixtures</td>
<td>Not necessary</td>
<td>Fly ash</td>
<td>Silica fume**</td>
<td>Silica fume**</td>
</tr>
<tr>
<td>Permeability coefficient (cm/s)</td>
<td>&gt; 10^-10</td>
<td>10^-11</td>
<td>10^-12</td>
<td>&lt; 10^-13</td>
</tr>
<tr>
<td>Freeze-thaw protection</td>
<td>Needs air entrainment</td>
<td>Needs air entrainment</td>
<td>Needs air entrainment †</td>
<td>No freezable water †</td>
</tr>
</tbody>
</table>

* WRA = Water reducing admixture; HRWR = high-range water reducer.
** Also may contain fly ash.
† See "Porosity, Freeze-Thaw Durability, and Corrosion Resistance" in Chapter 5.
appeal stems from its ability to carry heavy loads with smaller size members. Unlike its normal-weight counterpart, HSLWC reduces dead weight loads even further because members are not only stronger, but also lighter, lowering foundation costs for a structure. One type of construction in particular that takes advantage of its strength, light weight, and durability characteristics is arctic offshore drilling platforms. The reduced density is also advantageous where thermal resistance is important in a load-bearing member.

Traditionally, compressive strength tests are made at 28 days, but many high-rise structures now requiring HSC employ a construction schedule whereby the structural elements in the lower floors are not fully loaded for periods of a year or more. Under these circumstances, it is reasonable to specify compressive strengths based on either 56- or 90-day results, thereby taking advantage of the strength gain that occurs after 28 days.

The upper limit of concrete strength at 90 days and beyond appears to be 25,000 to 30,000 psi (172 to 207 MPa)\(^{12}\) with some estimates for very special materials (see box on page 43) ranging as high as 106,000 psi (731 MPa).\(^{13}\) As 19,000-psi (131-MPa) concretes have already been batched,\(^{14}\) delivered by a few ready mix producers, and placed by contractors in some major structures (see Fig. 2), the idea of 25,000-psi concrete in the near future may be quite feasible with certain aggregates and other materials. Cement pastes have already been made and tested to failure at strengths of approximately 25,000 psi.

The number of precasters that routinely produce concrete with strengths above 6000 psi is rather limited. Under careful control and through the use of low water-cement ratios, water-reducing admixtures, and pozzolans, high-compressive-strength precast concrete products can be consistently produced with quality aggregates and cements. At precasting plants, low-slump concrete is consolidated in forms by prolonged vibration or shock methods. However, the more fragile forms used in cast-in-place construction do not permit the same compaction procedures, and more plastic and workable concretes are necessary to avoid segregation and honeycomb. Furthermore, special handling, placing, and quality control techniques may be necessary to ensure the achievement of high strength.

With new technology, a few ready mix producers, as already mentioned, are capable of producing 19,000-psi (131-MPa) concrete; but even without the

\[\text{Building Height, ft} \]

\[\text{Building Height, m} \]

12,000 psi (82.7 MPa)
12,000 psi (82.7)
12,000 psi (82.7)
12,000 psi (82.7)
12,500 psi (82.2)
14,000 psi (96.5)
17,000 psi (117.2)
19,000 psi (131.0)
19,000 psi (131.0)

- Reinforced concrete frame
- Composite concrete/steel frame
- Also includes one experimental column of 17,000 psi

**Fig. 2. High-strength concrete shapes new U.S. skylines.**
most recent developments, careful adherence to every aspect of good concrete practice can yield strengths of over 14,000 psi (96 MPa) at 56 days. To be successful, close cooperation is required from the project engineer, the ready mix producer, the contractor, and the testing agency.

A ready mix producer should not attempt to supply high-strength concrete without an extensive mixture development program. As higher strengths become more common, more is learned about the materials required for the production of HSC. The producer needs to know which factors affect compressive strength and how to vary those factors for the best results. Each variable should be analyzed separately in developing the mix proportions. As each material is chosen for its optimum performance, it should be incorporated into the mixture design as the remaining variables are studied. An optimum mixture is then developed for the materials on the basis of performance, cost, and quality control.

Quality control for high-strength concrete warrants additional attention. Many testing methods used for normal-strength concrete are not adequate for HSC. To truly complete the process of optimizing the mixture design, further research into proper testing is required.

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**METRIC CONVERSION**

In reporting data in this publication, U.S. customary units are usually presented first, followed by their derived SI metric equivalents in parentheses. An exact value for the metric counterpart is not given; instead, the closest value for the intended accuracy of measurement is provided. This holds true especially for strengths, as exact values are rarely given even when reporting the measurement in the units in which it was measured. For example, concrete with a measured compressive strength of 19,300 psi would often be referred to as "19,000"-psi concrete.

Throughout this publication, converting to metric equivalents is intended to be straightforward and not introduce a false level of accuracy. SI units are determined using "soft" conversion procedures. This is done by applying the appropriate conversion factor from ASTM E380 exactly, then rounding to the number of significant figures giving equivalent accuracy. For example, a stress of 19,300 psi is converted to SI units as follows:

\[(19,300 \text{ psi})(6.895 \times 10^6 \text{ Pa/psi}) = 133,073,500 \text{ Pa} = 133,074 \text{ MPa}\]

Rounding to three significant figures (since 19,300 contains three significant figures) leads to:

19,300 psi = 133 MPa

For research reports and technical documents reporting work conducted based on the metric system, SI units will be the primary system of measurement and U.S. customary units will be the secondary system of measurement.

For a more extensive discussion of conversion and rounding, attention is directed to Section 5 of ASTM E380-92, Standard Practice for Use of the International System of Units (SI).
CHAPTER 2
Materials

High-strength concrete is made with the same basic ingredients as normal-strength concrete. Its production is achieved by optimization of the following factors: (1) characteristics of the cementing medium, (2) characteristics of the aggregate, (3) proportions of the paste, (4) paste-aggregate interaction, (5) mixing, consolidating, and curing, and (6) testing procedures. Some “exotic” materials and/or methods are being explored through research, but attention to the six basic areas above is of extreme importance whether using existing or new materials and techniques.

Cement
A fundamental factor involved in producing HSC is the cement paste. Without a high-quality binder, the production of HSC is impossible. Selection of a portland cement for HSC should be based on comparative strength tests of concretes at 28 and 90 days. A cement that yields the highest compressive strength at the later age (90 days) is obviously preferable. Concrete samples for comparative strength testing (cement efficiency) should be as nearly identical as possible, so modifications should be made one at a time. Lowering the sand content is the preferred method of balancing increases in the cement content, leaving the rest of the mixture unchanged. Some of the more finely ground portland cements such as Type III (high-early-strength) will have higher mixing water requirements for equal workability, particularly at low water-cement ratios, and may promote rapid stiffening in hot weather. (Water-cement ratios typically are expressed as the total weight of water to the total weight of cement. Water-cementitious materials ratios are expressed as the total weight of water to the total combined weights of all cementitious materials. In both cases, the total weight of water excludes that absorbed by the aggregates, but includes any water introduced into the mixture as part of an admixture.) From the standpoint of development of ultimate concrete.

compressive strength, it appears that cements having a high (that is, greater than 50%) percentage of tricalcium silicate (C₃S) and a greater fineness will be the best indicators of optimum performance (see box on “Optimizing Cement”). The increased fineness appears to be advantageous if high early strengths are desired or if a long curing period cannot be provided. In actual practice, high fineness cements are not generally used.

OPTIMIZING CEMENT
Cement beneficiation—a control of fineness—improves the performance of a given amount of cement over both the short and long term.* In this process, finish grinding is used to limit the maximum particle size to 20 µm and reduce the number of particles smaller than 2 to 5 µm, thereby optimizing what is known as the particle size distribution or PSD. Cement PSD plays a role not only in the rate of strength development, but also in the ultimate strength of the concrete through a more rapid and complete hydration of the cement particles. At 28 days, beneficiation increased compressive strengths from 9% to 22% for samples tested according to ASTM C109. Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. or 50-mm Cube Specimens), and variations in clinker composition did not significantly alter these conclusions. Cement strength also can be improved significantly by matching optimum sulfate addition in PSD-controlled cement. This work underscores the importance of monitoring the grinding process to produce the highest quality cement possible from the raw materials, and to do it using the least amount of energy.

Cement manufacturers do not routinely produce PSD-controlled cements. If it appears that this type of cement would be beneficial on a certain project or in a particular area, the ready mix producer should work with the cement supplier to evaluate the feasibility of obtaining PSD-controlled cement.
Coarse Aggregate

Since aggregates comprise the largest fraction of the volume of concrete, the characteristics of the aggregate significantly influence the properties of the concrete, including strength.

The strength of concrete up to about 5000 psi (34 MPa) depends essentially on the quality of the hardened cement paste that binds the aggregate particles together. The aggregate at this strength level nearly always has a greater strength than the cement paste. In HSC, however, the strength of the cement paste is high enough to rival the strength and other vital properties of the aggregate. The strength of the aggregate, the bond or adhesion between the cement paste and aggregate, and the absorption characteristics of the aggregate all become more important in HSC than in normal-strength concrete because any one of these properties could be the limiting factor for ultimate strength.

The gradation of coarse aggregate of a given maximum size may vary over a relatively wide range within ASTM limits. If the gradation does vary, the strength of concrete will not be appreciably affected providing the proportion of fine aggregate produces concrete of good workability without requiring a corresponding increase in the water-cement ratio, especially in stiff dry mixes. Coarse aggregate gradation can exhibit curious behavior; a short discussion can be found in Chapter 3 under “Coarse Aggregate.”

There is practical value in determining the optimum size of coarse aggregate for different concrete strength levels. The optimum size depends on such factors as (1) relative strength of the cement paste, (2) cement-aggregate bond, and (3) strength of the aggregate particles. Standard tests are not readily available to measure these factors adequately. However, a trained petrographer can often provide insight on the potential of an aggregate to produce HSC. The chemical content of the aggregate—that is, the minerals present—does lend some insight into predicting the interaction between cement paste and aggregate particles. Still, trial batches provide the most practical information for choosing the best aggregate for a concrete mixture.

In normal-strength concrete, as coarse aggregate size is increased, mixing water requirement is reduced. The net effect is a lower water-cement ratio and higher strength. Water requirement is a function of the overall fineness of the solid ingredients. However, in HSC, the large sizes of coarse aggregate tend to reduce concrete strength, probably because of the smaller surface area available for bond and disruption of continuity in the concrete. In cement-rich, high-strength mixtures, the effect of size itself, that is, use of small aggregates—\( \frac{3}{4} \), \( \frac{1}{2} \), or \( \frac{3}{8} \) in. (19.0, 12.5, 9.5 mm)—usually is sufficient to offset the effects of the higher mixing water demand, and strength increases with decrease in aggregate size.\(^7\)

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**Fig. 3.** Effect of cement content on compressive strength at 28 days for various maximum sizes of aggregate in different types of concrete.\(^8\)
Fig. 4. Effect of size of coarse aggregate on compressive strength at 28 and 91 days in different types of concrete.\(^{(8)}\)

Therefore, the concrete producer should make trial batches using coarse aggregates meeting the requirements of ASTM C33, Specifications for Concrete Aggregates, for size numbers 57 (1 in. max.), 67 (3/4 in. max.), 7 (1/2 in. max.), and 8 (3/8 in. max.). Some ready mix producers have found that 1/2-in. maximum size coarse aggregate gives optimum strength.

Fig. 3 shows that a 4-in. (100-mm) slump concrete with a cement content exceeding about 600 lb per cu yd (360 kg/m\(^3\)) will produce higher compressive strength in different types of concrete with smaller-size aggregate. Fig. 4 shows the effect of maximum aggregate size on 28- and 91-day compressive strengths of different types of concrete with varying cement contents. Both figures also demonstrate that a water reducer-retarder admixture is beneficial to strength development.\(^{(8)}\)

In concretes of constant cement content and maximum aggregate size, variations in compressive strength are attributable mainly to differences in mixing water requirements among aggregate sources. Aggregate shape, surface texture, and deleterious coatings are apparently responsible for these variations in mixing water requirements of similarly-graded materials from different sources. As particle shape departs from a smooth, rounded configuration to one that is increasingly rough and angular, mixing water requirements in normal-strength concretes increase with a corresponding decrease in strength unless cement content is increased. On the other hand, cement-aggregate bond increases as aggregate particle shape changes from smooth and rounded to rough and angular, and this must be considered in selecting the aggregate for HSC. Again, trial mixtures will be the most accurate predictor of (best) performance.

Aggregate void content can be used as an index of differences in particle shape and texture of aggregates of the same grading. ASTM C29, Test Method for Unit Weight and Voids in Aggregate, is the method to follow when determining the void content of an aggregate sample.

Mixing water requirement tends to increase as aggregate void content increases because of changes in particle shape and texture. For example, for each 1% increase in coarse aggregate void content, the mixing water requirement of concrete increases about 1/2 gal per cubic yard (2.5 L/m\(^3\)). However, the shape and texture of fine aggregate particles rather than that of coarse aggregate has a much greater effect on water demand. Measurements of void content for fine and coarse aggregates from the same source...
show a similar trend. This similarity allows the concrete producer to use fine aggregate void content to predict mixing water demand and the resultant effect on the compressive strength of concretes made with aggregates from a given source.\(^9\)

In concretes of equal water-cement ratios, use of different types of aggregate will produce concretes of different strengths. The strength variations attributable to aggregate type apparently are due to variability in the degree of bond developed between the paste and aggregate and to variability in the strength of the aggregate particles themselves. The physical parameters affecting the bond of cement paste to aggregate include the roughness, porosity, and shape of the aggregate. Chemically, the mineralogy of an aggregate can also play an important role in the development of bond between paste and aggregate. Using four different types of coarse aggregates in a very-high-strength concrete mixture (water-cement ratio = 0.27\%), Albicin and Mehta found that compressive strength and elastic modulus of concrete were significantly influenced by the mineralogical characteristics of aggregates. Crushed aggregates from fine-grained diabase and limestone gave the best results. Concretes made from a smooth river gravel and from a crushed granite that contained inclusions of a soft mineral were found to be relatively weaker in both strength and elastic modulus.\(^10\)

In making trial mixtures, it is important to select relatively hard and strong coarse aggregates that do not break down and produce fines during mixing. Crushed rocks such as fine-grained traprock (basalt or diabase), limestone, or quartzite, usually are suitable. Strengths developed with these aggregates will be higher with higher specific gravity and moderate absorption (1.5\% to 2.5\%) of the particles. The ideal aggregate for HSC should be clean, cubical, angular, 100\% crushed, and with a minimum of flat and elongated particles.\(^11\) In concretes of low water-cement ratio, it is beneficial to have the coarse aggregate in a saturated surface dry condition; this will provide an additional source of curing water to the interior of the concrete.\(^12\)

Some natural gravel aggregates may not be as suitable for making HSC as crushed rock unless the gravel aggregates are unweathered (irregularly shaped) or crushed. In the case of aggregates manufactured by crushing, particles more nearly cubical in shape are generally preferred to elongated particles. Although there has been limited field experience with it, air-cooled slag also may be satisfactory.\(^13\) In addition, HSC has been made with heavyweight aggregates that produce high density for radiation shielding.\(^14\)

Structural lightweight aggregates produce wide variations in the properties of concrete even though they may be similar in appearance and produced by similar processes. One reason for the variability is the pronounced but not readily determinable absorption characteristics of these materials. The absorption differences may account for a large part of the strength variations attributed to the aggregate per se. Lightweight-aggregate concretes differ considerably in the amount of mixing water required to attain proper workability because of grading, shape, and surface texture of the aggregate used. Many lightweight aggregates have porous surfaces and absorb more water than normal-weight aggregates. If these aggregates are not prewetted, they will absorb water from the mixture and raise the amount of water required for proper workability. If this happens, additional amounts of cement will be required to maintain the water-cement ratio and provide adequate strength. This higher cost can be avoided simply by using proper material preparation, that is, prewetting.

