RMC Research Foundation

Preparation of a Performance-based Specification for Cast-in-Place Concrete

Prepared by:

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In Cooperation With:

Because even the best can become better.

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Disclaimer

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Executive Summary

As part of its initiative to facilitate a construction industry change from prescription specifications to performance specifications (P2P), the National Ready Mixed Concrete Association (NRMCA) commissioned this review of the international state-of-the-art. A literature search was made and a large number of documents were consulted.

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-cement or water-cementitious ratio, 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. 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.

In Europe, representatives of 28 countries produced a concrete specification to ensure durability performance for use by all European Economic Community members. Where necessary to meet countries' special needs, an amendment to this specification is allowed.

Other agencies such as the UK Highway Agency and FHWA have major ongoing efforts to produce performance specifications. A major part of these efforts involves the education of the stakeholders. If this change is to be enacted in the USA, a similar effort will have to be undertaken.

Closer to home, the Canadian Standards Association has produced an enviable document: "A23.1-04/A23.2-04 Concrete materials and methods of concrete construction/ Methods of test and standard practices for concrete." While not strictly a performance specification, a great deal is to be learned from it and it is discussed in some detail in this report. The ACI 318 Building Code is also discussed; there may be opportunities within the current regulations for effective use of performance specifications and ideas are discussed herein for proposing modifications and expanding those opportunities. A stepwise modification is recommended.

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. Suggestions for transition and implementation are included in this report. The authors thank NRMCA and the RMC Research Foundation for the opportunity to explore this exciting topic in depth.

Chapter 1 Introduction and General Issues

1.1 What is a performance specification?

It is useful to begin the discussion by sampling a range of definitions of the term "Performance Specification."

1.1.1 *Definitions*—As documented on its website, NRMCA discusses [In 1.1] a performance specification as follows:

"A performance specification is a set of instructions that outlines the functional requirements for hardened concrete depending on the application. The instructions should be clear, achievable, measurable and enforceable. For example, the performance criteria for interior columns in a building might be compressive strength and weight since durability is not a concern. Conversely performance criteria for a bridge deck might include strength, permeability, scaling, cracking and other criteria related to durability since the concrete will be subjected to a harsh environment.

Performance specifications should also clearly specify the test methods and acceptance criteria that will be used to enforce the requirements. Some testing may be required for pre-qualification and some for jobsite acceptance. The specifications should provide flexibility to the contractor and producer to provide a mix that meets the performance criteria in the way that they choose. The contractor and producer will also work together to develop a mix design for the plastic concrete that meets additional requirements for placing and finishing, such as flow and set time, while ensuring that the performance requirements are not compromised.

Performance specifications should avoid requirements for means and methods and should avoid limitations on the ingredients or proportions of the concrete mixture.

The general concept of how a performance-based specification for concrete would work is as follows:

- There would be a qualification/certification system that establishes the requirements for a quality control management system, qualification of personnel and requirements for concrete production facilities.
- The specification would have provisions that clearly define the functional requirements of the hardened concrete.
- Producers and contractors will partner to ensure the right mix is developed, delivered and installed.
- The submittal would not be a detailed list of mixture ingredients but rather a certification that the mix will meet the specification requirements, including pre-qualification test results.
- After the concrete is placed, a series of field acceptance tests would be conducted to determine if the concrete meets the performance criteria.
- A clear set of instructions outlining what happens when concrete does not conform to the performance criteria.

1.1.2 *U.S. Federal Highway Administration*—Chapter 2 of the FHWA Performance Specifications Strategic Roadmap is devoted to a detailed description of performance specifications. It states "A performance specification defines the performance characteristics of the final product and links them to construction, materials and other items under contractor control."

1.1.3 *Canadian Standard CSA A23.1*—Annex J to this standard is a guide for using Table 5. A performance concrete specification is defined 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."

1.1.4 *UK Highway Agency*—This agency defines performance specifications as follows:

- **"Output measures** define the end product of works carried out on the network. This is usually in the form of a series of outputs that will deliver the desired outcome. For example meeting road surface skid resistance requirements is one output that will help enable the safety outcome to be realized.
- **Outcome measures** define the benefits that should be delivered as a consequence of the works carried out on the network. This will usually take the form of the level of service required. For example journey time reliability or level of safety."

1.1.5 *Cement and Concrete Association of New Zealand*—"A performance-based specification prescribes the required properties of the concrete but does not say how they are to be achieved."

1.2 Why have performance specifications become an issue now?

The competing or sometimes complimentary philosophies of prescriptive vs. performance specifications have been around as long as there have been concrete specifications. In 1928 ACI Committee E-1 and CRSI Committee on Engineering Practice proposed their "Joint Code-Building Regulations for Reinforced Concrete." This document was the precursor to what many consider to be the "first" ACI Code, published in 1936 and also called "—Building Regulations For Reinforced Concrete," (A. C. I. 501-36T)[1] These early documents permitted use of concrete mixtures without "preliminary tests of the materials to be used," as long as the water/cement ratio (w/c) met the following prescriptive requirements.

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[1] *Proposed by Committee 501, Standard Building Code*, the new code" was presented as revised and tentatively adopted, 3Znd Annual Convention, American Concrete Institute, Feb. 25, 1936.*

Table 1.2
Joint Code - Building Regulations for Reinforced Concrete
American Concrete Institute and Concrete Reinforcing Steel Institute, 1928
Assumed Strength of Concrete Mixtures for Plastic Concrete

Assumed compressive strength* at 28-days in pounds per square inch	Water/cement ratio in U.S. gallons per sack of cement	Water/cement ratio in lb water per lb cement.	Approximate ratio of cement volume to dry total aggregate volume
1500	8¼	0.73	1:7
2000	7½	0.67	1:6
2500	6¾	0.60	1:5¼
3000	6	0.53	1:4½

*Strength value assumed in structural design.

The 1929 "Joint Code" went on to require tests of at least one specimen per 100 cubic yards (CY) of concrete placed. Interestingly, this early set of regulations permitted a performance-based alternative to the prescriptive w/c requirements for concrete strength, by allowing pre-qualification of a mixture on the basis of test data correlating strength to w/c. Four different w/c values had to be tested with 4 specimens each (the forerunner of today's "3-point curve") and the w/c approved for production was that value corresponding to a compressive strength 15% higher than specified (forerunner of today's so-called "overdesign"). Once the proposed mixture was approved, no substitutions in materials were permitted without additional tests. A bias toward the prescriptive specification of w/c was apparent, however, as the frequency of testing had to increase to 1 specimen per 50 CY placed if w/c had been established on the basis of contractor testing. There is no mention of durability or permeability in the 1928 Joint Code.

The state of the technology in these early days of the industry can be gauged from this statement from A.R. Lord's Handbook of Reinforced Concrete Building Design, published in 1928: "Engineers are so accustomed to thinking of concrete for buildings in terms of 2,000-lb [per in^2] strength at 28 days that it may be novel to consider using a 3,000-lb [per in^2] concrete as the basic mix." (Lord, 1928, p186.) But changes were soon to be in the works.

S.C. Hollister, visionary engineer and educator, was president of ACI in 1933-34. In his outgoing address he predicted the advent of chemical admixtures and high strength concrete by saying, *"One may grow so accustomed to the surrounding conditions that they are accepted as a sort of status not subject to review…Who may say, for example, whether it is possible to achieve mobility or workability with an agent other than water…We see the many varied and intriguing avenues of development that present themselves...Imagine, for example, the concrete with an available strength of 10,000 pounds per square inch. Smaller columns, thinner and lighter beams and slabs would at once result. Present limitations...would at least double. A new basis of design would be required. The achievement of today was the goal of yesterday."* Seventy one years after Hollister's predictions, today's concrete has become a complex and truly "engineered material" and this development has intensified the debate surrounding performance specifications.

Over this same time period of concrete's transition to an engineered material, many concrete producers have likewise transitioned from being merely "truckers" who deliver concrete mixed in accordance with a specified recipe to being well informed on concrete materials, including complex aggregate grading, chemical admixtures and a wide range of cementitious materials. Similarly, when the 1928 Code was published the design professionals had responsibility for preparing detailed prescriptive specifications and conducting careful inspections of the mixing process. More recently, fewer specifications require predetermined concrete recipes or materials and production inspections. Likewise, there has been a shift in the responsibility for concrete ingredients and mix proportions toward the concrete producer and away from the design professional. Today's review of concrete mixture submittals "for general conformance with the contract documents" is a significant evolution from the fully specified mixture proportions of only a few years ago.

Other changes that have swept the industry include recognition that for many modern concrete applications, strength is no longer the only, or even the most important, issue. Portland cement is not the only cementitious material; water content and aggregate size are not the only factors that influence slump and w/c is not the only factor influencing permeability. Air content is easily specified and readily measured in the field, but freeze thaw durability and scaling resistance are more dependent on air void size and distribution in the paste than on total air volume in the concrete. Chemical and mineral admixtures affect air, workability, setting time, bleeding, rate of strength gain, and early and later age strength. These same admixtures may or may not be mutually compatible. At the same time that it has become more difficult to write a prescriptive specification that can take advantage of these developments and avoid their pitfalls. It has become evident that evaluating the durability of concrete is more difficult than evaluating strength. It is more difficult to predict or assure the long-term service life of concrete than it is to predict or assure the short-term load capacity.

Thus the simultaneously increasing demand for improved concrete durability and the growing complexity of concrete mixture design and proportioning lead us back to the prescription-to-performance debate. Interest is further fueled by the changes in construction technique that have accompanied these newer concrete materials developments. An example of all of these factors is a high-performance, high-density, low-permeability concrete. Such mixtures often blend portland cement with one or more cementitious materials such as silica fume and fly ash or slag, use up to two performance grades of water-reducing admixture, incorporate at least 3 sizes of aggregate and may have set-retarders and/or corrosion inhibitors plus an air entraining admixture. Proportioning such a mixture requires experience with these specific materials, including recognition that the normal relationships between workability and water content, and between strength and water/cementitious materials ratio (w/cm), need to be re-calibrated. Handling, placing, finishing and curing such a mix requires experience as well to accommodate rapid surface drying, rapid setting and a high shrinkage potential. So, if the question is, "Why discuss performance specifications now when prescriptive specs have been used since the early ACI codes in 1928?" One answer is that we are now demanding more *of* the concrete and that it may be difficult to take full advantage of the wide range of material and construction combinations and options under a strictly prescriptive specification

1.3 The essence of prescription vs. performance

The “Prescription to Performance” (P2P) initiative is directed toward a shift in the focus of concrete specifications. A prescriptive specification focuses on the properties of the raw materials, mixture proportions, the batching, mixing and transport of the fresh concrete, and the full range of construction operations from placing to curing. Prescriptive specifications rely on observed or implied relationships between the details specified and the final, in-place, or “End Product” or “End Result,” performance of the concrete. Under a prescriptive specification the end product performance may or may not be described. In contrast, a pure performance specification “starts with the end in mind,” fully describing the required performance characteristics of the end product, leaving materials selection, proportioning and construction means and methods up to the party contractually bound to comply with the specifications. Under a pure performance specification it is the responsibility of the concrete producer-contractor team to select materials and conduct construction operations that will produce the required concrete performance. Proponents of prescriptive specifications say, “Here is how we want you to proportion and install the concrete, and if done in accordance with these instructions, the results will be satisfactory.” Proponents of performance specifications say, “Just tell me what you want done, don’t tell me how to do it.”

Keys to the concept of performance specifications include:

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 correlate choices of materials, mixtures and construction techniques to the 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.

These four keys present at least the following challenges:

a.) Under current, predominantly prescriptive specifications, end product performance is not always comprehensively spelled out at the specification stage. For example, prescriptive specifications may not explicitly include requirements for abrasion resistance, scaling resistance or limitations on concrete cracking. Nevertheless, unsatisfactory performance in any of these categories is often pointed out after the concrete has been installed. The rationale for finding the concrete unsatisfactory may be that these common end-result requirements are generally implied and that the concrete would have been satisfactory if the prescriptive requirements would have been met. In contrast, performance specifications require an “up front” description of owner expectations. In most cases, this can take significant additional effort and expertise beyond that required for prescriptive specifications by design professionals working on the owner's behalf.

b.) Some commonly expected (although uncommonly specified) performance characteristics are not readily clearly definable or readily quantified. In-place cracking, movements due to shrinkage, scaling, pop-outs, color variations or local incidents of abrasion are easy to spot, but more difficult to describe in an unambiguous way.

c.) Despite an explosion of research and development into new concrete test methods, the industry does not yet have a comprehensive suite of test methods or the predictive models to allow their use to reliably predict service life in general.

d.) Some contractors and concrete producers will need additional training to be able to select materials and construction operations that will produce the required concrete. Design professionals will also need additional training or special expertise to develop the reliable performance requirements.

1.4 Advantages and disadvantages

The primary advantage to specifying end product performance is that a knowledgeable concrete producer-contractor team has the flexibility to develop a unique combination of materials and construction methods that will achieve the owner-designer's stated objectives. Performance specifications will therefore work well when the producer-contractor team has the necessary expertise; the owner-designer can clearly articulate the requirements, and appropriate and sufficiently precise test methods are available for documenting the specified performance. A prescriptive specification may work best when there is a reliable connection between the specified materials, means, and methods and the desired outcomes. The simpler the concrete mixture and the less restrictive the required outcomes, the more likely a prescriptive specification will be an efficient and reliable way to specify concrete. As the P2P Initiative is implemented it will be necessary to identify those opportunities for which performance specifications offer the greatest advantage, as well as to identify situations where a more conventional approach is more appropriate. Further comments on the advantages and disadvantages for both prescriptive and performance specifications are listed in Tables 1.4(a) 1.4(b).

Table 1.4(a) Advantages and Disadvantages of Prescriptive Specifications

Prescriptive Specifications	
Advantages	**Disadvantages**
Some designers and producers may have more confidence in, and be more comfortable with, traditional prescriptive approach	Some designers and producers may not be confident that prescriptive specifications lead to desired end performance
Expertise required at the spec-writing stage.	Some spec-writers may not have such expertise, especially with modern materials combinations.
Value and effectiveness of the product is "designed-in" by the specifier.	Limited opportunity for optimization of the concrete beyond spec-writing stage.
Newer materials and methods can be implemented if the specifier has remained technologically current.	Limited opportunity to take advantage of producer's unique access to materials, material combinations, plant, equipment, technology, expertise or knowledge of local materials and conditions.

Table 1.4(a) Advantages and Disadvantages of Prescriptive Specifications (cont'd.)

Advantages	Disadvantages
The specification reflects the spec-writer's understanding of the relationship between the desired properties of the concrete and the specified materials, means and methods.	The relationships implied in the prescriptive requirements may not be as reliable or the same as the relationships assumed for the specific materials or project conditions.
The specification writer has the opportunity to control any aspects of the process, from concrete materials selection and proportioning to batching, mixing, transporting, placing, consolidating, finishing and curing the concrete. This control is exercised through prescriptive specification requirements.	The interests of all parties may not be represented in the prescribed specification, i.e., raw materials suppliers, concrete producer, concrete placing contractor, concrete finishing contractor, general contractor, construction manager, owner, investor, end user.
Basic specification compliance tests are inexpensive, generally accepted and commonly available.	Basic specification compliance tests may not tell us as much as we would like to know. Test results may be more variable (less reliable) than supposed. Conventional results may reflect the material as delivered and as subsequently cured under standard conditions, rather than as installed and as cured by actual field conditions. Standard tests may report results at concrete ages other than are critical for assurance of quality. Standard tests may not enable accurate prediction of longer-term concrete performance in the actual environment.
Prescriptive specifications could be interpreted to limit the concrete producer's responsibility to adhere to the prescribed requirements, and could be interpreted to limit concrete producer's liability for post-chute influences on concrete behavior.	Producer often ends up being liable for post-chute concrete behavior anyway, at least until expensive tests demonstrate placing, consolidation, finishing or curing problems.
Concrete producer only need batch required materials in the required manner. Concrete materials and mixture expertise may not be required for typical applications.	Since limited expertise is required, limited expertise is applied; a lowest common denominator industry emerges. Concrete producers have limited technical, economic or creative control on product.
In the absence of explicitly defined end-results, contractual performance requirements can be implied in addition to the explicitly stated prescriptive requirements. The owner-designer may object to subsequent concrete performance regardless of compliance with prescriptive specs.	In the absence of explicitly defined end-results, and if no desired end results can be implied, the owner-designer may be dissatisfied with the end product but have limited recourse if all the prescriptive requirements were met.
Prescriptive specifications can be written to clearly separate the concrete producer's responsibility from the concrete contractor's responsibility.	Even with prescriptive specifications, lines of responsibility can be blurred, especially when testing is conducted on concrete sampled anywhere beyond the truck chute or anytime after job site addition of water.
Prescriptive specifications "level the playing field," allowing concrete producers with a wide range of levels of expertise to compete.	Prescriptive specifications diminish incentive for a given concrete producer to optimize a mixture or to exercise quality control beyond the level of competitors.

Table 1.4 (b) Advantages and Disadvantages of Performance Specifications

Performance specifications	
Advantages	**Disadvantages**
Designers can focus on what is needed rather than how to get it (not all designers are familiar with *how* to best achieve end results)	Specifying how to achieve satisfactory concrete has been a traditional design responsibility. Engineers may be concerned over a perceived reduction in control
Opportunity to focus on the concrete behaviors and characteristics that really matter.	Specifier may not be sure about what those characteristics are, nor about how to measure them. Reliable tests may not be available to quantify the desired outcomes. Performance tests may be more expensive, more time consuming or require more special expertise compared to conventional tests.
Concrete producer-contractor team has technical, logistical, economic “creative control” or influence on the product. Opportunity to take advantage of unique materials, material combinations, plant, equipment, technology, expertise, knowledge of local materials and conditions. Flexibility in mix proportioning can be opportunity to produce a better overall mixture, or a more economical mixture that meets all performance requirements, or both. A more durable product leads to lower life-cycle cost.	End product properties are influenced by materials, concrete production, concrete delivery, mix adjustments by contractor, placing, consolidation, finishing, adjustments to mix properties at surface, ambient conditions, moisture control, temperature control. There are many parties involved, and each party has a unique influence on the product. It may be difficult to separate those influences and responsibilities. There may be increased cost in the prequalification stage and durability-related or in-place testing may be more expensive. It may be difficult to take advantage of life-cycle economic benefit in a low bid (first-cost) contract.
Assumed relationships between concrete performance and mix characteristics can be augmented or replaced with tests of concrete properties.	Tests beyond the routine slump, air and cylinders are likely to be more expensive and more complicated, and their precision must be taken into account in the specification.
In those cases where prescriptive specifications are interpreted to give the producer-contractor full responsibility for end-result concrete behavior, even when prescriptive requirements have been met, a switch to performance specs does not necessarily result in any additional responsibility.	In those cases where prescriptive specifications clearly limit the producer’s responsibility to comply with instructions, the switch to performance specs and the accompanying responsibility for end results is a considerable increase in responsibility.

1.5 Available options

Given that any method for specifying concrete materials and construction services will have both advantages and disadvantages, the challenge (and the opportunity) is to develop appropriate specifications that maximize the advantages and minimize the disadvantages. This also means having a range of available specification-types that may be most appropriate in any given situation. For example, as detailed in Chapter 2 of this report, BS 8500 defines five approaches to specifying concrete:

Designed concrete—(similar to current practice under ACI 318)
Designated concrete—(a specific and certified mix that meets requirements of designed concrete.)
Prescribed concrete—(fully prescriptive, “recipe” specification.)

Standardized prescribed concrete—(a “standard mix” as with many public works-type standard mixes.)
Proprietary concrete—(Full performance)

As seen in more detail in Chapter 2 of this report, the official definitions of these options are a bit difficult for the North American audience to understand, but they cover the range from pure performance to pure prescriptive to calling for a specific, pre-approved, proprietary concrete mixture. As evidence that “there is nothing new under the sun,” Elwyn Seelye’s classic civil engineering reference book, “Specifications and Costs” (first published in 1946) has model specifications for both prescriptive or “Fixed Ratio” concrete mixtures and for performance-oriented “Controlled Concrete.” In the first case, “Concrete shall be, by dry volume, of those proportions that are shown on the drawings.” In the second case, “Controlled Concrete shall conform to the following requirements,” followed by a table showing “Class of Concrete,” and “28-Day Compressive Strength.” (Seelye, 1946)

Blends of philosophies within a given specification are frequently encountered. ACI 318, for example, allows for acceptance for strength on the basis of strength test results (performance), but for durability limits are placed on maximum w/cm (prescription.) Likewise the CSA (Canadian) “performance” specification includes prescriptive w/cm limits. NRMCA has already developed an example of a “minimally prescriptive” specification that recognizes the current prescriptive limits of ACI 318, but allows for maximum flexibility via end product performance requirements.

Further options exist in the distinction between performance characteristics that are used for acceptance of the concrete, in contrast to those used to adjust the amount paid. Payment schemes can be developed to provide incentives for good performance and to exact penalties for marginal performance, as long as the concrete that remains in place has met minimum requirements. Examples of such arrangements are discussed in Chapter 2. A related issue, however, is that given the joint responsibility generally inherent in performance specifications, fairly distributing cash bonuses or penalties among the parties who contributed to the concrete quality can be a knotty problem.

1.6 Concept of “Point of Performance”

Given the multiple stages of concrete production and installation, and that “custody” of the concrete changes hands multiple times before the properties of the end product are fully developed, one question is “at what point in the process do we specify and evaluate the concrete?” This is further complicated by the fact that concrete performance is to some extent in the eye of the beholder. Contractually speaking, performance is in the eye of the party who wrote the specification and thus defined the required performance characteristics. To a concrete producer buying raw materials, “end-product performance” applied to aggregates may be defined by density, aggregate grading or uniformity of the FM (Fineness Modulus) of the sand, or compliance with ASTM C33 with no further stipulation as to where or how to extract the rock or how to process it. Similar examples could be given for requirements for the performance of cement or cementitious materials or admixtures. A purely performance-minded concrete producer might not ask for cement mill test reports, and might not even demand that cement meet specific chemical or fineness requirements of ASTM C150, specifying instead that the cement meet requirements for strength, rate of strength-gain, soundness, shrinkage, setting time, water demand, uniformity, and limited expansion in ASR tests. Likewise a performance-minded buyer of chemical and mineral admixtures might say, “don’t tell me what they are made of, just guarantee that they will perform in the concrete and that they are mutually compatible.” While some of these performance characteristics for raw materials are easily specified; readily evaluated with long-established test methods and the responsibility for meeting them is rather clear, the situation gets complicated when the raw ingredients are combined.

To a contractor buying concrete from the producer, “performance” might be defined in terms of concrete quantity delivered per hour, workability, pumpability, finishability, setting time or early-age strength for formwork or shoring removal. If performance is evaluated at the point of discharge from the concrete truck, responsibility is fairly clear, but as soon as evaluation moves to the point of discharge from the pump, responsibility starts to get fuzzy. If the concrete is not “pumpable,” does the concrete producer have to redesign the mixture or does the pumping service have to change equipment? The project owner on the other hand may not be concerned with any of these raw materials, fresh concrete or construction issues. To the owner, performance is defined by having sufficient in-place load carrying capacity to allow the safe operation of the facility and sufficient in-place durability to withstand the service environment for the financially intended life of the facility. The idea of a performance specification can therefore imply different things to different players and achieving that required performance can (and must) become the joint responsibility of more than one party. Since the owner’s chief interests are the in-place, long-term properties of the concrete, meeting such requirements will necessarily be the joint responsibility of the raw materials suppliers, concrete producer, formwork subcontractor, pumping subcontractor, placing and finishing subcontractor, and the General Contractor (GC) or Construction Manager (CM) managing the entire process. It is therefore necessary to be more definitive, and to talk about the “point of performance,” i.e., when and where in the multiple processes of concrete making to curing and protecting are we going to define the required performance of the concrete? The related question is “who bears the responsibility for achieving the specified performance?”

The following example focuses on specifying and installing a superflat industrial floor and demonstrates that the terms “concrete performance,” “performance specification” and “point of performance” can take on different scope and meaning for various parties to the overall project. (This example considers only the flatness aspects of the floor and ignores other critical performance characteristics such as strength, cracking and abrasion resistance.)

Table 1.6
Example of multiple responsibilities and multiple performance criteria for a superflat industrial floor

Example Performance Requirement	Party setting the performance requirement	Party obligated to achieve the specified performance	Point of Performance	Is Performance Measurable?
Superflat floor	Owner-specifier	General contractor	Hardened concrete floor, in service	Flatness can be measured at any time. Conventional flatness criteria are intended to apply prior to shrinkage and curling.
Finishing to proper tolerances	General contractor	Concrete Floor Placing and Finishing contractor	Hard concrete floor, day after placing	Place/finish must be evaluated prior to curling.
Consistent rate of concrete delivery	Concrete Floor Placing and Finishing contractor	Concrete producer	At concrete delivery	Observed on site
Consistent timing and rate of concrete placement	Concrete Floor Placing and Finishing contractor	Concrete producer, pumping contractor, place-finish crew	As observed during placing	Observed on site
Consistent concrete finishability	Concrete Floor Placing and Finishing contractor	Concrete producer	As observed during finishing	Somewhat subjective. Influenced by crew, equipment, and weather
Consistent concrete bleeding	Concrete Floor Placing and Finishing contractor	Concrete producer	As observed during finishing	Can be, but is rarely measured
Consistent concrete setting characteristics	Concrete Floor Placing and Finishing contractor	Concrete producer	As observed during finishing	Test for concrete setting not yet standardized

Example Performance Requirement	Party setting the performance requirement	Party obligated to achieve the specified performance	Point of Performance	Is Performance Measurable?
Cement with consistent setting behavior	Concrete producer	Cement manufacturer	As evaluated at cement delivery to concrete batch plant	Is typically reported by cement producer, but rarely measured later.
Cementitious materials with consistent setting behavior	Concrete producer	Cementitious materials supplier	As evaluated at delivery to concrete batch plant	Can be, but is rarely measured
Chemical admixtures with consistent setting behavior	Concrete producer	Admixture supplier	As evaluated at delivery to concrete batch plant	Can be, but is rarely measured
Aggregate with consistent grading	Concrete producer	Aggregate producer	As evaluated at aggregate delivery to concrete batch plant	Can be measured, but rarely done during concrete production
Concrete with controlled shrinkage (and related curling)	General Contractor	Concrete producer	Prequalify materials?—as evaluated prior to construction Sample at time of construction to verify	ASTM C157 for samples taken on site, but no reliable in-situ test.
Contribution to shrinkage (and related curling) of the entire range of concrete ingredients from aggregates to admixtures	Concrete producer	Cement, cementitious materials, aggregate and admixture suppliers	Prequalify materials?—as evaluated prior to construction Sample at time of construction to verify	ASTM C157 for samples taken on site, but no reliable in-situ test.
Contribution to shrinkage and related curling from timing of finishing and curing, type and duration of curing, and job site microclimate	General Contractor	Concrete Floor Placing and Finishing contractor	After construction but before service loading	ASTM C157 for samples taken on site, but no reliable in-situ test.

Example Performance Requirement	Party setting the performance requirement	Party obligated to achieve the specified performance	Point of Performance	Is Performance Measurable?
Influence of subgrade preparation specification and compliance, installation of reinforcing or dowels	Owner-specifier	General contractor and parties other than the concrete placing and finishing contractor or the concrete producer.	Fundamental quality is defined prior to concrete placement, but effect on floor performance not evident until after construction.	Compaction tests and inspection of reinforcing & dowels prior to concrete placement
Accuracy of anticipated loads, floor thickness, joint spacing, and detailing, reinforcement	Owner	Designer-specifier	Fundamental quality is defined during design, but effect on floor performance not evident until after construction.	End results can be measured, but can be complicated to attribute effects to specific sources

As shown in this example, the performance required by the owner is a consequence of design, materials and construction performance. Performance specifications can thus be efficient for the owner, quickly zeroing-in on the key operational characteristics of the installed concrete, but they become equally efficient for the concrete producer only when the concrete materials performance aspects that contribute to the owner's required performance have been identified and can be controlled. The contractor must likewise control construction operations to achieve the owner's requirements. Satisfying the owner's performance requirement specification requires that the various parties influencing performance accept their mutual responsibility.

From the owner's overall project perspective, there is no question that the most meaningful point of performance is the hardened concrete, in place, at an age of concrete that is indicative of the service-life capacity and longevity. However, the frequently acceptable state of the practice is to evaluate concrete properties as sampled at either the point of discharge from the concrete truck, sampled at the point of placement or both. From the results of these tests the in-place capacity and durability are projected or assumed on the basis of known or implied relationships. (In many cases the in-place concrete properties can be measured using standard tests developed for that purpose, but such test programs are not necessarily the norm.) Thus one could consider a less comprehensive but more conventional performance specification that targets the performance of concrete as sampled at the time of casting. For example, the concrete strength value that is most meaningful in determining structural capacity is the in-place strength value, as influenced by materials, mixing, consolidation, curing and in-place time-temperature history. However, most frequently this in-place value is inferred on the basis of standard cylinders sampled at the time of placement and cured under laboratory conditions. Thus one could specify the strength of standard lab-cured cylinders as a performance criterion. Similarly, air content in the fresh concrete, (or even air bubble size in the fresh concrete using the air void analyzer) are viable performance criteria. Even if the performance-minded specifier chose to ignore slump as a performance criterion, the concrete contractor might demand that concrete arrive at the site at a particular slump thus re-introducing slump as a performance requirement for the concrete producer.

1.7 Potential Performance, Prequalification and Identity Testing

It is difficult, time consuming and expensive to deal with hardened concrete that has been determined to be unsatisfactory. This reality heavily influences decisions about how to specify and evaluate concrete, and how to control and assure its quality. In contrast, consider a typical industrial example of manufacturing steel bolts for construction purposes. The bolts can be made and tested at the factory and only shipped if found to be satisfactory. Alternatively, the bolts could be sampled and tested upon delivery on-site, and only used if proven to be satisfactory. If the bolts are no good they can be scrapped or shipped back, and replaced with a new batch. Even in the worst case, unsatisfactory bolts in-place can still be removed and replaced without destroying the structure.

Switching from steel bolts to concrete, the quality control environment is far more complex. Concrete's properties are not developed at the time of shipment, and in almost all cases the concrete must be installed long before its properties can be reliably measured (even though it can be sampled before installation). Further, the installation process itself affects the concrete properties. Further still, if the concrete is found to be unsatisfactory it is not a simple matter to replace it with a new batch. For this reason the industry has developed a number of intermediate checks such as review and approval of proposed concrete mixtures, prescriptive specifications for raw materials and mix proportions, and fresh concrete tests of temperature, slump and air content, and accelerated strength tests to limit (but not eliminate) the chances of ending up with an unsatisfactory material in place.

Under a performance specification, owners and specifiers may minimize the chances of ending up with unsatisfactory, hardened concrete in-place by first demanding evidence that the proposed concrete materials, mixture and methods have the potential to meet specification requirements. It may therefore be necessary to "prequalify" the materials and or methods on the basis of historical records of performance or by providing laboratory test data. It makes sense to approve the use of a "known" winning combination of materials and construction technique, especially when a fresh set of tests to demonstrate performance requires more time than normally is available before the concrete is needed on site. However, given the inherent variability in concrete materials, batching and mixing, even if a mixture has been prequalified, it will still be necessary to prove that the concrete actually delivered, placed and finished is in fact the same material that was demonstrated to have been satisfactory during the prequalification process. "Identity Testing" is the term used in BS 8500 to describe such on site testing to validate the identity of the mixture. Identity testing seeks to verify some key characteristic of the concrete that relates to the desired performance and could take the form of typical slump, air and strength tests, water-content, fresh concrete air void analysis, some non-destructive or in-place method. For example, consider a performance requirement for an in-place value of 1000 coulombs for the ASTM C1202 Rapid Chloride Permeability Test and assume that a mix had been prequalified based on pre-construction C 1202 testing. During actual construction the challenge is to perform a suite of tests on concrete sampled at the time of placement that can be used to verify that the concrete as delivered is substantially the same as the concrete that had previously been shown to meet the 1000 coulomb requirement. This could be some combination of water content, fresh unit weight, compressive strength or field calorimetry, for example. There may also be periodic C 1202 tests on samples as delivered, accelerated strength testing and/or of cores extracted from the structure. Further, differences in sampling, numbers of samples or test conditions can make it appropriate to set different acceptance criteria for in-place or jobsite tests compared to controlled laboratory tests used for prequalifying a concrete mixture.

