

ACI 329R-14

Report on Performance-Based Requirements for Concrete

Reported by ACI Committee 329



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This report discusses the differences between performance and prescriptive requirements for concrete, and provides information on developing performance requirements as an alternative to the current prescriptive requirements in codes and specifications. Performance-based requirements allow the contractor and concrete producer to be more innovative in concrete applications, providing an element for sustainability of concrete construction. The essential elements of a performance-based requirement are reviewed, which include the desired performance characteristics, sampling and testing procedures to verify these characteristics, and acceptance criteria. Because acceptance criteria are crucial elements of effective performance specifications, factors to consider in developing criteria that distribute risks to the owner and members of the construction team are also discussed. Considerations for implementing performance-based requirements on a project are presented and development of performance-based requirements for durability emphasized. Alternative performance-based requirements are proposed for the prescriptive durability requirements in ACI 318.

Keywords: acceptance criteria; bonus-penalty provisions; building code; durability; in-place tests; performance specification; prescriptive specification; quality assurance; responsibility; sampling; sustainability; test methods.

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CHAPTER 1—INTRODUCTION

1.1—Background

1.1.1 Prescriptive and performance specification—A specification is an explicit set of requirements to be satisfied by a material, product, system, or service (ASTM 2013). In the concrete construction industry, the primary types of specifications are materials specifications and construction specifications. The former provide minimum requirements for composition and properties, and the latter form part of the contract between owner and contractor. Specifications can be of the prescriptive or performance type, or they may include components of each. A prescriptive specification for concrete focuses on the properties and composition of raw materials; mixture proportions; batching, mixing, and transport of fresh concrete; and a range of construction operations from placing to curing. Prescriptive specifications rely on observed or implied relationships between the details specified and the desired final, in-place, or end-product concrete performance. Under a prescriptive specification, the desired end-product performance may or may not be described. A performance specification, however, defines required results, the criteria to judge performance, and verification methods without requirements for how the results are to be obtained. An alternative name used by some agencies is end-result

specification (ERS). The Federal Highway Administration (FHWA) has invested considerable resources to promote the use of performance-related specifications (PRS) in its projects (FHWA 1998). The PRS approach is intended to ensure the completed product will perform as specified.

Prescriptive and performance specifications have been in existence as long as code requirements and specifications for concrete have existed. For example, in 1910, the National Association of Cement Users (NACU), the forerunner of ACI, adopted its “Standard Building Regulations for Reinforced Concrete” (NACU 1910). These regulations provided alternatives for concrete strength:

Concrete composed of materials meeting the requirements of these regulations, mixed in proportion of one part of cement and six parts of aggregate (fine and coarse), shall develop a compressive strength of 2000 pounds per square inch in 28 days when tested as 8-in. diameter cylinders 16 in. long under laboratory conditions of manufacture and storage, using the same consistency as is used in the field. When the proportion of cement is increased, using the best quality of aggregates, an increase may be made in all working stresses proportional to the increase in compressive strength at 28 days, as determined by actual tests, but this increase shall not exceed 25 per cent.”

Thus, it is seen in this early document governing concrete construction, there were elements of prescriptive and performance requirements.

In 1936, ACI adopted the “Building Regulations for Reinforced Concrete (ACI 501-36T),” which served as a basis for many provisions that are still in use (American Concrete Institute 1936). ACI 501-36T permitted a performance-based alternative to the prescriptive water-cement ratio (w/c) requirements for different design strengths. Alternative mixture proportions were permitted by prequalifying a mixture on the basis of test data correlating strength to w/c . Four different w/c values had to be tested, and the w/c approved for production was that value corresponding to a compressive strength that was:

- a) 20 percent greater than the design strength when design strength was less than 2500 psi (17 MPa)
- b) 15 percent greater than the design strength when design strength was 2500 psi (17 MPa) or above

These requirements are the forerunner of today’s required strength based on standard deviation of historical data. Once the proposed mixture was approved, no substitutions in materials were permitted without additional tests.

For durability, ACI 501-36T stated that “All concrete exposed to the weather shall have a minimum ultimate 28-day compressive strength of not less than 3000 lb per sq. in.” According to ACI 501-36T, design professionals were responsible for on-site inspection of construction, including maintaining records of “the quality and quantity of concrete materials, the mixing and placing of the concrete, and the placing of the reinforcing steel.”

Today, the responsibility for site verification of concrete production has shifted away from the licensed design professional toward the concrete producer. The licensed design professional, however, is still responsible for review or approval of the submitted mixture ingredients and proportions.

Other changes in the concrete industry since these early codes were written include:

- a) Recognition that concrete strength is not the only characteristic considered in developing an acceptable concrete mixture for a project
- b) Portland cement is not the only cementitious material
- c) Water content and aggregate size are not the only factors that influence slump
- d) The w/c is not the only factor influencing permeability

A variety of admixtures have emerged to impart characteristics to a concrete mixture that are otherwise difficult or impossible to attain by varying only the basic ingredients of cement, aggregate, and water. Chemical admixtures and supplementary cementitious materials (SCMs), such as pozzolans and slag cement, affect factors including air content, air-void characteristics, workability, setting time, bleeding, rate of strength gain, long-term strength, and resistance to fluid penetration. In addition, combinations of the various cementitious materials and admixtures may or may not be mutually compatible.

It is difficult to write prescriptive specifications that make use of these developments while, at the same time, avoiding their pitfalls. It is evident that evaluating concrete durability is more difficult than evaluating strength. The increasing demand for improved concrete durability and growing complexity of concrete mixture proportioning add importance to the debate of prescriptive versus performance-based requirements.

Interest in performance-based requirements is fueled by the changes in practice that have evolved to enhance concrete durability and sustainability. For example, consider the high-performance, low-permeability concretes required to ensure durable structures under severe exposures. Such mixtures often use portland cement along with one or more SCM, may use one or more type of admixture, including a corrosion inhibitor, and may incorporate at least three sizes of aggregate. Developing an acceptable mixture requires experience with specific materials, including recognition that traditional relationships, such as those between workability and water content and those between strength and w/c , are affected by a variety of factors, such as types and amounts of admixtures and SCM. In addition, the compatibility of admixtures with cementitious materials should be investigated (Taylor et al. 2006). To ensure durability, the risk of cracking should be controlled. Curing of concrete characterized by rapid surface drying, rapid setting, and a high shrinkage potential requires special attention.

The reason performance-based requirements should be considered when prescriptive requirements have been the mainstay of the concrete industry is that more is demanded of concrete, and using a strictly prescriptive specification

makes it difficult to take full advantage of the wide range of available options under a performance specification.

