

Guide to Quality Control and Assurance of High-Strength Concrete

Reported by ACI Committee 363



American Concrete Institute®



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Guide to Quality Control and Assurance of High-Strength Concrete

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Guide to Quality Control and Assurance of High-Strength Concrete

Reported by ACI Committee 363

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High-strength concrete (HSC) has emerged as a viable material to use as an alternative to conventional normal-strength concrete in infrastructure systems to reduce member cross section, extend member span length, reduce the number of system members, or enhance system sustainability. This guide offers general information on the quality control and testing of HSC. Recommendations are based on the current state of knowledge gained from worldwide experimental research, analytical work, and field applications of HSC systems used in concrete structures.

Keywords: acceptance criteria; compressive strength; concrete placement; creep; curing; delivery; modulus of elasticity; sampling; shrinkage; statistical concepts; strength evaluation; testing; trial batching; quality assurance; quality control.

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CHAPTER 1—INTRODUCTION AND SCOPE

1.1—Introduction

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 (HSC). HSC is considered one type of high-performance concrete (HPC) that is most often specified for enhanced strength characteristics, although may also be specified for its improved durability. ACI 363R was the first document produced by this committee in 1984, and contained significant information regarding material selection, mixing and placing, inspection and testing, physical properties, structural design, economics, and examples of applications.

This guide is an extension of ACI 363R and presents guidelines to facilitate the proper evaluation of HSC through correct quality control (QC) and testing. HSCs 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 QC 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 QC and testing effort.

1.2—Scope

This guide discusses QC and testing practices of HSC. HSC usually is associated with structures that have been optimized for performance. Therefore, a high degree of confidence in concrete quality should be achieved through the inspection and testing process. This process can be conducted by the producer and contractor as QC and by the owner or the owner's representative as quality assurance (QA). Those involved in QC and testing need to know the unique characteristics of HSC

to better assist the architect/engineer in evaluating the structure's potential performance.

Concrete with a specified compressive strength of 10,000 psi (70 MPa) can be produced from local aggregates in all areas of the U.S. 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.

Because the definition of HSC has changed over the years, ACI Committee 363 defined a range of concrete strengths for its activities, as explained in ACI 363R. For the purpose of this guide, HSC is defined as having a specified compressive strength of 8000 psi (55 MPa) or greater, and it does not include polymer-impregnated concrete, epoxy concrete, or concrete made with artificial normalweight and heavyweight aggregates. Changes in material properties, production and inspection techniques, or testing methods occur continuously from lower-strength to higher-strength concretes. Experience shows that in most cases, the special measures recommended in this guide should be applied for concrete with compressive strength greater than approximately 8000 psi (55 MPa).

CHAPTER 2—NOTATION AND DEFINITIONS

2.1—Notation

f'_c = specified compressive strength of concrete, psi (MPa)

2.2—Definitions

ACI provides a comprehensive list of definitions through an online resource, "ACI Concrete Terminology," at <http://terminology.concrete.org>. Definitions provided herein complement that resource.

concrete, high-strength (HSC)—concrete that has a specified compressive strength of 8000 psi (55 MPa) or greater.

quality assurance (QA)—actions taken by an organization to provide and document assurance that what is being done and what is being provided are in accordance with the contract documents and standards of good practice for the work.

quality control (QC)—actions taken by an organization to provide control and documentation over what is being done and what is being provided so that the applicable standard of good practice and the contract documents for the work are followed.

self-consolidating concrete (SCC)—is highly flowable, nonsegregating concrete that can spread into place, fill the formwork, and encapsulate the reinforcement without any mechanical consolidation. In general, SCC is concrete made with conventional concrete materials and, in some cases, with a viscosity-modifying admixture (VMA). SCC has also been described as self-compacting concrete, self-placing concrete, and self-leveling concrete, which all are subsets of SCC.

water-cementitious material ratio (w/cm)—the ratio of the mass of water, excluding that absorbed by the aggregate, to the mass of cementitious material in a mixture, stated to 1 decimal.

CHAPTER 3—PLANNING

3.1—Introduction

QC and testing of HSC is more critical than it is 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 HSC is controlled by the quality and uniformity of the ingredients, and by the mixing, placing, and curing conditions. A high level of QC is very important 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 HSC.

This chapter reviews critical activities before the start of construction. A preconstruction meeting is very important to clarify the roles of the members of the construction team and review the planned QC 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 HSC 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.

3.2—Preconstruction meeting

Small variations in mixture proportions and deviations from standard testing practices can have greater adverse effects on the strength of HSC than on 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 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 should also 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 is 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. Because HSC relies on a low water-cementitious material ratio (w/cm) 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 because the producer is familiar with and responsible for the product. Individuals should be identified, such as the concrete supplier's QC personnel, who will have the authority to add admixtures or water at the site. For 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.

3.3—Trial batches

Data on some HSC mixtures used previously are given in Tables 3.1 to 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 HSC mixtures.