Many of the structural lightweight aggregates can be used for high-strength concrete if the producer selects a maximum aggregate size of 1/2 in. (12.5 mm) or less. With a fixed cement content and slump, replacement of the lightweight fines with natural sand usually will increase the compressive strength with many lightweight aggregates, particularly those with an unfavorable particle shape in the lightweight fines. With a few aggregates, the use of natural sand has little or no effect on compressive strength but will improve other properties of the concrete. The natural sand will, of course, raise the unit weight of the concrete and decrease the advantages accruing to lower weight.

Lightweight aggregates used in concrete may be natural, but more often they are manufactured. One positive aspect of this fact—often overlooked—is that manufacturing introduces a level of control that does not exist with a natural material. A controlled material has properties that are well defined and fairly consistent.

**Fine Aggregate**

The shape and surface texture of fine aggregate has a greater influence on water demand of concrete than that of coarse aggregate because fine aggregates contain a much higher surface area for a given weight. For example, in sands of the same grading, a 1\% increase in fine aggregate voids may induce a 1-gal-per-cubic-yard (5-L/m\(^3\)) increase in water demand to maintain an equal slump. The bond of paste to fine aggregate is less significant than bond to coarse aggregate because of the large surface area available in the fine aggregate for bonding. Since the surface area of all aggregate particles must be coated with cement paste, maximizing the coarse-to-fine aggregate ratio (CA/FA) can result in the most efficient, and therefore economical, use of cementitious materials. The optimum ratio of CA/FA will probably be apparent from trial batches based on workability of the mixture. Rounded and smooth fine aggregate particles (natural sand) are better from the viewpoint of workability than sharp, rough particles (manufactured sand). Concrete mixtures of the same slump and cement factor and containing natural sand produce higher strengths than concretes containing manufactured sands as shown in Fig. 5.\(^15\)

The particle shape and grading of these materials are
probably responsible for the strength differences. On the other hand, because HSC relies on the use of water-reducing admixtures for placeability, even angular sands may be used to make HSC with excellent results.

The grading of fine aggregate within typical specification limits is not highly critical except that a slightly coarse sand probably would be more beneficial if available and not economically prohibitive. This is because the coarser fine aggregate particles have a lower water demand. If such sands are available, the preferable range of fineness modulus is 2.70 to 3.20 with a maximum of about 2% passing the No. 100 (150 μm), 0% to 10% passing the No. 50 (300 μm), and 35% to 45% passing the No. 30 (600 μm) sieves. These sands will also produce the most workable mixture for a given amount of water.

Washing the sand may be necessary. Natural sands containing large quantities of mica, clay, or other deleterious materials should be avoided as they may increase water demand and affect hydration and bond of cement paste to aggregate. Also important is uniformity of grading from batch to batch of both the fine and coarse aggregates because of its effect on workability.

**Mixing Water**

Use of cool mixing water at 40°F (4°C) instead of warm water at 70°F (21°C) will increase the slump of concrete about 1 to 2 in. (25 to 50 mm), which is desirable in terms of workability. If, in turn, the amount of mixing water is reduced to compensate for the increase in slump, the strength of the concrete will be increased. However, cool mixing water is seldom available and the problems associated with the use of ice are not worth the effort for the small, if any, increase in strength.

**Chemical Admixtures**

The benefits to be realized from use of admixtures in high-strength concrete have practically mandated their use. By the mid-1980's, it was estimated that 80% of all concrete produced in North America contained at least one type of admixture. A common practice is to use a high-range water-reducing admixture or "superplasticizer" in combination with a water-reducing retarder. The superplasticizer will reduce the amount of water required by 15% to 40%, but it often increases slump loss, making it difficult to place the concrete properly even though true setting time is extended slightly. The high rate of slump loss is overcome by the addition of the water-reducing retarder which extends the time of set and permits the placement of a very low water-cement ratio concrete.

Admixture dosages in high-strength mixtures generally exceed manufacturer’s recommendations, which pertain to conventional concrete. Systems of multiple admixtures are often required to achieve a mixture that is flowable and remains so during
Table 2. Typical Proportions in Commercially Available HSC Mixtures, USC (SI Metric Units)*

<table>
<thead>
<tr>
<th>Ingredient, units per cu yd (m³)</th>
<th>Mixture number</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Cement, Type I, lb (kg)</td>
<td>950 (564)</td>
</tr>
<tr>
<td>Silica fume, lb (kg)</td>
<td>—</td>
</tr>
<tr>
<td>Fly ash, lb (kg)</td>
<td>—</td>
</tr>
<tr>
<td>Coarse agg., SSD, lb (kg)**</td>
<td>1800 (1068)</td>
</tr>
<tr>
<td>Fine agg., SSD, lb (kg)</td>
<td>1090 (647)</td>
</tr>
<tr>
<td>HRWR, Type F, fl oz (litre)</td>
<td>300 (11.60)</td>
</tr>
<tr>
<td>HRWR, Type G, fl oz (litre)</td>
<td>—</td>
</tr>
<tr>
<td>Retarder, Type D, fl oz (litre)</td>
<td>29 (1.12)</td>
</tr>
<tr>
<td>Total water, lb (kg) †</td>
<td>267 (158)</td>
</tr>
<tr>
<td>Water-cement ratio</td>
<td>0.281</td>
</tr>
<tr>
<td>Water-cementitious materials ratio</td>
<td>0.281</td>
</tr>
</tbody>
</table>

*Source: Reference 17.
**Maximum nominal aggregate size: Mixtures 1-5, 1/2-in.; Mixture 6, 1-in.
†Weight of total water in mix including water in admixtures.

transport and placing. See Table 2 for typical admixture dosages in commercially available HSC mixtures. Extending the setting time with a combination of admixtures can necessitate leaving test cylinders undisturbed for 48 hours to avoid damage that may occur by moving them too soon.

Usually, the main components of water reducers or retarders are water soluble organic compounds which can be divided into four groups: (1) salts of lignosulfonic acid, (2) hydroxyacetic acids, (3) carbohydrates, and (4) other compounds, either organic or inorganic. Lignosulfonate-based compounds are the most commonly used water-reducing admixtures. Water-reducing admixtures and retarding admixtures are often treated as one category because the main components used for retarders are also present in water-reducing and retarding admixtures. As a result, many retarders reduce mixing water and many water reducers retard the setting time of concrete. The reason behind the reduced water requirement or retarded set is that these admixtures slow down the rate of hydration of the cement during the first few hours.

Superplasticizers (high-range water reducers) are also broken down into four main groups: (1)sulfonated melamine formaldehyde condensate, (2) sulfonated naphthalene formaldehyde condensate, (3) modified lignosulfonates, and (4) others including sulfonic esters and carbohydrate esters. SMF- and SNF-based admixtures are the more commonly used, so most of the information available refers to these compounds. They work by helping to disperse particles of cement when mixing water is added, which causes the cement paste to behave more like a fluid. This deflocculation of cement particles plastiizes the paste to such a degree that these compounds have been dubbed “superplasticizers”.

Some cast-in-place, high-strength concrete is used for applications that do not require air entrainment as, for example, interior columns and shear walls of high-rise buildings. Since air will reduce the compressive strength, no air-entraining agent should be used in these concretes. Water-reducing admixtures, especially those based on lignosulfonates, will generally entrain a certain amount of air in concrete, usually in the 1%-3%-range. To counteract this unwanted secondary effect, manufacturers of lignosulfonate-based water reducers will often add a defoaming agent to reduce air entrainment. However, if high-strength concrete is to be used under saturated freezing-and-thawing conditions, especially when deicers are used (for example, parking decks), air-entrained concrete must be used despite a potential strength loss of 3% for each 1% of entrained air. (While this strength reduction has been observed in conventionally-prepared concretes, some experimental work indicates that it may not be the total amount of entrained air, but rather the distribution and pore size of the air voids that lowers the strength of the concrete, especially in flexure and tension. See Chapter 3, “Pastes,” and Chapter 6, “Special Materials,” for more information on entrained air and MDF products.) If used, the amount of entrained air should be within the recommended range for normal-strength concrete for the particular aggregate size and exposure condition (more information on the durability of air-entrained HSC appears in Chapter 5, “Porosity, Freeze-Thaw Durability, and Corrosion Resistance”).

Chemical admixtures for concrete, including high-strength concrete, should meet the requirements of ASTM C494, Specifications for Chemical Admixtures.
for Concrete. Trial mixtures should be made with the admixture and job materials at temperatures and humidities anticipated on the job. This permits an evaluation of the compatibility of an admixture with other admixtures and job materials as well as an evaluation of the effects of the admixture on the properties of the fresh and hardened concrete. The amount of admixture recommended by the manufacturer or the optimum amount determined by laboratory trial batches should be used.

Mineral Admixtures

Finely divided mineral admixtures are powdered or pulverized materials added to concrete before or during mixing to improve or change some of the plastic or hardened properties of portland cement concrete. These admixtures are generally natural or byproduct materials. Based on their chemical or physical properties, they are classified as (1) cementitious materials, (2) pozzolans, (3) pozzolanic and cementitious materials, and (4) nominally inert materials.

Of these four categories of mineral admixtures, pozzolans are presently the most important to the production of high-strength concrete. The two pozzolans most commonly used in HSC are fly ash and silica fume; but ground granulated blast-furnace slag also is used, especially in Canada. Pozzolanic and cementitious materials are used more for energy conservation and to help lower the cost of concrete. The inert materials do not impart additional strength to concrete, but are used to improve workability or reduce alkali-aggregate reactions.

Cementitious materials are substances that alone have hydraulic cementing properties (set and harden in the presence of water). They include ground granulated blast-furnace slag, natural cement, hydraulic hydrated lime, and combinations of these and other materials. Ground slag made from iron blast-furnace slag is a nonmetallic product consisting essentially of silicates and aluminosilicates of calcium. Ground slag in the presence of water and an activator, NaOH or CaOH, both supplied by portland cement, hydrates and sets in a manner similar to portland cement. Ground slag for use in concrete should conform to ASTM C989, Specification for Ground Granulated Blast-Furnace Slag for Use in Concrete and Mortars.

A pozzolan is a finely divided mineral admixture that by itself possesses little or no cementitious value. Pozzolanic action is a secondary effect; as cement hydrates, it releases calcium hydroxide which will react with water and pozzolans to produce compounds possessing cementitious properties. At this point in its development, HSC typically has one or more cementitious materials or pozzolans added to it to improve its strength (see Table 1). Fly ash added alone to concrete mixtures can help achieve strengths up to about 12,000 to 15,000 psi (83 to 100 MPa). Beyond this point, usually both fly ash and silica fume or slag and silica fume are used to produce HSC. These materials are added as admixtures, that is as additions to concrete, rather than partial replacements for portland cement.

Fly ash is produced as a byproduct of the combustion of pulverized coal in electric power generating plants. Mineral impurities in the coal fuse during combustion and are carried away from the combustion chamber by exhaust gases. Due to the wide range of composition of coals, the properties of fly ash can vary greatly, so acceptance and uniformity tests should be made according to ASTM C618, Specification for Fly Ash and Raw or Calcined Natural Pozzolan for Use as a Mineral Admixture in Portland Cement Concrete.

Silica fume (see box) is a by-product resulting from the reduction of high-purity quartz with coal in electric arc furnaces in the manufacture of silicon and ferrosilicon alloys. It should conform to ASTM C1240, Specification for Silica Fume for Use in Hydraulic-Cement Concrete and Mortar. Like fly ash, silica fume is an airborne material and has a spherical shape. But unlike fly ash, silica fume is extremely fine—most particles are less than 1 μm in diameter, and the average particle diameter is about 0.1 μm—with a surface area of about 20,000 m²/kg. For comparison, fly ash typically ranges from 300 to 500 m²/kg, ground slag from about 400 to 600 m²/kg, Type I cement from 300 to 400 m²/kg, and tobacco smoke’s surface area is about 10,000 m²/kg. Many high-strength concretes contain silica fume; very- and ultra-high-strength concretes almost always contain it. Silica fume improves concrete strength through physical and chemical modifications of the binding paste. The variation in the way these admixtures are used to improve the strength of concrete can be readily correlated to their physical differences.

### SILICA FUME IN CONCRETE

Silica fume has played an important role in the development of high-strength concrete. It has helped bring about strength increases unknown only a short time ago. In the early 1980’s, very little published information existed on the use of silica fume in concrete. In the early 1990’s, more is known about silica fume and its use in concrete, but much still remains to be learned.

Silica fume is presently available in various forms—bulk, densified, slurry, and blended with portland cement. As might be expected with a newer material, there is disagreement as to exactly which form presents the best combination of ease of handling and optimal performance in concrete. Each form has its own advantages and disadvantages.

Generally, the addition of silica fume increases the cohesiveness, viscosity, and water demand of fresh concrete. More air-entraining agent is required to achieve the same level of air entrainment. Bleeding is reduced, allowing quicker finishing and less chance of porous transition zones between paste and aggregate. However, increased strength remains the main reason for using silica fume in most HSC applications, although other benefits are obtained simultaneously.
Table 3. Typical High-Performance Concrete Compositions, SI Metric Units (U.S. Customary Units)*

<table>
<thead>
<tr>
<th>Concrete composition</th>
<th>HPC projects (see box)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Water-cementitious materials ratio **</td>
<td>0.35</td>
</tr>
<tr>
<td>Water, kg/m³ (lb/yd³)</td>
<td>195 (329)</td>
</tr>
<tr>
<td>Cement, kg/m³ (lb/yd³)</td>
<td>505 (851)</td>
</tr>
<tr>
<td>Silica fume, kg/m³ (lb/yd³)</td>
<td>—</td>
</tr>
<tr>
<td>Fly ash, kg/m³ (lb/yd³)</td>
<td>60 (101)</td>
</tr>
<tr>
<td>Slag, kg/m³ (lb/yd³)</td>
<td>—</td>
</tr>
<tr>
<td>Coarse aggregate, kg/m³ (lb/yd³)</td>
<td>1030 (1736)</td>
</tr>
<tr>
<td>Fine aggregate, kg/m³ (lb/yd³)</td>
<td>630 (1062)</td>
</tr>
<tr>
<td>Water reducer, mL/m³ (oz/yd³)</td>
<td>975 (25)</td>
</tr>
<tr>
<td>Retarder, L/m³ (oz/yd³)</td>
<td>—</td>
</tr>
<tr>
<td>Superplastizer, L/m³ (oz/yd³)</td>
<td>—</td>
</tr>
<tr>
<td>( f'_c ) at 28 days, MPa (psi)</td>
<td>64.8 (9,400)</td>
</tr>
<tr>
<td>( f'_c ) at 91 days, MPa (psi)</td>
<td>78.6 (11,400)</td>
</tr>
</tbody>
</table>

*Source: References 20 and 21.
**Weight of superplastizer should be added to the weight of water to obtain w/cm ratio; see Chapter 2, "Cement", for further discussion.