1.1.2 Prescription to performance initiative (P2P)—In 2002, the Research, Engineering and Standards Committee (RES) of the National Ready Mixed Concrete Association (NRMCA) embarked on an initiative called P2P—“Prescription to Performance”—to introduce performance specifications as alternatives to traditional prescriptive specifications (Bickley et al. 2006a; Hover et al. 2008). There was concern that prescriptive specifications can hinder concrete producers from providing mixtures that optimize available materials while meeting the owner’s needs. Similarly, overly prescriptive requirements may stifle the concrete contractor’s capability to use innovative methods that support sustainability principles (1.5) and produce an acceptable product.

The P2P steering committee commissioned a project to review state-of-the-art industry practices internationally on performance specifications (Phase I) and to explore alternatives to existing prescriptive specifications for concrete (Phase II). Background information in this report relies heavily on the first P2P publication (Bickley et al. 2006a). The second report, which is referred to as the *P2P Phase II Report*, is a guide on writing performance-based requirements as alternatives to the prescriptive requirements in current ACI reference specifications (Hover et al. 2008). The Phase II report is described in greater detail in Chapter 6. The P2P project team observed that while there was an almost universal interest in performance, primarily for durability and sustainability, there were few performance specifications. A majority of the reviewed international standards defined exposure conditions for each country, prescribing limits for concrete mixtures that, on the basis of past research or experience, would result in the desired durability. The review revealed there is an almost universal use of supplementary cementitious materials (SCMs), such as fly ash, slag cement, and silica fume, either as separate additions or incorporated in blended cements. The specification documents assumed statistical quality control was used to ensure consistent conformity to the owner’s requirements.

Authors of the *P2P Phase I Report* (Hover et al. 2008) observed that, depending on the perspective of the stakeholder, the term “performance specification” can have different meanings. Due to the wide array of options and valid interpretations, it is imperative the term be carefully defined in any given context. Parties could agree in principle to execute work under the performance specification umbrella while having widely differing views about mutual expectations.

The *P2P Phase I Report* (Hover et al. 2008) concluded that the lack of reliable, consistent, and standardized test procedures for evaluating concrete performance is frequently cited as a major barrier to the adoption of performance-based requirements. Most tests available are performed under standardized conditions, serving as indicators of relative performance rather than measures of actual performance in service. Relative to tests conducted under prescriptive standards, performance tests can be expensive, time consuming, and lack tested precision. The short time

available to respond to a bid request and to start construction creates difficulties for a concrete producer required to develop a performance mixture and perform prequalification testing.

1.1.3 Establishment of ITG-8R—The Strategic Development Council (SDC), one of three organizations operating under the ACI Foundation, has embraced the need for performance-based requirements in the concrete industry. The SDC's mission is to facilitate the advancement of concrete technology by providing a forum for predicting and prioritizing key challenges facing the concrete industry, assisting ACI in timely adoption of innovative technologies and best practices, and providing a framework for consortia-directed development programs leading to commercialization. The SDC adopted a strategy for accelerated technology acceptance by identifying industry-critical technologies and applying resources to address these areas. In 2004, SDC identified the move from prescriptive to performance-based requirements as an industry-critical technology area and created an accelerated technology implementation team to address the need. After further evaluation, however, the team chose the innovation task group (ITG) mechanism of ACI to address the issue. The ACI Technical Activities Committee (TAC) evaluated the application for an ITG and approved the creation of ITG-8. The mission of ITG-8 was to develop a report on performance criteria and test methods for concrete materials that could be used in codes and specifications. In 2010, ACI published ITG-8R-10. This report is based on the ITG-8R-10 document with some revisions.

1.2—Objective and scope

The objectives of this report are as follows:

- a) Provide an introduction to performance specifications and discuss how they compare with prescriptive specifications
- b) Discuss the essential features of performance specifications
- c) Discuss how performance-based requirements can be used as alternatives to traditional prescriptive requirements

With respect to the third objective, the performance-based tests and criteria discussed in this report are intended to serve as examples and should not be interpreted as specification requirements. Design professionals should determine what is applicable to their projects in accordance with established codes and local practice.

Chapter 1 is an introduction to performance-based requirements and compares them with prescriptive requirements. Of special importance are the differences in the responsibilities of various parties under performance-based and prescriptive requirements. **Chapter 2** provides definitions used in this report.

Chapter 3 discusses the three principal elements of performance-based requirements:

1. Required performance characteristics
2. Sampling and testing methods
3. Acceptance criteria

A summary is provided of common and less common test methods used to confirm performance requirements are met.

Emphasis is placed on test methods available for assessing the durability potential of a concrete mixture.

Chapter 4 discusses acceptance criteria, reviews key consideration factors, and discusses actions that may be taken when the acceptance criteria are not met.

Chapter 5 addresses implementation of performance-based requirements on new projects. The various means of enhancing communication between affected parties are reviewed. There is discussion on the use of bonus-penalty provisions in contract documents. Finally, the technical challenges to implementation of performance specifications are discussed.

Chapter 6 reviews prescriptive durability requirements of **ACI 318** and **ACI 301** as opportunities to develop performance-based requirements. Examples are provided of performance-based requirements as alternatives to prescriptive durability requirements (**ACI 318**). These examples are based on the *P2P Phase II Report* (Hover et al. 2008).

Chapter 7 provides a summary of the report and lists future activities to facilitate implementation of performance-based requirements.

This report is not intended to provide a comprehensive set of performance-based requirements that can be incorporated directly into contract documents as alternatives to traditional prescriptive requirements.

It is important to recognize that a performance specification does not preclude the use of some prescriptive requirements when that is the most practicable approach for developing a workable project specification. Likewise, largely prescriptive specifications sometimes include some performance-based requirements. These hybrid specifications have worked well and are expected to continue to do so in the future. This report does not suggest that prescriptive specifications should be replaced with performance specifications. There are many cases where prescriptive specifications are the best solutions for all stakeholders. Rather, Committee 329 takes the position that because performance specifications encourage innovation, the industry should advance toward establishing performance-based alternatives to prescriptive requirements.

1.3—Performance-based requirements

As mentioned previously, a prescriptive specification defines the materials and methods of concrete placement. In contrast, a performance specification for concrete starts with the end state in mind, and describes the required quality characteristics of the end product, leaving the details about materials selection, proportioning, and construction means and methods up to the party bound contractually to complying with the specifications. Under a performance specification, the concrete construction team, which includes the concrete producer, general contractor, placement contractor, and the concrete contractor, is responsible for selecting and proportioning materials and conducting construction operations that will result in the required performance. Prescriptive specifications state how to proportion and install the concrete such that, if done in accordance with instructions, the outcome will be satisfactory. Performance specifications, however,

state the results required and how to evaluate the work, but do not direct how to execute the work.