While pre-qualification or pre-certification provides evidence to the owner-specifier that the producer-contractor *can* install a product that meets the performance specifications, it does not prove that such has actually been done. It is likely, therefore, that performance specifications will include requirements for pre-construction demonstrations of suitability that could range from the simple submittal of historical data as evidence of past performance all the way to the casting of demonstrations or sample slabs that could be evaluated by in-place methods. But, it is also likely that additional testing during or after construction would supplement such pre-qualification. This is because of the significant potential for batch-to-batch variation of the concrete due to variations in the raw materials themselves and the fundamental difficulties in precisely controlling water and air.

1.8 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 1.2, 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 1.8 Concrete Properties of Interest

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

The NRMCA-sponsored P2P contractors' joint task group (Sylvester Schmidt, Chair) has developed a list of performance characteristics oriented around various applications. For example, concrete for exterior pavements should place easily, be finishable, have no pockmarks, set in a reasonable time, be freeze-thaw and scaling resistant, have low permeability and low shrinkage. For tilt-up concrete early-age flexural strength is critical along with setting time, consistent color and low shrinkage. Tilt-up finishability was considered important, but not as critical as for a floor. Indoor slabs-on-grade were said to require low to minimum shrinkage, consistent set times, good finishability and good workability (in that order).

1.9 Exposures and Exposure Classes

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 term "remaining serviceable" would require further quantitative definition.) Nevertheless, clearly and unambiguously specifying the service environment that the concrete must endure puts all bidders on an equal footing in regard to the expectations for durability and challenges each prospective supplier-contractor team to jointly figure out ways to economically blend concrete materials technology with construction practice to achieve the required endurance.

Standardized "Exposure Classes" can be developed to serve as descriptions of common environmental exposures. This has been done effectively in the Canadian Standard as discussed in detail in Section 2. It should be noted that ACI 318 addresses many of these issues in various tables, but it is not focused to make it prominent. Thus it is rare when a specification based on ACI 318 deliberately and clearly points out the required exposure. For example, according to ACI 318 Table 4.2.1, the required total air content depends on whether the exposure is severe or moderate. Table 4.2.2 shows required maximum w/cm as a function of whether the concrete will be exposed to deicing chemicals and Table 4.3.1 lists requirements for sulfate resistance as influenced by the sulfate concentration in the soil or water in contact with the concrete. If the concrete producer is to be responsible for making the correct selections from the table, then the specifier has to explicitly define the exposure. Such definition can be made via standardized exposure classes as discussed in detail in Chapter 2.

1.10 Prescription and Performance elements in the ACI 318 Building Code

1.10.1 *Durability Requirements*—The 318 Code contains elements of both prescriptive and performance specifications. Chapter 4 contains tables of durability requirements in terms of maximum w/cm, total air content, limitations on supplementary cementitious materials, limits on chloride content and requirements for cement types, each as a function of exposure. Since the code does not explicitly require that exposures be defined in the drawings and specifications, some would consider it clear that the tables are to be used by the design professional in establishing minimum requirements for the concrete mixture and that these requirements are to be inserted in the project specifications. In some cases, however, project specifications imply that it is the contractor's responsibility to consult the code and to determine the appropriate concrete mixture requirements. This latter approach is unambiguous only when the specifier explicitly defines the expected exposure conditions. The Commentary, section R 4.1, reinforces the interpretation that the durability requirement tables are for the engineer's use by stating that "Chapters 4 and 5 of earlier editions of the code were reformatted in 1989 to emphasize the importance of considering durability requirements before the designer selects f_c' and cover over the reinforcing steel."

While maximum w/cm, minimum air content, limitations on supplementary cementitious materials, limits on chloride content and requirements for cement types are clearly prescriptive in nature, some flexibility for materials selection and proportioning remains in that there are no maximum or minimum limits on the total weight of cement or supplementary cementitious materials nor are there maximum or minimum water contents. The code imposes no requirement on aggregate content except that which derives from the limits on nominal maximum size of coarse aggregate (ACI 318 Chapter 3) and good mixture proportioning practice. Even air content is given as a function of coarse aggregate size (ACI 318 Table 4.2.1), which is an approximate (if indirect) way to account for the need for more air as paste content increases. (The increased surface area of smaller aggregates demands more paste—thus higher air content is required for mixtures with smaller aggregates.)

1.10.1.1 *w/cm limits*—As seen earlier, prescriptive requirements for w/c (water/cement ratio) were incorporated in codes as far back as 1928 and a prescriptive option for w/c based on strength was built-in to every code through 1986. [The modern versions of the code use the term water/cementitious materials ratio (w/cm)]. The prescriptive association between w/c [w/cm] and strength was dropped in 1989, but the more performance-oriented approval of mixtures on the basis of strength test results plotted as a function of w/c (the 3-point curve) remains to the current (2005) edition. Although w/c had been limited by code for freeze-thaw durability since 1947 (6 gal/sack = 0.53), the current more comprehensive Table 4.2.2 "Requirements for Special Exposure Conditions," describes maximum w/cm limits and minimum f'_c values for permeability control, deicer scaling resistance, and corrosion protection. This table first appeared in 1989. Further, Table 4.3.1 "Requirements for Concrete Exposed to Sulfate-Containing Solutions," includes maximum limits on w/cm depending on sulfate exposure.

The concept behind these tables is fundamental to portland cement concrete behavior. The porosity and permeability of hardened cement paste is intimately connected to the volume of mix water, as much of the volume initially occupied by mix water in the fresh paste remains as pore space in the hardened paste. A more porous paste implies a more porous mortar and a more porous mortar implies a more porous concrete. This was conclusively demonstrated in a large number of tests ranging from pioneering work on pastes (Powers et al.) to the classic permeability studies on mortars and concretes conducted by the Bureau of Reclamation in association with dam construction in the western U.S. The conclusion is always the same: for any given mixture permeability decreases as w/c (or w/cm) decreases. But it is not true that permeability is uniquely or absolutely defined by w/c or w/cm across all mixtures when aggregate size and content, total paste content, total water content, paste composition (different types of cementitious materials), age or method of test are allowed to vary.

The high-pressure permeability tests conducted by Ruetters, Vidal and Wing in 1935 (Ruetters et al. 1935) showed that pastes are far more permeable than mortars or concretes at the same w/c and that for concrete at any given w/c, the permeability can vary by a factor of 10 to 100 as other mixture ingredients change. (The scatter was considerably narrowed when the results were recomputed as permeability per lb of cement per ft^3) Nevertheless, these results were based on portland cement as the only binder and therefore do not begin to reflect the differing capacity of various supplementary cementitious materials to affect permeability. Further, if the issue is in-place permeability, the significant influences of consolidation, finishing and curing need to be taken in account as well.

It is clear, then, that the w/cm table values do not define a particular level of *concrete* permeability (although for a pure cement binder, the limiting values may come closer to defining a level of *cement paste* permeability). It may be that these requirements could evolve along the lines of ACI's older default requirements for w/c based on specified strength that were used only when no other strength vs w/c data were available. Prescriptive w/c values could be overridden on the basis of test data, and proposals along these lines are currently before ACI 318 subcommittee A. If a permeability value were specified (or some similar property that relates to transport of fluids and dissolved solids through hardened concrete), a value of w/cm could be determined that would meet that specified requirement for a given set of concrete materials..

Allowing for an increase in the limiting w/cm values when supported by test data can be advantageous to all parties. This is because any given mixture requires a basic water content to achieve the necessary workability (pumpability, compactability and finishabilty) and the requisite total cementitious materials content is determined by dividing water content by w/cm. For any given level of workability and water demand, the lower the w/cm, the higher the total cementitious material content and the greater the paste content. More paste requires more air and as paste content goes up, total aggregate content must go down. Higher paste and lower aggregate generally lead to increased shrinkage and creep, and the combination of high paste content and low w/cm increases the risk of plastic shrinkage cracking for any given rate of evaporation. Increased paste content also increases total heat of hydration with a greater temperature rise and risk of thermal cracking and strength reduction. Controlling these heat effects requires changing the blend of cementitious materials or use of other mixture- and construction-related cooling techniques. Thus, requiring a w/cm that is lower than it needs to be to develop the desired permeability can therefore increase the cracking potential of the concrete if paste content is not limited. Specifying a minimum cement content that is higher than needed to meet strength and/or durability criteria can have the same effect.

As a final comment on w/cm, Table 4.2.2 also requires a minimum f'_c with each maximum value of w/cm, and the relationship between strength and w/c is approximately the relationship shown for air entrained concrete in ACI 211.1 "Standard Practice for Proportioning Concrete Mixtures." As stated in the code commentary, the minimum strength requirements "will ensure the use of a high quality cement paste," and help to guard against mismatched specifications such as "Max. w/cm shall be 0.40, and f'_c *shall be 3000 psi.* The strength requirements are a pragmatic recognition that since w/cm and permeability are not normally evaluated, strength is often the only indicator of concrete quality. Concrete that truly has a w/cm of about 0.40 is likely to have a 28-day compressive strength in excess of 5000 psi. Exceptions are possible, of course, given the wide range of materials available, but the current code has no specific provisions for accommodating such exceptions. If a clearly defined end performance requirement were available and specified in lieu of w/cm, perhaps the strength associated with that characteristic could be determined for a specific mixture.

1.10.1.2 *Freeze-Thaw Durability and scaling resistance*—The prescriptive requirements for w/cm when the concrete is to be exposed to freezing and thawing while in moist condition and for deicer salt scaling have been addressed in the previous section, and the total air content requirements were introduced in section 1.10.1. It is further noted that ACI 318 Table 4.2.1 is entitled TOTAL AIR CONTENT, with no further distinction between so-called entrained and entrapped air. Further, the text in section 4.2.1 describes air content tolerance “as delivered,” which can be interpreted as clarification that the requirements in the table are to be applied at the truck chute and not necessarily at any other point in the construction process. ACI 318 makes no mention of air bubble size in the fresh concrete or air content, air void size or air void distribution and spacing in the hardened concrete.

If total air content is seen as a durability characteristic by itself, then one could consider the 318 Table 4.2.1 values to be performance criteria. If total air content is seen as one of the factors leading to freeze-thaw resistance, with the needed air content varying with paste content and air void size, then table 4.2.1 is prescriptive. Of course if freeze-thaw resistance is the desired end result, then demonstrated performance in a freeze-thaw test would be the most useful measure and it is entirely possible that fully successful performance could be achieved in some mixtures at total air contents significantly lower than those required by Table 4.2.1. (This can be the case with low paste content and a stable system made up predominantly of microscopically small air voids.) On the other hand, when the air voids are predominantly large, it is possible that the total air contents required by the code will not necessarily lead to the desired durability. The code-mandated total air content is therefore only part of the story, and either freeze-thaw tests or air void analyses are needed to increase confidence (but still not guarantee) freeze-thaw durability. This is why use of the Air Void Analyzer (AVA) to test fresh concrete, or ASTM C457 microscopical analysis of hardened concrete are of great interest, especially if specifications move from the prescriptive air content to a more performance-oriented criterion. Note also that since freeze-thaw durability or deicer salt scaling resistance are dependent on both materials and construction procedures (such as finishing and curing), prequalification of a concrete mixture based on freeze-thaw or scaling tests demonstrates only the potential of the material to achieve the required durability (Hover, 1994). It may be necessary to demonstrate this potential; however, for certain combinations of cementitious materials and admixtures as proof of compatibility, especially when the producer wants to prove that durability can be achieved at air contents or spacing factors that are outside the values recommended for conventional mixtures. However, if standard freeze-thaw or scaling tests are being contemplated for prequalification testing, the multi-month duration of these procedures has to be kept in mind.

If in-place freeze-thaw resistance were the objective, there would be little question that the most meaningful point of sampling would be as handled, pumped, squeezed, dropped, pressurized, depressurized, consolidated, finished and cured in-place. While current code provisions can be interpreted to imply testing fresh concrete at the truck chute, sampling at the point-of-placement is increasingly common, yet there are no clearly required values for total air content at the point-of-placement. Some specifiers automatically invoke the Table 4.2.1 air content values at placement, which can be too conservative when the air bubbles remaining after handling and consolidation are predominantly small. This leads to the need to batch the concrete at higher than normal air contents to accommodate the normal losses that occur during handling. This can in turn lead to significant drops in strength. This confusion is avoided if in-place hardened air void system criteria or freeze-thaw testing are specified as performance requirements in lieu of reliance on total air. Related discussions are found in Chapters 2 and 3 of this report.

Table 4.2.3 “Requirements for Concrete Exposed to Deicing Chemicals,” sets limits on the maximum percent of total cementitious materials by weight for flyash, slag, silica fume and other pozzolans. Under a more performance-oriented approach a concrete producer might be permitted to demonstrate that resistance to freeze-thaw damage and deicer scaling can be achieved with a particular combination of cementitious materials, when finished and cured as the contractor intends. With appropriate lead time this might be an opportunity for effective prequalification via actual freeze-thaw or scaling tests.

1.10.1.3 *Corrosion Protection*—The first line of defense against corrosion of embedded metals is to inhibit the penetration of water, oxygen, carbon dioxide and salts from the concrete surface to the level of the embedded metal. Section 7.7 of the 318 Code sets minimum requirements for the depth of cover with the requirement that in a corrosive environment concrete protection shall be “suitably increased, and denseness and nonporosity of the protecting concrete shall be considered.” (ACI 318 Section 7.7.5) This provides for the interesting interplay of a structural design feature (bar cover) and the material property of the concrete. Given that deeper bar cover is often associated with wider crack widths at the concrete surface, overall performance of the completed structure might be improved with the coordination of bar cover and concrete materials properties.

Permeability-related properties of the concrete have already been addressed in regard to w/cm requirements, but it may be reiterated that the use of supplementary cementitious materials such as flyash, slag, silica fume or other pozzolans can be an effective way of decreasing the permeability of the concrete. It is expected that within a given set of materials and proportions, permeability will decrease with w/cm. Across a wide range of material combinations and proportions the value of w/cm that leads to a particular and desired value of permeability is expected to vary. Adjusting the code limit on w/cm on the basis of mixture composition is not currently permitted within the ACI 318 Code provisions.

To reduce the amount of potentially corrosive chloride in concrete the Code sets limits on the “maximum water soluble chloride ion concentration.” As discussed in more detail in Chapter 3 of this report, these limits vary with exposure condition and between reinforced and prestressed concrete, but there are no options for differences in concrete composition, permeability or w/cm.

1.10.1.4 *Sulfate Durability*—In addition to the w/cm limits mentioned earlier, minimum strengths and requirements for allowable types of cementing materials are included in Table 4.3.1. These requirements are based on the nature and severity of the sulfate exposure. Limits on w/cm and associated values of f'_c are intended to limit permeability to reduce the ingress of sulfates and the earlier comments about a mix-specific correlation among w/cm, strength and permeability apply. Given the wide range of cementitious materials available and the wide range of types and concentrations of sulfate exposures, it is difficult to make a one-size-fits-all approach in the code, but it is equally difficult to allow multiple exceptions and adjustments in the absence of performance tests that would demonstrate the sulfate resistance of a given mixture.

1.10.2 *Concrete not exposed to aggressive exposures*—It is important to note that when durability is not a concern the code imposes no prescriptive limits of any kind on w/c, w/cm, air, cement content or percentages of supplementary cementitious materials. Thus the ACI 318 door is open for performance specifications of concrete that will not be exposed to aggressive conditions. With the exception of a Chloride limit of 1%, the Code imposes no prescriptive limits in the absence of freezing and thawing or risk of corrosion or sulfate attack, unless the finished structure is intended to have a low permeability.

1.10.3 *Strength Requirements*—Chapter 5 of the code unfortunately makes concrete strength requirements appear far more complex than they actually are. As is common in any rational quality control system, the code provisions recognize that accepting concrete whose average strength equals the specified strength is unreasonable since about ½ of the concrete accepted would have below-average strength and therefore below-specified strength. Code provisions also recognize that rejection of all concrete with strength results lower than a specified "minimum" is just as unreasonable, as the cost and frustration associated with a zero-tolerance policy would be prohibitive. The code therefore requires that concrete mixtures be selected that demonstrate at least a 99% chance of meeting the two principal strength requirements:

> ACI 318 5.6.3.3 (a) Every arithmetic average of any three consecutive strength tests equals or exceeds f_c';
>
> ACI 5.6.3.3 (b) No individual strength test (average of two cylinders) falls below f_c' by more than 500 psi when f'_c is 5000 psi or less; or by more than $0.10f_c'$ when f_c' is more than 5000 psi.

Working backward from these reasonable requirements, any concrete mixture that meets both of the acceptance criteria 99% of the time will have a readily predictable average strength that will always be higher than the specified strength and here the code imposes a strictly performance-oriented requirement. The amount by which the required average concrete strength must be higher than the specified strength depends on the level of precision of the concrete producer-test lab team. (This level of precision is indicated by the value known as the "Standard Deviation.") The lower the demonstrated variability in cylinder test results, (lower standard deviation) the lower is the required difference between specified and average strength.

These provisions contain no arbitrary "safety factors" and merely express the reality of everyday "normal" variability. Unfortunately, ACI uses the misleading term "overdesign" to refer to the difference between specified and required average strength. Thus a fully rational procedure that incorporates tolerance for occasional low breaks; provides the owner with 99% confidence regardless of producer and is self adjusting across concrete producers with varying levels of sophistication and quality control, is made to look like an arbitrary strength requirement above and beyond that which is really needed.

There is a common and perhaps dangerous misconception that the code requirements for concrete strength "overdesign" are an extra layer of conservatism in addition to other factors of safety applied in structural design. In actuality, the code has an integrated, 3-part approach to establishing structural reliability. First, "Load Factors" take into account the variability of service loads and the likelihood that the structure will experience an overload during its service life. The value of these load factors takes the nature and predictability of various loads and load combinations into account. Second, the code applies a Strength-Reduction Factor that accounts for a difference between computed and actual strength of a member, based on factors such as variable dimensions and rebar placing tolerances, and reflects the nature and consequences of structural failure. Third, the variability in the strength of the concrete itself is accounted for only by the statistical quality control requirements on concrete strength. The load and strength reduction factors are based on the assumption that the concrete strength meets the two strength acceptance requirements 99% of the time. Thus the code provides a comprehensive and interdependent approach to reliability: load factors, strength reduction factors and the statistical quality control requirements for concrete strength. The load and strength reduction factors are not intended to make up for a shortfall in concrete quality and once the structure is designed, concrete that fails to meet the code requirements for strength will reduce the design load carrying capacity. This is why the situation has to be investigated when concrete strength test results drop below currently specified values.

These strength requirements began to take their current format with the introduction of the 1971 Code, but the bottom line is that for most concrete producers and labs, compliance with the code requirements for compressive strength requires that the average concrete strength will be about 10 to 15% greater than the specified strength. The 1928 ACI code required 15% greater than f_c', and this requirement was carried all the way to the 1963 code that immediately preceded the 1971 code, at which time today's slightly more rigorous statistical approach appeared.

A final comment on strength is that a fully performance-based, in-place strength requirement is embedded in ACI 318 Section 5.6.5.4:

> **5.6.5.4**—Concrete in an area represented by core tests shall be considered structurally adequate if the average of three cores is equal to at least 85 percent of f_c' and if no single core is less than 75 percent of f_c'. Additional testing of cores extracted from locations represented by erratic core strength results shall be permitted.

This code provision is an interesting example of an in-place requirement that is different from the requirements for the corresponding standard lab-cured test. In this case in-place strength of 85% f_c' is acceptable compared to approximately 1.10 to 1.15 f_c' for the average of lab-cured test results (recall that the statistical quality control provisions require an average strength that often turns out to be 10 to 15% greater than f_c'). However, some portion of this difference has also been attributed to the differences between cores and cylinders, and to conditioning of cores.

1.11 Changing Role of Testing

A transition to performance specifications literally means a transition to performance testing as well. But, if we can only specify those properties that we can reliably test, our current range of specifiable performance criteria are limited to our current battery of approved, standardized tests. Chapter 3 of this report is dedicated to a discussion of available tests.

From the owner's perspective the most meaningful tests are those that evaluate the concrete properties as influenced by materials, proportions, mixing and transport, placing, consolidating, finishing, curing and concrete temperature, i.e., in-place testing of the hardened concrete. As seen in Chapters 2 and 3, while many proven options are available to evaluate in-place strength, fewer alternatives are ready to go for evaluating durability, although C 457 (microscopical analysis) and C 1202 (rapid chloride) are viable candidates in most cases. In general, we have few means of reliably predicting durability without testing samples extracted from the hardened structure. It is also likely that since laboratory-cured cylinders have been traditionally considered an acceptable basis for evaluating concrete strength, they will continue to play a significant role in performance testing. Where reliable mixture-specific correlations can be demonstrated between various properties of interest and the results of more conventional tests such as density, cylinder strength or beam strength, such common tests might be considered an acceptable surrogate.

Since the fully hardened, in-place properties are the most desirable but also the most difficult to get and are often at least 28 days too late, there is an intense need to evaluate the concrete earlier to get an early warning of problems or to gain early confidence that all will be well. The sooner information is obtained about the early-hardened properties of any given load of concrete, the sooner any adjustments can be made to the materials, proportions or processes for subsequent concrete placements; the sooner remedial measures can be initiated on the concrete already installed or the sooner construction practices can be altered (i.e. longer form or shoring removal times, or extended curing). Early-age or accelerated strength testing is useful in this regard, and becomes absolutely essential as the consequences of later-age discovery of unsatisfactory concrete become more expensive. Likewise, the sooner that durability-related test results such as C 1202 (Rapid Chloride) or C457 (Microscopical analysis) become available, the sooner remedial action such as requiring a sealer on marginal concrete or the sooner mix proportions or admixtures can be changed.

From a logistical perspective tests are needed that can be performed on the fresh concrete at the time of delivery (when we can still accept, reject or adjust the product) that will provide data for predicting the likelihood that required hardened properties will be achieved. But aside from slump, air and unit weight, we have no tests that are fast enough to allow an accept/reject decision on the truck at hand. The challenge of predicting performance from air or unit weight has already been discussed and predicting performance on the basis of slump may be impossible. The water content test and Air Void Analyzer are examples of "Fresh Concrete" tests that have the potential to deliver truly useful information for predicting long-term performance, but this information can at best be used to influence subsequent loads as the concrete evaluated by these tests will already be in the structure by the time the results are available.

As a final comment on tests of fresh concrete, given the influence of subsequent construction operations it remains entirely possible that concrete that is satisfactory at the point of delivery will not yield the desired performance characteristics in place. Alternatively, if concrete is found to be unsatisfactory at the point-of-delivery, it is unlikely that subsequent construction operations will bring substantial improvement. Thus there remains a need for some type of screening tests for the fresh concrete, if only to serve as an early warning for material that may be unsatisfactory. Screening tests could include air or water content, or density (unit weight of fresh concrete) for example. Cylinders are undeniably useful but cannot return immediate data (except for their as-cast weight).

As discussed earlier in this chapter, given the variables that affect concrete performance and the consequences of installing unacceptable concrete, it makes sense to pre-certify concrete production facilities as having the capability of making the kind of concrete that is required, and to pre-qualify specific mixtures and materials based on their demonstrated potential to meet all performance requirements. Under normal circumstances this pre-qualification would only be step one, followed by screening tests at delivery and the program of subsequent tests of hardened concrete. However, given that the ability to meet performance requirements starts with appropriate plant and equipment, concrete-making materials and knowledgeable personnel, it also makes sense to develop certification programs or expand existing ones to be able to identify those operations that are broadly capable of meeting the specifications. Likewise, personnel certification programs should be expanded, especially into the skill areas of mix design with modern materials, effect of construction operations on concrete quality, and use of advanced quality control and quality assurance testing. Furthermore, the certification of plants and personnel not only elevates knowledge level but also establishes pride and credibility. (See also Section 3.8 of this report, "General Considerations in regard to Testing"—for a further discussion of testing and certification)

1.12 Risk and Responsibility

Chapter 2 of this report includes a discussion of the Canadian Standard's clear demarcation of the responsibilities accruing to each party when buying, specifying, installing or producing concrete under CSA A23. (See A23, Table 5.) Under other systems, standards and codes the responsibilities and associated risks may not be so clearly defined. This section therefore presents a more general discussion.

ACI's Committee on Responsibility in Concrete Construction (ACI RCC-05) reports that "Construction has now reached a level of complexity that makes design input from constructors and subcontractors desirable and sometimes essential. This input, whether submitted as value engineering proposals, responses to performance requirements or design alternatives, has a legitimate place in concrete construction." But, in the case of a conversion to performance specifications, taking this "legitimate place" will entail some redistribution of risk and responsibility. RCC goes on to cite the "over-riding principle…that responsibility and authority must be congruent." This suggests that if the concrete producer and contractor are to be held ultimately responsible for concrete performance, then it is reasonable to give them freedom of action to provide a product that meets the demanding performance requirements developed by the design professional. In one sense this means that the producer-contractor will take on additional responsibility in return for the added freedom to select and proportion materials, and to plan means and methods of construction. Viewed another way, on many current projects the concrete producer and contractor are already heavily responsible for concrete behavior, even when following prescriptive specifications. For many producer-contractors, the principle of "congruency of authority and responsibility" under a performance specification might simply mean getting the freedom that comes with the *current* level of responsibility. However, under a prescriptive specification based on sampling at the truck chute, responsibility for end-result concrete problems frequently tends to gravitate toward the concrete producer. Under a clear performance specification with at least some in-place testing of hardened concrete, the contractor's joint responsibility for in-place concrete performance may become more visible.

Under a performance specification design professionals will have a clearer responsibility to articulate exposure conditions and performance characteristics. However, committing to a discrete list of explicitly required concrete performance criteria introduces the risk that an unspecified, long-term performance problem may develop. For example, if the stated performance criteria included strength, shrinkage, permeability and frost resistance, but did not specifically require immunity to ASR, who is responsible if ASR develops sometime later? This is not to suggest, however, that the responsibility for a problem like ASR is necessarily clear under a conventional prescriptive specification that does not include explicitly stated requirements for special ASR-related testing.

Another interesting issue is raised in the RCC document by first stating that "it can be appropriate [for the design professional] to delegate certain aspects of engineering design to specialty engineers working for the constructor or subcontractors. When any of this design work involves engineering (as opposed to simply detailing), it should be done under the control of an engineer who is licensed in the state of the project and who takes responsibility for such work." Many concrete materials engineers would agree that concrete mixture design and proportioning is in fact "engineering." RCC's report also raises the issue of the design professional's responsibility to review mix submittals: "The Design Professional should review the mixture proportions and submittals concerning materials, procedures and testing data, but the Constructor remains responsible for compliance with the requirements of the Contract Documents. If approval is required, the Contract Documents should state so specifically."

At the top of the performance specification pyramid, the owner gains the opportunity for clarity of expected performance, but along with the design professional the owner has to accept the risk associated with a finite list of those quantifiable objectives. Under current specifications there is a tendency to seek relief from the contractor for a wide range of longer-term performance problems, some of which may come from unstated exposures or unspecified service conditions. Pinning these down puts most of the cards on the table. In a related issue, the performance criteria selected have to be indicative of the concrete's ability to meet the owner's functional needs. When the UK Highways Agency studied the risks of adopting performance specifications, one of its concerns as owners of the highway network and as buyers of construction services was "inappropriate application of performance measures resulting in a situation whereby suppliers can meet targets without achieving the desired outcome." A related concern was "Mismatches between contract performance requirements and client objectives." If the performance criteria are overspecified relative to the owner's needs, the product is unduly expensive and if the criteria are underspecified the result can be "poor operational performance, excessive maintenance and premature replacement."

1.13 A Few Comments about the current general state of practice

When considering new or alternative approaches to specifying concrete construction, it can be helpful to be reminded of the current state of practice. The following outline has been developed for that purpose, serving as a background for further thinking about specifications in general.

1. Qualifications:
    a. There is a broad range of expertise and experience in the marketplace.
    b. It can be difficult to qualify contractors or producers on basis of quality record or expertise.
    c. Experience often works against a knowledgeable producer and contractor in a low bid situation, especially when specifications are subject to interpretation.

2. Concrete Mixture Pre-placement Approval (Prequalification) is based on one or more of the following:
    a. Historical records for strength performance.
    b. Lab tests to document strength record.
    c. Use of the ACI 318 "Three-point-curve" to demonstrate strength as a function of w/c (w/cm).
    d. The detailed ACI 318 Chapter 5 statistical method for mix approval based on strength.
    e. Producers do not frequently prequalify on basis of air, freeze-thaw testing, scaling resistance testing, corrosion protection or permeability (or its surrogate tests). (The lead time for these tests can be excessive and there is no guarantee that the pre-placement mixture is same as the mixture actually installed.)

3. We often specify:
    a. Minimum cement or minimum total cementitious contents:
        i. The Code is silent on this.
        ii. The Code does set limits of proportions of SCM's based on % by mass of total cementitious materials for various exposures.
        iii. The Code dictates cement type or pozzolan or slag use for various sulfate exposures.
    b. Max aggregate size:
        i. ACI 318 Chapter 3 matches ACI 211.1
    c. W/c (w/cm):
        i. W/c is either directly incorporated into project specifications for special exposure conditions or included by reference to ACI 318 Chapter 4 for freeze-thaw, deicers, corrosion and sulfate exposures.

    d. Temperature:
        i. ACI 301 has limits for max and min
        ii. ACI 305 recommends mix specific waiver based on tests for max temperature.
        iii. No specific temperature guidance from ACI 318, but there are caveats to avoid harmful effects.
    e. Slump:
        i. ACI 318 gives no guidance on slump.
        ii. ACI 211 has some outdated, pre-admixture recommendations.
        iii. ACI 301 has some outdated recommendations.
    f. Air:
        i. Air content is either directly incorporated into project specifications for special exposure conditions or included by reference to ACI 318 Chapter 4. ACI 318 values are for "total air, as delivered." No ASTM C457 hardened air values are implied. Code values are tied to old ACI 211 assumptions of mortar content based on water-contents as a function of maximum aggregate size, but with no adjustment for admixtures or aggregate grading.
    g. RCPT for corrosion-sensitive structures:
        i. ACI 318 gives no guidance for RCPT values, but the code does specify bar cover and allows adjustments of cover depth based on concrete quality.
    h. Compressive strength:
        i. Test specimens are lab cured.
        ii. Statistical quality control.
        iii. Effectively there is as "option" for in-place testing via cores.

4. We do not often specify:
    a. Air void system parameters (we check them after the fact if we have a problem and then often act as though ASTM C 457 was specified),
    b. Shrinkage (we check after the fact if we have a problem and then often act as though ASTM C 157 was specified),
    c. Actual concrete material transport properties such as actual permeability, sorptivity, or diffusivity,
    d. Curing measures required to achieve a durable surface (CSA A23.1-04 has addressed this issue),
    e. Measures of curing effectiveness.

