Guide to Specifying Concrete Performance

Phase II Report of Preparation of a Performance-Based Specification For Cast-in-Place Concrete

Developed by:
Kenneth C. Hover
John Bickley
R. Doug Hooton

Reviewed and Approved by the NRMCA P2P Steering Committee

P2P INITIATIVE

NRMCA

Guide to Specifying Concrete Performance

Phase II Report of Preparation of a Performance-Based Specification for Cast-in-Place Concrete

Developed by
John Bickley, Consultant, Toronto, Canada
R. Doug Hooton, University of Toronto, Toronto, Canada, and
Kenneth C. Hover, Cornell University, Ithaca, New York

in consultation with
RMC Research & Education Foundation and
NRMCA P2P Steering Committee

March 2008

Reviewed and Approved by the NRMCA P2P Steering Committee

Acknowledgements

This document was underwritten by the RMC Research & Education Foundation. The RMC Research & Education Foundation is a non-profit organization dedicated to continuous research and enhancing the educational opportunities for the ready mixed concrete industry.

The development of this document was coordinated by the National Ready Mixed Concrete Association (NRMCA) and members of the P2P Steering Committee of the Research, Engineering and Standards Committee of the NRMCA.

NRMCA is a leading industry advocate working to expand and improve the ready mixed concrete industry through leadership, promotion, education and partnering ensuring that ready mixed concrete is the building material of choice.

Contents

Preface

This guide for preparing a performance-based concrete specification has been developed in the format of a model specification that can be modified by the user in scope and in level of detail. A commentary has been provided as text in the right hand column of the guide specification. The commentary not only explains certain specification provisions, but also provides guidance for the specifier and contractor/producer[1] where choices or options are available. While commentary text is not intended as specification requirements, the specifier could use commentary text as a basis for developing specification requirements or for adding additional detail to the specification requirements that have been proposed in this document. This guide is the distillation of over three years of debate and discussion among consultants, designers, concrete producers, and materials suppliers; and represents one method of satisfying the current concrete materials requirements of the ACI 318 Building Code using a performance-based rather than a prescriptive specification. Key features or concepts in this guide include the following:

1. The guide is organized into three parts. Part I addresses those specification provisions that are based on the concrete materials requirements of ACI 318-08. Section 3 in Part I of this guide allows use of ASTM C1202 testing (resistance to chloride penetration) in lieu of meeting the w/cm requirements of ACI 318, and would thus require the concurrence of the Building Official. Likewise the performance alternative to the prescriptive requirements of Table 3.b requires approval of the Building Official. Part II addresses the workability and temperature of fresh concrete in terms that are fully compatible with the requirements of ACI 301-05. Part III offers optional specification requirements that are not currently addressed by either ACI 318 or ACI 301, and would be specified only when applicable to the special needs of a particular project. These optional provisions apply only when specified, and no default requirements apply.
2. In accordance with ACI 318-08, the specifier must state the exposure classification to which the subject concrete will be exposed. Various strength and durability requirements follow from exposure classifications. There are no default durability requirements, and the contractor/producer is not expected to assume such. Note that ACI 318-08 only addresses exposures to freezing and thawing, soluble sulfates in soil or water, conditions that need precautions to minimize corrosion of reinforcing steel and conditions that will need low permeability for concrete members in contact with water. Other exposure conditions are beyond the scope of the ACI 318-08 Exposure Classifications, and must be addressed separately by the specifier. Some of the guidance provided in this document may be helpful in addressing other exposure or durability concerns.
3. In many cases the following guide specification provides the contractor/producer with one or more options for demonstrating compliance with specification requirements. The option chosen by the contractor/producer, along with the required information that must accompany each option, is to be documented in a pre-construction submittal to the engineer of record.

[1] The term "Contractor/Producer" is used throughout to denote that although the contractor is directly responsible to the owner, it is generally the concrete producer who will respond to the various requirements for concrete and provide the documentation required.

4. In general the specifier will approve the proposed concrete mixture in advance of construction operations (pre-qualification), and in many, but not all cases, specified properties of the pre-qualified mixture will be verified for acceptance at the point of discharge. Pre-qualification permits evaluation of a proposed concrete mixture on the basis of more detailed or time-consuming laboratory-type performance tests that are not generally suitable for jobsite verification.

5. In some cases the specifier may prefer to evaluate concrete performance at the point of placement. While this is logically sound, it is logistically difficult for several reasons. First, while some guidance exists in various documents, no standard method exists for sampling concrete at the point of placement, and methods in use vary widely. Questions remain about how to secure a representative sample, how to do so in a safe manner, and whether to attempt to sample immediately prior to impact at the point of placement, after impact, before or after consolidation, and whether to retrieve and then re-compact a sample that has been placed, consolidated, and perhaps finished.

   Requirements for point-of-placement sampling and testing should therefore be accompanied by a specific sampling protocol. Further, it is to be expected that concrete properties, especially air content and density, will be affected by placing, consolidation, finishing and curing operations. Typically specified properties, including total air contents of Table 3.a are intended for sampling at the point of discharge from the transport unit, and over many years of experience some losses from those values are expected and have been found acceptable (and in some cases beneficial), as long as a satisfactory air void system remains in place. As suggested in ACI 304, it can be helpful to establish a relationship between desired properties at the point of placement and those properties specified for acceptance of the concrete at point of discharge, but such requires a rigid protocol for how to sample, and recognition of the significant and rapid changes in placing method and placing rate that take place on a typical site. At the specifier's option a procedure for establishing such a relationship could be made part of the pre-qualification requirements, but such has not been built in to the specification. Thus, the scope of this model specification is limited primarily to pre-qualification and to discharge of concrete by the concrete supplier at the end of the truck chute. It is anticipated that further development and experience in the use of performance specifications, the increasing use of a number of advanced test procedures and further development of additional test procedures will facilitate the use of performance specifications after concrete placement, and in the hardened structure.

6. An important aspect of testing the properties of concrete from samples obtained from the structure is the change of control of the product from the concrete supplier to the concrete contractor and the appropriate assignment of responsibility if specification requirements are not met. It is anticipated that as performance specifications evolve, there will be a need for increased coordination and partnering between these two parties to ensure that specified requirements are achieved. In this guide specification, most tests and criteria for properties of concrete in the structure are deferred to referee evaluations when there is non-compliance with samples obtained at the point of discharge. This specification further recognizes that the acceptance criteria for measured properties should become more lenient as one moves from tests of lab-mixed concrete, to tests on jobsite samples, to samples from the hardened structure. This is necessary to account for the changing components of variability at these points of sampling and testing when measuring performance properties.

7. This guide specification concentrates on performance and not on means, methods, or materials, and while there are multiple requirements herein for submittal of concrete performance records, there are no requirements for a full disclosure of ingredients or proportions. This does not imply, however, that non-standard materials or ingredients are acceptable without prior notification and approval of the engineer of record. However, should concrete as supplied fail to meet one or more performance requirements, the purchaser may need to know the composition of the mix in order to determine the causes of failure and to evaluate the adequacy of the work.

8. When writing a performance specification, specifiers must recognize that some traditional prescriptive requirements (such as slump) do not correlate well with actual concrete performance, and unverified w/cm is not a particularly useful parameter, nor does w/cm have a fixed relationship to permeability as is often implied. Similarly, when responding to a performance specification, contractors must recognize that their role in scheduling, ordering, handling, placing, finishing, and curing concrete has significant impact on the in-place properties that are the chief interest of the owner, and suppliers must recognize that reliable control of total water content is more important in the performance world than in the prescriptive world. Specifiers and contractor/producers must also recognize that significant time and effort may be required in the development or collection of data needed to pre-qualify a concrete mixture.

9. Given that a performance specification can allow a knowledgeable contractor/producer to provide a superior product by allowing the freedom to apply unique expertise, it follows that specifiers should consider establishing some minimum level of contractor/producer qualifications to be eligible to work under a performance specification. This might include evaluation of reputation and experience, submission of a quality plan, and in some cases certifications of personnel and production facilities. NRMCA has recently published "Preparation Guidelines for Quality Manual for Ready Mixed Concrete Companies," and "Ready Mixed Concrete Company External Quality Audit Checklist for Compliance with Quality Plan," both of which would be useful in establishing or evaluating required levels of qualification of concrete producers.

10. While many concrete properties and associated tests and criteria are covered in this specification, it does not imply that all properties are appropriate for all concrete on any given project. For most construction the quality assurance procedures as required in ACI 318 are recommended with additional properties invoked as appropriate for structures of a more critical nature that could impact public safety or special needs. It is the specifier's prerogative to include or exclude requirements for concrete with an understanding of the requirements of the structure, local codes and associated costs.

11. Owners, specifiers and contractor/producers are encouraged to review the document, "Preparation of a Performance-based Specification for Cast-in-Place Concrete – Phase I, " by Bickley., J.A., Hooton, R.D., and Hover, K.C., published by and available from the RMC Research & Education Foundation, Silver Spring, MD, January, 2006. This report contains more detailed discussions of the advantages and disadvantages, test methods, the international state of the practice, and risks and responsibilities associated with performance specifications.

Part I: Specification Provisions in Accordance with the Requirements of ACI 318-08

	Performance Specification	Commentary
1. Compressive strength of concrete		
	(sampled in accordance with ASTM C172 and tested in accordance with ASTM C 31 and C 39).	Compressive strength requirements under this performance specification are unchanged from the traditional approach described in ACI 318.
1.1	Specified value — Specify 28-day compressive strength f'_c, AND all applicable exposure classifications from Table 1. The required 28-day compressive strength shall be the higher of: (a) Value of f'_c as specified in contract documents (b) Value of f'_c associated with the specified exposure classification as shown in Tables 2.a-d. (c) Value of f'_c that has been demonstrated to correlate with the R'_c in the ASTM C1202 test when specified in accordance with 3A, or (d) Value of f'_c that has been demonstrated to correlate with the required w/cm when specified in accordance with 3B. Mixture shall be pre-qualified to achieve the required average strength, f'_{cr}, along with other plastic properties as required and strength shall be verified by sampling at the point of discharge in accordance with ASTM C172, unless specified otherwise.	The specifier is reminded that the 2008 edition of the ACI 318 code requires that both the required compressive strength and all applicable exposure classification(s) be specified. The contractor/producer is not expected to assume the environmental conditions to which the concrete will be exposed. Further, in setting the specified compressive strength requirements the specifier is advised to review Tables 2.a-d which contain values of minimum specified compressive strength associated with the exposure classifications. The contractor/producer is required to furnish concrete that is designed to the average strength level, f'_{cr} that will meet the higher of f'_c as specified in contract documents, the value of f'_c associated with the specified exposure classification as shown in Tables 2.a-d, or values of f'_c that were developed from correlating strength with the results of ASTM C1202 tests, or with values of w/cm, as described in Sections 3A and 3B.
1.2	Specifier's options	
1.2.1	Specifier may optionally indicate an alternative age for specified compressive strength, f'_c	For high strength concrete it may be beneficial to allow the specified strength to be achieved at later ages, like 56 or 90 days, if the anticipated service loads are applied at a later time. This allows for lower cementitious materials content with corresponding improvements in regard to heat generation, shrinkage, and environmental sustainability. For fast track projects or for post-tensioned construction, the specified strength might be at ages earlier than 28 days.
1.2.2	Specifier may optionally require strength cylinders to be taken at point of placement, *in addition* to taking strength cylinders at the point of discharge from the transportation unit.	Default requirement is for sampling at the point of discharge. However, if the specifier opts to require sampling at the point of placement to evaluate any possible impact of handling or placing, samples are still required at the point of discharge to evaluate the material as-delivered.
1.2.3	Specifier may optionally waive the requirement for	In cases where concrete strength is not critical to the