The success of performance specifications is linked to the following factors:

- a) The governing building code and standards not referenced by building codes permit performance-based alternatives
- b) Ability of the specifier to define the quality characteristics appropriate for the owner's intended use of the concrete
- c) Ability of the specifier to describe these quality characteristics clearly, unambiguously, and quantitatively so that performance can be evaluated
- d) Availability of practical and reliable test methods that evaluate the required quality characteristics
- e) Ability of the specifier to define statistically-based acceptance limits that take into account the inherent variability of each test method
- f) Ability of the specifier to understand the risks to be assumed by the various members of the construction team for the sampling and acceptance plan that is developed
- g) Ability of the specifier to recognize conflicts between requirements and take appropriate actions to minimize such conflicts
- h) Ability of the construction team to develop concrete mixtures and construction techniques, leading to end results that comply with performance requirements
- i) The performance-based alternatives are economically viable and are capable of being achieved by all stakeholders
- j) Creation of a climate of trust where the owner and specifier can interact with the construction team in a cooperative manner.

These factors are, in turn, associated with several challenges:

- a) Under current, predominantly prescriptive specifications, all of the desired end-product quality characteristics may not be stated explicitly. In contrast, performance specifications should include explicit descriptions of owner expectations. In most cases, developing the required quality characteristics involves expertise beyond that required to write prescriptive specifications that have historical bases. Moreover, design professionals may need additional training or special expertise to develop effective performance requirements. An ineffective specification can lead to failure to achieve the desired performance for the structure even if the requirements of the contract have been met. An overly restrictive specification relative to the owner's needs, however, might increase the cost of materials without enhancing in-place performance.
- b) Some commonly expected quality characteristics are not easy to define or quantify, such as acceptable amounts of cracking due to plastic shrinkage or drying shrinkage.
- c) There is a lack of generally accepted short-term test methods for durability and models to predict reliably the in-place performance over the design life of the structure.
- d) Acceptance criteria need to consider the in-place variability of the concrete properties and the inherent variability of the test methods. The selected criteria need to balance the

owner's and the contractor's risks with regard to incorrect acceptance decisions.

- e) Some contractors and concrete producers will require additional training to learn how to select materials and construction operations that will produce the required end results.

Some of these challenges are discussed in greater detail in [Chapter 5](#).

1.4—Comparison of performance-based and prescriptive requirements

A project that uses performance-based requirements may include some or all of the following elements:

- a) A qualification and certification system that audits for conformance to a quality control management system, qualification of personnel, and requirements for concrete production facilities. The RMC Research & Education Foundation has developed guidelines for concrete producers on developing such a quality management system ([Twitty 2008](#)).
- b) Provisions in the specifications that clearly define the end-result performance requirements.
- c) A requirement that the construction team develops the optimized concrete mixture and plans the necessary field operations to ensure that the owner's expectations are met.
- d) A submittal format that does not include a detailed list of mixture proportions, but rather includes a listing of the materials used, test results, and certification that the mixture includes acceptable materials and will meet the performance requirements.
- e) A series of field acceptance tests performed at predetermined intervals after the concrete is placed and cured to determine if the concrete meets the performance criteria.
- f) A clear set of provisions to identify actions required if test results fail to meet acceptance criteria.

The primary advantage to specifying end-product performance is that a knowledgeable construction team has the flexibility to tailor the selection of materials, develop appropriate mixture proportions, and implement construction methods that will achieve the owner's objectives while staying within budget. Performance specifications will succeed only if the design professional clearly articulates the end-result requirements, the construction team has the necessary expertise to bid and execute the work, and appropriate test methods are available for documenting the in-place performance.

The RMC Research & Education Foundation funded an experimental study to demonstrate the differences in performance when concrete was designed to meet performance criteria, compared with concrete designed to meet commonly used prescriptive requirements ([Obla and Lobo 2006](#)). The study considered three applications: concrete floor slab construction, high-performance concrete (HPC) for a bridge deck, and the prescriptive w/cm requirements for durability used in ACI 318. The study concluded that performance-based mixtures had equal or better performance compared with the prescriptive mixtures and can allow for significant optimization of mixture proportions by knowledgeable and qualified concrete producers.

Table 1.4a—Advantages and disadvantages of prescriptive specifications (Bickley et al. 2006a)

Advantages	Disadvantages
Some designers and producers may have more confidence in and be more comfortable with a traditional prescriptive approach.	Some designers and producers may not be confident that prescriptive specifications lead to desired end performance.
Value and effectiveness of the product is designed-in by the specifier.	Limited opportunity for optimization of the concrete beyond specification-writing stage. Some specifiers may not have the expertise to specify an optimum mixture, especially with combinations of modern materials.
Newer materials and methods can be implemented if the specifier has remained informed of advances in concrete technology.	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.
The specification reflects the specifier's understanding of the relationship between the desired properties of concrete and specified materials, means, and methods.	The relationships implied in the prescriptive requirements may not be reliable for the specific materials or project conditions.
The specifier has the opportunity to control any aspect of the process, from concrete materials selection and proportioning to batching, mixing, transporting, placing, consolidating, finishing, and curing the concrete.	The interests of all parties may not be represented in the prescribed specification; for example, raw materials suppliers, concrete producer, concrete placing contractor, concrete finishing contractor, general contractor, construction manager, owner, investor, and end user.
Basic specification compliance tests are inexpensive, generally accepted, and commonly available.	Basic specification compliance tests may not provide enough information. Conventional test results may reflect the material as delivered and, subsequently, cured under standard conditions, rather than as installed and as cured by actual field conditions. Standard tests may report results at ages other than are critical for long-term performance. Standard tests may not enable accurate prediction of longer-term performance for the actual exposure.
Prescriptive specifications could be interpreted to limit concrete producer's responsibility to adherence to the prescribed requirements, and could be interpreted to limit concrete producer's liability for post-delivery influences on concrete behavior.	Producer often ends up being liable for post-delivery concrete behavior, at least until expensive tests demonstrate placing, consolidation, finishing, or curing problems.
Concrete producers only need batch-required materials in the required manner. Concrete materials and mixture expertise may not be required for typical applications.	Because limited expertise is required, limited expertise is applied; a lowest common denominator industry emerges. Concrete producers have limited technical, economic, or creative control of product.
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 any time after addition of water at the job site.
Prescriptive specifications level the playing field, allowing concrete producers with disparate levels of expertise to compete.	Prescriptive specifications diminish incentive for a given concrete producer to optimize a mixture, to innovate, or to exercise quality control beyond the level of competitors.