5. We often measure:
    a. Temperature of fresh concrete,
    b. Slump of fresh concrete,
    c. Air content of fresh concrete,
        i. At truck chute
        ii. Sometimes at point of placement (although there are no standard procedures for doing so and no clear acceptance criteria for air content beyond the point of discharge from the concrete truck)

    d. Strength under lab cured conditions,
    e. Rapid Chloride test when specified,
        i. Specimen commonly cut from a 4-inch cylinder as sampled at truck chute.
        ii. Specimen sometimes cut from core extracted from structure

6. We do not often inspect or measure:
    a. W/c or various quantities of water,
        i. Water content in drum when truck is loaded
        ii. Changes in aggregate moisture content during production
        iii. Water added on site
        iv. Retempering water or water applied to concrete surface or finishing tools
    b. Quality of aggregate (including grading) during production,
    c. Quantity of aggregate during production,
    d. Quality of cementitious materials during production,
    e. Quantity of cementitious materials during production,
    f. Unit weight (density) or yield of fresh concrete,
    g. Air bubble size in fresh concrete (Air Void Analyzer),
    h. In-place strength of concrete (Field cured cylinders are NOT the same as in-place testing),
    i. In-place RCPT of concrete,
    j. In-place temperature of the concrete,
    k. In-place curing effectiveness,
    l. In-place degree of consolidation,
    m. In-place air void system parameters,
    n. In-place air void system parameters at the concrete surface.

7. Tests, variability and precision:
    The values given below are approximate (Half the D2s limits) and simplified. For complete and accurate information on variability and precision refer to the relevant ASTM Standard.
    a. Slump:
        i. time dependency is not normally taken into account.
        ii. precision = ± 0.43 inches
    b. Air:
        i. one air pot = 0.1% volume of 8 CY truck
        ii. precision = ± 0.4%
        iii. One core examined by ASTM C 457 examines about 1,000 of the 1,000,000,000,000 air voids in a 100 CY placement. (At $500 per test we can't afford statistical significance.)
        iv. C 457 precision = ± 1.16%
        v. AVA Spacing factor = ± 25%
    c. Strength:
        i. Reported cylinder strength is also a function of cylinder maker and cylinder breaker.

            1. precision = ± 4%
        ii. Cores are sensitive to moisture conditioning
            1. Precision=±6.5%
    d. ASTM C1202 Rapid Chloride Test:
        i. Precision = ±21%
    e. ASTM C 157 Length Change:
        i. precision = ± 0.0037% cured in water and 0.0069% cured in air
    f. AASHTO Microwave oven test for w/c:
        i. ± 0.03 to 0.05

8. We have reasonably reliable relationships between:
    a. W/c (w/cm) and the strength of a given concrete mixture at a given maturity,
    b. W/c and the permeability of a given hardened, portland cement paste (no SCM's) at a given maturity
    c. Strength of a given hardened portland cement paste and maturity,
    d. Total paste content and shrinkage,
    e. Total water content and shrinkage,

9. We do not have reliable, mix-independent relationships between:
    a. Slump and water content
    b. Slump and w/c or w/cm
    c. Slump and strength
    d. Slump and risk of segregation (in the presence of admixtures)
    e. Slump and pumpability
    f. Slump and finishability
    g. Slump and response to vibrator
    h. Air content (alone) and frost resistance
    i. Air content (alone) and deicer scaling resistance
    j. Strength and durability
    k. Strength and w/c or w/cm
    l. W/c or w/cm and permeability over a broad range of mixtures and binders
    m. Strength as represented by cylinders cured in the laboratory and cores extracted from the structure
    n. Strength indicated by either cylinders or cores and the strength of the concrete surface exposed to weather and traffic.
    o. Permeability or conductivity of concrete at mid-depth of a core or cylinder vs. at the surface

Chapter 2 Review of Current Specifications and Publications Related to Specifications

2.1 Reference Materials

A worldwide search was made for documents relevant to this project. In addition,, the personal libraries of the researchers produced a significant number of references and colleagues of the research team in many countries assisted in the process. Many inquiries to Central and South America, the Middle East and parts of Asia drew no response. It is believed that the references obtained constitute a comprehensive and current overview of the present state-of-the-art of performance specifications. The references consulted are listed in Chapter 5 and are grouped in five separate classifications:

5.1 Current Specifications Incorporating Performance Requirements
5.2 Papers and Articles on Performance Specifications
5.3 Test Methods
5.4 Papers, Guidelines and Articles on Test Methods and on the Application of Test Methods
5.5 Other References

In categories 5.1 and 5.2 the specifications referred to are those incorporating requirements in addition to slump, air content and compressive strength.

2.2 Review of Documents

In reviewing the documents summarized below it becomes clear that the term "Performance Specification" means different things to different people. Overwhelmingly, the term is meant to define the characteristics of a mixture that will result in the hardened concrete in a structure that has the properties that will provide both strength and serviceability, increase durability and hence the planned service life. Where differences in the definition arise they relate to the culture and practice in the different countries. In many countries, performance criteria are established by sophisticated, often long-term, test procedures that are either applied pre-construction or used to satisfy the requirements of exposure classes of concrete the characteristics of which can be specified. In the ultimate form the term applies to contracts where the specified properties are checked during construction. In this case there is again a major difference between the significance of tests made on test specimens cast from the fresh concrete as it is delivered and tests made directly on the concrete in the structure or on specimens removed from the structure. The last example would represent the ultimate "pure" performance specification.

To facilitate the assessment of existing specifications, a table has been inserted after the review of each document. These tables list the properties of the hardened concrete (other than compressive strength) covered by the document and indicate with a check mark (✓) at which stage of a contract (✓) the document proposes that tests defining performance are to be made. Where tests are made prior to the start of a contract it will often be the practice to make confirmatory tests during construction. The tables show this and indicate whether or not the tests are made on concrete in the finished structure. Specification documents are not always clear about when tests are made on concrete mixes proposed for a project. It has been assumed, however, that where a performance property is specified (such as shrinkage for instance) and the mix is the supplier's responsibility the supplier will determine the shrinkage of a mixture prior to offering it for sale.

2.3 Australasia

2.3.1 *Australia*

2.3.1.1 *AS 1379-1997, amended 2000*—"Specification and Supply of Concrete" Two grades of concrete are considered:

Normal Grade: This concrete is specified primarily by compressive strength and is concrete that can be produced by plants throughout Australia. Values are given for chloride and sulphate contents, shrinkage and mass (density) plus a table of minimum 7-day strengths that are all 50% of the 28-day specified strengths. The customer ordering the concrete is to specify slump, maximum size of aggregate, method of placement and air-entrainment if required.

Special Grade: Concrete requiring characteristics additional or different from normal grade concrete and which cannot be assumed to be available at all locations. A table of alternative criteria is provided, most of which are prescriptive. *Special Grade concrete can be ordered as either prescriptive or performance. Where special-class performance concrete is ordered the volume and quality have to be stated. The commentary on the standard notes that, as in any transaction, the concrete supplier has the right to refuse to accept an order as performance concrete rather than prescriptive concrete.*

Quality assessment of concrete can be by either "Production assessment" or "Project assessment". These are defined as follows:

> *"Production assessment—an assessment procedure for concrete specified by strength grade, carried out by the supplier and based on the statistical assessment of standard compressive tests on concrete, specified by compressive strength and produced by a specific supplying plant".*
>
> *"Project assessment—an assessment procedure for concrete specified by strength grade, specified at the customer's option, which provides alternative test data for the statistical assessment of concrete supplied to a specific project strength".*

In practice most concrete is evaluated by the production assessment process. Project assessment is often carried out by a concrete supplier other than the supplier of the performance concrete. (Day, 2005a, Day, 2005b)

The concrete supplier has to determine chloride and sulphate contents and shrinkage of the most frequently supplied mix every 6 months. Production assessment requires statistical control based on a mix designated by the supplier as a controlled grade and that is expected to be the most frequently tested over a 6-month period. Additional cylinders of the controlled grade mix are to be tested at an early age after standard or accelerated curing as an indication of potential strength problems with the mix.

Supplementary Cementing Materials (SCMs) are addressed. The use of fly ash, ground granulated iron blast furnace slag and silica fume is covered by three AS standards. Blended cements contain greater than 5% fly ash or granulated iron blast furnace slag or both and/or up to 10% silica fume.

Table 2.3.1.1

Concrete property	Testing phase relative to construction schedule		
	Before	During	
		On test specimens	In-place
Mass (density)	✓	-	-
Chloride content	✓	-	-
Sulphate content	✓	-	-
7-day strength	✓	-	-
Flexural strength	✓	-	-
Indirect tensile strength	✓	-	-
Drying shrinkage	✓	-	-

2.3.1.2 "Australian Standard AS 3600 "Concrete Structures" provides for durability considerations by the use of exposure classifications as follows:

Exposure Classifications

No.	Surface and exposure environment	Sub classifications	Exposure classifications
1	In contact with ground	4	A1, A2, U
2	In interior environments	2	A1 , B1
3	Above ground	6	A1,A2,B1,B2
4	In water	4	A1, B1,B2,U
5	Other environments	1	U

Detailed requirements for strength, resistance to freezing and thawing, cover, chemical content and curing are specified according to the exposure classification. For exposure U no requirements are given, but an assessment of durability has to be made in each case. One variable in determining exposure classification is geographical location. A map is provided dividing Australia into tropical, arid and temperate zones, and requirements differ according to location. Additional guidance is given for marine structures that are dealt with in a recommended practice reviewed in 2.3.1.3."

2.3.1.2 *Recommended Practice*—Performance Criteria for Concrete in Marine Environments: Concrete Institute of Australia, (2001).

It was concluded that reinforcement corrosion was the prime cause of the deterioration of Australian marine structures. Various models for the prediction of service life were considered.

In developing this recommended practice, specifications of 12 authorities in Australia and specifications in seven other countries were reviewed. A range of prescriptive criteria was noted. Performance criteria considered that would affect concrete suppliers included sorptivity, volume of permeable voids, permeability by the ASTM 1202 procedure and chloride diffusion. The various test procedures are described, including their possible shortcomings, and are then rated for use as design tools, for pre-qualification or for quality control as "Acceptable, Poor or Unacceptable" as shown in the following Table:

Table 2.3.1.2 (a)

Suitability	Strength	Sorptivity	Water absorption	ASTM C1202	Chloride Diffusion	Permeable Voids
As design tool						
Link to design life	3	3	3	3	2	3
Confidence in extrapolation to design life	3	3	3	3	3	3
Overall	3	3	3	3	3	3
For prequalification						
Duration of test	1	1	1	1	2	1
Rational approach to satisfying criterion	1	2	2	2	2	2
Overall	1	2	2	2	2	2
For quality control						
Repeatability	1	3	2	2	2	3
Duration of test	1	1	1	1	3	1
Overall	1	3	2	2	3	3

The numerical performance numbers are defined as follows:

1 Acceptable
2 Poor (not fully acceptable but adequate for the circumstances)
3 Not acceptable (providing deficient result analysis)

The choice of the word "poor" for a 2 rating conflicts with the explanation in brackets. If one takes tests with rankings of 1 and 2, then all six tests are deemed useful for prequalification testing and strength, water absorption and ASTM C 1202 are deemed useful for quality control tests during construction.

Details were given of current development and research on alternative means of assessing performance. These include a modified ASTM C 1202 test, ion migration, long-term steel corrosion data, electrical impedance of concrete and a cyclic chloride penetration test.

Table 2.3.1.2 (b)

Concrete property	Testing phase relative to construction schedule		
	Before	During	
		On test specimens	In-place
Sorptivity	✓		
Permeable voids	✓		
ASTM C 1202	✓		
Chloride diffusion	✓		
Modified ASTM C 1202	✓		
Ion migration	✓		
Long term steel corrosion data	✓		
Electrical impedance	✓		
Cyclic chloride penetration test	✓		

Sorptivity test limits only apply to concrete containing blended cements.

The problem of the short time usually available for pre-qualification tests between bidding and the start of construction and the time it takes to make some performance tests is noted, a factor that will face concrete suppliers in future contracts using performance specifications.

Exposure Classes are discussed for structures exposed to marine conditions.

Table 2.3.1.2 (c)

Authority	Design life: years	Exposure Class
AS 1600 Concrete Structures	40-60	Normal B2
		Normal C
		Special B2
		Special C
AUSTROADS Bridge Design Code	100	Special B2
		Special C
Roads and Traffic Authority, New South Wales	100	Special B2*
		Special C+

* Permanently Submerged
\+ Tidal and splash zone

Varying prescriptive criteria are specified or suggested for each exposure class, including minimum strength, binder type, minimum binder content, maximum water-binder ratio, curing, cover and sorptivity penetration. "Cement" refers to portland or blended cement or a mixture of either with fly ash, slag or silica fume. The ratio of water to "cement" is designated as water-binder ratio.

2.3.1.3 *Ho and Chirgwin, (1996) "A performance specification for durable concrete"*—The use of the sorptivity test and the factors affecting test results are discussed. Data for a range of trial mixtures containing SCMs are given. The sorptivity test, in use by the New South Wales Roads and Traffic Authority since 1990 (RTA), is specified as a performance test for the finished work. Contract specifications require contractors to propose a concrete mixture that will meet strength and sorptivity criteria. Tests are made before the mixture is adopted to confirm that it meets the sorptivity limits specified. Sorptivity limits have been established for four exposure environments: these are the limits the contractor has to meet.

Table 2.3.1.3

Concrete property	Testing phase relative to construction schedule		
	Before	During	
		On test specimens	In-place
Sorptivity	✓		✓

Criteria for prequalification and in-place tests are the same.

2.3.2 *New Zealand*

2.3.2.1 *CCANZ 2000 "Specifying Concrete for Performance"*—The document does not preclude the use of prescriptive criteria in a specification. The document offers guidance to specification writers but the New Zealand authors considered it premature to write a performance specification at that time (2000). Some tests are cited that will be reviewed later. The document makes it clear that not all performance criteria are wholly or partially the responsibility of the concrete supplier: for instance cover to reinforcement. Similarly in a slab on grade, particularly where floor flatness limits are stated, the supplier will have to produce an abrasion resistant floor with the appropriate finishing characteristics, but the flooring contractor has a major impact on the finished quality. The responsibilities of the parties will need to be clear in a performance specification. Mix criteria are given to reduce shrinkage. The criteria listed are mostly the responsibility of the concrete supplier but the owner may have to check the shrinkage characteristics of the concrete as supplied. How, and how soon is soon, is not stated. For concrete placements where heat generated by hydration may be a concern, the specifier can mandate maximum temperature, maximum temperature rise and maximum gradients within the placement and between the concrete and ambient. The supplier will need to formulate the lowest heat mixture that meets strength and placing requirements, but the contractor will have a role in deciding placement size, form insulation, time of form removal and in protecting the concrete from possible adverse temperature effects and monitoring temperatures to confirm compliance. Two papers referred to in the text are reviewed later (Bamforth, 2000 and Figg, 2001). That the consequences of failure to meet performance criteria and a procedure for dealing with them needs to be dealt with in the specification is discussed (for an example of a procedure to deal with failures refer to the Ontario Ministry of Transportation system of referee testing for air void systems. See 2.8.2.6.) The document assumes that suppliers use statistical data as part of their QC. Specifying maximum coarse aggregate size is prescriptive. In a placement with dense reinforcement and equally in a mass pour the maximum size of coarse aggregate is a significant issue. Will the supplier always check such requirements with the contractor? Similarly, if a higher than normally specified strength or a lower diffusion coefficient is specified will the supplier be prepared with suitable proven mixtures?

Supplementary Cementing Materials are considered. Fly ash and slag and/or silica fume or metakaolin are recommended for mass concrete, the latter two materials to reduce calcium hydroxide formation. Blended cements containing slag, fly ash or silica fume are recommended for the tidal and splash zones of marine structures.

Table 2.3.2.1

Concrete property	Testing phase relative to construction schedule		
	Before	During	
		On test specimens	In-place
Floor flatness			✓
Shrinkage	✓		
Thermal contraction	P		
Crazing	P		
Plastic shrinkage	✓	✓	
AAR	P		
Abrasion resistance	P		✓
Chemical resistance	P		
Chloride attack	P		
Maturity			✓
Cover			✓

Notes: P: Prescriptive solution

Specific requirements for determining durability properties are given in New Zealand Specifications as follow.

2.3.2.2 *Changes to New Zealand Standards-Specifying Concrete for Performance, Seminar, 2004*—The seminar was run to deal with changes to two standards, NZS 3104 "Specification for Concrete Production", and NZS 3109, "Concrete Construction" and proposed changes to a third, NZS 3101 "Concrete Structures Standard" In the introduction to the seminar it was noted that a concrete industry forum had been held in 2000. At this forum the need for performance based specifications was highlighted. It was concluded that the technology involved is unwieldy, still evolving and that such a document would quickly become out of date. Instead, the TR 10 document CCANZ 2000 "Specifying Concrete for Performance" (reviewed above) was prepared to describe present capabilities and limitations and to offer useful references for performance specification authors. A copy was included in the seminar notes.

Clause 2.10.2.1 of NZS 3104 states:

> *"For all special concrete mixes* (as defined in the standard) *the Purchaser or designer shall specify the properties required, together with specified testing and compliance tolerances. The concrete producer shall assume responsibility for the mix designs to meet the specified requirements. Any grounds for non compliance are to be stated by the producer".*

2.3.2.3 *DZ 3101 "Concrete Structures Standard"*—The seminar notes reviewed changes in the NZS 3101 chapter on Design for Durability. The added sections cover protection against aggressive soil and groundwater, and provide protection for reinforcing and metal inserts (hardware) in cast in place (CIP) concrete, solutions for service lives of 50 and 100 years, the use of SCMs, guidelines for the use of life prediction models and supplementary durability enhancement measures. Other revised sections deal with cracks, abrasion of floors due to traffic and other types of structures due to erosion.

Table 2.3.2.3(a)

Concrete property	Testing phase relative to construction		
	Before	During	
		On test specimens	In-place
Chemical attack	P		
Cover			✓
Chloride ingress	P		
CIP hardware	P		
Abrasion			✓
AAR		✓	
Carbonation			
Freeze-thaw resistance		✓	
Chloride content		✓	
Sulphate content		✓	

Table 2.3.2.3 (b) Exposure Classes

Exposure Classes	Relate to	No. of sub classes
A1	Relatively benign environment	2
A2	Relatively benign environment	2
B1	Moderately aggressive environment	3
B2	Aggressive environment	5
C	Aggressive chloride environment	No Subclasses
XA	Chemical attack, primarily acid	3
U	Requires special design consideration	2
AR	Abrasion	4

Guidance to meet these durability classes for a service life of 50 or 100 years is tabulated. They include minimum strength, maximum water-binder ratio, minimum cover, minimum binder content, curing and air entrainment.

Supplementary cementing materials are addressed. For exposure classes XA it is stated that combinations of cement and supplementary cementitious materials provide significantly increased resistance to chemical attack. For class C exposures SCMs are mandatory.

The Seminar notes also include a new guideline on Alkali Silica Reaction and changes to NZS 3104 and NZS 3109.

2.3.2.4 *NZS 3104 Concrete Production*—The two main classes of structural concrete are Normal concrete (N) and Special concrete (S). S is for concrete outside the strength range of 17.5-50 MPa with performance requirements that are not necessarily measured by strength. The onus is placed on the structural designer to not only specify the special properties required of the concrete but also to state by which test procedures or other means compliance can be demonstrated. Chapter 5 of *NZS 3104* is a good primer on all considerations in producing and using Performance Specifications. Chapter 6 provides examples of how to deal with issues in performance specifications.

2.3.2.5 *CCANZ Publication TR 3 "Alkali-Silica Reaction"*—Guidance is provided for "Low, Standard and Extraordinary" levels of precaution against ASR.

Table 2.3.2.5

Concrete property	Testing phase relative to construction schedule		
	Before	During	
		On test specimens	In-place
Maximum Alkali content by mass of concrete	✓	✓	

2.3.2.6 *NZS 3109 Concrete Construction as amended in 2003*—The seminar notes provide a checklist for the use of the amended standard.

2.4 Asia

2.4.1.*China*—The Chinese Code Committee is reviewing the Norwegian Annex to EN 206-1.

2.4.1.1 *Three Gorges Project: China Yangtze Three Gorges Project Development Corporation (CTGPC)*—For the Three Gorges Dam the following criteria were specified:

Table 2.4.1.1

Location	Compressive Strength	Max w/c ratio	Max agg size mm	Freeze-Thaw resistance	Permeability	Tensile value 10^{-4}	Max fly ash content %	Total alkali content (kg/m^3)
Internal	$C15_{R90}$	0.60	150	D_{100}	S_8	0.70-0.75	40-45	2.5
Foundation	$C20_{R90}$	0.55	150	D_{150}	S_{10}	0.80-0.85	35	2.5
External	$C20_{R90}$	0.50	150	D_{250}	S_{10}	0.80- 0.85	30	2.5

No details were available in the document available to the authors as to the interpretation of the subscripts in this table.

2.4.2 *Malaysia*

2.4.2.1 *Twin Towers, Kuala Lumpur City Centre*—The contract was originally governed by a prescriptive specification. Mix designs were the responsibility of the concrete supplier. For compressive strengths of 50 MPa or greater the concrete supplier had to provide modulus, creep and shrinkage data.

Table 2.4.2.1

Concrete Property	Testing relative to construction phase		
	Before	During	
		On test specimens	In-place

Modulus of elasticity	✓		
Creep	✓		
Shrinkage	✓		

The concrete supplier found most of the limits to be inappropriate for mixes required to be pumped up to heights of 1150 feet. For the 80 MPa (11,600 psi) concrete the water-cement limitations were too restrictive as were the specified aggregate gradings. Extensive trials and the use of fly ash and silica fume produced mixes that were controlled and tested by the concrete supplier. An example of a contract where the concrete quality was governed by the "Production assessment" approach allowed by Australian specifications. For the 80 MPa (11,600 psi) concrete an average strength of just under 100 MPa (14,500 psi) and a standard deviation of 3 MPa was achieved (Day, K., 2005a, 2005b, Day, J., 2005c).

2.5 Africa

2.5.1 *South Africa*

2.5.1.1 *Alexander and Stanish, "Durability design and specification of reinforced concrete structures using a multi-factor approach*—This currently unpublished paper is primarily concerned with durability indices. It provides a seven-step progression to performance specifications:

1. “Define exposure classes related to the mechanism(s) of deterioration.
2. Derive a quantitative design methodology, including definition of end of design life.
3. Develop test methods that relate to the input parameters of the design method.
4. Produce provisional conformity criteria and calibrate against traditional solutions.
5. Establish limitations of test applicability.
6. Ensure production control and acceptance testing.
7. Conduct full scale trials and long-term monitoring to confirm conformity requirements.”

Exposure classes for carbonation and corrosion induced by chlorides in seawater have been drafted in terms of the European standard EN 206. Durability indices have been developed to characterize cover concrete based on transport characteristics for chlorides, water and oxygen. The tests proposed are chloride conductivity, oxygen permeability and sorptivity. Service life modelling is considered the best approach to defining the qualities required of cover concrete but is considered too sophisticated for most specifiers. A "Deemed to satisfy" approach is recommended and values applicable to South African exposure conditions and for a range of mix formulations are suggested. The degree to which compliance can be measured still to be determined.

Table 2.5.1.1 (a)

Concrete Property	Testing phase relative to construction		
	Before	During	
		On test specimens	In-place

Chloride conductivity	✓	✓	
Oxygen permeability	✓	✓	
Sorptivity	✓	✓	

Table 2.5.1.1 (b) Exposure Classes

Exposure Classes	Relate to	No. of sub-classes
XS0	Exposed to airborne salt	2
XS1	Permanently submerged	2
XS2	Permanently submerged on one side	2
XS3	Tidal splash and spray zones	2
XC	Chloride induced corrosion	3

Supplementary cementing materials are discussed. Chloride conductivity values are given for mixes containing 30% fly ash, 50% ggbfs, 50% ground granulated “Corex” slag and 10% silica fume.

2.5.1.2 *Alexander et al, Towards Specifying Concrete Durability with Confidence: Principles and Progress*—Based on the work by Alexander and Stanish described above contracts are being let based on specifications incorporating the Durability Index (DI) approach. While further work is necessary to improve the reliability of the Water Sorptivity and Chloride Conductivity tests, it is expected that this work including round robin tests will be complete by the end of 2005. In the meantime experience is being gained in this approach and the use of these tests.

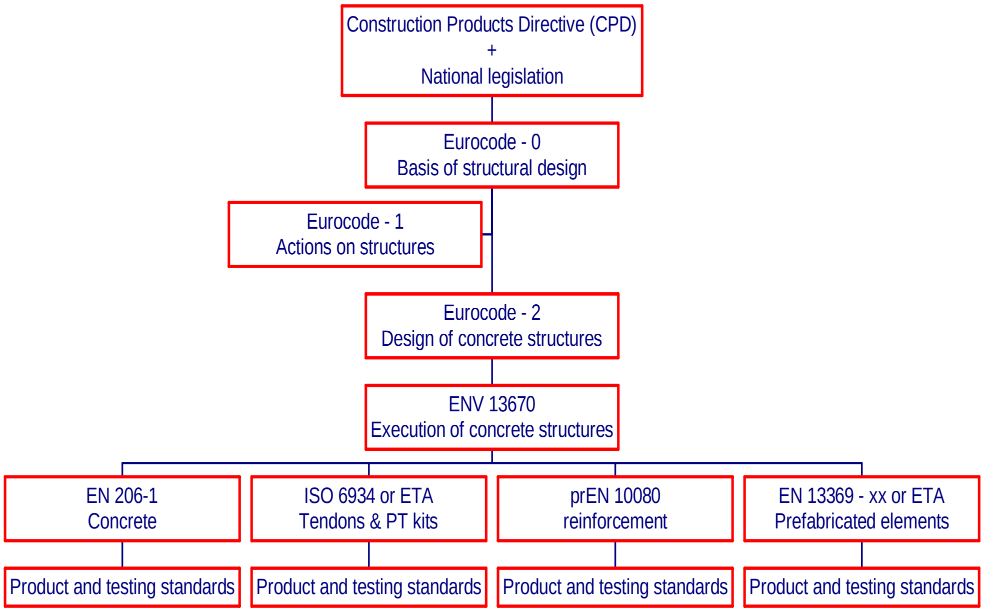
Table 2.5.1.2

Concrete property	Testing phase relative to construction		
	Before	During	
		On test specimens	In-place
Oxygen permeability	✓		
Water sorptivity	✓		
Chloride conductivity	✓		

2.6 Europe

2.6.1 *European Committee for Standardization*—The European structure for construction standards is shown in the following diagram.

Present (or near future) situation



The standard that is relevant to this project is EN 206-1. In theory this standard should apply to all European Economic Community (EEC) members. However, each nation is free to produce an annex to this standard to take into account issues that are specific to that nation's practice. An example of this is the Norwegian National Annex to NS-EN 206-1. This is dated December 28, 2004. There are 28 countries involved in the adoption of this standard (see Appendix B). All but Spain have adopted EN 206-1 or produced a national annex. To date only the United Kingdom (BS 8500), Ireland (IS 206-1) and Germany DIN (1045-2) have an official published annex in English but access has also been obtained to unofficial English versions of the Norwegian and Italian annexes.

Feeding into the committee producing the EEC standards is an EEC funded group called Duranet. This group publishes an annual newsletter and has run workshops in Berlin in 1999, in Tromso in 2001, and in Copenhagen in 2002. A list of the technical presentations that provides technical data to the group is available. The presentations can be downloaded from the internet at www.duranetwork.com .The European approach is both more philosophical and more technical than that adopted to date by North American standards committees. The result in the European documents is a complex list of exposure conditions and many permutations of concrete mixtures. The intent is to produce concrete designed for specific service lives under specific exposure conditions.

2.6.1.1 *EN 206*—In the introduction the following statement is relevant to performance specifications:

> *"During the development of this European Standard, consideration was given to detailing a performance-related approach to the specification of durability. For this review, a review of performance related design and test methods has been*

undertaken. However, CEN/TC 104 concluded that these methods are not yet sufficiently developed for them to be detailed in this standard, but CEN/TC 104 recognised that some CEN Members have developed confidence in local tests and criteria. Therefore this standard permits the continuation and development of such practices valid in the place of use of the concrete as an alternative to the prescriptive approach. CEN/TC 104 will continue to develop performance-related methods for assessing durability at the European level".

Exposure Classes are discussed. In clause 5.3.2, the standard contains a large number of exposure classes of concrete according to exposure to carbonation corrosion, chlorides other than in sea water and chlorides in sea water, freeze-thaw attack, with or without de-icing agents and chemical attack. The assumed service life is 50 years.

Table 2.6.1.1

Exposure Class	Relates to	No. of sub-classes
X0	No risk of corrosion or attack	No sub-classes
XC	Carbonation induced corrosion	4
XD	Chlorides not from sea water	3
XS	Chlorides from sea water	3
XF	Freeze-thaw with or without de-icing agents	4
XA	Chemical attack	3

For performance-related design methods *"the requirements related to exposure classes may be established using performance-related design methods for durability and may be specified in terms of performance-related parameters, e.g. scaling of concrete in freeze-thaw test. Guidance on the use of an alternative performance-related design method with respect to durability is given in Annex J (informative). The application of an alternative method depends on the provisions valid in the place of use of the concrete"*

Table F.1 of EN 206-1 gives prescriptive recommendations for the limiting composition of concrete mixes to meet the various exposure classes given earlier in clause 5.3.2. Included are minimum cement content, maximum water-cement ratio, minimum strength and air content.

Supplementary cementing materials are discussed. Only fly ash and silica fume are included in this standard. Ground granulated blast-furnace slag is most commonly found as a component of blended cements, rather than as an SCM. A notable exception to this would be the UK.

Test Procedures are addressed. Test procedures listed or implied in this standard are included in Table 11 of Part III of this report.

Annex J of EN 206-1 "Performance-related design methods with respect to durability" is a good summary of the European philosophy. The Annex provides guidance for the many parameters to be considered in the design and application of performance based mixtures. It allows the use local knowledge and practice and test methods that have been established as reliable in the particular jurisdiction. This is an important issue with regard to the adoption of more performance-oriented specifications in North America. For example, a state or other specifying entity may use a test method that has been demonstrated to be effective in that particular jurisdiction even though the test method is not universally approved. In such a case the specifier can make use of such a test to implement a more performance-based specification. A decision making process in how to arrive at a performance specification is not covered in this Annex.

2.6.1.2 *Duracrete Final Technical Report: Probabilistic Performance based Durability Design of Concrete Structures, May 2000*—The program covered by this report was a Brite EuRam (EEC Research Program) project carried out by representatives of six countries and is a summary of the work of 8 task groups. The findings of this project were a resource to the committees drafting EN 206-1 and annexes. The background, basis and concept of durability design were reviewed.

The following deterioration processes were studied: Carbonation, chloride penetration, corrosion induced by chlorides and carbonation, cracking and spalling, and freeze-thaw attack (with and without salt). The relevant test procedures available were evaluated as follows:

- Carbonation
  - Natural carbonation
  - Accelerated carbonation
  - CEMBUREAU method
  - TORRENT method
- Chloride penetration
  - Rapid chloride migration method
  - Chloride profiling method
- Reinforcement corrosion
  - Two-electrode method
  - WENNER probe
  - Multi-Ring-Electrode
- Freeze-Thaw damage
  - Capillary suction of water
  - Capillary suction of de-icing solutions

Details were given, as an example, of the rapid chloride migration test. The document established three levels of project quality control. Levels 1 and 2 involve standard tests and QA procedures. Level 3, which is the highest level, would include in-situ tests.

2.6.2 *France*

2.6.2.1 *Baroghel-Bouny (2004): "Durability Indicators: A Basic Tool for Performance Based Evaluation and Prediction of RC Durability*—A common approach in many of the papers reviewed for this project is the use of the term Durability Indicators (DI). A DI is defined as a key material property that has a clear physical meaning. This study covers the following material properties: porosity (accessible to water), diffusion coefficient (chloride intrusion), permeability (to gas and to liquid water) and calcium hydroxide content (how this latter index is interpreted is not clear to the authors.) Based on these test procedures, five classes of potential durability were established, from very low to very high. Examples are given for guidance. It is stated that for new structures the classes developed provide guidance for durability design prior to construction.