	Performance Specification	Commentary
	on-site verification of strength of a pre-qualified mixture.	performance of the structure, the specifier may waive the requirement for on-site verification of compressive strength for a mixture that has been pre-qualified.
1.3	Contractor/Producer Options — In the event that the value of minimum ***f'*ᶜ** associated with the specified exposure classification in Tables 2.a-d is greater than the value of f'_c as specified in contract documents, the contractor may elect to demonstrate that the concrete meets the requirements for either w/cm, or ASTM C1202 (Resistance of Concrete to Chloride Ion Penetration) results, as shown in Tables 2.a-d in lieu of meeting the requirements for minimum f'_c also listed in Tables 2.a-d. In such cases compressive strength shall meet the requirements of ACI 318 for the value of f'_c as specified in contract documents.	See Section 3 for further discussion of meeting w/cm or ASTM C1202 requirements in lieu of strength requirements associated with exposure class in Tables 2.a-d.
1.4	Pre-qualification — Concrete mixtures must be pre-qualified for compressive strength prior to use on the project. Concrete supplier shall submit evidence that the concrete mixture to be furnished to the project can meet the requirements for compressive strength, in accordance with ACI 318.	Evidence required for pre-qualification is as described in Chapter 5 of ACI 318 and Section 4 of ACI 301, and consists of historical data of mixture performance, if available for the class of concrete, or laboratory batch data documenting that the proposed mixture achieves the required average strength, f'_{cr}, and other requirements of the project specification.
1.5	Point of discharge — Compliance of the designated mixture with strength requirements must be verified by sampling concrete at point of discharge from the transportation unit in accordance with ASTM C 172.	
1.6	Point of placement — Specifier may optionally require strength cylinders at point of placement, in addition to taking strength cylinders at the point of discharge. Evaluate results in accordance with ACI 318.	Point of placement sampling, if optionally specified, must be accompanied by standard sampling and testing at the point of discharge. This is because the cause and ultimate remedy for unsatisfactory results at the point of placement cannot be effectively determined without a baseline of test results for concrete sampled prior to placement. See note 5 in Preface.
1.7	Hardened concrete, in-place — Tests of cores extracted from hardened concrete shall be used only in the case that any strength test of standard-cured cylinders, in accordance with ASTM C 39, fails to comply with the ACI 318 requirements for the specified value of f'_c. In such case extract and condition cores in accordance with ASTM C42, and evaluate results in accordance with the provisions for core testing in ACI 318.	Investigation of low-strength test results is described in Section 5.6.5 of ACI 318.

2. Air content of fresh concrete

	(sampled in accordance with ASTM C172 and tested in accordance with ASTM C 173 or C231)	Under performance options the contractor/producer can propose an air content lower than specified on the basis of sufficient data to support the proposal.
2.1	Specified value — Specify all applicable exposure	Specifier is reminded that there is no default

	Performance Specification	Commentary
	classifications from Table 1. Unless otherwise specified, air entrained concrete is required only if exposure class for the structural member is specified as F1, F2 or F3 from Table 1. Mixture shall be pre-qualified and air content shall be verified at point of discharge in accordance with ASTM C 172, unless otherwise specified. Specified total air content at the point of discharge in accordance with Table 3.a. Additional requirements pertaining to exposure classification F3 are shown in Table 3.b.	requirement for air entrained concrete. Specified air content is that value associated with the specified exposure classification, unless another value for air content is specified, or a lower air content has been approved on the basis of 2.3. Specified air content is based on the nominal maximum size of the coarse aggregate used in the mixture and the tolerance for acceptance tests conducted at the point of discharge from the transportation unit at the jobsite is ±1.5%.
2.2	Specifier Options	
2.2.1	Specifier may require a value for air content other than that associated with the exposure classification in Table 3.a.	Specifiers are cautioned against arbitrarily increasing required air content due to the lower w/cm and increased paste content that is generally required to compensate for the accompanying reduction in compressive strength.
2.2.2	Specifier may require sampling and testing of air content at the point of placement *in addition* to requiring sampling and testing of air content at the point of discharge.	Point of placement sampling, if optionally specified, must be accompanied by standard sampling and testing at the point of discharge. This is because the cause and ultimate remedy for unsatisfactory results at the point of placement cannot be effectively determined without a baseline of test results for concrete sampled prior to placement. See note 5 in the Preface.
2.2.3	Specifier may optionally waive the requirement for on-site verification of air content of a pre-qualified mixture.	In cases where resistance to damage by freezing and thawing or resistance to scaling is not critical to the performance of the structure, the specifier may waive the requirement for on-site verification of air content for a mixture that has been pre-qualified.
2.3	Contractor/Producer Options — The contractor/producer may submit information supporting the adequacy of air content lower than that shown in Table 3.a for the specified exposure condition. Approval of the proposed air content shall be based on documentation that the proposed mixture meets at least one of the requirements of 2.3.1, 2.3.2, or 2.3.3. When any one of these options is selected, tests of air content in fresh concrete must also be performed at the point of placement. At the specifier's option these tests may be waived for acceptance after development of sufficient data demonstrates that handling or placing does not degrade the desired air void system.	Achieving resistance to damage by freezing and thawing with an air content lower than the values of Table 3.a can work to the advantage of all parties to the contract. As air content increases, the w/cm must decrease to maintain strength, and this is generally accomplished by increasing cementitious materials content. The resulting increase in paste content not only increases cost but can lead to increased heat of hydration and shrinkage. Likewise, the higher the air content, the more difficult it is to control air in fresh concrete. Further, in many cases concrete with a lower total air content than that shown in Table 3.a has proven to be resistant to damage from freezing and thawing. At the contractor/producer's option the required total air content values shown in Table 3.a can be replaced by lower values, when documentation of resistance to damage from freezing and thawing and air content stability during handling and placement is provided. Three options for acceptable documentation are provided in 2.3.1, 2.3.2, and 2.3.3. Note, however, that concrete with an air content lower than the values in Table 3.a may perform well in service because the specific exposure condition of the concrete element in question is less severe than assumed in the ACI 318 exposure classifications (more

	Performance Specification	Commentary
		moderate weather conditions or lack of saturation such as is often the case with vertical members), or because air losses in handling and placing the concrete are less than normally expected, or because the average size of the air voids is sufficiently small that durable, in-place concrete results at lower air content. For these reasons the performance criteria in 2.3.1 vary with exposure classification, and the contractor must demonstrate the stability of the air content with tests at the point of placement.
2.3.1	Minimum air content in fresh concrete (with a tolerance of -0%) for a designated mixture shall be that which achieves a durability factor of 80%, 85%, or 90% for exposure classifications F1, F2, and F3, respectively, when tested to 300 cycles by ASTM C666 Procedure A. Air content shall not be less than 3.0% (with a tolerance of -0%). Pre-qualification test samples shall be obtained from production size concrete batches of a minimum of 3 cubic yards.	Under option 2.3.1 the minimum acceptable air content is the lowest value which achieves the specified performance in freeze-thaw tests with a minus zero tolerance at the point of acceptance to the value that has been pre-qualified. To guard against air losses in handling and placing, it is recommended that air content of fresh concrete must be monitored at the point of placement in addition to at the point of discharge.
2.3.1.1	When this option is selected, tests of air content in fresh concrete must also be performed at the point of placement. At the specifier's option these tests may be waived for acceptance after development of sufficient data to demonstrate that handling or placing does not degrade the desired air void system.	
2.3.2	For exposure classifications F1, F2, and F3, minimum air content in fresh concrete (with tolerance of -0%) shall be that which achieves a mass loss of less than 1.0 kg/m^2 when tested to 50 cycles by ASTM C672 and scaled mass is recorded. Air content shall not be less than 3.0% (with tolerance of -0%). Pre-qualification test samples shall be obtained from production size concrete batches of a minimum of 3 cubic yards.	Under option 2.3.2 the minimum acceptable air content is the lowest value which achieves the specified performance in scaling tests with a minus zero tolerance. A modification of the current ASTM C672 test is specified in which all debris from the scaled surface of specimens is collected by means of filtering the brine washed from specimens. The debris is oven dried and its cumulative mass is divided by the exposed surface area of the specimen. (There is insufficient data to permit reliable modification of the scaling criteria for different exposure classes.)
2.3.2.1	When this option is selected, tests of air content in fresh concrete must also be performed at the point of placement. At the specifier's option these tests may be waived for acceptance after development of sufficient evidence to demonstrate that handling or placing does not degrade the desired air void system.	
2.3.3	For exposure classifications F1, F2, and F3, minimum air content in fresh concrete shall not be less than 3.0% (with tolerance of -0%) and shall be that which produces a satisfactory air void system in hardened concrete with a *maximum* spacing factor of 0.008 inches as evaluated by ASTM C 457 with a minimum hardened air content of 3.0% (with tolerance of -0%). Pre-qualification test samples shall be obtained from	As an alternative to the ASTM C 666 Test Method for Resistance of Concrete to Rapid Freezing and Thawing, or C 672 Test Method for Scaling Resistance of Concrete Surfaces, both of which can take several months to complete, mixtures may be pre-qualified on the basis of their ability to achieve a Spacing Factor of 0.008 inches with a minimum air content of 3.0%, regardless of exposure classification. (There is insufficient data to permit reliable modification of the

	Performance Specification	Commentary
	production size concrete batches of a minimum of 3 cubic yards. When this option is selected, tests of air content in hardened concrete must be performed from samples at the point of placement, or extracted from the structure.	spacing factor for different exposure classes.) Since spacing factor depends on both air content and the size of the air voids, and since both can be modified by handling and placing the concrete, it is necessary to verify spacing factor at the point of placement. Effect of placement methods and conditions that can have an impact air void systems should be evaluated.
2.3.4	For options 2.3.1, 2.3.2, and 2.3.3, the maximum air content in fresh concrete shall be no greater than 3.0% higher than the minimum air content values established.	Provision 2.3.4 limits the range of acceptable air content in fresh concrete to 3% to limit variations in other related properties such as strength and density.
2.3.5	Unless otherwise specified, the prescriptive requirements of Table 3.b for exposure classification F3 may be waived for concrete that has been pre-qualified on the basis of test results per 2.3.1, 2.3.2 or 2.3.3, and for which air content is verified at the point of placement in accordance with 2.6, and concrete is wet-cured for at least 7 days.	The limits on the quantities of supplementary cementitious materials indicated in Table 3.b can be waived by the specifier if documentation of adequate freeze-thaw or scaling performance is evident for concrete mixtures as per 2.3.1, 2.3.2 or 2.3.3.
2.4	Pre-qualification — Concrete mixtures must be pre-qualified for air content prior to use on the project. Submit data that the proposed concrete mixture has an air content in the fresh state that meets the requirements of Table 3.a. Alternatively submit request to use a lower target air content and provide supporting data that the concrete complies with 2.3.1, or 2.3.2, or 2.3.3.	It can be helpful for the contractor/producer to pre-qualify the mixture in accordance with 2.3.1, 2.3.2, or 2.3.3 even when intending to meet the table values for total air content. Data thus collected can be used to resolve any questions concerning low air content of fresh concrete that may arise during construction.
2.5	Point of discharge — Unless waived by the specifier, the air content of fresh concrete, for mixtures that have been pre-qualified, shall be verified at point of discharge. Fresh concrete is acceptable when air content is as required in Table 3a with a tolerance of ±1.5%. Fresh concrete is acceptable when air content is equal to or greater than an alternate air content value pre-qualified by meeting the requirements of 2.3.1, or 2.3.2, or 2.3.3 at both the point of discharge and the point of placement. The measured air content from acceptance tests conducted at the jobsite shall not be less nor more than 3% greater than the pre-qualified value. On-site addition of air entraining admixture followed by adequate mixing is permitted to increase air content.	
2.6	Point of placement — When optionally specified, fresh concrete sampled at the point of placement, *prior to consolidation*, is acceptable when air content is as required in Table 3.a, or is equal to or greater than an alternate air content value pre-qualified by meeting the requirements of 2.3.1, or 2.3.2, or 2.3.3. Point of placement sampling, prior to	Point of placement requirements are the same as point of discharge. However, pre-qualification of lower acceptable air content can be useful in demonstrating the acceptability of total air content at point of placement that may be less than the values shown in Table 3a. Note that when air is measured at point of placement, strength test specimens should also be obtained at point

	Performance Specification	Commentary
	consolidation, is required when provisions 2.3.1, 2.3.2, or 2.3.3 have been selected. At the specifier's option point of placement tests may be waived for acceptance after development of sufficient data to demonstrate that handling or placing does not degrade the desired air void system. On-site addition of air entraining admixture followed by adequate mixing is permitted to increase air content. Air content of fresh concrete must always be measured at the point of discharge when companion samples are tested from the same load at point of placement.	of placement, due to the influence of air content on strength. Sampling at point-of-placement should be conducted in a manner that minimizes the sampling variations discussed in note 5 of the Preface.
2.7	Hardened concrete, in-place — Tests of cores extracted from hardened concrete shall be evaluated only in the case that tests of air content in fresh concrete fail to comply with specification requirements. In such case evaluation of hardened concrete shall be on the basis of total hardened air content only unless air void system parameters such as spacing factor have been specified. Concrete is acceptable if total air content of hardened concrete is equal to or greater than the value established at pre-qualification, or if the total air content of hardened concrete is a minimum 3.0% with average spacing factor from 3 cores of 0.010 inches with no single value > 0.015 inches. This evaluation shall be conducted in accordance with ASTM C 457.	

