Acceptance Criteria for Durability Tests

Minimizing the risks of accepting defective concrete or rejecting acceptable concrete

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For the industry to shift toward performance-based specifications,[1] it's necessary to identify tests and criteria that can be used to define performance. Strength-based criteria for mixture proportioning, job-site acceptance, and referee testing for low-strength situations are well established in ACI 318-05.[2] These concepts are statistically-based attempts to balance risk between the producer and purchaser. Similar concepts are also appropriate for other performance tests and criteria.

Current durability provisions in industry standards rely on a prescriptive water-cementitious material ratio (*w/cm*) intended to control permeability along with a specified minimum compressive strength f'_c that serves as an acceptance criterion. Depending on the types and proportions of supplementary cementitious materials and admixtures, however, there can be a large difference in the permeability of two concrete mixtures with the same *w/cm*. An alternative to specifying maximum *w/cm* is to specify performance criteria based on ASTM C 1202-05,[3] "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration," commonly referred to as the rapid chloride permeability (RCP) test (Fig. 1). While the method has its detractors, it's perhaps the only standardized test that provides a reasonably good indicator of concrete permeability in a reasonable amount of time.

While many engineers are specifying use of the RCP test primarily for mixture qualification, there seems to be an increasing trend to use this test for concrete acceptance purposes. Establishing target values for the producer and associated acceptance criteria for the delivered product, however, requires consideration of the precision of the test method.

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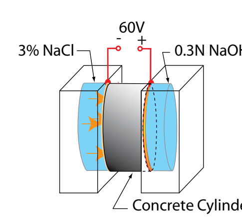

Chloride Ion Penetration	
Charge Passed, Coulomb	Chloride Penetrability
> 4000	High
2000 to 4000	Moderate
1000 to 2000	Low
100 to 1000	Very Low
<100	Negligible

Fig. 1: ASTM C 1202 (RCP) test setup and suggested qualitative indicators in the test method

TESTING VARIATION

When selecting a test for qualification or acceptance of concrete, the precision of the test method and the associated risks of accepting defective concrete or rejecting acceptable concrete must be considered. Compared to compressive strength tests per ASTM C 39,[4] RCP tests tend to have a large testing variability, as indicated in the precision statements for the methods. ASTM C 39-05 indicates that the within-test coefficient of variation V (standard deviation divided by the average) of companion 6 x 12 in. (150 x 300 mm) cylinders prepared under field conditions is 2.9%, and that the acceptable range of two individual cylinder strengths prepared from the same sample of concrete and tested by one laboratory is 8.0%. In comparison, ASTM C 1202-06 reports a single-operator V of test results (measured in triplicate) to be 12.3% and an acceptable range of 42%. While the precision estimates are not directly comparable due to the methods used to develop them, the comparison illustrates that RCP test results are significantly more variable than strength test results.

To put these numbers in perspective, consider a project with an f'_c of 5000 psi (35 MPa) and a specified maximum RCP of 1000 coulombs. If two compressive strength results of 4000 and 6000 psi (28 and 42 MPa) are reported, the 4000 psi (28 MPa) result, which is 20% below f'_c, is clearly a cause for inquiry. If two RCP test results of 800 and 1200 coulombs are reported, does the 1200 coulomb result, which is 20% above the specified maximum, deserve an inquiry as well? Because the acceptable testing range is 42%, it's quite possible that this result is due to normal testing variability and that a retest of another set of specimens made from the same batch of concrete would yield a value lower than 1000 coulombs. In this case, the test result of 1200 coulombs should not be a cause for inquiry.

To correctly address these issues, rational, statistically-based acceptance criteria for the RCP test should be developed. The criteria should be devised to minimize the risks of accepting defective concrete or rejecting acceptable concrete while taking into consideration the typical practice of sampling and testing concrete on project sites. The acceptance criteria proposed in this article use the same widely accepted concepts as those currently used for compressive strength. It is also assumed that RCP test results follow a normal distribution.

ESTABLISHING STATISTICALLY-BASED ACCEPTANCE CRITERIA

Currently, there are no industry-recommended, statistically-based acceptance criteria for the RCP test. Consequently, any test result above the specified value is considered a “failure” and a cause for inquiry. A more reasonable approach would be to calculate a required average RCP result using equations similar to those defined in ACI 318-05 for calculating the required average compressive strength. An even more reasonable approach would be to modify these equations to reflect the precision associated with the RCP test.