Table 2.6.2.1

Property	Testing phase relative to construction		
	Before	During	
		On test specimens	In-place
Permeability	✓		
Chloride diffusion coefficient	✓		
Calcium hydroxide content	✓		

Note: The practicality of these tests from the point of view of time to complete, cost and sophistication raises significant issues. This paper provides assistance in pre-determining the quality of concrete needed to meet three types of exposure. None of the procedures are suitable for Quality Assurance. A concrete supplier would have to prove the compliance of his or her mixture if these performance properties are specified.

Data on Supplementary Cementing Materials are given in this and the following paper for mixtures containing supplementary cementing materials.

2.6.2.2 *Bouny: "Which toolkit for durability evaluation as regards chloride ingress into concrete? Part II: Development of a performance approach based on durability indicators and monitoring parameters*—The chloride diffusion coefficient is a DI that can be used in predictive models. In this study three types of chloride penetration test were evaluated.

2.6.3 *United Kingdom*

2.6.3.1*"Developments in Durability Design & Performance-Based Specification of Concrete", Concrete Society* —This report reviews developments in analytical methods for the durability design of concrete structures. Testing for durability and specifications for durability performance are discussed. Selection of appropriate concrete mixtures is based on exposure classes related to specific deterioration mechanisms as follows:

Table 2.6.3.1

Exposure Class	Relates to	No. of sub-classes
X0	No risk of corrosion or attack	No sub-classes
XC	Carbonation induced corrosion	4
XD	Chlorides not from sea water	2
XS	Chlorides from sea water	3
XF	Freeze-thaw with or without de-icing agents	4
XA	Chemical attack`	3

The above table would appear to be the origin of the exposure class concept used in the Eurocode standard EN 206.

A wide range of tests is reviewed, including a summary of the time taken to carry out the tests. Most of the tests listed are expensive and take significant time to complete.

2.6.3.2 *Bamforth, 2002, "Concrete Durability by Design: Limitations of the current prescriptive approach and alternative methods of durability design"*—The paper develops deterministic methods of predicting time to corrosion due to chloride penetration or carbonation or a combination of both.

2.6.3.3 *Hall, 2003 "BS EN 206-1. The European concrete standard-another challenge?*—The article draws attention to the fact that the introduction of EN 206-1 results in many new and different (from past UK practice) technical requirements. Highlighted are the needs to provide all relevant information to the supplier and for the supplier to give notice to the purchaser of any non-conformity not obvious to the purchaser.

2.6.3.4 *Harrison, 2003 "BS EN 206-1/BS 8500 basics: conformity and identity testing"*—BS 8500 Concrete-Complimentary Standard to BS EN 206-1 has two parts: Part1: Methods of specifying concrete and provides guidance to the specifier and Part 2: Specification requirements for constituent materials and the concrete.

This article provides guidance on conformity (producers' compliance) and identity testing (clients' testing). The definitions are as follows:

Conformity testing: Tests and procedures undertaken by the producer to verify the claims made on the delivery ticket.

Identity testing: Acceptance testing in all but name. It "identifies" whether a particular batch or batches of concrete come from a conforming population.

Both are based on statistical criteria. Producers can base their evaluations on "families of mixes", i.e. a group of related concretes for which a reliable relationship between relevant properties has been established and documented. Criteria are given for confirming that a mix truly belongs to a particular family. Accredited conformity certificates can be provided by the British Standards Institute (BSI) or by the Quality Scheme for Ready Mixed Concrete (QSRMC). These agencies will confirm that the supplier has achieved conformity and has correctly reported cases of non-conformity.

It is suggested that where concrete conformity is certified by a third party agency, identity testing should not be necessary. Spot checks by the purchaser and testing of doubtful batches are, however, suggested. Independent testing is suggested for producers not holding third-party accreditation.

2.6.3.5 *Rhodes, 2003 "Implications of the new concrete standards-a ready mixed concrete producers view"*—The standards contain new requirements for the producer on conformity. The specifier is the person or body responsible for compiling the technical requirements in the form of a specification to be passed on to the concrete producer. For the ready mix producer the specifier is the purchaser. The gist of the article is a warning of the complexity of the new specifications and the need to be really familiar with them.

2.6.3.6 *Concrete, January 2003, BS EN 206-1: The future of ready-mixed concrete*—A brief article noting the advent of the new standards. It notes that BS 8500 offers no less than five approaches to specifying concrete:

Designated concrete
Designer concrete
Prescribed concrete
Standardised prescribed concrete
Proprietary concrete

Six exposure classes of concrete are covered in the standard

XO No risk of corrosion or attack
XC Corrosion induced by carbonation
XD Corrosion caused by chlorides other than seawater

XF Corrosion caused by chlorides in seawater
XA Chemical attack

2.6.3.7 *Harrison, 2003 The new concrete standards−getting started*—This might be called Eurostandards for Dummies. The reader is led step by step through the process of determining the recommended concrete quality and specifying it to the producer. Which documents are needed by a specifier is listed followed by a glossary of terms entitled "Jargon busting". Many of the European terms are foreign to North Americans, so this glossary is a necessary journey through their standards. Initial selection of a mixture is based on cover to reinforcement and characteristic strength. One complication with the European standards is that they provide for the use of cubes or cylinders in determining compressive strength and provision has to be made for the use of either. The next steps are determining the intended working life and identifying the relevant exposure conditions and hence the appropriate exposure class. All other physical and constructability properties are then reviewed for inclusion. An example of mix selection is given. To assist in preparing the specification and providing the necessary information a set of forms are presented. The section on conformity details the supplier's responsibilities. BS EN test standards lists the test standards published by BSI and provides a table showing European equivalents to current BSI tests.

2.6.3.8 *Chamberlain, "The new European Standards on testing concrete-a specifier's view"*—The article is mainly concerned with the effects of changing to European standards and whether the UK standards are harmonized with the European ones. The significance concerns inclusion as a CE-designated product by the European wide Contracts Products Directorate. These issues are of little interest to North Americans.

2.6.3.9 *BS 8500 Concrete- Complimentary Standard to BS EN 206-1*−This document consists of two parts: Part 1: Method of specifying and guidance for the specifier and Part 2: Specification for constituent materials and concrete. Exposure classes follow closely those of EN 206-1, but there are many sub classes for concrete’s resistance to chemical attack.

Table 2.6.3.9 (a)

Exposure Class	Relates to	No. of sub-classes
X0	No risk of corrosion or attack	No sub-classes
XC	Carbonation induced corrosion	4
XD	Chlorides not from sea water	3
XS	Chlorides from sea water	3
XF	Freeze-thaw with or without de--icing salts	4
XA	Chemical attack	19*, 14+

*Classes related to ground contamination, + Classes related to chemical attack.

Fly ash, slag and silica fume are specified in blended cements and in combinations of cement and SCMs. The design of concrete mixtures using this standard is complex and in some cases the use of a specialized computer program is recommended (Harrison, 2003). A reader wishing to understand the following table is advised to refer to the full text of BS 8500.

Table 2.6.3.9 (b)
Five approaches to the specification of concrete per BS 8500

a) ***Designated concretes*—**Where concrete is intended for the uses given in Table A.6 or Table A.7, the appropriate designated concrete is identified. The adequacy of the associated strength class is checked using Table A.8 and the specification is then drafted in accordance with **4.2**. Guidance on the selection of designated concrete is given in **A.4**. The alpha-numeric references used to identify designated concretes are only applicable where third-party certification is selected as the option in specifying the concrete. Where the option selected is not to use a certified concrete, the method of designation/specification given in b), c) or d) below is used. It is stressed that the reference to third-party certification does not make such a method of specification obligatory: it has been included with the support of industry bodies wishing to maintain the progress which has been achieved in quality levels as a result of such certification.
b) ***Designed concretes*—**This approach offers more flexibility to the specifier than designated concretes, which do not cover every application and every constituent material. The environments to which the concrete is to be exposed are identified from **A.2**. Using the intended working life and the minimum cover to reinforcement, the limiting values of composition are determined for each of the identified exposure classes using the guidance in **A.5**. The requirements for the concrete are selected from this composite of limiting values plus structural and fire considerations, and the specification is then drafted in accordance with **4.3**.
c) ***Prescribed concretes*—**This approach allows the specifier to prescribe the exact composition and constituents of the concrete. It is not permitted to include requirements on concrete strength, and so this option has only limited applicability. The specification is drafted in accordance with **4.4**.
d) ***Standardized prescribed concretes***—These were previously known as standard mixes in BS 5328. This approach is appropriate where concrete is site-batched on a small site or obtained from a ready mixed concrete producer who does not have accredited third-party certification. The appropriate standardized prescribed concrete is identified from Table A.7 and the specification drafted in accordance with **4.5**. Indicative strengths for standardized prescribed concretes are given in Table A.9. Standardized prescribed concrete may be used as an alternative to the GEN series of designated concretes.
e) ***Proprietary concretes***—This approach is appropriate where it is required that the concrete achieves a performance, using defined test methods, outside the normal performance requirements for concrete, e.g. where self-compaction is required. The proprietary concrete is selected in consultation with the concrete producer and the project specification is then drafted in accordance with **4.6**.

NOTE 1 to Table 2.6.3.9 (b): This method of specification is not suitable for initial use in public procurement contracts as the specification, in effect, determines [limits the choice of] the concrete producer. BSI has not substantiated any claimed performance made for proprietary concrete by any producer.

Effectively, these five classifications can be explained in a rearranged order as follows:

Designed concretes

Concretes derived from exposure classifications and defined by limiting criteria such as cement type and content, maximum water-cementitious ratio and sulfate and chloride conditions. 3rd party certification is not required.

Designated concretes

Basically the same as **Designed concrete** *except that 3rd party certification is required. Simpler to specify than* **Designed concrete***. Generally limited to buildings rather than civil construction.*

Prescribed concretes

Completely prescription. Generally used on low technology sites or for establishing specialty mixes such as an architectural finish established by trials and the ingredients and proportions then specifically stated.

Standardized prescribed mixes

Low quality applications with basic control and high cement contents, generally housing and small buildings. Low potential consequences of low strength.

Proprietary concretes

Based on performance specifications and developed by the concrete supplier for special requirements such as self-compacting concrete, or concretes to meet very stringent criteria for abrasion or impermeability. This category would be designated by our standards as a Performance Specification.

2.6.3.10 *UK Highway Agency, Nationwide Projects: Developing Performance Specifications*—This Agency is developing performance specifications and in April 2003 published the following format for discussions. The following is a summary of the headings and talking points to be followed in the extensive consultation process envisaged:

Foreward—The chief executive, Tim Matthews, explains the rationale for the program.
The Consultation Process—The Agency is seeking input from contractors, consultants, authorities (counties and major cities) product manufacturers, materials suppliers, specialist advisers, financial advisors, road users and those with environmental concerns. It should be noted that the Agency is concerned with all aspects of the planning, financing, design, construction, operation and maintenance of roads so that its proposed adoption of performance specifications is not limited to concrete supply and use.

1. *What is a performance specification?*—Focus should be on output measures that define the quality of the end product or outcome measures that define the benefits delivered.
2. *Why use performance specifications?*—To optimize service levels while offering better value for money.
3. *Benefits*—Better value and price certainty
4. *Risks*—Greater flexibility and better value for money should offset the perceived risks.

Performance Specifications—The sub-headings are:

1. *Impacts*—More risk management, increased trust, greater involvement of suppliers and consequent changes in culture. The end result could be significant synergies.
2. *Feedback from "Paving the Way"*—This last item was a consultation process (December 1999) which asked what would be the benefits of working under a

performance specification and what functions would not be suitable under a performance specification?

Agency's current thinking—Option 1: Developing Existing Specifications: Least risk but low benefit. Option 2: Performance Specifications for Maintenance only: Existing performance specifications would be expanded to include major maintenance and renewal of network assets. Option 3: Full Performance Specifications: Would transfer risk from the Agency to suppliers but allow suppliers to innovate.

Issues

Technical Governance—The Agency is an arm of the Government. The role of the agency cannot be delegated. Agency Design and Contract manuals detail all aspects of road construction and are largely prescriptive. Performance type documents would transfer risk to the suppliers but the responsibility for updating practice would need to be defined. The European codes are expected to be useful as models.

Issues for Suppliers—All aspects of risk management. Innovation would now be allowed and suppliers should therefore play a role in developing performance specifications. The maintenance of best practice will be important. The Agency will need to have quality management systems in place to audit performance and guarantee service life.

Issues common to Suppliers and the Agency—Performance specifications will need to ensure quality, include indicators to ensure real and measurable targets and confirm performance. Flexibility to accommodate local differences and to change with technology improvements will need to be included. There will be an impact on tender periods. This last point is a potentially major issue in North America where tender periods are short and construction starts very soon after a tender award.

Question:

Issues for Suppliers—Benefits, performance measurement, risks and cultural changes.

Issues for the Agency—Extent of implementation, maintenance of governance, impact on suppliers and future indicators of performance.

Issues common to suppliers and the Agency—Adequate detail and audit. Updating as needed and the effect of suppliers’ willingness to exchange information. Impact on the bidding process.

2.6.4 Norway

2.6.4.1 *NS-EN 206-1*—A large number of exposure classes are tabulated as follows:

Table 2.6.4.1

Exposure class	Relate to	No. of sub-classes
XO	No risk of corrosion or attack	No sub-classes
XC	Carbonation induced corrosion	4
XD	Chloride exposure except sea water	3
XS	Chloride exposure from sea water	3
XF	Exposure to freezing and thawing	4
XA 1-3	Chemical attack	3
XA 4	Chemical attack from fertilizers	No sub-classes
XSA	Extreme chemical environment	No sub-classes

These are met by prescriptive requirements, based on local experience and practice. These include maximum water-binder ratio, air content, minimum binder content and type of cement. Cement types include those incorporating limestone filler, silica fume, fly ash and slag in various percentages. Requirements are given for Designed concrete. With the exception of a test for water penetration no other non-traditional tests are recommended. With regard to the water penetration test high variability is noted and the need to state clear and concise conformity requirements is emphasized.

2.6.5 Italy

2.6.5.1 *UNI EN 206-1*—Similar to Norway a large number of exposure classifications are given identical to the Norwegian exposure classes tabulated above, together with prescriptive requirements for mixtures. (Minimum cement contents are common to the EU specs. Also the use of SCMs would appear to be widespread and some standards give specific combinations of cementitious materials as meeting specific exposure classes.)

Table 2.6.5.1 Exposure Classes

Exposure Class	Relates to	No. of sub-classes
X0	No risk of corrosion or attack	No sub-classes
XC	Carbonation induced corrosion	4
XD	Chlorides not from sea water	3
XS	Chlorides from sea water	3
XF	Freeze-thaw with or without de-icing agents	4
XA	Chemical attack`	3

Prescriptive requirements are given for minimum cement content, maximum water-cement ratio, minimum strength and minimum air content.

Supplementary Cementing Materials: Only fly ash is allowed.

2.7 North America

2.7.1 *USA*

2.7.1.1 *Federal Highway Administration*—This agency has instituted a programme entitled "Performance Specifications Strategic Roadmap: A Vision for the Future: Spring 2004". The Roadmap consists of five chapters:

1. Examining the Issues
2. Performance Specifications
3. Defining the Future
4. Organization and Management
5. A Viable Option

The timeline provides for adopting Performance Guide Specifications by 2008 and the program involves seven task forces and five expert task groups overseen by a technical working group. The PDF version of the roadmap document does not mention budgets, but this initiative would appear to be the realization of the 1991 FWHA rating of this task as research priority "number one."

2.7.1.2 *Virginia*−In September 2004 the State of Virginia published a draft end-result specification for concrete. This is not a pure performance specification in that it requires the supplier to submit extensive details of the concrete mix designs for review. Payment for structural concrete is based on strength and rapid chloride permeability (ASTM C 1202). The C 1202 test is modified requiring 7 days moist curing at 73^o F (23^o C) followed by 21 days at 100^o F (38^o C). This is done to provide increased maturity for mixtures containing fly ash or slag that better indicates their longer term (3 to 6 month) performance. Pay factors are based on the percentage of test results within limits (PWL) provided the PWL exceeds 50. Thus a bonus can be earned (small) or a penalty may be incurred (can be large). Similar criteria apply to cover to reinforcement and slab thickness in continuously reinforced pavement.

2.7.1.3 *Sprinkel, 2004, on Performance Specifications for High Performance Concrete Overlays on Bridges*—The Virginia Department of Transportation let a contract for a high performance concrete overlay using a performance specification. Acceptance and payment were based on the contractor meeting specified test results for critical performance criteria. These criteria were air content, permeability to chloride ions and bond strength as well as a high compressive strength. All the specified criteria were met and exceeded so that the contractor received a 6% bonus. Further, the bid price using the performance specification was 15% below the previous average using prescriptive specifications. Even after paying the contractor a bonus the cost was 9% below previous contracts.

Supplementary Cementing Materials: Silica fume was used in overlay mixtures.

2.7.1.4 *Mokarem et al, "Development of Performance Specifications for Shrinkage of Portland Cement Concrete*—The first objective was to develop performance specifications for the shrinkage of concrete based on a precise test method. The tests were based on a range mixes typical of those used by the Virginia Department of Transportation. The second objective was to assess the accuracy of existing prediction models for unrestrained shrinkage. Restrained and unrestrained shrinkage tests were made as well as compressive strength and elastic modulus tests. Based on the results of the restrained shrinkage tests it was possible to set limits for unrestrained shrinkage. It was concluded that if a percentage length change is limited to 0.0300% at 28 days and 0.0400% at 90 days the probability of cracking due to drying shrinkage is reduced. These values could be used as performance criteria in a specification for the mixes and materials used in this study.

2.7.1.5 *Minnesota DOT*—Minnesota has been making progress toward performance-related specifications for concrete pavement since it committed to a program of contractor mix design in 1992. MinnDOT has been inserting special contract provisions in selected projects to evaluate effectiveness of test methods and forms of specifications, and has matched this with a program of training and certification for both the MinnDOT personnel who have to adapt to the new approach, and for contractors and concrete suppliers who will be submitting the new mixture designs. Hover's Federal Highway Administration short course (1999) was an outgrowth of the training and certification program in Minnesota. Concrete Materials Engineer Doug Schwartz maintains a continuing dialog with the supplier and contractor base on the topic of concrete specifications.

While conventional "curb and gutter" or municipal pavement concrete (primarily ready mixed) is for the most part still based on prescriptive specs, innovation has come in the larger concrete paving projects, many of them having on-site batch plants, short haul times and slip-formed paving machines. To encourage contractors to take advantage of modern concrete materials technology the state has offered a bonus for optimized aggregate grading, for example. While minimum cementitious materials requirements remain, there has been an effort to reduce them to more reasonable, more economical, and more efficient levels. On selected projects water content is estimated with the microwave oven test (AASHTO T 318) at the batch plant. Post-plant water is thus not monitored nor does it figure into specification requirements, but on short hauls with slip-formed concrete this may not be as significant as it would be with longer, more variable haul time and placing methods that make a higher slump more desirable. When specified, the w/cm at the plant is limited to 0.40, with a sliding scale for bonuses and penalties that is based on impact of w/cm on concrete behavior and on MinnDOT's level of experience and confidence with the precision of the test.

2.7.1.6 *Indiana DOT*—Indiana has been a lead state in pioneering performance specifications for concrete pavement (Kopac, 2002). Indiana used a performance related specification for portions of Interstate 465 in Indianapolis, cited by Kopac as the first such trial in the US. Key elements of the Indiana specification include acceptance of as-constructed pavement lots on the basis of concrete flexural strength, pavement thickness, air content and smoothness. To paraphrase the specification, if a constructed quality characteristic for a lot or section exceeds the target value, the contractor receives an incentive pay adjustment. Conversely, if a constructed quality characteristic for a lot or section is between the target value and "Rejectable Quality Limit," (RQL), a penalty is assessed. In either case the amount of the pay adjustment is based on the expected increase or decrease in future life cycle costs.

Specifically, the concrete is to be workable and have the following properties:

Minimum Portland cement content	260 kg/m3 (440 lbs/yd3)
Maximum water/cementitious ratio	0.450
Minimum Portland cement/fly ash ratio	3.2 by mass (weight)
Minimum Portland cement/GGBFS ratio	2.3 by mass (weight) 80
Target air content	6.5% - 7.5%
Minimum flexural strength	3800 kPa (550 psi) at 7 days

A trial batch is required for testing "by the Contractor's certified technician to verify that the [mixture] meets the concrete mix criteria."

2.7.1.7 *Port Authority of New York and New Jersey*—Speaking from the owner's perspective Bognacki et al. (2002) have reported positive outcomes with performance-based specifications. The Port Authority of New York and New Jersey has been specifying concrete based on estimates of water content in the fresh concrete, shrinkage and rapid chloride permeability. Its specification includes prescriptive elements such as w/cm limit of 0.45, air of 3.5 to 5.5%, and aggregate grading. Flexural and compressive strengths are specified as well. The authority concluded that the microwave test for water content (AASHTO T-318) was viable and effective. It also observed "neither flexural nor compressive strength alone are a good indicator of durable concrete." Bonus incentives were achieved based on 80% of the concrete in the lot having a w/cm ≤ 0.45 and 70% of the concrete having air content above 3.5%. On one project 50% of the concrete lots earned a bonus and on another 62% earned a bonus.

2.7.1.8 *Taylor, 2004*—The prime reason for a change to performance specifications is said to be the need to improve the probability of achieving the desired service life of a structure at reasonable cost and with minimal disputes. It is pointed out that most current specifications are a mix of prescriptive and performance requirements. The article concerns itself primarily with the issues to be faced and suggests nine steps that need to be taken to change to primarily performance criteria quoted verbatim as follows:

"1) The owner sets out the service life and maintenance level required for the structure and defines the environment to which it will be exposed;

2) Owners/designers select appropriate "index tests" that correlate with the environment and the required service life. They will have to accept a given relationship between likely performance of the structure and the selected index test based on experience or published data. An example would be to accept that a concrete pavement containing 6% entrained air (spacing factor<200 µm [0.008 in.]), among other parameters, is likely to survive 50 years of salting and severe winters;
    - This approach would require that appropriate test methods and limits be relevant [to] deterioration mechanisms;
    - The scatter in test results [test method precision] will have to be accommodated when selecting limits;
    - Sufficient experience or models and data must be available to assure owners that the correlation between tests and service life is valid;
    - Preferably, most tests would be performance based: for instance, measurement of alkali-silica reaction (ASR) expansion of the concrete system would be preferred to imposing chemical limits such as alkali contents; and
    - Some tests would still be prescriptive in nature, however, because they are the most cost-effective: for instance, a limit on chloride content might be imposed rather than measuring corrosion rate;

3) A specification is prepared that establishes the tests and the acceptable limits of their results, appropriate for the project to maximize the probability that the required service life will be achieved;

4) The contractor/ready mixed concrete supplier proposes a concrete system, including materials, proportions and details. The system is prequalified using tests conducted on mockups or previously constructed systems. Some of these tests may take time. For instance, ASTM C 1293 for ASR takes up to 2 years;

5) Quality Assurance/Quality Control (QA/QC) activities are based on pre-correlated rapid tests to document that the concrete system in place is equivalent to that which was prequalified. These may be limited to proving that the concrete was batched correctly, has an adequate air void system, and has been cured sufficiently; or may be tied to the prequalification tests such as ASTM C 1260 for ASR;

6) A correlation between tests for prequalification and those for QA/QC must be available or determined at the prequalification stage;

7) QA/QC testing will be required at each change of "ownership", that is, when materials are delivered to the plant, when concrete leaves the mixer truck and after curing is complete;
8) A type of warranty system may still be required for "gray" areas until sufficiently reliable index tests are developed and proven; and
9) As numerical predictive models become more acceptable, they may substitute for some testing at the prequalification stage."

The process of developing performance specifications has to involve all the parties to a contract and clearly, improved communication between all parties will be required where such specifications are used. Considerable concern is expressed about the current inadequacy of the number of confirmatory tests of acceptable reliability that can be used as a basis for acceptance of concrete in the structure. It is suggested that for now the application of this approach may be restricted to a small percentage of contracts. As experience is gained, test procedures are improved, and a body of experience and data builds, more extensive use will occur.

2.7.2 Canada

2.7.2.1 *CSA A23.1 Concrete Materials and Methods of Concrete Construction*—This is Canadian Standards Association's (CSA) main Canadian Standard on concrete. In the 2004 edition the Owner is offered two options for the specification of concrete: Performance or Prescription. Each option delineates what the Owner will specify and what the Contractor and Supplier shall do. It is stated that 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"*. It is thus clear that the responsibility of the concrete supplier ends with the discharge of the appropriate concrete mix from the mixer or delivery unit. The contractor on the other hand will be responsible to place, compact and cure 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 Table 5 of the standard as shown below as Table 2.7.2.1(a).

Guidance on the use of Table 5 is given in Annex J of CSA A23.1 and this is reproduced in its entirety in Appendix C of this document.

CSA's comprehensive table of exposure classes (Table 1 of A23.1-04) is reproduced in Table 2.7.2.1(b) of this report. This table is followed by Table 2.7.2.1(c), which is a slightly modified version of CSA A23.1 Table 2. Five major exposure classifications are provided, the sub-classes dealing with different degrees of severity.

Requirements are given for the concrete properties that meet each exposure class. These include maximum water-cementing ratio, minimum compressive strength and age at test, air content and type of curing. For the two most extreme exposures maximum coulomb limits are given based on the ASTM C 1202 test.

Annexes provide guidance on High-Performance concrete and concrete made with a high volume of Supplementary Cementing Materials (SCM). Supplementary Cementing Materials discussed include pozzolans, slag, fly ash and silica fume are allowed, as well as blends of SCMs.

Table 2.7.2.1(a) “Table 5” from CSA A23.1 Concrete Materials and Methods of Concrete Construction

Table 5
Alternative methods for specifying concrete

(See Clauses 4.1.2.1, 4.1.2.3, 4.1.1, 5.2.4.3.2, and 8.1.5, and Annex J.)

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 (see Annex J*); (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-qualification 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.

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2. Most Provincial Ready-Mixed Concrete Associations have acceptable certification schemes"

Table 2.7.2.1(b) A23.1-04 Table 1: Exposure Classes

A23.1-04 **©Canadian Standards Association**

Table 1
Definitions of C, F, N, A, and S classes of exposure

(See Clauses 4.1.1.1.1, 4.1.1.5, 4.4.4.1.1.1, 4.4.4.1.1.2, 6.6.7.5.1, and 8.4.1.2, and Table 2.)

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 2 and 3).
S-2	Concrete subjected to severe sulphate exposure (Tables 2 and 3).
S-3	Concrete subjected to moderate sulphate exposure (Tables 2 and 3).

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 Tables 2 and 3.*

Table 2.7.2.1(b) Modified 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)	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 Notes:

* The water-to-cementing materials ratio shall not be exceeded for a given class of exposure, regardless of exceeding the strength requirement.

** 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 in this Table.

*** To allow proper finishing and wear resistance, Type N concrete intended for use in an industrial concrete floor with a toweled 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 troweled finish is required. Interior ice rink slabs and freezer slabs with a steel troweled 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 C_3A content).

2.7.2.2 *Canadian HPC specifications from various provincial and municipal agencies*—The following table summarizes performance criteria:

Table 2.7.2.2
Performance Criteria in Canadian Provincial and City Specifications
For High-Performance Concrete

Province	C1202	C457	Scaling	Shrinkage	Sorptivity	Toughness	Durability
British Columbia		✓ 1				✓ 5	
Alberta	✓	✓ 1		✓ 2			
Manitoba	✓	✓ 1		✓ 2			
New Brunswick	✓	✓ 1					
Nova Scotia	✓	✓ 1					
Ontario	✓ 7	✓ 1a	✓ 3a		✓ 6		
Quebec	✓	✓ 1	✓ 1b	✓			✓ 8
Newfoundland	✓	✓ 1					
Toronto	✓	✓ 1					
Toronto Airport	✓ 7	✓ 1a					
Montreal	✓	✓ 1c	✓ 3b				
Edmonton	✓	✓ 1	✓ 3				
Consultant	✓	✓ 1	✓ 3	✓ 4			
Calgary	✓	✓ 1	✓ 3				

Notes:

1. Average spacing factor not more than 0.23 mm (0.009 in) and no single value greater than 0.26mm (0.010 in).

1a. Average and maximum 0.25 mm (0.010 in) and 0.30 mm (0.012 in), respectively. Tests made on cores.

1b. As in note 1 but tests made on cores.

1c. Maximum spacing factor 0.23 mm (0.009 in) before pumping; 0.325 mm (0.013 in) after pumping

2. Cracks over 0.3 mm (0.012 in) to be repaired.

3. 0.4 kg/m^2 (0.75 lb/yd^2) mass loss /30 cycles.

3a. 0.5 kg/m^2 (0.90 lb/yd^2) mass loss /50 cycles

3b. 0.5 kg/m^2 (0.90 lb/yd^2) mass loss /56 cycles

4. 0.25-0.35 (average crack width (mm) x crack length (m) per m^2 of concrete surface area. (This is numerically equivalent to specifying that the cumulative area of cracks visible on the surface is no more than 0.025 to 0.035% of the concrete surface area.)

4a. Length change by ASTM C 666

5. Current toughness criteria for fibre reinforced concrete.

6. Undergoing extensive site trials on contracts.

7. Tests made on cores.

8. Tests by ASTM C 666.

Supplementary Cementing Materials are addressed. Slag, fly ash and silica fume are extensively used in HPC. In many cases a combination of two SCM's is used. Low coulomb values (ASTM C 1202) are readily achieved in mixes incorporating silica fume.

2.7.2.3 *Manitoba Ready Mixed Concrete Association (Rooke, 2004)*—The document produced by Rooke for this association is titled "Performance Concrete" and is subtitled "A guide to Statistical Analysis of Concrete Mix Designs".

The introduction consists of three sections: "How Strong is Strong Enough?" "Performance Specifications" and "Over-Design Factor". The rationale for the production of this document is the publication of CSA A23.1-2004 and the anticipated trend to more performance-based specifications. Guidance is given on frequency of testing and the documentation and interpretation of test data. This is a short, clear guide document that will assist suppliers in meeting performance requirements for compressive strength.

2.7.2.4 *New Brunswick Draft Performance Specification*—The Province of New Brunswick was one the first Provinces to adopt HPC for the construction of Provincial's Bridges, and is a lead authority on the use of progressive technology in construction. Currently, a performance-oriented specification is being developed. The following comments relate to the latest draft circa April 2005.

The draft, that is not yet finalised or approved, quotes the current (2004) edition of CSA A23.1 verbatim on "Roles and Responsibilities" as laid down in Table 5 and Annex J of that document. The contractor is required to maintain "an industry recognized quality control (QC) plan that prevents or corrects defects and non-conformity in the concrete."

The definition of a performance-based specification for the type of contract let by the Province is not yet finalized but will form part of the specification.

In the event of a dispute over the results of tests to determine Air Void System Parameters (ASTM C457) or Chloride Ion Penetration (ASTM C1202), the Contractor is free to request referee testing at his expense. Sublots of concrete are rejected if the compressive strength is more than 5 MPa (725 psi) below the specified compressive strength. In this event the Contractor has the option of coring, in which case the compressive strength of each of three cores, taken at locations specified by the Engineer, has to exceed the specified strength less 5 MPa. In the event of confirmation of a failure concrete production may be suspended. Additional testing and/or remedial measures are available to the Contractor. Payment after acceptance provides for payment reduction for non-compliance or concrete removal. Properties covered by the payment reduction system are compressive strength, air void system, chloride permeability, temperature of concrete in-place, temperature differentials in-place and finishing tolerances. Tests for air void parameters and chloride permeability are made on cylinders cast from fresh concrete.) Acceptance criteria follow:

Table 2.7.2.4

Test	Standard	Acceptance criteria
Air void system	ASTM C 457	0.230 mm (0.009 in.) average, 0.260 mm (0.010 in.) max
Chloride permeability	ASTM C 1202	With corrosion inhibitor: 1500 coulombs
		Without corrosion inhibitor: 1000 coulombs
Shrinkage	ASTM C 157	Superstructure: max 0.04% @ 7 days
		Substructure: 0.05% @ 7 days

The specification gives detailed requirements for the quality of materials, and for the placing finishing and curing of concrete. Test details including mix designs (mixture proportions) are to be submitted to the Engineer.

