Guide to Quality Control and Testing of High-Strength Concrete

Reported by ACI Committee 363

John A. Bickley*
Chairman

Pierre-Claude Aïtcin	Said Iravani	Henry G. Russell*
Scott D. Alexander	Tarif M. Jaber	Michael T. Russell*
Ronald G. Burg*	Anthony N. Kojundic	Kenneth L. Saucier
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Kingsley D. Drake	William F. Perenchio	John T. Wolsiefer
A. Samer Ezeldin	Michael F. Pistilli*	J. Francis Young
Michael R. Gardner	William F. Price	Paul Zia
Neil R. Guptill	Vaughn R. Randall	

* Members of task groups that developed this guide.

The special quality control and testing needed to measure reliably the strength of specimens of high-strength concrete and to achieve high-strength concrete consistently are discussed. Preconstruction and construction procedures are covered, including planning trial mixtures, preconstruction meetings, batching, placing, curing, and testing. The concept of prequalifying suppliers and laboratories is introduced. A method for the evaluation of data is included.

Keywords: batch-plant inspection; core tests; curing; high-strength concrete; in-place testing; inspection; placing; preconstruction meeting; prequalification; quality control; sampling; testing; trial batches.

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ACI 363.2R-98 became effective May 5, 1998.

CHAPTER 1—INTRODUCTION

1.1—Scope

This guide discusses quality control and testing practices of high-strength concrete. High-strength concrete usually is associated with structures that have been optimized for performance. Therefore, a high degree of confidence in concrete quality must be achieved through the inspection and testing process. This process can be conducted by the producer and contractor as quality control and by the owner or the owner's representative as quality assurance. Those involved in quality control and testing need to know the unique characteristics of high-strength concrete to better assist the Architect/Engineer in evaluating the structure's potential performance.

Concrete with a specified compressive strength of 70 MPa (10,000 psi) can be produced from local aggregates in all areas of the U.S.A. and Canada. When the specified strength substantially exceeds that produced previously in a particular market area, special measures are necessary to make a successful progression to the use of the higher-strength concrete. This guide details those measures.

1.2—Objectives

The cement and concrete industry's interest in high-strength concrete prompted the American Concrete Institute to form ACI Committee 363 in 1979. The mission of the committee was to study and report information on high-strength concrete. ACI 363R-84, "State-of-the-Art Report on High-Strength Concrete," was the first document produced by this Committee. That report contained significant information regarding material selection, mixing and placing, inspection and testing, physical properties, structural design, economics, and examples of applications. It was updated in 1992.

This guide is an extension of ACI 363R, and presents guidelines to facilitate the proper evaluation of high-strength concrete through correct quality control and testing. High-strength concretes may be produced with innovative materials and procedures not covered in this guide. This guide is not intended to restrict the use of new or innovative quality control practices or testing methods as they become available or necessary. The user is cautioned that this guide is for general usage only, and individual projects may require additional quality control and testing effort.

1.3—Definition of high-strength concrete

Since the definition of high-strength concrete has changed over the years, the Committee defined a range of concrete strengths for its activities, as explained in ACI 363R. For the purpose of this guide, high-strength concrete is defined as having a specified compressive strength of 40 MPa (6000psi), or greater, and it does not include concrete made with exotic materials or techniques. The word "exotic" indicates special concretes, such as polymer-impregnated concrete, epoxy concrete, or concrete made with artificial normal-weight and heavy-weight aggregates.

Although 40 MPa (6000 psi) is the current dividing line between normal-strength and high-strength concrete, this compressive strength level is not associated with drastic changes in material properties, production and inspection techniques, or testing methods. In reality, changes occur continuously from lower-strength to higher-strength concretes. However, experience shows that in most cases, the special measures recommended in this guide should be applied for concrete with compressive strength greater than about 55 MPa (8000 psi).

CHAPTER 2—PLANNING

2.1—Introduction

Quality control and testing of high-strength concrete are more critical than is the case for normal-strength concrete, because seemingly minor deviations from specified requirements can result in major deficiencies in quality or test results. For example, it is well documented (Carino et al. 1994) that compressive-strength test results are more sensitive to testing conditions as the strength of the concrete increases.

The quality of high-strength concrete is controlled by the quality and uniformity of the ingredients, and by the mixing, placing, and curing conditions. A high level of quality control is essential for those involved in the production, testing, transportation, placing, and curing of the concrete. Careful consideration of placing restrictions, workability, difficulties during transportation, field curing requirements, and the inspection and testing process is required. Thorough planning and teamwork by the inspector, contractor, Architect/Engineer, producer, and owner are essential for the successful use of high-strength concrete.

This chapter reviews critical activities prior to the start of construction. A preconstruction meeting is essential to clarify the roles of the members of the construction team and review the planned quality control and testing program. Special attention is required during the trial-batch phase to assure that selected mixtures will perform as required under field conditions. Planning for inspection and testing of high-strength concrete involves giving attention to personnel requirements, equipment needs, test methods, and the preparation and handling of test specimens. Additional general information on the inspection of concrete is contained in ACI 311.4R.

2.2—Preconstruction meeting

Small variations in mixture proportions and deviations from standard testing practices can have greater adverse effects on the actual or measured strength of high-strength concrete than with normal-strength concrete. Therefore, project participants should meet before construction to clarify contract requirements, discuss planned placing conditions and procedures, and review the planned inspection and testing programs of the various parties. The effects on the concrete of time, temperature, placing, consolidation, and curing should be reviewed. Acceptance criteria for standard-cured test specimens, in-place tests, and core test results should be established. The capabilities and qualifications of the contractor's work force, the inspection staff, and the testing and batching facilities also should be reviewed.

The preconstruction meeting should establish lines of communication and identify responsibilities. It is especially important to review the procedures the inspector will follow when noncompliance with contract requirements is found or suspected. Such advance understanding minimizes future disputes, and allows members of the construction team to participate in the quality process. Timely and accurate reporting are important. Arrangements should be made to distribute inspection reports and test data as soon as possible. Trial production batches should have established a workable mixture, but it may be necessary to make adjustments due to site conditions, such as changing weather. Since high-strength concrete relies on a low water-cementitious materials ratio for strength potential, responsibility for field addition of water and admixtures should be discussed and defined clearly. The ready-mixed concrete producer is essential to that discussion since the producer is familiar with and responsible for the product. Individuals should be identified, such as the concrete supplier's quality control personnel, who will have the authority to add admixtures or water at the site. To permit verification that the concrete provided conforms to established requirements, procedures should be established for documenting what, when, and how much was added to the concrete at the site.

2.3—Trial batches

Data on some high-strength concrete mixtures used previously are given in Tables 2.3.1 to 2.3.3. These data are provided only for guidance, and trial batches with local materials would supersede these tables for specific projects. ACI 211.4R provides guidance on proportioning some high-strength concrete mixtures.

Where historical data are not available, the development of an optimum high-strength concrete mixture requires a large number of trial batches (Blick et al. 1974; Cook 1982). Materials and proportions initially should be evaluated in the laboratory to determine the appropriate material proportions and their relative characteristics. Sufficient lead time should be allowed, since high-strength mixtures containing fly ash, silica fume, or ground granulated blast furnace slag often are evaluated at 56 and 90 days. After the work has been completed in the laboratory, production-sized batches are recommended because laboratory trial batches sometimes exhibit strengths and other properties different from those achieved in production. For instance, the efficiency of small laboratory mixers is much less than that of production mixers, which can affect the dispersion and performance of chemical and mineral admixtures. Since high-strength concretes usually contain both chemical and mineral admixtures, including silica fume, and a high volume of cementitious materials, they tend to be more sticky than conventional concrete mixtures. Production trials can be used to establish optimum batching and mixing sequences that can reduce problems prior to the start of the project. Where truck mixing is used, the maximum load that can be mixed adequately should be determined, but practice has shown that this usually is less than 90 percent of the truck's rated mixing capacity. Based on experience, batches of high-strength concrete smaller than 3 m^3 (4 yd^3) should not be mixed in truck mixers.

2.4—Prequalification of concrete suppliers and preconstruction testing

Bidders should be prequalified prior to the award of a supply contract for concrete with a specified strength of 70 MPa (10,000 psi) or higher, or at least 7 MPa (1000 psi) higher than previously produced in the market local to the project. The implications of the project specifications, whether prescription- or performance-based, should be fully understood by all bidders.

Trial batches—The complexity of the prequalification process depends on local experience. Where the specified strength has been widely produced for previous projects, a review of available test data may adequately measure performance. When a strength higher than previously supplied is specified, or where there is limited experience in the supply of that strength concrete, a more detailed prequalification procedure should be carried out. This should generally include the production of a trial batch of the proposed mixture proportions. The trial concrete should be cast into monoliths representative of typical structural sizes on the project. Fresh concrete should be tested for slump, air content, and temperature. Hardened concrete should be tested to determine compressive strength and modulus of elasticity based on standard-cured cylinders and on cores drilled from the monolith. Strengths of cores and standard-cured cylinders tested at the same age should be correlated. In massive elements, core strength may vary with distance from the surface due to different temperature histories. Therefore, relationships should be established for a specific core depth. If cores need to be removed during construction, the correlation allows interpretation of core strength results. The monolith also should be instrumented to determine the maximum internal temperature and the temperature gradients developed throughout the cross section.