If f'_c is greater than 5000 psi (35 MPa), ACI 318-05, Section 5.6.3.3, states that strength shall be considered satisfactory if the strength test results, defined as the average strength of at least two cylinders, meet both the following criteria:

1) The average of any three consecutive strength tests equals or exceeds f'_c; and
2) No individual strength test is less than $0.90f'_c$.

A parallel construction is proposed for the RCP test result acceptance criteria. The (up to six times) higher testing variability of the RCP test method relative to the compression test method, however, provides strong justification for an increase in the number of consecutive test results used to calculate an average. Also, the relatively large range of single-operator results deemed acceptable in the precision statement of the RCP test method provides justification for a higher allowable difference between an individual test result and the specified permeability. In the proposed criteria, the specified permeability based on RCP test results is denoted as p'_c, and a test result is defined as the average of at least two specimens.

To reflect the precision of the RCP test method, it’s proposed that RCP test results be considered satisfactory if they meet both of the following criteria:

1) The average of any five consecutive test results is equal to or lower than p'_c; and
2) No individual test result is greater than $1.30p'_c$.

Note that durability and resistance to fluid ingress are inversely related to RCP test results, so the concrete producer must proportion mixtures to obtain a required average RCP result p'_{cr} lower than p'_c (in contrast, the producer must proportion mixtures to obtain a required average strength value f'_{cr} greater than f'_c).

CASE STUDY

To demonstrate how the current and the ACI 318-based approaches compare with the proposed approach, p'_{cr} is determined for a p'_c of 1500 coulombs in the following examples. These examples are based on an assumed overall coefficient of variation for RCP test results of 0.30 that includes testing and batch-to-batch variation. This value is based on the data from a bridge project with an average RCP test result of 1800 coulombs, shown in Fig. 2. The strength test results for the same project had a coefficient of variation of 0.084 with an average of 7480 psi (51.6 MPa) and are also shown in Fig. 2. ACI 214R-02,[5] “Evaluation of Strength Test Results of Concrete,” indicates that an overall coefficient of variation of 0.09 to 0.11 for strength test results is “good” control in general construction testing.

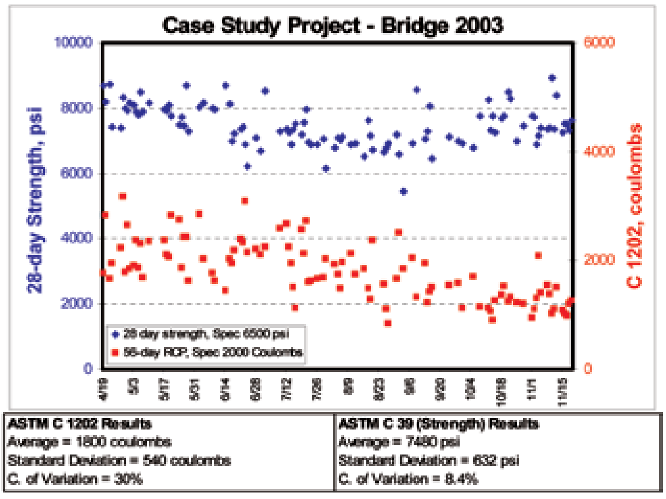

Fig. 2: Strength and RCP test data for a bridge project illustrating differences in test result variability

Current approach

Using fundamental statistical concepts that assume a normal distribution of RCP test results, a concrete producer must choose a level of risk and proportion the mixture accordingly. If a 99% confidence level (or a 1-in-100 failure rate) is chosen for an individual test (this is the same confidence level used for calculating required average strengths in ACI 318-05), the required average permeability for the mixture can be calculated as $p'_{cr} = p'_c - 2.33(Vp'_{cr})$, which can be expressed as follows

$$p'_{cr} = \frac{p'_c}{(1 + 2.33V)} \quad (1)$$

Inserting $V = 0.30$ and $p'_c = 1500$ coulombs in this equation results in $p'_{cr} = 883$ coulombs.