A prescriptive specification, however, may work best when there is previous history or empirical evidence that the specified materials and the specified means and methods will result in the required performance. The simpler the required concrete mixture and the less restrictive the required outcomes, the more likely a prescriptive specification is an efficient and reliable way to prepare contract documents. Specifiers should avoid unnecessary prescriptive requirements that can lead to costly mixtures that are prone to cracking and poor durability, such as minimum cementitious materials content, maximum w/cm , maximum limits on supplementary cementitious materials (SCMs), prohibition of SCMs, slump limits, and limits on characteristics of component materials not related to performance.

The specifier should recognize situations where performance specifications offer the greatest advantage and, conversely, should be prepared to identify situations where a more conventional prescriptive approach is appropriate. For example, a prescriptive approach may be best for small projects or where the concrete producer does not have the resources to supply concrete in accordance with a performance specification. In addition, prescriptive limits are appropriate when there is no practicable method to measure the intended performance characteristics, such as finish-

ability. As discussed in [Chapter 6](#), reference standards, such as ACI codes and specifications that may be used in contract documents, should include these performance-based requirements as alternatives to existing prescriptive requirements. Including performance-based provisions in the building code, or including provisions that will allow alternatives that are deemed to satisfy the intent of building code requirements, are essential before design professionals can include such requirements in contract documents.

Tables 1.4a and 1.4b summarize the advantages and disadvantages of prescriptive specifications and performance specifications, respectively.

Because any method for specifying concrete materials and construction services will have its advantages and disadvantages, the challenge and opportunity is to develop effective specifications that maximize advantages and minimize disadvantages. This also means the specifier should have the flexibility to use the specification type that is most appropriate in any given situation.

Blends in specification philosophies are frequently encountered within existing standards. For example, [ACI 318](#) allows for acceptance of concrete on the basis of strength test results, which is performance-based, but durability limits invoke a maximum w/cm , which is prescriptive-based. Likewise, the

Table 1.4b—Advantages and disadvantages of performance specifications (Bickley et al. 2006a)

Advantages	Disadvantages
Specifiers focus on what is needed rather than how to get it. Not all specifiers are familiar with how to best achieve end results.	Specifying how to achieve satisfactory concrete has been a traditional responsibility of the licensed design professional. Engineers may be concerned over a perceived reduction in control.
Opportunity to focus on concrete behaviors and characteristics that really matter.	Specifier may not be sure about what those characteristics are, or about how to measure them. Reliable tests may not be available to assess whether desired outcomes are satisfied. Performance tests may be more expensive, more time-consuming, or require more special expertise compared with conventional tests.
Construction team has technical, logistical, economic, and creative control over the product. Opportunity to take advantage of unique materials, material combinations, plants, equipment, technology, expertise, knowledge of local materials, and conditions. Flexibility in mixture proportioning can be an opportunity to produce a better overall mixture, 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, on-site mixture adjustments by contractor, placing, consolidation, finishing, adjustments to mixture proportions at surface, ambient conditions, moisture control, and temperature control. Many parties are 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 mixture characteristics can be augmented or replaced with tests of relevant concrete properties.	Tests beyond the routine slump, air content, and cylinder strength will likely be more complicated and increase the cost of quality assurance testing. Test precision should be considered when developing acceptance criteria.
In those cases where prescriptive specifications are interpreted to give the construction team full responsibility for end-result concrete behavior, even when prescriptive requirements have been met, a switch to performance specifications does not necessarily result in any additional responsibility.	In those cases where specifications clearly limit the producer's responsibility to comply with prescriptive provisions, the switch to performance specifications, with an emphasis on end results, will complicate the assignment of responsibility among members of the construction team.

alternative performance specification in the Canadian Standards Association (CSA) on concrete construction ([CSA A23.1/A23.2](#)) includes prescriptive *w/cm* limits. The [NRMCA \(2009\)](#) has developed recommendations on how specifications for concrete materials can be improved by eliminating prescriptive provisions when not applicable and allowing flexibility via end-product performance requirements.

Further options exist in the distinction between quality 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 bonuses for exceptional performance and reduce payments for less-than-specified performance, provided the concrete that remains in place meets minimum requirements. The underlying concept of such pay adjustment factors is that increased payment for a higher level performance compensates the contractor for the higher cost associated with improved quality, and can be justified by the owner for an anticipated longer service life. Penalties for less-than-specified performance compensate the owner for potentially higher-than-expected maintenance costs to achieve the design service life. Examples of such arrangements are discussed in [Chapter 5](#).

1.5—Sustainability and performance-based requirements

1.5.1 Introduction—The World Commission on Environment and Development (WCED) defines sustainable development as “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” ([U.N. WCED 1987](#)). In short, sustainability is stewardship of resources. To be sustainable, one should attempt to balance environmental, social, and economic impacts of an action.

In an effort to be more sustainable, the concrete industry should evolve toward the implementation of manufacturing processes that reduce environmental impact. Innovation is the tool by which environmentally sustainable practice is optimized. Performance specifications of concrete may provide the mechanism to create the opportunities for innovations to occur.

1.5.2 Sustainability initiatives within concrete industry—As terms such as “sustainable development” and “environmental stewardship” are being woven into the fabric of our society, the concrete industry finds itself responding to the challenges of sustainable development and trying to understand how environmental stewardship can be incorporated into the industry’s best practices. One challenge that the concrete industry faces is the sheer diversity of the industry. The concrete industry is made up of smaller independent yet related industries such as raw material extraction, material sciences, design, production, manufacturing, transportation, construction, maintenance, and repair. Although these smaller industries work together as constituents of the concrete industry, the concrete industry quite often finds itself fragmented by conflicting interests. Recognizing the importance of unifying the industry as it moves toward sustainability, the industry has undertaken initiatives designed to align the views of its constituents with the greater purpose of the industry. More notable initiatives are:

a) *Vision 2030*—Published in January 2001, this document was a collective voice of an executive level group representing a cross section of the industry. The group identified specific goals to achieve their vision for the United States concrete industry by 2030 ([Plenge 2001](#)).

b) *NRMCA initiatives*—These include the Prescriptive to Performance (P2P) Initiative (1.1.2) and the NRMCA Sustainability Initiative.

c) *Joint sustainability initiatives*—Partner organizations in the Concrete Joint Sustainability Initiative (CJSI) committed their strengths, resources, and commitment to charting a course to a sustainable future for the concrete industry (CJSI 2010).