Typical HPC mixtures incorporating pozzolans (and one with no pozzolans) produced in the United States, Canada, and France are shown in Table 3. These examples demonstrate that there is no single recipe for making high-strength concrete, and a wide range of materials can be used.

EXAMPLES OF HIGH-PERFORMANCE CONCRETE

Five examples are listed below to illustrate various HPC projects. Table 3 provides data on the composition of concretes used on these projects:

1. Water Tower Place (Chicago, 1975): an example of high-strength achievement prior to the use of superplasticizers.
2. Joigny Bridge (France, 1989): was constructed using HPC without silica fume; this was done to demonstrate that HPC can be produced and used in construction even when silica fume is not economically available.
3. La Laurentienne Building (Montreal, 1984): two experimental columns illustrate how the combined use of a superplasticizer and retarding agent was necessary due to cement availability and long delivery time.
4. Scotia Plaza (Toronto, 1987): an example of HPC containing ground granulated blast-furnace slag and silica fume as partial cement replacements.
5. Two Union Square (Seattle, 1988): HPC unrivaled for its performance at a major construction site.

These examples illustrate there is no single recipe for making HPC. Concrete composition can usually be adapted to local conditions if the best available materials are selected. Success ultimately depends, to a large degree, on lowering the water-cementitious materials ratio while making a concrete that offers the best combination of performance, ease of placement, and optimum cost-to-benefit ratio.
CHAPTER 3
Proportioning

High-strength or high-performance concrete contains the same basic ingredients as normal-strength concrete—namely, cement, aggregates, and water. However, in HSC (1) entrained or entrapped air is generally reduced or removed, (2) the addition of normal and high-range water-reducing admixtures becomes almost mandatory to ensure workable mixtures at very low water-cement ratios, and (3) pozzolans are used to help improve the paste by a combination of physical and chemical processes. Table 1 concisely summarizes the major differences in mixture proportions and ingredients corresponding to normal-strength concrete and three high-strength categories. As the sole mineral admixture, fly ash can increase strengths up to about 12,000 to 15,000 psi (83 to 100 MPa), but to exceed this value, silica fume becomes necessary to achieve a cement paste that is as uniform and dense as practical. In some literature, this is referred to as a “DSP” material or a “densified system containing homogeneously arranged ultrafine particles”. H. Bache, Z. Fordo, L. Hjorth, and others at Denmark’s Aalborg Portland originated the basic system underlying development of DSP products that focuses on a highly-modified cement paste. The paste incorporates (1) a large dosage of silica fume of a size range two orders of magnitude smaller than that of the portland cement used, (2) an effective superplasticizer provided in a dosage large enough to ensure physiochemical defloculation of both the portland cement and the silica fume, and (3) effective mixing and mechanical processing to produce a completely consolidated paste with a minimum water content. The basic idea is only a minimum amount of space exists between cement grains in fresh paste, and this space is filled in by the much finer silica fume particles. In this way, high strength is derived from the usual chemical bonds created by the cement hydrates, while pozzolans combine with free lime in the paste to create more silicate hydrate gel, thus forming an exceptionally dense and uniform paste.

It was noted earlier that HSC can be made from a wide range of materials, and in varying proportions. This flexibility in mixture design allows for the most efficient and economical use of available materials. At concrete strengths under about 12,000 to 15,000 psi (83 to 100 MPa), silica fume and ground granulated blast-furnace slag are not generally used. For concrete with strengths between 6000 and 12,000 psi, ACI 211.4R, Guide for Selecting Proportions for High-Strength Concrete with Portland Cement and Fly Ash, should be consulted. For mixtures incorporating additional mineral admixtures, ACI suggests consulting the admixture and ready mix suppliers as the best source of proportioning information for these materials.

High-strength lightweight concrete (HSLWC) is a special form of HSC. The lighter unit weight of this material is achieved by using lightweight aggregates. Both the fine and coarse aggregate can be lightweight, but overall results are optimized by combining lightweight coarse aggregate with natural sand or a combination of natural sand and lightweight fine aggregate.

According to ACI 213R, Guide for Structural Lightweight Aggregate Concrete, structural concrete made with lightweight aggregate has an air-dried unit weight at 28 days of 90 to 115 lb per cubic foot (1440 to 1840 kg/m³) and a compressive strength of greater than 2500 psi (17.2 MPa). Like HSC, specifications for HSLWC include minimum values for compressive strength, maximum values for water-cement ratio, and a range of limits for air content. Slump is not used as much as a control for HSC for two reasons: First, slump is obtained with HRWR and not extra water. The water-cement ratio then takes on increased importance as a quality control measure and its maximum value should be strictly enforced. Second, slump does not have much meaning for flowing concrete, and most HSC and HSLWC is flowing. Finally, a maximum value for dry unit weight is always specified, the more common values...
being between 100 and 110 lb per cubic foot (1600 and 1760 kg/m³). HSLWC follows the same ACI classification as HSC: Compressive strength is 6000 psi (41 MPa) and above, and it is typically specified at 56 or 90 days.

**Paste**

As mentioned previously, an important factor in making HSC is the cement paste, and the amount of paste required is largely dependent on the type and grading of aggregate. Certainly the aggregate’s mineralogy, texture, and other properties influence the properties of the concrete. However, inasmuch as it is possible to separate the importance of one ingredient from another in a nonhomogeneous system like concrete, it is the paste—its uniformity and density—that holds the most promise for future developments in terms of greatly improving not only compressive strength, but other properties as well, especially flexural and tensile strengths.

The highest strength concretes are made with normal-weight aggregates, but lightweight aggregates are also capable of producing concretes with elevated compressive strengths. The fact that high-strength concrete can be made with lightweight aggregate offers proof that high-quality paste really is an important factor in the production of HSC.

The mixture should have a cementitious materials content of between 600 and 1000 lb per cubic yard (360 to 600 kg/m³), with the exact amount depending on the desired strength. For any given set of materials, mixing, and delivery conditions, there is a maximum strength that may not be increased by simply adding more cement. Higher cement efficiencies are obtained at high-strength levels with smaller maximum aggregate sizes. The unit strength in psi (MPa) obtained for each pound (kg) of cement used in a cubic yard (m³) of concrete can be plotted to form a strength efficiency envelope (Fig. 6). The figure shows that aggregates with smaller maximum size provide the most efficient use of cement in high-strength concretes. For example, for given materials, a maximum aggregate size of 7/8 in. (12.5 mm) produces the highest cement efficiency for a 6000-psi (41-MPa) mixture; for a 7000-psi (48-MPa) mixture, a maximum size aggregate close to 3/8 in. (9.5 mm) gives the best cement efficiency.

In developing proportions for HSC, comparisons should be made between mixtures having equal slumps. ACI 211.4R 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 to 100 mm) for HSC made without HRWR. Many HSC mixtures are proportioned to achieve a flowing condition—slumps in excess of 7 1/2 in. (190 mm)—by the addition of HRWR in excess of the manufacturer’s recommended dosage. Flowing concrete is acceptable for HSC as long as there is no tendency for segregation.

Very low water-cement ratios are necessary to ensure the paste is as dense as possible: So low are the ratios that, in fact, some of the cement will never hydrate (but this is also true in more conventional concretes). Currently, the lowest optimal water-cement ratio appears to be close to 0.22. This small amount of water will combine chemically with the cement grains resulting in a paste of very low porosity.

One concept used to explain cement strength behavior is the gel-space ratio. It is defined as “the ratio of the volume of hydrated cement paste to the sum of the volumes of the hydrated cement and the capillary pores.” It was noted earlier in Chapter 2 that a reduction in strength of about 5% occurs for each 1% of entrained air added to the mix. From research on high-performance concretes, though, it appears it is not so much the amount of air, but the distribution and size of the capillary pores which limit strength. Griffith theory examines the tensile and flexural strengths of brittle materials and relates them to measurable physical characteristics and material constants. The important conclusion based on this research states that the stress required to induce tensile cracking is inversely related to the square root of the critical crack length (which may be a pore). In other words, if pore size can be controlled (and limited to a desired maximum), the tensile
Coarse Aggregate

Although fine aggregate has a greater influence on the amount of paste, and therefore the amount of mixing water required for a given mix, coarse aggregate will occupy the largest volume of any single ingredient in a concrete mixture. The amount of coarse aggregate in a mixture is also directly dependent on the amount of fine aggregate, especially where workability is concerned. Careful selection of the coarse aggregate, then, is a critical step in producing the most efficient mixture, and one with the best properties in both the fresh and hardened concrete.

Concrete should be proportioned with enough paste not only to coat all the aggregate particles, but also to fill all the voids between particles. Because HSC requires such a rich mixture, it is advantageous to use the least amount of cement paste possible to coat particles and fill voids. In the aggregate proportioning process, the principles of minimum voids and minimum surface area come into conflict with one another. Continuously-graded mixes offer the least voids but a larger surface area. Gap-graded mixes offer less surface area but more voids. Is less paste needed for filling voids or coating the surface area? Research to answer this question is attributed to D.O. Ehrenburg. Basically, Ehrenburg’s idea is to use gap-graded coarse aggregate to maximize the number of particles of maximum size that will fill a given volume, and then maximize the number of (gap-graded) particles that will fit between these particles, thereby minimizing void space and surface area of particles at the same time. This approach tends to minimize particle interference, which is especially beneficial for workability of very low water-cement ratio mixes necessary to produce high-strength concrete. The amount of cement paste required will then also have been efficiently minimized on the basis of both minimum surface area and minimum void space. Even though continuously-graded aggregates appear to work best in normal-strength concrete, gap-graded mixes may offer advantages in HSC.

Lightweight aggregate for structural concrete is manufactured from various materials by a number of methods; it is most often expanded shale, clay, slate, slag, or pelletized fly ash. By definition, none of these aggregates are dense. In addition, most of them are porous. It is difficult to determine the amount of mixing water absorbed by the aggregate and that which contributes to water-cement ratio (but it can be done). For this reason, water-cement ratio is not regularly used as a means of proportioning structural lightweight concretes. Instead, the mixture is designed for a certain aggregate and the physical characteristics assessed on the basis of cement content at a given slump.

Fine Aggregate

Because it has a much larger surface area than coarse aggregate for a given weight, the fine aggregate (sand) can influence the amount of mixing water required and affect the properties of fresh and hardened paste more than the coarse aggregate. Since all aggregate in concrete must be coated with paste, the shape and grading of fine aggregate as well as its proportion to coarse aggregate will have a direct impact on paste requirements. More cement paste is required when more fine aggregate is used, and this results in a costlier mixture. The less sand used, however, the harsher the mixture and workability may be seriously impaired. A balance must be struck in proportioning high-strength mixtures. In general, using the least sand consistent with necessary workability has given the best strength for a given paste.

Chemical Admixtures

The manufacturers of water-reducing admixtures usually recommend dosages required to produce
specific results. For water reducers or retarders, typical suggested dosages are in the range of 200 to 400 mL per 100 kg of cement (about 3 to 6 fl oz per 100 lb of cement). The dosage can be varied to obtain the desired concrete properties under particular job conditions. Caution and control are the watchwords when exceeding the manufacturer’s recommended dosage. Serious retardation of the setting time of concrete has been caused by excessive amounts of water-reducing admixtures. Furthermore, an overdose almost always reduces the early strength of concrete, while later strength may or may not be significantly reduced (see Fig. 8). The type admixture is also important with respect to overdosing.

For superplasticizers (high-range water reducers), the recommended dosage is usually much higher than that for normal water-reducing admixtures. Very often, the dosage is measured as a percentage by weight of the cement in a mixture. This range is typically between 0.5% and 1.0%. A commonly used dosage for liquid superplasticizers is 5 to 20 mL per kg of cement, or about 8 to 40 oz per 100 lb of cement. Table 2 shows HRWR dosages for some commercially available high-strength ready mix concretes. Although it is not very common to use multiple HRWR admixtures, mix Number 6 in Table 2 incorporates two of them, illustrating how versatile a process mix design really can be.

The effectiveness of a water reducer can vary significantly in terms of both water reduction and degree of retardation. Changes in concrete temperature, increases in cement fineness, and changes in aluminated content (C₃A), soluble alcalies, and free lime (CaO) in the cement will all influence water reduction and degree of retardation. The admixture must be compatible with the cement. The most important cement properties that relate to admixture incompatibility are the type and amount of calcium sulfate (gypsum) additive and the amount of soluble alcalies. Composition of the cement, composition and rate of use of the admixture, and temperatures of the concrete and surrounding air will all affect the rate of slump loss. Corrective measures include additional mixing to remove false set, or a change in the source, dosage, or time of addition of the admixture.

Water-reducing admixtures (WRA), usually available in liquid form, are added to the concrete with a portion of the mixing water. Additions of normal WRA have their greatest impact if added just at the end of mixing time of aggregates, cement, and total water. However, in order to assure uniform dispersion throughout the mixture under the constraints imposed by continuous batching, the most efficient practical usage of WRA involves incorporating them into the mixture just after 15 to 30 seconds of mixing the cement, aggregates, and one-half the water.

