

Specifying Concrete for Durability

Performance-Based Criteria Offer Best Solutions

By **Karthik Obla, Colin Lobo, Lionel Lemay, NRMCA**

Introduction

A specification for concrete construction is a set of instructions from the owner, typically written by a design professional as his representative, to the concrete contractor. A specification eventually forms the basis of a contract, a legal agreement, between the owner and the contractor and establishes the joint and separate responsibilities of the various stakeholders in the construction team toward achieving the objectives of the owner. For that reason, the specification should be written in terse mandatory language with clear, measurable and achievable requirements.

Based on numerous concrete specification reviews conducted by the authors, the following points are suggested in developing specifications for concrete construction:

- Compliance with industry reference documents, especially guidance documents written in non-mandatory language, should be avoided. These documents discuss various options and, if a specific option is needed for the project, it should be written in the specification.
- The specification should not include a general statement requiring compliance with the building code. It is the design professional's responsibility to establish provisions of the code that apply to the project and write them in the specification. Do not apply code provisions to portions of structures for which they are not applicable.
- The specification should avoid outlining details of construction means and methods as the expertise of the contractor is stifled.

- The specification should avoid dictating details of the mixture proportions as the concrete producer's expertise is stifled. Often the contractor and concrete supplier can work out the requirements of plastic concrete for construction.
- Project requirements "implied" by specification clauses controlling means and methods or mixtures detract from clarity, are not enforceable and should be avoided. State the required performance in measurable terms.
- Requiring the use of specific brands of products or equipment should be avoided when alternative equivalents are available.
- Avoid the adding-on requirements to a set of conditions that currently work as this can cause a different problem. Avoid making acceptance criteria more restrictive than accepted industry practice as that may not be achievable or could cost more for no associated benefit.
- Submittals prior to the start of work should be limited to documenting conformance to the specification requirements. This process can be significantly simplified from the current practice.

The aim of this paper is to help the architect and engineer:

1. Improve the concrete specifications in order to achieve better concrete quality;
2. Choose the right performance criteria in place of prescriptive criteria for concrete subject to harsh environments;
3. Identify and understand the tests and criteria that could be used to satisfy the project performance requirements.

Compressive Strength

Concrete compressive strength is the most common test conducted for acceptance of concrete. Test cylinders are prepared for standard curing in accordance with ASTM C 31 and tested in accordance with ASTM C 39. The ACI 318 Building Code establishes statistically-based acceptance criteria for cylinder tests and criteria for strength tests on cores when the cylinder test criteria are not achieved. The strength test is one of the more precise tests with a single lab coefficient of variation at 2.8% and a multi-lab coefficient of variation of about 5%. Certification programs are in place for field and laboratory technicians to ensure more reliable testing of jobsite concrete samples. ASTM C 31 has historically required 6 x 12-inch cylinders as the standard size test specimen. It also permits 4 x 8-inch specimens when specified. There is considerably greater use of these 4 x 8-inch specimens because they afford ease of handling and more reliable jobsite curing and it is now advisable that the specification allow their use. We recommend including a clause in the specification requiring the use of 4 x 8-inch cylinders for compressive strength tests.

Although strength is not typically a good indicator of concrete durability, most concrete will require a minimum level of strength for structural design purposes regardless of the application. When the structural element is not subject to durability concerns, specified compressive strength is the preferred performance criteria. Do not specify maximum w/cm or minimum cementitious content as this will most likely cause an inherent specification conflict. Concrete can have a wide range of compressive strength for

a given w/cm or total cementitious content. For each set of materials there is a unique relationship between the strength and water-cement ratio. A different set of materials has a different relationship as illustrated in Figure 1. At 0.45 water-cement ratio these three mixtures have strengths of approximately 6000, 5000 and 4000 psi respectively. These differences in strength can occur simply by changing the aggregate size and type used in the mix as described in ACI 211.

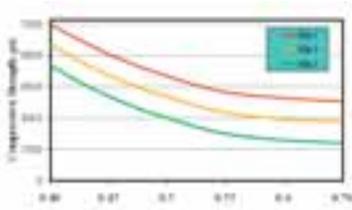


Figure 1. Does w/cm control strength?

ACI 318 establishes a process whereby the concrete producer can document his past test records to establish mixture proportions for the proposed project. When this test record exists, the required average strength of concrete for the proposed work should be established based on the standard deviation of the strength test results from the past work. The submittal should require field or laboratory test records for each class of concrete to demonstrate the concrete will meet the required average compressive strength. The specification should not require the required average strength at a fixed value, say 1200 psi, over the specified strength. The procedure for calculating standard deviation and required average compressive strength based on the specified strength should be derived from the equations in Table 5.3.2.1 of ACI 318. This ensures that producers who maintain low strength variability (standard deviation) can optimize concrete mix designs for a lower average strength. Concrete supplied by producers exercising good quality control will frequently result in fewer problems on a project.