This approach is obviously overly conservative and is even more stringent than the current ACI 318 approach for acceptance of concrete strength. Clearly, this approach requires a concrete producer to proportion a mixture for an extremely low p'_{cr}.

TABLE 1:
COMPARISON OF JOB-SITE ACCEPTANCE CRITERIA AND TARGET AVERAGE RCP TEST VALUES FOR p'_c = 1500 COULOMBS

Approach	Acceptance criteria	p'_{cr}, coulombs
Current	Individual $\leq p'_c$	883
Similar to ACI 318 strength provisions	Average of three tests $\leq p'_c$ and individual test $\leq 1.1p'_c$	971
Proposed approach	Average of five tests $\leq p'_c$ and individual test $\leq 1.3p'_c$	1143

ACI 318-based approach

In this approach, ACI 318-05 Eq. (5-1) becomes $p'_{cr} = p'_c - 1.34(Vp'_{cr})$ and results in p'_{cr} = 1070 coulombs. ACI 318-05 Eq. (5-3) becomes $p'_{cr} = 1.1p'_c - 2.33(Vp'_{cr})$ and results in p'_{cr} = 971 coulombs. The producer must proportion the concrete for the smaller of these two values or p'_{cr} = 971 coulombs.

While this approach is better than the current approach, it's still conservative because it doesn't account for the higher testing variability of RCP tests compared to strength tests. The 1.34 coefficient in the first equation comes from $2.33/\sqrt{3}$ and is tied to the strength acceptance criteria that the average of three consecutive tests should equal or exceed the specified value. The 1.1 coefficient in the second equation is tied to the strength acceptance criteria that an individual test result can't be more than 10% below the specified value.

It's not appropriate to subject two test methods with widely different testing variability to the same level for concrete acceptance.

Proposed approach

The approach proposed previously in this article can be expressed as the following two equations

$$p'_{cr} = p'_c - (2.33/\sqrt{5})(Vp'_{cr}) \quad (2)$$

$$p'_{cr} = 1.3p'_c - 2.33(Vp'_{cr}) \quad (3)$$

resulting in p'_{cr} values for the current example of 1143 and 1148 coulombs, respectively, and allowing the producer to proportion the mixture for a p'_{cr} of 1143 coulombs.

This is a more reasonable approach because it takes into account the higher variability of the RCP test. Table 1 summarizes the acceptance criteria and p'_{cr} determined using the three different approaches.

Clearly, 1143 coulombs is much easier to attain than 883 coulombs. The current approach is the most conservative but will result in concrete mixtures with a much lower *w/cm* and much higher paste content, thus resulting in a greater tendency for cracking. Cracked concrete will lead to reduced durability even if the RCP test results in the lab are very low.

STATISTICAL EVALUATION

When the ACI 318-05 approach to determining f'_{cr} is used, a small percentage of tests are expected to fall below f'_c. For good quality control producing a standard deviation of the compressive strength test results that is smaller than $0.1f'_c$, ACI 318-05 Eq. (5-1) controls for f'_{cr}, and about 9% of tests would be expected to produce strengths below f'_c. When the standard deviation exceeds $0.1f'_c$, ACI 318-05 Eq. (5-3) controls for f'_{cr}, and the percentage of tests that would be expected to produce strengths below f'_c is less than 9% and continues to decrease as the standard deviation increases. This small percentage of tests falling below f'_c has been shown to be acceptable through the long use of the acceptance criteria for compressive strength tests currently in ACI 318-05.

Similar predictions can be made for the percentage of RCP tests that will exceed p'_c using the proposed approach. When the RCP test results have a standard deviation that is smaller than $0.233p'_c$, Eq. (2) controls for p'_{cr}, and about 15% of tests would be expected to produce results above p'_{cr}. For larger standard deviations, Eq. (3) controls, and a smaller percentage (that decreases as the standard deviation increases) would be expected. Compared to the commonly accepted 9% of strength tests falling below f'_c, 15% of RCP tests exceeding p'_{cr} is not significantly more lenient considering the higher variability of the RCP test.