**Fig. 8.** Effect of quantity of two types of water-reducing admixture on compressive strength of concrete.
Table 4. Comparative Performances of a Normal (ASTM C494 Type A) Commercial Water Reducer Using Different Addition Procedures*

<table>
<thead>
<tr>
<th>Procedure for addition of water reducer</th>
<th>Plain mix</th>
<th>Immediate addition with total gauging water</th>
<th>Delayed addition at end of mixing period</th>
<th>Delayed addition with part of gauging water after initial mixing period of 30 sec.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent of water reducer by weight of cement</td>
<td>—</td>
<td>0.25</td>
<td>0.25</td>
<td>0.25</td>
</tr>
<tr>
<td>Water-cement ratio</td>
<td>0.60</td>
<td>0.56</td>
<td>0.53</td>
<td>0.54</td>
</tr>
<tr>
<td>Setting times (hr:min)**</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Initial</td>
<td>2:20</td>
<td>2:50</td>
<td>3:30</td>
<td>3:05</td>
</tr>
<tr>
<td>Final</td>
<td>6:45</td>
<td>7:05</td>
<td>8:10</td>
<td>7:30</td>
</tr>
<tr>
<td>Compressive strength, MPa (psi)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1 day</td>
<td>4.1 (595)</td>
<td>6.2 (900)</td>
<td>6.0 (870)</td>
<td>5.4 (765)</td>
</tr>
<tr>
<td>3 days</td>
<td>9.7 (1405)</td>
<td>17.1 (2480)</td>
<td>17.4 (2525)</td>
<td>17.4 (2525)</td>
</tr>
<tr>
<td>7 days</td>
<td>20.2 (2930)</td>
<td>28.6 (4145)</td>
<td>29.7 (4305)</td>
<td>29.2 (4235)</td>
</tr>
<tr>
<td>28 days</td>
<td>35.1 (5090)</td>
<td>39.7 (5855)</td>
<td>42.3 (6135)</td>
<td>41.0 (5945)</td>
</tr>
</tbody>
</table>


**Mortar has been screened from concrete mix with No. 4 sieve.

The many benefits realized over the plain mixture include results that are more consistent, a lengthening of the setting time, and a higher water reduction with a corresponding increase in compressive strength (see Table 4).\(^{29}\)\(^{29}\) Adding WRA in this way also increases the tendency to entrain more air, but in most cases this amount is not excessive and should pose no problems.

Superplasticizers are deflocculating agents and will have their greatest impact on cement particles if introduced into the mixture a few minutes after all other ingredients have been thoroughly mixed (no more than 5 minutes later).\(^{29}\)\(^{29}\) The effect of delayed addition of a superplasticizer can be seen in Fig. 9.\(^{29}\)\(^{29}\) With high-range water reducers as with normal water-reducing admixtures, it may be that the best practical efficiency—uniform dispersion and mixing time—is achieved by adding them with the last portion of the mixing water when mixing is almost complete.

**Mineral Admixtures**

While finely divided mineral admixtures have various effects on the properties of fresh concrete, their addition to the mix can be beneficial to the ultimate strength and durability of the concrete. Fly ash may cause a slight reduction in the water demand of the mixture. This can be explained by the fact that fly ash particles are rounded and smooth and help to lubricate the mix. In HSC mixtures available at ready mix plants, fly ash often accounts for 10% to 30% by weight of the cement.

Silica fume admixture has a much higher degree of fineness than cement—surface area of 20,000 m²/kg compared to 400 m²/kg. This probably accounts for

Fig. 9. Effect of delayed addition of superplasticizer on slump of concrete.\(^{29}\)© 1980, Noyes Publications, with permission.
Table 5. Composition of Experimental Concretes Produced in a Ready Mix Plant, SI Metric Units (U.S. Customary Units)*

<table>
<thead>
<tr>
<th>Concrete composition</th>
<th>Reference</th>
<th>Silica fume</th>
<th>Fly ash</th>
<th>Slag + silica fume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water-cementitious materials ratio **</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
<td>0.30</td>
</tr>
<tr>
<td>Water, kg/m³ (lb/yd³)</td>
<td>127 (214)</td>
<td>128 (216)</td>
<td>129 (217)</td>
<td>131 (221)</td>
</tr>
<tr>
<td>ASTM Type II cement, kg/m³ (lb/yd³)</td>
<td>450 (758)</td>
<td>425 (716)</td>
<td>365 (615)</td>
<td>228 (384)</td>
</tr>
<tr>
<td>Silica fume, kg/m³ (lb/yd³)</td>
<td>—</td>
<td>45 (76)</td>
<td>—</td>
<td>45 (76)</td>
</tr>
<tr>
<td>Fly ash, kg/m³ (lb/yd³)</td>
<td>—</td>
<td>—</td>
<td>95 (160)</td>
<td>—</td>
</tr>
<tr>
<td>Slag, kg/m³ (lb/yd³)</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>183 (308)</td>
</tr>
<tr>
<td>Dolomitic limestone coarse aggregate, kg/m³ (lb/yd³)</td>
<td>1100 (1854)</td>
<td>1110 (1871)</td>
<td>1115 (1879)</td>
<td>1110 (1871)</td>
</tr>
<tr>
<td>Fine aggregate, kg/m³ (lb/yd³)</td>
<td>815 (1374)</td>
<td>810 (1365)</td>
<td>810 (1365)</td>
<td>800 (1348)</td>
</tr>
<tr>
<td>Superplasticizer, L/m² (oz/yd²) †</td>
<td>15.3 (396)</td>
<td>14 (362)</td>
<td>13 (336)</td>
<td>12 (310)</td>
</tr>
<tr>
<td>Slump after 45 minutes, mm (in.)</td>
<td>110 (4.3)</td>
<td>180 (7.1)</td>
<td>170 (6.7)</td>
<td>220 (8.7)</td>
</tr>
<tr>
<td>$f'_{c}$ at 28 days, MPa (psi)</td>
<td>99.3 (14,400)</td>
<td>110.2 (16,000)</td>
<td>90.0 (13,100)</td>
<td>105.1 (15,200)</td>
</tr>
<tr>
<td>$f'_{c}$ at 91 days, MPa (psi)</td>
<td>108.6 (15,800)</td>
<td>117.6 (17,100)</td>
<td>111.3 (16,100)</td>
<td>121.3 (17,600)</td>
</tr>
<tr>
<td>$f'_{c}$ at 1 year, MPa (psi)</td>
<td>119.4 (17,300)</td>
<td>126.8 (18,400)</td>
<td>125.1 (18,100)</td>
<td>126.5 (18,300)</td>
</tr>
</tbody>
</table>

* Source: References 20 and 21.
** Weight of superplasticizer should be added to the weight of water to obtain w/cm ratio; see Chapter 2, "Cement," for further discussion.
† Sodium salt of naphthalene sulfonate.

the complicated behavior observed between amount of silica fume used and water demand of a concrete mixture. Except for specific conditions, silica fume dramatically increases the water demand of a mixture. However, for high-cement content mixes having water-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. For those particular conditions, the admixture helps to disperse the cement grains. As collected" powdered silica fume gives slightly better results than densified silica fume in reducing the amount of superplasticizer needed for equal workability. Silica fume is usually added to a high-strength mixture as an addition to, rather than as a partial replacement for, the cement and accounts for about 8% to 16% of the weight of portland cement in commercially available mixtures. Without the addition of retarding and superplasticizing admixtures, HSC containing silica fume would be difficult, if not impossible, to place.

It is possible, within reason, to replace a portion of the cement in high-performance concrete by less costly cementitious materials—such as certain fly ashes and ground granulated blast-furnace slags—to provide the same dense matrix, but with lower chemical reactivity. In addition to usually costing less than portland cement, these replacements nearly always allow a significant reduction in superplastici-
CHAPTER 4

Realization

As any chain is only as strong as its weakest link, high-strength concrete can only be achieved if all steps in its production are given due consideration. This begins with the choice of good materials and proper proportioning as already discussed, and continues with careful mixing, placing, curing, testing, and quality control.

Mixing

Concrete can be mixed by any of the following methods: (1) Central-mixed concrete is mixed completely in a stationary mixer and is delivered either in a truck agitator, a truck mixer operating at agitating speed, or a special nonagitating truck; (2) Shrink-mixed concrete is mixed partially in a stationary mixer and completed in a truck mixer; and (3) Truck-mixed concrete is mixed completely in a truck mixer.

Most of the high-strength ready mixed concrete presently delivered is produced in central-mix operations; not only is this more efficient, but the greater control provided means more consistent results. Shrink mixing is another common way to produce HSC for strengths up to about 13,000 psi (90 MPa). Central mixing provides more control than shrink mixing and should be used whenever possible to increase consistency, especially at strengths over about 13,000 psi. Whatever mixing method or combination of methods is chosen—central-mixed, shrink-mixed, or truck-mixed—the ability to control the producing operation depends greatly on the personnel involved.

Tests to determine the most effective procedure for charging and mixing should be made for all mixtures. Ribbon loading of materials helps to produce uniformly mixed batches of concrete, but other procedures may work equally well. Under usual conditions, up to about 10% of the mixing water is placed in the drum before the solid materials are added. Water is then added uniformly with the solid materials, leaving about 10% to be added after all other materials are in the drum. The materials should be added simultaneously at such rates that the charging time is about the same. If a water reducer is used, it should always be added at the same time in the charging cycle for consistency, preferably as late as possible to increase its effectiveness but not so late that uniform dispersion will be sacrificed.

For truck mixing (also known as dry batching), up to about 85% of the water is added first with 50% of the aggregate and all of the silica fume (when in slurry form or densified). Water should not be added while charging cement and fly ash because this can produce balling.

With some drum mixers, a very dry mix may require the addition of some water and the coarse aggregate first. Otherwise, the coarse aggregate surface does not become sufficiently wetted and, as already mentioned, this is extremely important in the interior of the concrete to assure proper hydration and development of strength during curing. With turbine mixers, all materials can be fed simultaneously but not so fast as to overload the mixer motor. The mixer should be running while feeding the materials.

Mixing of HSC can follow conventional procedures. Mixtures with high cement factors probably benefit from slightly longer mixing times. Drum mixers should do an excellent job of mixing within 90 to 120 seconds at a rate of 15 to 18 rpm. Turbine mixers should be field tested for mixer performance before a minimum mixing time is established. The very cohesive nature of HSC mixtures tends to make them adhere to the mixer drum. Low-slump, non-air-entrained mixtures with small-size aggregates may be very sticky and difficult to mix even though longer-than-normal mixing times are used. Whether central mixing or shrink mixing, maintaining the mixer drum in good condition is a simple and effective way to optimize the mixing process.

The mixing water and, if necessary, the aggregates should be cooled to obtain the lowest practical
concrete temperature down to 40°F (4°C) with an upper limit of 75°F (24°C) for concrete as delivered to the forms. Lower temperatures will provide the best workability for a given set of ingredients at the given mixture proportions. This is because mixing water requirement increases—with resultant strength reduction—as temperature of the fresh concrete increases. Also, the rate of slump loss increases markedly with prolonged mixing and increased concrete temperature.

Retempering with water should be avoided with HSC and the water-cementitious materials ratio should be strictly enforced. Production methods should be such that no retempering is necessary. But, when unexpected delays occur, and a particular load becomes unworkable, the lack of slump may necessitate adding additional HRWR. Water should be added only up to the maximum water-cementitious materials ratio prescribed.

Second and even third dosages of superplasticizer can be added after the initial dosage to restore slump, but this practice is not generally recommended. Fig. 10 shows the effect of repeated dosages of an SMF superplasticizer on the slump of concrete.\(^{(20)}\) (The amount of the second and third doses are the same as the first.) Similar results are obtained with an SNF superplasticizer, and it is interesting to note that compressive strength is not adversely affected. The reason for this is that strength gain is directly related to reduction in entrained air. Here again, though, adjusting the mixture with second and third dosages of HRWR may be difficult to achieve because admixture quantities and remixing time can not be as tightly controlled in the field as at the batch plant.

Part of the difficulty associated with the rate of slump loss is the difficulty in pinpointing its cause. The numerous variables affecting loss of slump include the initial slump value; the type and amount of cement; the type, amount, and time of addition of superplasticizer; humidity; temperature; mixing method; and the presence of any other admixtures. A slight change in one or more of these factors could greatly affect the rate of slump loss. At present, HSC is produced by strict adherence to quality controls and retempering by any method is not recommended. Optimizing placement, delivery, and coordination is preferable to any jobsite modification of the mixture.

Yet another variable becomes important when considering slump loss of HSLW concrete. Lightweight aggregates often have porous surfaces, and water is readily absorbed. In a lightweight concrete mixture, a direct relationship exists between the amount of water absorbed by the aggregate and loss of slump. Knowing the rate at which lightweight aggregates absorb water is therefore beneficial to the mixing process. Studies carried out on certain expanded clays and a sintered fly ash revealed some important characteristics of these lightweight aggregates.\(^{(29)}\) For example, for all the aggregates tested, most of the water absorption occurred within the first two minutes, and thereafter water was absorbed much more slowly. Also, within the first 30 minutes, all aggregates absorbed more than half of the total water absorbed at 24 hours. Knowledge of the aggregate water absorption characteristics simplifies the process of batching lightweight mixtures, assuring proper mixing in a minimum of time.

**Placing**

Placing high-strength concrete, whether it be normal-density or lightweight, involves more care than normal-strength concrete. High-rise structures are but one example of the many projects that regularly make use of concrete pumps during construction. An effective method of placing concrete, pumping allows a single input point for the delivered concrete as well as horizontal and vertical mobility. This results in less confusion—for drivers delivering concrete, for equipment operators, and for placing crews—and faster, more efficient placement.

There must be close liaison between the contractor and the ready mix producer so concrete can be rapidly discharged after arrival at the jobsite. Final adjustments to the concrete mix, though not recommended, should only be made at the direction of and under supervision of the concrete producer's technicians on the site. Direct radio or telephone communication is necessary for relaying adjustments between the jobsite and the batch plant. Delays in delivery must be eliminated, and sometimes it may be necessary to reduce batch sizes if placing procedures are slower than expected. Rigid surveillance must be exercised on the jobsite to control any inclination to retemper with water. The contractor should be prepared to receive the concrete and must be equipped to handle, place, and consolidate a sometimes sticky, cohesive, possibly low-slump material.

![Fig. 10. Effect of repeated dosages of SMF superplasticizer on slump of concrete. I-1st dosage, II-2nd dosage, III-3rd dosage.\(^{(20)}\) © 1980, Noyes Publications, with permission.](image-url)
Even though HSC tends to be a sticky, cohesive material when fresh, segregation can pose problems when using lightweight aggregate. Because these aggregates are less dense than the paste, they tend to float, especially in fluid mixtures. Surprisingly, much work has been done on HSLWC with slumps greater than 8 in. (200 mm) without any segregation problem. It appears to be less of a problem than for normal-strength concrete. As a precaution, though, immediately prior to discharge from the ready mix truck, the drum should be rotated approximately ten revolutions at mixing speed to minimize segregation of HSLWC.\(^{(25)}\)

Consolidation of HSC is very important in achieving the potential strength. Fig. 11 shows the substantial effect that incomplete consolidation may have on compressive strength and other properties of concrete.\(^{(24)}\) Concrete must be vibrated as quickly as possible after it has been placed in the forms. When internal vibration is used, high-frequency vibrators should be small enough to allow sufficient clearance of the vibrator head between the reinforcing steel and forms. Over-vibration of very workable normal-strength concrete can result in segregation or loss of entrained air, or both. However, most HSC is of a flowing consistency. It requires little vibration and contains little air.