While the traditional testing age for strength tests is 28 days, the design professional has some flexibility to change the test age to suit the project requirements. An early age strength requirement may be appropriate for fast track construction but could detract from the durability of the

concrete. If project schedules anticipate later live load applications on the structure, it might be appropriate to specify strength requirements for later test ages, such as 56 or 90 days. This allows the use of higher volumes of supplementary materials such as fly ash, slag and silica fume, which generally result in more durable concrete and support sustainable construction.

Durability

When it comes to concrete durability, engineers should not rely solely on specifying a minimum compressive strength, maximum water-cement ratio, minimum cementitious content and air entrainment. There are better ways to quantify durability. Low permeability and shrinkage are two performance characteristics of concrete that can prolong the service life of a structure that is subjected to severe exposure conditions. But how should these properties be specified and measured? What should the acceptance criteria be? Below we will describe the latest quality assurance and quality control methods used for concrete to withstand corrosion, alkali silica reaction and sulfate attack.

For durability provisions, the ACI 318 Building Code generally relies on the w/cm to reduce the permeation of water or chemical salts into the concrete that impacts its durability and service life. However, along with the w/cm, the code requires a concomitant specified strength level, recognizing that it is difficult to accurately verify the w/cm and that the specified strength (which can be more reliably tested) should be reasonably consistent with the w/cm required for durability.

It should be stated that strength should not be used as a surrogate test to assure durable concrete. It is true that a higher strength concrete will provide more resistance to cracking due to durability mechanisms and will generally have a lower w/cm to beneficially impact permeability. However, it should be ensured that the composition of the mixture is also optimized to resist the relevant exposure conditions that impact concrete's durability. This means appropriate cementitious materials for sulfate resistance, air void system for freezing and thawing and scaling resistance, adequate protection to

prevent corrosion either from carbonation, chloride ingress or depth of cover, a low paste content to minimize drying shrinkage and thermal cracking, and the appropriate combination of aggregates and cementitious materials to minimize the potential for expansive cracking related to alkali silica reactions.

Permeability

Many aspects of concrete durability are improved by reducing the permeability of concrete. The ACI 318 Building Code addresses an exposure condition (Table 4.2.2) for "concrete intended to have a low permeability when exposed to water" by requiring a maximum w/cm of 0.50 and a minimum specified strength of 4000 psi. This recognizes that a lower water-cement ratio is important to control the permeability of concrete.

The problem with the code requirement is that one parameter of w/cm by itself does not assure the owner that compliance with this requirement will not adversely effect other properties of concrete. Figure 2 is an illustration of the volume fractions of the composition of two concrete mixtures at the same w/cm. One mixture has a lower paste (water + cementitious material) content and will likely have different performance than the mixture with the higher paste volume. Some likely problems with the mixture with the higher paste content could be a higher heat of hydration, higher potential for cracking, lower modulus of elasticity, higher creep and different resistance to durability to chemical elements depending on the composition of the cementitious material.



Figure 2. Same w/cm can mean different paste contents and varying performance

With the extensive use of supplementary cementitious materials and innovative chemical admixtures, a concrete mixture can be optimized for a low permeability in more

ways than by just controlling the w/cm. Standardized tests exist that can help identify mixtures with low permeability. ASTM C 1202, *Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*, often called the Rapid Chloride Permeability Test (RCPT), is one method that is increasingly used in performance oriented specifications. The charge passed, in units of coulombs, is used as performance criteria for permeability. Specifications include limits between 1000 and 2500 coulombs for various applications. Figure 3 is an illustration that shows varying levels of charge passed (coulombs) as a measure of permeability for concrete mixtures at the same w/cm depending on the cementitious materials used in the mixture.

The RCP test method is very sensitive to specimen handling and until there is more experience with specimen preparation and care for initial curing in the field, its use as a jobsite acceptance test is not recommended. However, this test could be

used as a pre-qualification test in lieu of specifying low w/cm ratio. ASTM C 1202 provides some discussion of the relative potential for chloride ion penetrability based on the charge passed through the concrete specimen. RCP values greater than 4000 coulombs will allow a high level of ion penetrability; values between 2000 and 4000 coulombs are moderate; 1000 to 2000 is considered low and lower values are very low. Values below 2000 to 2500 coulombs afford sufficiently low "permeability" for most applications. Although the RPCT is not a direct measure of permeability, there is a wide body of evidence that concrete with lower coulomb ratings using this test is more resistant to chloride ingress.