2.8 Penalties and Bonuses for Concrete.

2.8.1 *USA*

2.8.1.1 *Virginia*—In the end-result specification published in 2004 and referred to in 2.7.1.2, provision is made for bonuses and penalties based on strength and rapid chloride permeability test results. For an HPC overlay contract a bonus was provided based on strength, air content, permeability to chloride ions and bond strength. The contractor realized a bonus and the contract cost was lower than on previous contracts with prescriptive specifications.

2.8.2 *Canada*—With the exception of Ontario, no province pays bonuses for work that complies with or exceeds specification requirements, but all exact penalties for failures to meet specification requirements. The following is a summary of penalties charged by some provinces and cities (Bickley and Mitchell, 2001).

2.8.2.1 *Alberta*—Cracks to be measured in width and length. Those over 0.3 mm (0.012 in) in width to be repaired. Penalties are charged for understrength concrete (strength lower than specified) down to 42 MPa, below which the concrete is unacceptable.

Table 2.8.2.1 Penalties for Understrength Concrete

Test Results		Penalty:	
MPa	psi	\$C/m^3	\$US/yd^3
50 or over	7250	nil	nil
49-50	7110-7250	20	13
48-49	6960-7110	40	26
47-48	6820-6960	60	39
46-47	6670-6820	80	52
45-46	6530-6670	100	65
44-45	6380-6530	130	84
43-44	6240-6380	180	117
42-43	6090-6240	200	130
Below 42	Below 6240	Reject	

Note: Conversion based on August 2005 exchange rate of \$1 Canadian = \$0.83 U.S.

2.8.2.2 *City of Calgary*—Work has been performed for the City of Calgary in which the consultants required tests in advance of construction to determine the cracking potential of the proposed mix. Details are unavailable. Cracks over 0.2 mm. in width in the structure are repaired. A number of penalties are imposed for failures to meet specification requirements:

Table 2.8.2.2

Test	Unit	Penalty:
		\$C/ m³ (\$US/yd³)
Strength	3.5-4.5 MPa (510-650 psi) below specification	70 (45)
	> 4.5 MPa (650 psi) below specification	150 (97) or remove
Air content	0.2% outside limits	60 (39)
	> 0.2% outside limits	150 (97) or remove
RCP	601-1200 coulombs (based on spec. of 600 coulombs)	40 (26)
	> 1200 coulombs	250 (162) or remove

2.8.2.3 *Alberta Consultant's Specification*

Table 2.8.2.3 (a)

Test	Unit	Penalty:\$C/m³ (\$US/yd³)
Strength	3.5-4.5 MPa (510-650 psi) below	50 (32)
	> 4.5 MPa (650 psi)below	100 (65)or remove
Air Entrainment	Up to 0.2% outside range	60 (39)
	> 0.2% outside range	150 (97)or replace
Permeability	1001-2500 coulombs (based on spec of 1000 coulombs)(Point of sampling unclear)	250 (162)
	> 2500 coulombs	No payment, plus apply acceptable protection or replace

Cracking is measured as follows: 1.) Measure the estimated crack length of cracks greater than 0.2 mm (0.08 in) wide. 2.) Multiply length by the average crack width of each crack and sum these areas. 3.) Divide by the area under consideration in square meters, where such area is defined by a perimeter 500 mm (19.7 in) beyond the nearest crack under consideration.

Table 2.8.2.3 (b)

Unit	Penalty: \$C/m³ (\$US/yd³)
0 to 0.30	No deduction
0.31-0.60	\$ 100 (65) plus specified repair
0.61-1.0	\$ 200 (130)
> 1.0	No payment plus acceptable protection or replace

2.8.2.4 *Newfoundland and Labrador*—The penalty for failure to meet strength requirements is: $ (adjusted concrete price) = (bid price)-$10 (specified strength-tested strength (MPa)). For example, if the concrete strength is low by 5 MPa, then the penalty would be $50CDN/m^3.

2.8.2.5 *Northwest Territories*

Table 2.8.2.5

28 Day Compressive Strength:		Penalty	
MPa	Psi	$C/m^3	$US/yd^3
35 and above	5080 and above	Nil	Nil
34-35	4930-5080	15	10
33-34	4790-4930	30	19
32-33	4640-4790	45	29
31-32	4500-4640	60	39
30-31	4350-4500	80	52
29-30	4210-4350	110	71
28-29	4060-4210	150	97
27-28	3920-4060	200	130
Below 27	Below 3920	reject	

2.8.2.6 *Ontario Ministry of Transportation Special Provision No 904S11, December 2004*—For normal structural concrete the quantity and quality of the air-void system in the hardened concrete are specified. The minimum volume of air must be 3% and the maximum spacing factor of each lot must not exceed 0.230 mm (0.09 in.). 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 (0.07 in) 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 (0.10 in.) 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 (0.18 in.) and an air content of 1% no payment would be made.

2.8.2.7 *Ontario* Ministry of Transportation Special Provision No 904S13, December 2004—For high-performance structural concrete the maximum coulomb value (ASTM C 1202) and the quantity and quality of the air-void system in the hardened concrete are specified. 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 (0.10 in.). 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 (0.10 in). The penalty for coulomb values higher than 1000 is calculated as follows: Payment Reduction in dollars 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 (0.012 in) wide or wider.

Table 2.8.2.7

Durability criteria	Testing phase relative to construction		
	Before	During	
		On test specimens	In-place
ASTM C1202			✓
ASTM C457			✓

2.8.2.8 *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) determines 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. PWL greater than 95% earns a bonus. When the PWL is less than 90% and greater than or equal to 50%, a 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 sublot 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."

Each lot will be divided into sublots of approximately 10 m^3 to 1000 m^3. Sublot sizes shall be established based on the estimated concrete quantity such that each lot contains a minimum of 10 sublots. One set of acceptance cylinders will be made from each sublot. The loads of concrete to be sampled will be selected by the Contract Administrator on a random basis.

The Owner may require additional cylinders from selected batches of concrete placed in critical areas; however, these tests will not be used as part of the following payment determination.

2.8.2.9 *City of Montreal*—The City of Montreal has two concrete specifications. 3VM-10 and 3VM-20 deal with normal concrete under 50 MPa (7,250 psi) compressive strength and HPC 50 MPa (7,250 psi) and higher compressive strength, respectively.

Both specifications are a combination of prescriptive and performance requirements. Both refer to CSA A23.1 as the guide specification altered only by specific requirements in these two documents.

Table 2.8.2.9

Concrete property	Testing phase relative to construction		
	Before	During	
		On test specimens	In-place
ASTM C 1202	✓	✓	
Air void system	✓	✓	
Scaling (BNQ Test)	✓	✓	

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Chapter 3 Test Methods for Performance Evaluation

3.1 Introduction

To provide confidence for all parties considering the adoption of performance specifications, there is a need for quick, reliable performance tests for concrete properties, including durability, which have to go far beyond current reliance on the 28-day compressive strength as the sole arbiter of concrete quality. The lack of adequate performance-related test methods is one of the main factors inhibiting the move from prescriptive to performance specifications. Related to this is the issue of using tests for prequalification of a supplier's mixtures for specific performance and exposure conditions. While this is useful, and testing can be completed in advance of placement, it does not remove the need for testing during construction, to ensure that the pre-qualified mixture is being supplied and maintained.

As well, a concrete supplier may prefer that performance only applies to the concrete as it leaves the chute of the truck, but the owner's perspective is that it should apply to the performance of the structure. This has resulted in adoption of end-result specifications (ERS), where concrete acceptance is evaluated using in-place testing (e.g. for strength, air-void system, RCPT coulombs, depth of cover). This obviously requires that the concrete be properly placed, protected, and cured by the contractor, and that the supplier and contractor must work together to meet these ERS test requirements.

Therefore, three kinds of performance tests need to be considered and are discussed in this chapter:

1. Prequalification tests on concrete mixtures.
2. Construction testing at delivery.
3. In-place testing.

Test methods and performance limits are key to adopting performance-based specifications, but a number of questions need to be answered, such as:

1. What test methods are out there now and are others ready for adoption?
2. What performance parameters can we really measure with confidence?
3. Where are the gaps in our knowledge related to performance testing?

In this chapter, Question 1 has been addressed and attempts have been made to address the other two.

3.2 Fresh Concrete Tests

3.2.1 *Workability*—The slump test, while a measure of consistency rather than true workability, is still the most widely used concrete test in the world. It has limitations in the low slump range, where tests such as the Vebe test are more appropriate. However, that is more of an issue for dry cast, precast concrete operations. The accuracy of the slump test as an acceptance measure breaks down at slumps exceeding about 6 inches. For concretes at high slumps, the advent of Self-Consolidating Concrete (SCC) has resulted in the slump flow test (the same procedure except that the diameter of the slumped concrete is measured along with the presence of any halo due to bleeding). Limits on the slump flow test and other flow tests for SCC (L-box and J-ring) have been adopted in CSA A23.1 (2004); ASTM Subcommittee C09.47 is working to standardize these tests. While there has been much recent work on rheology of concrete (Ferraris, de

Larrard, and Martys, 2001; Banfill et al, 2000; Banfill and Domone, 2002), it is unlikely that this will have an impact on testing of fresh concrete in the near future.

3.2.2 *Air Content*—Currently, the pressure method and volumetric method are used to determine total air content on fresh concrete. Also of concern is getting a measure of the air void distribution, but until recently there has not been a test method applicable to concrete in its plastic state. There has been work by several DOT's, especially Kansas DOT, and the FHWA on the use and adoption of the Danish fresh concrete air void analyzer (AVA) test. In this test, a sample of mortar extracted from concrete is injected into the bottom of a column filled with a glycerin mixture and stirred. The air bubbles rise up in the column at a rate dependent on their size (small ones rise slower). The buoyant mass of all the air bubbles is measured with time as they are trapped under a balance at the top of the column. This provides an air void size distribution as well as total air content. There is increasing interest in this test, but it has not yet been standardized.

3.2.3 *Density (Unit weight)*—Density (unit weight) measurements on fresh concrete can also provide some measure of uniformity of air contents in air-entrained concrete, and as a test for consistency of all concretes. It has the advantage of simplicity, often being determined by weighing the pressure air meter bucket, prior to measuring air content in the field. Density tests are also used to determine and verify yield of concrete as delivered.

3.2.4 *Temperature of Fresh Concrete*—ASTM C1064 can be used on site to measure the temperature of the concrete. This can be important either where minimum or maximum values have been specified for extreme temperature conditions or when there is concern with slump-loss for concrete, especially HPC with high-range water reducers that is to be pumped. In addition, temperature of fresh concrete can influence the potential for thermal cracking in massive concrete elements.

3.2.5 *Water in Fresh Concrete*—AASHTO T318 is a test method to dry a concrete sample in a microwave oven and is used to estimate the water content in fresh concrete [Nagi & Whiting, 1994]. While there has been some resistance to its adoption, several highway departments and the Port Authority of New York and New Jersey have adopted it [Bognacki et al, 2002]. Other agencies have not found it to be sufficiently precise. As with any test method, specified acceptance criteria must account for the precision of the test, which in this case is in the range of the ability to estimate w/c to within about ± 0.03 to ± 0.04 (Dowell & Cramer, 2002) There have also been nuclear based methods to measure the cement and water contents of plastic concrete but these have not been very successful [HITECH, 1998].

3.3 Tests on Hardened Concrete

3.3.1 *Mechanical Properties*—Strength tests (ASTM C39), based on site cast cylinders typically performed at 28 days of age, are the most common concrete performance acceptance tests. However, the results are received 28 days too late to prevent low-strength concrete from being used. Lower than normal densities of cylinders taken after mold removal can be used as an early indicator of the potential for low-strength cylinders, either due to a higher air or water content. ASTM C 684 describes four accelerated tests for compressive strength. While these have been used successfully on isolated projects they have not found wide acceptance. In addition, in-place strength development can be estimated using Maturity methods such as ASTM C 1074 or pullout strengths as in ASTM C 900. However, the C 684, C 900 and C 1074 methods require calibration with tests on job concretes before use. These tests are discussed in more detail later. Splitting tensile (ASTM C 496) or flexural (ASTM C78 or the less-preferable C 293) tests are used in some cases (eg. pavements) for performance acceptance. Abrasion tests (ASTM C 1138, C 418, C 944, C 779) have been used in some instances for hydraulic structures and pavements, although their use is not common. More information is provided in 3.5.6.

3.3.2 *Volume Change Properties*—Cracking of concrete due to plastic shrinkage, autogenous shrinkage, drying shrinkage, thermal gradients and creep are of concern to durability of structures since cracks act as rapid pathways for penetration of water and other aggressive fluids into concrete. The effects of cracking are to accelerate degradation. Table 3.3.2 lists some of the tests currently available to measure free (C 157) and restrained (AASHTO PP 34-99, The Passive or Restrained "Ring Test") drying shrinkage and other measures of volume change. The ASTM volume change subcommittee (C09.68) is currently standardizing a similar restrained shrinkage ring test (Attiogbe, Weiss, and See, 2004) and the fiber subcommittee C09.42 is standardizing two plastic shrinkage test methods for fiber-reinforced concrete. ASTM subcommittee C01.31 is currently considering a method to measure chemical shrinkage of cement paste. ASTM has a creep test, C 512, and the RILEM early-age volume change committee is working on a tensile creep apparatus to measure early age deformations due to various early-age stresses. Several international standards, such as CSA A23.1 (2004) and AS1379 (1997) have optional requirements for drying shrinkage, using essentially ASTM C 157.

In CSA these are for prequalification of concrete mixtures every two years, but few local specifiers are requiring testing as part of concrete acceptance when "Low-Shrinkage Concrete" is specified. In CSA A23.1, modified from C 157 in that wet curing is only maintained for 7 days, and shrinkage is determined after 28-days of drying (following the 7-day curing period.). The optional maximum shrinkage limit after 28 days of drying is 0.040%. The Australian AS1379 standard has a maximum shrinkage prequalification requirement, to be performed every six months on the most common mixture produced by a plant.

The US Army Corps of Engineers has standard methods used to determine thermal properties of concrete, including thermal coefficient of expansion, specific heat and heat capacity as also listed in Table 3.3.2. AASHTO recently developed a provisional method for thermal coefficient of expansion that is based on FHWA procedure (AASHTO TP60-00)

Other early-age volume change properties, such as autogenous shrinkage are being measured, but will likely not be adopted as standard tests for several years. There is currently a RILEM committee (TC 195-DTD,) evaluating test methods for autogenous shrinkage, and there is a new task group formed under ASTM subcommittee C09.68 (Volume Change) to standardize an autogenous shrinkage test.

Table 3.3.2—Volume Change/Cracking Tests

Std. Test No.	Property Measured	Prequal. Test?	Acceptance Test?		Strengths	Weaknesses	Improvements Needed
			On Cores	In-Place			
ASTM C 157 Drying shrinkage	Length Change. Length Change vs. Time Curve.	√	√ (cast prisms)		• Simple	• Too long. • Operator sensitive. • Lack of correlation to field performance.	• Shorten duration. Establish relationship to field conditions (restraint, etc.) and incidence of cracking.
AASHTO PP-34-99 Restrained shrinkage ring test	Cracking-visual Time to first crack	√			• Simulates cracking potential	• Not always reproducible	• Establish relationship to field conditions (restraint, etc.) and incidence of cracking. • Improve precision
RILEM Proposed tensile creep	Length Change	√			• Useful for early age cracking	• Not a standard test	• Establish relationship to field conditions (restraint, etc.) and incidence of cracking
ASTM C 512 Creep	Length Change. Length Change vs. Time Curve	√			• Needed for prestressed and columns	• Too long. Operator sensitive. • Lack of correlation to field performance. • Logistically difficult to perform	• Shorten duration. Establish relationship to field conditions (restraint, etc.) and incidence of cracking.
CRD-C 124 Specific heat	Energy-Input & Output	√			• Useful for thermal cracking	• Lack of correlation to field performance.	• Establish relationship to field conditions (restraint, etc.) and cracking.
CRD-C 39 Thermal Coef. of Expansion	Length change with temperature	√			• Useful for thermal cracking	• Value changes at early ages	
CRD-C 36 Thermal Diffusivity	Rate of temperature rise	√			• Useful for thermal cracking	• Rarely performed	
CRD-C 44 Thermal Conductivity	Calculated from diffusivity and specific heat	√			• Useful for thermal cracking	• Rarely performed	

3.4 Durability Tests

3.4.1 ***General*****—**Most deterioration processes involve two stages. Initially, aggressive fluids (water or solutions with dissolved solids or gases) need to penetrate or be transported through the capillary pore structure of the concrete to reaction sites (*e.g*., chlorides penetrating to metallic reinforcement, sulfates penetrating to reactive aluminates) prior to the actual chemical or physical deterioration reactions. A standard acceptance test or tests to measure fluid transport rates, or a related index test, is fundamental to developing performance-based durability specifications.

Test methods related to measurement of various durability properties exist in many standards (*e.g*. ASTM, AASHTO, Corps of Engineers (CRD), individual DOT's) in North America. Other test methods also exist in other standards outside of North America. As well, countless other non-standard test methods have been described in the open literature which may or may not be useful or stand up to ruggedness and precision requirements for jobsite acceptance of concrete. Limits based on some of these standard test methods are specified in ACI, ASTM, BOCA, CSA (Canadian Standards Association) and individual DOT specifications, amongst many others. Each of these specifications embodies different test limits in many cases, based on use of different test methods. Unfortunately, tests do not exist for all of the relevant durability or performance concerns. As well, existing tests are not always rapid, accurate and repeatable, nor do they necessarily (i) have a good scientific basis, (ii) adequately represent any or all of the exposure conditions in place or (iii) relate to field performance.

In the tables provided in the following sections, test methods are identified and grouped based on the durability/performance issue addressed. Available ASTM, AASHTO, CRD, USBR and CSA test methods are identified; where possible, European and other national test methods have also been included in the summaries. These methods are tabulated by property tested. In the tables, the tests are broken down as follows:

1. Type of test and standard number
2. The type of specimen tested
3. The property measured
4. Strengths of the method
5. Weaknesses of the method
6. Improvements needed

Laboratory-based methods are identified as well as in-place field tests where they are known to exist. One unfortunate problem identified is the common lack of methodology for checking the validity of test methods and specification limits for assurance of durability in the anticipated field exposure conditions.

3.4.2 *Resistance to Ingress of Aggressive Fluid*—The resistance of concrete to the ingress of aggressive fluids is fundamental to its durability to most forms of degradation. Unfortunately, it is not practical to measure this property directly because of the extreme experimental difficulties and the long times involved. Therefore, most of the tests described are indirect or index methods. In most specifications, there are no limits placed on permeability, diffusion, absorption or other direct measures of fluid penetration resistance. Instead, typically, upper limits on *w/cm* and/or minimum strengths are specified in various tables in ACI 318 and ACI 301 for concrete to be exposed to specific aggressive exposures. This leads to cases in which, for example, all 0.40 *w/cm*, 35 MPa

(5000 psi) concretes would satisfy the specification for chloride exposure, even though a concrete with portland cement as the only binder will have much lower resistance to chloride diffusion than one incorporating supplementary cementing materials (SCM's) at the same w/cm. Therefore, to provide a better measure of "equivalent" performance, it would be preferable to specify a limit using a rapid index test for fluid penetration resistance. Until recently there have been very few standardized test methods for measuring such properties. Also, many methods are not rapid, and in the case of rapid tests, there is not always widespread acceptance due to perceived or real limitations of the procedure.

Existing standard test methods are listed in Table 3.4.2 (see next page) and are described in the following.

3.4.2.1 *AASHTO T259 Chloride Ponding Test*—This test has been used for decades by many highway agencies. A concrete slab is cast and moist cured for 14 days, then air cured to 28 days. The top surface is bermed and ponded with a salt solution for 90 days. Cores are then taken from the exposed surface and sliced into approximately half-inch thick discs. Each disc is crushed and the chloride content of each layer is determined. Unfortunately, this test requires almost six months to complete and there is no clear way provided for interpretation of the results in the method (McGrath and Hooton, 1999). Transport mechanisms in this test also include undefined components of absorption, diffusion and wick action. This test has been recently standardized with some modifications as ASTM C 1543.

3.4.2.2 *ASTM C 1556 Chloride Bulk Diffusion Test*—This was adapted from Nordtest NT Build 443. Slices taken from concrete cores or cylinders are sealed on all faces except one, then immersed in a sodium chloride solution for a fixed period. After exposure, the surface is ground or milled off in successive 1-2mm layers. Each of the powdered layers is acid digested, then titrated to obtain the chloride content. The chloride content is plotted as a function of depth, then a numeric solution of the diffusion equation is fitted to the data to determine the apparent diffusion coefficient and a surface chloride concentration. While it appears to be a useful method for prequalification of concrete mixtures and provides input data for service-life-prediction models such as LIFE 365, it takes about three months to complete.

Table 3.4.2—Standard Tests for Fluid Penetration Resistance

Std. Test No.	Property Measured	Prequal. Test?	Acceptance Test?		Strengths	Weaknesses	Improvement Needed
			On Cores	In-Place			
ASTM C 1202/ AASHTO T277	Electric/ conductivity charge passed	√	√	√	• Rapid • Equipment available • In Common use	• Affected by conductive admixtures and chloride contamination • An indirect test since it measures conductivity	• Improve multi-lab precision • Increase number of samples • Shorten test to minimize heating
Army Corps CRD 163	Water permeability				• Sensitive to low-permeability concretes	• Slow and can-not always measure flow	• Improve flow measurements
AASHTO TP64/Nordtest NT492	Chloride penetration	√	√		• Rapid and chloride front not affected by pore fluid conductivity	• Basis for diffusion value in NT Build 492 questioned	
ASTM C 1556	Bulk Diffusion	√	√		• Measures diffusion	• 3-month test	
ASTM C 1543	Chloride Penetration Profile?					• 6-month test	
AASHTO T259	Chloride penetration					• 6-monyh test	• Reasonable way to analyze results
Wenner Resistivity (Non-standard)	Surface resistivity			√	• Rapid	• Not yet standardized • Affected by chlorides, moisture, carbonation	
ASTM C 1585	Rate of Absorption		√		• Simple	• Sample conditioning is critical	• Develop field test as standard
ASTM C642	Absorption and permeable voids	√			• Simple	• Measures porosity (of permeable pores) not permeability • Potential for damage induced by drying	• Dry as last step

3.4.2.3 *Water Permeability*—There are no direct tests for water permeability in ASTM or CSA standards. The Corps of Engineers has two tests for water permeability, CRD 48 and CRD 163. The former is only sensitive to low cement content concretes, typical of mass concrete in hydraulic structures. The latter, using a high-pressure triaxial cell, is able to measure flow through lower permeability concretes and modifications to increase sensitivity have been proposed (El-Dieb and Hooton, 1995), but not incorporated in the standard. With both methods, obtaining data is sometimes problematic and slow.

3.4.2.4 *AASHTO T277/ASTM C 1202*—The so-called Rapid Chloride Permeability Test (RCPT), originally developed by D. Whiting (1981) as a rapid alternative to AASHTO T259 ponding test, has been used since 1983 and has become the most widely accepted "permeability" test method in North America as well as in many parts of the world. It has also been widely criticized for various reasons, including the fact that it is neither a true permeability nor a chloride diffusion test. 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 six-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 six-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" six-hour value without the effects of heating (McGrath and Hooton, 1999; Julio-Betancourt and Hooton, 2004). Also ASTM C09.66 is currently balloting a modified version of C1202, where the one-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).

While C 1202 limits are not currently used in the ACI 318 specification, a limit of 1500 coulombs has been specified in the Canadian CSA S413 Parking Structures Standard since 1994. The newly issued CSA A23.1 (2004) has adopted a 56-day limit of 1500 coulombs for reinforced concrete exposed to de-icer salts (C-1 exposure class) and 1000 coulombs for HPC exposed to de-icer salts where extended service life is required (C-XL exposure class). It is noted that the RCP test results, as with strength, will vary with concrete maturity, especially for concrete containing supplementary cementing materials. Therefore in specifying limits and interpreting the results it is necessary to consider the age or maturity at which the test is conducted. This test has been widely used in the field, particularly on structures made with High-Performance concrete and data related to this use are given later.

3.4.2.5 *AASHTO TP64 Rapid Migration Test*—The Rapid Migration Test (RMT) was originally proposed by Tang and Nilsson (1992) in Sweden and was standardized as Nordtest NT Build 492 (Stanish, Hooton and Thomas, 2001, 2005). In AASHTO TP 64 a

50-mm (2-in.) long, 100-mm (4-in.) diameter concrete sample is saturated using the vacuum saturation procedure of the RCPT. Similar to T277, the sample is then clamped inside a silicone rubber tube between a sodium chloride solution on one side and a sodium hydroxide solution on the other.

Initially a 60 volt potential is applied across the sample and based upon the initial current measured, the voltage is adjusted according to a table to bring it to a range suitable for the level of conductivity of that particular concrete specimen. The voltage is then applied for 18 hours. The applied voltage drives the chloride ions into the previously uncontaminated concrete. Upon removal, the concrete sample is split in half along its length. The broken faces are then sprayed with 0.1 molar silver nitrate solution, a colorimetric indicator. The silver nitrate reacts with any stable chloride ions that are present to form a white layer, while the uncontaminated area turns brown. The average depth of chloride penetration is obtained by taking measurements at 10 mm (1/2 in.) intervals across the diameter. The average value is then divided by the product of the applied voltage in volts and time in hours to rate the sample.

The main difference between AASHTO TP 64 and Nordtest NT Build 492 is that NT 492 allows calculation of a non-steady state, chloride diffusion coefficient. This was considered for the AASHTO test, but the theory behind the calculation has been questioned (Stanish et al, 2004).

This test ranks multiple concretes in the same order as ASTM C1202, but has the advantage of not being influenced by strongly ionic admixtures, such as calcium nitrite. As well, the specimen does not experience a temperature rise during the test. The test also has been shown to have a somewhat lower variability than the RCPT (Hooton et al, 2001). It is believed that the Rapid Migration Test has some advantages over ASTM C 1202 and it could be used as a quality assurance test for evaluation of concrete quality. However, the C 1202 test is widely available and most agencies, test labs and concrete producers are familiar with it.

3.4.2.6 *Resistivity Tests*—Some researchers and various agencies have used electrical resistivity tests, such as the 4-point Wenner probe, for evaluating both lab and field concretes. Resistivity is the inverse of conductivity. To date, none of these tests have been standardized. They are quick and easy to perform but are affected by the moisture content (degree of saturation), and the presence of conductive ions in the concrete pores (eg. chlorides, calcium nitrites).

3.4.2.7 *Rate of Absorption (Sorptivity) Tests*—ASTM C 1585 was standardized in 2004. After conditioning concrete slices from cores or cylinders in a specified low humidity environment, the rate of absorption of water into one face of the disc is measured. Generally, sorptivity will decrease with lower w/cm and increased maturity of the concrete, and is influenced by SCM's. Since water is only absorbed on one face, this test has scope for evaluating the quality of curing when either the finished or formed face is tested. This test is related to the British BS1881 Initial Surface Absorption Test (ISAT) test developed by Levitt and adopted in the 1970's, but the test configuration and test procedures are better defined (Hall, 1989). However the ISAT test can also be used as a non-destructive test in the field (but results are severely affected by differences in in-situ moisture conditions) (Nokken and Hooton, 2002). Several field sorptivity tests exist, but all suffer from the strong influence of degree of saturation of the in-situ concrete when tested. To deal with this, as well as improve the test procedures, DeSouza, Hooton and

Bickley (1997, 1998, 2000) developed an improved field sorptivity test and a method to correct for in-situ moisture effects by measurement of relative humidity and temperature of the surface before test. The Ontario Ministry of Transport has drafted a standard test method for this procedure, but will not implemented it until a more specific procedure for making moisture corrections is in place (current research by Hooton). Sorptivity tests have been used in the field in Australia, U.S. and Canada and data related to this use is given later.

3.4.2.8 *Absorption and Voids Test* Values for the water absorption and volume of permeable pores obtained using ASTM C 642, (although not a permeability test), have been used as indicators of concrete quality.

3.5 Specific Durability Issues

3.5.1 *Alkali-Aggregate Reaction*—Resistance of a concrete to Alkali-Aggregate Reaction (AAR) requires pre-testing or knowledge of aggregate performance by the concrete producer. If tests indicate that the aggregates are reactive, the producer then needs to either change aggregate supply or develop concrete mixtures which, as demonstrated by performance testing, will prevent deleterious expansion and cracking when those aggregates are used.

The Appendix to the aggregate specification, ASTM C 33, simply lists various test method limits without providing any real guidance as to selection of appropriate test methods. The list in C 33 includes C 227 mortar bars, C 287 quick chemical tests, C1260 accelerated mortar bars and C 1105 or C 1293 concrete prisms (Tables 3.5.1a and 3.5.1b). Various other ASTM specifications use ASTM C 441 (or C 227 with Pyrex glass synthetic aggregate) to determine the efficacy of a pozzolan or slag (C 618, C 1240, C 989) or blended cements (C 595, C 1157) in controlling ASR However, ASTM C 1567 (similar to CSA A23.2-28A) has just been standardized in 2004, which uses a modification of the C 1260 aggregate test. The actual aggregate is tested with a specific pozzolan or slag and the expansion after 14 days exposure must be less than 0.10%. It is likely that this test will be adopted in some of the specifications for evaluation of job materials

In C 150, there is only the optional prescriptive low-alkali portland cement limit of 0.60% equivalent sodium content. ASTM C 1157 *Performance Specification for Hydraulic Cement* has an optional 14- and 56-day expansion requirement for *Low Reactivity with Alkali-Reactive Aggregate* using the ASTM C 227 mortar bar test made with Pyrex glass aggregate. The test has been found to not be very satisfactory and alternative methods are being investigated.

As an alternative to a producer having to test mitigative measures for each cementitious materials-aggregate combination, CSA has developed a guide and flow chart for selecting levels of mitigative measures to minimize the risk of deleterious expansion and cracking (CSA A23.2-27A). In the CSA Guide, only petrographic analysis (ASTM C 295), the rapid mortar bar test (CSA A23.2-25A, ASTM C 1260), and the concrete prism test (CSA A23.2-14A, ASTM C 1293) are used to identify whether aggregates are reactive and establish the level of reactivity (Thomas, Hooton and Rogers, 1997).