HSLWC contains aggregates that can absorb additional water, especially under the pressure induced by concrete pumping. Unfortunately, conflicting information exists on the exact effect of water absorbed by the aggregate. Is the water-cement ratio affected? The usual solution to maintaining pumpability of structural lightweight concrete is to prewet the aggregate at the ready mix plant. According to ACI 213R, other recommendations that aid in pumping structural lightweight concrete include the following: use the largest size pump line available; keep all lines the same size, avoiding rapid reductions in pipe diameter; and reduce the operating pressure. The consolidation of HSLWC should not involve excessive vibration. Unlike conventional HSC, which can withstand over-vibration and perhaps even benefit from it, HSLWC can segregate.\(^{(23)}\)

**Curing**

The strength-producing properties of the cement paste are due to the chemical reaction (hydration) between cement and water. Hydration requires time and favorable temperature and moisture conditions. Hydration takes place very rapidly at first and then more and more slowly. When a concrete element is subjected to a drying atmosphere, the internal relative humidity of the concrete decreases; when it drops below about 80%, hydration virtually stops.

The rate at which the relative humidity inside concrete decreases while drying is of considerable importance. Moisture migrates very slowly through concrete, so cement continues to hydrate beneath the outer 3 to 4 in. (75 to 100 mm) of concrete for a long period of time after exposure to drying (see Fig. 12).\(^{(25)}\) In concretes of very low water-cement ratio, the relative humidity decreases more slowly than in concrete of high water-cement ratio due partly to the reduced permeability. This indicates that HSC will continue to develop strength for a longer period of time than normal-strength concrete.

Use of curing compounds will keep concrete from drying out, but will not provide an additional source of curing water in concretes of very low water-cement ratio. HSC is typically placed with water-cement ratios in the range of 0.2 to 0.3, well below the 0.4 required for (complete) hydration of the cement,\(^{(39)}\) so water curing is the preferred method of curing during the first 24 hours. Water curing will help achieve

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**Reduction in concrete properties, %**

![Diagram of Reduction in concrete properties, %](image)

**Fig. 11.** Comparative effects of incomplete consolidation on concrete properties.\(^{(24)}\)

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**Curing**

![Graph of Relative humidity, %](image)

**Fig. 12.** Typical relative humidity distribution in 6x12-in. (150x300-mm) cylinders moist cured 7 days and then dried in air at 73°F (23°C) and 50% relative humidity.\(^{(35)}\)
more thorough, though not complete, hydration leading to improved strength and surface quality of the concrete. Complete hydration of the cement is not necessary, and for HSC not even desirable because higher strengths can be attained at less than total hydration.\(^9\)

The first 24 hours are the most critical time to provide additional curing water, but this can not be done for formed concrete: water curing is rarely done in practice. For vertical members like columns and walls it would be difficult, if not impossible. After 24 hours, HSC develops such a low porosity that very little water can penetrate the surface. However, moist curing up to as long as 28 to 90 days has been shown to increase the compressive strength.

Another means of assuring sufficient curing moisture for the interior of the concrete is to use normal-weight aggregates in a saturated condition. This produces higher compressive strength in concretes with low water-cement ratios, especially at ages less than 90 days.

Unlike normal-weight aggregates, most lightweight aggregates are porous and absorb considerable water during mixing that can transfer to the paste during hydration; although this is a source of curing water, lower strengths may be the result if the water-cement ratio is altered. To control the uniformity of the concrete, lightweight aggregates should be prewetted prior to mixing, but deliberate soaking of lightweight aggregate is not recommended. Prewetted aggregates may cause a reduction in durability of concrete, especially when the aggregate is saturated or becomes so during mixing. However, with proper curing and air drying, freeze-thaw action should not affect the hardened concrete. Saturated aggregates, normal-weight or lightweight, should not be used in concrete in a severe environment—wet freeze-thaw conditions, deicers, or other aggressive agents—unless a long period of air-drying (at least 30 days) is possible before such exposure. Otherwise frost damage may occur.

Damp burlap will prevent loss of moisture from cylinders and help maintain the required temperature of 60°F to 80°F (16°C to 27°C). Storage at lower temperatures, but above freezing, may increase 28-day strengths but will decrease earlier age strengths. In the wintertime, plywood curing boxes equipped with light bulbs or small thermostatically controlled electric heaters have been used successfully. Maximum minimum thermometers should be used.

Coverings of damp burlap are highly recommended in curing boxes. Curing boxes with a small can of ice are a practical means of obtaining the desired temperature control in hot weather. When curing boxes are not used in the summertime, store cylinders in the shade; coverings of damp burlap will provide some cooling due to evaporation of water. In the summertime, covering damp burlap with polyethylene plastic sheets must be avoided. The plastic sheeting prevents evaporation and its cooling effect. Wet burlap on top of plastic sheeting is acceptable when cylinders are stored in the shade.

The specimens should be carefully transported to a laboratory and placed in standard moist curing. Normally, this is done after 24 hours, but with some high-strength concretes, certain admixtures may retard the initial and final set such that moving the specimens at 24 hours would damage them. On one particular project, it was necessary to leave the cylinders at the jobsite for 40 hours before they could be safely moved to the testing laboratory. At all times from molding to testing, the cylinders should be carefully protected from loss of moisture.

Data from on-going research suggests that curing in a moist room is sufficient for high-strength concrete. Underwater curing is not required, and may, in fact, yield slightly lower measured compressive strengths.

More interest is being given to the use of smaller test samples; for example, the 4x8 in. (100x200 mm) cylinder is gaining acceptance as a replacement for the 6x12 in. (150x300 mm) cylinder. The smaller cylinders give slightly higher compressive strengths. Many factors influence the measured compressive strength of cylinders including specimen size and aspect ratio, preparation of the ends of the specimen, and size of the test machine’s bearing block. Trying to establish a correlation between specimen size and standard deviation instead of simply observing a trend might lead to defining a cause/effect relationship when none exists. Some researchers have found that standard deviations are larger with the smaller cylinders, some have found them smaller, and some have found no difference. In order to avoid incorrect conclusions, more work needs to be done specifically addressing the differences encountered with testing smaller size high-strength cylinders.

Fig. 13 compares strengths of the two cylinder sizes, and linear regression analysis verified that strengths from the smaller cylinders were within about 1% of strengths from the larger cylinders.\(^{17}\) The smaller size offers a number of distinct advantages: Smaller cylinders (1) are simpler to fabricate; (2) are easier to handle and transport; (3) require less storage space; (4) are more economical; and (5) can

**Testing**

The testing agency should follow standard ASTM methods of sampling, molding, curing, and testing of cylinders for determination of compressive strength. Specimens for HSC may be cast in reusable steel molds or single-use plastic molds. Since the plastic molds are designed for a single use, using them more than once may not provide the best results. In the past, tin and paper molds were also used with adequate results, but their use has greatly diminished. Paper (cardboard) molds produce lower strengths.

Fresh concrete for HSC test cylinders should be finished very smooth, level, and parallel to the opposite end to reduce the preparation required for testing. After cylinders are molded, they must be covered with a plastic cap, or metal or glass plate. Plastic caps may distort the surface, so an alternative would be to use plastic bags and rubber bands.
utilize smaller testing machines. With regard to the latter, a 20,000-psi (138-MPa) concrete tested to failure in the smaller size cylinder would require a load of only 251,000 lb (114,000 kg); the same concrete tested in the larger cylinder would require 565,000 lb (256,000 kg).

Since capping of cylinders becomes more critical as the strength of the concrete increases, particular care must be taken in this phase of compressive strength testing. Capping jigs should be carefully checked for planeness and alignment, and the capping compound, in addition to being an adequately strong material, should be used in a very thin layer of uniform thickness. Proprietary sulfur mortars made specifically for capping concrete cylinders should be used. However, some sulfur capping compounds are unsuitable for high-strength specimens, particularly when caps are more than 1/8 in. (3 mm) thick. Homemade sulfur compounds and reused compounds must be avoided. A waiting period of at least 2 hours between capping and testing of cylinders capped with sulfur should be strictly enforced. In fact, for strengths over 10,000 psi (69 MPa), cylinders should be capped at least 24 hours prior to testing. Frequent tests of 2-in. (50-mm) cubes are recommended to insure that capping compounds develop 5000 psi (34 MPa) in 2 hours.

Currently, there are several research programs investigating the requirements for compressive strength testing of HSC specimens. While much work is being focused on end conditions of cylindrical specimens, there is no clear consensus as to minimum requirements. Consideration of capping material strength alone may not be sufficient. A suitable capping material may require a combination of strength, elasticity, and "flow" under load. Until specific criteria are developed for a capping material for use with HSC, it is suggested that specific capping materials and procedures be evaluated by comparing compressive strength results for capped specimens to those for surface ground specimens. If results for the capped specimens are statistically similar to those of surface ground specimens, the capping material and procedures can be considered adequate. Laboratories that are successfully using capping materials for HSC specimens typically cap specimens at least 24 hours prior to testing. After capping, and before testing, specimens are returned to moist storage (not under-water) with the capped ends protected from direct exposure to dripping water.

Capping may be eliminated if the ends of the hardened concrete cylinders are ground to the required tolerances. In recent studies of HSC, initial capping was done using a commercially available high-strength “grey” sulfur-based capping compound. Some difficulties were encountered when testing concretes above 15,000 psi (103 MPa) because of end conditions of the cylinders and intrinsic limitations of the capping compound. Specimens with sulfur caps exhibited columnar failures, and test results were skewed toward lower strengths and higher standard deviations for both 4x8 and 6x12 specimen sizes. Because of skewed data and intrinsic strength limits of the sulfur-based capping compound, surface grinding of cylinder ends was investigated. Surface grinding reduced skewness of data, reduced standard deviations, and resulted in the desired cone failures of compression specimens. Lapping is another method which may be used, but in addition to being costly and time-consuming, it sometimes produces a convex surface which is unacceptable for compressive strength testing.

Polymer pads are a possible alternative to capping compounds for concrete strengths up to about 18,000 psi (124 MPa) provided the concrete surfaces are very smooth. Surface smoothness should be the aim of any specimen preparation, whether it be careful finishing of the freshly cast concrete cylinder or cutting or grinding the ends of a hardened cylinder.

Bearing blocks on testing machines should be carefully checked for planeness and alignment. It is important that cylinders be properly centered in the testing machine. High-strength concrete cylinders may explode on breaking (see Fig. 14). Therefore, a protective screen should be used to surround the cylinder or testing machine. In addition, the operator should wear goggles, safety glasses, or a face shield.

Crushing the cylinders to determine the type of failure and fracture should be required. The practice in some laboratories of failing to test a cylinder to fracture should be discouraged. Inadequate caps may be revealed by the appearance of the cylinder after testing. Normally, the cylinder should break into two conical end sections with the caps intact. If the break is through the cap or the specimen splits vertically, a careful check should be made of the quality of capping material and planeness of caps and machine bearing surfaces. Abnormal fracture and reduced strength may result from wedging action or uneven stress distribution when thick, irregular caps are used to correct excessively rough cylinder end surfaces. Very-high-strength specimens sometimes split along vertical planes even with proper caps; such splitting may be evidence of a cap that has flowed and introduced lateral forces.
necessary. Also, routine sampling of all materials in the mixture may be necessary to control uniformity of the concrete.

Specifications usually require that the strength of concrete delivered to a project meet or exceed a specified value, allowing only a very few tests to fall below that value. To satisfy these requirements, it is necessary to aim at an average strength higher than the specified minimum. The level of the average strength required depends on the control exercised over the variables that influence the strength of the concrete. The less effective the control exercised, the more variability possible in the test results, and the higher the average strength required to meet the specification requirements.56

The production of concrete having a high compressive strength will involve achieving a low variance in test results because, in most cases, it will not be possible to produce concrete having an average strength significantly higher than the specified strength. A good history of strength tests—more than 30—for a given set of materials will be helpful to take advantage of the lowest standard deviation possible. The lower coefficients of variation normally obtained on HSC projects are a result of increased vigilance in quality control on the part of the concrete producer.

The maturity concept is a relatively new method of determining the in-place strength of concrete.57 Maturity is defined as the integral with respect to time of the curing temperature measured from a datum temperature. Based on a predetermined relationship (laboratory) between strength and maturity factor for a given concrete mixture, accurate time-temperature records of the in-place concrete can provide an estimate of the strength at that point in time. With the long curing periods associated with HSC, the concept of maturity can provide a viable method of tracking strength gain, allowing estimates of the strength to be made at any time without the need for an inordinate number of cylinders.58

Monitoring density, both fresh and hardened, is an often overlooked quality control measure that can be of significant benefit in a quality control program for HSC. Small changes in density may result in large changes in compressive strength and may also indicate inconsistencies in batching operations. Therefore, it is suggested that unit weight be determined on plastic concrete each time samples are obtained. Density should also be determined on each and every hardened concrete sample prior to testing. Accurate density determination can be made on hardened samples by weighing in air and weighing submerged in water. The procedure is covered in ASTM C642, Test Method for Specific Gravity, Absorption, and Voids in Hardened Concrete.

**Quality Control**

A comprehensive quality control program is required at both the concrete plant and the jobsite to guarantee consistent production and placement of high-strength concrete. Inspection of production and concreting operations from stockpiling of aggregate through completion of curing is important. Closer production control than is normally obtained on most projects is

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**Fig. 14.** High-strength concrete cylinders should be tested to fracture. This one explodes as it breaks.
CHAPTER 5

Properties

Although deriving its name from one of its most important attributes, high-strength concrete has other physical properties which make it a highly desirable building material. Its modulus of elasticity, drying shrinkage and creep, porosity, permeability, durability, corrosion resistance, thermal properties, adiabatic temperature rise, and bond to steel may affect where and when this material is chosen over normal-strength concrete. Some of these properties can be very different in high-strength concrete. Code changes are needed to address these differences, and current research will provide the basis for future code revisions relating to the use of this material. To assure a conservative design when using codes written for lower strength concrete, it is important to understand the ways in which HSC behaves differently from normal-strength concrete.

High-strength lightweight concrete will usually be chosen for its combination of strength and weight characteristics. Aggregate density influences certain concrete properties, but high-strength concretes of normal and low density have more similarities than differences. Mentioning the similarities between lightweight and normal-density concrete seems trivial; discussing the differences in properties provides valuable information.

**Strength**

Much of this publication is devoted to the compressive strength of HSC, the limit of which presently appears to be 25,000 to 30,000 psi (172 to 207 MPa) at 90 days. Fig. 15 shows the compressive strengths of a number of pastes made with several cements. Their strengths are plotted against both water-cement ratio and the measured densities of the specimens. As the pastes were anywhere from 1-1/2 to 11 years old, the samples can be considered to have essentially reached their ultimate degree of hydration. Of particular interest in this figure is the point of intersection of the two straight-line portions; it occurs at a water-cement ratio of 0.40, very close to the lowest ratio at which concrete can be placed while still allowing the complete hydration of portland cement. (Note: Theoretically speaking, cement is completely hydrated at a water-cement ratio of about 0.27, but in actuality 0.22 to 0.25 is the experimental maximum observed and all cement pastes at any ratio will have some unhydrated cement.) The amount of unhydrated cement becomes more evident as the water-cement ratio drops below 0.40. It is important to note that in pastes with strengths higher than about 8000 psi (55 MPa)—corresponding to a water-cement ratio of about 0.40—hydration of the portland cement will not be complete. The binding matrix in such concretes will consist of a combination of hydrated cement and clinker.

