Durability and Performance Requirements in Canadian Cement and Concrete Standards

캐나다 시멘트 및 콘크리트의 내구성 및 제성능에 대한 규준

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Abstract

Traditional standards and specifications for concrete have largely been prescriptive, (or prescription–based), and can sometimes hinder innovation and in particular the use of more environmentally friendly concretes by requiring minimum cement contents and SCM replacement levels. In December 2004, the Canadian CSA A23.1-04 standard was issued which made provisions (a) for high-volume SCM concretes, (b) added new performance requirements for concrete, and (c) clearly outlined the requirements and responsibilities for use in performance-based concrete specifications. Also, in December 2003, the CSA A3000 Hydraulic Cement standard was revised. It (a) reclassified the types of cements based on performance requirements, with both Portland and blended cements meeting the same physical requirements, (b) allows the use of performance testing for assessing sulphate resistance of cementitious materials combinations, (c) includes an Annex D, which allows performance testing of new or non-traditional supplementary cementing materials.

From a review of international concrete standards, it was found that one of the main concerns with performance specifications has been the lack of tests, or lack of confidence in existing tests, for judging all relevant performance concerns. Of currently used or available test methods for both fresh, hardened physical, and durability properties, it was found that although there may be no ideal testing solutions, there are a number of practical and useful tests available. Some of these were adopted in CSA A23.1-04, and it is likely that new performance tests will be added in future revisions. Other concerns with performance standards are the different perspectives on the point of testing for performance. Some concrete suppliers may prefer processes for both pre-qualifying the plant, and specific mixtures, followed only with testing only 'end-of-chute' fresh properties on-site. However, owners want to know the in-place performance of the concrete, especially with high-volume SCM concretes where placing and curing are important. Also, the contractor must be aware of, and share the responsibility for handling, constructability, curing, and scheduling issues that influence the in-place concrete properties.

Introduction

There has been a recent surge in interest in sustainable development as well as "green buildings". Concrete structures already offer many advantages for sustainable development. They are almost exclusively made with local materials (reducing energy in transportation), most concretes already contain some level of recycled materials (supplementary cementing materials (SCM) which are by-product wastes of other industrial processes, and some chemical admixtures which are derived from pulp and paper wastes), the thermal mass of concrete building envelopes helps to reduce Heating and air-conditioning (HVAC) requirements, interior and exterior surfaces can be left untreated, and light-coloured, sun-exposed surfaces help reflect solar radiation. The sustainability of concrete structures can be further enhanced by using higher levels of cement-replacement materials, and by better design for durability performance (extending service life), even in severe environments.

Sometimes standard specifications, which are often prescriptive in nature, can be an impediment to these latter issues, either by putting prescriptive restrictions on materials and concrete proportions, by not providing durability performance specifications, or by not allowing options based on performance tests.

There is a current trend away from prescriptive towards performance specifications in North America and around the world. Prescriptive specifications are the norm and have been developed by local experience but are often conservative. They also often inhibit innovation since new materials and methods do not fit into the prescriptive mould. This is of significance when 'sustainable concretes', such as those containing High-Volume SCM's (HVSCM), are being considered (The CSA A23.1-04 makes provision for the use of HVSCM concretes). However, adoption of true performance-based specifications presupposes that we have a clear understanding of all the performance issues that can affect concrete. It also assumes that there are appropriate performance test methods in place to evaluate all of the performance issues for: concrete materials, fresh concrete, hardened concrete, and durability. It also assumes that performance can either be measured in time to affect the outcome, and/or can be used to pre-qualify concrete mixtures. Most parties to construction are familiar with testing for fresh and hardened properties of concrete, but the biggest challenges in this regard relate to requirements for durability.

While there are many types of aggressive exposures which might require a multitude of durability tests, the common element is that most aggressive exposures require that the permeability or fluid penetration resistance of concrete be minimized. Therefore adoption of one or more tests for penetration resistance is fundamental to ensuring durable concrete.

Much of this paper will focus on performance specifications, such as the CSA A23.1-04, and how they are (or can) be implemented in construction specifications to allow the use of innovative concrete materials and proportions.

Review of Current Performance Standards

While there are many definitions of concrete performance specifications, the Canadian CSA A23.1-04 (2004) defines it as follows: "A performance concrete specification is a method of specifying a construction product in which a final outcome is given in mandatory language, in a manner that the performance requirements can be measured by accepted industry standards and methods. The processes, materials, or activities used by the contractors, subcontractors, manufacturers, and materials suppliers are then left to their discretion. In some cases, performance requirements can be referenced to this Standard, or other commonly used standards and specifications, such as those covering cementing materials, admixtures, aggregates or construction practices".