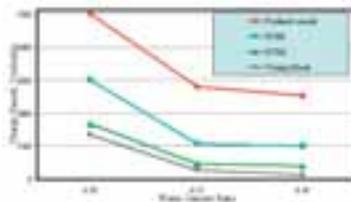


Figure 3. Does w/cm control permeability?

Another method that provides a visual indication of the depth of chloride penetration under an electrical field is the rapid migration test, currently a provisional AASHTO standard — AASHTO TP 64. This method is considered more reliable as it provides a quantifiable measure of the depth of penetration of an ionic species and avoids some of the shortcomings of ASTM C 1202. Although this test is not currently in wide use, it may eventually become the basis for pre-qualifying concrete for permeability. However, we do not recommend its use as a jobsite acceptance method at this time.

ASTM C 1556, *Method for Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion*, is a recently standardized method that measures chloride ion concentration at different depths of a test specimen that has been immersed in chloride solution. From the measured chloride ion concentration at different depths the apparent diffusion coefficient can be calculated. This method is rather involved and takes time to obtain results. It should only be used as a pre-

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qualification test. At this point, this is a very good research test and, until experience is gained by more commercial testing labs, we do not recommend this test be used in specifications for pre-qualification or acceptance.

Corrosion of Reinforcing Steel

Corrosion of steel is an electrochemical process whereby iron, in the presence of moisture and oxygen, converts to rust that occupies about six times more volume than the original iron. Because of its high alkalinity, concrete creates a passive layer around steel and prevents it from corroding. This breaks down if the concrete carbonates (reacts with carbon dioxide in the air) to the level of the steel, which causes a reduction in the alkalinity. Chloride ions that reach the steel will also break down the passivity provided by concrete. Several steps can be taken to reduce failure due to corrosion of steel reinforcement. Ensuring that there is adequate clear cover of concrete to the steel delays the onset of corrosion. Another means of delaying the onset of corrosion is by reducing the permeability of the concrete, using epoxy coated reinforcement or corrosion inhibitors, a chemical admixture that is added when concrete is mixed. Non-corrosive reinforcement is probably the best, but not a very cost effective option at this time. Chlorides typically come from sea water or deicing salts.

For corrosion protection of reinforcement in concrete exposed to chlorides from deicing chemicals, salt, brackish water, seawater or

spray from these sources, the ACI 318 Building Code requires a maximum w/cm of 0.40 and a minimum specified compressive strength of 5000 psi (Table 4.2.2). The building code also includes limits for maximum water soluble chloride ions in concrete as a percent by weight of cement. The limits vary from 1.0 for reinforced concrete that will be dry in service to 0.06 for prestressed concrete. A common source of chlorides in the ingredients used for concrete is from chemical admixtures, generally accelerating admixtures. Non-chloride admixtures can be used when these limits apply.

These measures alone may not be adequate to achieve low permeability concrete to protect against corrosion. Use of supplementary cementitious materials such as fly ash, slag, silica fume, etc., is essential. Rather than specifying concrete mixture constituents to achieve low permeability (never a guaranteed step), the engineer can require ASTM C 1202 test data showing a value between 1000 and 2500 coulombs. Other methods discussed under the section of permeability are also applicable to this protection against corrosion.

Cracking due to shrinkage must be minimized. Even though the effect of cracking on rebar corrosion is still a subject of study, the general understanding is that cracks of small width (less than 0.2 mm) perpendicular to the reinforcement may not impact corrosion significantly.

The specification should ensure that the structure as constructed has adequate clear cover from the reinforcing steel. ACI 318 R 7.7.5 recommends minimum cover of 2 to 2.5 inches for concrete exposed to salt water. However, excessive cover in negative moment regions can cause cracking under service loads.



Figure 4. Corrosion of steel rebar due to chloride ingress

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In addition, epoxy coated reinforcement can be a good choice. However, epoxy coated rebars are not recommended for concrete that will be submerged as in a very moist environment as the epoxy layer has been observed to de-bond. Different types of corrosion inhibitors are also available. Dosages should be used according to manufacturer recommendations. Carbonation of good quality concrete is generally a slow process and is not a concern if adequate cover is provided.

Sulfate Attack

Sulfate ions are found in ground water and soil in some regions of the U.S. For the most part, alumina bearing compounds in cementitious materials react with sulfates forming expansive reaction products. Some sulfate salts also react with the cement hydration products to form gypsum, which also results in a volume expansion. In some cases the cement hydration products are broken down resulting in a loss of cementitious properties. Protecting against sulfate attack requires using the appropriate

cementitious materials and reducing the ingress of sulfates into the concrete.



