Performance Specifications for Durable Concrete

Current practice and limitations

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The ultimate goal of the Prescription-to-Performance (P2P) initiative of the National Ready Mixed Concrete Association (NRMCA) is to develop and encourage implementation of performance specifications, when appropriate, in the U.S. concrete industry. As part of this initiative, we've reviewed existing standards and specifications for concrete from several countries. In this article, we provide summaries of a couple of the relevant standards and propose initial steps for modifying common U.S. practice. More detail can be found in our full report.[1]

PERFORMANCE DEFINED

Unlike a prescriptive specification that defines a concrete mixture in terms of its constituents and their proportions, a performance specification defines a concrete mixture in terms of measurable plastic and hardened properties that show the mixture will satisfy certain performance criteria. The difference between these two approaches can be illustrated by looking at durability.

In prescriptive specifications, durability is intended to be achieved by requiring particular ingredients (such as fly ash or air-entraining admixtures), proportions (such as minimum cementitious materials content or maximum water-cementitious material ratio [*w/cm*]), or construction operations (such as wet curing for a specified duration). Each of these requirements is actually a means to an end, and durable concrete is likely to be (but not always) the result of following these means. Under a prescriptive specification, the means are verified; under a performance specification, the end is verified in terms of measured concrete properties, either at the truck chute, or more comprehensively, in-place. These properties (or performance criteria) are usually selected for common environmental exposures (exposure classes) anticipated for the concrete and are verified by sophisticated, often long-term, test procedures that can be used to prequalify the concrete mixture, verify that the prequalified mixture has been delivered to the site, or both.

To paraphrase NRMCA's definition,[2] the ideal performance specification is a set of clear, measurable, and enforceable instructions that outline the application-specific functional requirements for the hardened concrete and avoid requirements for the means, methods, ingredients, and proportions to achieve these requirements. For example, the only functional requirement for an interior building column, where durability is rarely an issue, might be minimum compressive strength. The functional requirements for a bridge deck, however, might include minimum strength, low permeability, scaling resistance, a low amount of cracking, and other criteria related to durability.

Of course, verification of these functional requirements will require that test methods and acceptance criteria are clearly defined, with some testing required for prequalification and some for job-site acceptance both before and after the concrete is placed. Instead of the detailed list of mixture ingredients typical of submittals for a prescriptive specification, the submittals for a performance specification would be a certification that the mixture will meet the specification requirements and the prequalification test results.

Other key components of a workable performance specification system would include:

- A qualification/certification system that establishes the requirements for a concrete production facility, the facility's quality control management system, and the facility's personnel;
- Producers and contractors that partner to ensure that the right mixture is developed, delivered, and installed;
- Sufficient flexibility to allow the producer to provide a mixture that meets the performance criteria (including prequalification test results) while satisfying the contractor's requirements for placing and finishing; and
- Requirements for field acceptance tests needed to verify the concrete meets the performance criteria as well as a clear set of instructions defining the actions required if those test requirements aren't met.

CURRENT U.S. PRACTICE

Because it defines mandatory, specific limits for some constituents of concrete mixtures subjected to deleterious and aggressive environments, Chapter 4 of ACI 318-05[3] is prescriptive in nature. As such, the requirements included in ACI 318-05 imply that, if the specified limits and good construction practices (such as specified in ACI 301-05[4]) are followed, durable concrete will result. This isn't necessarily true, however, as the requirements contained in ACI 318-05:

- Don't define the quality of the air-void system for freezing-and-thawing durability of the in-place concrete;
- Place limits on supplementary cementitious materials (SCMs) that may be less than the optimum required to provide a mixture with resistance to sulfate attack or alkali-silica reaction; and
- Place restrictions on cement type that may, inadvertently, preclude the use of proven, superior alternatives.

Thus, the current, prescriptive limits stated in ACI 318-05 can restrict the ability of a progressive concrete producer to maximize the use of current technology and provide the owner a fully satisfactory product at the least possible cost. Further, these limits can even produce unintended consequences. For example, although the current requirements for minimum cementitious materials content or maximum *w/cm* are intended to ensure durable concrete is produced, concrete mixtures meeting those requirements may have more shrinkage and cracking and therefore be less durable than alternative, noncompliant mixtures with lower cement contents.

In current U.S. practice, the design professional doesn't necessarily define the exposure conditions in the project specifications. The contractor or concrete supplier must therefore infer the applicable durability requirements from the provisions contained in Chapter 4 of ACI 318-05. The resulting ambiguity isn't conducive to creative collaboration within the design-construction team.