A recent literature review was made of concrete performance standards from around the world (Bickley, Hooton, and Hover, 2006). The following is a summary of some of the general findings from that review:

"It became clear that while there was an almost universal interest in performance, primarily for durability, there were few specifications that contained any pure performance criteria. Most defined exposure conditions that pertained to each country and then tabulated concrete mixture contents and limits that studies had shown would result in the desired durability. These include maximum limits for water to cement or water to cementitious materials ratio limits, minimum cement contents and an acceptable range of air contents. There is an almost universal use of supplementary cementitious materials such as fly ash, granulated ground blast furnace slag and silica fume, as additions or in blended cements. All the specification documents assumed the use of statistical quality control to assure consistent conformity at the lowest cost."

"It also became clear that the term "performance specification" means many things to many different people. This is not necessarily because of any misinterpretation. This is because there is such a wide array of options and valid interpretations, making it imperative that the term be carefully defined in any given context. Parties could agree in principle to execute work under the performance specification umbrella, and yet have widely differing views about mutual expectations."

"A lack of reliable, consistent and standardized test procedures for evaluating concrete performance is frequently cited as a major barrier to the adoption of performance specifications. Some of the available tests can be expensive, take a long time to run and may not be as precise as desired. Short bid times and quick construction starts create a difficult situation for a concrete supplier faced with the need to develop a performance mixture and to perform prequalification testing. In a number of jurisdictions, such as State Highway Departments, some advanced tests have been site proven and then specified in subsequent years for pay items in contracts."

"On the other hand, in the face of an international mindset that says that testing technology has not yet caught up with performance philosophy, there are a wide range of tests that are available today, and have been used successfully on important concrete projects, and these tests methods can be called into action to support performance-based specifications. While some may complain that current tests are not ideal or are insufficiently accurate or precise, which of our everyday concrete quality tests are ideal? If a new test only has to be as accurate, as precise, or as meaningful as the slump test, there may be many new developments to choose from."

"The advent of performance specifications could significantly change the distribution and sharing of responsibility among owner, contractor and concrete supplier. It would be up to the owner (through design professionals) to clearly specify performance requirements together with the test procedures used for acceptance. In the case of true end-result specifications based on hardened, in-place concrete properties, the execution of these requirements would be the joint responsibility of contractor and concrete supplier. They would assume the risk involved and would have to work closely to determine the appropriate concrete mixture. Quality management programs would also be required from both since the successful installation of a concrete mixture would be imperative to achieving acceptance by the owner."

"The transition to performance specifications as another, complimentary way of doing business will require a dedicated educational effort, and advantages and disadvantages will have to be made concrete, so to speak. The motivation will have to come from clear benefits that can be shared at many levels of the industry, and not just because it is time for a change."

In that same review (Bickley, Hooton, and Hover, 2006), the following keys to the concept of performance specifications were identified:

a.) The ability of the specifications writer to discern the performance characteristics appropriate to the owner's intended use of the concrete.
b.) The ability of the specifications writer to describe these performance characteristics clearly, unambiguously, and quantitatively so that performance can be evaluated.
c.) The availability of reliable, repeatable test methods that evaluate the required performance characteristics (along with performance compliance limits that take into account the inherent variability of each test method).
d.) The ability of the concrete producer-contractor team to choose combinations of materials, mixtures, and construction techniques to meet required characteristics so that projects can be planned and bid, risks and costs can be assessed, and materials and construction operations adjusted to comply with performance requirements.

Concrete Performance Characteristics

One clear advantage of performance specifications is that they focus attention on the concrete properties that are the most important for a given situation. Conventional testing often concentrates on slump, air content, and 28-day cylinder strength, even though one or more of these properties may not be relevant to the owner's desired performance, while more relevant performance requirements may not be tested at all. As presented in the National Highway Institute Highway Materials Course Manual (Hover, 2002) one way to look at a broader range of concrete properties is shown in Table 1, where concrete is evaluated as it transitions from the fresh to the hardened state. While the "Fresh Concrete" properties are rather conventional and the hardened concrete list is expanded well beyond the typical cylinder break, the transitional properties are frequently not specified but are nevertheless critical to the safe and economical progress of a concrete construction project. It is instructive to note that within this list (which could be expanded), relatively few properties are commonly specified and tested, even though owner satisfaction is commonly based on a far larger set of criteria.