Qualified suppliers can be selected based on their successful preconstruction trials. After the start of construction, further trials are desirable to confirm the field performance of the submitted and accepted mixtures. Further testing may also be required on full-scale mock-ups of structural subassemblages to determine the potential for cracking problems, such as at the interface between structural elements of different thickness.

Provisions in the project specifications for concrete with a specified strength of 70 MPa (10,000 psi) or higher, or at least 7 MPa (1000 psi) higher than previously supplied, should assign the concrete supplier responsibility for quality control of the mixed concrete and its ingredients.

Variations in temperature and humidity during the project may adversely affect the characteristics of the concrete. Laboratory and field tests should be performed to evaluate the effects of environmental conditions on the properties of freshly-mixed and hardened concrete. In particular, slump loss between the batch plant and the project site should be evaluated to assure adequate slump at the time of placing. During periods of high temperature or low humidity, it may be necessary to adjust the concrete mixture using retarding or high-range water-reducing admixtures in varied dosage rates and addition sequences.

In-place strength—It is also useful to correlate accelerated and in-place tests with standard cured cylinders following the procedures in ACI 228.1R. The potential strength of concrete supplied to a site cannot be known too soon. Any serious shortfall of in-place strength is better discovered early rather than late. If in-place testing is to be used, it is recommended that a correlation with standard-cured cylinders be made at the prequalification trials. ACI 228.1R provides guidance on the limitations of various in-place test methods.

Air entrainment—For air-entrained mixtures, close control of air content is required. The air content and resulting air-void system in the hardened concrete is particularly important for high-strength concrete subjected to cycles of freezing and thawing under moist conditions. High-strength concrete has excellent resistance to freezing and thawing if it contains an appropriate volume of air and an adequate air-void system. ACI 201.2R gives requirements for total air content and ACI 212.3R lists requirements for air-void parameters for protection against damage from freezing and thawing. ACI 212.3R characterizes a satisfactory air-void system as having a spacing factor of 0.20 mm (0.008 in.) or less, and a specific surface of 24 mm^2/mm^3 (600 $in.^2/in.^3$) or greater. Some high-strength concretes, including concretes with low air contents (less than 4 percent) and coarse air-void systems (spacing factors greater than 0.20 mm or 0.008in.) have proven durable in freezing and thawing environments (Philleo 1986). If a high-strength concrete does not have an air-void system meeting the recommendations of ACI 201.2R and ACI 212.3R, its resistance to freezing and

Table 2.3.1—Composition of experimental concretes produced in a ready-mixed concrete plant (CPCA 1995)

Mixture ingredients and concrete properties	Concrete type				
	Reference	Silica fume	fly ash	Slag + silica fume	
Water-cementitious materials ratio	0.30	0.30	0.30	0.30	0.25
Ingredients, kg/m^3 (lb/yd^3)					
Water	127 (214)	128 (216)	129 (217)	131 (221)	128 (216)
Cement ASTM Type II	450 (759)	425 (716)	365 (615)	228 (384)	168 (283)
Silica fume	—	45 (76)	—	45 (76)	54 (91)
Fly ash	—	—	95 (160)	—	—
Slag	—	—	—	183 (308)	320 (539)
Dolomitic limestone					
Coarse aggregate	1100 (1850)	1110 (1870)	1115 (1880)	1110 (1870)	1110 (1850)
Fine aggregate	815 (1370)	810 (1370)	810 (1370)	800 (1350)	730 (1230)
HRWR,* L/m^3 (fl oz/yd^3)	15.3 (395)	14 (362)	13 (336)	12 (310)	13 (336)
Slump					
after 45 min, mm (in.)	110 (4 $^1/_4$)	180 (7)	170 (6 $^3/_4$)	220 (8 $^3/_4$)	210 (8 $^1/_4$)
Average compressive strength					
at 28 days, MPa (psi)	99 (14,360)	110 (15,950)	90 (13,050)	105 (15,230)	114 (16,530)
at 91 days, MPa (psi)	109 (15,810)	118 (17,110)	111 (16,100)	121 (17,550)	126 (18,280)
at 1 year, MPa (psi)	119 (17,260)	127 (18,420)	125 (18,130)	127 (18,420)	137 (19,870)

*High-range water-reducer for these mixtures was a sodium salt of a naphthalene sulfonate.

thawing and deicer scaling should be evaluated by laboratory testing according to ASTM C 666 and ASTM C 672. Samples for these tests should be obtained from concrete produced and placed in a manner consistent with anticipated field methods. While there is some controversy among researchers as to exact limits, it is believed that only concretes with exceptionally low water-cementitious materials ratios (less than 0.21) and high compressive strength (greater than 135 MPa or 20,000 psi) are likely to be resistant to freezing and thawing damage without air-entrainment. However, existing codes require air entrainment in concretes exposed to freezing and thawing, irrespective of strength level.

Achieving and maintaining a satisfactory air-void system in high workability mixtures containing high-range water-reducing admixtures can be difficult, especially when the concrete is placed by pumping (Lessard et al. 1996). Pumping over long distances with upward or downward vertical runs can reduce the number of small air bubbles, and increase the number of larger ones. This can increase the spacing factor to an unacceptable value. Therefore, it is important that the air-void characteristics be evaluated on hardened samples taken at the point of placing the concrete.

Temperature considerations—Each high-strength concrete mixture has unique heat evolution and heat dissipation characteristics for a particular curing environment. Maximum temperatures and thermal gradients, and their effects on constructability and long-term design properties, should be determined during preconstruction trials. Computer simulation of the likely thermal history can be used to establish appropriate curing and protection (Roy et al. 1993). In addition, temperature-matched curing systems may be used to evaluate the effects of temperature history on strength development (Wainright and Tolloczko 1983).

The higher cement contents of high-strength concrete develop high internal concrete temperatures and thermal gradients in excess of 20 C/m (11 F/ft) are possible, especially in uninsulated mass placements. However, Burg and Ost (1992) have shown that thermal gradients were similar to those for conventional-strength concretes. Tests on 1 m (3 ft) square columns (Cook et al. 1992) showed lower cracking tendency in high-strength concrete due to thermal gradients because of the higher internal tensile strengths at any given age. Burg and Ost (1992) have shown that in-place strength and stiffness were not adversely affected where the maximum internal

Table 2.3.2—High-strength concrete mixtures used for different projects (CPCA 1995)

Mixture ingredients and concrete properties	Mixture number*					
	1	2	3	4	5	6
Water-cementitious materials ratio	0.35	0.37	0.27	0.31	0.25	0.25
Ingredients, kg/m^3 (lb/yd^3)						
Water	195 (329)	165 (278	135 (228)	145 (244)	130 (219)	134 (226)
Cement	505 (851)	451 (760)	500 (843)	315 (531)	513 (865)	416 (701)
Silica fume	—	—	30 (15)	36 (61)	43 (72)	34 (57)
Fly ash	60 (101)	—	—	—	—	—
Slag	—	—	—	137 (231)	—	—
Coarse aggregate	1030 (1740)	1030 (1740)	1100 (1850)	1130 (1900)	1080 (1820)	1100 (1850)
Fine aggregate	630 (1060)	745 (1260)	700 (1180)	745 (1260)	685 (1160)	710 (1200)
Admixtures, L/m^3 (fl oz/yd^3)						
Water reducer	0.98 (25)	—	—	0.90 (23)	—	—
Retarding admixture	—	4.50 (116)	1.80 (47)	—	—	0.450 (12)
Air-entraining admixture	—	—	—	—	—	0.125 (3)
HRWR	—	11.25 (290)	14.00 (362)	5.90 (153)	15.70 (406)	5.00 (129)
Average compressive strength						
at 28 days, MPa (psi)	65 (9430)	69 (10,000)	93 (13,490)	83 (12,040)	119 (17,260)	75 (10,880)
at 91 days, MPa (psi)	79 (11,460)	87 (12,620)	107 (15,520)	93 (13,490)	145 (21,030)	—

*Mixture number:
1 = Water Tower Place, Chicago (1975)
2 = Joigny Bridge, France (1989)
3 = La Laurentienne Building, Montreal (1984)
4 = Scotia Plaza, Toronto (1987)
5 = Two Union Square, Seattle (1988)
6 = Portneuf Bridge, Quebec (1992)

temperature during hydration reached 78 C (172 F). The Architect/Engineer should understand the effects of heat generation in the various structural elements and address these in the project specifications (ACI 207.2R). Specifications for mass concrete often limit the temperature difference between the concrete interior and surface. On a high-rise project in Seattle, Drake (1985) established a maximum acceptable differential of 22C (40 F) between the center and exterior of a 1.8m (6 ft) cube. On a high-rise project in Montreal, Aïtcin et al. (1985) considered a gradient of 20 C/m (11 F/ft) to be acceptable. Ghosh and Bickley (1978) developed a method of calculating the maximum temperature differential to control cracking in the wall of the CN Tower. A temperature differential of 20 C (36F) was found to be acceptable for the 0.5 m (1.5 ft) thick walls.

CHAPTER 3—QUALITY ASSURANCE AND QUALITY CONTROL

3.1—Introduction

Quality assurance (QA) and quality control (QC) are defined in ACI 116R as follows:

Quality assurance—actions taken by an owner or the owner's representative to provide assurance that what is being done and what is being provided are in accordance with the applicable standards of good practice for the work.

Quality control—actions taken by a producer or contractor to provide control over what is being done and what is being provided so that the applicable standards of good practice for the work are followed.