3. Resistance to Fluid Penetration of hardened concrete

	Performance Specification	Commentary
		To address the need to limit penetration of gas and liquid into hardened cement paste, ACI 318 sets limits on the maximum w/cm permitted for various exposure classifications, as shown in Tables 2a-d. While it is clear that in general the permeability of concrete increases exponentially with w/cm, the specific value of permeability at any given w/cm varies significantly in response to materials characteristics such as total water and total paste content, aggregate content and grading, and the type and proportions of supplementary cementitious materials. Time-temperature history (maturity) as well as the duration and type of curing also critically influence permeability and related properties, as does the age of the concrete or specimen at the time of test. Thus the limiting values of w/cm required by ACI 318 are prescriptive in nature, and do not necessarily correlate to specific values of measurable concrete performance. For this reason Section 3, Resistance to fluid penetration of hardened concrete, allows the contractor/producer two options for demonstrating compliance with the w/cm requirements of Tables 2.a-d.

	Performance Specification	Commentary
		Option 3A allows the contractor/producer to demonstrate the acceptability of a proposed concrete mixture on the basis of measured performance by means of ASTM C 1202 (Resistance to Chloride ion Penetration). ASTM C 1202 acceptance criteria vary by exposure classification as shown in Tables 2a-d. Considering the cost and available proficiency of local laboratories to conduct ASTM C 1202 to the desired precision, the specifier may permit use of compressive strength tests as an indicator of resistance to chloride penetration when a sufficiently reliable correlation has been established between the two concrete properties based on the documentation in the submittal for the designated concrete mixture. Option 3B allows the contractor/producer to demonstrate acceptability of the proposed mixture on the basis of traditional w/cm requirements by estimating the w/cm of fresh concrete. Unless specified otherwise, results of compressive strength tests are used as an indicator of w/cm on the basis of a correlation developed by the contractor/producer documented in the submittal for the designated concrete mixture. When permitted or optionally required by the specifier, results of AASHTO T 318 microwave oven drying tests can be used as an indicator of w/cm on the basis of a mix-specific correlation developed by the contractor/producer. Sections 3A and 3B are intended as mutually exclusive alternatives, to be selected by the contractor/producer. While the use of ASTM C1202 is a more direct and truly performance-oriented approach, estimating w/cm rather than measuring resistance to chloride ion penetration might be preferred when the C1202 test is not economically available, or when specific combination of materials such as the use of some corrosion inhibiting admixtures is known to skew the results of the C 1202 test.

3A Resistance to Chloride Ion Penetration, R'_c

	(in accordance with ASTM C1202, with alternative use of compressive strength as an indicator of chloride penetration resistance) Section 3A is an alternative to Section 3B, either section apply only when the specified exposure classification requires a maximum allowable w/cm. It is not intended that both sections 3A and 3B would be required.	Section 3A permits the contractor/producer to demonstrate the acceptability of a concrete mixture on the basis of ASTM C1202 (Resistance to Chloride Penetration) test results, as an alternative to complying with the w/cm requirements of ACI 318, as described in 3B. Option 3A thus permits the contractor/producer to take advantage of materials technology that can be used to deliver a mixture at a sufficiently low value of chloride ion penetrability, and to do so more reliably than mere compliance with the more generic and approximate values of w/cm or levels of compressive strength. Tables 2.a-d indicate the specified value of ASTM C1202 results, R'_c, (Coulombs) associated with each

	Performance Specification	Commentary
		applicable exposure condition. As these are specified values, compliance is achieved when the average test result is *lower than* the specified value, in a manner analogous to the current practice that required average strength test values must be *higher than* the specified value f'_c. Use of this option is beyond the scope of the current ACI 318 Building Code, and as such its use should be approved by an authorized building official for those structures governed by the Building Code.
3A.1	Specified value — Specifier must state all applicable exposure classes from Table 1. Use of ASTM C1202 is a permitted alternative to the exposure-class-based w/cm and f'_c, requirements shown in Tables 2a-d. Specified values of resistance to chloride penetration, R'_c, are also shown in Tables 2.a-d. Mixture shall be pre-qualified. Resistance to Chloride Ion Penetration shall be verified on samples obtained at point of discharge by ASTM C 172 and measured by ASTM C1202 when so indicated in Tables 2a-d, unless specified otherwise.	
3A.1.1	When option 3A is elected all requirements of Tables 2.a-d other than minimum specified compressive strength and w/cm remain in force. Similarly, when the durability-related minimum compressive strength requirement is replaced by compliance with C1202 requirements per this option, specified compressive strength remains as f'_c as described in Section 1.	
3A.2	Specifier Options	
3A.2.1	The option of demonstrating mixture compliance by means of Section 3A is permitted, unless specified otherwise. Specifier must state when use of Resistance to Chloride Ion Penetration is not permitted as an alternative to both the w/cm and f'_c requirements of Tables 2a-d. When the provisions of Section 3A are not permitted, compliance with the specifications for resistance to fluid penetration of hardened concrete shall be evaluated by the provisions of Section 3B.	If the option of Section 3A is not permitted, note that no currently available and standardized test method permits a directly measured verification of w/cm without prior knowledge of batch weights of cement and other supplementary cementitious materials. Thus, w/cm cannot be measured as a performance characteristic of concrete. For the purpose of evaluating compliance with the w/cm requirements, w/cm can be estimated as described in Section 3B.
3A.2.2	Specifier must state when use of Resistance to Chloride Ion Penetration is required in lieu of the w/cm and minimum f'_c requirements of Tables 2a-d.	
3A.2.3	Specifier must state when requirements for on-site verification at the point-of-discharge from the transport unit are other than as indicated in Tables 2a-d., by either requiring verification where none is required in the table, or by waiving verification where it is required in the table.	In determining whether to modify the requirements for on-site verification of resistance to Chloride Penetration, the specifier should consider the significance or criticality of the structure, and the cost and time of performing these tests. Using the accelerated procedure (see notes to Tables 2a-d) results will be available in about 28 days. Using the standard procedure, results will be available in about 60 days.

	Performance Specification	Commentary
		At current market values, a C1202 test is 10 to 20 times more expensive than a single cylinder test.
3A.2.4	Alternative values of R'_c may be specified in lieu of those in Table 4.4.1.	For critical applications, severe exposures, or extended service life it may be desirable to specify values of R'_c lower than those indicated in Tables 2.a-d. Achieving such values will typically require sophisticated combinations of materials, and may not be economically viable for all projects.
3A.2.5	Specifier must state when use of compressive strength results as an acceptance method are permitted to be used as an indicator of resistance to chloride ion penetration on the basis of mixture-specific correlation of data submitted with pre-qualification documentation, as described in 3A.4.2	In determining whether to permit the results of strength tests as an indirect indicator of resistance to chloride ion penetration, the specifier should consider the significance or criticality of the structure, the cost and time of performing these tests, and the reliability of the mixture-specific relationship between strength and the results of ASTM C1202 testing. See also the commentary to 3A.4.2. It is recommended that compressive strength be only considered as an indicator of chloride ion penetration resistance for exposure classifications F1, S1, and P1 and not for the more severe levels of exposure in each category.
3A.3	Contractor/Producer Options — Unless specified otherwise, contractor/producer may elect to demonstrate compliance with exposure class requirements by meeting the ASTM C 1202 requirements associated with any given exposure class in accordance with Section 3A. In such case the minimum specified compressive strength and w/cm requirements associated with Exposure Classes are thus waived when compliance is demonstrated by means of C 1202 test results. Alternatively, and unless specified otherwise, contractor/producer may elect to demonstrate compliance with exposure class requirements in accordance with the provisions of Section 3B, estimated w/cm.	
3A.4	Pre-qualification — Concrete mixtures must be pre-qualified prior to use on the project	
3A.4.1	Submit test data that documents that: R'_{cr} should be less than or equal to: $R'_c - 1.04\ S$, or $1.3R'_c - 2.33\ S$ Where R'_{cr} is required average chloride ion penetration for the mixture designed and proposed for the work. S is the standard deviation from at least 6 tests taken from a similar class of concrete. A test is defined as the average value of two slices taken from one or two 4 x 8 cylinders after discarding the top 1 in. of the cylinder.	The mixture pre-qualification requirements are similar to those for compressive strength with the required average strength, f'_{cr}, of the proposed mixture for the specified strength, f'_c. Mixtures designed to achieve this average value of chloride ion penetration, R'_{cr}, for a specified value R'_c will have a less than 1% probability of failing the acceptance criteria defined in 3A.5.2. For more discussion review "Acceptance Criteria for Durability Tests", Obla, K.H. and Lobo, C.L., ACI Concrete International, May 2007, pp. 43 – 48.
3A.4.2	When compressive strength results are permitted in accordance with 3A.2.5 for the purposes of verifying resistance to chloride penetration at the	The permeability and related transport properties of concrete are generally more sensitive to water content and w/cm than compressive strength. It is therefore

	Performance Specification	Commentary
	point of discharge, the contractor/producer must submit a mix-specific correlation between C 1202 test results and 28-day standard-cured compressive strength results for the proposed mixture. The submittal shall include test data and the proposed value of compressive strength that reliably corresponds to the required resistance to chloride penetration. With the specifier's approval this pre-qualified value of compressive strength may be used in-lieu of on-site verification of resistance to chloride penetration. Acceptance of concrete on the basis of strength is described in Section 1.	recommended that the correlation between strength and chloride penetration resistance include at least two RCPT test results for each of three batches of the proposed mixture, with one batch at the water content intended by the producer, and the other two at water contents at least 5% higher and at least 5% lower to represent a range of potential as-delivered variations of the mixture. This procedure is similar to the "three-point-curve" approach described in ACI 318 and ACI 301. Further, since air content has a generally greater impact on compressive strength than on the permeability or resistance to chloride ion penetration of concrete, it is important that air content be carefully controlled in establishing the required correlation. Unless the correlation specifically takes air content (or density) into account, and unless or until mix-specific data demonstrates otherwise, it is recommended that the strength test results used in the correlation be adjusted by adding 250 psi per 1% air above the specified air content, and subtracting 250 psi per 1% air below the specified air content. This approximate correction reduces the likelihood of misinterpreting the effect of variations in air content as variations in resistance to chloride penetration. When insufficient time is available to fully develop such a relationship prior to construction, the specifier may consider a transition to allowing strength as an indicator of resistance to chloride penetration as project data develop.
3A.5	Point of discharge	
3A.5.1	Unless specified otherwise, requirements for verification of resistance to chloride penetration at point of discharge vary with Exposure Classification and are indicated in Tables 2a-d.	
3A.5.2	When verifying resistance to chloride ion penetration from samples obtained at the jobsite both the following acceptance criteria shall apply: the average of all sets of 5 consecutive test results shall be ≤ R'_c; and no individual test ≥1.3 R'_c. A test is defined as the average value of two slices taken from one or two 4 x 8 cylinder after discarding the top 1 in. of the cylinder.	The acceptance criteria established for chloride ion penetration are based on the provisions that are used to establish the required average value, R'_{cr}, for the designated mixture in 3A.4.1. During the project the probability of failing the acceptance criteria defined in 3A.5.2 is at 1% or less if the concrete mixture is being produced under similar materials and conditions related to the variability assumed in establishing the required average value, R'_{cr}.
3A.5.3	When compressive strength is permitted as an indicator of resistance to chloride penetration, the value of compressive strength obtained at the point of discharge is evaluated as described in Section 1. No additional strength samples are required beyond those required for acceptance of concrete on the basis of strength as described in Section 1. Establishing a correlation between compressive strength and resistance to chloride ion penetration is described in 3A.4.2. Tests of	It is recommended that the compressive strength obtained at point-of-discharge be corrected to account for the effects of air content when such test results are used to indicate compliance with specified R'_c. See commentary to 3A.4.2.