Table 1 Concrete Performance Properties of Interest (Hover, 2003)

Fresh Concrete	**Transition**	**Hardened State**
Workability	Rate of slump loss	Compressive strength
Slump	Time to initial set	Tensile strength
Response to vibrator	Time to final set	Flexural strength
Pumpability	Rate of strength gain (compression)	Shear strength
Finishability	Rate of strength gain (tension)	Fatigue strength
Segregation	Rate of stiffness gain	Fracture toughness
Bleeding	Time to frost resistance	Elastic properties
Air Content	Tolerable rate of evaporation	Shrinkage
Stability of air bubbles	Plastic Shrinkage	Creep
Uniformity of mixing	Drying Shrinkage	Porosity
Consistency of properties	Temperature changes	Pore size distribution
Temperature		Permeability
Yield		Air void system
		Frost Resistance
		Abrasion resistance
		Sulfate resistance
		Acid resistance
		Alkali-resistance
		Thermal volume change
		Heat capacity
		Thermal conductivity
		Electrical conductivity
		Density
		Radiation absorption
		Color
		Texture
		Cost

Performance Specifications

The responsibilities of the various parties need to be clearly defined with a performance specification. This has been attempted in the recently issued CSA A23.1-04, the essence of which is shown in Table 2. In addition, Annex J was added to that standard which explains these issues in more detail.

Table 2: Prescriptive vs Performance Specification Responsibilities (adapted from CSA A23.1-04).

Alternative	The owner shall specify	The contractor shall	The supplier shall
(1) Performance: When the owner requires the concrete supplier to assume responsibility for performance of the concrete as delivered and the contractor to assume responsibility for the concrete in place.	(a) required structural criteria including strength at age; (b) required durability criteria including class of exposure; (c) additional criteria for durability, volume stability, architectural requirements, sustainability, and any additional owner performance, pre-qualification or verification criteria; (d) quality management requirements (e) whether the concrete supplier shall meet certification requirements of concrete industry certification programs; and (f) any other properties they may be required to meet the owner's performance requirements.	(a) work with the supplier to establish the concrete mix properties to meet performance criteria for plastic and hardened concrete, considering the contractor's criteria for construction and placement and the owner's performance criteria; (b) submit documentation demonstrating the owner's pre performance requirements have been met; and (c) prepare and implement a quality control plan to ensure that the owner's performance criteria will be met and submit documentation demonstrating the owner's performance requirements have been met.	(a) certify that the plant, equipment, and all materials to be used in the concrete comply with the requirements of this Standard; (b) certify that the mix design satisfies the requirements of this Standard; (c) certify that production and delivery of concrete will meet the requirements of this Standard; (d) certify that the concrete complies with the performance criteria specified; (e) prepare and implement a quality control plan to ensure that the owner's and contractor's performance requirements will be met if required; (f) provide documentation verifying that the concrete supplier meets industry certification requirements, if specified; and (g) at the request of the owner, submit documentation to the satisfaction of the owner demonstrating that the proposed mix design will achieve the required strength, durability, and performance requirements.
(2) Prescription: When the owner assumes responsibility for the concrete.	(a) mix proportions, including the quantities of any or all materials (admixtures, aggregates, cementing materials, and water) by mass per cubic metre of concrete; (b) the range of air content; (c) the slump range; (d) use of a concrete quality plan, if required; and (e) other requirements.	(a) plan the construction methods based on the owner's mix proportions and parameters; (b) obtain approval from the owner for any deviation from the specified mix design or parameters; and (c) identify to the owner any anticipated problems or deficiencies with the mix parameters related to construction.	(a) provide verification that the plant, equipment, and all materials to be used in the concrete comply with the requirements of this Standard; (b) demonstrate that the concrete complies with the prescriptive criteria as supplied by the owner; and (c) identify to the contractor any anticipated problems or deficiencies with the mix parameters related to construction.

The onus for meeting performance clearly rests with the producer up to point of placement. Since in-place performance is also affected by the contractor's placement methods, the producer must work with the contractor to ensure the owner's performance requirements are achieved. eg. the contractor (not the owner/specifier) should set the target slump to allow for proper placement and compaction for the situation, and the producer needs to provide this without reducing performance.

Volume Stability Tests

The CSA A23.1-04 standard has included an optional test requirement for pre-qualifying mixtures to be classified as low-shrinkage concrete. Concrete prisms are moist cured for 7 days then, after an initial length measurement is taken, a maximum shrinkage limit of 0.04% after 28-days drying at 50% relative humidity is specified. Since then, other shrinkage test requirements for acceptance have been invoked by engineers building water-retaining structures, and by the Ontario Ministry of Transportation for repair concretes.