In normal-strength concrete, flexural and tensile strengths are small and often ignored, partly because
design codes are conservative and suggest assuming a value of zero for these properties. With HSC, both flexural and tensile strengths are improved. In prestressed concrete design, the extreme fiber stress in tension is limited to \( 6 \times \sqrt{f'_c} \). A change in design assumptions is not needed. In the future, especially with the development of MDF products, design procedures may have to be altered to reflect a change in behavior of HSC versus conventional concrete (see Chapter 6).

For lightweight concrete, flexural and tensile strengths depend on the compressive strength, just as they do for normal-weight concrete. Normal-weight aggregates have a higher crushing strength, and they will generally produce concretes of higher compressive strengths. It has been mentioned that HSC is more brittle than conventional concrete, with higher strengths (increased age or cement content) rendering more brittle materials. This effect is more pronounced in lightweight concrete.

The modulus of elasticity of structural lightweight concrete is usually taken to be about one-half to three-fourths that of normal-weight concrete of the same strength.\(^{25}\) Curing lightweight aggregate concrete takes on increased importance. Moist curing will allow the normal development of strength, but air drying has an adverse effect on tensile and therefore flexural strength.\(^{49}\) ACI 213R provides some guidelines on proper methods of curing structural lightweight concrete even though it is mainly intended for strengths from about 2500 to 6000 psi (17 to 41 MPa).\(^{25}\)

### In-Place Strength

Owing to the difference between field and laboratory curing conditions, in-place compressive strength of high-strength concrete can vary—it is usually lower than that measured on test cylinders. One way of checking in-place strength is to drill cores and compare them to cylinders made from the same material. As part of exactly such a test program on commercially available high-strength concretes, cores were drilled from a HSC sample (see Fig. 16) and tested at the same age as companion cylinders. The results from tests at 91 days and 14 months rather consistently showed the in-place compressive strength to be lower, in the vicinity of 85% of the specified design strength, \( f'_c \), of the concrete.\(^{17}\)

Building Code Requirements for Reinforced Concrete, ACI 318-89 (revised 1992) 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 \( f'_c \).”

Another important facet of in-place concrete is the long-term properties of the material and how they change with time. As concrete ages, changes in compressive strength are most influenced by the loading history and the relative humidity (RH) of the exposure. Water Tower Place (see Fig. 17) provided an opportunity for long-term testing to determine the effects of these two factors.\(^{49}\) After 18 years of aging, cylinders were tested for compressive strength. For unloaded specimens stored at 50% RH, the compressive strength either improved, remained basically the same, or decreased slightly. For loaded specimens, the strength increased somewhat if they were stored at 50% RH, and increased markedly if they were sealed against drying. Measurements on the modulus of elasticity were only taken on unloaded specimens that were stored at 50% RH, and very little change was noticed in the value for this parameter.\(^{61}\)

![Fig. 16. Four-ft-cube (1220-mm) specimens serve as a source for obtaining drilled cores for compressive strength testing of in-place concrete.\(^{17}\)](imageLink)

### Modulus of Elasticity

Modulus of elasticity, denoted by the symbol, \( E \), may be defined as the ratio of normal stress to corresponding strain for tensile or compressive stresses below the proportional limit of a material. (Stress is the amount of force per unit area, and strain is the ratio of length change to original length.) The stress-strain relationship and modulus of elasticity of concrete are important design parameters. Static determinations of modulus of elasticity provide one of the values useful for such design purposes as determining deformation and stress distribution between concrete and steel in reinforced or prestressed concrete members. The static modulus of elasticity also is useful for calculating the stresses resulting from shrinkage, settlement, or other distortions. Although concrete is not a perfectly elastic material, the theory of elasticity can be applied to it within limits of stress and time; a marked departure from linearity is noted at near-ultimate stress.

Unreinforced concrete also has a certain amount of ductility. This ductility, however, decreases with increasing concrete strength; in other words, the higher strength material is more brittle. At very high strengths, brittleness may increase to the point where additional attention to it is warranted during design.

The stress-strain relationship under increasing stress becomes almost a straight line as concrete strength increases and the slope of the ascending
Fig. 17. At time of completion in 1976, the 76-story Water Tower Place in Chicago was taller—859 ft (262 m)—than any other reinforced-concrete building built prior to that time.
portion of the curve increases (see Fig. 18). Stated differently, the modulus of elasticity increases with increasing compressive strength of concrete. ACI Committee 363 concluded that a strain value of 0.003—commonly assumed as the ultimate strain in design of flexural members—represents satisfactorily the experimental results for HSC, although it is not as conservative as it is for normal-strength concrete.

The rate of loading has an effect on the compressive strength and stiffness of concrete; faster rates of loading enhance both properties. The relative increase in static strength is greatest in lightweight aggregate concrete where the aggregate is weak and soft, and least in normal-weight aggregate concrete where the aggregate is strong and stiff. The softer aggregate in lightweight concrete gives it a higher strain capacity than normal-weight concrete and lowers its risk of cracking by up to one-third that of normal-weight concrete. Combined with its thermal resistance, this means that lightweight concrete will crack less under thermal loads.

In reinforced concrete design, it is desirable that the concrete not crush or substantially enter the descending branch of the stress-strain curve before the steel has reached its yield point. Steel and normal-strength concrete are a good match for each other because they have similar strains at yield. This means that efficient designs may be obtained because both materials will yield or fail at about the same load.

The modulus of elasticity of concrete, $E_c$, depends on the modulus of the cement paste, the modulus of the aggregate, and the relative amounts of paste and aggregate. As seen in the stress-strain curves of Fig. 18, for a given cement, different strengths and moduli will be obtained with different types and combinations of fine and coarse aggregate. Another important feature of these curves is that for all strengths and combinations of aggregates, their peaks (maximum stresses) occur at strains of about 0.002 to 0.004. In steel, an elastic strain of 0.001 corresponds to a stress of 30 ksi (207 MPa). Therefore, reinforcement with yield strengths between 60 and 75 ksi (414 to 517 MPa) will reach these yield points just before or as the concrete starts weakening. Since the minimum amount of steel is based on the cross-sectional area, increasing the strength of concrete reduces the size of the member, thereby reducing the minimum amount of reinforcing steel required. The question then that arises with HSC is whether or not the increased modulus promotes underdesign of the steel reinforcement.

Changes in modulus for a given concrete occur because of changes in the modulus of elasticity of the paste and increased bond with aggregates as curing continues. As the modulus of the paste increases, the concrete strength also increases, and for any given concrete mixture and curing condition there is a general empirical relationship between strength and modulus of elasticity (see box). Formulaic determinations of $E_c$ may be sufficiently accurate for most design, but in some cases such as buckling of long columns, a more precise value may be needed.

ASTM C469, Method of Test for Static Young’s Modulus of Elasticity and Poisson’s Ratio in Con-
CALCULATING THE MODULUS OF ELASTICITY OF CONCRETE

The equation

\[ E_c = w^{1.5} \times 33 \times \sqrt{f_c'} \] (1)

where

\( w \) = unit weight in pcf

\( f_c' \) = compressive strength in psi

defines a relationship between the weight, compressive strength, and modulus of elasticity of concrete (in psi) with strengths up to about 6000 psi and unit weights between 90 and 150 pcf; at strengths above 6000 psi, Equation (1) overestimates the value for \( E_c \). Part of the reason for poor estimates from this equation for concrete strengths above 6000 psi is the fact that the unit weight of HSC is not appreciably higher than that of normal-strength concrete. An alternative estimate for the modulus of elasticity of HSC can be made from another empirical relation. This equation\(^{16}\) is

\[ E_c = 40,000 \times \sqrt{f_c'} + 1.0 \times 10^6 \text{ psi} \] (2)

Although Equation (2) can be used when the concrete is of normal-weight and its strength falls in the range of 3000 to 12,000 psi, it is most useful for strengths above 6000 psi (41 MPa) because Equation (1) will be used between 3000 and 6000 psi (21 and 41 MPa). However, in this range, both equations are valid and give similar results.

If modulus of elasticity is an important design parameter, its value should be determined by test using the proposed materials and mixture proportions. Testing can determine a relationship between \( f_c' \) and \( E_c \) for a specific mixture with given materials. Testing is always the best way to determine the modulus and should be used when \( E_c \) is an important factor in the design.

\[ E_c = w^{0.43} \times 33 \times \sqrt{f_c'} \] metric (1)

where

\( 1500 \leq w \leq 2500 \text{ kg/m}^3 \)

\( f_c' < 41 \text{ MPa} \)

\[ E_c = 3320 \times \sqrt{f_c'} + 6900 \text{ MPa} \] metric (2)

where

\( 21 \text{ MPa} < f_c' < 83 \text{ MPa} \).

Fig. 19. A concrete cylinder with extensometer attached to obtain data relating applied load to deformation of the concrete specimen. Data are plotted as a stress-strain curve from which modulus of elasticity is determined.

greater variation; inaccurate measurement of the strains, or changes in the way the modulus is determined from the stress-strain data being two common causes. With strains less than 0.004, some inaccuracies may very easily be introduced during measurement. Working from stress-strain curves, it is most common to use the secant modulus, although the modulus can also be taken as either the initial or tangent modulus. But even when it is agreed upon to use the secant modulus, the value used may be taken at between 25% and 50% of the ultimate compressive strength. It is also important to note that the age of the concrete has an effect on the modulus; if measured at an early age, the compressive strength may not have reached its potential, and the value for the modulus could therefore be lower. As discussed above, the modulus is often estimated by use of an equation based on the compressive strength. Even though concrete is a variable material, slight changes in the measured compressive strength have little effect on the modulus.

The modulus of elasticity of paste is a function of water-cement ratio and age. Its magnitude can range up to 4.5 to 6.5 \( \times 10^6 \) psi (31 to 45 GPa). Most lightweight aggregate has a modulus very similar to that of paste, whereas the modulus of normal-density aggregate is usually considerably higher. In general, the lower the absorption of the aggregate, the higher the modulus of elasticity of the aggregate. Therefore, the greater the volume of paste per unit of aggregate, the lower the modulus of elasticity should be at comparable degrees of hydration or strength. This merely emphasizes that compressive strength alone is not a good indicator of modulus of elasticity of different concrete mixtures over the whole range of
Table 6A. Comparison Between Development of Compressive Strength and Modulus of Elasticity, U.S. Customary Units*

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<tr>
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<th>Mix 3 $f'_c$ psi</th>
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*Source: Reference 17.

Strengths possible with the same materials used in different proportions. What is important is how the strength was obtained for any given set of materials—by a change in mixture proportions or water-cement ratio or by longer curing. For any particular mixture, however, strength is a good indicator of the modulus of elasticity: the modulus increases with strength. In the high-strength region, the modulus does not increase as rapidly as strength and may approach some limiting value.

Earlier work by Magura, Pfeifer, and Hognestad revealed some important concepts relating concrete strength to its modulus of elasticity. A conventional concrete and a high-strength concrete were both made from the same aggregate to demonstrate the influence of compressive strength on modulus of elasticity. The modulus for the higher strength concrete (same materials) was larger at all ages, and increased with an increase in compressive strength.

Equations to determine $E_c$ (see box) may prove acceptable, but due to the many variables involved, more accurate $E_c$-values are provided from stress-strain measurements made on actual HSC specimens. Using stress-strain data from high-strength concretes commercially available in the Chicago area, Table 6 lists the values for compressive strength and modulus side-by-side for comparison. In exhibiting the same trend—namely, as concrete gains compressive strength its modulus also increases—this data confirms the conclusions of the earlier work noted above.

The modulus of elasticity of concretes made with lightweight aggregates is not influenced materially by the volumetric concentration of aggregate in the mixture. This is because the modulus of the aggregate is generally about the same as that of the paste. Normal-weight sand is often used with lightweight aggregates to increase the modulus of elasticity. Depending on the type of lightweight aggregate and sand content, the modulus of elasticity of sand-lightweight concrete is normally 20% to 50% lower.
Table 6B. Comparison Between Development of Compressive Strength and Modulus of Elasticity, SI metric Units*

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*Source: Reference 17.

than that for normal-weight concrete of equal strength, with the greater difference occurring in the low-strength range. A modulus of 3.5 x 10^6 psi has been obtained for a sand-lightweight concrete with a 28-day compressive strength of 7000 psi and a wet unit weight of 118 lb per cubic foot ($E'_c = 24$ GPa, $f'_c = 48$ MPa, unit weight = 1890 kg/m³).

Drying Shrinkage and Creep

Drying shrinkage of concrete is due mainly to the evaporation of chemically uncombined water. The consideration of drying shrinkage in design may be highly critical for some structures and relatively unimportant for others. Shrinkage can affect performance and appearance. The amount of tolerable shrinkage depends on jointing and design details.

Creep of concrete is the dimensional change or increase in strain with time due to a sustained stress. Creep of concrete may be either beneficial or detrimental, depending on the prevalent structural conditions. The effects of creep as well as the effects of drying shrinkage should be considered and, if necessary, compensated for in structural designs. With increasing heights of buildings, the importance of time-dependent shortening of columns and shear walls becomes more critical because of the cumulative nature of such shortening. Since high-strength concrete undergoes somewhere in the vicinity of 40% to 70% of the specific creep of normal-strength concrete, members fabricated of HSC will experience slightly smaller shortening.

Shrinkage and creep of concrete are related phenomena and are controlled by similar parameters. If these parameters are not known, they can be predicted by the design engineer. The parameters affecting drying shrinkage and creep include: (1) total water content—this is the most important factor affecting drying shrinkage, (2) cement paste content
and characteristics, (3) physical characteristics of the aggregate, (4) age of concrete when exposed to drying or when an external load is applied, (5) size and shape of the concrete element, (6) amount of reinforcement, and (7) environmental exposure conditions, such as relative humidity, temperature, and carbon dioxide content of the ambient air.\(^{(5,25,34)}\)

As the variables above indicate, drying shrinkage and creep behavior are complicated because so many variables are involved. In addition, the interaction of the variables can further complicate matters. Most experimental studies of shrinkage and creep have been very specific in scope, leaving much to be learned about these two phenomena in HSC. Changes in size and shape of member affect, at all ages, both the shrinkage and creep of concrete stored under drying conditions.\(^{(55)}\) The larger the member, the smaller the ultimate values of shrinkage and creep, and the more time required to undergo these dimensional changes.\(^{(55)}\) Conclusions drawn from research on shrinkage and creep behavior of small specimens will provide conservative estimates for use in design of actual structural elements. The effect of size must be taken into account when extrapolating data from small specimens to actual structures. Otherwise, the conservatism is too great. Observations made on full-scale structural elements provide an excellent chance to compare theoretically-predicted quantities—based on small specimens—with actual in-service measurements.\(^{(43)}\)

The cement paste that surrounds the aggregate and "glues" the concrete together largely determines the drying shrinkage and creep behavior. Cement paste in HSC is composed of cement, water, admixtures, and possibly a small amount of entrapped air. The cement itself can vary in chemical composition and fineness, and both of these properties will influence the rate of hydration, and therefore, the strength gain of concrete. The strength of concrete at time of loading affects the amount of creep. Drying shrinkage may also be affected by the physical or chemical composition of the cement, but with the use of an optimum amount of gypsum, cement type \textit{per se} does not significantly affect creep or drying shrinkage. Drying shrinkage is generally unaffected by changes in water-cement ratio—unless this includes changes in total water content—while creep will increase with an increase in water-cement ratio.\(^{(56)}\) Creep strains are reduced with higher strengths that are obtained by a decrease in water-cement ratio either by adding more cement and/or reducing the amount of water.