1.5.3 Examples of sustainability through performance specifications—Allowing alternative methods of executing concrete work through performance specifications allows concrete producers and concrete contractors to be more innovative. Sections 1.5.3.1 through 1.5.3.3 present several examples to illustrate how performance specifications will support environmentally sustainable practices.

1.5.3.1 Reducing potable water use—According to NRMCA (2009), the United States ready mixed concrete industry spends an estimated \$25 million annually in the management and disposal of water. Cleaning trucks and production equipment generate an estimated 3 billion gal. (10 million m³) of processed water that should be managed and properly disposed. As the industry moves in a direction of environmental stewardship, use of potable water should be reduced while use of alternative sources of water increased. Performance specifications may foster a culture of innovation that can advance the industry beyond existing practices. Some promising innovations that can reduce the demand for potable water include incorporating rain water, pond water, and recycled water during the batching process, and the inclusion of saturated lightweight aggregate in concrete to provide a more efficient use of water during curing. Specifications that allow outside-the-box thinking should result in the conservation of valuable potable water, potentially reducing pollution and saving money.

1.5.3.2 Reducing waste—It is estimated that an average of 5 percent of ready mixed concrete produced in the United States is returned to the plant (Obla et al. 2007). Performance specifications would allow a resourceful manufacturer to develop innovative techniques that recapture the raw materials for future reuse, as opposed to sending the material to a landfill. Available options for reuse include reclaimed aggregate, reuse of gray water, and the incorporation of fresh returned concrete in new batches, when permitted. The reuse of returned concrete will result in reduced expenses to the ready mixed concrete industry. It will also help sustainable development by reducing the demand for virgin materials.

1.5.3.3 Reducing CO₂ emissions and energy use—Every ton (tonne) of limestone replaced in the production of portland cement by supplementary cementitious materials (SCMs) reduces CO₂ by approximately 1/2 ton (tonne) per ton (tonne) of cement. In addition, every ton (tonne) of cement replaced by SCM reduces CO₂ by approximately 1 ton (tonne) (Choate 2003). Energy consumption can also be reduced by replacing a small portion of cement clinker with limestone. For example, the use of 2.5 percent limestone filler in each ton (tonne) of cement would reduce energy consumption in the United States by approximately 110,000 BTU (116 MJ) and reduce CO₂ emissions by approximately

2.5 percent (Nisbet 1996). Through a performance-based alternative, the concrete producer will have the leeway to tailor the design of the concrete mixture to the specific needs of the project while optimizing the use of SCM, thus creating opportunities to reduce CO₂. However, the specifier should balance these gains against other unintentional consequences; for example, extending the construction schedule due to reduced rate of strength gain associated with some high-volume SCM mixtures.

1.6—Responsibilities of involved parties

1.6.1 Point of performance—Because of the multiple stages of concrete production and placement, and because custody of the concrete can change hands several times before the properties of the end product are fully developed, at what point in the process should the concrete be specified and evaluated? This question is further complicated when the parties involved with the varying stages of concrete production, placement, and curing have different opinions about its performance.

Contractually speaking, concrete performance will most likely be viewed in terms of the specifier and, therefore, defined by the required quality 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 fineness modulus (FM) of sand, or compliance with ASTM C33/C33M, with no further stipulation as to where or how to extract the rock or process it.

Similar examples could be used for requirements for the performance of cement, cementitious materials, or admixtures. A purely performance-minded concrete producer might not ask for cement mill test reports or demand that cement meet specific chemical or fineness requirements of a cement specification, specifying instead that the cement meet requirements for strength, rate of strength-gain, soundness, shrinkage, setting time, water demand, uniformity, and test results documenting mitigation of alkali-silica reactivity (ASR). Those involved in quality control would obtain reports on the single source uniformity of cement from the cement supplier in accordance with ASTM C917, or reports of the uniformity of other ingredient materials in accordance with ASTM C1451.

Likewise, a performance-minded buyer of chemical admixtures and SCMs might not be interested in their chemical composition but would want assurance that the characteristics of the materials remain uniform between shipments, will perform consistently in the concrete, and be mutually compatible. To provide some safeguard against unpredictable long-term performance, the purchaser of concrete can require certification that constituent materials conform to standard specifications. While some of these quality characteristics for constituent materials are easily specified and readily evaluated with long-established test methods, and the responsibility for meeting them is clear, conditions become more complicated when raw materials are combined. In some cases, nonconforming materials can be blended to meet performance requirements.

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, bleeding characteristics, elimination of entrained air in normalweight concrete that has to receive a hard-trowel finish, or early-age strength for formwork or shoring removal. When requirements in project specifications conflict with some of the requirements of the contractor, these conflicts should be resolved before concreting begins. When performance is evaluated at the point of discharge from the concrete truck, responsibility is clear, but when evaluation moves to the point of discharge from the pump, responsibility starts to become vague. 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 probably won't be concerned with raw materials, fresh concrete, or construction issues. To the owner, concrete performance is defined by sufficient load-carrying capacity of the structure to allow safe operation, sufficient durability the intended service life, and the required appearance as established by demonstration placements. The concept of a performance specification can have different implications to each party involved in regard to achieving required performance and, therefore, should be a joint responsibility. Because the owner's primary interests are the in-place, long-term properties of concrete, meeting such requirements is the joint responsibility of the raw materials suppliers, concrete producer, formwork subcontractor, pumping subcontractor, placing and finishing subcontractor, and the general contractor or construction manager that manages the process from start to finish. This makes it essential for a more definitive discussion about the point of performance. Discussion points include:

- a) When and where in the multiple processes of concrete-making to curing and protecting will the required performance of the concrete be defined?
- b) Who is responsible for achieving the specified performance?
- c) At what point in the construction process will the responsibility of a particular party end?

Table 1.6, which is taken from the *P2P Phase I Report*, is an example dealing with a superflat industrial floor, to demonstrate that the terms "concrete performance", "performance specification", and "point of performance" can take on a different scope and meaning for the various parties involved with the overall project. Table 1.6 considers only the flatness aspects of the floor and ignores other critical quality characteristics such as strength, cracking, and abrasion resistance. Despite the small scope of this example, it illustrates the high number of processes and team members that influence the end result.