Table 3.5.1a—Alkali Silica Reaction Test Methods

Std. Test No.	Property Measured	Prequal. Test?	Acceptance Test?		Strengths	Weaknesses	Improvements Needed
			On Cores	In-Place			
C 1260	Potential for expansion due to aggregate reactivity	√			• Rapid • Repeatable	• Not applicable to low alkali cements • Is an aggregate test and is not applicable for evaluation of low alkali cement-aggregate combinations	• Reduce false positive
C 1293	Potential for expansion due to aggregate reactivity	√			• Reliable relative to field experience	• Too long	• Accelerate
C 289	Alkali reduction & silica dissolution	√				• Not reliable, especially with carbonate aggregates	• Test method not used by CSA
C 441	Effectiveness of SCMs in reducing Expansion					• Pyrex glass is too reactive and variable	• Test method not used by CSA • Consider use of C1567 instead
C 227	Potential for expansion due to aggregate reactivity	√				• Alkali leaching reduces expansion	• Test method not used by CSA
C 295	Mineralogy	√			• Rapid	• Only measures potential risk • Requires special expertise	
C 1157	Effectiveness of Blended Cement in reducing Expansion	√			• Rapid	• Unreliable- uses C227 with Pyrex	• Consider use of C1567 instead
C 856	Damage, gel					• After the fact	
Uranyl acetate	Reaction Product				• Rapid	• After the fact	
C 1567	Expansion	√			• Rapid • Evaluates job mix combinations	• Can be conservative	

Table 3.5.1b—Alkali Carbonate Reaction Tests

Std. Test No.	Property Measured	Prequal. Test?	Acceptance Test?		Strengths	Weaknesses	Improvements Needed
			On Cores	In-Place			
C 1105	Expansion	√			- Repeatable	- Too slow	- Replace with C1293
C 1293 CSA A23.2-14A	Expansion	√			- Faster than C1105	- Still too long	- Need to accelerate
C 586	Expansion	√			- Exp. tendencies usually evident after 28 days	- Qualitative measure of aggregate performance in concrete	
Microbar Test	Expansion	√			- Rapid test (suitable for both ACR & ASR)	- Evaluate only aggregate performance; slower than C1260	- Not yet standardized or widely used, but being considered by CSA
CSA A23.2-26A	Chemical Composition	√			- Simple and rapid	- Prescriptive	
C 295	Mineralogy	√				- Only measures potential risk	
C 856	Damage, Gel					- After the fact	

Table 3.5.2: Sulfate Resistance Tests

Std. Test No.	Property Measured	Prequal. Test?	Acceptance Test?		Strengths	Weaknesses	Improvements Needed
			On Cores	In-Place			
C 1038	Potential expansion due to excess cement sulphate content	√			• Performance	• Claims that results not as conservative as C265	• Expansion limits and age may need scrutiny
C 265	Dissolved sulfate test for detection of excess cement sulphate content	√			• Semi-performance	• Precision of test is poor and is no longer referenced in C150 Spec.	
C 452	Potential sulfate resistance as determined by expansion	√			• Performance	• Only valid for Portland cements	
C 1012	Potential sulfate resistance as determined by expansion and mass loss.	√			• Performance test valid for blended cements and SCM-Portland mixtures	• Takes too long	• Need to accelerate

For alkali-silica reaction, in CSA A23.2-27A, once the level of reactivity of the aggregate is established, the type and required service life of the structure along with the level of exposure to moisture are used to establish the level of mitigating measures needed. There is then a table where a producer can choose to either a) not use the aggregate, b) restrict the alkali loading of the concrete to a certain level (alkali loading is defined as the equivalent alkali content of the portland cement multiplied by the portland cement content of the concrete mixture, this concept is also used in BS 8500), or c) use a specified minimum quantity of a pozzolan or slag (of specified chemical compositions) or combinations of pozzolans and slag. If the producer wants to use a lower level of mitigating measures then that mixture must be tested using a modified ASTM C 1293 (CSA A23.2-28A) by measuring expansion for two years. For alkali-carbonate reaction, no mitigating measures have been found to be effective (Rogers and Hooton, 1992).

3.5.2 *Sulfate Resistance*—The ACI 318 and CSA A23.1 concrete codes provide limits on *w/cm* as well as on the types or performance levels of the cementing materials that are to be used for various levels of sulfate ions in the soil or ground water. The *w/cm* limits as a control on permeability are necessary since it is very important to minimize sulfate penetration as sulfate resistant cements only slow the rate of sulfate reactions. Also, in some cases where evaporation can occur from one face of a structure (eg. slabs on grade, culverts or tunnel liners), severe premature sulfate-salt related damage can occur on or below the evaporative face regardless of the type of cement used. The w/cm limits are therefore used as a way of limiting ingress of sulfates. There is no standard sulfate resistance test method for evaluation of concrete, since such tests would take many years to achieve reliable results. The tests that exist are only for evaluating the chemical resistance of the cementing materials combination to be used in the concrete (Table 3.5.2). Sulfate resistant portland cement is evaluated using ASTM C 452 (a mortar bar expansion test where excess sulfates are added to the mixture). Blended cements and combinations of pozzolans or slag with Portland or blended cement are evaluated using ASTM C 1012. In this test, mortar bars are exposed to sulfate solutions after a strength of 20 MPa (2850 psi) has been achieved. The downside of this is that the test takes at least six months and in some cases 12 months to determine equivalent performance to Type II or V cements, such as in ASTM C1157, C 989, C 618 and C 1240 specifications. In the ACI 201-2R document (not yet adopted by ACI 318), for showing resistance to very severe sulfate exposure (SO_4 content > 10,000 ppm in water, or > 2.00% water soluble SO_4 in soil), 18 months are needed.

In the new European code, there has been no agreement on a standard test to evaluate the sulfate resistance of cementitious materials.

3.5.3 *Freezing and Thawing and Salt Scaling Resistance*—It is generally acknowledged that for concrete to possess adequate resistance to cyclic freezing and thawing while in a critically saturated state, it must have sufficient strength prior to freezing, the coarse aggregates must be frost resistant and, in most cases, an adequate entrained air-void system is needed. Specifications such as CSA A23.1 require fresh concrete to have sufficient air, but also require a maximum air-void spacing factor to be achieved in hardened concrete (230 μm (0.009 in.) on average with no single value in excess of 260 μm (0.010 in.), determined using the ASTM C 457 microscopic method). ASTM C 457 is used for acceptance in some instances, typically in End Result Specifications (ERS). It is slow and tedious to perform. Several image analysis systems have been proposed to help automate this test and the most promising is a Danish device called Rapid Air 457. For aggregate acceptance, many specifications use tests such as the ASTM C 88 Magnesium Sulfate Soundness or the Micro-Deval test to assess the freezing and thawing resistance of coarse aggregates for use in concrete, in addition to testing concrete directly using ASTM C 666 (Vogler and Grove, 1989).

Two categories of concrete tests have been developed.

a) *In Water* (see Table 3.5.3a)—ASTM C 666, Procedure A, is used to evaluate the resistance of concrete mixtures to cyclic freezing and thawing while submerged in water (except for Procedure B, when samples are drained prior to freezing and samples are frozen in air). The loss of dynamic modulus of elasticity due to internal cracking is used as the measure of resistance. Other properties, such as mass loss (a measure of surface scaling) or length change (internal damage) can also be included. While this test is commonly used (with different agencies using different acceptance criteria, (see Vogler and Grove, 1989) and can show the individual benefits of air-entrainment and frost resistant aggregates, it has been criticized for being overly aggressive (Sturrup, Hooton, Mukherjee, and Carmichael, 1987). In Europe, several tests have been developed, including the CIF test (Setzer), and the Swedish test SS 13 72 44 (prEN 12390-9). In the CIF test, concrete slabs (sides sealed with epoxy) are dried in air at 65% rh for 21 days then saturated by capillary suction with water for seven days prior to placement in a carefully controlled freezing and thawing chamber. Each 12-hour cycle is from +20C to -20C at 10C/h and a hold for 3h at -20C. The mass of scaled material is determined once removed in an ultrasonic bath after every four cycles and the internal damage is measured using ultrasonic pulse velocity to determine changes in dynamic modulus of elasticity. A 20% loss in dynamic modulus is used to determine damage and the number of cycles to attain this condition is measured. The Swedish test results have been compared to field performance (Petersson, 1997).

b) *In De-Icer Salt Solutions* (see Table 3.5.3b)—ASTM C 672 qualitatively measures the resistance of concrete surfaces to cyclic freezing and thawing in the presence of de-icer salts. Some agencies in Canada, such as MTO (OPS LS-412) and MTQ (BNQ NQ 2621-900), have modified this test to include quantitative measurement of the mass of scaled material/unit surface area. One concern with this test is that it appears to be overly severe for mixtures containing pozzolans and slag due to the lack of time allowed prior to testing for these materials to react and for the concrete to mature. While research is on-going, it appears that the Quebec BNQ test gives results which more closely predict field performance (Bouzoubaa, Bilodeau and Fournier, 2004). The differences between the BNQ test and ASTM C 672 are that: a) the surfaces are not given a brushed finish after trowelling, b) at 28 days of age, the 3% NaCl solution is ponded for seven days prior to freezing, and c) scaling mass losses are measured after 7, 21, 35 and 56 cycles of freezing, with automated cycling freezers running seven cycles per week.

Table 3.5.3a—Freezing and Thawing Related Tests

Std. Test No.	Property Measured	Prequal. Test?	Acceptance Test?		Strengths	Weaknesses	Improvements Needed
			On Cores	In-Place			
C666A,B	Mass loss, Dynamic modulus, Length change	√			• Rapid, Repeatable	• Pre-condition too short for SCM mixtures. • Overly harsh test	• Increase maturity of SCM mixtures before test (e.g. VDOT)
SS 13 72 44	Mass Loss	√			• Related to Field		
CIF	Ultrasonic Pulse Velocity	√			• Precise temperature cycle	• Expensive equipment	
C 457	Air Content, Spacing Factor, Specific Surface in hardened concrete		√		• Good correlation with F/T performance	• Sensitive to operator & sample prep. Not a direct measure of F/T durability	• Automate to remove operator sensitivity
Air Void Analyzer	Air Content, Spacing Factor, Specific Surface in plastic concrete			√	• Rapid and is performed on fresh concrete in-situ	• Not yet in mainstream use	• Guidance required for interpreting results to convert to C457 type output.

Table 3.5.3b—De-Icer Scaling Related Tests

Std. Test No.	Property Measured	Prequal. Test?	Acceptance Test?		Strengths	Weaknesses	Improvements Needed
			On Cores	In-Place			
C 672	Visual	√				• Pre-condition period too short for SCM mixtures	• Increase maturity of SCM mixtures before test (e.g. similar to VDOT RCPT). • Determine effect of MgCl2
C 672-Modified OPS LS-412	Visual & Mass loss	√				• Pre-condition period too short for SCM mixtures. • Too severe relative to field performance	• Increase maturity of SCM mixtures before test (e.g. VDOT). • Assess results after 5-10 cycles.
BNQ 2621-900	Mass loss	√			• Relates to field performance		
Swedish SS 137244	Mass loss	√			• Relates to field performance		
CDF (German)	Ultrasonic pulse Velocity	√			• Precise Freeze-Thaw Cycle	• Expensive Equipment	• Correlate field performance to lab test.
C 457 (based on cores from field)	Air Content, Spacing Factor, Specific Surface		√		• Good correlation with sealing resistance	• Sensitive to operator & sample prep. Not a direct measure of scaling resistance.	• Automate to remove operator sensitivity
Fresh Air Void Analyzer	% Air, Spacing Factor, Specific Surface			√	• Rapid • Tests fresh concrete	• Not yet in mainstream use	

In Europe, both the CDF test (Setzer and Auberg, 1995) and the Swedish standard test (SS137244) are being used. The relationship between the Swedish test, which may be adopted in the European standards and field performance, has been reviewed by Petersson (1997). In the CDF test, concrete slabs (sides sealed with epoxy) are dried in air at 65% rh for 21 days then saturated by capillary suction with a 3% sodium chloride solution for seven days prior to placement in a carefully controlled freezing and thawing chamber. Each 12-hour cycle is from +20C to -20C at 10C/h and a hold for 3h at -20C. The mass of scaled material is determined once it's removed in an ultrasonic bath after both 14 and 28 cycles. In the Swedish test, concrete cores or slabs are cured as desired then conditioned in air for seven days prior to ponding at 28 days with water for three days, then replacing the water with 3% NaCl solution. The specimens are sealed with a rubber membrane then insulated on all sides except the test face. Freezing cycles are between 20C and -18C with one cycle per day. Mass loss is measured after 28, 56 and optionally 112 cycles, with several criteria including acceptable results if <1.0kg/m2 at 56 cycles and very good results if <0.10kg/m3 at 56 cycles. This test can also be performed with water on either cut, cast or formed surfaces to serve as a freezing and thawing test.

3.5.4 *Chloride Content*—The chloride content of concrete is limited in most codes such as ACI 318, CSA A23.1 and BS 8500 for use in reinforced and prestressed concrete in different exposure conditions (see Table 3.5.4a). ASTM C 1218 is specified in ACI 318 for measurement of water-soluble chloride and a similar test A23.2-4B is used in CSA A23.1. This is not satisfactory where interference from some chloride-bearing (but generally insoluble) coarse aggregates are used (eg. limestones around both Chicago and Toronto). The problem occurs due to the crushing of the entire concrete sample, thus releasing the normally-bound chlorides in the coarse aggregate. In these cases, ASTM C 1524 ("Soxhlet" test) can be used to measure the soluble chloride content of the uncrushed aggregate independently. ASTM C 1152 is used to measure total chlorides (acid soluble). These test methods are summarized in Table 3.5.4b.

Table 3.5.4a
Maximum water-soluble chloride values from ACI, CSA and EN standards

Maximum % chloride by mass of cementing material	ACI C318-05	CSA A23.1-04	EN 206.1:2000
Prestressed	0.06	0.06	0.10 (0.20 if dry*)
Reinforced and exposed to chlorides	0.15	0.15	0.20
Reinforced in dry conditions	1.0	1.0	0.40*
Reinforced in damp conditions		0.15	0.20*
Other reinforced concrete construction	0.30		
Non-reinforced	-	-	1.0

*** Assumed, since it was not clear from Table 10 of EN 206.1**

Table 3.5.4b—Chloride Content Tests

Std. Test No.	Property Measured	Prequalif Test?	Acceptance Test?		Strengths	Weaknesses	Improvements Needed
			On Cores	In-Place			
C 1152	Acid-soluble chloride in concrete	√			• Total Chloride-reproducible	• Primary interest in water soluble chloride	
C 1218	Water-soluble chloride in concrete	√				• Can remove innocuous chlorides that are locked in coarse aggregate	• Development of Soxhlet test for concrete needed
C 1524	water-extracteable chlorides in aggregate only (Soxhlet)	√			• Only measures chlorides available for corrosion	• Only useable for aggregate, not concrete	• Development of Soxhlet test for concrete needed

Well-compacted and cured concrete with sufficient depth of cover, which also has high resistance to chloride and carbon dioxide ingress, is needed to extend the time before the onset of corrosion of reinforcement. The ASTM C 1202/AASHTO T 277 test can be used as a rapid index test for chloride penetration resistance, as discussed previously. The use of pozzolans or slag will help to both reduce the rate of chloride ingress and most supplementary cementing materials will also increase the chloride binding capacity of the concrete. Use of some types of corrosion inhibiting admixtures, such as calcium nitrite, can also raise the concentration of chlorides required to initiate corrosion. Most of the other measures that can be taken to improve corrosion resistance (eg. depth of cover, type of reinforcement, surface sealers and membranes) are outside the control of the concrete producer. Some corrosion-related tests are listed in Table 3.5.4c.

3.5.5 *Acid Resistance*—Concrete is vulnerable to being dissolved in many acids. Different acids react very differently with concrete. Information about the effects of particular acids (and other aggressive chemicals) is given in a Portland Cement Association Bulletin (PCA, 1997).

Acids will reduce the alkalinity of the pore solutions and result in destabilization and dissolution of C-S-H as well as calcium hydroxide. The best way to limit the rate of attack is to reduce the permeability of concrete by a combination of low *w/cm*, use of SCM's, and by proper curing. Other than that, one has to rely on surface coatings that act as barriers between the acid and the concrete.

There are no standard test methods known to be available which specifically evaluate resistance of concrete to acids.

3.5.6 *Abrasion and Erosion Resistance*—Resistance to abrasion is achieved by design of concrete with high-strength at the surface, that has been well-cured concrete made with abrasion resistant aggregates. Additional benefits can be attained through use of silica fume (to improve bond of paste to aggregates) and by use of fiber reinforcement (to reduce loss of surface paste). There are several ASTM test methods (Table 3.5.5) contained in C 1138, C 994, C 779 and C 418. Most of these tests measure mass loss or depth of abrasion. Abrasion resistance limits have not been commonly specified, except for specific hydraulic structures and pavements.

Table 3.5.4c—Corrosion Related Tests

Std. Test No.	Property Measured	Prequal. Test?	Acceptance Test?		Strengths	Weaknesses
			On Cores	In-Place		
C 876	Voltage potential				• Rapid, Non-destructive. • Sometimes correlates with corrosion performance	• Not a direct measure of corrosion rate and not always accurate
G 109	Time-to corrosion and rate of corrosion	√			• Suitable for relative comparison of concrete mixtures	• Does not account for field conditions
C 1556	Bulk diffusion	√			• Suitable for relative comparison of concrete mixtures	• Not for concrete that has been exposed to chlorides in the field
C 1202	Conductivity	√			• Provides a rapid indication of resistance to chloride ion penetration	• Does not directly relate to corrosion activity
C 1543	Chloride penetration	√			• Measures direct penetration of chloride ions into concrete	• Slow
C 876	Voltage potential				• Sometimes correlates with corrosion performance	• After the fact • Not a direct measure of corrosion rate and not always accurate
LPR and GP*	Corrosion current and corrosion rate				• Data has been used for in-service evaluation • Provide information on corrosion rate	• After the fact. • Not widely used and reliability is questioned • Works better in the lab

* LPR = Linear Polarization Resistance, GP = Galvapulse

Table 3.5.5—Abrasion and Erosion Tests

Std. Test No.	Property Measured	Prequal. Test?	Acceptance Test?		Strengths	Weaknesses	Improvements Needed
			On Cores	In-Place			
C 944	Mass loss and depth of wear from rotating cutters	√			• Applicable to in-place concrete	• Sensitive to specimen prep. • Not applicable to textured surfaces.	• Reproducibility
C 779	Depth of wear by three methods: revolving disk, ball bearings, dressing wheels	√			• Can be used to assess surface treatments and finishing	• Does not assess length of service • Precision is good only on revolving disk method	• Reproducibility on 2 of 3 methods
C 418	Abraded volume by sandblasting	√			• Simulates abrasion under traffic	• Does not assess length of service	
C 1138	Abraded volume and depth of wear under water with ball bearings	√			• Simulates abrasion under water • Can be used to assess overlays	• Most concrete use is not underwater	

3.6 Test Methods for Performance Specifications

3.6.1 *Tests Currently Ready for Adoption in Specifications*—A number of tests either have or could be adopted in performance specifications. These are listed in Table 3.6.1 along with a few tests that could be ready in a few years. Most of them would be suitable for prequalifying concrete mixtures, provided sufficient lead-time is available to develop the data. Several of these tests are discussed later in Examples of Advanced Test Procedures, Section 3.7.3. Performance limits for each test would have to be established in advance by the Owner or the Owner's representative.

Table 3.6.1a

Properties of concrete that can currently be specified in a performance contract

Properties can be confirmed precontract by the supplier		
Property	ASTM #	Lead time required
Density (Unit Weight) Yield and air content of fresh concrete	C 138	
Density of fresh and hardened structural lightweight concrete of fresh concrete	C 567	
Early-age strength	C 39	
Flexural strength	C 78	
Density Absorption and Permeable voids of hardened concrete	C 642	
Shrinkage	C 157	180 days
Freeze-thaw resistance	C 666	90 days
Modulus of elasticity	C 469	
Creep	C 512	1-2 years
Splitting tensile strength	C 496	
Scaling	C 672	90 days
ASR-to evaluate aggregates	C 1260	2 weeks
	C 1293	1 year
ASR-to evaluate job combinations	C 227	3-6 months
	(CSA A23.2 -28A)	2 years
ASR-to evaluate job combinations except when low alkali cement used	C 1567	2 weeks
Alkali content	Chemical analysis	
Rapid Chloride Permeability	C 1202	28-56 days

Notes: For precision statements see the text of the cited ASTM test.
Where lead-time is not stated, it will be at the age specified.

Table 3.6.1b
Properties of concrete that may be specified in a performance contract in the near future (some have been used already)

Air-void system	C 457	14
Sorptivity	C 1585	28-56
Rapid Migration Test	AASHTO TP64	28-56
Chloride Bulk Diffusion	C 1556	35 days after sampling

3.6.2 *Tests Used Outside the USA*—For information, Table 3.6.2 lists the tests discussed or implied in the international documents reviewed in Part II of this report.

Table 3.6.2—Test Procedures listed in Countries outside the U.S.

Property **Document**

Australia

Mass	AS 1379-1997, amended 2000
Chloride content	
Sulfate content	
7-day strength	
Flexural strength	
Indirect tensile strength	
Cracking	
Sorptivity	Ho and Chirgwin, 1996
Permeable voids	
ASTM 1202	
Chloride diffusion	
Modified ASTM C1202	
Ion migration	
Long term corrosion data	
Electrical impedance	
Cyclic chloride penetration test	

New Zealand

Floor flatness	CCANZ 2000 Specifying Concrete for Performance
Shrinkage	
Thermal contraction	
Crazing	
Plastic shrinkage	
AAR	
Abrasion resistance	
Chemical attack/resistance	
Chloride ingress/attack	
Maturity	
Cover	
Chemical attack	DZ 3101 Concrete Structures Standard
Cover	
Chloride ingress	
Cast-in-place hardware	
Abrasion	
AAR	

New Zealand-continued

Carbonation	DZ 3101 Concrete Structures Standard
Freeze-thaw resistance	
Chloride content	
Sulfate content	
Sorptivity	
Absorption	
Accelerated carbonation testing	
Alkali content	CCANZ Publication TR 3 Alkali-Silica Reaction

Malaysia

Modulus of elasticity	Twin Towers Specification, Kuala Lumpur
Creep	
Shrinkage	

South Africa

Chloride conductivity	Alexander and Stanish, In press University of Capetown and Alexander et al Concrete, no 107, September 2004
Oxygen permeability	
Sorptivity	

Europe

Sorptivity	European Standard EN 206-1
Chloride content	
Carbonation	
Chloride induced corrosion not from sea water	
Chloride induced corrosion from sea water	
Freeze-thaw attack	
Chemical attack	
Splitting tensile strength	
AAR	
Density: Normal-weight	
Density: Lightweight	
Density: Heavy-weight	
Resistance to water penetration	
Resistance to abrasion	
Heat development during hydration	
Water-cement ratio of fresh concrete	
Cement content	
Flexural strength	
Pullout force	
Ultrasonic pulse velocity	

Europe-continued

Accelerated carbonation	Duracrete final report
CEMBUREAU method	
TORRENT method	
Rapid chloride migration method	
Chloride profiling method	
Two-electrode method	
WENNER probe	
Multi-ring-electrode	
Freeze-thaw: Capillary suction of water	
Freeze-thaw: Capillary suction of De-Icing Solutions	

England

Cover	BS 8500,
Carbonation	
Chloride transport	
Gas permeability	
Chloride threshold	
Leaching of reaction products	
Freeze-thaw	
Sulfate/seawater attack	
Other chemical attack	
Abrasion	
Temperature rise and differentials	
Thermal expansion	
AAR	
Delayed Ettringite Formation	
Drying shrinkage	
Density	
Tensile splitting strength	
Flexural strength	
Static modulus of elasticity	
Water absorption	
Analysis of hardened concrete	
Temperature matched curing of test specimens	

France

Permeability	Baroghel-Bouny, 2002 and 2004
Chloride diffusion coefficient	
Calcium hydroxide content	

Canada

ASTM C 1202	HPC Contracts
Air void system	
Scaling	
Shrinkage	
Sorptivity	
Toughness	
Freeze-thaw durability	

3.7 In-Place Testing

3.7.1 *Determination of In-Place Strength*—The test methods standardized in North America for estimating in-place compressive strength are summarized in Table 3.7.1. Of course, ASTM C 42 core tests are commonly used when standard cylinders do not meet the specified strength. In some End Result specifications, core strengths are used to determine compliance. While several other methods can be used in specific circumstances to obtain limited information none have been in common use in the past. In recent years two methods of determining the in-place strength of concrete have proven to be the most reliable and practical, and have found increasing use.

3.7.1.1 *Maturity Testing*—The strength of a concrete mix at any age is a function of the maturity of the concrete in terms of the integral of time and temperature above a certain base value. Plowman (1956) postulated a systematic approach to determining the strength of concrete based on a temperature-time approach using -10°C as a base temperature. The subsequent very extensive response to this paper pointed out flaws in the relatively simple approach used by Plowman and introduced a number of other important factors. In general it was concluded that, if maturity testing is carried out by recognizing and applying these limiting factors, the approach can be used with confidence for early age testing of concrete in structures. Subsequent interest by Akroyd and Smith-Gander (1956) led to developing an accelerated compressive test that imparted a significant maturity to concrete specimens by using boiling water and testing specimens at an age of 29 hours. This technique was used successfully on the construction of the Forth Road Bridge (UK) in 1958. In-place strengths were predicted using this test procedure and, if strength was predicted to be marginal, no further concrete placements were added to the structure until later age standard tests had been performed.

In 1971 and 1972 maturity tests were made on two buildings at the University of Waterloo in Ontario using thermocouple readings that were converted to strength values based on a strength-maturity curve predetermined by trial mixes of the concrete proposed for the project (Goldes, 1973 and Mukherjee, 1975). The use of this procedure on this and other projects enabled form removals to be made safely at early ages and thus accelerate the construction schedule. The extensive use of maturity to predict in-place strength was first used on the construction of the CN Tower in Toronto during the winter of 1973-1974 (Smith and Bickley, 1974) Subsequently improved standard procedures for maturity testing were developed, based on the more reliable Arrhenius equation (ASTM C 1074).

Recently, maturity testing has been adopted as a preferred test procedure for highway structures by FHWA (FOCUS, October 2002). Determining the maturity of concrete is based solely on a time-temperature history. Practice is to require a physical confirmation of the strength of the concrete in the structure by testing concrete specimens made from the concrete used in the placement being evaluated or by pullout testing (ACI 228).

Table 3.7.1a—Estimating In-Place Compressive Strength

Test	ASTM	Strengths	Weaknesses
Rebound number	C 805	Simple	Sensitive to surface quality and moisture condition
Penetration resistance	C 803	Simple but uses an explosive charge	Sensitive to surface hardness and not accurate for concrete over 4000 psi
Pullout	C 900	Correlates accurately with compressive strength. Tests are completed in the field	Inserts should be pre-placed
Break-off	C 1150	Useful if relevant correlation made	Found to be difficult to make on a construction site
Ultrasonic pulse velocity	C 597	Accurate at very early ages. May be useful for comparisons	Not accurate once concrete has gained significant strength
Maturity method	C 1074	Simple and accurate	Needs correlation for each concrete mix. Does not measure a strength property of the concrete
Cast-in-place cylinders	C 873	Accurate measure of in-place strength	Costly if used in appropriate numbers. Laboratory needed to test specimens
Combined methods		Maturity testing can determine when a specified strength has been reached. Pullout tests can then confirm the in-place strength.	

Table 3.7.1b—Estimating In-Place Durability

Test	ASTM	Strengths	Weaknesses
Field Sorptivity	-	Simple to perform Commercial devices available Non-destructive	Sensitive to surface moisture and temperature
Rapid Chloride Permeability	C 1202	Relates to chloride penetration resistance and permeability	Requires coring
Air Void Properties	C 457	Evaluates in-place air content and spacing factor	Requires coring and polishing

3.7.1.2 *Pullout Testing*—The earliest reference to pullout testing was in 1938 (Skramtajev). Subsequent research (Malhotra 1975) and field trials showed that there is a reliable, accurate and repeatable relationship between pullout strength and the compressive strength of concrete. Until the introduction of the Lok-Test system in the late 70's there was not a portable, simple-to-use and accurate method for making pullout tests in the field. Because of the simplicity and reliability of the LOK version of the pullout test it has found wide acceptance worldwide. Many papers have been published on the use of this test system and it has been standardized by ASTM C 900 and practice detailed in ACI 228.1R-03. The practical and economic value of this test procedure was established through use on many construction projects (Bickley 1982 and 1984). Pullout testing and maturity testing were combined on the Scotia Plaza project in Toronto, Canada, to provide form removal as early as 11 hours after casting combined with a high assurance of safety.

3.7.2 *Use of In-Place Tests Other than for Strength*—Other tests performed on in-place concrete typically involve removal of cores from the structure, as in several highway agency ERS. A number of these are discussed in the examples in 3.7.3. The most common one appears to be ASTM C 1202 coulomb testing.

3.7.2.1 *ASTM C 1202*—This test has become popular in North America for contracts specifying HPC. Most states, provinces and some cities specify a maximum coulomb value. This varies in different jurisdictions. In the U.S., values between 2,000 and 2,500 coulombs are recommended for bridge decks (Ozyildirim, 2003). 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 with slag or fly ash as replacements for a percentage of Portland cement and QC is good, there is no difficulty in achieving this value.

In February 2003, members of Canadian Standards committee A23.1 were asked to supply rapid chloride permeability test (RCPT) data (ASTM C1202) from HPC and C-1 Concretes, especially from field projects. 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 3.7.2.1, and more details are provided in Appendix B. Of 785 tests of HPC listed in Appendix C (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, 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 day, 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.

Another option to shorten the need for 56-day testing, used by Virginia DOT, is to use 28-day C 1202 tests 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 longterm benefits. This curing regime was found to give coulomb values similar to those obtained at 3-6 months when cured at 23°C.

It has been suggested that any specification limits (e.g. 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, based on the variability of the test results.

Table 3.7.2.1—Summary of ASTM C 1202 Data from Canadian Projects

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> 1,500
C1	23	12	52.2	1,500	**
C1/C2	6	No spec	-	-	5> 1,500**
C2	24	No spec	-	-	24> 1,500**
C1 + CI	2	No spec	-	-	2> 1,500

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

3.7.2.2 *Air Void Analysis*—In Ontario, the MTO requires in-place concrete to be tested for air content and spacing factor. For each test, a single core is cut longitudinally, and the contractor must send one half for independent testing. The other half is retained by the MTO in case of dispute.

The reliability of the test procedures in ASTM C 457 has long been the subject of ongoing disputes between the ready mixed concrete industry and customers for concrete. In most jurisdictions that specify this procedure, the test is performed on specimens cast from the concrete at the point of discharge from the mixer truck. The concern has been that the placing and compaction of the concrete would modify the air-void system from the point of discharge, particularly when the concrete had been pumped—and for good reason. In Ontario, MTO and sometimes other owners perform this test on cores drilled from the finished structure. Initially, this practice led to a number of disputes. Over a number of years the situation improved due to the combined efforts of both admixture suppliers and concrete producers who are paying more attention to air entraining admixture formulation and admixture compatibility, contractors and concrete pumpers who are learning about boom and hose configurations and pumping rates, and testing agencies who are learning how to take representative samples at the point of placement. It is now rare that a test for air-void quality fails to meet MTO criteria and when this occasionally happens it is generally attributable to a significant and identifiable departure from good practice.

Not only has CSA standard A 23.1 added specific magnification requirements for use in ASTM C 457 observations, but the Ontario Ministry of Transportation (MTO) runs a mandatory annual correlation program for all testing laboratories wishing to provide services on their projects. MTO has also introduced a referee procedure that can be initiated by either the contractor or the Ministry representative and test samples are retained for this purpose. In addition, ASTM C 457 provides data on the variations inherent in the test. Further information is provided in STP 169C (Hover, 1994).

In a paper presented in 2004 (Schell, 2004) recent MTO experience was summarized as follows:

Table 3.7.2.2 (a)
Ontario Ministry of Transport Experience in ASTM C457 Testing

Year	No of Contracts	No of Test Results	
		Pass	Fail
2002	38	261	7
2003	39	316	3

Notes: Failures were typically conventional concrete, not HPC. Problems occurred on parapet walls and piers. No apparent issues with pumped concrete.