Chemical admixtures are usually added to HSC with the goal of reducing the amount of water required to place the mixture. They are often added in combinations of two or three per mixture, and their net result on the hardened properties may be difficult to predict. Compared to nonplasticized concretes of equal mixture proportions (and equal water-cement ratios), SMF superplasticizers increase drying shrinkage and creep by about 10%. However, they also allow a reduction in mixing water requirement, and this tends to offset the increase.\(^{(57)}\) At present, the general consensus is that superplasticized concretes experience approximately the same creep as reference concretes, but not without exception.

Mineral admixtures also have various effects on shrinkage and creep. Although the drying shrinkage of plain and fly ash concretes appears to be about the same after 400 days, fly ash concrete at later ages tends to creep less than plain concrete.\(^{(58)}\) This is most likely due to the strength increase imparted by the fly ash. Silica fume is another mineral admixture used in HSC, and as strengths exceed about 12,000 to 15,000 psi (about 83 to 100 MPa), its use is becoming more common. Silica fume is extremely fine and impairs workability of the mixture under all but very specific conditions (see Chapter 3, "Proportioning"). For this reason, a HRWR must be used if silica fume is part of the mixture. The low water content and improved strength should both result in decreases in the amount of creep over conventional concrete; this has been observed to be true for most silica fume concrete. Actual tests conducted on commercially available HSC mixtures show the creep coefficient—the ratio of creep deformation to initial elastic deformation—to be about the same as that of conventional concrete, that is between 1.5 and 4.0.\(^{(17)}\)

In a study of Water Tower Place, a 76-story reinforced concrete building in Chicago (see Fig. 17), calculated values for time-dependent shortening of columns exhibited satisfactory agreement with measured values, especially during construction (see Fig. 20).\(^{(60)}\) Three- and five-year data for Column D2 at two levels—both 9000-psi (62-MPa) concrete—are shown in Figs. 21A and 21B, respectively.\(^{(40,59)}\) Beyond 5 years (and up to 13 years), some columns were not accessible for monitoring, making the (partial) 13-year data less valuable for comparative purposes. The results of this long-term study indicate that tall concrete buildings can be designed and built so that shortening and differential movements do not affect the strength or serviceability of the structure.\(^{(60)}\)

The role of aggregate in concrete is to minimize the paste content and to restrain the shrinkage and creep of the paste, thereby reducing the overall shrinkage.
Fig. 21. Comparison of calculated and measured vertical shortening for 9000-psi (62-MPa) concrete columns located at Levels B4-B3 and 15-16 in Water Tower Place.
and creep of concrete. The effectiveness of aggregate in reducing shrinkage and creep increases as the volumetric fraction of coarse aggregate in concrete increases with the exception of HS LW as already noted. The mineralogical composition and physical properties of coarse aggregate also are important in providing restraint to shrinkage and creep. Because of the great variation in aggregate within any mineralogical or petrological type, it is not possible to make specific statements about the magnitude of shrinkage or creep of concrete made with aggregates of different types. However, generally speaking, hard aggregates with high density and high modulus of elasticity coupled with moderate porosity or absorption produce concrete with the lowest drying shrinkage and creep. Other aggregate variables such as grading, maximum size, and particle shape influence shrinkage and creep of concrete only to the extent that they affect the paste content required for adequate workability.

At high compressive strengths, some structural lightweight aggregate concretes exhibit lower drying shrinkage than concrete made with average normal-weight aggregates. Partial or full replacement of the lightweight fines by natural sand usually reduces shrinkage for concretes made with most structural lightweight aggregates. In terms of creep properties, there is little difference between normal-density and structural lightweight aggregate concretes at equal, high compressive strengths.60

A concrete element loaded at an early age exhibits a much larger specific creep (actual creep strain at a
particular time per unit of sustained stress) than the same element loaded later. This means that creep decreases with decrease in stress-to-strength ratio at the time of loading. Also, because of a gradual increase in modulus of elasticity with age, the elastic shortening per unit stress of older concrete is smaller than that of concrete loaded at an earlier age. Figs. 22A and 23A compare laboratory measured creep and drying shrinkage data up to 3 years for concretes used in Chicago’s Water Tower Place, and Figs. 22B and 23B include 13-year data. Note that the higher strength concretes experience much lower specific creep strain and that as the age at loading goes up, ultimate creep markedly decreases. The sealed specimens (at 28 days) also showed that concretes sealed against drying will have less creep than specimens exposed to drying conditions. The difference between the creep of sealed and drying specimens is often called drying creep. Drying creep of high-strength concrete is much less than for normal-strength concrete. Shrinkage specimens (Figs. 23A and 23B) show no clear relationship between strength and drying shrinkage, and this agrees with previously noted trends.

Creep is a linear function of the stress-strength ratio for stresses up to 50% of the ultimate strength of the concrete (normal service load stresses fall well below 50%). Under a constant load, the greater the increase in strength of the concrete, the smaller will be the creep.

Moisture diffusion from concrete becomes increasingly more difficult as cement hydration proceeds, particularly with very low water-cement ratio concrete. Consequently, the rate and magnitude of drying shrinkage and creep are reduced as hydration progresses. Fig. 24 shows the drying shrinkage of 3x3x11-in. (75x75x280-mm) prisms determined in accordance with ASTM C157, Test Method for Length Change of Hardened Hydraulic-Cement Mortar and Concrete. Additional prisms were cast with Monfore humidity wells buried in the middle of the prisms. The relative humidities in these wells were measured periodically while the prisms were subjected to the same drying conditions as the shrinkage prisms. There was good correlation between internal relative humidity and drying shrinkage.

The amount of drying shrinkage and creep is also a function of environmental conditions. Obviously, the relative humidity, temperature, and air circulation will influence both rate of drying and ultimate drying shrinkage and creep. Concrete subjected to a continuously dry environment, such as an interior building column, will exhibit greater drying shrinkage and creep than concrete exposed to high humidities or to a long moist-curing period.

For constant relative humidity, changes in temperature have a negligible effect on the creep and shrinkage of concrete. Humidity of the air, however, tends to vary inversely with temperature. Hence creep and shrinkage strains tend to be less for lower temperatures because of both the higher relative humidity and the lower rate of evaporation.

The environment is only one part of the exposure conditions; another part is the amount of member exposed to those conditions—the surface area of the member, or more correctly, the volume-to-surface area. As the ratio of volume-to-surface area increases, both the amount and rate of shrinkage and creep decrease, ultimate deformation decreases, and the time required to attain ultimate deformation is lengthened (slower rate). In comparing prisms and cylinders made from high-strength concrete, it was
use of HSC at present is in the columns of buildings—an environment which is often well controlled in terms of humidity and temperature. Perenchio and Klieger found HSC had excellent resistance to freezing and thawing and attributed this to the greatly reduced freezable water content and increased tensile strength of HSC.\(^{56}\) However, some uncertainty still remains regarding the durability of HSC because Perenchio and Klieger did not perform deicer-scaling tests (see box).

Whiting\(^{59}\) did perform deicer-scaling tests as well as freeze-thaw tests to determine the minimum air content needed for durability of high-strength concrete. The samples tested had 28-day compressive strengths of 6000, 8000, and 10,000 psi (41, 55, and 69 MPa). All non-air-entrained concretes performed poorly in both freeze-thaw and deicer-scaling tests regardless of strength or type of curing. With air entrainment, the results were improved, and type of curing had a greater effect on durability. In Whiting’s research, another variable was introduced into the testing by the incorporation of fly ash into the two higher strength mixtures. This was done to make the 8000- and 10,000-psi concretes more typical of commercially produced HSC. The 6000-psi mixture contained no fly ash. Results indicated that moist-cured, air-entrained, high-strength concretes (8000 and 10,000 psi) performed satisfactorily with respect to freezing and thawing in water, but were less resistant to applications of deicing agents than were air-entrained concretes prepared at the lower strength level (600 psi). This was true even with air contents between 7% and 8% in the fresh concrete. This study suggests that in the anticipated absence of deicing chemicals, a reduction in the amount of air entrainment required in HSC—down to 3% to 4% percent—might be allowed. It should be noted that ASTM C672, Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals, is a stringent test. The nature of the test is such that results may not readily correspond with actual performance of concrete in service.

Mehta\(^{83}\) noted that concretes—even when air-entrained—containing finely divided mineral admixtures are generally more vulnerable to surface scaling in the presence of deicers than corresponding plain portland cement concrete mixtures. Probably the finer pore structure of the admixed concrete is responsible for the increased scaling. Additionally, he stated that as the quantity of fly ash in air-entrained concrete is increased to very high proportions, more scaling damage is likely to occur. These conclusions, according to Mehta, are confirmed by several studies cited by Berry and Malhotra.\(^{64}\) Presumably, the above discussion pertains to any concrete containing mineral admixtures, not necessarily just high-strength concretes. Only research specifically designed to determine the influence of mineral admixtures—both type and amount—on deicer scaling resistance of HSC can answer this question definitively.

The very low water-cement ratio at which HSC is typically placed is a large part of the reason that the porosity of the material is so low. Silica fume, due to

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**Porosity, Freeze-Thaw Durability, and Corrosion Resistance**

The pore structure of high-strength concrete may lend some insight into explaining the behavior of this material in certain environments. The most common noticed that prisms sustained drying shrinkages greater than or equal to the cylinders and did so at an increased rate.\(^{17}\) The smaller volume-to-surface area ratio of the prisms permitted faster drying. This phenomenon can have some impact in the design and erection of an actual structure, as for example, when a large column and thin wall undergo differential shortening and are used to support opposite ends of a beam or girder.

The shrinkage and creep of reinforced concrete is less than that for plain concrete, the difference depending on the amount of reinforcement. Steel reinforcement restricts but does not prevent drying shrinkage. In reinforced concrete structures with normal amounts of reinforcement, drying shrinkage is commonly assumed to be 200 to 300 millionths.
DURABILITY

The American Concrete Institute defines durability as "the ability of concrete to resist weathering action, chemical attack, abrasion, and other conditions of service." Careful use of the term "durability" is required to distinguish freeze-thaw durability from resistance to deicer scaling. Both are measures of concrete's ability to resist weathering action, but concrete can be resistant to the action of freezing and thawing and yet not be resistant to deicer scaling.

Although researchers have demonstrated that the two properties, resistance to freezing and thawing and resistance to deicer scaling, are drastically different, a myth in the industry purports the two to be the same. Many concretes that perform well in exposures to freezing water fail upon exposure to deicers. To further negate any correlation between test results, specimens are different in the two procedures: Freeze-thaw testing involves a concrete prism, while the test for deicer scaling is performed on a small slab with a dike around its periphery to pond deicer solution.

Some laboratories and product manufacturers use ASTM C666, Test Method for Resistance of Concrete to Rapid Freezing and Thawing, to determine concrete's resistance to weathering. Although an excellent measure of freeze-thaw resistance, this test normally does not use a deicer solution, and, therefore, it is not a test for deicer scaling-resistance of concrete. Deicer exposures are much more severe than freezing and thawing in water. If concrete is to be exposed to deicers in service, then a deicer test must be used to evaluate that concrete in the laboratory.

The test for deicer scaling is ASTM C672, Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals. Because this accelerated test is more severe than most field conditions, mixes that fail in the laboratory sometimes perform well in service. However, a mixture that fails sooner in the laboratory can be expected to fail sooner in service. Well-designed portland cement concrete mixtures have survived severe deicer environments for more than 40 years without any signs of deterioration.

Also according to ACI, durability factor is "a measure of the change in a material property over a period of time as a response to exposure to an influence that can cause deterioration, usually expressed as a percentage of the value of the property before exposure." For concrete specimens subjected to ASTM C666, a generally accepted durability factor in the industry is 80% or above after 300 cycles of freeze-thaw. Concrete meeting this criteria is then said to be freeze-thaw durable.

its extreme fineness, is another reason. It fills the voids between even the smallest cement particles. This has two important effects: (1) it reduces the pore size so much that water can not freeze, and (2) it makes the pore system more discontinuous. Therefore, water outside HSC has a difficult time penetrating the surface once the pore structure has been developed, usually within 24 hours after placement. Absorption of a good concrete will generally fall below 10% and as low as 2% in exceptional cases. Cylinders from five high-strength concrete mixes were tested for water absorption. Even after 600 days under water, no specimen gained more than 1 lb per cubic foot (16 kg/m³) or 0.7% by weight of concrete. The low water-cement ratio, low water content, and low porosity of HSC each lead to the same conclusion: Since there is not much free water in the concrete to freeze, HSC should have good freeze-thaw resistance.

Water absorption is generally expected to be higher for lightweight than for normal-weight concrete, but this depends on the quality of the cement paste surrounding the aggregate and the hydraulic pressure on the concrete. A higher absorption does not necessarily mean that a concrete will have poor durability or high permeability. Hardened concrete properties are more important than the properties of the aggregate from which it is made. Surprisingly, lightweight concrete is likely to be less permeable than a dense aggregate concrete of the same strength. The most influential parameter affecting the durability of lightweight concrete is the initial moisture content of the aggregate from which it is made. If the moisture content of a lightweight aggregate can be kept below 5%, concrete from which it is made will have a durability factor of better than 80%, even after 300 freeze-thaw cycles (see box). Between 5% and 9% entrained air, varying the air content had very little effect on durability.

Along with an increase in compressive strength of HSC there is an increase in tensile strength. Under cyclical temperature changes, concretes with higher strengths can better withstand the expansive and contractive forces which changing temperatures induce. In many highway and bridge applications, though, it is not just temperature cycling that concrete must withstand. Chemical deicers, through direct or indirect contact, also must be endured. But, as discussed above, conflicting research suggests anywhere from good to inadequate performance of HSC under the combination of deicers and freeze-thaw cycling. While a low water-cement ratio does reduce chloride ion ingress, it has not been conclusively proven that the lowered chloride permeability of HSC is adequate. For the five HSC cylinders tested for water absorption (noted above), the relative ranking of the mixtures was identical to that of the rapid chloride permeability test. Entrained air offers the best defense against chemical deicers in the presence of freezing and thawing, but it also reduces the strength of the material.