These definitions are used in this guide. The duties of QA and QC personnel should be defined clearly in the contract documents, based on the principles set out in the ACI 116R definitions.

Comprehensive and timely QA/QC permit confidence in the use of advanced design procedures, frequently expedite construction, and improve quality in the finished product. Conversely, the results of poor QA/QC can be costly for all parties involved. QA/QC personnel must be experienced with their respective duties, including the batching, placing, curing, and testing of high-strength concrete. QA/QC personnel should be able to provide evidence of such training or experience, or both. Personnel in charge of QA/QC programs should demonstrate capabilities at least equivalent to

Table 2.3.3—Typical proportions in commercially available high-strength concrete mixtures (70 to 140 MPa or 10,000 to 20,000 psi) (Burg and Ost 1992)

Mixture ingredients and concrete properties	Mixture number*					
	1	2	3	4	5	6
Water-cementitious materials ratio	0.280	0.287	0.290	0.220	0.231	0.320
Ingredients, kg/m^3 (lb/yd^3)						
Water*	158 (266)	160 (270)	155 (261)	144 (243)	151 (255)	141 (238)
Cement, ASTM Type I	564 (950)	475 (800)	487 (820)	564 (950)	475 (800)	327 (550)
Silica fume	—	24 (40)	47 (80)	89 (150)	74 (125)	27 (45)
Fly ash	—	59 (100)	—	—	104 (175)	87 (147)
Coarse aggregate SSD†	1070 (1800)	1070 (1800)	1070 (1800)	1070 (1800)	1070 (1800)	1120 (1890)
Fine aggregate SSD	647 (1090)	659 (1110)	676 (1140)	593 (1000)	593 (1000)	742 (1250)
Admixtures, L/m^3 (fl oz/yd^3)						
HRWR, Type F‡	11.6 (300)	11.6 (300)	11.2 (290)	20.1 (520)	16.4 (425)	6.3 (163)
HRWR, Type G‡	—	—	—	—	—	3.2 (84)
Retarder, Type D	1.12 (29)	1.06 (27)	0.97 (25)	1.46 (38)	1.50 (39)	—
Slump, mm (in.)	195 (7$^3/_4$)	250 (9$^3/_4$)	215 (8$^1/_2$)	255 (10)	235 (9$^1/_4$)	205 (8)
Average compressive strength of 152 by 305 mm (6 by 12 in.) cylinders						
at 28 days, MPa (psi)	79 (11,400)	89 (12,840)	92 (13,330)	119 (17,250)	107 (15,520)	73 (10,600)
at 91 days, MPa (psi)	87 (12,550)	100 (14,560)	96 (13,920)	132 (19,120)	119 (17,310)	89 (12,850)

*Mass of total water in mixture including water in admixtures
†Maximum nominal aggregate size: Mixtures 1 to 5, 12.5 mm ($^1/_2$ in.); Mixture 6, 25.0 mm (1 in.)
‡High-range water-reducer meeting ASTM C 494

certification as an ACI Concrete Construction Inspector. Other quality control personnel should demonstrate capabilities at least equivalent to certification as an ACI Concrete Field Testing Technician—Grade I.

This chapter reviews critical issues dealing with the quality of high-strength concrete and concludes with specific recommendations for incorporation of these concerns into the QA/QC program. Some of these recommendations are not unique to high-strength concrete, but represent good practice for quality concrete in general. However, as has been mentioned, the quality of high-strength concrete can be affected adversely if care is not exercised in all phases of production, inspection, and testing.

3.2—Concrete plant

QA/QC personnel should concentrate their efforts at the concrete plant until consistently acceptable batching is achieved. Thereafter, spot checking the plant is recommended unless the complexities of the project demand full-time monitoring. In many cases, full-time inspection at the batching facility is not necessary. Full-time inspection is recommended for concretes with design strengths greater than 70MPa (10,000 psi).

At the concrete plant, QA/QC personnel should ensure that the facilities, moisture meters, scales, and mixers (central or truck, or both) meet the project specification requirements and that materials and procedures are as established in the planning stages. QA/QC personnel should be aware of the importance of batching high-strength concrete, such as using proper sequencing of ingredients, especially when pozzolans or ground slag are used. Scales, flow meters, and dispensers should be checked monthly for accuracy, and should be calibrated every six months. Moisture meters should be checked daily. These checks and calibrations should be documented. Plants that produce high-strength concrete should have printed records for all materials batched. Entries showing deviations from accepted mixture proportions are provided with some plant systems.

The QC or QA inspector should be present at the batching console during batching and should verify that the accepted types and amounts of materials are batched. Batch weights should fall within the allowable tolerances set forth by project specifications. ASTM C 94 and the National Ready Mixed Concrete Association (NRMCA) Plant Certification plan contain weighing tolerances applicable to high-strength concrete production. These tolerances should be followed if not otherwise specified.

When not witnessing the entire batching operation, QA/QC personnel should perform or witness the following tests at least once daily (or once per eight-hour shift):

- Moisture content of fine and coarse aggregates in accordance with ASTM C 566.
- Aggregate gradations (fine and coarse) in accordance with ASTM C 136.
- Material finer than the 75-µm (No. 200) sieve in accordance with ASTM C 117.

Moisture content tests should be repeated after rain and the other tests should be repeated after deliveries of new batches of materials.

High-strength concrete may rely on a combination of chemical and mineral admixtures to enhance strength development. Certain combinations of admixtures and portland cements exhibit different strength development curves. Therefore, it is important for QA/QC personnel to watch for deviations in the type or brands of mixture ingredients from those submitted and accepted. Substitutions should not be allowed without the prior understanding of all parties. Reference samples of cementitious materials should be taken at least once per day or per shipment in case tests are needed later to investigate low strengths or other deficiencies.

Sources of additional mixture water such as “wash water” or any “left-over” concrete remaining in the truck drum prior to batching should be identified. These should be emptied from the truck prior to batching.

3.3—Delivery

High-strength concrete can be successfully mixed and transported in a number of ways. The QA/QC personnel should recognize that prolonged mixing will cause slump loss and result in lower workability. Adequate job control must be established to prevent delays. When practical, withholding some of the high-range water-reducing admixture until the truck arrives at the job site or site-addition of high-range water-reducing admixtures may be desirable. Newer high-range water-reducing admixtures with extended slump retention characteristics may preclude the need for job-site additions of admixture to recover slump. Truck mixers should rotate at agitation speed while waiting for discharge at the site. Failure to do so may lead to severe slump loss.

When materials are added at the site, proper mixing is required to avoid non-uniformity and segregation. QA/QC personnel should pay close attention to site mixing and should verify that the mixture is uniform. ACI 304R contains information on proper mixing.

Truck mixers used to transport high-strength concrete should be inspected regularly and certified to comply with the Check List requirements of the NRMCA Certification of Ready Mixed Concrete Production Facilities. Truck mixers should be equipped with a drum revolution counter, and their fins should comply with NRMCA criteria.

The concrete truck driver should provide a delivery ticket that contains the information specified in ASTM C 94. Every ticket should be reviewed by the inspector prior to discharge of concrete.

Chemical admixtures can be used to increase workability time. High-range water-reducing admixtures often are used to increase the fluidity of concrete for a definite time period. QA/QC personnel should be aware of that time frame and should know whether redosing with additional admixture is permitted. If the batch is redosed, the amount of admixture added to the truck with a calibrated delivery system should be recorded and the truck drum should be turned at least an additional 30 revolutions at mixing speed. Therefore, the delivery ticket should also provide a space for recording the following information:

- Water or admixtures added by authorized personnel at the job site.
- Approximate quantity of concrete in truck when additional water or admixture is added.
- Number of drum revolutions at mixing speed after the addition of water or admixture.

Addition of water at the job site should be permitted only if this was agreed to at the preconstruction meeting and provided that the maximum specified water-cementitious materials ratio is not exceeded.

3.4—Placing

Preparations at the project site are important. In particular, the contractor should be ready for placing the first truckload of concrete. QA/QC personnel should verify that forms, reinforcing steel, and embedded items are ready and that the placing equipment and vibration equipment (including standby equipment) are in working order prior to the contractor placing concrete.

High-strength concrete is typically produced with slumps in excess of 200 mm (8 in.). Despite their fluid appearance, these mixtures require thorough consolidation (Fiorato and Burg 1991). All concrete should be consolidated quickly and thoroughly. Standby vibratory equipment is recommended, with at least one standby vibrator for every three required vibrators. The provisions in ACI 309R should be followed for proper consolidation.

In construction, different strength concretes are often placed adjacent to one another. QA/QC personnel should be aware of the exact location for each approved mixture. When two (or more) concrete mixtures are being used in the same placement, it is mandatory that sufficient control be exercised at the point of discharge from each truck to ensure that the intended concrete is placed as specified.

Many times “mushrooming” is performed over column and shear wall locations when placing floor slabs; that is, high-strength concrete is “mushroomed” around those locations to form a cap prior to placing lower strength concrete around it in the slab. QA/QC personnel should be aware of how far the cap should extend. Since cold joints are not allowed between the two concretes, the inspector should determine that the high-strength “mushroom” is still plastic enough to blend with the lower strength slab concrete. Planning is necessary to determine the best procedures. Consideration should be given to the use of retarding admixtures. The boundary between the high-strength concrete and lower-strength concrete should be consolidated thoroughly by vibration. The inspector should maintain field notes regarding “mushroom” placements so that there is a record of placement.