Where historical data are not available, the development of an optimum HSC mixture requires a large number of trial batches (Blick et al. 1974; Cook 1982). Materials and proportions should initially be evaluated in the laboratory to determine the appropriate material proportions and their relative characteristics. Sufficient lead time should be allowed because high-strength mixtures containing fly ash, silica fume, or slag cement are often 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 admixtures and supplementary cementitious materials. Because HSCs usually contain both chemical admixtures and supplementary cementitious materials including silica fume, and a high volume of cementitious materials, they tend to be stickier than conventional concrete mixtures. Production trials can be used to establish optimum batching and mixing sequences that can reduce problems before 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% of the truck's rated mixing capacity. Based on experience, batches of HSC smaller than 4 yd³ (3 m³) should not be mixed in truck mixers.

3.4—Prequalification of concrete suppliers and preconstruction testing

Bidders should be prequalified before the award of a supply contract for concrete with a specified strength of 10,000 psi (70 MPa) or higher, or at least 1000 psi (7 MPa) 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.

3.4.1 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

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

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

Table 3.2—High-strength concrete mixtures used for different projects (CPCA 1995)

Mixture ingredients and concrete properties	Mixture No.*					
	1	2	3	4	5	6
<i>w/cm</i>	0.35	0.37	0.27	0.31	0.25	0.25
Ingredients						
Water, lb/yd ³ (kg/m ³)	329 (195)	278 (165)	228 (135)	244 (145)	219 (130)	226 (134)
Cement, lb/yd ³ (kg/m ³)	851 (505)	760 (451)	843 (500)	531 (315)	865 (513)	701 (416)
Silica fume, lb/yd ³ (kg/m ³)	—	—	30 (15)	61 (36)	72 (43)	57 (34)
Fly ash, lb/yd ³ (kg/m ³)	101 (60)	—	—	—	—	—
Slag, lb/yd ³ (kg/m ³)	—	—	—	231 (137)	—	—
Coarse aggregate, lb/yd ³ (kg/m ³)	1740 (1030)	1740 (1030)	1850 (1100)	1900 (1130)	1820 (1080)	1850 (1100)
Fine aggregate, lb/yd ³ (kg/m ³)	1060 (630)	1260 (745)	1180 (700)	1260 (745)	1160 (685)	1200 (710)
Admixtures						
Water reducer, fl oz/yd ³ (L/m ³)	25 (0.98)	—	—	23 (0.90)	—	—
Retarding admixture, fl oz/yd ³ (L/m ³)	—	116 (4.50)	47 (1.80)	—	—	12 (0.450)
Air-entraining admixture, fl oz/yd ³ (L/m ³)	—	—	—	—	—	3 (0.125)
High-range water reducer, fl oz/yd ³ (L/m ³)	—	290 (11.25)	362 (14.00)	153 (5.90)	406 (15.70)	129 (5.00)
Average compressive strength						
At 28 days, psi (MPa)	9430 (65)	10,000 (69)	13,490 (93)	12,040 (83)	17,260 (119)	10,880 (75)
At 91 days, psi (MPa)	11,460 (79)	12,620 (87)	15,520 (107)	13,490 (93)	21,030 (145)	—

*Mixture No. 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); and 6 = Portneuf Bridge, Quebec (1992).

performance. When strength higher than previously supplied is specified, or where there is limited experience in the supply of that strength of 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.

Table 3.3—Typical proportions in commercially available high-strength concrete mixtures (10,000 to 20,000 psi [70 to 140 MPa]) (Burg and Ost 1992)

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

*Mass of total water in mixture including water in admixtures.

[‡]Maximum nominal aggregate size: Mixtures 1 to 5, 1/2 in. (12.5 mm); Mixture 6, 1 in. (25 mm).

[‡]High-range water-reducer meeting ASTM C494/C494M requirements.

The monolith should also 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 mockups 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 10,000 psi (70 MPa) or higher, or at least 1000 psi (7 MPa) higher than previously supplied, should assign the concrete supplier responsibility for QC 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 ensure 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.

3.4.2 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.

3.4.3 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 HSC subjected to cycles of freezing and thawing under moist conditions. HSC in exterior vertical members is usually not critically saturated with water and has a *w/cm* below 0.4; therefore, air entrainment is not required. When needed, HSC 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 0.008 in. (0.20 mm) or less and a specific surface of 600 in.²/in.³ [24 mm²/mm³] or greater. Some HSCs, including concretes with low air contents (less than 4%) and coarse air-void systems (spacing factors greater than 0.008 in. [0.20 mm]) have proven durable in freezing and thawing environments (Philleo 1986). If an HSC does not have an air-void system that meets the recommendations of ACI 201.2R and 212.3R, its resistance to freezing and thawing and deicer scaling should be evaluated by laboratory testing according to ASTM C666/C666M and C672/C672M. 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 concrete with an exceptionally