EXEMPLARY PERFORMANCE

Exposure classes

In specifications used in Australia, New Zealand, South Africa, the European Union (EU), and Canada, exposure classes are defined for specific regional durability concerns. Only the Australian, New Zealand, and Canadian standards, however, have definitive provisions for specifying on a performance basis. Examples of exposure classes used in Australia and Canada are shown in Table 1 and 2, respectively.

Australia stands out as a leader in the use of performance-based specifications. The Australian standard[5] provides an outstanding system for the owner and producer to assess and maintain a quality product. Although it will probably be a long time before this approach is accepted throughout North America,

TABLE 1:
EXAMPLES OF EXPOSURE CLASSES IN AUSTRALIA PER AS 3600[5]

Surface and exposure environment	Exposure class
External surfaces above ground	
within 1 km (0.6 mile) of coastline	B2
within 1 to 50 km (0.6 to 31 mile) of coastline	B1
farther than 50 km (31 mile) from coastline and	
within 3 km (1.9 mile) of industrial polluting area	B1
in tropical zone	B1
in temperate zone	A2
in arid zone	A1
Surfaces in contact with water	
in soft or running water	U
in fresh water	B1
in seawater and	
permanently submerged	B2
in splash zone	C

the development and application of quality management systems is a worthwhile goal for the concrete industry. We believe that coupling these systems with an exposure class system modeled after the Canadian example can lead to adoption of performance-based specifications in U.S. practice.

TABLE 2:
Exposure subclasses per CSA A23.1[10]

Subclass	Definition
Chloride exposures	
C-XL	Structurally reinforced concrete exposed to chlorides or other severe environments with or without freezing-and-thawing conditions, with higher durability performance expectations than the C-1, A-1, or S-1 classes.
C-1	Structurally reinforced concrete exposed to chlorides with or without freezing-and-thawing conditions. Examples: bridge decks, parking decks and ramps, portions of marine structures located within the tidal and splash zones, concrete exposed to seawater spray, and salt water pools.
C-2	Nonstructurally reinforced (that is, plain) concrete exposed to chlorides and freezing and thawing. Examples: garage floors, porches, steps, pavements, sidewalks, curbs, and gutters.
C-3	Continuously submerged concrete exposed to chlorides but not to freezing and thawing. Examples: underwater portions of marine structures.
C-4	Nonstructurally reinforced concrete exposed to chlorides but not to freezing and thawing. Examples: underground parking slabs-on-ground.
Freezing-and-thawing exposures	
F-1	Concrete exposed to freezing and thawing in a saturated condition but not to chlorides. Examples: pool decks, patios, tennis courts, freshwater pools, and freshwater control structures.
F-2	Concrete in an unsaturated condition exposed to freezing and thawing but not to chlorides. Examples: exterior walls and columns.
Not exposed to exterior influences	
N	Concrete not exposed to chlorides or to freezing and thawing. Examples: footings and interior slabs, walls, and columns.
Exposed to chemical attack	
A-1	Structurally reinforced concrete exposed to severe manure and/or silage gases, with or without freezing-and-thawing exposure. Concrete exposed to the vapor above municipal sewage or industrial effluent, where hydrogen sulfide gas may be generated. Examples: reinforced beams, slabs, and columns over manure pits and silos, canals, and pig slats; and access holes, enclosed chambers, and pipes that are partially filled with effluents.
A-2	Structurally reinforced concrete exposed to moderate to severe manure and/or silage gases and liquids, with or without freezing-and-thawing exposure. Examples: reinforced walls in exterior manure tanks, silos, and feed bunkers, and exterior slabs.
A-3	Structurally reinforced concrete exposed to moderate to severe manure and/or silage gases and liquids, with or without freezing-and-thawing exposure in a continuously submerged condition. Concrete continuously submerged in municipal or industrial effluents. Examples: interior gutter walls, beams, slabs, and columns; sewage pipes that are continuously full (for example, forcemains); and submerged portions of sewage treatment structures.
A-4	Nonstructurally reinforced concrete exposed to moderate manure and/or silage gases and liquids, without freezing-and-thawing exposure. Examples: interior slabs on grade.
Exposed to sulfate attack*	
S-1	Concrete subjected to very severe sulfate exposures.
S-2	Concrete subjected to severe sulfate exposure.
S-3	Concrete subjected to moderate sulfate exposure.