3.5—Curing

The potential strength and durability of high-strength concrete will be fully developed only if it is properly cured for an adequate period prior to being placed in service or being subjected to construction loading. Many acceptable methods for curing are available, as discussed in ACI 308. However, high-strength concretes are extremely dense and impermeable. Therefore, appropriate curing methods for various structural elements should be selected in advance. QA/QC personnel should verify that the accepted methods are properly employed in the work.

High-strength concretes usually do not exhibit much bleeding, and without protection from loss of surface moisture, plastic shrinkage cracks have a tendency to form on exposed surfaces. Curing should begin immediately after finishing, and in some cases other protective measures should be used during the finishing process. Curing methods include fog misting, applying an evaporation retarder, covering with polyethylene sheeting, or applying a curing compound.

Water curing of high-strength concrete is recommended because of the low water-cementitious materials ratios employed. Klieger (1957) reported that concretes with low water-cement ratios benefited more by the application of additional surface water than concretes with high water-cement ratios. Water curing of vertical members is usually impractical, and other curing methods should be employed, such as leaving the forms in place. For interior columns, additional curing after formwork removal is usually is not necessary since durability is not a problem. The period during which the forms are in place may be adequate in such instances. When forms are released or removed at early ages (typically less than one day) the need to prevent thermal cracking by providing insulation should be considered, particularly in cold weather.

The inspector should monitor and record ambient temperatures and temperatures at the surface and center of large concrete components so that the design/construction team can effectively make any adjustments, such as changes in mixture proportions or the use of insulating forms, during the course of the project. Concrete delivered at temperatures exceeding specification limits should be rejected, unless alternative procedures have been agreed to at the preconstruction meeting. The inspector should monitor that curing procedures are according to project specifications, particularly those at early ages to control the formation of plastic shrinkage cracks.

CHAPTER 4—TESTING

4.1—Introduction

Measurement of mechanical properties during construction provides the basic information needed to evaluate whether design considerations are met and the concrete is acceptable. Experience indicates that the measured strength of high-strength concrete is more sensitive to testing variables than is normal-strength concrete. Therefore, the quality of these measurements is very important. Factors having little or no effect on tests of 20 MPa (3000 psi) concrete can be significant on tests of high-strength concrete, especially for compressive strength.

This chapter provides guidance on the special considerations for successful testing of high-strength concrete. The chapter begins with background information on compressive strength testing. This is followed by discussions of sampling, amount of testing, and various details about test specimens.

4.2—Background

In a research program on compressive strength testing of high-strength concrete, Burg et al.* point out: "The various ASTM standards that prescribe the methods to cast, cure, prepare specimen ends, and test concrete specimens were developed based on concretes with compressive strengths in the order of 1500 to 6000 psi (20 to 40 MPa)." Researchers have long investigated various methods of determining compressive strength and suggested different capping materials and methods. Gonnerman (1924) studied the effects of cylinder end conditions on measured compressive strength using various capping materials, such as beaver board, cork, lead, rubber, and white pine. The currently used sulfur-based caps, along with caps made from plaster of Paris, hydrostone, and dry shot, were investigated by Troxell (1942). Werner (1958) investigated the effects of rough cylinder ends prior to capping and end planeness requirements, and concluded that for compressive strengths exceeding 35 MPa (5000 psi) the provisions of ASTM C 192 would require revision.

Henning (1961) concluded that steel cylinder molds were preferable to waxed paper molds when testing concretes with strengths over 35 MPa (5000 psi). However, test standards were not changed to reflect his recommendation.

Testing and acceptance standards based on past studies may not be applicable to high-strength concretes that are now commercially available. Sanchez and Hester (1990) pointed out the requirement for strict attention to quality control on projects incorporating concrete with strengths of 85 to 100MPa (12,000 to 14,000 psi). In a cover story on testing high-strength concrete in *Engineering News Record*, it was noted that the availability and development of higher strength concrete had out paced the updating of testing practices to ensure reliable results (Rosenbaum 1990).

Inadequate testing techniques and interlaboratory inconsistencies have been found to cause more problems than have actually occurred with the concrete. Hester (1980) found differences in measured compressive strengths between laboratories to be as high as ten percent, depending upon the mixture and laboratories used. In a series of tests at four laboratories on cylinders from one load of high-strength concrete, differences in measured strengths as high as 11 percent at age 28 days, as shown in Fig. 4.2.1 were observed.† In that study, one laboratory fabricated the cylinders and ground their ends. The cylinders were subsequently shipped to the four laboratories for testing, which was done under direct observation of the investigators. Thus, even when specimen fabrication is not a variable, wide variations in measured strengths can occur.

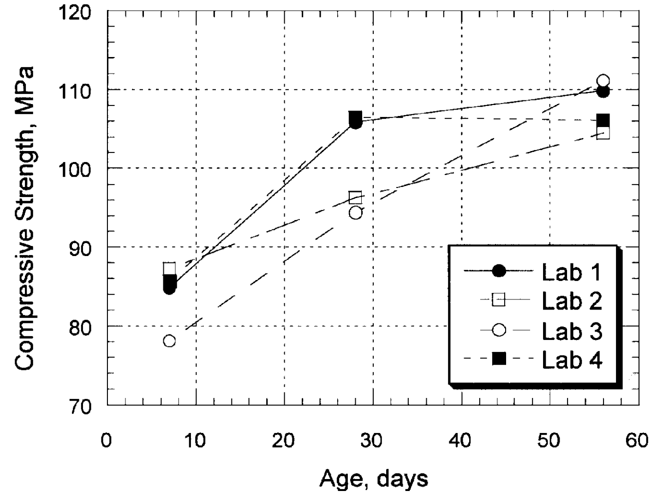

Fig. 4.2.1—Interlaboratory variation of measured compressive strength (based on unpublished study by Hooton and Bickley).

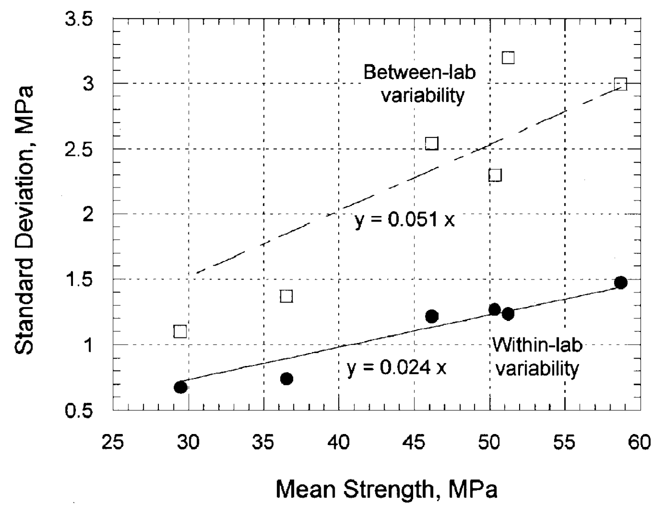

Fig. 4.2.2—Within-laboratory repeatability and between-laboratory reproducibility from interlaboratory program with 15 laboratories (5 replicates for each concrete mixture), based on data by Kennedy et al. 1995

Kennedy et al. (1995) found that within-laboratory and between-laboratory standard deviation increased as the mean compressive strength of the concrete increased (Fig 4.2.2). In that study, data were obtained from an interlaboratory program involving 15 laboratories, six mixtures, and five replicates per mixture. The data are compared with other interlaboratory studies in Fig. 4.2.3. The data from Detwiler and Bickley (1993) were based on blind testing of a similar group of laboratories and are not directly comparable to the interlaboratory study. In the blind testing, laboratory personnel were not aware which specimens being tested belonged to the interlaboratory program. The data by Gray

* Burg, R. G.; Detwiler, G.; Jansen, D.; and Williams, T. J., "An Interlaboratory Study of the Factors Affecting Compression Testing of High-Strength Concrete," manuscript in preparation.
† Private communication, R. D. Hooton and J. A. Bickley.

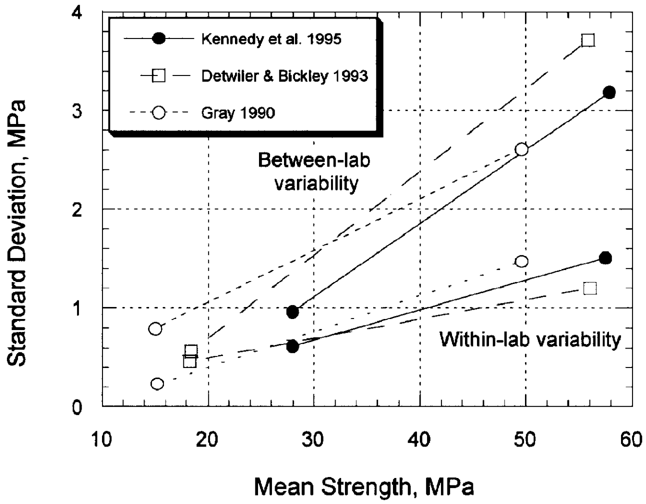

Fig. 4.2.3—Comparison of variability in three interlaboratory studies (adapted from Kennedy et al. 1995).

(1990) were from another interlaboratory program in British Columbia.