Durability Tests

Most deterioration processes involve two stages. Initially, aggressive fluids (water, ionic solutions with dissolved salts, gases) need to penetrate or be transported through the capillary pore structure of the concrete to reaction sites (*e.g.*, chlorides penetrating to reinforcement, sulfates penetrating to reactive aluminates) prior to the actual chemical or physical deterioration reactions. Therefore, a standard acceptance test or tests to measure rates of ingress of aggressive fluids, or a related rapid index test, is fundamental to the development of performance-based durability specifications. These are discussed later in the paper.

Test methods related to measurement of various durability properties exist in various standards (e.g. ASTM, AASHTO, Corps of Engineers (CRD), individual DOT's) in North America and abroad. Limits based on some of these test methods are specified in ACI, BOCA, CSA and individual DOT specifications, amongst many others. It was reported by Roumain (2002) that in the US alone there are over 2000 specifications for concrete. Each of these specifications employs different test methods and different test limits.

Another issue is that tests do not exist for all of the relevant durability or performance concerns. As well, existing tests are not always rapid, accurate, or repeatable, nor do they necessarily adequately represent any or all of the exposure conditions in-situ. The lack of adequate performance-related test methods for concrete is one of the main factors that inhibits the move from prescriptive to performance specifications. A couple of examples related to specific durability issues are used to illustrate need for relevant test methods.

Limits on specific penetration resistance properties (eg. Bulk chloride diffusion in ASTM C 1556, water sorptivity in ASTM C 1585), or vapour transport (ASTM E 96) may need to be adopted for pre-qualification, but for acceptance, a rapid permeability-index test, such as ASTM C 1202 or the Rapid Chloride Migration Test, Nordtest NT492 (also AASHTO TP-64), may need to be adopted. Because it is relatively simple and rapid, the ASTM C 1202 test has become widely used for this purpose.

The new Canadian CSA A23.1-04 concrete standard introduced ASTM C 1202 rapid chloride penetration index limits for prequalification of concrete mixtures to meet (a) C-1 exposure conditions (concrete exposed to freezing in a saturated condition with de-icer salts, 35 MPa, air-entrained, 0.40 w/cm max.) of 1500 coulombs at 56 days, and (b) C-XL exposure (like C-1 but where extended service life is required, 50MPa, air-entrained, 0.37 w/cm max.) of 1000 coulombs at 56 days. These limits will effectively mandate the use of either blended cements or SCM's in all such concretes.

Beyond prequalification, the Ontario Ministry of Transportation (MTO) is using coulomb limits based on random coring, for payment in its End-Result Specifications (ERS) for high-performance concrete structures. This will be detailed later.

Several direct or indirect measures of fluid penetration resistance have been used in specifications for some high-profile structures such as the Confederation Bridge in Canada, the Tsing Ma Bridge in Hong Kong, and the Oresund Bridge between Denmark and Sweden, to name a few. Some of the tests such as for chloride diffusion are useful for service life prediction and have been used to pre-qualify concrete mixtures, but the length of time to complete these tests does not make them suitable for quality control tests during construction. As a result, more rapid index tests are often adopted for this purpose. The most common durability test used for quality control testing continues to be ASTM C 1202 'coulomb' testing. This test has become popular in North America for contracts specifying HPC. The test involves sandwiching a water-saturated disc of concrete between two cells filled with conductive solutions. An electrode in each cell is connected to 60V DC and the current flowing through the concrete disc is measured, and integrated over a 6-hour period to determine the total charge passed in coulombs. It is really a reasonable but somewhat awkward measure for bulk conductivity (inverse of resistivity). However, in general, conductivity is related to the volume and connectivity of the pore system in concrete: the same primary factors that influence both permeability and chloride ingress. In this test, concretes with high conductivity exhibit heating due to the 60V DC potential applied over the 6-hour test period. While this is not of concern for concrete with coulomb values less than 1500, the heating increases conductivity and exaggerates the coulomb values obtained for concretes with higher permeability. This is the reason that it has been suggested to multiply the 30 minute reading by 12 to obtain a "equivalent" 6-hour value without the effects of heating (McGrath and Hooton, 1999; Julio-Betancourt and Hooton, 2004). Also ASTM subcommittee C09.66 is currently considering a modified version of C1202, where the 1-minute conductivity is measured and used as the test result. The other problem with this test is that admixtures that greatly increase the ionic conductivity of the pore fluids in concrete will result in unfairly high coulomb values that do not reflect its chloride diffusion resistance. The most notable example of this is with calcium nitrite corrosion inhibitors. However, in many instances, this test is a useful index test (Hooton et al, 2000).

Many States, Provinces, and some City specifications include a maximum coulomb limit at a given age. This varies in different jurisdictions. In the USA values between 2,000 and 2,500 coulombs are recommended for bridge decks (Ozyildirim, 1998). In Canada, on HPC contracts, the maximum value of 1,000 coulombs is almost universally used for cast-in-place concrete. Where mixes containing silica fume are used, often in ternary mixtures with slag or fly ash as replacements for a percentage of Portland cement and where Quality Control (QC) is good, there is no difficulty in achieving this value.