Test data for 2003 were as follows:

Table 3.7.2.2 (b)
Ontario Ministry of Transport Experience in ASTM C457 Testing

	Conventional Concrete	HPC
Median air content: %	6.0	5.7
Standard deviation: %	0.70-2.3	1.2-2.6
Range	2.7-11.7	3.1-12.4
Median spacing factor: mm	0.146	0.163
Standard deviation: mm	0.012-0.060	0.023-0.050
Range: mm	0.011-0.354	0.071-0.280

The following table is a summary of other Canadian experience with the C 457 test:

Table 3.7.2.2 (c)
Canadian Experience in ASTM C457 Testing

Source	Normal (N) or HPC (H)	No of Results	Mean: mm	Range	Complied
MTO, 1999	H	52	0.150	0.065-0.310	51 complied
GTAA Elevated road	H	28	0.134	0.098-0.173	All complied
GTAA Bridge 201	H	4	0.203	0.173-0.232	All complied
MTQ 1997	H 60 MPa	6	0.208	0.157-0.319	All complied
MTQ 1997	H 50 MPa	7	0.177	0.125-0.218	All complied
MTO 2003	N	319	0.146 N	0.011-0.354	316 complied
	H		0.163 H	0.071-0.280	
		416			412 complied

The number of tests in compliance was 99%.

3.7.2.3 *Field Sorptivity and Permeability Tests*—Rate of absorption and in-place gas or water permeability tests can be used to evaluate finished or cast surfaces after curing, provided the concrete has had a period of air drying. The moisture content of the near surface region needs to be directly or indirectly measured as well since results are sensitive to moisture condition (Nokken and Hooton, 2002). A number of commercial test devices are available, some of which are summarized in the ACI Committee 228 (non-destructive testing) document.

Sorptivity tests have been used in Australia and by Virginia DOT as a performance test for in-place quality. In Ontario, MTO has been using the sorptivity test on contracts for several years but has not yet made it a specified performance test pending developing a solution to the problem of determining and incorporating the surface moisture content calculation into the test result (DeSouza, Hooton and Bickley, 1997; 1998).

In Ontario, a sorptivity test was successfully used on an HPC bridge deck. Finishing was by a Bidwell finishing machine except for a narrow band along each edge that was finished by hand. The test clearly distinguished between the quality of the machine finished area and the hand finished edges:

Table 3.7.2.3
Field Sorptivity Data, Ontario Ministry of Transport

Finish	Sorptivity: mm/min.$^{1/2}$	
	Mean Value	Standard Deviation
Machine	0.054	0.012
Hand	0.090	0.002

3.7.3 *Examples of the Use of Advanced Test Procedures*—Several agencies have already used what many would consider to be advanced test procedures in their specifications. A few examples of these are provided below.

a) *FHWA: Strategic Highway Research Program High Performance Concrete Projects*—Circa 1995, a program was established to assist states wishing to explore the potential benefits of High-Performance Concrete (HPC). Funding was provided to offset the start-up costs of designing, specifying, constructing and testing prototype HPC bridges. The program applied to both precast and cast-in-place HPC. In 1999 FHWA published a bi-monthly periodical titled *HPC Bridge Views*, (www.cement.org/bridges). This magazine reports on current state bridge projects together with items of interest relevant to the use of HPC. To date, nearly 40 issues have been published. A continuing topic is testing. Some states specify the ASTM C 1202 test. In accordance with the ASTM procedure test specimens can be either cast cylinders or cores drilled from hardened concrete. It is not clear from the literature if any states are testing cores taken from the hardened concrete in the structure. A significant number of states are specifying ASTM C 1202, so a significant body of data is being compiled.

b) *Virginia DOT*—The 2004 end result specification provides for payment for structural concrete based on strength and ASTM C 1202 results.

A 2004 HPC overlay contract specified performance criteria for air content, ASTM C 1202 permeability and bond strength. The contractor won a bonus and the cost to the state after allowing for the bonus was 15% less than for previous similar contracts.

Values for shrinkage have been established that can be used as performance criteria.

c) *Ontario Ministry of Transportation (MTO)*—In the mid 1990s the MTO decided to promote the use of HPC bridges as a strategy to increase service life and minimize repairs. Starting with a small prototype bridge in 1996 the proportion of HPC bridges built has gradually increased (over 60 by 2002). MTO policy with regard to testing is to specify new or modified test procedures for at least a year but not to make the test results part of the contract requirements. By this procedure, experience in the use of the test procedure is gained and provides a basis for adopting or rejecting the new procedure.

d) Port Authority of New York and New Jersey—The Port Authority has required that concrete mixtures be prequalified 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).

The Port Authority has also made use of the AASHTO T318 microwave water content test on fresh concrete.

3.8 General Considerations with Regard to Testing

It is axiomatic that tests are required to determine if a concrete mixture meets specified requirements. With a purely prescriptive specification, compliance with such tests are not usually the responsibility of the contractor or his/her concrete supplier. With a change to performance specifications there will be significant changes in responsibilities. Before attempting to define these changes it is worth considering the various factors that affect testing.

3.8.1 *Lead Time*—Typical lead times for bidding and for the start of construction after a contract award are very short. A review of the tables attached to this section of the report show that few qualification tests can be completed in a short period of time; some take months or even years to complete. However, it is possible that if prequalification were the norm, producers would have these data available for typical mixtures, as are currently available for test records of strength tests.

3.8.2 *Quality of testing*—The integrity of a test result is vital. Only laboratories complying with requirements of standard practice in ASTM C 1077 as verified by an independent inspection program such as that administered by CCRL should be used and testing personnel should be certified by ACI or another valid certification program. An important factor in the reliability of a testing company is a company owner's desire and ability to perform the tests in accordance with accepted protocol and to transfer that concern and commitment to the people doing the actual testing. Current technician certification programs do not include many of the durability tests discussed, nor are labs currently required to conform to any requirements pertaining to these tests. Industry organizations should consider developing reference sample testing programs ("Round-Robin" or Interlaboratory Tests) and encouraging laboratories to participate.

3.8.3 *Cost of Testing*—Too often contracts for testing are awarded on the basis of lowest bid without due assessment of the capability or track record of the testing company. The performance of a valid test requires strict adherence to the test procedure. It is not possible to cut corners or otherwise attempt to increase productivity in order to reduce unit costs.

3.8.4 *Cost of Preconstruction Test Programs*—The development and proving of concrete mixtures where durability or high strength characteristics have to be met can be costly as well as needing significant lead-time.

3.8.5 *Current Situation*—The only test procedures that are currently universally accepted are those to determine slump, fresh air content and strength (compressive/flexural/indirect tensile). It can therefore be concluded that for general use, a current performance oriented specification must be limited to these parameters.

There are, however, jurisdictions where more sophisticated test methods have been used to the extent that there is confidence in their validity and practicality. In such cases performance requirements can include the locally accepted tests. Examples would be the FHWA High-Performance Concrete program, now several years old and implemented by a large number of states. Other examples are the practices of the Virginia DOT, the Ontario Ministry of Transportation and the Concrete Canada program. As discussed, these programs make use of tests for shrinkage, rapid chloride permeability, sorptivity, and air void system parameters in hardened concrete.

3.8.6 *In-Place Testing*—An Owner buys a structure. Increasingly Owners require test data obtained on samples taken from the finished structure. This practice has significant implications for the concrete supplier. There is a need for both the concrete supplier to deliver the appropriate concrete and the contractor to place, compact and cure it to so that the required properties develop means that both are inextricably joined by similar interests and are dependent on each other. The supplier may be able to show that the concrete supplied had the specified potential, but in the case of a dispute both supplier and contractor will be parties to the actions and costs that result from a failure. Also, it must be recognized that acceptance criteria for in-place tests may be different than for those conducted in standardized conditions. For example, according to CSA A23.1-04, the average air void spacing factor must be less than 230 μm (0.009 in.), but a single value of up to 260 μm (0.0010 in.) is permitted. Therefore a value of 230 μm (0.009 in.), or less would be required for prequalification, but a single field value of 260 μm (0.0010 in.) would be satisfactory.

3.8.7 *How Soon is Soon Enough?*—Tests made by, or on behalf of, the Owner need to be made and reported to all relevant parties in a timely fashion in order to minimize damages in the event of a failure. Results need to be forthcoming quickly.

3.8.8 *How Reliable is Reliable Enough?*—The test procedures used and the acceptance limits specified must take into account the inherent variability of the tests.

3.8.9 *What are the Timelines?*—Currently, on a national level only the slump, air content and strength can be specified as performance parameters. However, based on extensive experience in a number of competent jurisdictions, a larger number of performance related tests can be used. These are the ASTM C 1202 rapid "permeability" test and the determination of the air void system in accordance with ASTM C 457. Expanding the use of these tests would make their wider adoption in national specifications possible in the near future. Sorptivity also has potential for performance specifications, but is less widely used at the present time.

3.9 Responsibility

Responsibility for the performance of a concrete mixture supplied to a performance specification will fall on the concrete supplier who will also need to demonstrate by prior testing that the mixture has the potential to meet the specified criteria. It will also be necessary for the Contractor to be able to prove good practice in installing the concrete. Again, the owner is interested in the performance of the structure and prequalification testing alone will not alleviate the requirements for compliance with in-place (or end-result) test limits. In this case, the shared responsibility between different parties, such as the producer and the contractor, can pose a problem unless they are working together with a clear understanding of the factors involved.

Chapter 4 Summary, conclusions, and recommendations

4.1 General

4.1.1 *Definitions*—There are multiple definitions of the term "performance specification." The Cement and Concrete Association of New Zealand clearly states "A performance-based specification prescribes the required properties of the concrete but does not say how they are to be achieved." NRMCA defines a performance specification as "a set of instructions that outlines the functional requirements for hardened concrete depending on the application. The instructions should be clear, achievable, measurable and enforceable." In either of these definitions and in many others there is room for interpretation as to whether the terms "required properties" or "hardened concrete" refer to hardened properties in the structure, hardened properties as sampled from the point of delivery, hardened properties as cast from prequalification testing or perhaps some combination. (Added complication comes from the likelihood that a contractor setting performance requirements for a concrete producer would include a number of fresh concrete requirements in addition to any hardened concrete requirements.) In the minds of many the term "performance specification" automatically conjures in-place properties of concrete as influenced by materials, proportions, construction operations and control of temperature and moisture. For others the term "performance specification" implies merely the freedom to supply concrete that meets point-of-discharge requirements without the customary qualifications or limitations on ingredients and proportions and without the need to submit documentation concerning materials or proportions. For still another group, the term "performance specification" implies that concrete is supplied on the basis of historical record or pre-construction test results, with only spot checking to verify that the mix delivered remains substantially the same as originally approved. In reality a performance specification can be any or all of these and users of the convenient catch phrase must carefully define it to avoid miscommunication. It may not be helpful to secure agreement to use "performance specifications" if the agreeing parties hold differing concepts. In all cases, however, there is a need to define the responsibility for product control and to allocate the authority to make the decisions about how to carry out that product responsibility.

4.1.2 *Keys to the concept of performance specifications*

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.

These four keys present at least the following challenges:

a.) Under current, predominantly prescriptive specifications, end product performance is not always comprehensively spelled out at the specification stage. For example, prescriptive specifications may not explicitly include requirements for abrasion resistance, scaling resistance or limitations on concrete cracking. Nevertheless, unsatisfactory performance in any of these categories is often pointed out after the concrete has been installed. The rationale for finding the concrete unsatisfactory may be that these common end-result requirements are generally implied and that the concrete would have been satisfactory if the prescriptive requirements would have been met. In contrast, performance specifications require an "up front" description of owner expectations. In most cases, this can take significant additional effort and expertise beyond that required for prescriptive specifications by design professionals working on the owner's behalf. In some cases the mechanisms involved are understood, but a reliable measure of end result performance is not easily obtained. In such cases it can be necessary to rely on an "index test" or to retain a prescriptive option that has served well. For example, strength test results might be used to estimate abrasion resistance based on a correlation with a given set of materials.

b.) Some commonly expected (although uncommonly specified) performance characteristics are not readily clearly definable or readily quantified. In-place cracking, movements due to shrinkage, scaling, pop-outs, color variations or local incidents of abrasion are easy to spot, but more difficult to describe in an unambiguous way.

c.) Despite an explosion of research and development into new concrete test methods, the industry does not yet have a comprehensive suite of test methods, or the predictive models to allow their use to reliably predict service life in general.

d.) Some contractors and concrete producers will need additional training to be able to select materials and construction operations that will produce the required concrete. Design professionals will also need additional training or special expertise (such as through certification) to be able to develop reliable performance requirements.

4.1.3 *This is not new*—The concept of performance specifications is not new. The ability to gain acceptance of concrete on the basis of proven performance requirements has been part of the ACI Building Code since its early days. Nevertheless, conventional concrete specifications include many prescriptive elements that also have their origins in the earliest code, perhaps reflecting an era when designers were masters of the selection and proportioning of concrete materials, and concrete producers purchased raw materials and batched in accordance with the specified instructions. Over the last several decades, however, concrete materials have become increasingly complex, with a growing number of combinations and permutations of cements, cementitious materials, admixtures, and aggregate types and grading. This not only means that there is a wider range of options for meeting any given concrete requirement, but also that it is more difficult for the design professional to stay current with concrete materials and construction technology as it has become a specialty field. Many producers have transitioned from being merely "truckers" who deliver concrete mixed in accordance with a specified recipe to being well informed on concrete materials, including complex aggregate grading, chemical admixtures and a wide range of cementitious materials. More recently fewer specifications require predetermined concrete recipes or materials and production inspections. Likewise there has been a shift in the responsibility for concrete ingredients and mix proportions toward the concrete producer and away from the design professional. Today's review of concrete mixture submittals "for general conformance with the contract documents," is a significant evolution from the fully specified mixture proportions of only a few years ago.

4.1.4 *Advantages and disadvantages*—There are advantages and disadvantages to the use of either performance or prescriptive specifications. The challenge is to find ways to combine the two types as appropriate for various applications to maximize the advantages and minimize the disadvantages. Performance may be called for when there are clear economic, logistical or scheduling benefits to be gained and those benefits can be shared with the designer and owner.

4.1.5 *Combinations of specification methods*—Arguments pitting performance against prescriptive specifications may not be productive. At issue is the most effective combination of specification requirements, with a sequence of prequalification, on-site testing at delivery and in-place evaluation of hardened concrete. One result of performance specifications is the ability to link payment to demonstrated quality. This results in penalties for quality that falls short of specified requirements but is acceptable (see 2.7.1.2, 2.7.1.3, 2.8.1.1 and 2.8.2). In a few cases, bonuses are also paid for achieving or surpassing the specified minimum quality. Ideally, these bonuses or penalties could be connected to anticipated life-cycle costs, but there are no clear examples of this to date. Where bonuses have been paid, concrete has been found to be either more consistent in quality or, in one documented case, cheaper [Sprinkel 2004]. Options on some projects would include separate sets or types of requirements for acceptance and for pay.

4.1.6 *Prequalification*—It makes good sense to qualify a mix for field use on the basis of preconstruction testing and/or historical record. Such prequalification demonstrates that the mixture and concrete producer have the potential to meet project requirements. However, the reality of batch to batch and day to day variability in some concrete production facilities (especially the variability in air and water content) make it necessary to demonstrate that the material delivered to the job (and in some cases as-placed, consolidated, finished and cured) lives up to its prequalification expectations. In some cases the difference between prequalification results obtained on concrete cast and tested in the laboratory vs. performance of actual production concrete needs to be considered when evaluating laboratory test results.

4.1.7 *Performance characteristics*—On any given job, regardless of type of specification, there may be a large number of concrete performance characteristics that are expected by the designer and owner. On that same job some of those expectations will have been incorporated in the formal specifications, while others will have been assumed to develop if the few specified properties are achieved. Performance specifications focus on specific concrete properties and hold the potential to clarify what is and what is not expected of the concrete.

4.1.8 *Durability*—The common concern worldwide is design for durable concrete. Common to most specifications is the use of Exposure Classes that clearly define expectations about the types of exposure that constitute the service environment of the concrete. Even under current and predominantly prescriptive specifications ambiguity is greatly diminished when the specifier clearly states the severity of the freeze-thaw environment, salt exposure, need for reduced permeability and sulfate exposure. When this is not clear it can be difficult for the producer-contractor to comply with building code requirements or to ensure designer-owner satisfaction. ACI 318-05 contains the rudiments of exposure classes within the tables now in Chapter 4 of the code. It is suggested that these tables be amalgamated, following perhaps the approach used in CSA A23.1-04 (Table 1). The exposure classes listed in CSA A23.1 are of course based on Canadian climate, geological conditions, and construction practice. But, with 15 U.S. states partially or wholly north of Southern Ontario, Canada and the occurrence of very hot Canadian summers, many parts of the United States experience similar exposure conditions. Similarly, major issues such as ASR and sulfate attack are common to both countries. Finally, construction practices in both countries have many similarities and there is significant interchange of construction culture between engineers of both countries in forums such as ACI and companies that operate on both sides of the border. Similar exposure classes do not require much of a stretch of the imagination.

4.1.9 *Code freedom for concrete in benign environment*—The ACI 318 Building Code does not inhibit performance specifications for concrete that does not have special durability requirements. This type of concrete represents a significant segment of the concrete construction market that could be pursued for an entrée to performance specifications. Specifiers should avoid imposing special durability requirements in situations where no harsh service environment exists, as they may thus invite other problems in addition to higher cost. An example was pointed out in Chapter 1, in which a specification that leads to high paste content as a result of minimum cement or maximum w/c requirements can result in increased shrinkage cracking.

4.1.10 *Code limits for concrete in aggressive environment*—For durable concrete, the current 318 Building Code limitations on w/cm and percentage of supplementary cementing materials (for deicer salt exposure, for example) are restrictive and can lead to undesirable consequences such as increased shrinkage and cracking while nevertheless providing the desired durabilty. However, these requirements might evolve toward performance alternatives as in the case of w/cm code requirements that used to be in place for concrete strength. The statistical quality control features of Chapter 5 of the code are reasonable and protect owner and producer, even though ACI chose the unfortunately misleading term of "overdesign" to describe the difference between specified strength and required average strength. It is likely that any meaningful performance criteria will have a similar statistical basis. Anticipating this, the Manitoba Ready-Mixed Concrete Association has produced a guide document to help apply this approach to performance contracts (see 2.7.2.3).

4.1.11 *Share and transfer of responsibility*—In making the transition to Performance Specifications the concrete supply industry needs to be clear about the potential for a very significant transfer of responsibility. If true end-product performance is specified, requiring the in-place assessment of hardened concrete, the concrete producer and contractor become jointly responsible for the quality of the finished structure. However, if the "point of performance" is specified as the point of discharge of the concrete, the concrete producer's share of responsibility with the contractor is not significantly different than with a prescriptive specification. The owner's risk is likely to be minimized by an in-place, hardened concrete point of performance, with its joint responsibility of the producer-contractor team. The concrete producer's risk is likely to be minimized if acceptance were based on the delivery of a prequalified product. Decisions about the point in the construction sequence at which the concrete properties are to be evaluated thus have a critical impact on risk and responsibility. Further, taking advantage of performance specifications mandates greater dialogue between contractors and their concrete suppliers. Concrete suppliers will need to be proactive in determining the concrete mix characteristics needed by the contractor in placing, compacting and finishing as well as meeting the performance criteria for the hardened concrete. Contractors cannot be relied upon entirely to clarify these needs when asking for prices.

4.2 International Perspective and Progress

4.2.1 *Overall assessment*—A study of the current world literature on specifications makes it clear that performance is a hot topic and that performance specifications are the "Holy Grail" that many desire and are seeking. There is a worldwide concern about the durability of concrete and the effect of quality of installation on that final, in-place quality. In reviewing a large number of documents from around the world, however, few true performance specifications were found and these only contained pure performance criteria for some properties of concrete. To paraphrase a popular quotation, "When all is said and done, there is a great deal more said than done on the topic of performance specifications."

At the moment most specifications that address performance delineate exposure conditions that affect the service life of concrete and provide parameters to be verified that are assumed to be indicative of the concrete's ability to achieve the desired service life. These parameters are based on experience and/or durability indices derived from research studies and, in some cases, field experience. In many cases specifications provide tables of mandatory limits to water-cementitious ratios, minimum cement contents and air entrainment. There is almost universal use of supplementary cementitious materials such as fly ash, ground granulated blast furnace slag and silica fume. Without exception the levels of quality control required to guarantee a consistent and economic product are based on statistical analyses of test results, at least for strength.

The literature search uncovered few examples of performance specifications where the quality of the end product was stated and the product details left entirely to the concrete supplier. In all instances where this issue was discussed the consensus was that the test procedures needed before this approach can be extensively implemented have not yet been proven to be reliable or repeatable to the degree that would make them viable from a practical and legal point of view. On this basis it would seem that at the moment any performance criteria in specifications for general use that are to be made the responsibility of the concrete supplier are limited to slump, air and strength.

Among the most highly developed new codes and specifications that have appeared on the international scene in recent years, the Euro Code with its nationalized amendments may be the most comprehensive and the most complex. Cultural and language differences make the European Economic Community EN standards difficult to navigate, however. BS 8500 is particularly complex and it is considered that the approach to determining and ordering a concrete mixture in these standards, and in BS 8500 particularly, are unnecessarily and unattractively complicated for U.S. practice. Some of the complication has resulted from having to accommodate the needs of the 28 EC countries in one standard. Australian and New Zealand documents are progressive, enlightened and clear but are not truly performance based. The Canadian A23.1 is also not strictly performance based, but contains many elements that are adaptable with little or no modification to a performance oriented specification, particularly in regard to durable concrete.

4.2.2 *U.S. Initiatives*—Within the U.S. many states have taken important steps toward performance specifications, both independently and under the leadership of FHWA's Roadmap. A few of the growing number of state experiences have been detailed in this report. Virginia's experiences have been discussed in Chapters 2 and 3 in regard to shrinkage and rapid chloride permeability. Kansas has been exploring air void analysis, and Minnesota has been among the states that have encouraged "contractor-based mix design" and has been controlling water content in certain applications. The Port Authority of New York and New Jersey has had good experience by focusing on water content, shrinkage and rapid chloride permeability.

4.3 Testing and Quality Management

4.3.1 *Testing*—To provide confidence for all parties under the adoption of performance specifications, there is a need for quick, reliable performance tests for concrete properties, including durability, which have to go far beyond current reliance on the 28-day compressive strength as the sole arbiter of concrete quality. The lack of adequate performance-related test methods certainly hinders the move from prescriptive to performance specifications and there is no question that new developments in testing will facilitate the use of performance specifications. Nevertheless, Chapters 2 and 3 of this report detail a number of effective approaches based on current technology.

4.3.2 *Multi-stage testing*—A transition to performance specifications literally means a transition to performance testing. Pre-qualification testing would be step one, followed by screening tests of fresh concrete at delivery and a program of subsequent tests of hardened concrete, possibly of samples that had been taken from the truck chute, but more comprehensively from the structure itself. The Duracrete report, in establishing levels of QA, rated in-place testing as the highest level. There is already a developing trend to make tests on the concrete in the finished structure (see 2.3.1.3, 2.7.1.3 and 2.7.2.2). An owner's primary concern is concrete that's in the finished structure.

4.3.3 *Screening tests*—Screening tests of fresh concrete are likely to continue to be based on slump, temperature and total air content, although slump may not be required by the specifier in lieu of more meaningful tests of the hardened concrete properties. Performance-oriented contractors may have slump requirements, however. Fresh concrete tests such as density (fresh unit weight) may become more important as ways to identifying mixes, quantifying batch to batch uniformity and for providing additional data concerning air.

4.3.4 *Other tests*—Other tests that can be performed on fresh concrete, but cannot be used as a screening test due to the time required to obtain a result (prior to discharging the concrete) include the air void analyzer and the microwave test for estimating water content. Even though a w/cm value may not be specified under a pure performance specification, once a proposed mixture has been preapproved for use via a prequalification process, water content may be an effective identity test to validate that the preapproved mix has in fact been delivered to the job, within the limits of the precision of the test method.

4.3.5 *Tests of mechanical properties*—Standard cylinder tests are likely to play a role in performance requirements, but it is also likely that focus will shift toward in-place testing and/or to accelerated strength tests to provide early confidence (or early warning) that the desired outcomes will be achieved. (Given the need for early prediction of later-age performance, accelerated tests such as the *four test methods* described in *ASTM C 684, give an estimate of 28-day compressive strength between 5.5 and 49 hours depending on which procedure is chosen.).* Cylinder weight may become more commonly used as an early indicator of low-strength cylinders. Abrasion tests will be more common when abrasion has been defined as an in-service exposure. Given the strong association among cracking, functionality and owner-designer satisfaction, early and later age volume-change tests will become more common.

4.3.6 *Durability concerns*—The prime concern of all that the authorities reviewed is durability. Without exception all include the use of SCMs either as additions at the concrete plant or in blended cements as an aid to achieving durability. When it comes to testing hardened concrete for durability in regard to the ingress of aggressive substances, many tests have been developed but few are standardized and none are considered ideal (but what tests are considered ideal?). Nevertheless, it is likely that AASHTO T277/ASTM C 1202-rapid chloride permeability testing will remain a significant tool for evaluating concrete performance in the foreseeable future. The ASTM C 1202 test has been used extensively in specifications by Virginia DOT, in Australia and by highway departments in Canada. Ontario specifications for the use of this test base acceptance on these results of tests on cores taken from the finished structure. The ASTM C 1585 sorptivity test has not had extensive use in North America but has been used for acceptance in Australia and a field version has been used in Canada.

4.3.7 *ASTM C 457*—For evaluating the freeze-thaw durability of concrete in place, actual freezing and thawing tests are available but are difficult to employ, expensive and time consuming. ASTM C 457 microscopic analysis of air void system parameters is likely to be important and has been extensively used by Canadian highway departments. In Ontario the test is made on core samples taken from the structure.

4.3.8 *ASR and Sulfate Reactions*—For the specific durability issues of alkali-silica reaction or sulfate reactions, a number of specialty tests are available. Given the role of flow through porous media as a factor in either of these deteriorative mechanisms, specific ASR or Sulfate testing should be coupled with permeability and transport-type tests. C 1567 is probably most appropriate for job mixture ingredient qualification after aggregates are determined to be potentially reactive by C 1293 or prior field service.

4.3.9 *Need for rapid approval*—A practical difficulty in implementing performance specifications is the short bidding period followed by a short time before work commences. This is common in North American contracts. Tests to determine whether concrete mixtures meet ASR, diffusion and creep requirements need very long lead times while freeze-thaw, shrinkage and scaling take at least three months. Further, the longer it takes to perform a test, the more likely it is that raw materials will have changed by the time the actual production concrete is produced. An example of a supplier's responsibility is given in the Australian specification (2.3.1.1) that requires ready mixed concrete producers to determine the chloride and sulfate contents and the shrinkage of their most commonly supplied mixture every six months

4.3.10 *Quality management*—In-place concrete properties depend on both the quality of the concrete delivered to the site and the quality and workmanship of construction operations such as placing, consolidating, finishing, curing and protection from the weather. Prior to approving concrete and allowing it to be placed, a design professional may require evidence from the concrete supplier that the mixture has the potential to meet the specified criteria and may also require evidence from the contractor of the ability to install the concrete.

A performance specification will therefore require a quality management program from the contractor (party holding contractual responsibility to the owner) who will in turn require such a program from the concrete supplier. In view of the clarification of responsibilities inherent in any specification, but particularly in a performance specification, it must be clear that when the terms Quality Assurance and Quality Control are used, the ACI definitions in "ACI 116, Cement and Concrete Terminology" apply as follows:

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

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

It has been suggested in the European (EEC) specifications that not only independent entities such as CCRL (CCRL inspects, does not certify) would be able to certify compliance of concrete mixtures but that this could also be done by national organizations such as NRMCA or regional concrete associations. (NRMCA has Quality Plan Guideline and Process of Certification for QC projects close to completion, and has a similarly long established program that addresses the certification of plants and trucks, plant managers, delivery and sales professionals, and concrete technologists.) The Precast/Prestresed Concrete Institute (PCI) has been operating a successful plant certification program for over 30 years [Wilson,1968, PCI 1999, PCI 2001]. However, owner acceptance of certification by producer associations will require demonstration of a clear lack of bias. Along these lines the EEC program requires that concrete suppliers report deficiencies in their operation to owners and contractors in a timely fashion.

Concerns about suppliers who may not be technically capable of producing performance concrete will be allayed by maintaining and expanding NRMCA's certification programs. Such a program must be, and must be perceived as, rigorously applied and maintained. This would also imply that only certified suppliers be allowed to supply to performance-based specifications. (Similar requirements exist in Quebec, Ontario, NZ, Britain, and in other locations, etc.)

It has been suggested in Europe that where a supplier and his/her concrete mixtures are certified by an acceptable third party, QA testing is not necessary unless a problem is seen. This will be a hard sell in North America, at least until the use of performance specifications is a mature practice or until enough on-site tests have proven the uniformly satisfactory behavior of the concrete.

It is to be expected that concrete suppliers will have reservations about the validity of tests particularly when a failure to meet specification is reported. Some jurisdictions deal with this by having a referee system that can carry out retests to satisfy all parties with regard to the disputed test result (see 2.7.2.4 and 2.8.2.6.) While questions may remain about how to select an impartial referee and who would pay for such service, the specifications might state that referee testing is not only at the request of the Contractor (or his Supplier) but that the contractor pays for it.

4.3.11 Typically, a concrete supplier will have a portfolio of many mixes that have been developed to meet price inquiries. Also typical of most contracts is a short bid time period and a rapid construction start after a bid award. Pre-testing all, or even a significant number, of these mixes to meet anticipated performance demands would be horrendously expensive and take up to several years to complete. How concrete suppliers will cope with this aspect of performance specifications is not clear.

One possible approach is the "Family of Mixes" concept put forward in the UK. These are groups of related concretes for which a reliable relationship has been established and documented. Criteria are given in BS 8500 for confirming that a mix truly belongs to a particular family. A recognized authority can provide certificates of conformity to confirm membership of a family of mixes. In the UK this certification can be provided either by a totally independent authority such as the British Standards Institute or the concrete industry's Quality Scheme for Ready Mixed Concrete.

As tabulated in Chapters 1 and 3 there are now many properties of concrete that can be included in a performance specification. Many properties are measurable by an existing ASTM or AASHTO standard test method and can be specified as a minimum or maximum value. The more intractable problem now is the increasing number of durability criteria that can be specified for concrete. As new tests and criteria are developed it will become necessary to demonstrate that mixtures in the current inventory can meet the new requirements. In some cases current mixes will pass the new tests and in others adjustments followed by re-testing will be required. In such cases suppliers will develop the required data and make adjustments as necessary. In a few cases, such as with MTO specifications in Ontario, new criteria have been included for one or two years without being included as pay items, to allow suppliers to become familiar with the new tests and to develop suitable mixes.

4.4 How Do We Get There From Here?

4.4.1 *Introduction*—The FHWA has charted a roadmap to performance-based specifications and is working on arriving at the destination by 2008. This mirrors similar programs by the UK Highway Agency and these planned approaches obviously involve many people for many hours over extended periods. The EU surely did not produce its documents without an enormous expenditure of time by representatives from 28 countries. All three must have and are expending huge resources on the development of their performance specifications. It would be naïve to assume that substantive changes to the philosophy for specifying and ordering concrete would occur without a well-planned and protracted program. But there are other examples of the successful introduction of new and different technology in the concrete industry. When High-Strength concrete at or above the 10,000 psi (70 MPa) level was introduced, significant changes were needed in the design and production of concrete mixtures. In Chicago, Seattle, Toronto and other cities the consulting, testing and ready mixed concrete industries cooperated to develop concrete mixtures and QA/QC procedures. Ultimately, these became established practice and were enshrined in an ACI Guideline document. Similarly, at the beginning of the interest in High-Performance Concrete, FHWA in the U.S. and Concrete Canada in Canada provided the impetus, encouragement and expertise to the industry that has led to the widespread adoption of this material. As would be expected, practical difficulties with such aspects as finishing and curing occurred and original specifications were successively modified as experience was gained. The evolution of the 318 Building Code itself shows clear evidence of the ability of the industry to adapt and to prove the validity of good ideas. With this background and the clear examples of important changes happening around the world and closer to home in Canada and various U.S. state DOT's, we can expect progress on how we specify concrete. But how do we get there?