Because of the inherent variability in measuring compressive strength, ACI 214 and ACI 318 caution against reliance on a single test result. Adequate planning, with review of personnel and laboratory qualifications, and strict adherence to standard procedures should help prevent questions about the quality of testing during construction. The laboratory should be accredited or inspected for conformance to the requirements of ASTM C 1077. Field and laboratory testing personnel should be experienced and trained properly. They should have documented prior experience with high-strength concrete testing and have demonstrated the capabilities necessary for certification as ACI Concrete Field Testing Technician—Grade I and Concrete Laboratory Testing Technician—Grade I, or equivalent.

4.3—Sampling

As discussed in Chapter 5, statistical methods are an excellent means to evaluate high-strength concrete. For such statistical procedures to be valid, the data (slump, unit weight, temperature, air content, and strength) should be derived from samples obtained through a random sampling plan designed to reduce the possibility that choice will be exercised by the testing technician. Random number tables should be used to select trucks that will be sampled during the placing operations. The samples taken from a truck should represent the quality of concrete supplied. Therefore, composite samples should be taken in accordance with ASTM C 172. They should be combined and remixed to ensure uniformity before testing the properties of the freshly-mixed concrete or casting test specimens. Random sampling, however, does not replace the need to ensure that the first truckload of concrete conforms to the specifications.

These samples are representative of the quality of concrete delivered to the site and may not truly represent the quality of the concrete in the structure, which may be affected by site placing and curing methods. If additional test samples are required to check the quality of the concrete at the point of placement (as in pumped concrete) this should be established at the preconstruction meeting.

4.4—Amount of testing

Tests for air content, unit weight, slump, and temperature should be made on the first truckload each day to establish that batching is adequate. If adjustments are made to mixture proportions, the first truck after these changes have been made should be sampled. Subsequent tests should be performed on a random basis. When visual inspection reveals inconsistent concrete, it should be rejected unless additional tests show it to be acceptable. Such test results should not be counted in the statistical evaluation of the mixture unless they are made on samples taken at random.

The Architect/Engineer can generally take advantage of the fact that high-strength concrete containing fly ash or ground granulated blast-furnace slag develops considerable strength at later ages, such as 56 and 90 days. It is common to specify more test specimens than would normally be required. The technician should be prepared to take a large enough sample to cast all test specimens. Under no circumstances should the technician use other samples to “top off” test specimens. If the sample is too small, the concrete should be discarded and another sample taken. However, only a reasonable number of specimens can be made correctly within the correct time frame for each sample. No more than nine specimens should be made per sample unless sufficient personnel and facilities are available to handle them properly. While ACI 318 requires two specimens, at least three specimens per test age are recommended for high-strength concrete, with three held in reserve.

Where later ages are specified for acceptance purposes it may be desirable to make an early assessment of potential strength by testing early-age specimens or specimens with accelerated curing.

4.5—Compressive strength specimens

Since much of the interest in high-strength structural concrete is limited to compressive strength, these measurements are of primary concern. The primary function of standard laboratory-cured specimens is to provide assurance that the concrete mixture as delivered to the job site has the potential to meet contract specification requirements. The potential strength and variability of the concrete can be established only by specimens made, cured, and tested under standard conditions.

4.5.1 *Specimen size and shape*—ASTM C 31 specifies the standard specimen as a cylinder with a diameter of 152 mm (6 in.) and a height of 305 mm (12 in.). This specimen size has evolved over the years from practical considerations, and the design and construction team is familiar with the empirical values obtained. This specimen size may lead to practical problems when testing high-strength concrete because the crushing loads may exceed the capacities of available testing machines. However, 102 mm (4 in.) by 203 mm (8in.) cylindrical specimens have also been used successfully to determine compressive strength (Forstie and Schnormeir 1981).

Cook (1989) indicates that for a mixture with a design strength of 70 MPa (10,000 psi), the strengths of 102 mm (4in.) diameter cylinders were approximately five percent higher than those of 152 mm (6 in.) diameter cylinders. Burg and Ost (1992) found that, in the range of 70 MPa (10,000 psi) to 140MPa (20,000 psi), 102 mm (4 in.) diameter cylinder strengths generally were within about one percent of the 152mm (6 in.) diameter cylinder strengths. Carino et al. (1994) found that the differences were less than 2 percent. The latest edition of Canadian Standard CSA A23.1 requires a 5 percent reduction in the measured strength where 100 mm by 200 mm (4 in. by 8 in.) cylinders are used. This requirement is based on a definitive study by Day (1994).

The use of the smaller test cylinders is acceptable provided strength is determined in accordance with ASTM C 39. Recent unpublished research by Burg et al. suggests that where rigid upper platens are used the test results for both specimen sizes are the same. Carino et al. (1994) suggest that the strength differences between the two cylinder sizes may be related to differences in density. When 102 mm (4 in.) diameter cylinders have been used for QA/QC testing in the U.S.A., strength reductions have not been applied to the measured strengths.

Regardless of specimen size, the size used to evaluate trial mixture proportions should be consistent with the size specified for acceptance testing, and should be acceptable to the Architect/Engineer. If necessary, the relationship between the compressive strengths of the two specimen sizes can be determined at the laboratory or field trial stage using the testing machine that will be used for the project.

4.5.2 *Mold type*—Molds should meet the requirements of ASTM C 470. The type of mold material, the ability to hold its shape, and its watertightness can have a significant effect on measured compressive strength. Consolidation is more effective with rigid molds. Rigid single-use plastic molds with wall thicknesses of 6 mm ($^1/_4$ in.) or greater have been used successfully for 70 MPa (10,000 psi) concrete (Forstie and Schnormeir 1981). Plastic molds with wall thickness less than 6 mm ($^1/_4$ in.) should have a cap to maintain a circular shape. Close-fitting caps also can be used to minimize loss of moisture. Flat caps should be avoided as they deform the concrete surface. A domed cap providing a clearance of at least 13 mm ($^1/_2$ in.) should be used. In all cases loss of moisture must be prevented. Even high-quality cardboard molds produce compressive strength results about 13 percent lower than when steel molds are used (Blick 1973). Therefore, cardboard molds are not recommended. Because of these noted differences, the mold type used for field specimens should be the same as the mold type used to develop the design mixture.

4.5.3 *Consolidation of test specimens*—Test specimens should be consolidated properly. Applicable ASTM C 31 and ASTM C 192 procedures should be followed.

4.5.4 *Field handling and curing*—Proper field handling and initial curing of compressive-strength test specimens during the first 48 hours are important aspects for ensuring standard conditions, because the later-age strength of concrete specimens can be sensitive to initial curing temperatures. Chamberlin (1952) studied the effects of initial and subsequent curing temperatures on the strength development of normal-strength concrete test cylinders. For specimens with non-standard initial curing temperatures maintained for up to 24 hours prior to standard laboratory curing at 23 C (73F), he reported that:

- At age 28 days and later, the test cylinders with higher initial curing temperatures had lower strength.
- At later ages, the strength was dependent upon the initial temperatures, but was only slightly affected by the length of time this temperature was maintained.

There are indications that the later-age strength of high-strength concrete may not be as sensitive to the early-age temperature as is normal-strength concrete. For example, Aïtcin and Riad (1988) indicate that the early temperature rise due to hydration of high-strength mixtures containing silica-fume with water-cementitious materials ratios below 0.30 dramatically increases the 7-day strength without affecting the 28-day strength. Those results were based on test cylinders subjected to a temperature cycle similar to that obtained in two large high-strength concrete columns.

The curing of high-strength concrete in a structural element normally varies from the curing of representative standard specimens from samples obtained in accordance with ASTM C 172 and prepared and cured in accordance with ASTM C 31. The internal temperature of the concrete member may greatly exceed the ambient temperature, while test specimens are cured at about 23 C (73 F). Although standard test specimens used to evaluate the potential strength of the concrete may be cured at lower temperatures than the in-place concrete, studies (Day 1994) have shown that the 28-day strength of standard, laboratory-cured specimens is a good indicator of potential strength. Furthermore, design equations were developed on the basis of compressive strength determined by standard-cured cylinders and structural performance based on large scale specimens. If an accurate determination of the strength in a high-strength concrete component is required, temperature-matched cured test specimens (Wainright and Tolloczko 1983) should be used instead of standard-cured test specimens.

An adequate working area for specimen fabrication and an initial curing facility should be provided at the job site. It is more difficult to maintain the proper initial curing temperature with high-strength concrete specimens than with lower-strength concrete specimens because of the higher heat of hydration. As a result, the temperature of the field curing environment can easily exceed the upper limit of 27 C (80 F) allowed by ASTM C 31. The curing environment can be improved by providing ventilation around specimens, and by submerging the specimens in temperature-controlled water baths. The testing technician should monitor the ambient curing temperatures in the field with maximum/minimum thermometers or continuous temperature recorders. These temperatures should be reported with the strength test data.

Since work by Aïtcin and Riad (1988) established that maximum temperatures just below 27 C (80 F) during hydration did not reduce ultimate strength, the ASTM limit of 27C (80F) appears to be an appropriate upper limit for standard field curing. The 1994 edition of CSA A23.1 requires initial (field) curing temperature for test cylinders of concretes with specified strengths of 70 MPa (10,000 psi) or higher to be 23 ± 2 C (73.5 ± 3.5 F).

Use of in-place testing is recommended to determine the adequacy of curing, form removal time, or when a structure may be put into service. Techniques for in-place testing are discussed in ACI 228.1R. However, field-cured cylinders are appropriate in the precast industry and, if they are to be used, the storage and handling of field-cured specimens should be discussed at the preconstruction conference.

