QA/QC Testing for Concrete in Harsh Environments

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Abstract

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 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. This paper describes a general concept of specifying and acceptance for concrete in harsh environments. It will provide guidance on which tests to specify, the precision of each test and the appropriate acceptance criteria.

Introduction

Low permeability and resistance to chemical attack are 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, the ACI 318 generally relies on low w/cm to reduce the permeation of water or chemical salts into the concrete. However, along with the w/cm, ACI 318 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 emphasized that strength (or prescriptive criteria such as minimum cement content) should not be used as a surrogate to assure durable concrete. It is true that a higher strength concrete can provide more resistance to cracking 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 and chloride ingress, 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.

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. ACI 318 establishes statistically-based acceptance criteria for cylinder tests. 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 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.

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 set 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. In addition, concrete supplied by producers exercising good quality control will frequently result in fewer problems on a project.

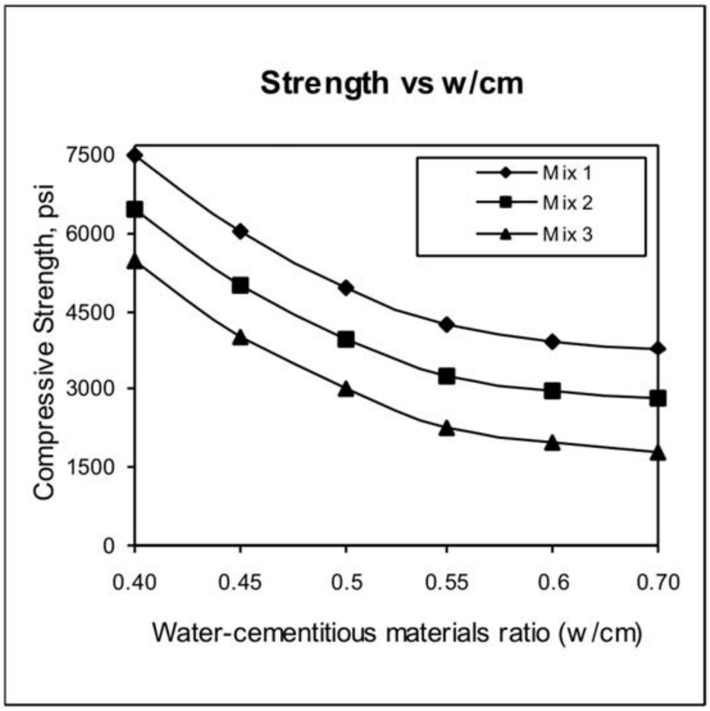

Figure 1. W/cm alone does not control strength.

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 earlier 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. Avoid specifying early age strength requirements for the purposes of form removal, post-tensioning, or other construction process since these are issues related to means and methods of construction and are the responsibility of the contractor.

Permeability

Many aspects of concrete durability are improved by reducing the permeability of concrete. ACI 318 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 lower water-cement ratio generally results in lower permeability.

The problem with ACI 318 requirement is that low w/cm by itself does not assure the owner that low permeability will result. Figure 2 is an illustration of the volume fractions of the composition of two concrete mixtures at the same w/cm. One mixture has lower paste (water + cementitious material) content and will likely have different performance than the mixture with the higher paste content. 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 chemical elements depending on the composition of the cementitious material.