Thermal Properties

The thermal properties of high-strength concrete are important in analyzing the effects of temperature variations. These properties—conductivity, diffusivity, specific heat, and coefficient of expansion—of high-strength concrete are within the common range for conventional-strength concrete. For example, when exterior columns partially or fully exposed to the weather are subjected to seasonal temperature variations, their lengths change relative to the interior columns which remain
stable in a controlled environment. In low buildings, this can be ignored. However, in taller buildings with exterior columns, temperature stresses must be considered.\(^{(30)}\)

Conductivity, \(k\), the rate of heat flow through a unit thickness of material, and diffusivity, the rate at which temperature changes will take place within the mass of hardened concrete, are both greatly affected by the type of aggregate. Within narrow limits, however, conductivity is a function of the unit weight of the concrete. It is also affected by moisture content of the concrete as shown in Fig. 25. This figure presents average \(k\)-values for concretes in oven-dry, normally dry, and saturated moisture conditions. The normally dry unit weight of concrete is attained after moisture equilibrium is achieved with normal ambient weather conditions. The water-cement ratio and strength have little or no effect on these properties. Diffusivity of concrete varies between 0.02 to 0.08 sq ft per hr (0.002 to 0.007 m\(^2\)/hr).

Specific heat, the heat capacity of concrete, varies from 0.20 to 0.28 Btu/lb·°F (834 to 1167 J/kg·°K). Specific heat is affected very little by the mineralogical character of the aggregates or the high cement content of HSC mixtures. In general, the specific heat varies directly with variation in the temperature and moisture content of the concrete.

Coefficient of expansion, the change in length per unit length with changes in temperature, is usually between 3.5 to 7.0 millionths per °F (6.3 to 12.6 millionths/°C). The thermal expansion and contraction of concrete varies with such factors as type and amount of aggregate, richness of the mixture, water-cement ratio, temperature range, concrete age, and relative humidity (degree of saturation of concrete). Of these, aggregate type probably has the greatest influence. Ranges for normal-weight concretes made with siliceous aggregates are 5.0 to 7.0 millionths per °F (9.0 to 12.6 millionths/°C) and 3.5 to 5.0 millionths per °F (6.3 to 9.0 millionths/°C) for concretes made with limestone or calcareous aggregates. The values in each case depend on the mineralogy of specific aggregates. Approximate values for structural lightweight concretes are 4.0 to 6.0 millionths per °F (7.2 to 10.8 millionths/°C) depending on the amount of natural sand used. When a precise value is not required, a coefficient of 5.5 millionths per °F (9.9 millionths/°C) is frequently used. If greater accuracy is needed, tests should be made on the high-strength concrete mixture in question.

The thermal properties of high-strength lightweight concrete are improved over normal-density concrete. Its thermal coefficient of expansion is slightly lower than normal-density concrete. Its thermal conductivity is dependent largely on unit weight; the nonlinear relationship between the two means that a one-third reduction in weight lowers the \(k\)-value by as much as one-half.\(^{(30)}\) This, and the fact that the aggregate has been subjected to temperatures of over 2000°F (1100°C) during its manufacture, means that HSLWC is quite stable at high temperatures.\(^{(30)}\)

### Adiabatic Temperature Rise

The extent to which hydration of cement raises the temperature of concrete depends on the size of the concrete element and its environment. Heat dissipation depends on the type of form, amount of exposed surface, and ambient temperatures at the various surfaces of concrete. The low thermal conductivity of concrete results in a slow rate of heat exchange between concrete and its surroundings. Therefore, at early ages, heat is generated in concrete at a higher rate than it can be transmitted to exposed surfaces.
The result is a heat buildup approximating adiabatic conditions. Departure from adiabatic conditions is greatest near the cooling surfaces.

The elevated temperatures due to heat generation in high-strength concrete will have no detrimental effects on compressive strength and, in fact, may produce a slight increase in strength. A study of commercially available high-strength concretes revealed that cores from near the surface and those at the center of a 4-ft (1220-mm) cube did not have significantly different strengths, even though a maximum temperature differential of 30°F (14°C to 17°C) was attained during early curing (see Fig. 26). This indicates that the early heat rise in the center of the cubes did not measurably affect core strengths. Still, in massive sections, such as large columns and transfer girders, it may be necessary to consider limiting the amount of temperature rise above the final stable temperature by reducing the temperature of the concrete as placed to avoid temperature stresses.

Thermal stresses occur as the temperature of the concrete rises and then drops essentially to the temperature of its surroundings. The temperature at the center of a concrete member is higher than that at the exposed surfaces. Thus, as the outer surface cools and tends to shrink, compressive stresses are set up in the center and tensile stresses in the cooler outer surfaces. When these tensile stresses become greater than the tensile strength of the concrete, cracking occurs. However, cracking is not expected to occur any more frequently in high-strength concrete than in normal-strength concrete because of the rapid compressive strength development in HSC and corresponding tensile strength increases.

Heat generation of the concrete depends on the cement content, water-cement ratio, and the heat of hydration of the cement used. The heat generated per unit volume of concrete is directly proportional to the cement content. Additionally, low water-cement ratios increase the rate of heat generation. Together, the relatively low water-cement ratios and high cement contents tend to increase the heat of hydration of high-strength concrete as compared to normal-strength concrete. The heat rise in HSC will be approximately 10°F to 12.5°F per 100 lb of cement per cu yd (9.4°C to 11.7°C/100 kg of cement/m³).

**Bond of Concrete to Steel**

The bond of concrete to steel increases with increases in compressive strength of the concrete and with the incorporation of a superplasticizer into the concrete. The ultimate bond stress varies approximately as the ratio of bar embedment length to bar diameter, \( l_a/d_b \), and as the square root of the compressive strength (\( \sqrt{f'_c} \)). The resulting relationship of bond to compressive strength is curvilinear, that is, bond strength increases less rapidly as the compressive strength of the concrete is increased. The ACI Building Code establishes a maximum value of 100 psi for \( \sqrt{f'_c} \). This means that reduction in the development length of reinforcing bars is not allowed for concrete strengths in excess of 10,000 psi (69 MPa). For commercially available high-strength concretes, materials technology is outpacing available engineering information.

Since the compressive strength, and therefore tensile and flexural strength, of lightweight concrete is lower, especially when the concrete is air-cured as is usually the case at a jobsite, ACI 213R recommends a modification of the development length of reinforcing bars. The bond strength will be adversely affected and the embedment length will have to be increased to compensate for the reduction of bond. Fortunately, the reduction in dead load provided by lightweight concrete works in favor of the embedment length and may even completely offset the changes associated with reduced strength. However, in no case should the reinforcing bars have shorter development lengths than for normal-density concrete of equal compressive strength.
CHAPTER 6
General

Applications, Advantages, and Limitations
At present, high-strength concrete is a specialized material. It has had a major impact on high-rise buildings. It can solve certain design problems, but may not be the only method of doing so. By carrying loads more efficiently than conventional concrete and reducing the total amount of material placed, using HSC will lower the overall cost of a structure.

Many years may be required to develop adequate strength-cost-mixture proportion data, and the thorough analysis needed to put it to use, but the cost savings to be realized are well worth the effort.

Cost/benefit data from a ready mix company have been plotted as a set of curves in Fig. 27, making it easy to see that cost optimization is possible with high-strength concrete.

The method of optimizing the cost of concrete itself is multifaceted, beginning with material selection, mixture proportioning, etc., and ending with determination of the lowest cost per allowable stress (cents per psi or MPa). It should be noted that the types of curves shown in Fig. 27 are unique to each ready mix supplier.

The process of cost optimization of a structure involves more than just optimizing the cost of concrete; it also includes optimizing costs of rein
forcement, formwork, and labor. All these cost data should be considered, but the emphasis must still return to producing a quality concrete having the desired fresh and hardened properties. As mentioned earlier, the decision to go into production of HSC should not be undertaken lightly. It is a process that evolves over time and each bit of knowledge gained will improve the succeeding attempts at mixture proportioning.

Another factor that influences the choice of this material is need: Though the cross sections of structural elements can be reduced, is HSC actually necessary? Would regular-strength or lightweight concrete do the job just as well—or better? Floors of high-rise buildings are often constructed of sanded structural lightweight concrete—the coarse aggregate is lightweight and the fine aggregate is natural sand—to reduce the dead load of a structure. For parking structures, tall buildings, or any building with very large loads, space savings are being realized through the use of HSC.

It is increasingly common for high-rise buildings to be constructed with at least some HSC. To date, one of the most widely used applications of HSC has been for columns in high-rise reinforced concrete buildings where the weight of concrete in the column itself is of relatively little concern. Fig. 28 illustrates a building under 10 stories high that benefited from the use of HSC. In this structure, irregular floor plans and unusual structural configurations were more easily accommodated than would have been with normal-strength concrete. HSC has also been used in several buildings to provide increased lateral stiffness to resist wind loads.

Bridges should soon realize even greater benefits using HSC, especially if durability (see Chapter 5) can be enhanced without sacrificing strength. Studies were recently completed at Construction Technology Laboratories, Inc. to determine the feasibility of producing high-strength concrete bridge members by mass production techniques. Results from this testing program will serve as a guide to future design, construction, and acceptability of HSC prestressed girders (see Fig. 29).9,29

Finally, there is the uncertainty about HSC: What does it do? What doesn’t it do? What can it do? What can’t it do? Long-term observations of in-place HSC members will reveal not only a better understanding of the material, but also—based on how the material performs—new ideas for potential uses. While more research on the material and its engineering properties will be beneficial, organizing, combining, and utilizing existing information is of equal, if not greater, urgency.

A small group of engineers from the United States, Japan, Australia, and New Zealand recently met for three days in Kyoto, Japan to discuss the future of HSC. Their goal was to look at the considerable amount of existing research and decide how best to put it to use. The outcome of this planning meeting was that small groups would write state-of-the-art reports on the structural aspects of this material. As ambitious as this project is, it is still limited in scope, dealing only with the following structural topics: (1) compression members, (2) flexural members, (3) anchorage and bond, (4) shear and torsion, (5) beam-column joints, (6) design practice, and (7) confinement.

Special Materials
In the research and development stage are two classes of materials, both modifications of portland cement concretes. They are “densified systems containing homogeneously arranged ultrafine particles” or DSP products, and macro-defect free “cements” or MDF products.

DSP products are similar to high-strength concrete at this time because both use silica fume to impart additional strength to the material. The physical and chemical densification of the paste helps to improve not only the compressive strength, but tensile and flexural strengths as well (see box).9

MDF products may be based on portland cement or calcium aluminate cement and incorporate a water soluble polymer in a mixture with a limited amount of water. Polymer chains are absorbed onto the

Fig. 28. Georgia’s Fulton County Judicial Center in Atlanta is another benchmark for high-strength concrete, placing the material in a major public building under 10 stories in height.
cement grains, and as hydration proceeds, the hydration products are deposited in and around the polymer chains. Hydration further depletes the supply of water so that the polymer chains dehydrate and exert strong contractile forces on the system.(22)

MDF cements may hold more promise for development than DSP products, but by varying the type of aggregate, cement, chemical admixtures, and processing and curing methods, both products have the potential to be used for much more than simple building materials. Although these products often employ "exotic" materials or processes, new technology developed for either type might eventually enhance the properties and performance of present-day high-strength or high-performance concrete.

Fig. 29. The first of several 10,000-psi (69-MPa) high-strength prestressed concrete girders tested in flexure at Construction Technology Laboratories, Inc., Skokie, Ill. The girder reached a deflection of 24 in. (610 mm) before the maximum load was achieved.

ADVANCED CEMENT-BASED MATERIALS: RESEARCHERS BREAK THE 100,000-PSI BARRIER

Prof. J. Francis Young (University of Illinois) and Dr. Ping Lu (visiting scholar from Tongji University, China) have produced cement compacts with compressive strengths exceeding 100,000 psi (690 MPa). The technique employed consists of application of pressure and heat to cure samples using a cell first developed by Prof. Della Roy at Pennsylvania State University nearly 20 years ago to produce a cylindrical specimen.

Silica fume was found to be an essential ingredient for providing more efficient compaction. For example, compaction for 1 hour at 60,000 psi (410 MPa) and 320°F (160°C) gave samples with strengths of 50,000 psi (340 MPa) without silica fume, and 63,000 psi (430 MPa) with the addition of 5% silica fume at a water-silica fume ratio of 0.085. Subsequent moist curing for 28 days increased these values to 73,000 psi (500 MPa) and 89,000 psi (610 MPa) respectively.

When samples at a water-silica fume ratio of 0.073 were compacted for 2 hours and 65,000 psi (450 MPa) at 390°F (200°C), the strength obtained was 80,000 psi (550 MPa). This increased to 90,000 psi (620 MPa) after a further moist curing of 28 days. Interestingly, when the well-cured pastes were strongly dried at 390°F (200°C), strengths of the compacts containing silica fume increased to 96,000 psi (660 MPa) for the less severe compaction conditions and 106,000 psi (730 MPa) for the more severe. Microstructural analyses showed the C-S-H (calcium silicate hydrate) binding phase to be similar to that found in cast DSP cement pastes.
CHAPTER 7

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**Related Publications**

Many of the publications cited in this text and list of references, as well as other related publications, can be purchased from the Portland Cement Association. The following are particularly useful:

*Building Code Requirements for Reinforced Concrete*, LT125D

*The Chemistry of Cement and Concrete*, LT132G

*Concrete Admixtures Handbook: Properties, Science, and Technology*, LT133T

*Design and Control of Concrete Mixtures*, EB001T

*Early High-Strength Concrete for Prestressing*, RX091

*Effects of Column Exposure in Tall Structures*, EB018D

*Effects of Curing and Drying Environments on Splitting Tensile Strength of Concrete*, DX141

*Engineering Properties of Commercially Available High-Strength Concretes*, RD104T

*An Evaluation of Some Factors Involved in Producing Very High-Strength Concrete*, RD014T

*General Relation of Heat Flow Factors to the Unit Weight of Concrete*, DX114

*“High-Performance Concrete: Removing the Myths,” Concrete Technology Today*, PL923B

*Influence of Size and Shape of Member on the Shrinkage and Creep of Concrete*, DX103

*Lightweight Aggregate Concrete for Structural Use*, DX017

*“Long-Term Properties of High-Strength Concretes,” Concrete Technology Today*, PL933B

*“Maturity Concept Determines Acceptable Strength Level,” Concrete Technology Today*, No. 4

*PCA Research on High-Strength Concrete*, RD093T

*Replacement of Lightweight Aggregate Fines with Natural Sand in Structural Concrete*, DX080

*Sand Replacement in Structural Lightweight Concrete—Creep and Shrinkage Studies*, DX128

*A Small Probe-Type Gage for Measuring Relative Humidity*, RX160

*Some Physical Properties of High-Strength Concrete*, RD056T

*Stress-Strain Characteristics of High-Strength Concrete*, RD051D

*Tensile Strength and Diagonal Tension Resistance of Structural Lightweight Concrete*, DX050

*Time-Dependent Behavior of Columns in Water Tower Place*, RD052B

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