	Performance Specification	Commentary
	air content must be made from the same sample used for making strength specimens to be used as indicators of resistance to chloride penetration.	
3A.6	Point of placement — Not applicable.	
3A.7	Hardened concrete, in-place	
3A.7.1	Tests of cores extracted from hardened concrete shall only be used in cases where any C 1202 or strength test result used to indicate C 1202 performance fails to comply with specified requirements. In such cases, extract and condition cores in accordance with ASTM C 42, and evaluate results in accordance with ASTM C 1202.	
3A.7.2	The following criteria shall apply for cores: the average of 3 cores shall be ≤ 1.3 $\boldsymbol{R'_c}$; and no individual core ≥ 1.5 $\boldsymbol{R'_c}$.	
3A.7.3	Strength tests of cores may be used as an indicator of resistance to chloride penetration only when permitted.	

3B Estimated Water/cementitious materials ratio

	(as indicated by compressive strength, with alternative for use of AASHTO T 318, Standard Method of Test for Water Content of Freshly Mixed Concrete Using Microwave Oven Drying) Section 3B is an alternative to Section 3A, either section applying only when the specified exposure classification requires a maximum allowable w/cm. It is not intended that both sections 3B and 3A would be required.	Section 3B provides a means to approximately evaluate or estimate the w/cm of a concrete mixture. While critical to the behavior of any given mixture, w/cm is a prescriptive rather than a performance characteristic. Further, while the batch weights of water (including all of the multiple sources of water in a concrete mixture) and cementitious materials must be measured accurately at the batching facility, neither the batch weights nor their ratios can be measured with precision after mixing. Reliably demonstrating compliance with a specified w/cm is therefore difficult, leading to two fundamental options: estimating the w/cm, or evaluating a performance characteristic of hardened concrete that has a demonstrable relationship with w/cm. Section 3B includes provisions for establishing a mixture-specific correlation between w/cm and compressive strength and then using strength as an indicator of w/cm. When permitted or required by the specifier, w/cm may be estimated on the basis of mixture-specific correlation data between w/cm and the water content obtained by the AASHTO T 318 microwave oven test.
3B.1	Specified Value — Specifier must state all applicable exposure classes from Table 1. Required w/cm shall be the value associated with the specified exposure classification in Tables 2a-d, unless specified otherwise. Mixture shall be pre-qualified on the basis of w/cm, and unless specified otherwise, w/cm shall be verified at point	

<table>
<tr><th></th><th>Performance Specification</th><th>Commentary</th></tr>
<tr><td></td><td>of discharge as indicated in Tables 2a-d.</td><td></td></tr>
<tr><td>3B.2</td><td>Specifier options</td><td></td></tr>
<tr><td>3B.2.1</td><td>The option of demonstrating mixture compliance by means of Section 3B is permitted unless specified otherwise. Specifier must state when estimated w/cm in accordance with Section 3B is not permitted as an alternative to the resistance to chloride penetration required for the exposure class in accordance with Section 3A. When the provisions of Section 3B are not permitted, compliance with the specifications for penetrability of hardened concrete shall be evaluated by the provisions of Section 3A.</td><td></td></tr>
<tr><td>3B.2.2</td><td>Specifier must state when use of estimated w/cm (3B) is required in lieu of the resistance to chloride penetration requirements of Tables 2.a-d.</td><td></td></tr>
<tr><td>3B.2.3</td><td>Specifier must state when requirements for on-site verification at the point-of-discharge are other than as indicated in Tables 2a-d, by either requiring verification where none is required in the table, or by waiving verification where it is required in the table.</td><td>In cases where w/cm is not critical to the performance of the structure, the specifier may waive the requirement for on-site verification of w/cm for a mixture that has been pre-qualified.</td></tr>
<tr><td>3B.2.4</td><td>Alternative w/cm requirements may be specified in lieu of those in Tables 2a-d. However, for structural elements governed by the ACI 318 Building Code, the specified w/cm should be at least as restrictive as the w/cm requirements of Tables 2a-d. Given the relationship between compressive strength and w/cm, the specified strength of concrete, f'_c, should be consistent with the specified w/cm.</td><td>Should the specifier opt to require a value for w/cm other than the values of Tables 2a-d associated with the specified exposure classification, that new value of w/cm should be at least as restrictive as the table value. Further, if a more restrictive w/cm is selected, the specified value of f_c' should be elevated as well to avoid a mismatch that can lead to misinterpretation of the specification. Reasonably consistent values of w/cm, taken from Tables 2a-d are shown in the table below. These relationships can significantly differ based on local materials used and whether the concrete is air entrained or not.
<table>
<tr><th>Specified values of f'_c</th><th>Reasonably consistent values of specified w/cm</th></tr>
<tr><td>< 4000 psi</td><td>0.50 or greater</td></tr>
<tr><td>4000 psi</td><td>0.50</td></tr>
<tr><td>4500 psi</td><td>0.45</td></tr>
<tr><td>5000 psi</td><td>0.40</td></tr>
<tr><td>> 5000 psi</td><td>0.40 or less</td></tr>
</table></td></tr>
<tr><td>3B.2.5</td><td>Specify when use of T 318 microwave oven test is permitted or required as an indicator of w/cm on the basis of a mixture-specific correlation submitted with pre-qualification documentation, as described in 3B.4.3.2.</td><td>See commentary to 3B.4.3.2 on AASHTO T-318 test method.</td></tr>
<tr><td>3B.3</td><td>Contractor/Producer options — Unless specified otherwise, contractor/producer may elect to demonstrate compliance with exposure class requirements by demonstrating estimated w/cm in accordance with Section 3B. Alternatively, and unless specified otherwise, contractor/producer may elect to demonstrate compliance with</td><td></td></tr>
</table>

	Performance Specification	Commentary
	exposure class requirements in accordance with the provisions of Section 3A, resistance to chloride penetration.	
3B.3.1	Unless specified otherwise, contractor/producer may elect to verify estimated w/cm at the point-of-discharge, when required to do so, by either a correlation with compressive strength, or a correlation with the results of AASHTO T 318 microwave oven testing.	
3B.4	Pre-qualification---Concrete mixtures must be pre-qualified for w/cm prior to use on the project.	
3B.4.1	Submit proposed mixture proportions or certification documenting that the w/cm of the proposed mixture is less than or equal to the value specified in Table 4.4.1.	
3B.4.2	When verification of estimated w/cm is required at the point-of-discharge, submit whether this shall be accomplished by means of correlation with compressive strength or by correlation with estimated water content by means of AASHTO T 318.	
3B.4.2.1	When compressive strength is used to estimate w/cm at the point-of-discharge, contractor/producer must submit a mix-specific correlation between w/cm and 28-day standard-cured compressive strength results for the proposed mixture. The submittal shall include test data and the proposed value of compressive strength that reliably corresponds to the required w/cm. Unless specified otherwise this pre-qualified value of compressive strength may be used in-lieu of on-site verification of w/cm. Acceptance of concrete on the basis of strength is described in Section 1.	The relationship between compressive strength and w/cm is generally reliable within a given set of materials, proportions, and air content. Therefore, when there are reasonable assurances that materials, proportions, and air content are stable, one can use the compressive strength results to verify that w/cm is approximately equal to the specified value. It is therefore recommended that the correlation between strength and w/cm include at least three strength test results for each of three batches of the proposed mixture, with one batch at the w/cm and water content intended by the producer, and the other two at water contents at least 5% higher and at least 5% lower to represent a range of potential as-delivered variations of the mixture. This procedure is similar to the "three-point-curve" approach described in ACI 318 and ACI 301. Further, since compressive strength varies inversely with air content at any given w/c, it is important that air content be carefully controlled in establishing the required correlation. Unless the correlation specifically takes air content (or density) into account, and unless or until mix-specific data demonstrates otherwise, it is recommended that the strength test results used in the correlation be adjusted by adding 250 psi per 1% air above the specified air content, and subtracting 250 psi per 1% air below the specified air content. This approximate correction reduces the likelihood of misinterpreting the effect of variations in air content as variations in w/cm.
3B.4.2.2	When AASHTO T 318 is used to estimate w/cm at the point of discharge, contractor/producer must submit a mix-specific correlation between w/cm and T 318 results for the proposed mixture. The	AASHTO T 318 is intended to measure the mass of water that can be removed from a sample of fresh concrete using the energy available in a conventional microwave oven. This value estimates to varying

	Performance Specification	Commentary
	submittal shall include test data and the proposed value of water content estimated by T 318. Unless specified otherwise this pre-qualified value of estimated water content may be used in-lieu of on-site verification of w/cm.	accuracy and precision the free water content in the concrete from which the sample was extracted, depending on the degree to which the paste/aggregate proportion of the sample matches that of the concrete, and the degree to which water has been absorbed into aggregates or bound via hydration. These factors depend in turn on mixture ingredients and proportions, and the age and temperature of the concrete when sampled. When the total mass of cementitious materials is known, and when sampling corrections are applied, the results of this test permit estimates of w/cm to values in the range of ±0.03 to ±0.05. While the AASHTO T 318 test has been used successfully to evaluate compliance with specified values of w/cm directly, it is used here as an indicator of w/cm by establishing a mixture-specific correlation between w/cm and estimated water content. This compensates for some of the mixture- and site-specific factors that affect the results of AASHTO T 318. It is therefore recommended that the correlation between strength and w/cm include at least two AASHTO T 318 test results for each of three batches of the proposed mixture, with one batch at the w/cm and water content intended by the producer, and the other two at water contents at least 5% higher and at least 5% lower to represent a range of potential as-delivered variations of the mixture. This procedure is similar to the "three-point-curve" approach described in ACI 318 and ACI 301. When insufficient time is available to fully develop such a relationship prior to construction, the specifier may consider a transition to allowing AASHTO T-318 results as an indicator of w/cm as project data develop.
3B.5	Point of discharge	
3B.5.1	When compressive strength is used to estimate w/cm, the value of compressive strength obtained at the point of discharge from the transport unit is evaluated as described in Section 1. No additional strength samples are required beyond those required for acceptance of concrete on the basis of strength as described in Section 1. Establishing a correlation between compressive strength and w/cm is described in 3B.4.2. Tests of air content must be made from the same sample used for making strength specimens to be used as indicators of w/cm.	It is recommended that the compressive strength obtained at point-of-discharge be corrected to account for the effects of air content when such test results are used to indicate compliance with specified w/cm. See commentary to 3B.4.2.1
3B.5.2	When water content as estimated by AASHTO T 318 is used to estimate w/cm, the measured water content obtained at the point of discharge shall be equal to or less than (w/cm + 0.05), where w/cm is as defined in the specification or associated with the specified exposure classification. The measurement shall be based on the average of 2 specimens tested from the same concrete	The acceptance criteria set at (w/cm + 0.05) reflects a ±0.05 precision of the measured water content when using the AASHTO T 318 procedure to estimate w/cm. The correction for the coarse aggregate content in the sample is a precaution that may be necessary because of the potential error generated from obtaining small size samples that are not representative of the concrete batch. This correction for coarse aggregate may only be applied if there is concern that the result is significantly

	Performance Specification	Commentary
	sample. Measured water content shall be corrected by subtracting the weighted average of the absorption of the aggregates. The dried sample shall be saved. If the measured value is questionable, the sample shall be sieved over a No. 4 sieve and the weight of dry coarse aggregate (CA) determined as a percentage of the original sample weight. If CA of the sample varies from that in the submitted mixture by more than 5%, the measured water content shall be corrected: Corrected water = $(1 - CA_{batch}) / (1 - CA_{sample})$, where CA is the decimal fraction of coarse aggregate in the submitted mixture and the sample, respectively.	higher than that of the designated mixture.
3B.6	Point of placement — Not applicable.	
3B.7	Hardened concrete, in-place — Not applicable.	Methods of evaluating w/cm in hardened concrete are not sufficiently precise for the purposes of evaluating specification compliance.