*Definitions of the range of sulfate contents in soil, groundwater, and recycled aggregates plus criteria for cement type, strength, and limiting water-cement ratios for S-1, S-2, and S-3 are given in Table 3 of Reference 10.

Australian provisions

Within AS 1379, "Specification and Supply of Concrete,"[6,7] two grades of concrete (normal and special grade) are defined. Normal grade concrete is specified primarily by compressive strength and can be produced by plants throughout Australia. Limiting values are given for chloride and sulfate contents of the hardened concrete, shrinkage, density, and 7-day compressive strength. In addition to strength, the customer ordering the concrete specifies slump, maximum aggregate size, method of placement, and air entrainment if required by the exposure conditions.

Special grade concrete is specified when characteristics not available in normal grade concrete are required. Although special grade concrete can be ordered using either prescriptive or performance criteria, most of the criteria provided in the standard are prescriptive, and the concrete supplier has the right to refuse to accept an order based on performance requirements rather than prescriptive requirements.

Quality assessment of concrete can be by either production or project assessment. Production assessment is conducted by the supplier and is based on the statistical assessment of standard compressive tests of concrete specified by compressive strength and produced by a specific plant. Project assessment, specified at the customer's option, provides alternative test data for the statistical assessment of concrete supplied to a specific project. In practice, most concrete is evaluated by the production assessment process, and the testing normally described as quality assurance (QA) in North American specifications is wholly or mostly carried out by the concrete supplier. Project assessment testing can be conducted by a commercial testing laboratory or by a concrete supplier other than the supplier to the project.[8,9]

TABLE 3:
ESTABLISHED TEST METHODS APPLICABLE TO PERFORMANCE SPECIFICATIONS

Property	ASTM Standard	Required lead time
Compressive strength	C 31 and C 39	35 days to obtain materials and make and test concrete mixtures at ages up to 28 days
Compressive strength in-place	C 900 and C 1074	
Density (unit weight), yield, and air content of fresh concrete	C 138	
Density of fresh and hardened structural lightweight concrete	C 567	
Early-age strength	C 39	
Flexural strength	C 78	
Density, absorption, and permeable voids in hardened concrete	C 642	
Shrinkage	C 157	180 days. Can assess at earlier ages based on prior tests
Resistance to freezing and thawing	C 666	90 days
Modulus of elasticity	C 469	35 days
Creep	C 512	1 to 2 years
Splitting tensile strength	C 496	35 days
Scaling	C 672	90 days
Alkali-silica reaction, to evaluate aggregates	C 1260 C 1293	2 weeks 1 year
Alkali-silica reaction, to evaluate mixture	C 227 CSA A23.2-28A[9]	3 to 6 months 2 years
Alkali-silica reaction, to evaluate job combinations except when low-alkali cement is used	C 1567	2 weeks
Alkali content	Chemical analysis	Specify in contract documents

Note: For precision statements, see the text of the cited test standards.

Canadian provisions

The Canadian standard provides an example of a performance specification for a country with durability concerns comparable to those in the U.S. Within CSA A23.1, "Concrete Materials and Methods of Concrete Construction,"[10] five major exposure classes (with numerous subclasses dealing with different degrees of severity) are defined (Table 2). The concrete properties required for each class or subclass include maximum *w/cm*, minimum compressive strength, and maximum and minimum air content and also may require a specific type of curing. For the two most extreme exposures to chlorides, maximum limits for the total coulombs passed when measured per ASTM C 1202 at 56 days are also provided.

Also within CSA A23.1[10] (as well as the other national standards using exposure classes), limits are placed on the constituents or properties that will produce concrete meeting the durability requirements of each exposure. Thus, the standard can be used in a prescriptive manner by requiring compliance with the tabulated limits. The exposure classes can, however, also be used in a performance specification. In this case, although the concrete supplier is not bound to follow the tabulated values, the supplier can use the values for guidance.

As an example, for a prescriptive specification it would only be necessary for the design professional to specify "C-1 concrete." The supplier would then proportion a concrete mixture that met all the tabulated criteria for a C-1 exposure. For a performance specification, it would be sufficient to specify "Concrete shall be supplied and installed to resist Exposure Class C-1," along with the specific tests and acceptance criteria. Where appropriate, it would also be necessary to state the required service life for which the concrete is to remain durable.