4.5.5 *Transporting to laboratory*—Test specimens should be transported to the laboratory after 16 hours and before 48 hours after casting. The technician should exercise caution to ensure that the specimens have gained sufficient strength to resist handling stresses before shipping to the laboratory. This is particularly important when retarding or high-range water-reducing admixtures are added. During transportation, the specimens should be protected by adequate cushioning material to prevent damage from jarring and should be protected from damage by freezing temperatures or loss of moisture.

4.5.6 *Laboratory curing*—Standard laboratory moist-curing after initial standard curing at the job site should strictly follow ASTM C 31.

4.5.7 *Specimen preparation*—ASTM C 39 requires that the ends of test cylinders be ground or capped so that the loading surfaces are plane to within 0.05 mm (0.002 in.). When high-strength concrete cylinders are capped, the thickness and strength of the cap is more important than for lower-strength concrete. Gaynor and Wedding (1964), Saucier (1972), and Lobo et al. (1994) investigated the effect of the thickness of sulfur mortar caps on compressive strengths of normal and high-strength concretes. A uniform cap thickness of 2 mm ($^1/_{16}$ in.) or less was found to be necessary for high-strength concrete. Thicker caps result in reduced measured compressive strength.

Capping should comply with ASTM C 617. Sulfur mortars with 50 mm (2 in.) cube strengths between 55 and 70 MPa (8,000 and 10,000 psi) at the time of testing are acceptable for high-strength concrete up to design strengths of 70 MPa (10,000 psi). Above 70 MPa (10,000 psi), test strengths less than the actual strength of the specimens may be obtained with greater variability in the test results (Rosenbaum 1990). Due to friction between the cap and steel platen, the cap is confined and has a higher strength than the 50 mm (2 in.) cube strength. The beneficial effect of confinement was demonstrated by Gaynor and Wedding (1964), who reported that the compressive strength of 50 mm (2 in.) diameter cylinders of capping compound increased as the height of the cylinder was reduced. Capping has been used successfully for strengths up to 117MPa (17,000 psi) provided cap thickness is limited to 2mm ($^1/_{16}$ in.) (Lobo et al. 1994). However, not all capping materials are satisfactory. For concrete strengths above 70 MPa (10,000 psi), tests should be made to demonstrate the suitability of the capping material. Typically, capped cylinders are tested and compared with cylinders prepared by end grinding. It appears that the compressive strength of the capping material may not be the only, or even the most important, mechanical property; the elastic modulus may be just as important.* Further research is needed in this area.

Without prior experience, testing of sulfur mortars before production testing of concrete is recommended to determine optimum melting temperatures and the time after casting required to develop adequate strength. Specimens should never be tested immediately after capping. ASTM C 39 requires at least 2 hours of waiting after capping; longer times may be needed for high-strength concrete (Lobo et al. 1994). Laboratory technicians should practice with the designated capping material to produce a consistent 2 mm ($^1/_{16}$ in.) thick cap. The ends of test cylinders should be sawn or ground if necessary to produce uniformly thin caps. This is especially important when the finished ends of cylinders are rough or not perpendicular to the cylinder axis. Caps should be sounded for air voids by tapping with a coin (see C 617) prior to testing. Hollow caps should be removed and specimens recapped. Sulfur mortars should not be reused.

The problems associated with capping can be eliminated by grinding the ends of test cylinders using equipment made for that purpose. Pistilli and Willems (1993) suggested that specimen ends be ground to a planeness of 0.025 mm (0.001in.) and 0.3 degrees perpendicularity for concretes exceeding design strengths of 70 MPa (10,000 psi). Cylinders with ends prepared by grinding have less variable test results and a higher average strength for concrete stronger than 70 MPa (10,000 psi).

Unbonded cap systems, composed of polymeric pads in restraining rings (Fig. 4.5.1), have been used successfully on high-strength concrete up to 130 MPa (19,000 psi) (Pistilli and Willems 1993).† However, test specimens should be prepared carefully so that poor end conditions do not have a negative effect on the test results. ASTM C 1231 tolerance requirements for the planeness of ends should not be exceeded and its other requirements should be followed. At present, ASTM C 1231 does not permit the use of unbonded caps for acceptance testing of concrete with strength above 50 MPa (7000 psi). However, the qualification testing procedure in ASTM C 1231 can be used during the trial batch stage to demonstrate whether an unbonded cap system is suitable for the particular concrete. Since unbonded caps result in explosive failures of test cylinders, even when high-capacity, stiff testing machines are used, safety precautions should be used to avoid injury to laboratory personnel.

* Vichit-Vadakan, W., undergraduate research study, NIST and Cornell University, manuscript in preparation.

† Chojnacki, B, and Read, P., "Compressive Strength Procedures for Testing High-Strength Concrete," Trow Consulting Engineers report to CANMET, unpublished.

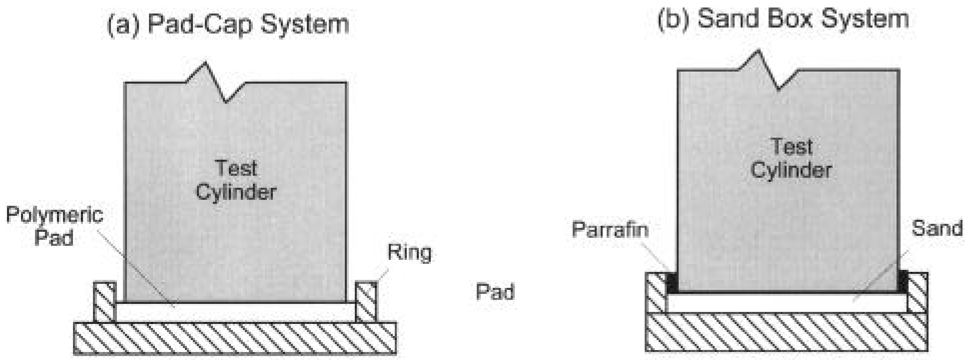

Fig. 4.5.1—Unbonded cap systems: (a) polymeric pads restrained by metal ring, and (b) sand in rigid metal container (Boulay and de Larrard 1993, Boulay 1996).

An alternative unbonded capping method using dry sand (Fig. 4.5.1) has been introduced in France (Boulay and de Larrard 1993, Boulay 1996). Similar procedures were explored in the U.S. in the late 1920s (Carino et al. 1994). In this approach, a steel mold is used to hold dry sand. The cylinder is positioned in the sand using a jig similar to that used for capping with sulfur. The sand is vibrated, and molten paraffin is poured around the cylinder to keep the sand in place while the other end is prepared in a similar fashion. The compressive strength of cylinders tested using the sand box system have been found to be from 0 to 5 percent lower than ground cylinders, depending on strength level. The method has been adopted as a standard in France.

4.5.8 *Testing apparatus*—Due to the higher loads carried by high-strength concrete test specimens, compression machine characteristics influence results (Noguchi and Tomosawa 1996). Machine characteristics that may affect the measured strength include calibration accuracy, longitudinal and lateral stiffness, alignment of the machine components, type of platens, and the behavior of the platen spherical seating. Testing machines should meet the requirements of ASTM C 39. Based on practical experience, it is recommended that the machine should have a load capacity at least 20 percent greater than the expected ultimate load of the cylinders. Premature damage to testing machines and loss of calibration have occurred as a result of large numbers of explosive failures at high loads. Testing machines should incorporate devices to protect personnel from concrete fragments that may be propelled during explosive failures.

Carino et al. (1994) summarized the desirable stiffness characteristics of testing machines:

"Testing machine stiffness is an important factor in compressive strength testing. The effect of longitudinal stiffness on the post-peak response is understood, and hard machines are needed to avoid explosive failures. On the other hand, the effect of longitudinal stiffness on strength is not understood. There are conflicting opinions and data, so additional study is warranted. The effect of lateral stiffness on strength is understood. A laterally stiff machine assures uniform straining of the specimen in the presence of eccentric loading, due to either heterogeneity of the specimen or misalignment. The adequacy of the lateral stiffness can be evaluated by a proving device that measures the uniformity of straining as a function of degree of misalignment."

British Standard BS 1881, Part 115, describes one procedure for evaluating the lateral stiffness of testing machines. A metal tube instrumented with strain gages is positioned between the loading platens at different amounts of eccentricity and the strain gage readings are recorded. A laterally stiff machine can maintain uniform deformation of the tube with increasing eccentricity of the tube.

The use of proper platen size and design is critical. The upper platen should have a spherically-seated bearing block that is able to rotate and achieve full contact with the specimen under initial load. However, to ensure uniform compression of the test specimen, the block should be fixed when approaching the ultimate load. The spherical bearing block and seating should be kept clean and coated thinly with a light oil. The block will not become fixed properly if pressure-type greases are used.

Fig. 4.5.2 shows the ASTM C 39 dimensional requirements for the spherically-seated platen of a compression testing machine. Laboratories typically use the same platen for testing 102 mm (4 in.) and 152 mm (6 in.) diameter cylinders. Work by Burg et al. indicates that load transfer from spherically-seated platens into test specimens can affect the measured strength. Some platens that meet the dimensional requirements of ASTM C 39 produce non-standard load transfer into high-strength 152 mm (6 in.) diameter specimens, but can transfer load properly for 102 mm (4 in.) specimens. This may explain cases where 102 mm (4 in.) cylinders have higher measured compressive strength than 152 mm (6 in.) cylinders. In those cases, the smaller diameter specimens may actually represent a more realistic measure of the compressive strength.