4. Additional requirements for sulfate resistance

		Requirements for sulfate exposures (Classes S1, S2, and S3) are shown in Table 2.b. Requirements for w/cm, minimum f'_c, and alternative requirements for resistance to chloride penetration are addressed in Section 3. This section addresses compliance with the C1012 requirements in Table 2.b.
4.1	Specifier must state all applicable exposure classes from Table 1. Specification requirements are associated with the specified exposure classification in Table 2.b, unless specified otherwise. Where the alternative cementitious materials performance option in Table 2.b is used, the proposed mixture shall be pre-qualified for sulfate resistance on the basis of ASTM C1012 test results, but there is no requirement for verification beyond pre-qualification. However, field verification for resistance to penetration may be required depending on exposure category.	
4.2	Specifier Options	
4.2.1	Specifer determines frequency of testing.	Testing cementitious materials is recommended at no longer than 6-month intervals, or whenever sources change, or whenever test results indicate variable cementitious materials.
4.2.2	Specifier may elect to permit pre-qualification of a proposed combination of cementitious materials on the basis of documented service records of satisfactory performance in lieu of the prescriptive materials requirements of Table 2.b.	A history of satisfactory field performance in concrete is in many cases the most reliable method of evaluating the potential of a given combination of materials to be considered sulfate-resistant with concentration of soluble sulfates in the given environment that comes in contact with concrete. When field performance in-service is to be assessed as evidence of satisfactory

	Performance Specification	Commentary
		performance, the concrete in-service should be at least 8 years old, and consideration should be given to: (a) the type and amount of cement in the concrete in-service compared to the proposed mixture; (b) the exposure conditions of the concrete in-service compared to the proposed structure; (c) the effects of supplementary cementitious materials and w/cm in the concrete in-service compared to the proposed mixture. Further, any such comparison is valid only to the extent that the materials used in the concrete in-service are known and are matched by the materials to be used in the proposed mixture.
4.3	Contractor/Producer options — When cementitious materials are proposed that are other than those defined in the prescriptive requirements of Table 2.b, submit ASTM C1012 data or documentation of service performance acceptable to the specifier. Submit request to use alternative to w/cm and f'_c as in Section 3.	
4.4	Pre-qualification — Cement Type in conformance with Table 2.b or alternate cementitious materials in accordance with C 1012 expansion criteria in performance option of Table 2.b. Documentation of acceptable performance in-service may be submitted for approval when permitted. See Section 3 for alternatives to w/cm and f'_c	The provisions of Table 2.b are the same as in ACI 318-08, the only difference being the performance alternative to w/cm and f'_c
4.5	Point of discharge — Not applicable, pre-qualification of cementitious materials only. However, field verification for resistance to penetration may be required depending on exposure category.	
4.6	Point of placement — Not applicable, pre-qualification only.	
4.7	Hardened concrete, in-place — Not applicable, pre-qualification only.	

5. Additional requirements for corrosion protection of reinforcing steel

		Requirements for corrosive exposures (Classes C1 and C2) are shown in Table 2.d. Requirements for w/cm, minimum f'_c, and alternative requirements for resistance to chloride penetration are addressed in Section 3. Section 5 addresses compliance with the chloride ion content requirements in Table 2.d.
5.1	Specified Value — Specifier must state all applicable exposure classes from Table 1. Chloride ion limits are associated with exposure category C as shown in Table 2.d. Concrete mixture shall be pre-qualified for chloride ion content. Unless otherwise specified, there is no	

	Performance Specification	Commentary
	requirement for verification beyond pre-qualification.	
5.2	Specifier Options — Specifier may require chloride limits that are more restrictive than those shown in Table 2.d.	Note that more restrictive chloride limits may be more difficult and/or expensive to achieve, and may require special aggregates or admixtures. Note also that chloride that is absorbed into the pores of aggregate particles may be less deleterious than chlorides on the aggregate surface or in the paste.
5.3	Contractor/Producer Options — Not applicable.	
5.4	Pre-qualification — Pre-qualify proposed mixture by documenting chloride ion content, either by testing using ASTM C1218, or by calculation from chloride contents of components and mixture proportions. Chloride limits are associated with specified exposure class in Table 2.d. See Section 3 for alternatives to the values of w/cm and f'_c associated with exposure class in Table 2d.	
5.5	Point of discharge — For Exposure Class C2, see Section 3A for optional verification of C1202 tests, or Section 3B for optional verification of w/cm.	
5.6	Point of placement — Not applicable, pre-qualification only.	
5.7	Hardened concrete, in-place — Not applicable, pre-qualification only.	

Part II: Specification Provisions for fresh concrete compatible with the Requirements of ACI 301-05

	Performance Specification	Commentary
6.	**Workability of fresh concrete as indicated by Slump or Slump Flow at the point of discharge.**	
	(As sampled by ASTM C172 and tested in accordance with ASTM C 143/C 143M or by ASTM C 1611/C 1611M)	Workability of the concrete is specified in terms of performance. The contractor/producer develops a mixture that meets the workability requirements of the specification, determines the value of slump or slump flow corresponding to that level of workability, and reports that recorded slump or slump flow as part of the pre-qualification submittal. Upon pre-qualification the value of slump or slump flow becomes the value that is to be verified for acceptance at the point of discharge from the transport unit.
6.1	Specified concrete performance — unless otherwise specified:	
6.1.1	Concrete shall have, at the point of delivery, a consistent slump or slump flow that enables the concrete to be placed without segregation, to be well and thoroughly consolidated into the forms and around reinforcing and prestressing steel, and other embedments, and allows for controlled bleeding and setting time leading to a satisfactory finished surface as defined by flatness, texture, and surface hardness.	
6.1.2	The specific value of slump or slump-flow, subject to the performance requirements of 6.1.1, shall be reported by contractor/producer in the pre-qualification submittal. Concrete shall be sampled at point of discharge from the transport unit in accordance with ASTM C172, and is considered acceptable when the measured value of slump or slump flow is within the ASTM C94 tolerance (for slump) or ±3in. (for slump flow) of the submitted, pre-qualified value. Determine slump by ASTM C143/C143M or slump flow by ASTM C1611/C1611M.	
6.2	Specifier Options — Specifier may optionally waive the requirement for on-site verification of slump or slump-flow of a pre-qualified mixture.	In cases where slump or slump flow is not critical to the performance of the structure, the specifier may waive the requirement for on-site verification of these properties for a mixture that has been pre-qualified. When concrete has been pre-qualified on the basis of properties such as shrinkage or resistance to chloride penetration, for example, such properties may not be routinely verified in the field due to the length of time required to perform such tests. In such case there may

	Performance Specification	Commentary
		be value in evaluating slump or slump flow as indicators of batch-to-batch consistency or repeatability of the pre-qualified mixture.
6.3	Contractor/Producer Options — Contractor shall select and submit value for slump consistent with 6.1.1.	The contractor/producer must recognize that given the requirement to set the value of slump or slump flow, that value submitted for pre-qualification becomes the value required for acceptance of the concrete, and shall be enforced with the same authority as had the specifier selected the same value.
6.4	Pre-qualification — Concrete mixtures must be pre-qualified for slump or slump-flow prior to use on the project. Submit documentation that the proposed concrete mixture meets the workability requirements of 6.1.1 and report the slump or slump flow of fresh concrete that was sampled and tested for all other pre-qualification evaluations.	
6.5	Point of discharge — Sample by ASTM C 172, evaluate slump in accordance with ASTM C 143. Slump must be within the ASTM C 94 tolerances for Slump, based on the slump level furnished. Evaluate slump-flow in accordance with ASTM C1611. Slump flow must be within ± 3 inches of the submitted value.	
6.6	Point of placement — Not applicable.	Note the requirements for mixture performance at placement in 6.1.1.
6.7	Hardened concrete, in-place — Not applicable.	

7. Temperature of fresh concrete as delivered

	(as sampled by ASTM C 172 and measured by ASTM C 1064)	Temperature of fresh concrete as delivered is the focus of this specification section. Temperature of fresh concrete as delivered is easily and inexpensively measured and has an immediate influence on the ability to place, consolidate, and finish the concrete and on the need for early action to prevent rapid drying at the concrete surface. Temperature of fresh concrete also influences the in-place temperature of recently cast concrete, and thus affects the need to control in-place concrete temperature. As the concrete hardens in-place temperature is influenced by the rate of the release of heat of hydration, and this rate is likewise influenced by concrete temperature. Concrete temperature during setting and hardening affects thermal stresses and the rate of strength gain and the ultimate level of strength attained. A combination of ambient conditions, dimensions of the concrete element, and requirement for in-place concrete properties may make it advisable to specify concrete temperature at other than the point of discharge from the transportation unit. While such requirements are beyond the scope of this specification, this specification does permit considerable flexibility in setting fresh concrete temperature limits in the context

	Performance Specification	Commentary
		of the effect on both fresh and hardened concrete.
7.1	Specified value — Unless specified otherwise temperature of fresh concrete as delivered shall meet the requirements of either 7.1.1 or 7.1.2.	
7.1.1	Temperature of fresh concrete as delivered shall be in accordance with the requirements of Section 4.2.2.8 of ACI 301.	
7.1.2	Temperature of fresh concrete as delivered above or below the limits of Section 4.2.2.8 of ACI 301 is permitted under the conditions of 7.1.2.1 and 7.1.2.2.	Guidelines for demonstrating acceptability of higher temperature are included in ACI 305.1, Specification for Hot Weather Concreting.
7.1.2.1	Concrete temperature at delivery shall be within the limits established by the contractor/producer during pre-qualification, having demonstrated that such limits permit the concrete to develop specified properties and do not induce undesirable effects in the concrete or the structure.	
7.1.2.2	Specifier determines those concrete properties that are sensitive to concrete temperature and must be verified as acceptable as influenced by the fresh concrete temperatures proposed by the contractor/producer.	In addition to the effects of concrete temperature on fresh concrete behavior such as workability, setting, and plastic shrinkage, consideration should be given to the subsequent effects on heat of hydration and the temperature of hardening and hardened concrete as well. Effects to consider include differential thermal stresses, and the influence of temperature on both the rate of strength gain and on the ultimate strength achieved.
7.1.2.3	When required by the specifications the contractor/producer shall develop and submit for approval a thermal control plan for maintaining concrete temperature within the limits established in 7.1.2.1.	While the specifier will define the requirements for a thermal control plan, such a plan may include the following elements: (a) Assumptions for ambient conditions; (b) Proposed fresh concrete temperatures at delivery; (c) Proposed maximum in-place concrete temperatures; (d) Methods for controlling in-place temperature so that concrete properties are not compromised by temperature, temperature differences, or by temperature gradients; (e) Evidence that the proposed methods and concrete temperatures will produce the desired concrete properties and will not induce undesirable effects.
7.1.2.4	When option 7.1.2 is exercised, all concrete property data submitted for pre-qualification shall have been obtained for concrete that was within ±5°F of the maximum or minimum temperature limits requested in 7.1.2.1.	
7.2	Specifier Options.	
7.2.1	Specify maximum, and/or minimum concrete temperature at delivery if other than as required by ACI 301.	

