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).

Advantages
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 compressive 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**

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 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.

Compressive Strength
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) with some estimates for very special materials ranging as high as 106,000 psi (731 MPa). As 19,000-psi (131-MPa) concretes have already been batched, 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.

Production, Optimization, Testing
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 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.

References
3. “ACBM researchers break the 100,000 psi barrier,” Cementing the future, National Science Foundation Center for Science and Technology of Advanced Cement-Based Materials, Northwestern University, Evanston, Illinois, Fall 1992, page 8.

Autoclaved Cellular Concrete Update

A demonstration tour of U.S. electric utility plants continues to pick up steam as testing progresses on production of a specialty concrete that is popular around the world but has never before been widely used in the United States.

The Electric Power Research Institute’s North American Cellular Concrete (NACC) tour is now at the Tennessee Valley Authority in Chattanooga, Tenn. TVA is the sixth of eight stops for a mobile plant capable of producing sample blocks of autoclaved cellular concrete (ACC), a lightweight building material for structural and architectural applications (floors, roofs, walls, etc.).

The tour is demonstrating small-scale production possibilities of a material that has eluded much of North America, particularly the United States, for a variety of market-related and financial reasons. NACC believes it can overcome a chief obstacle of the past—plant start-up costs of $20-$50 million—with small production assemblies costing in the $3-$5 million range.

While by no means the first attempt to bring ACC to U.S. markets—efforts date to the 1920’s—NACC has a few new twists: lower equipment costs and an ACC mixture design that substitutes fly ash for sand.

NACC and EPRI have timed the effort to cope with management and disposal of large volumes of fly ash. Equally timely, although not immediately exploitable due to the uncertainty of permanent ACC production facilities, is the timber crisis, which has left the construction industry, especially home builders, grappling for alternatives to wood frame construction.

ACC, also known as aerated concrete, is produced by mixing portland cement, lime, aluminum powder, and water with a large proportion of a silica-rich material. In lieu of silica sand, NACC is using fly ash from its host utility plants. Project managers have opted to use Type III cement in each of the mixtures, partly due to the variety of fly ashes. When mixtures are batched into a mold, the aluminum powder reacts chemically to create millions of tiny hydrogen bubbles, causing the material to expand to nearly twice its volume.

Following removal from the mold, the foam-like material is wire cut into blocks or slabs and moved into an autoclave—an airtight chamber with pressurized steam. Autoclaving for 10 to 12 hours spurs a second chemical reaction that gives the highly porous material its strength, rigidity, dimensional stability, and other unique properties (see box). Typical ACC compressive...
Concrete in a Marine Environment

Seawater contains significant amounts of sulfates and chlorides. Although sulfates in seawater are capable of attacking concrete, the expansive reaction that is characteristic of sulfate attack. Calcium sulfoaluminate, the reaction product of sulfate attack, is more soluble in a chloride solution and can be more readily leached out of concrete, thus resulting in less destructive expansion. This is a major factor explaining observations from a number of sources that the performance of concrete in seawater with portland cement having tricalcium aluminate (C₃A) contents as high as 10%, and sometimes higher, have shown satisfactory durability, providing the permeability of the concrete is low and the reinforcing steel has adequate cover.

The maximum permissible water-cement ratio for the submerged portion of a structure is 0.45 by weight. For portions in the splash zone and above, the maximum permissible water-cement ratio is 0.40 by weight. Water-cement ratios as high as 0.50 by weight may be used provided the C₃A content of the cement does not exceed 8%.

Cements meeting the requirements of ASTM C150, Specification for Portland Cement, and ASTM C595, Specification for Blended Hydraulic Cements, and meeting the C₃A requirement noted above, that is, not more than 10%, are acceptable for concrete in a marine environment. In the case of C595 blended cements, this limitation applies only to the portland cement clinker used in the blended cement.

In addition to the proper selection of cement and water-cement ratio, other requirements for securing economical and durable concrete in a marine environment include: (1) adequate air entrainment, (2) low slump, (3) adequate consolidation, (4) uniformity of batching, mixing, transporting, and placing, (5) a smooth finish free from surface voids and other defects, (6) adequate concrete cover over reinforcement [minimum 2 in. (50 mm), preferably 3 in. (75 mm)], and (7) sufficient curing to develop the required impermeability and other desired properties of the concrete.

For More Information
may be produced by intergrinding or other blending processes. C1157 does require that the ingredients of the blended cement be reported and that the ingredients, including processing and functional additions, independently meet any applicable specifications.