4.4.2 *A Multi-step plan*—Taylor (2004) has postulated nine steps in the transition from Prescription to Performance. The following list of considerations and actions needed to achieve this transition builds on the "Taylor" plan and on NRMCA intentions.

1. Develop or modify an example performance specification (or minimally prescriptive specification) that takes advantage of the freedoms and opportunities afforded by current 318 Building Code. Carefully describe the conditions under which this can be recommended for use.

2. In the process of developing this model identify those code provisions or other aspects of standard practice that represent a barrier to taking advantage of the performance specification philosophy.

3. Draft specific change proposals for consideration by ACI 318 (or other jurisdictional bodies such as AASHTO) that would allow for advantageous use of performance specifications. Given that the cooperation and support of recognized authorities is a prerequisite to substantive changes in how concrete is specified, evaluated and accepted, it is essential that the prescription to performance initiative be coordinated with groups such as ACI committees 318 and 301. ACI 318 "Building Code Requirements for Structural Concrete" is the "Bible" for design professionals in the U.S., much of South America and elsewhere, and ACI 301, "Specifications for Structural Concrete," is also widely used. It will be necessary to work with these ACI committees to assist in code, commentary and specification amendments that can expand performance-oriented options and provisions. In addition to working with performance vs. prescriptive requirements, attention would be given to establishing a clearer system of exposure classifications or requirements. In common with worldwide practice these prescriptive tables would, for specific exposures, include restrictions on type of cement or cementitious combination, minimum cementitious content, water-cement or water-cementitious ratio and air content. Once a set of exposure classes has been agreed on, the next step is to produce criteria in tabular form that are essential requirements (initially some may be prescriptive) for concrete mixtures in order to assure the potential ability of concrete mixtures that incorporate these criteria's ability to meet durability requirements. Initially, the critical properties of concrete needed to meet the requirements of each exposure class may well be prescriptive, but in time would become performance criteria.

Later, as practice changes and suitable test methods become available, any prescriptive requirements in the tables can be progressively deleted in favor of performance criteria.

4. A more comprehensive model performance specification can be made available as code provisions permit.

5. Industry acceptance is expected to be incremental as opportunities arise for project teams to capitalize on advantages of performance specifications. In the first such iteration it is probable that only a few properties of concrete will be included as performance requirements. These would be those for which proven tests with known and acceptable variability are available to check compliance. These tests would also be in common and extensive use, and already considered useful by the design professionals. Candidate tests and properties could include density of normal, heavy and lightweight concretes, early-age compressive strength, flexural and splitting tensile strength, permeable voids, chloride permeability, freeze-thaw resistance, de-icer scaling, modulus of elasticity, shrinkage and creep. For all these properties only a minimum or maximum average value needs to be specified along with a minimum or maximum value for a single test result (based on the precision of the test). Although early experience may only incorporate a few performance requirements this experience would inform developing code modifications.

6. There are also tests already in somewhat specialized use that have the potential for wider application in the near future. These are "The Rapid Chloride Permeability Test" (ASTM C 1202), the determination of air void system quality by ASTM C 457, and sorptivity using the procedure in ASTM C 1585 modified for in-place use.

7. Use of performance specifications would expand along with demonstrated success and benefits, and with the incorporation of additional properties as additional tests are proven to meet accuracy and variability. The procedure for bringing these tests into wider use can most easily be accomplished by an authority such as a Department of Transportation. A new test can be specified for use on contracts for one or more years but for information rather than as a contractual issue. By this means extensive field experience can be gained and the utility of the test determined. Emphasis on certification programs is expected to increase, with attention to not only concrete production and construction, but also for testing facilities and testing technicians.

8. An essential part of effecting a change in mindset for stakeholders to adopt performance specifications will be education to not only encourage the appropriate use of performance specifications, but also to encourage thinking the problem all the way through. (For example, on two concrete tunnel liner contracts in Ontario (Canada), a diffusion coefficient was specified. However, the requisite test required 120 days per specimen, and test and tunnel liner production on the second contract was 1,000 units per week. Clearly the use of a 120-day test was technically justified from the perspective of performance, but logistically unmanageable.) NRMCA has already started this educational or “orientation” process but it will be necessary to provide clear and detailed recommendations in the future based on the findings of this, other studies and on field

experience as it accumulates. Unsubstantiated hype will have a devastating effect, as will any appearance of being self-serving (as pointed out from the floor at the March 3 steering committee meeting.). The literature review identified several helpful and effective examples of articles, websites, papers, reports and brochures for paving the way for new specifications. For example, the current edition of CSA A23.1, Annex J "Guide for selecting alternatives using Table 5 when ordering concrete" is a concise and clear aid. A similar annex should be part of the revision of ACI 318 or similar material should become part of the commentary. Such guidance will play a part in the gradual education and transitional thinking of those involved in choosing between prescription and performance or in deciding how to make the most effective blend of the two types. As already initiated at NRMCA, the education program should include all stakeholders. Effective use of performance specifications requires that all parties understand basic concrete technology in all phases from material acquisition to in-place service. Through education and certification that qualifies companies to bid and participate on performance projects there is a genuine opportunity to “raise the bar.”

9. Postscript

Appendix D is an excerpt from a poster exhibited by Ken Day of Australia at the Concrete Institute of Australia Conference in Brisbane in 2003. Mr. Day has some thought provoking ideas related to concrete specification and supply.

Chapter 5 References

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> Summary of Proposal Submitted by John A. Bickley, P.Eng., R. Douglas Hooton, P.Eng., and Kenneth C. Hover, P.E.
> http://www.nrmca.org/P2P/Summary%20of%20Performance-based%20Specification%20Research.pdf

Experimental Case Study Demonstrating Advantages of Performance Specifications Summary of Proposal Submitted by National Ready Mixed Concrete Association
http://www.nrmca.org/P2P/Summary%20of%20P2P%20Lab%20Study.pdf

The P2P Initiative – Continued Prescriptive Specification versus Performance Specifications
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Appendix A

Countries with membership in the European Code Committee on Concrete

Austria	France	Latvia	Portugal
Belgium	Germany	Lithuania	Slovakia
Cyprus	Greece	Luxembourg	Slovenia
Czech Republic	Hungary	Malta	Spain
Denmark	Iceland	The Netherlands	Sweden
Estonia	Ireland	Norway	Switzerland
Finland	Italy	Poland	United Kingdom

Appendix B
ASTM C 1202 Test Results from Canadian Construction Projects

The ASTM C 1202 (AASHTO T 277) test frequently used in North America, especially for contracts specifying HPC. Most U.S. state and Canadian Provincial DOTs, as well as some cities specify a maximum coulomb value. This varies in different jurisdictions. In the U.S., values between 2,000 and 2,500 coulombs are recommended for bridge decks (Ozyildirim, 2003). In Canada, on HPC contracts, the maximum value of 1,000 coulombs is almost universally used for cast-in-place concrete. Where mixtures containing silica fume are used, often together with slag or fly ash as replacements for a percentage of Portland cement and QC is good, there is no difficulty in achieving this value. On a major re-decking of the Jacques-Cartier Bridge in Montreal the specified coulomb value for the precast units was 500 and this value was met using a Portland cement containing interground silica fume.

On Ontario Ministry of Transportation (MTO) contracts the test is made on cores drilled from the finished structure. A 10 mm (0.6 in) slice is first removed from the top of the core, then the next two 50 mm (2 in) slices are used for the test. In 2001 and 2002 three HPC contracts had unacceptable test results. In 2003 six of the seven HPC contracts had acceptable results. On the seventh, major problems resulted in unacceptable results. On the six contracts with acceptable results, the data can be summarized as follows:

Average values: 272-609 coulombs
Median value for all contracts: 551 coulombs
Standard deviation of results: 41-159 coulombs
Individual results 188-984 coulombs

Members of Canadian Standards Committee A23.1 were asked in February 2003 to supply rapid chloride permeability test (RCPT) data (ASTM C1202) from HPC (now exposure class C-XL) and class C-1 Concretes, especially from field projects. The purpose was to see if limits of 1000 coulombs on HPC and perhaps higher values for C-1 concretes (a value of 2000 or 2500 has been suggested by Ozyildirum, 2003, HPC Bridge Views #26, but lower values for more severe environments than Virginia) or concretes with corrosion inhibitors (possibly 1500) are reasonable.

Summary of C 1202 Data

A preliminary analysis of the data suggest that for HPC, a limit of 1000 coulombs at 28 days is feasible, while a 56-day option would provide some flexibility and reduce failure rates (Data Sets #1, 2, 6, 10, 14, 15, 16, 19, and 20). Of 785 tests of HPC listed in Appendix C, only 60 or 7.6% exceeded 1000 coulombs. In the Canadian HPC projects constructed from 1990-2000 (Bickley and Mitchell, 2001) very few coulomb values exceeded 1000. Therefore, the 1000 coulomb limit at 56 days was adopted in CSA A23.1-04 for Class C-XL (extended service life, or HPC.)

For HPC with calcium nitrite corrosion inhibitor (it raises the conductivity and coulombs as noted in ASTM C 1202), a value of 1500 coulombs would be reasonable (Data Sets #3, 18) but perhaps at 56 or 90 days.

For CSA Class C-1 concrete (max. 0.40 w/cm, min. strength = 35MPa), 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. (As expected, T10 cement C-1 concretes in Data Sets 4, 9, 13 and 21 all resulted in much higher coulombs. Therefore, straight Portland cement should not be used in C-1 concrete. This is consistent with chloride diffusion data, where straight Portland cement concretes have much higher diffusion values than those containing SCM's.) An alternative for C-1 concrete would be to use 2000 coulombs at 28 days. Either way, this would effectively eliminate the use of plain Portland cement concrete from meeting C-1. In CSA A23.1-04, a limit of 1500 coulombs at 56 days was adopted.

Another option used by Virginia DOT is to use 28d RCPT tests but provide accelerated curing to cylinders (7d at 23°C then 21d at 38°C) to allow SCM's to more fully hydrate. This curing was found to give values similar to those obtained at 3-6 months when cured at 23°C.

It has been suggested by Suresh Gurjar that any specific limits (eg 1000 coulombs) should allow for individual values to exceed that limit as long as they don't exceed it by, say 25%, and the average does not exceed the limit. This is similar to how the air void spacing factor is handled in A23.1. Based on the Precision statement in C1202, the within-lab standard deviation is 12.3% and the between-lab value is 18.0%, based on single tests.

A good summary of the merits and problems associated with the C 1202 test is given in *HPC Bridge Views* Issue No. 12, November/December 2000.

Concrete Canada. This Network of Centers of Excellence on High-Performance concrete promoted the use of HPC on a Canada wide basis from 1990 to 1998. Included in the 1994-1998 phase was an aggressive implementation policy that saw the technology transferred to real projects.

As a result of this program HPC is specified for bridges by nearly all Provincial transportation ministries and by most large cities. After variations in early practice nearly all bridge cast in place concrete is 50 MPa, contains silica fume, often contains slag or fly ash and is required to meet an ASTM C 1202 maximum coulomb rating of 1,000. On one contract where two competent laboratories made tests the variability of the ASTM C 1202 tests was only about half that indicated by the precision statement in the ASTM test method.

As a result of reviewing the data collected in 2003, CSA A23.1-04 contains limits of 1000 coulombs by 56 days for exposure class C-XL concretes and 1500 coulombs by 56 days for class C-1 concretes. For concretes containing corrosion inhibitors, these limits apply to the same mixtures made without the corrosion inhibitor for prequalification purposes. It is likely that the next edition or an amendment will contain allowances for single test values exceeding theses limits, when these limits are used for acceptance, as long as the average is less and the single coulomb values do not exceed by an amount yet to be determined. Single test coulomb values of 1250 (for C-XL) and 1750 (for C-1) have been suggested but not adopted.

Meeting 1000 coulombs at 28 days is difficult without the use of silica fume, but it is possible to do so at 56 or 90 days. However, almost all HPC projects (meeting what is now exposure class C-XL) have used silica fume (often combined with slag or fly ash). Meeting 1500 coulombs at 56 days (for normal bridge and parking structures meeting exposure class C-1) is certainly possible with appropriately designed slag or fly ash concretes or at 28 days if an accelerated curing procedure is allowed to be used.

Appendix C

Annex J of CSA A23.1

Annex J (informative)
Guide for selecting alternatives using Table 5 when ordering concrete

Note: *This Annex is not a mandatory part of this Standard.*

J.1 Introduction

The purpose of this Annex is to provide background information and guidance to users of this Standard on the selection of either of the two alternatives for specifying and ordering concrete found in Table 5: performance and prescriptive. In particular, the focus is on the materials selection and the design of concrete mixtures for the performance option, and the enhancement of this approach in accordance with this Standard. The advantage of the performance approach is that the contractors and materials suppliers are free to use their expertise, innovative talent and other resources at their disposal to design and deliver the product in the most efficient and economical manner. This is consistent with the owner's interest, which is generally to own a structure which will fulfill his/her needs at reasonable cost. In most circumstances the owner has no vested interest in the nature of the constituent materials or the methods used, provided that the performance requirements are met. The incorporation of performance language within this Standard began in the 1994 edition. In the 2004 edition, Table 5 was modified significantly, reducing the number of alternatives for specifying concrete to two through the elimination of the "common" alternative. Enhancements were also made in other areas of the Standard to facilitate the adoption of the performance approach for concrete construction and to remove the barriers to doing so. The performance and prescriptive alternatives now given in Table 5 are intended to provide a clear definition of the roles and responsibilities of the various parties when specifying concrete, and to emphasize the importance of the need for the concrete to perform as intended in both the plastic and hardened states. Many challenges accompany such a significant change in the concrete materials and construction industry. These include the importance of ensuring clear understanding of the roles and responsibilities of all interested parties; the need for formal quality control, quality assurance and verification processes; and the importance of writing project specifications that capture the intent of the performance option and that clearly articulate the expected performance criteria in measurable or verifiable terms. This Annex contains information and direction on all of these issues.

J.2 Background

The early development of this Standard was based largely on empirical relationships between prescribed materials, mix designs and construction methods and the corresponding overall performance of the concrete in service. The construction industry has since seen a move away from the prescriptive approach toward a performance approach. Furthermore, the "common" alternative has become a much less viable option, due to the lack of clarity in defining the roles and responsibilities for specifying the various mix design parameters and for assuming responsibility for the concrete mix proportions. In concert with this general direction, this Standard has, over several editions, acquired a combination of prescriptive and performance language. The essence of an effective performance specification is that the performance requirements are stated in measurable terms and that the ability of the finished product to meet those requirements can be verified at the time the construction is complete. In many instances the state of the art has not yet developed to the point where performance can be conveniently verified at the necessary time. For this reason, there are significant portions of the Standard, beyond the selection of materials and mix designs, that are likely to remain prescriptive in nature for the foreseeable future. However, for purposes of specifying and ordering ready mixed concrete, it is believed that adopting a performance approach and eliminating the “common” alternative are timely. Accordingly, the 2004 edition provides the owner with the option of following either the prescriptive or performance approach. The purpose of this Annex is, therefore, to provide guidance and background information to the user when specifying and ordering concrete, with a view toward enhancing and facilitating a performance approach.

J.3 What is performance?

J.3.1 General

During the course of a construction project a number of parties will be involved in the production and construction of concrete, and the custody of the concrete and its constituent materials will change hands several times, with each custodian having the ability and opportunity to affect the final performance of the concrete. Therefore, each of the parties will have different and sometimes conflicting performance requirements. A definition of performance is therefore paramount. Clauses J.3.2 to J.3.4 set out key terms and the criteria that must be taken into consideration when specifying concrete on a performance basis.

J.3.2 Performance concrete specification

A performance concrete specification is a method of specifying a construction product in which the 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.

J.3.3 Prescriptive concrete specification

A prescriptive concrete specification is a method of specifying a construction product in which all processes, activities, materials, proportions and methods used to achieve the intended final outcome are specified in mandatory language contained in the project specifications. The contractors, subcontractors, materials suppliers and manufacturers must then follow a prescribed process and use prescribed materials and proportions to deliver the product.

J.3.4 Performance criteria

J.3.4.1 General

In order to accommodate the interests of the various parties, the measurement and verification of the performance of concrete should be defined in terms set out in Clauses J.3.4.2 to Clauses J.3.4.4.

J.3.4.2 Plastic state

The essential performance characteristics are
(a) uniformity;
(b) placeability;
(c) workability (the ability to be placed and consolidated to completely fill the forms without unacceptable surface blemishes, loss of mortar, colour variations, segregation, etc.);
(d) finishability (including limitations on the acceptable amount of bleeding); and
(e) set time.

For the most part, these performance characteristics will be of interest to the contractors, concrete suppliers and subcontractors involved in placing and finishing the concrete.

J.3.4.3 Hardened state

The essential performance characteristics are
(a) physical properties of compressive, flexural or tensile strength and modulus, as applicable;
(b) rate of strength development;

(c) durability in the expected service environment; this includes resistance to corrosion, scaling, deleterious expansion, chemical degradation, freeze-thaw attack, abrasion and other deterioration processes to which the concrete may be exposed;
(d) volume stability (limitations on acceptable volume changes due to shrinkage, creep and thermal differentials caused by heat of hydration);
(e) appearance and architectural characteristics (i.e., limitations on acceptable levels of shrinkage cracking);
(f) surface texture (non-skid finish, steel trowel finish, etc.); and
(g) geometrical requirements (i.e., flatness and levelness, slope for drainage, etc.).

For the most part, the properties of the hardened concrete will be of interest to the designer and owner, but in some cases they will also be of interest to the contractor and concrete supplier.

J.3.4.4 Specifying performance criteria

The challenge when preparing a performance specification for concrete is to state performance requirements that can be satisfied and that can be measured by accepted industry standards and methods. Specifications are normally written by and for the owner, whose interest is usually, but not always, long-term. The required performance criteria must therefore be stated in terms that can be measured early in the life cycle of the concrete and can be used to verify at that time that the long-term performance criteria will be met. Hence, the verification process becomes an essential and critical part of the success of the performance approach. Without a comprehensive and reliable verification process, the owner's performance requirements cannot be verified at the appropriate time and the process is not workable.

J.4 Roles and responsibilities

J.4.1 Performance specifications

J.4.1.1 Owner

Prior to endorsing the use of a performance specification, the owner must have confidence that this approach will meet his/her objectives. This requires reliance on the design team to prepare an effective performance specification and on the implementation of a reliable quality assurance process that will verify that the performance criteria will be met. The owner is therefore responsible for appointing a competent design authority and implementing an appropriate quality assurance process. Often responsibility for quality assurance will be delegated to the design authority.

J.4.1.2 Design authority

The designer is responsible for
(a) establishing the performance criteria, usually in consultation with the owner;
(b) preparing the technical specification that states the performance criteria in appropriate terms; and
(c) under the direction of the owner, conducting quality assurance and reviewing quality assurance reports, or both, to ascertain on the owner's behalf that the performance criteria have been met.

J.4.1.3 Contractor

The construction team is responsible for procuring concrete and related materials and incorporating them into the structure in a manner that meets the performance requirements. The contractor is also responsible for conducting appropriate and sufficient quality control to demonstrate and document that the performance requirements have been met. The quality control documents must be communicated to the design authority and owner in a manner, and according to a schedule, that will accommodate the quality assurance process.

J.4.1.4 Concrete supplier

The concrete supplier is responsible for procuring materials and producing concrete that will, in its plastic and hardened states, meet the performance requirements. This includes responsibility for implementing a quality control program to demonstrate and document that the product as delivered is of appropriate quality and will meet the performance requirements. Since in a typical construction project the custody of the concrete transfers from the supplier to the contractor while in its plastic state, a high degree of coordination is required between supplier and contractor to ensure that the final product meets the performance criteria and that the quality control processes are compatible and demonstrate compliance.

J.4.2 Prescriptive specifications

J.4.2.1 Owner

The owner is responsible for appointing a competent design authority and implementing an appropriate quality assurance process. Often responsibility for quality assurance will be delegated to the design authority. The use of the prescriptive approach transfers responsibility for the prescribed materials and processes from the contractor and supplier to the owner and design authority. The owner is therefore responsible for ensuring that the prescribed materials and processes will meet the performance requirements.

J.4.2.2 Contractor

The construction team is responsible for supplying materials and conducting the work in accordance with the prescribed requirements. The contractor is also responsible for conducting appropriate and sufficient quality control to demonstrate and document that the prescribed requirements have been met.

J.4.2.3 Concrete supplier

The concrete supplier is responsible for supplying concrete in accordance with the prescribed requirements, and for conducting appropriate and sufficient quality control to demonstrate and document compliance.

J.5 Selecting an alternative

J.5.1 General

In selecting an alternative for specifying concrete in accordance with Table 5, it is up to the owner and his/her representative to determine the relative merits, costs and other implications (including intellectual property rights) associated with the prescriptive and performance approaches. To some extent this will involve a risk management approach.

J.5.2 Prescriptive environment

In a prescriptive environment, the owner and his/her representative must make decisions about the balance between capital investment and long-term maintenance costs. From a purely concrete materials perspective, this risk-based approach makes the owner responsible for matching long-term performance expectations with material selection and mix design parameters, and the owner must make conscious decisions about his/her front-end and life-cycle costs. The owner empowers the consultant/architect to design a concrete structure that will meet certain performance criteria, considering primarily in the medium and long term. The consultant then prescribes the materials, quantities, mix design parameters and methods to achieve the intended performance. The contractor, on the other hand, is most concerned with the short-term performance characteristics (e.g., plastic concrete and strength gain properties) that will most cost-effectively enable construction of the works. These properties need to be established to ensure the required medium- and long-term requirements are met. Key assumptions, therefore, include the following:

(a) The consultant is knowledgeable enough about the most cost-effective way to correlate the prescriptive directions/measures with the medium- and long-term performance.

(b) The general contractor will follow the prescriptive directions and plan construction methods and sequence without compromising the medium- and long-term performance. In the prescriptive environment, the owner, through the consultant, takes the lead role in monitoring the materials and methods to determine that the prescription has been followed.

J.5.3 Performance environment

J.5.3.1 General

In a performance environment, the owner stipulates the required performance of the concrete and then relies on the contractor and his/her suppliers and subtrades to provide materials and methods to achieve the performance required. Superimposed on the owner's performance requirements, which normally focus on the medium to long term, are the contractor's short-term performance requirements.

J.5.3.2 Quality management

Verification of concrete quality to ensure performance to this Standard and the project specifications is the responsibility of the owner. Quality plans must take into account that there are quality management elements both internal and external to the owner's concrete acceptance requirements, and that these elements must be tailored to each specific project and the concrete performance that is being sought. This includes ensuring that the contractor has in place an industry-recognized quality control (QC) plan (e.g., an ISO 9000 type of process) that prevents or corrects defects and nonconformity in the concrete, and that is commensurate with the size and complexity of the project. Care must be taken during the contractor selection and award stages of a project to ensure that contractors and suppliers are provided with the necessary incentives for the added effort and cost of maintaining such a QC process. The external QC effort (e.g., inspection and testing for verification and acceptance) made by the owner must complement and balance the internal QC effort made by the contractor, ensuring that the contractor's QC systems are in place, operating effectively and preventing or correcting nonconformance. In a performance environment, a higher level of responsibility is placed on the contractor and all of his/her suppliers (ready mix, hardware, reinforcing steel, etc.) and subcontractors (formwork, reinforcing steel, pumping, placing finishing, etc.) for the internal QC effort. The owner, in turn, must balance this effort by reviewing the QC plans and records of primary contractors, subcontractors, suppliers and secondary suppliers, and by conducting independent quality assurance, testing and verification of concrete and other material properties to validate the results of the contractor's processes. The owner should also undertake an independent audit of the quality management system.

J.5.3.3 Components of specifications

Project or contract specifications must include pre-qualifiers and post-qualifiers. Pre-qualifiers include the experience, proprietary mix design performance record, testimonials, proposal evaluation, integrated quality control plan evaluation, contractor-to-subtrades communication plan evaluation and other criteria necessary to allow the owner to place reliance on the contractor and suppliers and subtrades. Post-qualifiers include the qualitative or subjective evaluation, quantitative or objective evaluation, quality control results, quality assurance results, rationalization of discrepancies between quality control and quality assurance, and other criteria necessary for the owner to be satisfied that the performance criteria have been met. Performance-based contract documents (owner-contractor) will typically include plans and specifications complete with

(a) clearly articulated and understood roles and responsibilities of all parties, including owner, consultant, contractor, supplier, subcontractors, testing agency, etc.;
(b) terms and conditions for interaction among owner, contractor and supplier;
(c) clearly understood definitions of performance and point of delivery;
(d) pre-qualifiers (past performance and quality plan) and post-qualifiers (quality control and quality assurance);
(e) performance criteria—durability, architectural requirements, volume stability, strength and structural requirements—and test methods and acceptance criteria;
(f) reference to (contractor-supplier) quality plan;
(g) penalties for non-compliance; and
(h) procedures for dispute resolution.

J.5.3.4 Verification process

An effective performance specification will require a comprehensive verification process in which quality control and assurance processes verify and ensure that the performance criteria are being met. There are two components of the quality control program. Some of the performance criteria are, of necessity, subjective in nature (e.g., appearance and freedom from surface blemishes). It will be necessary to define in some measurable way how the performance will be evaluated. Also, some parameters overlap into responsibility for design and serviceability (e.g., freedom from cracking). Again, it will be necessary to define these types of parameters in a way that can be effectively evaluated.

J.6 Summary

The adoption of a performance approach to supplying concrete and building a structure will obviously be a departure from the traditional approach. Recent experience has demonstrated that success is achieved when the owner has confidence in the ability of the contractors and suppliers to meet the performance criteria, and the contractors and suppliers embrace the concept of quality control to the point where the quality control process not only identifies and corrects deficiencies, but provides persuasive evidence to the owner that the required performance will be met.

APPENDIX D

Concrete Quality Control
Yesterday, Today & Tomorrow

As presented at the Poster Session, Concrete in the Third Millenium, 21st Biennial Conference, Concrete institute of Australia and New Zealand Concrete Society, Brisbane, July 17-19, 2003.

Ken W. Day

Introduction

The title is not strictly correct because most of the types of control listed are in use today. The categories are not separated according to geographic location, local per capita income, expenditure on plant, knowledge of concrete properties, or even computer literacy. They are also not necessarily in time sequence. The basic division is on the grounds of philosophical concepts of those in a position to impose regulations or take management decisions.

It is noticeable that such persons or bodies are often either without personal experience of concrete production or are inhibited from innovation by assumptions as to the reaction of superiors, clients or authorities.

Readers can assess for themselves whether the degree of conservatism revealed has been beneficial to the community.

Discussion

A stage has been reached where the production of low-variability concrete of almost any reasonably desired strength (or w/c ratio) can be achieved almost totally automatically.

The main inhibiting factor is that purchasers, structural designers and other specifiers often do not understand the situation or are inhibited by out-of-date regulations, textbooks or other sources of advice.

The best control is being achieved where suppliers receive encouragement to control and are allowed to profit by the attainment of such control.

Where a supplier is inhibited by minimum cement content specifications or not allowed to design and adjust his mixes freely, he is essentially denied the possibility of making additional profit through using good materials, good plant or knowing or caring anything about mix design or quality control.

Under such conditions the worst suppliers are the most competitive and control technology develops slowly if at all.

The author has been involved in concrete QC in several countries, including Australia, USA, UK, South Africa, New Zealand and several in S.E. Asia. In his opinion Australia is currently well served by its regulatory equipment and industry practices compared to UK and especially USA.

Conclusion

The presented list should enable specifiers, controllers and producers to see where they are on the list and to consider where they would like to be.

It may be a few years yet before the "Just-in Time" mix design advocated in point 21 above is acceptable anywhere. However, the author remains as confident that it will eventually come to pass as he was in the 1950s that statistical quality control of concrete would eventually become a reality

Development Stages

The states of philosophical development are seen as:

1. Prescription specification directly supervised by the engineer or owner.

2. Strength specification but hedged by limiting minimum cement content and enforced by minimum strength on an individual truck basis.

3. Recognition that, at a given strength, the concrete with the lowest cement content is the most durable and desirable, since high water content is more deleterious than low cement content. (logically leading to total abandonment of minimum cement content specification).

4. Reluctant permission to use a limited proportion of fly ash, blast furnace slag etc, (seen as a lower quality substitute aimed only at cost reduction).

5. Requirement that pozzolanic materials be used for one or more of: heat generation reduction, permeability reduction, durability improvement, ASR resistance, crack reduction, ecological desirability.

6. Reluctant permission to use chemical admixtures (following decades of successful but unauthorized use).

7. Requirement that various admixtures be used to retard set, reduce water content, shrinkage, heat generation, bleeding, segregation, permeability etc, and improve durability.

8. Recognition that statistics are applicable to concrete and of the importance of low variability, leading to the use of a target strength incorporating standard deviation.

9. Recognition that variability cannot be accurately assessed from a very limited number of results.

10. Recognition of testing error, leading to discarding of low result from widely separated pairs rather than penalization for such a result.

11. Recognition that it is far more efficient to ensure that no unsatisfactory concrete is produced rather than try to detect individual unsatisfactory truckloads. (this one took a few decades after Juran's dictum "control the mass and not the piece" was recognized in the mechanical world and is still not universally understood).

12. Recognition that the concrete supplier is in a far better position to control his concrete than the purchaser, leading to ISO certification of suppliers rather than control of the supplied concrete by the purchaser (will someone please tell the Americans about this?).

13. Availability of batching equipment which can record full details of every truckload and even predict its strength with reasonable accuracy as it leaves the plant.

14. Availability of truck-mounted workability monitoring and control gear "to close the last loophole" (why is no one interested in this?).

15. Recognition that low variability is an important goal and that it depends on continuous adjustment of mix proportions as the properties of input materials vary rather than rigid adherence to approved proportions (another one the Americans are yet to understand).

16. Recognition that mix adjustment based on production test data is much more accurate than trial mixes (also not in USA).

17. Recognition that CUSUM (cumulative sum) analysis enables test results (strength, density, slump, temperature and dozens of others) from any number of widely different mixes to be plotted on the same graph, removing the need for a control mix and giving much faster detection of change. (full marks to UK for being the first to introduce cusum, and to officially recognize that it is approximately three times as efficient as normal Shewhart graphing, - but why, after about four decades of use for strength results, have they not realized that it can be used for everything else as well with great advantage).

18. Recognition that pro-active adjustment based on input material tests can reduce variability – even though less accurate than reactive adjustment based on concrete tests and so not replacing the latter.

19. Availability of software which can instantaneously calculate the revised proportions necessary for a change in coarse or fine aggregate grading (or a change of material).

20. Availability of software that can optimize a whole range of hundreds of mixes in a few minutes. (optimize meaning automatically select the most economical aggregate proportions which will provide the nominated fresh concrete properties and combine this with the precise cement content required to achieve the specified strength, taking into account current early age test data)

21. Availability of software that can proportion the next truck of concrete in a few seconds, taking into account desired fresh and hardened properties, current test data on concrete and aggregates, and temperature and haulage time/distance.

22. Availability of software and facilities that will automatically email nominated individuals if any truck is dispatched bearing concrete likely to be unsatisfactory for almost any reason.

23. Availability of hardware and software enabling concrete test specimens to be weighed, measured and compression tested automatically with the results being automatically entered in the control system, assessed and reported by e-mail where appropriate.

24. Availability of hardware and software enabling the current strength of concrete in any part of a newly cast structural insitu or precast element to be read and the future strength growth to be predicted.