	Performance Specification	Commentary
7.2.2	Specify if concrete temperature requirements of 7.1.1 may not be modified on the basis of 7.1.2.	
7.2.3	For critical sections and particularly for mass concrete the specifier may optionally include requirements for in-place concrete temperature over time periods beginning at the time of placement.	Quantitative guidance on in-place concrete temperature beyond the time of delivery is beyond the scope of this guide specification. However, a comprehensive thermal control plan, as described in 7.1.2.3, would be a key part of the contractor/producer's response to in-place concrete temperature requirements.
7.2.4	Specify when a thermal control plan is required, and describe the required elements of that plan.	The requirement for a comprehensive thermal control plan should depend on the type of structure and the ambient weather conditions. The more massive the concrete placement or the more extreme the ambient weather conditions the more justified is the need for a thermal control plan. (See commentary to 7.1.2.3)
7.2.5	Specifier may optionally waive the requirement for on-site verification of concrete temperature of a pre-qualified mixture.	In cases where temperature of fresh concrete is not critical to the performance of the structure, the specifier may waive the requirement for on-site verification of temperature of fresh concrete for a mixture that has been pre-qualified.
7.3	Contractor/Producer Options — In accordance with 7.1.2, contractor/producer may request alternative temperature limits in a submittal that demonstrates the acceptability of concrete temperatures that are higher or lower than those required in Section 4.2.2.8 of ACI 301. Submittal shall include a thermal control plan when specified.	
7.4	Pre-qualification — Pre-qualification for concrete temperature is not required unless temperature limits are set by means of 7.1.2, which includes pre-qualification requirements in 7.1.2.4.	
7.5	Point of discharge — Unless specified otherwise concrete temperature at point of discharge from the transport unit shall be in compliance with values specified in 7.1.1 or 7.1.2.	
7.6	Point of placement — Not applicable.	
7.7	Hardened concrete, in-place — Not applicable unless specified.	The concrete temperature requirements of 4.2.2.8 of ACI 301 are intended to apply to concrete temperatures "immediately after placement." A thermal control plan that addresses in-place concrete temperature beyond the time of delivery is recommended for critical concrete placements, especially for mass concrete.

Part III: Optional Specification Provisions

	Performance Specification	Commentary
8.	**Bulk Density of fresh concrete**	
	(as sampled by ASTM C 172 and tested in accordance with ASTM C 138)	Bulk density of fresh concrete may be optionally specified as a means of inferring the subsequent equilibrium density of hardened structural lightweight concrete, or as a means of quantifying the uniformity of the normalweight fresh concrete, or as a means of checking air content determined by alternate methods. For lightweight concrete, equilibrium density of hardened concrete can be calculated using the method of ASTM C 567 on the basis of bulk density of the fresh concrete and mixture-specific materials characteristics.
8.1	Specified value — When optionally required bulk density of fresh concrete shall be within the tolerance limits of 8.4 and 8.5 of the specified value. Mixture shall be pre-qualified and bulk density shall be verified by sampling at point of discharge in accordance with ASTM C 172, unless specified otherwise. Alternatively the equilibrium density of the hardened lightweight concrete shall be specified, and the required bulk density of fresh concrete shall be that corresponding to the specified equilibrium density, as computed using the methods of ASTM C 567. No value of bulk density of fresh normalweight or heavyweight concrete or other density-related property is specified by default.	Bulk density of fresh concrete is not typically specified for normalweight concrete mixtures. Equilibrium density of hardened concrete is generally specified only for lightweight concrete, and a mixture-specific relationship can be established between fresh and equilibrium densities. Bulk density of fresh concrete can also be used as an indicator of batching and mixture control, and can be used as an identifying characteristic of a mixture that has been pre-qualified on the basis of one or more properties which cannot be readily verified at point of discharge.
8.2	Specifier Options	
8.2.1	Specify bulk density of fresh concrete only when applicable, and specify whether the value is to be achieved at other than the point of discharge from the transportation unit.	
8.2.2	Specify equilibrium density of hardened lightweight concrete only when applicable, from which the required bulk density of fresh concrete shall be determined by the methods of ASTM C 567. Specify whether the value is to be achieved at other than the point of discharge from the transportation unit. The contractor/producer will compute the required bulk density of fresh concrete on the basis of the specified equilibrium density and the proportions and properties of the concrete mixture ingredients, and shall submit the correlation between fresh bulk density and equilibrium density as part of pre-qualification.	
8.2.3	Specifier may optionally require bulk density of	For lightweight or heavyweight concrete the density of

	Performance Specification	Commentary
	fresh concrete as an identifying characteristic of a mixture that has been pre-qualified on the basis of one or more properties which cannot be readily verified at point of discharge. In such case the contractor/producer submits the density associated with proposed concrete mixture at the time of pre-qualification, and point-of-discharge testing is performed to verify that the pre-qualified mixture has been furnished, insofar as the density has been achieved.	concrete is itself a performance characteristic. Alternatively, a mixture may be pre-qualified on the basis of properties that will not always be verified at point of placement. Such properties include, but are not limited to alkali-reactivity, shrinkage, creep, or rapid chloride permeability. When the specifier desires additional confidence that the pre-qualified mixture is delivered to the project, bulk density tests of fresh concrete can be required. Results are compared to the density values reported for the mixture in the pre-qualification submittal.
8.2.4	Specifier may adjust the tolerance ranges for acceptance as described in 8.4 and 8.5.	
8.2.5	Specifier may optionally waive the requirement for on-site verification of bulk density of fresh concrete for a pre-qualified mixture.	In cases where density is not critical to the performance of the structure, the specifier may waive the requirement for on-site verification of density for a mixture that has been pre-qualified. When concrete has been pre-qualified on the basis of properties such as shrinkage or resistance to chloride penetration, for example, such properties may not be routinely verified in the field due to the length of time required to perform such tests. In such case there may be value in evaluating bulk density of fresh concrete as an indicator of batch-to-batch consistency or repeatability of the pre-qualified mixture.
8.3	Contractor/Producer Options — Not applicable.	
8.4	Pre-qualification	
8.4.1	Submit data demonstrating that fresh density of proposed mixture is within ±3 lb/ft^3 of the specified value for lightweight concrete, and ±4 lb/ft^3 for normalweight concrete, and ≥ the specified value for heavyweight concrete. When equilibrium density of hardened lightweight concrete is specified, submit information on relationship between equilibrium density and the bulk density of fresh concrete.	Tolerances given in 8.4.1 reflect the level of control associated with pre-qualification. Somewhat increased latitude is permitted for concrete sampled at point of discharge from the transportation unit.
8.4.2	When density tests are optionally specified as a means of verifying that a pre-qualified mixture was furnished, submit the value of bulk density recorded at the time that other test properties were determined.	When concrete has been pre-qualified on the basis of properties such as shrinkage or resistance to chloride penetration, for example, such properties may not be routinely verified in the field due to the length of time required to perform such tests. In such case there may be value in evaluating bulk density of fresh concrete as an indicator of batch-to-batch consistency or repeatability of the pre-qualified mixture. When bulk density is specified for this purpose, the value of density obtained by the concrete producer during the pre-qualification process becomes the required value for acceptance at the point of discharge with the associated tolerances.
8.5	Point of discharge	
8.5.1	For lightweight concrete, density must be within	The tolerance on bulk density of fresh concrete is

	Performance Specification	Commentary
	±4 lb/ft^3 of the specified value, or of that value which corresponds to the specified equilibrium density.	greater for acceptance on site than for pre-qualification.
8.5.2	For normalweight concrete, bulk density of fresh concrete must be within ±5 lb/ft^3 of the value documented in the pre-qualification.	
8.5.3	For heavyweight concrete, bulk density of fresh concrete must be equal to or greater than the specified value.	
8.5.4	When bulk density tests of fresh concrete is optionally specified as a means of verifying that a pre-qualified mixture was furnished, density must be within ±5 lb/ft^3 of the value submitted for pre-qualification.	The tolerance on bulk density of fresh concrete in 8.5.4 is an indicator of the desirable level of control and uniformity of the mixture.
8.6	Point of placement — Not applicable unless otherwise specified.	When in-place equilibrium density of hardened lightweight concrete is critical for fire rating, and it is to be computed from fresh density, it may be necessary to specify fresh density measures at the point of placement, as changes in the air content due to handling and placing will also change fresh density.
8.7	Hardened, in-place — Not applicable.	This guide specification evaluates hardened in-place equilibrium density on the basis of the corresponding bulk density of fresh concrete.

9. Drying Shrinkage

	(as indicated by ASTM C 157)	Drying shrinkage may be optionally specified for members where higher drying shrinkage of concrete is a concern for functional performance, such as curling of industrial floor slabs for example. No value of length change or other shrinkage-related property is specified by default.
9.1	Specified Value — When optionally required, maximum length change shall be ≤ specified value of ε_{sh}, relative to the length at de-molding, as determined by ASTM C157 for specimens wet cured for 7 days followed by 28 days of drying. Mixture to be pre-qualified for shrinkage when specified, but unless otherwise specified there is no requirement for verification beyond pre-qualification. Specifier shall identify those elements of the structure to which length-change requirements apply. No value of length change or other shrinkage-related property is specified by default.	Note that the shrinkage-related behavior of the concrete has a variable impact on the performance of different types of elements in a given structure. Further, factors such as environmental conditions, curing, cold and hot-weather protection, construction schedule, joint type and spacing, and details and amounts of reinforcement also influence shrinkage cracking, in addition to the shrinkage characteristics of the mixture. Note also that the ASTM C157 test procedure cannot measure shrinkage that occurs in the first 24-hours between casting and de-molding, and thus cannot discern the effects of autogenous, chemical, plastic, or drying shrinkage that may occur over that same time period.
9.2	Specifier's Options	
9.2.1	Specifier must state maximum value for length change, ε_{sh}, as determined by ASTM C 157. No such requirement exists by default unless so specified.	While a value for ε_{sh} of 0.05% relative to the length at de-molding can be achieved for most combinations of concrete-making materials, when setting acceptance criteria for length-change, it is recommended that the specifier become familiar with the shrinkage

	Performance Specification	Commentary
		characteristics of local concrete-making materials in addition to the requirements of the structure. It is important to know in advance if increased cost or delay may be incurred in satisfying length-change requirements due to the nature of locally-available aggregates and cementitious materials.
9.2.2	Requirements of 9.1 for test method or curing and drying protocol for test specimens may be revised as applicable.	Modifying the test to more nearly match field conditions may be useful, but limited data exist for appropriate criteria under non-standard test conditions. For faster results, the test may be revised to require wet curing for 7 days followed by 21 days of drying. The criteria for acceptability might also need to be revised if the test conditions are changed.
9.3	Contractor/Producer options — Not applicable.	
9.4	Pre-qualification — Documentation of proposed mixture complying with the shrinkage requirement.	
9.5	Point of discharge — Not applicable, pre-qualification only.	
9.6	Point of placement — Not applicable, pre-qualification only.	
9.7	Hardened concrete, in-place — Not applicable, pre-qualification only.	