Fig. 4.5.3 shows the key dimensions of two spherically-seated bearing platens used in an interlaboratory study conducted by Burg et al. to examine the effects of testing variables on the measured strengths of high-strength cylinders. Both platens satisfy the minimum dimensional requirements of ASTM C 39, however, one platen had a smaller ball radius and a thinner bearing plate. In addition, the smaller platen had a two-part bearing plate as shown in Fig. 4.5.3(b). In that study, a unique sensor system was used to measure the

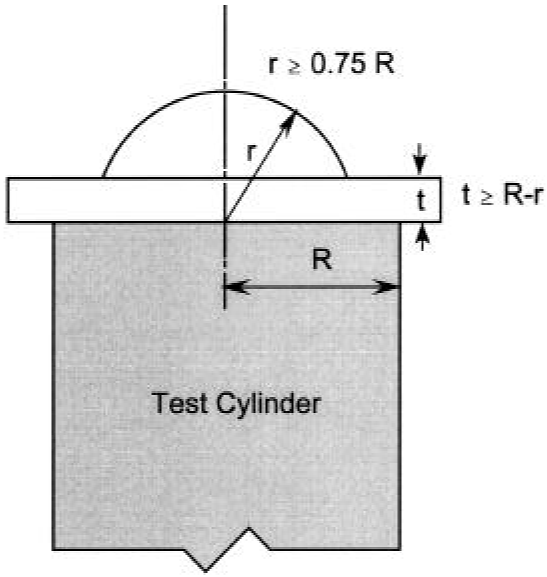

Fig. 4.5.2—Dimensional requirements for spherically-seated platen according to ASTM C 39.

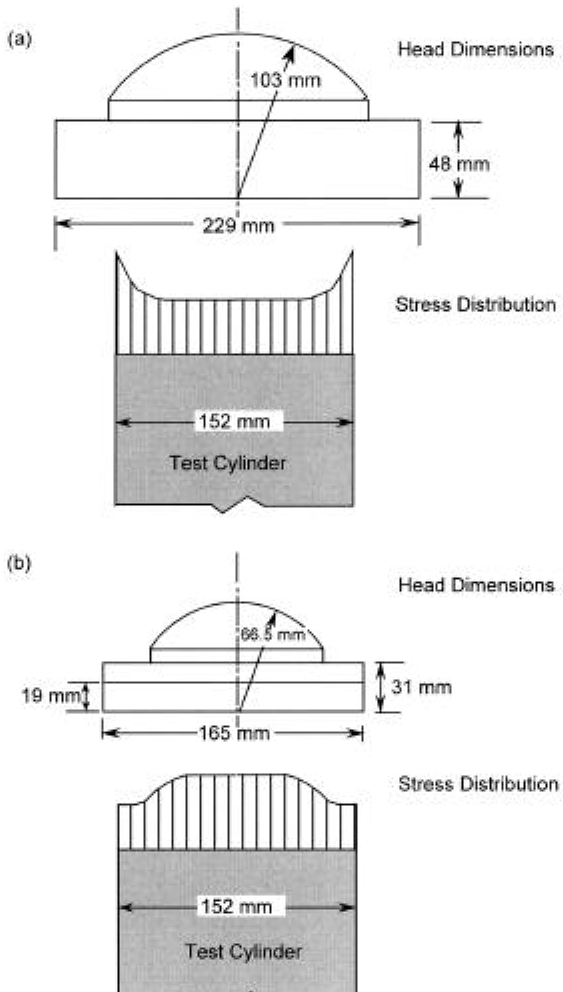

Fig. 4.5.3—Dimensions of: (a) "adequate," and (b) "inadequate" spherically-seated bearing blocks and approximate shape stress distributions on ends of cylinders (unpublished study by Burg et al.).

contact stresses between the platens and ends of a 152 mm (6 in.) diameter aluminum cylinder. The sensor system allowed comparison of the cylinder end stress distributions. Schematics of the measured distributions are shown in Fig. 4.5.3. It can be seen that the smaller spherically-seated block resulted in a concentration of the stress at the center of the cylinder, while the larger and stiffer block showed the expected distribution with higher stress at the perimeter.* Thus, the two blocks resulted in drastically different distributions at the end of the 152 mm (6 in.) diameter cylinder. Fig. 4.5.4 shows the reduction in measured compressive strength of 152 mm (6 in.) diameter cylinders tested with the less stiff spherically-seated platen compared with cylinders tested with the stiffer platen. It is seen that the adverse effect of the "inadequate" platen increased with increasing concrete strength. This study concluded that spherically-seated platens with large ball diameters and thick bearing plates should be used for testing 152 mm (6 in.) diameter cylinders.

Correct positioning of the specimen is crucial to uniform and accurate results. The permissible eccentricity of the test specimen depends on the lateral stiffness of the testing machine. To determine the criticality of specimen positioning for a particular testing machine, an aluminum cylinder the same size as the proposed test cylinders and instrumented with three strain gages at mid-height can be used. The cylinder is placed in the testing machine and loaded to the anticipated concrete cylinder failure load. Strain readings from each gage are recorded as the aluminum cylinder is loaded. If the specimen is properly positioned, strain readings should be nearly identical around the periphery of the aluminum specimen. If not, the specimen can be repositioned and the loading repeated. Once an acceptable location is determined it should be marked so that actual test specimens can be positioned properly.

Testing procedures and the condition and calibration of the machine should be investigated if compressive strength results are lower than expected or highly variable.

4.6—Prequalification of testing laboratories

A laboratory should be examined from two perspectives (Bickley 1993): how it has performed in the past and how well it is equipped to perform properly in the future. Past test data for high-strength concrete analyzed in accordance with ACI 214 will show within-test variability as a measure of the testing consistency of the laboratory. The qualifications and experience of technicians and inspectors should be reviewed. The laboratory should be accredited or inspected for conformance to the requirements of ASTM C 1077. The Architect/Engineer should recommend an acceptable testing laboratory.

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* It is commonly assumed that there is a uniform pressure distribution on the end of a perfectly flat cylinder loaded through a thick steel plate. However, this is not true. The pressure is higher near the perimeter and decreases to a relatively constant value in the central region of the cross section, similar to the distribution in Fig. 4.5.3(a). Additional information on the stresses in a loaded cylinder may be found in Carino et al (1994) and Ottosen (1984).

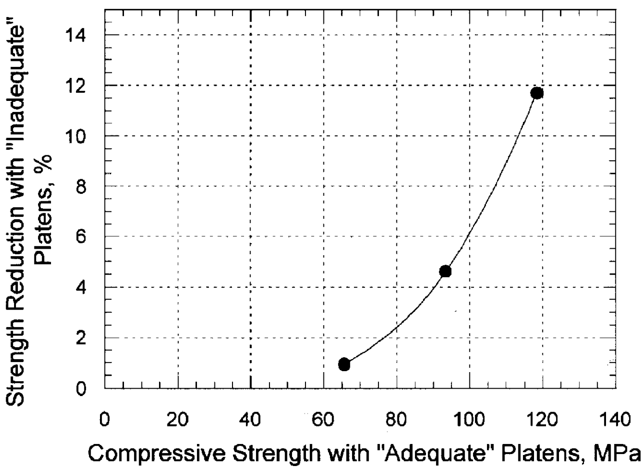

Fig. 4.5.4—Effect of spherically-seated platen on measured compressive strength of 150 mm (6 in.) cylinders as a function of concrete strength (adapted from an unpublished study by Burg et al.).

A comprehensive internal quality control protocol that covers test procedures; the use, care, and calibration of testing equipment; and the checking and reporting procedures to be followed is a sign of a well-run laboratory. Records should show that the protocol has been followed for previous projects.

Depending on the results of the review of the past and potential performance of the laboratory, some tests of personnel and equipment may be made to conclude the prequalification examination (Bickley 1993).

CHAPTER 5—EVALUATION OF COMPRESSIVE STRENGTH TEST RESULTS

5.1—Statistical concepts

The first step in evaluating quality control procedures is determining whether the distribution of the compressive strength test results follows a normal frequency distribution. Cook (1989) suggests that skewed distributions may occur for high-strength concrete because the compressive strength may be limited by the aggregate strength. This can be the case for concrete strengths exceeding 70 MPa (10,000 psi). The distribution should be investigated to determine if it deviates from a normal distribution. As suggested by Cook (1989), the skewness and kurtosis (peakedness of the distribution) are evaluated by calculating the third and fourth moments of the distribution about the mean. Available data indicate that a normal frequency distribution is achieved for concrete with compressive strength in the range of 40 to 70 MPa (6000 to 10,000 psi) (Cook 1982). Thus, the procedure recommended by ACI 214, which assumes a normal distribution, is usually a convenient tool for evaluating the quality of production and testing of high-strength concrete.

In the 1977 (Reapproved 1989) version of ACI 214, the numerical values of the standard deviation are related to evaluations of the quality of the work represented. A standard deviation less than 2.8 MPa (400 psi) represents an excellent degree of control, whereas a standard deviation greater than 5MPa (700 psi) represents poor control. In the case of high-strength concrete, defining quality-control categories based on absolute dispersion may be misleading, since standard deviations greater than 5MPa (700 psi) are not uncommon for 70MPa (10,000 psi) concrete on well-controlled projects.