As shown in Table 1.6, attainment of the performance required by the owner is affected by design, materials, and construction. Performance specifications, therefore, can be efficient for the owner, quickly zeroing in on key operational characteristics of the installed concrete. They become equally efficient, however, for the concrete producer when the concrete materials performance aspects that contribute to

the owner's required performance are identified and can be controlled. The contractor should, in turn, control construction operations to achieve the owner's requirements. Satisfying the owner's performance specification requires that the various parties influencing performance accept their mutual responsibility. From the owner's overall project perspective, the most meaningful approach for evaluation of performance is measurement of hardened concrete properties in the structure at an age that provides a reliable prediction of service life. The frequently acceptable state of the practice, however, is to evaluate concrete properties from samples taken at the point of discharge from the concrete truck, the point of placement, or both. From the test results, the in-place capacity and durability are estimated on the basis of known or implied relationships. In many cases, in-place concrete properties can be measured using standard tests developed for that purpose. Thus, a less comprehensive but more conventional performance specification could be considered that targets concrete performance based on tests of samples taken at the time of placement. For example, the most meaningful concrete strength value in determining structural capacity is the in-place strength value, which is influenced by materials, mixing, consolidation, curing, and in-place time-temperature history. More frequently, however, this in-place value is inferred on the basis of standard cylinders sampled at the time of placement and cured under laboratory conditions. Therefore, the strength of standard-cured cylinders could be specified as a performance criterion. Similarly, air content in the fresh concrete or air bubble size in the hardened concrete using microscopic analysis are viable performance criteria. Even when the performance-minded specifier chooses to ignore slump as a performance criterion, the concrete contractor might demand the concrete arrive at the site at a particular slump, thereby reintroducing slump as a performance requirement for the concrete producer.

1.6.2 Risk and responsibility—The **ACI Committee on Responsibility in Concrete Construction (RCC) (2005)** 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." The committee continues with "One over-riding principle ... is the simple notion that responsibility and authority must be congruent." This suggests that if the concrete producer and contractor are held responsible for concrete performance, they should have the freedom to provide a product that meets the requirements developed by the licensed 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 plan means and methods of construction. From another perspective, for many current projects, the concrete producer and contractor are already heavily responsible for concrete behavior, even when complying with prescriptive specifications. For many producer-contractors, the principle of congruency of authority and responsibility under a performance specification

Table 1.6—Example of multiple responsibilities and performance criteria for a superflat industrial floor (Bickley et al. 2006a)

Example performance requirement	Party setting the performance requirement	Party obligated to achieve the specified performance	Point of performance	Measuring performance
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	Hardened concrete floor, day after placing	Place and finish should 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 in-place not yet standardized
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 and sample at time of construction to verify	ASTM C157/C157M for prequalification testing. No standard method for field verification.
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 and sample at time of construction to verify	
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	
Influence of subgrade preparation specification and compliance, installation of reinforcement 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 reinforcement and 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

tion might simply mean gaining freedom of action with the same level of responsibility for the end product as is already implied in current prescriptive specifications.

One important difference, however, could be when, under a prescriptive specification based on sampling at the truck chute, responsibility for end-result concrete problems

frequently becomes the concrete producer's. Under a clear performance specification, with at least some in-place testing of hardened concrete, the contractor's shared responsibility for in-place concrete performance becomes more apparent.

The RCC report (ACI Committee on Responsibility in Concrete Construction 2005) also discusses the issue of the

design professional's responsibility to review mixture 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."

Under a performance specification, there is a question whether the concrete producer should be required to provide mixture proportions when it is certified that the materials used in the concrete conform to applicable specifications and the performance requirements were met. This will depend largely on contract requirements and local laws or regulations.

A key advantage to using performance specifications is the clarity with which the owner's expectations can be expressed. The licensed design professional is responsible for describing functional needs of the concrete in terms of a finite list of measurable properties. If these properties or criteria are over-specified, construction cost may be higher than needed to meet the owner's needs. If the performance requirements are not rigorous enough, any cost-savings may not compensate for the owner's inability to use the structure as intended. Under a performance specification, the contractor is aware of the owner's expectations in advance, making it less likely that the owner could make demands on the contractor for unspecified characteristics or attributes of the concrete.

1.6.3 Example of assignment of responsibility and review of CSA A23.1/A23.2—**CSA A23.1/A23.2** is the Canadian Standards Association's main standard on concrete construction. The owner is offered two alternatives for concrete specification—performance or prescription. Each alternative delineates what the owner will specify and job responsibilities of the contractor and supplier. It states that the performance alternative applies "when the owner requires the concrete producer to assume responsibility for the performance of the concrete as delivered and the contractor to assume responsibility for the concrete in place." Clearly then, the responsibility of the concrete producer ends when the concrete mixture is discharged from the mixer or delivery unit. The contractor, however, is responsible for placing, consolidating, and curing the concrete so that it develops the strength and durability characteristics required by the owner. Table 1.6.3 shows the responsibilities of the owner, contractor, and concrete producer for the two methods of specification. Note that there is usually no contractual relationship between the owner and concrete producer. Typically, the concrete producer is responsible contractually to the concrete purchaser, who may be a general contractor or the concrete contractor.

1.7—ACI codes and specifications

1.7.1 Overview—Two important types of ACI documents that address prescriptive and performance requirements are ACI codes and ACI reference specifications. Both are ACI standards that have gone through the ACI process documented in the "ACI Technical Committee Manual" (ACI

Technical Activities Committee 2014). There is often confusion, however, about the differences between codes and specifications.

1.7.2 ACI codes—ACI codes are intended to provide minimum requirements for structures to safeguard public safety, health, and general welfare. ACI codes can be adopted by reference by governmental or regulatory bodies for design regulation and construction of concrete structures. When so adopted, ACI codes become law, and violation of the code is a civil, or even sometimes criminal, offense. Because of their potential legally binding nature, ACI codes must be worded in explicit, mandatory language that results in just one interpretation of a requirement. In addition, ACI codes can cite only other mandatory language documents. An ACI code may be accompanied by a companion commentary that provides background information on code provisions and guidance on implementing complex provisions. Unlike the code, the commentary is advisory and not legally binding, although in some legal proceedings, courts have given the commentary weight as reflective of the code drafters' intent. ACI codes are directed to the licensed design professional who is responsible for the resultant design and preparation of contract documents. **ACI 318** is the primary design standard for the concrete construction industry in the United States and many countries worldwide.

ACI 318 contains elements of both prescriptive and performance requirements. The Code defines various exposure categories and classes and contains tables of durability requirements for each exposure condition in terms of maximum w/cm , minimum specified compressive strength, total air content, limitations on supplementary cementitious materials (SCMs) to prevent scaling, limits on chloride content, and requirements for cement types. ACI 318 requires that the licensed design professional assigns the exposure class for structural members based on severity of the anticipated exposure and incorporates this information in contract documents.