Figure 5. Expansion inside concrete due to deleterious sulfate attack

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ACI 318 Table 4.3.1 classifies different levels of sulfate exposure based on the concentration of sulfate ions in the soil or water anticipated to be in contact with the concrete. The code requires corresponding levels of maximum w/cm, minimum compressive strengths and cement types.

Portland cements that conform to ASTM Type II and V are used for moderate and severe sulfate conditions, respectively. Type II cements have a maximum limit of 8% on the tricalcium aluminate, C_3A , while Type V cements limit the phase to 5%. A portland cement might optionally be tested for sulfate resistance in accordance with ASTM C 452. Most fly ashes (primarily Class F), slag and silica fume provide resistance against sulfate resistance. These supplementary cementitious materials and blended cements are good options for sulfate resistance. The sulfate resistance of these materials and blended cements can be determined by ASTM C 1012, where mortar bars are immersed in sulfate solutions and expansion measured over time. This provides for a performance-based option for pre-qualifying the cementitious component of a concrete for sulfate resistance.

Table 2.3 of ACI 201.2R-01 has similar w/cm and compressive strength requirements as ACI 318 but addresses the performance alternative for the different cement types. The performance option requires optimizing the cementitious materials and their amounts and is as follows:

- Moderate (Class 1) sulfate exposure – ASTM C 1012 Expansion <0.10% at 6 months
- Severe (Class 2) sulfate exposure – ASTM C 1012 Expansion <0.10% at 12 months

Quality Assurance and Quality Control

Quality assurance and quality control testing for concrete is becoming more complex. In addition to typical concrete tests for strength, slump and air content, there are other performance-based tests that measure such properties as shrinkage, permeability and resistance to chemical attack. Many of these test methods are complicated and sensitive to variability in sampling and procedure. Some tests are best suited for pre-qualifying concrete mixtures while others are better suited for field acceptance.

The following terms are used throughout the discussion:

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 document 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 or good practice and the contract documents for the work are followed.*

Pre-qualification Tests — tests required in the specification that provide some level of assurance that concrete mixture(s) proposed for use on the project will meet the desired level of performance. For example, field or laboratory test records to demonstrate concrete will meet the required average compressive strength would be considered pre-qualification tests. Many durability tests should be conducted in a controlled laboratory environment or take significant time to obtain results and are better suited as pre-qualification tests. Pre-qualification tests are conducted before concrete is placed and test results are submitted to the project engineer/architect for review and/or approval.

Acceptance Tests — tests required in the specification to indicate concrete furnished to the project meets the specified acceptance criteria. For example, tests on concrete cylinders collected in the field during concrete placement and tested at 28 days. Acceptance (pass/fail) criteria should be indicated in the specification. Detailed procedures when concrete does not meet the acceptance criteria should also be provided in the specification. In many cases, alternative identity acceptance tests, such as strength and density, could be used as a means of verifying that the concrete delivered represents the concrete mixture in the submittal, especially when the tests conducted for pre-qualification are not conducive to jobsite schedules or conditions.

Prescriptive Specification — a set of instructions that includes clauses for means and methods of construction and composition of the concrete mix rather than defining performance requirements or in addition to some performance requirements. Many times intended performance requirements are not clearly indicated in project specifications and the prescriptive requirements may conflict with the intended or implied performance.

Performance Specification — 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 only, since durability is not a concern. Conversely, performance criteria for a bridge deck or parking garage might include, in addition to compressive strength for design loads, limits on permeability and shrinkage since the concrete will be subjected to a harsh environment. Performance specifications should also clearly specify the test methods and the acceptance criteria that will be used to verify and enforce the requirements. Some testing might be required for pre-qualification and some might be for jobsite acceptance. The specifications should provide flexibility to the contractor and producer to provide a mixture that meets the performance criteria in the way they choose. The contractor and producer will also work together to develop a mix design for the plastic concrete that meets additional requirement for placing and finishing, such as flow and set time, while ensuring the performance requirements for the hardened concrete 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.

* *Cement and Concrete Terminology, ACI 116R-00, American Concrete Institute, Farmington Hills, MI, 2000.*

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The other factor to provide sulfate resistant concrete is to prevent the sulfate salts from permeating into it. ACI 318 controls this by placing a maximum limit on the w/cm. For those structures not governed by the building code, permeability tests will be a performance-based alternative to the w/cm as discussed in the earlier sections.