10. Modulus of Elasticity

	(in accordance with ASTM C 469)	Modulus of elasticity is optionally specified only for those structures or structural elements for which vertical or lateral deformation, overall stiffness, or vibration control are critical to performance. No requirement for modulus of elasticity is specified by default.
10.1	Specified value — When optionally required, specify 28-day modulus of elasticity, E_c, as tested in accordance with ASTM C 469. Concrete mixture shall be pre-qualified for modulus of elasticity. Unless otherwise specified, there is no requirement for verification beyond pre-qualification. Specifier shall identify those elements of the structure to which modulus of elasticity requirements apply, and shall specify frequency of testing. No value of modulus of elasticity is specified by default.	When deciding whether to specify and test for modulus of elasticity the specifier should recognize the approximate nature of the relationship between elastic modulus and compressive strength as expressed in ACI 318 code equations. The reliability of these relationships depends on factors such as the type and quantity of aggregate, quality of paste-aggregate bond, moisture conditions during testing, and on the age, curing history of the concrete at time of test and strength level of the concrete. ACI 363 has alternative recommended empirical relationships between modulus of elasticity and strength for high-strength concrete. When elastic properties of the concrete are critical for structural performance it is recommended that the required value of E_c be specified. Note that the modulus of elasticity of the concrete has a variable impact on the performance of different types of elements in a given structure. Further, factors such as environmental conditions, curing, cold and hot-weather protection, construction schedule, and

	Performance Specification	Commentary
		structural and architectural details influence the impact of elastic deformation on structural performance. Note also that creep deformation may have more influence on performance than elastic deformation alone.
10.2	Specifier's Options	
10.2.1	Specifier has the option to require a minimum or maximum modulus of elasticity of concrete, and to state the age at which such values are to be measured in accordance with ASTM C 469. No such requirement exists by default unless so specified.	Desired structural performance may be a function of achieving an elastic modulus that is greater than or equal to some lower bound value, or less than or equal to some upper bound value. It is recommended that when both the values of E_c and f'_c are specified, they should be selected as a mutually dependent pair of values, related to each other as approximately indicated by the ACI 318 code equations. While values for E_c that are within about 15% of those predicted by the ACI 318 Code equations can be achieved for most combinations of concrete-making materials at normal strength levels, when setting acceptance criteria for E_c it is recommended that the specifier become familiar with the characteristics of local concrete-making materials as they affect elastic modulus, in addition to the requirements of the structure. It is important to know in advance if increased cost or delay may be incurred in satisfying requirements for modulus of elasticity due to the nature of locally-available aggregates. Further, it is recommended that modulus of elasticity be verified for high strength concrete when elastic deformation is critical to performance.
10.2.2	Specifier may optionally require verification of modulus of elasticity on the basis of cylinders sampled at the point of discharge. Frequency of testing is to be specified.	For structures in which vertical or lateral deformation, overall stiffness, or vibration control are critical to performance, it may be useful to periodically verify modulus of elasticity at point of discharge.
10.3	Contractor/Producer Options — Not applicable.	
10.4	Pre-qualification — Documentation of modulus of elasticity of proposed mixture as determined by ASTM C 469.	.
10.5	Point of discharge — Pre-qualification only unless otherwise specified.	
10.6	Point of placement — Not applicable, pre-qualification only	
10.7	Hardened concrete, in-place — Tests of cores extracted from hardened concrete shall be used only in the case that any test of modulus of elasticity of laboratory-cured cylinders fails to comply with the specified requirements. In such case extract and condition cores in accordance with ASTM C42, and test for modulus of elasticity in accordance with ASTM C 469. Unless otherwise specified, concrete is satisfactory if average modulus of elasticity of cores is at least 85% of specified value, and no single core is less than 75% of specified value.	As an alternative to extracting cores the specifier may consider non-destructive tests that will estimate the dynamic modulus of elasticity under small deformation. The static modulus of elasticity can be estimated from that value.

	Performance Specification	Commentary
11.	**Creep of concrete**	
	(in accordance with ASTM C 512-02 Standard Test Method for Creep of Concrete in Compression)	Creep limits may be optionally specified for structures in which long term deformation is critical to performance. No requirement is specified by default.
11.1	Specified value — When optionally specified, the creep coefficient C_c, defined as the ratio of concrete creep strain to elastic strain, at a stress level of 40% of f'_c, and extrapolated to 1 year, shall be ≤ to the specified value. Concrete mixture shall be pre-qualified for creep. Unless otherwise specified, there is no requirement for verification beyond pre-qualification. Specifier shall identify those elements of the structure to which creep requirements apply. No value of creep coefficient is specified by default.	Note that the creep-related behavior of the concrete has a variable impact on the performance of different types of elements in a given structure. Further, factors such as environmental conditions, curing, construction schedule, age at loading and details and amounts of reinforcement also influence creep deformation.
11.2	Specifier's Options — Specifier must state maximum value for creep coefficient, C_c. No such requirement exists by default unless so specified.	While a value for C_c of 2.0 can be achieved for most combinations of concrete-making materials, when setting acceptance criteria for creep coefficient it is recommended that the specifier become familiar with the creep characteristics of local concrete-making materials in addition to the requirements of the structure. It is important to know in advance if increased cost or delay may be incurred in satisfying creep requirements due to the nature of locally-available aggregates.
11.3	Contractor/Producer Options — Not applicable.	
11.4	Pre-qualification — Documentation of creep of proposed mixture as determined by ASTM C 512.	
11.5	Point of discharge — pre-qualification only.	
11.6	Point of placement — Not applicable, pre-qualification only.	
11.7	Hardened concrete, in-place — Not applicable.	
12.	**Alkali Silica Reactivity**	
	(as indicated by ASTM C 1260, C 1293, or C 1567)	Alkali Silica Reactivity limits may be optionally specified for conditions where there is a history of reactive aggregates and members that will be moist in service. No value of expansion or other property related to alkali- aggregate reaction is specified by default. This specification is limited to alkali silica reactivity and does not address requirements for alkali carbonate reactions, which is more rare.
12.1	Specified value — When required by specification, for alkali-silica reaction, the proposed cementitious materials and aggregate shall have an expansion at 16 days ≤ specified value of ε_{asr},	While useful for evaluating the required levels of pozzolan or slag needed to mitigate deleterious expansion, neither ASTM C1567 nor C1293 (see 12.2.2) account for the beneficial effects of using low-alkali cement or limiting the alkali loading of the

	Performance Specification	Commentary
	when tested in accordance with ASTM C 1567. When the mixture does not include supplementary cementitious materials, such as pozzolan or slag, the evaluation of the mixture shall be conducted in accordance with ASTM C 1260. Unless otherwise specified, there is no requirement for verification beyond pre-qualification. Specifier shall identify those elements of the structure to which alkali-silica reaction expansion criteria apply. No value of length change or other alkali-silica reactivity-related property is specified by default.	concrete mixture. ASTM C 1260 evaluates the potential of the aggregate for causing deleterious expansions in concrete due to ASR.
12.1.1	Aggregate from sources determined on the basis of petrographic analysis or test to be susceptible to the alkali-carbonate form of alkali-aggregate reaction shall not be used.	The test methods referenced in this section have been shown to be effective in identifying expansion caused by alkali-silica reactivity. These same methods may not be consistently useful when expansion of concrete is due to alkali-carbonate reactivity. Further, research has shown that neither low-alkali cement nor pozzolans or slag are effective in mitigating deleterious expansion due to alkali-carbonate reaction. For these reasons the use of aggregate susceptible to alkali-carbonate reactivity is beyond the scope of this document. Refer to the appendix to ASTM C33 for additional guidance.
12.2	Specifier's Options	
12.2.1	Specifier must state maximum value for length change, ε_{asr}, as determined by ASTM C1567 pr ASTM C 1260. No such requirement exists by default unless so specified.	While a limiting value for ε_{asr} of 0.10% relative to the length at de-molding is generally indicative of acceptable performance of the combination of cementitious materials and potentially reactive aggregate, it is recommended that the specifier become familiar with the reactivity of local concrete-making materials in addition to the requirements of the structure when setting a specified value. Given the sensitivity of alkali-silica reaction to the specific combination of cementitious materials and potentially reactive aggregate, it is critical that the tests be performed on the materials actually intended for use in the work. Test results should therefore be no older than 6 months and based on the same sources and types of cementing materials and aggregates proposed for use.
12.2.2	When pre-existing data are available, the specifier may permit pre-qualification of a proposed combination of cementitious materials and potentially reactive aggregate on the basis of ASTM C1293 expansion results at 2 years, with alkali content increased to 1.25% by weight of Portland cement. Specify acceptable expansion limit based on ASTM C1293. When the proposed mixture does not contain supplementary cementitious materials, such as pozzolans or slag, the expansion limit shall be based on the expansion of concrete prisms at 1 year.	The qualification of a cementitious-aggregate combination using ASTM C 1567 has been shown by research to correlate well with tests on concrete prisms with the same cementitious aggregate combination tested by ASTM C 1293 for a period of two years. ASTM C 1293 is considered a more reliable indicator of actual performance in the field. When supplementary cementitious materials, such as pozzolan or slag are used to mitigate ASR, a typically acceptable limiting value of expansion at 2 years is 0.04% relative to length at de-molding. When the proposed mixture does not contain supplementary cementitious materials, the suggested expansion criteria for determining the potential reactivity of the aggregate is 0.04% at 1 year.

	Performance Specification	Commentary
		However, unless data already exist for the specific materials proposed for use, the duration of this test is not considered reasonable for the purpose of pre-qualification of mixtures for project submittals.
12.2.3	Specifier may permit pre-qualification of a proposed combination of cementitious materials and potentially reactive aggregate on the basis of documented service records for proposed combination of materials as evidence of satisfactory performance.	A history of satisfactory field performance in concrete is in many cases the most reliable method of evaluating the potential for aggregate from a specific source to cause premature deterioration of concrete due to alkali-aggregate reaction. When field performance in-service is to be assessed as evidence of satisfactory performance, the concrete in-service should be at least 10 years old, and consideration should be given to: (a) the cement content and the alkali content of the concrete in-service compared to the proposed mixture; (b) the exposure conditions of the concrete in-service compared to the proposed structure; (c) the effects of supplementary cementitious materials and w/cm in the concrete in-service compared to the proposed mixture. Further, any such comparison is valid only to the extent that the materials used in the concrete in-service are known and are matched by the materials to be used in the proposed mixture. A petrographic study should be conducted to demonstrate that the aggregate in the examined structure has the same characteristics related to reactivity as the aggregate proposed for use. Such a field performance review must be conducted by a professional who is experienced in the assessment of alkali-aggregate reaction in structures.
12.3	Contractor/Producer Options — Not applicable.	
12.4	Pre-qualification — Document performance of proposed mixture based on expansion data per 12.2.1, or submittal of service records when permitted by 12.2.2.	
12.5	Point of discharge — Not applicable, pre-qualification only.	
12.6	Point of placement — Not applicable, pre-qualification only.	
12.7	Hardened concrete, in-place — Not applicable, pre-qualification only.	
13. Abrasion resistance		
		Abrasion resistance may be optionally specified for members where surface wear is a concern for functional performance such as for industrial floor slabs, for example. No requirement is specified by default.
13.1	Specified Value — When optionally required, specify test method and allowable abrasion loss	

	Performance Specification	Commentary
	as appropriate to the type of wear expected. Mixture to be pre-qualified for abrasion resistance when specified, but unless otherwise specified there is no requirement for verification beyond pre-qualification. When abrasion resistance is specified, specified ***f′c*** must be ≥ 4500 psi, with a 7-day minimum water cure. Specifier shall identify those elements of the structure to which abrasion-resistance requirements apply. No value of abrasion-resistance is specified by default.	
13.2	Specifier's Options	
13.2.1	Specifier has the option to require a maximum abrasion loss and associated test method, and to state the age at which such values are to be measured. No such requirement exists by default unless so specified.	Multiple abrasion tests are available, but each varies in the type of wear pattern induced and thus each may have varying relevance to the wear anticipated in service for the subject structure.
13.2.2	Specify when in-place abrasion testing is required. The test method, equipment, type of sample, curing history and allowable abrasion loss determined as mass loss per unit area or as average depth of wear are to be specified. When in place testing is required, it must be in addition to, not in lieu of pre-qualification testing.	Abrasion resistance is sensitive to placing, consolidating, finishing and curing measures in addition to sensitivity to the concrete mixture itself. For that reason baseline data is required to establish performance of the pre-qualified mixture, prior to conduct of in place testing. Note that not all abrasion test equipment is available in a portable version that permits in-place testing.
13.3	Contractor/Producer options — Not applicable.	
13.4	Pre-qualification---Documentation of proposed mixture complying with the abrasion resistance shrinkage requirement.	
13.5	Point of discharge — Not applicable.	
13.6	Point of placement — Not applicable.	
13.7	Hardened concrete, in-place — Abrasion tests on the finished and cured surface shall be conducted only when optionally specified.	