Whereas some of the durability requirements in ACI 318 on maximum w/cm , minimum specified strength, minimum air content, limits on chloride content, and requirements for cement types might be considered prescriptive in nature, these are stated for a specific exposure condition and some flexibility for materials selection and proportioning remains. For example, there are no maximum or minimum limits on the total mass of cement, SCM, or water. The only exception is a limit on the amount of SCM for concrete exposed to freezing and thawing and in continuous contact with moisture and exposed to deicing chemicals. The code imposes no requirement on aggregate content except that which derives from the limits on nominal maximum size of coarse aggregate (ACI 318-11, Chapter 3) and good mixture proportioning practice. Even air content is given as a function of coarse aggregate size (ACI 318-11, Table 4.4.1), which is an approximate, if indirect, way to account for the need for more total air content as paste content increases. Further movement toward performance-based requirements for concrete are found within ACI 318. One such example is the intent of Section 4.5.1 in ACI 318-11. This provision captures the

Table 1.6.3—Responsibilities of parties defined in CSA A23.1/A23.2

Specification	Owner	Contractor	Producer
Performance	(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, prequalification, or verification criteria (d) Quality management requirements (e) Whether the concrete producer shall meet certification requirements of concrete industry certification programs (f) Any other properties they may be required to meet the owner's performance requirements	(a) Work with the producer to establish the concrete mixture 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 prequalification performance requirements have been met (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 the standard (b) Certify that the mixture design satisfies the requirements of the standard (c) Certify that production and delivery of concrete will meet the requirements of the 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 producer meets industry certification requirements, if specified (g) At the request of the owner, submit documentation to the satisfaction of the owner demonstrating that the proposed mixture design will achieve the required strength, durability, and performance requirements
Prescriptive	(a) Mixture proportions, including the quantities of any or all materials (admixtures, aggregates, cementing materials, and water) by mass per cubic meter of concrete (b) The range of air content (c) The slump range (d) Use of a concrete quality plan, if required (e) Other requirements	(a) Plan the construction methods based on the owner's mixture proportions and parameters (b) Obtain approval from the owner for any deviation from the specified mixture design or parameters (c) Identify to the owner any anticipated problems or deficiencies with the mixture 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 the standard (b) Demonstrate that the concrete complies with the prescriptive criteria as supplied by the owner (c) Identify to the contractor any anticipated problems or deficiencies with the mixture parameters related to construction

essence of performance-based concrete by allowing the use of alternative combinations of cementitious materials to be considered to provide sulfate resistance. ACI 318 provides a means to verify the performance of the material combination by referencing a standard test method and specifying limits for acceptability.

Note that **ACI 318** is not directed to the contractor. Construction requirements in the Code are intended for placement in contract documents by the licensed design professional so that the structure is constructed in accordance with code requirements. The licensed design professional may refer to **ACI 301** as an alternative means for incorporating these construction requirements in the project specification.

1.7.3 ACI reference specifications—ACI reference specifications are intended for incorporation by reference in the contract between owner and contractor. An ACI reference specification, therefore, becomes a legally binding part of the contract. ACI specifications are written to the contractor and must be worded in explicit, mandatory language subject to only one interpretation.

Some ACI reference specifications are written to ensure that construction satisfies the minimum life safety requirements of a corresponding code. For example, ACI 301 is intended to complement ACI 318. Like ACI 318, ACI 301 is a combination of prescriptive and performance-based requirements. Most of ACI 301 requirements are,

however, prescriptive and provide explicit instructions to the contractor.

Examples of the prescriptive nature of ACI 301 include:

- a) Requirements placed on cement types
- b) Limits on slump and air content
- c) Limits on water-soluble chloride content
- d) Limits on SCM
- e) Minimum cementitious materials content in floors
- f) Minimum concrete temperatures in cold weather
- g) Requirements to submit actual design mixture proportions and concrete material certifications
- h) Requirements for handling and storing materials

Section 4 of ACI 301 allows some flexibility for materials selection and proportioning. Examples of performance-based requirements in ACI 301 are the lack of limits placed on cementitious materials content, except for minimum limits for industrial floors and shrinkage-compensating concrete. There are no limits on the amount of supplementary materials, except when concrete will be exposed to deicing salts. There are also no limits on water content.

Chapter 6 provides a more detailed examination of the prescriptive requirements in ACI 318 and ACI 301, which are the only ACI standards examined in this report.

CHAPTER 2—DEFINITIONS

ACI provides a comprehensive list of definitions through an online resource, “ACI Concrete Terminology,” <http://www.concrete.org/terminology/>

www.concrete.org/Tools/ConcreteTerminology.aspx. Definitions provided herein complement that resource.

acceptable quality level—the limiting level of actual quality at which the material or construction can be considered fully acceptable (for that quality characteristic) and full payment is expected.

acceptance plan—an agreed-upon method of taking samples and making measurements on those samples for the purpose of evaluating the acceptability of a lot of material.

concrete construction team—representatives of the general contractor, concrete contractor, concrete producer, and testing agency responsible for quality control.

concrete producer—the person, firm, or entity under contract for producing and delivering concrete for the work.

expected payment curve—a graphical representation of an acceptance plan showing the average pay the contractor is expected to receive over time as a function of the actual quality level of the work.

identity test—test used to verify that delivered concrete is similar to prequalified mixture.

lot—definite quantity of a product or materials accumulated under conditions that are considered uniform for sampling purposes.

lot tolerance percent defective—highest value of percent (or fraction) defective that the purchaser is willing to accept.

lower quality index—quality index based on the difference between the average of test results and the lower specification limit.

maximum value—the highest acceptable value of a measured property or dimension of a product or item.

minimum value—the lowest acceptable value of a measured property or dimension of a product or item.

nominal value—a representative value of a measurable property or dimension by which a product or item may be described.

operating characteristics curve—a graphical representation of an acceptance plan showing the probability of acceptance of a lot versus the quality level of a lot (percentage or fraction defective or percentage within limits).

owner's representative—the person, firm, or corporation with whom the owner enters into an agreement to act on the owner's behalf.

owner's team—the owner, owner's representative, and personnel responsible for quality assurance.

payment factor—a multiplication factor used to adjust the contractor's bid price per unit of work, based on the estimated quality of work.

penetrability—a general term related to the ease of fluid penetration into concrete, which may occur by permeation, absorption, and diffusion.