In 2003, members of Canadian Standards committee A23.1 provided the author with ASTM C 1202 test data from field projects where high-performance concrete (HPC) (also called extended service life concrete, CSA class C-XL) and normal severe chloride exposure class, C-1 concretes, had been specified. The purpose was to see if limits of 1000 coulombs on HPC, and 1500 coulombs for C-1 concretes, were both achievable and reasonable. Over 800 sets of test results are summarized in Table 3. Of 785 tests on HPC (of which 440 were cores extracted from bridge decks and 345 were site-cast cylinders), only 60 (7.6%) exceeded 1000 coulombs. In the Canadian HPC projects constructed from 1990-2000, very few coulomb values exceeded 1000 (Bickley and Mitchell, 2001). Therefore, as will be detailed later, the 1000-coulomb limit at 56 days was adopted in CSA A23.1-04 for Class C-XL (extended service life or HPC). For CSA Class C-1 concrete (max. 0.40 w/cm, min. strength = 35 MPa (5000 psi)), the data showed that 1500 coulombs would only be feasible at 56 or 90 days, and would require use of an SCM or blended cement. In CSA A23.1-04, a limit of 1500 coulombs at 56 days was adopted.

To shorten the need for 56-day testing, another option used by Virginia DOT in the US, is to use 28-day C 1202 test values, but provide accelerated curing to cylinders (7days at 23°C followed by 21days at 38°C) to allow SCMs to more fully react and better simulate their long-term benefits. This curing regime was found to give coulomb values similar to those obtained at 3-6 months when cured at 23°C (Ozyildirim, 1998).

As will be discussed later, it has been suggested that any specification limits (eg. 1000 coulombs) should be based on the average value achieved and allow for individual values to exceed that limit as long as they don't exceed it by, say 25%. This would reduce the chance of failure, due to variability of the test method.

Table 3—Summary of ASTM C 1202 Data from Canadian Construction Projects (prior to 2003)

CSA A23.1 Mix Class	No. of Test Results	No. out of Spec.	% Failure	Max coulombs specified	Comments
HPC (C-XL)	785	60	7.6	1,000	
HPC + CI	12	No spec	-	-	2/12 > 1,500
C1	23	12	52.2	1,500	**
C1/C2	6	No spec	-	-	5/6 > 1,500**
C2	24	No spec	-	-	24/24 > 1,500**
C1 + CI	2	No spec	-	-	2/2 > 1,500

Notes: * CI = corrosion inhibitor, ** = mixtures without SCMs gave much higher values

Types of Testing

Tests are performed at various stages in construction.

1. Pre-qualification: To provide a mixture that when placed under defined conditions can meet the specification.
2. Quality Control: To document that a) materials supplied meet spec. b) the concrete supplied is equivalent to that which was pre-qualified, c) pre-qualified placing practices are being followed. (ie. test at each change of ownership)
3. In-Place Testing: Using NDT and/or tests on cores extracted from the structure to ensure that the concrete supplied and the placement methods meet owner-defined performance levels as required in several highway agency End Result Specifications (ERS).

Concrete producers and contractors are often just interested in prequalification and quality control testing. However, owners are interested in performance of the structure, a number of highway agencies in North America have adopted or are currently considering the use of end-result specifications (ERS) where contractors are paid based on consistently meeting specified performance requirements using in-place testing of the structure. A number of these agencies have developed ERS with defined financial penalties for failure to meet the in-place requirements, some of which exceed the cost of the concrete and if performance is lower than a certain threshold, removal is required.

Ontario End Result Specifications

The Ministry of Transportation in Ontario uses an ERS which involves both bonus and penalty payments, thus providing a positive incentive to contractors. The in-place testing includes strength, air-void parameters (for frost resistance, using ASTM C 457), chloride penetration resistance (using ASTM C 1202), and recently requirements for maximum drying shrinkage have been added for bridge repair work. The contractor has to pay for random statistical coring, where the number of cores taken is based on the quantity of concrete and type of structural element. The Ontario Ministry of Transportation Special Provision No 904S11, December 2004 specifies the quantity and quality of the air-void system in the hardened concrete for normal structural concrete. The minimum volume of air must be 3 % and the maximum spacing factor of each lot must not exceed 0.230 mm. Tests are made on 2 cores drilled from the hardened concrete in the structure for each "lot" by the procedure given in ASTM C 457 using a magnification of 100x to 125x. Each core is split in half longitudinally and one half retained by the Ministry representative. There are provisions for referee testing at the request of either the Owner or the Contractor and for bonuses or penalties based on the compliance and consistency of the test results. Where the air content is greater than 4.0 %, up to a maximum of 7.0% and the spacing factor is 0.180 mm or less a table provides for a varying bonus in $\$/m^3$ based on a combination of the two properties. If the air content in the hardened concrete is below 3% or the spacing factor is 0.240 mm or more a penalty results, again determined from a table of air content and spacing factor values. At a spacing factor of 0.450 mm and an air content of 1% no payment would be made.