“This really is a unique development,” notes Steven Kosmatka, who as PCA’s manager of research and development tracks specifications and standards in the cement industry and serves on several ASTM committees. “For the cement industry, it’s our first foray into performance specifications.”

Six Types
C1157 sets physical requirements for the following six types of blended cement, mirroring the attributes of ASTM’s C150 cement types:

<table>
<thead>
<tr>
<th>Type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>GU</td>
<td>Blended cement for general construction use when a specialized type is not required</td>
</tr>
<tr>
<td>HE</td>
<td>High Early Strength</td>
</tr>
<tr>
<td>MS</td>
<td>Moderate Sulfate Resistance</td>
</tr>
<tr>
<td>HS</td>
<td>High Sulfate Resistance</td>
</tr>
<tr>
<td>MH</td>
<td>Moderate Heat of Hydration</td>
</tr>
<tr>
<td>LH</td>
<td>Low Heat of Hydration</td>
</tr>
</tbody>
</table>

In addition, any of the above types may be designated with Option R—Low Reactivity with Alkali-Reactive Aggregates. If Option R is invoked, the cement should be tested using ASTM Test Method C227, which uses crushed borosilicate (Pyrex) glass as the reactive aggregate. The expansion during this test should not exceed 0.020% at 14 days or 0.060% at 56 days. Additionally, pozzolans used in any blended cement also should be tested using C227 with a nonreactive sand to determine whether they have any potential for alkali-reactivity.

Optimizing Cements
As noted earlier, the new standard does not replace ASTM’s existing C595 standard; the new designations for six types of blended cement are simply an additional way to specify blended cements. “It gives cement companies far more leeway in formulating their product,” concedes Kosmatka. “For the first time, manufacturers can truly optimize cement, using ingredients available to them without the limitations of recipe specifications.”

Ultimately, performance-specified blended cements could spawn a new breed of products—special formulations that address specific customer needs such as resistance to alkali-aggregate reaction and sulfate reaction, to name two.

There are also environmental considerations. Blending portland cement with materials such as fly ash, ground granulated blast-furnace slag, kiln dust, or limestone means less embodied energy and reduced carbon dioxide emissions. And in the case of kiln dust, slag, fly ash, and other mineral byproducts, it’s a way to recycle waste materials into cement.

Acceptance?
But don’t expect an overnight shift from recipe to performance specifications; publication of the standard is only the beginning. It has yet to be accepted by ASTM C94 Specification for Ready-Mixed Concrete, the ACI 318 Building Code, ACI 301 Specifications for Structural Concrete for Buildings, and other important standards and codes organizations, a process that could take the rest of this decade. Moreover, acceptance may be only the first hurdle. Historically, U.S. specifiers have shied away from blended cements, perhaps finding a tandem set of cement types confusing. Adding a third set—C1157—to the existing C150 and C595 specifications may further complicate cement choices.

In any case, if use of a blended cement under ASTM C1157 is contemplated, or an order is placed, a request should be made for the manufacturer’s certification, which is discussed in Section 14 of the standard. This section requires the manufacturer to provide results of tests and chemical analyses and a list of specific constituents and functional additions, if any, contained in the cement specified.


New Research Results Announced
The following new research and development bulletins are now available. To purchase any of these bulletins in the United States, contact Portland Cement Association, Order Processing, P. O. Box 726, Skokie, IL 60076-0726; telephone 1-800/868-6733, or fax 708/966-9666 (24 hours a day, 7 days a week). In Canada please direct requests to the nearest regional office of the Canadian Portland Cement Association (Halifax, Montreal, Toronto, and Vancouver).

Guide Specification for Concrete Subject to Alkali-Silica Reactions, IS415T
This 8-page document, authored by the Portland Cement Association’s Alkali-Silica Reactivity/Pavement Durability Task Group, provides specifiers and engineers guidance with state-of-the-art approaches to control alkali-silica reactivity (ASR). The guide is compiled from the best of U.S., Canadian, and European approaches, including the Strategic Highway Research Program.

Alkali-silica reactivity (ASR) has been reported worldwide since 1940. Fortunately most concrete is not affected by this condition. Although
the risk of catastrophic failure and the number of affected structures are low, ASR-induced cracking can exacerbate other deterioration mechanisms such as occur in frost, deicer, or sulfate exposures. ASR can be controlled by the methods presented in this guide specification.

Most aggregates are chemically stable in hydraulic cement concrete without deleterious interaction with other concrete ingredients. However, this is not the case for concrete containing certain siliceous aggregates, resulting in detrimental expansion and cracking of concrete structures. The guide concisely informs the specifier how to determine if aggregates are potentially reactive by using petrography, a rapid mortar bar test (ASTM P214), and the Canadian concrete prism test. The guide provides three options to control ASR and methods to determine the effectiveness of mineral admixtures and blended cements.