The owner is offered two options for the specification of concrete: performance or prescription. The performance requirements apply "when the owner requires the concrete supplier to assume responsibility for the performance of the concrete as delivered and the contractor to assume responsibility for the concrete in place."[10] It is thus clear that the responsibility of the concrete supplier to provide a concrete mixture with the potential to meet the specified performance ends with the discharge of the appropriate concrete mixture from the mixer or delivery unit. The contractor is responsible for placing, consolidating, and curing the concrete so that it matures to have the strength and durability characteristics required by the owner. The text of the options is given in CSA A23.1, Table 5.[10] Guidance on the use of CSA A23.1, Table 5, is given in Annex J, "Guide for selecting alternatives using Table 5 when ordering concrete." This 6-page document is a useful guide to those writing and complying with performance specifications—its contents are reproduced in Reference 1.

EXTENSION TO U.S. PRACTICE

Verification

Verification is normally made by conducting standard established tests on fresh and hardened concrete. These tests are made on samples of concrete taken from loads being discharged at the construction site. In the ultimate performance specification, the concrete supplier (as in Australia) would conduct the quality control (QC) and QA tests, and the owner would have tests conducted on samples taken from the completed structure.

To verify that performance specifications are met, Table 3 summarizes a number of established test methods that are applicable to performance specifications. The widespread evolution and adoption of performance specifications will, however, depend on the development of more rapid and reliable test methods. Some of the more promising test methods that have already been standardized are listed in Table 4. Some methods, in particular ASTM C 1202 and C 457, have been used in performance specifications in Canada and, to a lesser extent, in the U.S. Both can be performed on samples cast from concrete at the time of placement or on cores drilled from the finished structure. ASTM C 1202 and methods similar to ASTM C 642 and C 1585 have also been used in Australia.

TABLE 4:
PROMISING TEST METHODS THAT HAVE BEEN STANDARDIZED AND ARE APPLICABLE TO PERFORMANCE SPECIFICATIONS

Property	Standard	Required lead time
Rapid chloride permeability	ASTM C 1202	28 to 56 days
Air-void system	ASTM C 457	14 days
Sorptivity	ASTM C 1585	28 to 56 days
Rapid migration test	AASHTO TP64[12]	28 to 56 days
Chloride bulk diffusion	ASTM C 1556	35 days after sampling

Adopting exposure classes in ACI 318

Because construction practices and harsh environments in Canada and the U.S. are similar, Table 5 of CSA A23.1[10] provides a useful reference for development of performance specifications in the U.S. Without changing any of the current prescriptive requirements, for example, ACI 318-05 could be modified to include an exposure class approach for both prescriptive and performance specifications, as shown in Table 5. Some of these exposure classes are quite broad in their scope and some refinement will undoubtedly occur. If the exposure class designations are simply applied to the existing requirements in ACI 318-05, they could be tabulated as shown in Table 5.

The adoption of an exposure class approach would be a first step in moving to a more performance-based specification in future versions of ACI 318. Versions of Table 5 have been provided to the RMC Research Foundation and ACI Committee 318. In later revisions, after industry acceptance of the exposure classes, it would be easier for performance requirements to be added and some of the prescriptive requirements to be removed. For example, maximum limits on SCMs and restrictive cement types for sulfate resistance could be replaced with performance testing, as was done in ACI 201.2R-01.[11]

In general, an engineer would specify compressive strength at a specific age and exposure class or classes (in some cases the concrete will need to meet the requirements of more than one exposure class). Concrete producers would use the table to establish the mixture design criteria. In the future, there could be two tables; one for prescriptive criteria and one for performance criteria, providing alternatives for the engineer, contractor, and producer.

BASIS FOR PERFORMANCE

The Australian, New Zealand, and Canadian specifications are the most performance-based of the standards we reviewed. As such, they offer insights into changes that

TABLE 5:
Proposed reformat of ACI 318-05 durability requirements by exposure class