Ontario Ministry of Transportation Special Provision No 904S13, (December 2004) requires high-performance structural concrete to have a maximum coulomb value

(ASTM C 1202) in addition to specifying the quantity and quality of the air-void system in the hardened concrete. Both values are established on cores drilled from the hardened concrete in the structure, arranged for and paid for by the contractor (at present the cores can be extracted anytime up to an age of 28 days, and are then stored in a standard curing environment). The maximum coulomb value specified is 1000 and for the air-void system the minimum volume of air must be 3% and the maximum spacing factor of a lot must not exceed 0.250 mm. There is a referee testing provision for the air-void system but not the coulomb value. There are bonus and penalty provisions for air-void systems and a penalty provision for coulomb values. The bonus and penalty determinations for air void quality and quantity are similar to procedure for normal structural concrete except that the default value for spacing factor is 0.250 mm. The penalty for coulomb values higher than 1000 is calculated as follows: Payment Reduction in dollars (CDN) per m^3 = (Actual test value in coulombs-1000) ÷ 5 (For example, for a test result of 2500 coulombs, the reduction in payment is \$300/m^3). There is also a requirement for repairing cracks 0.3 mm wide or wider.

In the Amendment to Provincial Specification OPSS 1350 (January 1995) Special Provision No 11S04, the Ministry specifications also provide bonuses and penalties based on the compliance and consistency of compressive strength results for both normal and high-performance concrete. The 'Percent Within Limits' (PWL) is used to determine payment using the specified compressive strength as the lower limit. If the PWL is 90 % or more, the lot to which the test results apply is acceptable resulting in full payment. A PWL greater than 95 % earns a bonus of up to 5%. When the PWL is less than 90 % and greater than or equal to 50 %, a scaled penalty is applied. At a PWL of less than 50 %, the lot is rejected and replaced. The MTO has had an end-result specification for compressive strength for many years and contractors consistently win bonuses under this approach. In 1991 MTO commissioned a 10-year research plan (Bickley, 1991). The test results of both prescriptive and end-result specifications were compared. The test results for the end-result specifications were more consistent with lower variability than those for the contracts where prescriptive specifications were used. Lot size is defined in the document as follows:

"The Contract Administrator will determine the lot and sub-lot size after discussion with the Contractor and before any concrete is placed. Each lot will contain concrete of one nominal 28-day strength. There shall be only one lot of each specified strength of concrete. If the quantity of concrete of one specified strength is greater than 5000 m^3, the Contract Administrator will consider proposals to divide the concrete into two lots, based on placement in separate structures or in different construction seasons."

In another example of ERS, the Port Authority of New York and New Jersey has required that concrete mixtures be pre-qualified to <1000 coulombs by ASTM C 1202. Samples were also taken from production concrete and were required to be <1500 coulombs in 80% of tests (<2250 coulombs for mixes containing calcium nitrite corrosion inhibitor).

Canadian Performance Standards

One effective way of specifying concrete durability is to require that the concrete remain serviceable for a minimum period of time in a specified environment. Prescriptive specifications usually approach durability by requiring particular ingredients (such as fly ash or air entraining admixtures), proportions (such as minimum cementitious materials content or maximum w/cm), or requiring construction operations (such as wet curing for a specified duration). Each of these factors is a means to an end where the required "end" is durable in-place concrete). Conceptually, requiring that the concrete remain serviceable for a given period of time when exposed to a particular set of environmental conditions specifies the "end result" itself.

The CSA A23.1-04 makes use of a table defining durability exposure conditions (adapted here as Table 4). For a particular exposure condition, requirements for maximum w/cm, minimum strength, limits on cementitious materials, maximum chloride permeability, and minimum periods and types of curing may apply, as shown in Table 5. Note that in Table 5, MS and HS cements refer to moderate and highly sulphate resistant Portland cements respectively, and that MSb and HSb refer to the use of blended cements or Portland-SCM mixtures used to achieve moderate and highly sulphate resistance respectively. The standard also allows use of combinations of Portland cements and supplementary cementing materials (SCM) at the concrete plant, based on meeting performance expansion limits using ASTM C 1012.