Table 1 – Exposure Categories and Classes

Table 1.a – Exposure Category F – Freezing and thawing exposure

Class	Description	Condition
F0	Not applicable	Concrete not exposed to freezing and thawing cycles
F1	Moderate	Concrete exposed to freezing and thawing cycles and occasional exposure to moisture
F2	Severe	Concrete exposed to freezing and thawing cycles and in continuous contact with moisture
F3	Very Severe	Concrete exposed to freezing and thawing cycles that will be in continuous contact with moisture and exposure to deicing chemicals

Table 1.b – Exposure Category S – Sulfate exposure

Class	Description	Water-soluble sulfate (SO_4) in soil, percent by weight	Sulfate (SO_4) in water, ppm
S0	Not applicable	$SO_4 < 0.10$	$SO_4 < 150$
S1	Moderate	$0.10 \le SO_4 < 0.20$	$150 \le SO_4 < 1500$ Seawater
S2	Severe	$0.20 \le SO_4 \le 2.00$	$1500 \le SO_4 \le 10{,}000$
S3	Very severe	$SO_4 > 2.00$	$SO_4 > 10{,}000$

Table 1.c – Exposure Category P – In contact with water requiring low permeability concrete

Class	Description	Condition
P0	Not applicable	Concrete where low permeability to water is not required
P1	Required	Concrete required to have low permeability to water

Table 1.d – Exposure Category C – Conditions requiring corrosion protection of reinforcement

Class	Description	Condition
C0	Not applicable	Concrete that will be dry or protected from moisture in service
C1	Moderate	Concrete exposed to moisture but not to external source of chlorides in service
C2	Severe	Concrete exposed to moisture and an external source of chlorides in service – from deicing chemicals, salt, brackish water, seawater, or spray from these sources

Table 2 – Requirements for Concrete by Exposure Class

Table 2.a – Freezing and thawing exposure

Exposure Class	Prescriptive alternative[5] for resistance to penetration		Performance alternative[5] for resistance to penetration	Prescriptive alternative[5] for air content	Performance alternative[5] for air content. Establish required air content by methods 2.3.1, 2.3.2, or 2.3.3
	Max w/cm	Min f'_c psi	Chloride resistance R'_c (Coulomb)*		
F0	-	-	---		
F1	0.45 (PQ[3])	4500	2000[1] 2500[2] (PQ[3])	Table 3a	C 666 durability factor ≥ 80%, or C 672 mass loss ≤ 1.0 kg/m^2, or C 457 Spacing factor ≤ 0.008 in. Air content ≥ 3.0% per 2.3.1, 2.3.2, or 2.3.3. (PQ[3])
F2	0.45 (FVR[4])	4500	2000[1] 2500[2] (FVR[4])	Table 3a	C 666 durability factor ≥ 85%, or C 672 mass loss ≤ 1.0 kg/m^2, or C 457 Spacing factor ≤ 0.008 in. Air content ≥ 3.0% per 2.3.1, 2.3.2, or 2.3.3. (FVR[4])
F3	0.45 (FVR[4])	4500	2000[1] 2500[2] (FVR[4])	Table 3a with additional prescriptive requirements of Table 3b.[6]	C 666 durability factor ≥ 90%, or C 672 mass loss ≤ 1.0 kg/m^2, or C 457 Spacing factor ≤ 0.008 in. Air content ≥ 3.0% per 2.3.1, 2.3.2, or 2.3.3. (FVR[4])

1. ASTM C1202 specimens immersed in lime-saturated water for 7 days at 73°F followed by 21 days of immersion in lime-saturated water at 100°F for a total of 28 days.
2. ASTM C1202 specimens immersed in lime-saturated water at 73°F for an age of 56 days.
3. PQ = Pre-qualification only, field verification not required.
4. FVR = Field verification required in addition to pre-qualification.
5. Either Prescriptive or Performance requirements apply, not both.
6. Requirements of Table 3.b are waived under performance option 2.3.1 or 2.3.2, and concrete is wet-cured for at least 7 days.

Table 2 – Requirements for Concrete by Exposure Class (Continued)

Table 2.b – Sulfate exposure

Exposure Class	Prescriptive alternative[9] for resistance to penetration		Performance alternative[9] for resistance to penetration Chloride Resistance R'_c (Coulomb)*	Prescriptive alternative[9] for materials requirements by type of cementitious material			Performance alternative[9] for materials requirements Pre-qualification based on ASTM C1012 maximum expansion	Additional requirements
	Max *w/cm*	**Min f'_c, psi**		**ASTM C150**	**ASTM C595**	**ASTM C1157**		
S0	---	---	---	-	-	-	---	
S1	0.50 PQ[3]	4000	2500[1] 3000[2] PQ[3]	II[5,6]	IP(MS), IS(<70)(MS)	MS	0.05% @ 6 m PQ	
S2	0.45 FVR[4]	4500	2000[1] 2500[2] FVR[4]	V[6]	-	HS	0.05% @ 6 m or 0.10 @ 12m[7] PQ	No calcium chloride admixtures
S3	0.45 FVR[4]	4500	2000[1] 2500[2] FVR[4]	V + pozzolan or slag[8]	-	HS + pozzolan or slag[8]	0.10% @ 18 m PQ	No calcium chloride admixtures

1. ASTM C1202 specimens immersed in lime-saturated water for 7 days at 73°F followed by 21 days of immersion in lime-saturated water at 100°F for a total of 28 days.
2. ASTM C1202 specimens immersed in lime-saturated water at 73°F for an age of 56 days.
3. PQ = Pre-qualification only, field verification not required.
4. FVR = Field verification required in addition to pre-qualification.
5. For seawater exposure, other types of portland cements with tricalcium aluminate (C_3A) contents up to 10 percent are permitted if the water-cementitious material ratio does not exceed 0.40.
6. Other available types of cement such as Type III or Type I are permitted in Exposure Classes S1 or S2 if the C_3A contents are less than 8 or 5 percent, respectively.
7. The 12m expansion limit only applies when the 6m limit is not met.
8. The amount of the specific source of the pozzolan or slag to be used shall not be less than the amount that has been determined by service record to improve sulfate resistance when used in concrete containing Type V cement. Alternatively, the amount of the specific source of the pozzolan or slag to be used shall not be less than the amount tested in accordance with ASTM C 1012 and meeting the Performance Alternative materials requirements.
9. Either Prescriptive or Performance requirements apply, not both.

Table 2 – Requirements for Concrete by Exposure Class (Continued)

Table 2.c – In contact with water requiring low permeability concrete

Exposure Class	Prescriptive alternative[4] for resistance to penetration		Performance alternative[4] for resistance to penetration
	Max w/cm	Min f'_c psi	Chloride resistance R'_c (Coulomb)*
P0	-	-	---
P1	0.50 (PQ[3])	4000	2500[1] 3000[2] (PQ[3])

1. ASTM C1202 specimens immersed in lime-saturated water for 7 days at 73°F followed by 21 days of immersion in lime-saturated water at 100°F for a total of 28 days.
2. ASTM C1202 specimens immersed in lime-saturated water at 73°F for an age of 56 days.
3. PQ = Pre-qualification only, field verification not required.
4. Either Prescriptive or Performance requirements apply, not both.

Table 2 – Requirements for Concrete by Exposure Class (Continued)

Table 2.d – Conditions requiring corrosion protection of reinforcement

Exposure Class	Prescriptive alternative[9] for resistance to penetration		Performance alternative[9] for resistance to penetration	[5]Max water-soluble chloride ion (Cl^-) content in concrete, percent by weight of cement[6]	Additional requirement
	Max w/cm	Min f'_c, psi	Chloride resistance R'_c (Coulomb)[8]		
Corrosion Exposure: Reinforced Concrete					
C0	-	-	---	1.00 (PQ[3])	-
C1	-	-	---	0.30(PQ[3])	-
C2	0.40 FVR[4]	5000	1500[1] 2000[2] FVR[4]	0.15(PQ[3])	Min. Cover[7]
Corrosion Exposure: Prestressed Concrete					
C0	-	-	---	0.06(PQ[3])	-
C1	-	-	---	0.06(PQ[3])	-
C2	0.40 FVR[4]	5000	1500[1] 2000[2] FVR[4]	0.06(PQ[3])	Min. Cover[7]

1. ASTM C1202 specimens immersed in lime-saturated water for 7 days at 73°F followed by 21 days of immersion in lime-saturated water at 100°F for a total of 28 days.
2. ASTM C1202 specimens immersed in lime-saturated water at 73°F for an age of 56 days.
3. PQ = Pre-qualification only, field verification not required.
4. FVR = Field verification required in addition to pre-qualification.
5. Water-soluble chloride ion content that is contributed from the ingredients including water, aggregates, cementitious materials, and admixtures shall be determined on the concrete mixture by ASTM C 1218 at age between 28 and 42 days.
6. When epoxy- or zinc-coated bars are used, these limits may be more restrictive than necessary. Specify if higher limits are allowed.
7. Minimum concrete cover requirements of ACI 318 7.7 shall be satisfied. See ACI 318 18.16 for unbonded tendons.
8. Where calcium nitrite corrosion inhibitor is to be used, the same concrete mixture, but without calcium nitrite, shall be pre-qualified to meet the requirements for resistance to chloride penetration (coulombs) in this table.
9. Either Prescriptive or Performance requirements apply, not both.

Table 3.a – Requirements for Total Air Content of Fresh Concrete[4] for Concrete Exposed to Cycles of Freezing and Thawing

Nominal maximum aggregate size, in.[1]	Air content, percent[2,3], Not less than the lower value nor greater than the higher value	
	Exposure Class F2 and F3	Exposure Class F1
3/8	6.0 to 9.0%	4.5 to 7.5%
1/2	5.5 to 8.5%	4.0 to 7.0%
3/4	4.5 to 7.5%	3.5 to 6.5%
1	4.5 to 7.5%	3.0% to 6.0%
1-1/2	4.0 to 7.0%	3.0% to 6.0%
2†	3.5 to 6.5%	2.5 to 5.5%
3†	3.0% to 6.0%	2.0 to 5.0%

1. See ASTM C 33 for tolerance on oversize for various nominal maximum size designations.
2. These air contents apply to total mixture. When testing these concretes, however, aggregate particles larger than 1-1/2 in. are removed by sieving and air content is measured on the sieved fraction. Air content of total mixture is computed from value measured on the sieved fraction passing the 1-1/2 in. sieve in accordance with ASTM C 231.
3. For f'_c greater than 5000 psi, reduction of air content indicated in Table 3a by 1.0 percent shall be permitted.
4. Unless specified otherwise, air contents apply to fresh concrete, as delivered. Some loss of air content is normal and is to be expected in handling, placing, and consolidation.

Table 3.b – Prescriptive Requirements for Concrete Subject to Exposure Class F3[1]

Cementitious materials	Maximum percent[2] of total cementitious materials by weight[3]
Fly ash or other pozzolans conforming to ASTM C 618	25
Slag conforming to ASTM C 989	50
Silica fume conforming to ASTM C 1240	10
Total of fly ash or other pozzolans, slag, and silica fume	50[4]
Total of fly ash or other pozzolans and silica fume	35[4]

1. Requirements of Table 3.b are waived under performance options 2.3.1 or 2.3.2, and concrete is wet-cured for at least 7 days.
2. The maximum percentages above shall include:
   (a) Fly ash or other pozzolans present in Type IP or I(PM) blended cement, ASTM C 595, or ASTM C 1157;
   (b) Slag used in the manufacture of a IS or I(SM) blended cement, ASTM C 595, or ASTM C 1157;
   (c) Silica fume, ASTM C 1240, present in a blended cement.
3. The total cementitious material also includes ASTM C 150, C 595, C 845, and C 1157 cement.
4. Fly ash or other pozzolans and silica fume shall constitute no more than 25 and 10 percent, respectively, of the total weight of the cementitious materials.