percent within limits—calculated percentage of concrete in a lot that meets specification limit(s); the value depends on the quality index and the number of tests from the lot.

performance-based requirements—provisions in codes or specifications that focus on defining end results.

performance test—a test that measures a basic characteristic that influences the in-place performance of the concrete.

prequalified mixture—a concrete mixture that is approved before start of construction on the basis of performance tests.

quality—the degree to which a product or service conforms to a given requirement.

quality characteristics—the characteristic of a unit or product that is actually measured to determine conformance with a given requirement.

quality control plan—a detailed description of the type and frequency of inspection, sampling, and testing deemed necessary to measure and control the various properties required by contract documents.

quality index—quotient obtained by dividing the difference between the average of test results and the specification limit by the standard deviation of the test results for a lot.

quality measure—any one of several measures that have been established to quantify quality, such as the mean, the standard deviation, the percent within limits, and the quality index.

rejectable—condition where owner has the option to require removal and replacement of a lot of installed material because of failure to meet acceptance criteria.

rejectable quality level—that limiting level of actual quality at which the material or construction can be considered unacceptable (rejectable), and the contractor may be required to remove and replace, take corrective action, or accept reduced payment.

required average strength—average strength of concrete used for mixture proportioning to ensure a high probability of meeting acceptance criteria for strength.

specialty engineer—licensed design professional retained by contractor to provide specific design service as part of work.

specification limit(s)—the limiting value(s) placed on a quality characteristic, established preferably by statistical analysis, for evaluating material or construction with respect to the specification requirements; the term can refer to either a lower specification limit, an upper specification limit, or both.

specified value—value of a measured property or dimension to which a product or an item is required to conform.

specifier—person or entity preparing and organizing the project specification for a construction project.

stakeholder—an individual or group with a direct or indirect interest in the outcome of an activity or project.

surrogate test—test to measure a characteristic of a material that can be used to substitute for a performance test.

upper quality index—quality index based on the difference between the average of test results and the upper specification limit.

work—entire construction or separately identifiable parts thereof required to be furnished under contract documents.

CHAPTER 3—ELEMENTS OF PERFORMANCE-BASED REQUIREMENTS

3.1—Quality characteristics

A critical step in developing a performance specification is to state the required quality characteristics, which is simply a description of the required results known to be related to performance. The required quality characteristics should be stated in quantitative terms referenced to a standard test method or, if not possible, stated in terms of conforming to an accepted reference standard. The latter approach is often used to judge the acceptability of surface finishes and appearance by the use of mockups. Ideally, quality characteristics should be tied closely to long-term performance. For example, if the objective is to ensure the concrete is resistant to freezing and thawing, it would be appropriate to specify minimum requirements for the air-void characteristics of the in-place hardened concrete.

Quality characteristics that are stated in quantitative terms are preferred because the product can be measured and an assessment made as to whether the requirements are met. When stating quality characteristics, therefore, it is necessary to state the tests that will be used for assessment and when and where they will be performed. Ideally, these tests should measure quality characteristics that have a direct relationship to in-place performance. This, however, might not always be practical, and surrogate tests may be used for acceptance. In addition, another suite of identity tests may be specified to verify the concrete delivered is similar to the prequalified mixture.

3.2—Prequalification, identity, and surrogate testing

When a portion of the concrete is found to be unacceptable after it has been placed, it is not a simple matter to remove and replace the deficient material. For this reason, a process has been developed to increase the likelihood that the in-place concrete will be acceptable. This process comprises three steps:

1. Using prescriptive requirements for raw materials or prequalification through testing or certification
2. Implementing a review and approval system for proposed concrete mixtures that may include laboratory trial batches or assessment of previous placements using the mixture.
3. Conducting a series of fresh concrete tests at the point of delivery or placement

Under a performance specification, the potential for unacceptable hardened concrete in place may be reduced by requiring evidence that the proposed concrete materials, the mixture, and installation methods have the potential to produce a finished product that meets specification requirements. It may, therefore, be necessary to prequalify the component materials and concrete mixtures on the basis of historical records of performance or by providing laboratory performance test data. It would be reasonable to approve the use of a known successful combination of materials and construction technique, especially when tests to demon-

strate specified performance require more time than is available before the concrete is needed on site. This approach is permitted by 5.4.1 of [ACI 318-11](#), which allows the licensed design professional to approve a mixture based on other experience or information, provided the specified compressive strength is less than 5000 psi (35 MPa).

Because of the inherent variability in concrete materials, batching, and mixing, even if a mixture has been prequalified, it is still necessary to confirm the delivered concrete is the same material as the prequalified mixture. The term “identity testing” is used by [BS 8500-2:2006](#) to describe on-site testing by the owner to validate the mixture identity. Identity testing seeks evidence that the delivered concrete is not different from the prequalified mixture. For example, consider a performance requirement for an in-place value of 1000 coulombs (C) using the rapid chloride permeability test (RCPT) in accordance with [ASTM C1202](#). Assume that a mixture had been qualified to meet this requirement based on prequalification testing. As part of prequalification testing, the fresh and hardened properties of the concrete are measured. During construction, the owner performs a suite of tests on concrete sampled at the time of placement to verify that the properties of the delivered concrete are not different from the prequalified concrete. Such identity testing could be some combination of tests for water content, fresh density, air content, or strength at a specified age. To confirm in-place properties, there may also be periodic RCPTs on cores extracted from the structure.

While prequalification provides evidence that the construction team can deliver a product that meets performance specifications, it does not prove that the installed materials will comply. It is likely, therefore, that performance specifications will include requirements for preconstruction demonstrations of the suitability of end results. This evidence could range from a simple submittal of historical data that demonstrate successful past performance, to the casting of mockups for evaluation by in-place methods. It is likely, however, that additional performance testing, during or after construction, will be required to supplement prequalification testing. There are many factors, from variations in the raw materials, uniformity of mixing, placement operations, to final curing methods, that affect in-place performance.

Ideally, the owner would prefer to use performance tests for evaluating suitability of the final product. Some performance tests, unfortunately, are impractical as acceptance tests because of cost, complexity, the length of time to obtain test results, lack of robustness for use in the field, or they are not applicable to concrete as delivered. For example, mortar or ASR tests of concrete specimens in accordance with [ASTM C1293](#) may require up to 2 years to complete. The owner may elect to base final acceptance on the results of surrogate tests. The acceptance limits for results of the surrogate tests would be based on correlations developed during prequalification testing. For example, suppose the performance requirement is that the reinforced concrete has to be durable under exposure to external chlorides, and the limit of acceptability is in terms of maximum charge passed. The producer has devel-