Two HVSCM concrete designations were created in the standard. HVSCM-1 is where there is more than 40% fly ash or 45% slag replacement of cement (or a combination of fly ash plus slag), and HVSCM-2 has more than 30% fly ash Or 35% slag.

Table 4 Exposure Classes adapted from CSA A23.1-04

Definitions of C, F, N, A, and S classes of exposure

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	Non-structurally reinforced (i.e., 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	Non-structurally reinforced concrete exposed to chlorides but not to freezing and thawing. Examples: underground parking slabs on grade.
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.
N	Concrete not exposed to chlorides nor to freezing and thawing. Examples: footings and interior slabs, walls, and columns.
A-1	Structurally reinforced concrete exposed to severe manure and/or silage gases, with or without freeze-thaw exposure. Concrete exposed to the vapour above municipal sewage or industrial effluent, where hydrogen sulphide 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 freeze-thaw 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 freeze-thaw 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 (e.g., forcemains); and submerged portions of sewage treatment structures.
A-4	Non-structurally reinforced concrete exposed to moderate manure and/or silage gases and liquids, without freeze-thaw exposure. Examples: interior slabs on grade.
S-1	Concrete subjected to very severe sulphate exposures (Tables are cited).
S-2	Concrete subjected to severe sulphate exposure (Tables are cited).
S-3	Concrete subjected to moderate sulphate exposure (Tables are cited).

Notes:
(1) *"C" classes pertain to chloride exposure.*
(2) *"F" classes pertain to freezing and thawing exposure without chlorides.*
(3) *"N" class is exposed to neither chlorides nor freezing and thawing.*
(4) *All classes of concrete shall comply with the minimum requirements of "S" class noted in other Tables*

Table 5 Abridged Version of CSA A23.1 Requirements in CSA A23.1-04 for Specifying Concrete Based on Class of Exposure

Class of Exposure	Maximum Water-to-cementing materials ratio*	Minimum specified compressive strength (MPa) and age (d) at test*	Air content (for 20 mm aggregate shown here)	Curing type Normal concrete (not High-volume SCM^{xx})	Cement Restrictions	ASTM C1202 Chloride ion penetrability test requirements and age at test**
C-XL	0.37	50 within 56 d	4-7 or 5-8% if exposed to freezing	Extended	-	<1000 coulombs within 56 d
C-1 or A-1	0.40	35 at 38 d	4-7 or 5-8% if exposed to freezing	Additional	- -	<1500 coulombs within 56 d
C-2 or A-2	0.45	32 at 28 d	5-8%	Additional		
C-3 or A-3	0.50	30 at 28 d	4-7%	Basic		
C-4**** or A-4	0.55	25 at 28 d	4-7%	Basic		
F-1	0.50	30 at 8 d	5-8%	Additional		
F-2	0.55	25 at 28 d	4-7%****	Basic		
N***	For structural design	For structural design	None	Basic		
S-1	0.40	35 at 56 d	4-5%	Additional	HS or HSb	
S-2	0.45	32 at 56 d	4-7%	Basic	HS or HSb	
S-3	0.50	30 at 56 d	4-7%	Basic	MS or MSb+	

Paraphrased Table Footnotes :

* The water-to-cementing materials ratio shall not be exceeded for a given class of exposure, regardless of exceeding the strength requirement. For HVSCM-1 concretes, max. w/cm is lowered by 0.05 all exposures.

** Where calcium nitrite corrosion inhibitor is to be used, the same concrete mixture, but without calcium nitrite, shall be prequalified to meet the requirements for the permeability index limit.

^{xx} For HVSCM concretes, curing requirements are more rigorous for some severe exposures.

*** To allow proper finishing and wear resistance, Type N concrete intended for use in an industrial concrete floor with a trowelled surface exposed to wear shall have a minimum cementing materials content of 265 kg/m^3.

**** The requirement for air-entrainment should be waived when a steel trowelled finish is required. Interior ice rink slabs and freezer slabs with a steel trowelled finish have been found to perform satisfactorily without entrained air.

\+ Other types of cements meeting LH, HS, HSb are also allowed Although LH cements are for low heat, they are allowed for moderate sulfate resistance based on their low C_3A contents).