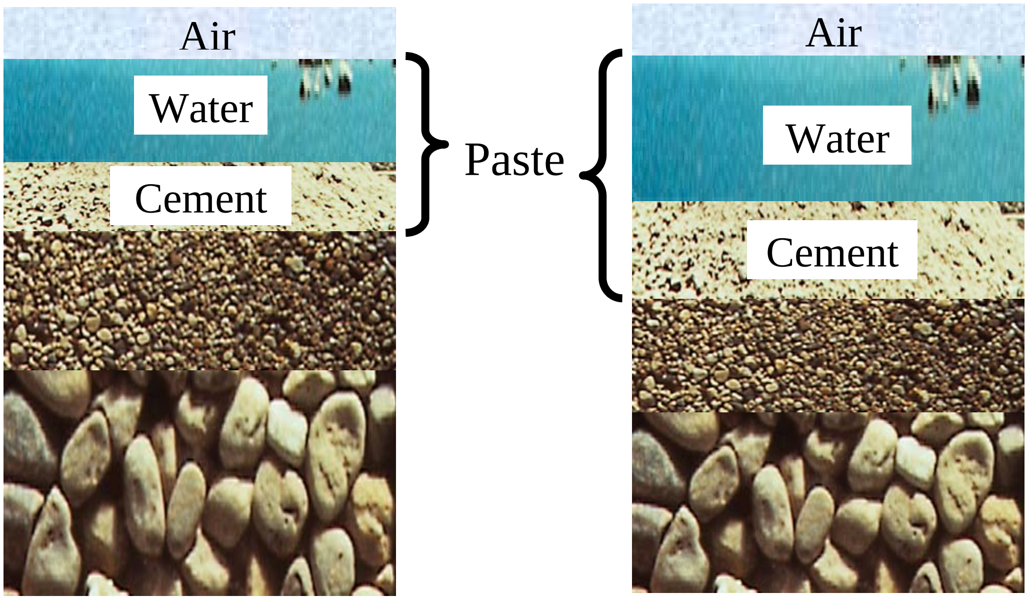

Figure 2. Same w/cm can mean different paste contents and varying performance

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

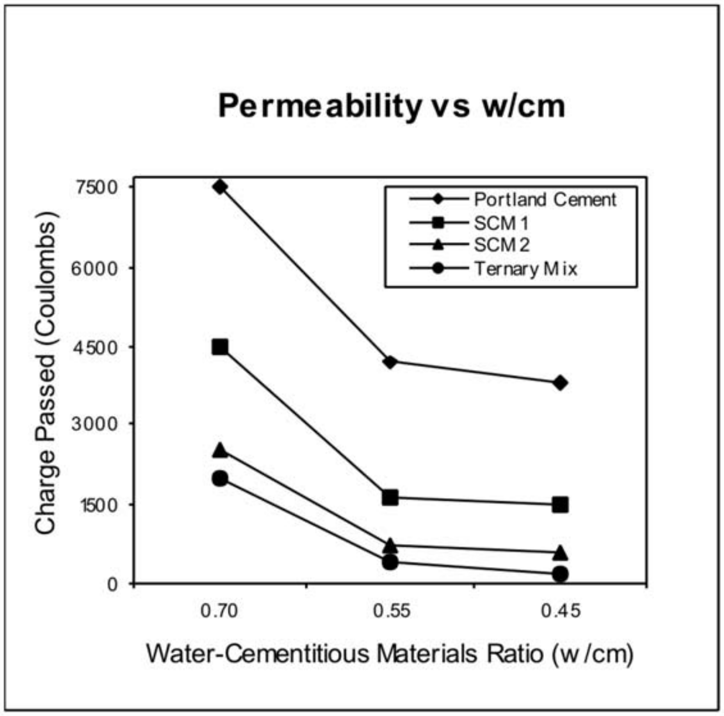

Figure 3. W/cm alone does not control permeability.

The RCPT 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. RCPT 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 100 to 1000 is considered to be very low. Values below 2500 coulombs afford sufficiently low “permeability” for most applications. Although the RCPT 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.

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-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 6 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 passive layer 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. Other 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.

Figure 4. Corrosion of Steel Rebar Due to Chloride Ingress

For corrosion protection of reinforcement in concrete exposed to chlorides from deicing chemicals, salt, brackish water, seawater, or spray from these sources, ACI 318 requires a maximum w/cm of 0.40 and a minimum specified compressive strength of 5000 psi (Table 4.2.2). ACI 318 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 and silica fume is essential. Rather than specifying concrete mixture constituents to achieve low permeability the engineer can require ASTM C 1202 test data showing a value between 1000 and 2500 coulombs for pre-qualifying concrete mixtures. Other test methods discussed under the section of permeability are also applicable to this protection against corrosion. When the RCPT is used it is suggested that the test be conducted at a later age say 56 or 90 days. Conversely the test can be accelerated and the results obtained at 28 days by curing for a portion of the time in hot water.

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. In addition epoxy coated reinforcement can be a good choice. However epoxy coated reinforcement is not recommended for concrete that will be submerged as in a very moist environment 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. Sealers and Membranes are also very effective in reducing the ingress of chlorides. 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 with low permeability.

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. ACI 318 also 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 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
> Very Severe (Class 3) sulfate exposure – ASTM C 1012 Expansion <0.10% at 18 months

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 ACI 318, permeability tests could 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 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. The specifier should avoid requiring the use of a “non-reactive” aggregate because that may not be an option in some regions. Using low alkali cement (alkali content as Na_2O 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 expansion 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.

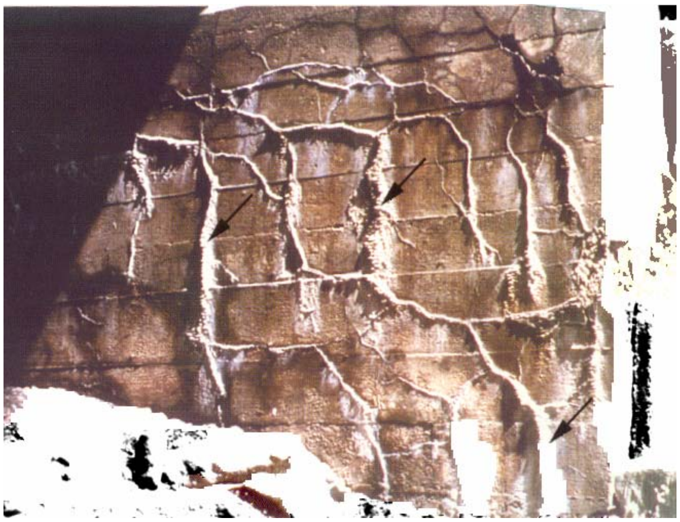

Figure 5. Cracking of a concrete bridge substructure due to ASR

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 elevated 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, but it takes one 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 that then the aggregate can 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 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.

Many project specifications include prescriptive elements such as minimum cement content or a specific dosage of supplementary cementitious material for durability. The ACI 318 Building Code **does not** require this prescriptive approach. The engineer should replace these prescriptive requirements with performance measures such as permeability and other types of tests as discussed in detail in this article. The specifier will still have to use a maximum w/cm criterion for structures governed by ACI 318 and in the case of Sulfate attack he is also restricted in his choice of cementitious material. Efforts continue to revise ACI 318 to allow more performance based provisions. However, the current version of ACI 318 still provides ample opportunity to design with performance specifications.

The National Ready Mixed Concrete Association is spearheading a major shift in the way concrete is specified called 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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