Exposure class	Exposure conditions	Air content	Maximum *w/cm**	Minimum f'_c, psi*	Cement type	Maximum SCM, %	Maximum Cl^-, %
F1	Moderate freezing-and-thawing cycles	Refer to Table 4.2.1	0.45	4500	—	—	—
F2	Severe freezing-and-thawing cycles	Refer to Table 4.2.1	0.45	4500	—	—	—
S1	Negligible sulfate exposure (SO_4 < 0.10% by weight in soil or SO_4 < 150 ppm in water)	—	—	—	—	—	—
S2	Moderate sulfate exposure† (0.10% ≤ SO_4 < 0.20% by weight in soil or 150 ≤ SO_4 < 1500 ppm in water)	—	0.50	4000	II, IP(MS), IS(MS), P(MS), I(PM)(MS), I(SM)(MS)	—	—
S3	Severe sulfate exposure (0.2% ≤ SO_4 ≤ 2.0% by weight in soil or 1500 ≤ SO_4 ≤ 10,000 ppm in water)	—	0.45	4500	V	—	—
S4	Very severe sulfate exposure (SO_4 > 2.0% by weight in soil or SO_4 > 10,000 ppm in water)	—	0.45	4500	V plus pozzolan‡	—	—
C1	Concrete intended to have low permeability when exposed to water	—	0.50	4000	—	—	—
C2	Exposed to deicing chemicals	Refer to Table 4.2.1	0.45	4500	—	Refer to Table 4.2.3	—
C3	For corrosion protection of reinforcement in concrete exposed to chlorides from deicing chemicals, salt, salt water, brackish water, seawater, or spray from these sources	Refer to Table 4.2.1	0.40	5000	—	Refer to Table 4.2.3	Refer to Table 4.4.1

* When more than one exposure class is considered, the lowest applicable maximum *w/cm* and highest applicable minimum f'_c shall be used.

† Seawater.

‡ Pozzolan that has been determined by test or service record to improve sulfate resistance when used in concrete containing Type V cement.

might be considered by ACI committees. While ACI 318-05 is mainly prescriptive in nature, by adoption of exposure classes, it can be reformatted to allow for future performance-based revisions. While there is no doubt that acceptance of concrete on a performance basis will be facilitated by future developments in both in-place testing and the ability to evaluate the potential durability of fresh concrete,[12] there are current, viable tests that can support a performance approach. Chief among these are the ASTM C 457 test for air-void system parameters in hardened concrete and the ASTM C 1202 rapid chloride permeability test or its variant, the AASHTO TP64[13] rapid migration test.

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References

1. Bickley, J.A.; Hooton, R.D.; and Hover, K.C., "Preparation of a Performance-Based Specification for Cast-in-Place Concrete," RMC Research Foundation, Jan. 2006, 155 pp. (available at www.rmc-foundation.org).

2. Lobo, C.; Lemay, L.; and Obla, K., "Performance-Based Specifications for Concrete," *The Indian Concrete Journal*, V. 79, No. 12, Dec. 2005, pp. 13-17.

3. ACI Committee 318, "Building Code Requirements for Structural Concrete (ACI 318-05) and Commentary (318R-05)," American Concrete Institute, Farmington Hills, MI, 2005, 430 pp.

4. ACI Committee 301, "Specifications for Structural Concrete (ACI 301-05)," American Concrete Institute, Farmington Hills, MI, 2005, 49 pp.

5. AS 3600-2001, "Concrete Structures," incorporating Amendments No. 1 and 2, Standards Australia, Sydney, NSW, 2001, 165 pp.

6. AS 1379-1997, "Specification and Supply of Concrete," incorporating Amendment 1-2000, Standards Australia, Sydney, NSW, 2000, 35 pp.

7. AS 1379 Supplement 1-1997, "Specification and Supply of Concrete—Commentary (Supplement 1 to AS 1379-1997)," incorporating Amendment 1-2000, Standards Australia, Sydney, NSW, 2000, 31 pp.

8. Day, K.W., "Perspective on Prescriptions," *Concrete International*, V. 27, No. 7, July 2005, pp. 27-30.

9. Day, K.W., private communication, Aug. 2005.

10. CAN/CSA-A23.1-04/A23.2-04, "Concrete Materials and Methods of Concrete Construction/Methods of Test and Standard Practices for Concrete," Canadian Standards Association, Toronto, 2004, 516 pp.

11. ACI Committee 201, "Guide to Durable Concrete (ACI 201.2R-01),"American Concrete Institute, Farmington Hills, MI, 2001, 41 pp.

12. Hooton, R.D.; Mindess, S.; Roumain, J.-C.; and Rear, K., "Proportioning and Testing Concrete for Durability," *Concrete International*, V. 28, No. 8, Aug. 2006, pp. 38-41.

13. AASHTO TP64-03, "Standard Method of Test for Prediction of Chloride Penetration in Hydraulic Cement Concrete by the Rapid Migration Procedure," American Association of State Highway and Transportation Officials, Washington, D.C., 2003.

Note: Information on the ASTM standards discussed in this article can be found at www.astm.org.

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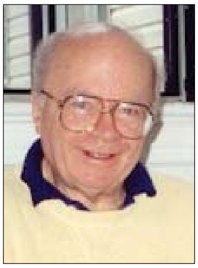

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