The CSA coulomb limits listed in Table 5 are intended for prequalification, but currently do not allow for the variability of the test results if used for acceptance testing during construction. As a result, it has been suggested to the CSA A23.1 committee that allowances for single test values to exceed the limit need to be added (similar to what is currently done for strength and hardened air-void testing). The following wording was suggested as a note to the 1500 coulomb requirement for Exposure Class C-1 concrete: "The suggested acceptance testing parameter for Concrete Exposure Class C-1 is 1500 coulombs average with no single result greater than 1750 coulombs. Considering that the ASTM C 1202 test is subject to variations, it is recommended that the target coulomb value be less than 1150 to have a reasonable assurance that the 1500 coulomb requirement in the Table will be met." Similar wording has been suggested for C-XL Exposure Class concrete, except with different coulomb values (average = 1000, max. single value = 1250, target = 700). It should be cautioned that these values have not yet been agreed upon.

High-Volume SCM Concrete Requirements

CSA A23.1-04 defines HVSCM concretes, as containing a level of SCM above that typically used in normal construction (About 75% of concrete in Canada contains some level of fly ash, slag or silica fume). Two catagories of HVSCM concrete are defined:

HVSCM-1: $\%FA/40 + \%S/45 > 1$
HVSCM-2: $\%FA/30 + \%S/35 > 1$
where, FA = fly ash, and S = ground granulated blast-furnace slag.

The requirements listed in Table 5 are modified in some cases when HVSCM concrete is used. The maximum water-to-cementing materials ratio of the concrete should meet the limits in Table 5, except when the concrete is exposed to freezing and thawing in which case the values in Table 2 is required to be reduced by 0.05 for HVSCM-1 in all exposure classes. For example, in C-1 Exposure the maximum water-to-cementing materials ratio in Table 5 is 0.40, but for HVSCM-1 concrete this maximum value shall be reduced to 0.35. Also, to account for the potentially slower rate of strength gain, the minimum specified 28day compressive strength requirements in Table 5 is specified at 56 days for HVSCM-1 concrete. To reduce the risk of carbonation-induced corrosion of reinforcement, for concrete exposed to moisture with < 50mm depth of cover, the maximum allowable w/cm for HVSCM-2 concrete is 0.45, and 0.40 for HVSCM-1 concrete. Finally, for severe exposure class categories such as C-1, F-1, S-1, and S-2, HVSCM-1 concretes are required to be moist cured for 10 days (as compared to 7 days for other types of concrete). For less severe A-3, A-4, C-3, C-4, F-2, N, S-3 exposure classes, 7 days moist curing is required for all HVSCM concretes (compared to 3 days for *other types of concretes).*

Comments on How to Help Ensure Performance

While various performance tests can be used for pre-qualification, QC, or testing in-place, there are far more issues which have to be addressed to obtain desired performance in aggressive environments. These are outlined in Annex J of CSA A23.1-04. A few points are listed below:

- Require all contract bidders to attend a pre-bid meeting to hear about special requirements—so they can't complain afterwards that they missed some of the performance requirements.
- Make contractors, including subcontractors, detail in their bid how they intend to meet the special requirements part of the bid submittal. eg. placement methods, *protection, curing, hot/cold weather provisions.*
- Do not accept low-price bids that are not responsive to the special requirements.
- Once work has commenced, require pre-pour meetings for important placements: The contractors, the suppliers, the subcontractors, including the finishers need to be aware of what needs to be done to ensure that the concrete can be delivered, placed, compacted, protected, finished, and cured to achieve the performance objectives. Even the person who will be fog misting , or applying other protective measures needs to be there to understand why it is important.

Achieving the owner's performance requirements requires more cooperation between the concrete suppliers, the contractors, and concrete finishers than often exists in typical practice.

Conclusions

CSA A23.1-04 provides detailed requirements and responsibilities for the various parties in performance-based specifications. It also includes new performance tests.

Performance specifications can allow for innovation in the supply of concrete, including HVSCM concretes by providing flexibility in materials supply and concrete proportions.

Performance means more than acceptance of concrete at the end of the truck chute. It means in-place performance of the structure, so the concrete producer and contractor have to work as a team to meet In-Place or End-Result specifications. Just as with prescriptive specifications, it is important to be clear when specifying performance as to the roles and responsibilities of: the designer (or owner), the contractor, and the concrete supplier. The contractor needs to be aware of the performance test program prior to bidding in order to allow for associated costs. Similarly, owners need to demand that successful bids are clearly responsive to special requirements for achieving performance objectives.

Rapid, reliable tests with appropriate limits are needed for the important performance issues.

Fundamental to performance of concrete in an aggressive exposure is meeting maximum limits on fluid penetration resistance. Since most rigorous methods are too slow and expensive to be used beyond pre-qualification of mixtures, rapid index tests are needed for quality control and in-place purposes. In CSA A23.1, the ASTM C 1202 'coulomb' test has been adopted for this purpose, although rapid chloride migration or water sorptivity tests maybe considered in future revisions.

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