Alkali Silica Reaction (ASR)

Alkali ions (Na⁺ and K⁺), primarily from the cement, cause a reaction with reactive silica mineral forms present in certain aggregate sources in the presence of moisture. This reaction forms an expansive alkali silicate gel that absorbs water and causes concrete to crack. Alkali salts can also permeate concrete from external sources such as deicing salts or sea water. To prevent ASR, the specifier should avoid requiring the use of a “non-reactive” aggregate because that may not be an option in some regions. Using a low alkali cement (alkali content as Na₂O eq. less than 0.6% by mass of cement) affords some level of protection. But it may not be sufficient if external sources of alkalis are possible or if alkalis could concentrate as the concrete dries out. Generally, combinations of silica fume, fly ash and slag are effective in reducing the potential for deleterious expansions due to alkali silica reactivity. Class F fly ash is more effective at mitigating ASR. Class C fly ash may have to be used at high replacement levels in order to be effective.



Figure 6. Cracking of a concrete bridge substructure due to ASR

Aggregates are expected to be non-reactive if they yield a 14-day expansion lower than 0.10% by ASTM C 1260 test or 1-year expansion lower than 0.04% by the ASTM C 1293 test. The ASTM C 1260 test is a very

severe test where a mortar bar is exposed to an alkaline solution at a higher temperature. Many aggregates that fail that test have shown to perform satisfactorily in the field. The ASTM C 1293 test is considered to be a more realistic test that is conducted on concrete. But it takes 1 year for the test to be completed as opposed to 16 days for the C 1260 test. So, should an aggregate fail the quick C 1260 test, it is suggested that the C 1293 test be conducted and, if it passes, the aggregate can then be considered as non-reactive. There are some aggregates that may pass the C 1260 and C 1293 tests and yet may fail in the field. These aggregates are very few in number and their behavior is well known in the area where they are typically used. Another alternative is to conduct a petrographic evaluation of the aggregates to identify and quantify the amount of reactive siliceous minerals. Field service history is also a good means of establishing the reactivity of an aggregate provided the mixture composition of the in-place concrete can be established and the structure has been in place for at least 7 to 10 years.

If an aggregate is determined to be potentially reactive in accordance with the above tests, or if the field performance of the aggregate indicates that it is reactive regardless of the results of any of the above tests, then that aggregate can still be used in concrete with appropriate mitigative measures. ASTM C 1567 is a rapid test that uses the aggregate with the test combination of cementitious materials. This test is a modification of ASTM C 1260 that is used to qualify the materials proposed for use on the job. Varying quantities of supplementary cementitious materials can be tested to establish the required quantity that minimizes the potential for deleterious expansions. Expansions less than 0.10% after 14 days exposure will qualify the combination of materials for use. This option is adequate in mitigating ASR. Lithium-based admixtures are also available to reduce the potential for ASR deterioration. Dosage requirements are established by the supplier based on the cementitious materials and the degree of reactivity of the aggregate.

Summary

In conclusion, when specifying concrete

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for durability, use performance-based pre-qualification and acceptance criteria whenever possible. Most criteria should focus on pre-qualifying concrete with some field acceptance tests that provide some level of assurance that the concrete proposed (that met pre-qualification criteria) was the concrete supplied for the project. Durability related criteria are only necessary when concrete will be exposed to a harsh environment. Most concrete used for

building construction is protected from exposure and therefore not subject to a harsh environment. Attempting to improve durability with prescriptive criteria such as limits on w/cm or cementitious materials content should be avoided. In this paper, guidance was provided to the specifying engineer on incorporating performance-based requirements in specifications to address corrosion, alkali silica reaction and sulfate attack. This paper will be developed further to address various other mechanical and durability properties of concrete.

Current specifications often require prescriptive elements such as a minimum cementitious content or a specific dosage of supplementary cementitious material to design for durability, generally with not much assurance that this will be achieved. The ACI 318 Building Code **does not** require this prescriptive approach. The engineer could potentially replace these prescriptive requirements with performance measures such as permeability tests as discussed in detail in this article. The specification will still have to use a maximum w/cm criterion for structures governed by the code and, in the case of sulfate attack, he is also restricted in his choice of cementitious material. Efforts continue to revise the building code to more performance-based provisions. However, the current code still provides enough opportunity to design with performance specifications.

The National Ready Mixed Concrete Association is spearheading a major shift in the way concrete is specified — the P2P Initiative (Prescriptive to Performance Specifications for Concrete). The goals of the P2P Initiative include allowing the use of performance-based specifications as an alternative to current prescriptive specifications. Details of the P2P Initiative can be found at www.nrmca.org/P2P. ■



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