This guide specification is modeled after the document Using Guide Specifications for Concrete Subject to Alkali-Silica Reactions published by the Mid-Atlantic Regional Technical Committee in 1993. As this group consisted of local concrete users, material suppliers, consulting engineers, and state transportation engineers, it focused on a regional approach to ASR. The PCA-version is designed to be used on a national level by owners, transportation and structural engineers, and others to provide safeguards against the occurrence of ASR failures.

Comparison of the Performance of Concretes Made with ASTM and AASHTO Type II Cements/Survey of Cement Specifications in Concrete Pavement and Bridge Construction, RP320T

Presently, there are two specifications for Type II cement, ASTM and AASHTO. The great majority of cements are produced under ASTM specifications, but many state highway projects require cements made to AASHTO specifications. For AASHTO Type II cements there is a maximum limit of 55% on C₃S whereas for ASTM Type II cements, this parameter is not limited. Other than a slightly more restrictive limitation on fineness for the AASHTO Type II cements, there are no other differences in the two cement specifications. To investigate if concrete properties differ as a result of using the different Type II cements, two pairs of cements were obtained, each pair included one ASTM Type II cement and one AASHTO Type II cement. Each pair was obtained from a single plant. Concretes were made with these cements using an identical mix design representative of paving applications. Fresh concrete properties, potential for plastic shrinkage cracking, heat development, compressive strength development, and drying shrinkage were measured for each concrete made with each cement. Results show there is little difference in concrete properties as a result of using either ASTM or AASHTO Type II cements.

Complete DX, RX, and RD Series, RX300

This newly compiled series is a collection of technical information from more than 50 years of research by the Portland Cement Association—over 500 bulletins—on cement and concrete. This complete set of all Development (DX), Research (RX), and Research and Development (RD) bulletins from 1939 to 1994 addresses hundreds of cement and concrete technology subjects. Air entrainment, alkalis, hydration, chemical analysis, strength, creep, durability, long-time properties, modulus of elasticity, pozzolans, temperature effects, and water content are just a few of the topics covered. As an aid in data searches, a comprehensive subject and author index (RD100T), which includes an abstract for each bulletin, is included with every order.

Few other sources provide so much cement and concrete information in so well-organized and concise a form. RD100T is also available in microcomputer database formats, further easing the process of information retrieval. Some of the out-of-print bulletins are available only as photocopies.

Fire Test of Concrete Beams Reinforced with Epoxy Coated Bars, RP321B

This 14-page research report presents the results of fire tests on concrete beams reinforced with epoxy-coated bars. Funded jointly by PCA and the Concrete Reinforcing Steel Institute, this study determined the fire endurance of two full-size concrete beams.

Both beams were 12x14-in. (300x350-mm) by 32-ft (9.8-m) long and made with carbonate aggregate concrete. Each was subjected to a fire test following the provisions outlined in ASTM E119, Standard Test Methods for Fire Tests of Building Construction and Materials. During the fire test the beams were loaded to simulate the end span of a continuous member, such that the applied moments at midspan and over the continuous support were equivalent to 40% and 50% respectively of the nominal moment strengths at corresponding sections. Tests were discontinued when the beams showed signs of imminent structural failure. Beam A was designed in accordance with ACI 318-83 provisions whereas Beam B met design criteria for the ACI 318-89 code. The mea-
Tilt-Up Walls Test Results, RP322D

This 20-page research report presents the results of experimental tests to supplement existing physical test data on various slender tilt-up walls. Furthermore, this work expands available test information through a series of experimental tests to include other types of tilt-up walls commonly seen in practice, such as walls with two layers of reinforcement, isolated footings, concentrated loads, and panels with openings. Authors A. Azzinamini, J. D. Gilkin, and R. G. Oesterle made three significant conclusions based on these tests:

- It was found that tilt-up walls with aspect ratios, h/t, as large as 60 can continue to sustain combined axial and lateral loads while loaded to deflected shapes well beyond wall cracking and first yield of reinforcement.
- Walls reinforced with two layers of reinforcing bars, one layer located near each face, provide a stiffer wall with higher ductility when compared to a wall with an equivalent total amount of reinforcement placed in one layer at the panel midthickness.
- A decrease in the size of isolated footings did not have a significant effect on the observed behavior or measured capacity of the tilt-up wall specimens.

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