For practical comparisons, the coefficient of variation is more useful for measuring the dispersion of compressive strengths, especially for high-strength concrete. The coefficient of variation is the standard deviation expressed as a percentage of the average strength. Anderson (1985) and Cook (1989) have suggested that the coefficient of variation be used because this value is less affected by the magnitude of the strengths obtained and is more useful in comparing the degree of control for a wide range of strength levels. Suggested standards of quality control are listed in Table 5.1.1.

These standards of control are based on the analysis of over seven hundred, 28-day compressive strength test results (average of at least two cylinders). In practice, high-strength concrete has a lower coefficient of variation than normal-strength concrete, not because of the strength level, but because a higher degree of control is maintained in the production and testing of high-strength concrete. Continual review of the field results and the maintenance of records in the form of control charts, or other means, is recommended to assess whether the desired level of control is being achieved.

Early-age control of concrete strength may be achieved by making and testing accelerated- cured specimens according to ASTM C 684, especially where later-age (56- or 90-day) strength tests are the final acceptance criterion. Evaluation of these data should follow job-specific criteria developed at an early phase of concreting.

Where ages later than 28 days are specified for acceptance, ACI 214 evaluation procedures can be used.

Table 5.1.1—Standards of concrete control for specified compressive strength over 35 MPa (5000 psi)

Overall variation					
	Coefficient of variation for different control standards, percent				
Class of operation	Excellent	Very good	Good	Fair	Poor
General construction testing	under 7.0	7.0 to 9.0	9.0 to 11.0	11.0 to 14.0	over 14.0
Laboratory trial batches	under 3.5	3.5 to 4.5	4.5 to 5.5	5.5 to 7.0	over 7.0
Within-test variation					
	Coefficient of variation for different control standards, percent				
Class of operation	Excellent	Very good	Good	Fair	Poor
Field control testing	under 3.0	3.0 to 4.0	4.0 to 5.0	5.0 to 6.0	over 6.0
Laboratory trial batches	under 2.0	2.0 to 3.0	3.0 to 4.0	4.0 to 5.0	over 5.0

5.2—Strength evaluation

ACI 318 recognizes that some strength test results are likely to be lower than the specified strength. However, the ACI-318 acceptance criteria are based on normal-strength concrete. It is recommended that high-strength concrete be judged acceptable if the following requirements are met:

- The average of all sets of three consecutive strength test results equals or exceeds the required f_c', and
- No individual strength test (average of two cylinders) falls below 0.90 f_c'. (This is different from the ACI 318 requirement.)

The latter criterion differs from the 3.4 MPa (500 psi) under strength criterion in ACI 318, because a deficiency of 3.4 MPa (500 psi) may not be significant when high-strength concrete is used.

High-strength concretes may continue to gain significant strengths after the acceptance test age, especially if fly ash or ground granulated blast-furnace slag are used. During the evaluations to establish mixture proportions, a strength development curve should be established indicating potential strength over time. However, if questions arise concerning the load-carrying capacity of a structure, ACI 318 allows investigation by analysis using core test results or by load testing. In cases where load testing a structure is not practical, analytical investigations using the strength results from extracted cores, or in-place tests (ACI 228.1R), are more appropriate. Tests to evaluate the durability of the concrete (see ACI 201.2R) should be performed separately on cores other than those used for strength tests.

As mentioned in Chapter 3, a correlation curve should be established for each high-strength mixture to relate the strength of extracted cores (normally 102 mm (4 in.) in diameter) to the strength of specimens used for acceptance testing, that is, 152 by 305 mm (6 by 12 in.) or 102 by 203mm (4 by 8 in.) cylinders. Then, if coring becomes necessary, the relationship has been established, agreed upon, and is ready for conclusive interpretation. In the absence of correlation data, the provisions of ACI 318 should be used. These provisions require that the average strength of a set of three cores be equal to at least 85 percent of f_c' and no single core be less than 75 percent of f_c'.

Cook (1989) reported that tests of 102 mm (4 in.) diameter cores taken from 760 by 760 mm (30 by 30 in.) columns of 10,000psi (70 MPa) concrete resulted in average strengths as shown in Table 5.2.1.

Burg and Ost (1992) reported on 102 mm (4 in.) cores drilled from 1220 mm (4 ft) cubes of concrete with compressive strength in the range of 70 to 140 MPa (10,000 to 20,000psi). Sets of three cores at 91 days and 14 months produced average strengths as shown in Table 5.2.2.

In tests at 1, 2, and 7 years of age on 102 mm (4 in.) diameter cores from columns made with 70 MPa (10,000 psi) concrete Bickley et al. (1991, 1994) obtained the results shown in Table 5.2.3. The cementitious system in this concrete was Type I portland cement plus silica fume and ground granulated blast-furnace slag.

Table 5.2.1—Strength cores from 760 mm (30 in.) square columns (Cook 1989)

Age at test, days	Moist-cured cylinder strength at same age, percent	
	Range	Average
7	94 to 105	99
28	84 to 97	91
56	78 to 94	84
180	78 to 94	86
365	93 to 107	98

Table 5.2.2—Strength of cores from 1220 mm (4 ft) cubes (Burg and Ost 1992)

Cementitious system	Age at test, days	28-day moist-cured 152 x 305 mm (6 x 12 in.) cylinder strength, percent	
		Range	Average
I	91	95 to 106	99
I + SF + FA		93 to 96	95
I + SF		85 to 90	88
I + SF		93 to 104	98
I + SF + FA		102 to 105	103
I + SF + FA		107 to 110	108
I + SF	426	109 to 123	117
I + SF + FA		104 to 106	105
I + SF		94 to 98	96
I + SF		100 to 111	107
I + SF + FA		104 to 113	109
I + SF + FA		122 to 124	123

*I = Type I portland cement; SF = silica fume; FA = fly ash

Table 5.2.3—Column core strength at later ages (Bickley et al. 1991, 1994)

Age at test, years	Average 28-day moist-cured cylinder strength, percent	
	Range	Average
1	90 to 109	97
2	91 to 107	100
7	97 to 100	99

Aïtcin and Riad (1988) reported 2-year core strengths from columns made with Type I cement and silica fume. The average 2-year core strength was 97 percent of the strength of 28-day moist cured cylinders.

These data indicate that the acceptance criteria for core strengths specified in ACI 318 are also applicable to high-strength concretes.

CHAPTER 6—REFERENCES

6.1—Cited standards

The documents of the various standards producing organizations referred to in this document are listed below with their serial designations.

American Concrete Institute

116R	Cement and Concrete Terminology
201.2R	Guide to Durable Concrete
207.2R	Effect of Restraint, Volume Change, and Reinforcement on Cracking of Massive Concrete
211.1	Standard Practice for Selecting Proportions for Normal, Heavyweight and Mass Concrete
211.4R	Guide for Selecting Proportions for High-Strength Concrete with Portland Cement and Fly Ash
212.3R	Chemical Admixtures for Concrete
214	Recommended Practice for Evaluation of Strength Test Results of Concrete
228.1R	In-Place Methods to Estimate Concrete Strength
304R	Guide for Measuring, Mixing, Transporting and Placing Concrete
308	Standard Practice for Curing Concrete
309R	Guide for Consolidation of Concrete
311.4R	Guide for Concrete Inspection
318	Building Code Requirements for Structural Concrete
363R	State-of-the-Art Report on High-Strength Concrete

American Society for Testing and Materials

C 31	Practice for Making and Curing Concrete Test Specimens in the Field
C 33	Specification for Concrete Aggregates
C 39	Test Method for Compressive Strength of Cylindrical Concrete Specimens
C 94	Specification for Ready-Mixed Concrete
C 117	Test Method for Materials Finer than 75-µm (No. 200) Sieve in Mineral Aggregates by Washing
C 136	Test Method for Sieve Analysis of Fine and Coarse Aggregates
C 172	Practice for Sampling Freshly Mixed Concrete
C 192	Practice for Making and Curing Concrete Test Specimens in the Laboratory
C 470	Specification for Molds for Forming Concrete Test Cylinders Vertically
C 566	Test Method for Total Moisture Content Aggregates by Drying
C 617	Practice for Capping Cylindrical Concrete Specimens
C 666	Test Method for Resistance of Concrete to Rapid Freezing and Thawing
C 672	Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals
C 684	Test Method for Making, Accelerated Curing, and Testing Concrete Compression Test Specimens
C 1077	Practice for Laboratories Testing Concrete and Concrete Aggregates for Use in Construction and Criteria for Laboratory Evaluation
C 1231	Practice for Use of Unbonded Caps in Determination of Compressive Strength of Hardened Concrete Cylinders

National Ready Mixed Concrete Association

QC Manual, Section 3, Checklist for Certification of Ready Mixed Concrete Production Facilities

Canadian Standards Association

CSA-A.23.1M Concrete Materials and Methods of Concrete Construction

British Standards Institution

Testing Concrete, BS 1881, Part 115, Specification for Compression Testing Machines for Concrete

The above publications may be obtained from the following organizations:

American Concrete Institute
P.O. Box 9094
Farmington Hills, MI 48333-9094
U.S.A.

ASTM
100 Barr Harbor Drive
West Conshohocken, PA 19428-2959
U.S.A.

National Ready Mixed Concrete Association
900 Spring Street
Silver Spring, Maryland 20910
U.S.A.

Canadian Standards Association
178 Rexdale Boulevard
Rexdale, Ontario M9W 1R3
Canada

British Standards Institution
2 Park Street
London W1A 2BS
England

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