The efficiency of an acceptance test and associated criteria can also be examined by developing an operating characteristic (OC) curve.[6,7] An OC curve evaluates the relative level of risk for the producer and the purchaser based on different levels of quality and is capable of distinguishing between satisfactory and unsatisfactory products. The concepts and associated mathematical derivations are discussed by Chung.[6]

The OC curves for strength using the ACI 318-05 acceptance criteria and for RCP tests using the proposed acceptance criteria are shown in Fig. 3. For a strength test result distribution with 9% of the individual tests less than f'_c, the producer's risk of acceptable concrete being rejected is 2%. The same level of producer's risk for RCP tests is obtained for RCP test results with about 15% exceeding p'_c. For a 5% producer risk, the corresponding percentages less than f'_c and greater than p'_c are 14 and 21%, respectively. The difference between the percentages is consistently about 6% for different levels of producer risk. This difference of 6% seems reasonable considering the higher testing variability of the RCP test.

Another way of evaluating an OC curve is to look at the purchaser's risk. A distribution of concrete strength tests with 20% below f'_c has a 90% probability of acceptance. Considering the proposed acceptance criteria, a similar distribution of RCP tests with 20% above specified RCP has a 95% probability of acceptance.

Because the existing ACI strength criteria have served us well over the years, it seems reasonable that durability acceptance criteria should be established at levels of risk similar to those used for strength tests.

REFEREE TESTING

ACI 318-05 includes provisions for strength test results that fail to meet the criteria. The criteria for cores obtained from the structure require the average of three cores to be equal or greater than $0.85f'_c$ and each individual core to be equal or greater than $0.75f'_c$. The criteria are different than that of standard cured specimens for strength tests to allow for curing conditions of concrete in the structure and the process of removing core specimens.

The same concepts for referee testing should apply to RCP tests on cores removed from the structure. Tests on these cores cannot be expected to be less than p'_c. This relationship needs to be developed by a research program similar to that used to establish the criteria for strength of cores.

SPECIMEN CURING

One of the limitations of ASTM C 1202 is that it suggests field curing procedures for specimens obtained in the field. This isn't appropriate when the test results will be used as a basis for acceptance. The type of curing and testing age for the RCP test specimens should be clearly indicated in project specifications. Because this test is very sensitive, it's imperative that initial curing in the field be in strict accordance with the requirements for strength tests (ASTM C 31[8], Section 10.1.2) if it will be used as an acceptance test. Subsequently, it's desirable to allow at least 90 days of moist curing. This allows slower reacting supplementary cementitious materials such as fly ash and slag cement to be used to attain low RCP values. If curing is limited to 28 days of moist curing, the use of a higher cementitious material content with more expensive supplementary cementitious materials may be required and could preclude the use of fly ash and slag cement.

The design professional should evaluate whether using results after a 90-day curing period provides a reasonable indicator of the potential performance of a structure that is intended to have a service life of over 50 years. In cases where waiting 90 days before accepting concrete test results isn't feasible, an accelerated specimen curing approach[9] that has been widely used by the Virginia Transportation Research Council (VTRC) can be adopted. This curing method requires 7 days of moist curing at 73 °F (23 °C) followed by 21 days of immersion in hot water maintained at 100 °F (38 °C). The results obtained by using this accelerated curing procedure have been found to correlate well with RCP test results obtained from specimens moist cured at 73 °F (23 °C) for 6 to 12 months.[9]

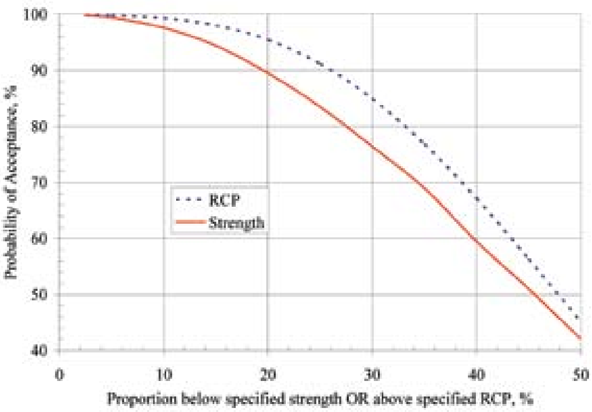

Fig. 3: Operating characteristic curves for strength (ACI 318-05 criteria) and RCP (proposed criteria)

CAUTIONS

RCP tests only provide an indication of concrete permeability. They don't work well when the concrete contains high concentrations of ionic solutions, such as inorganic corrosion inhibitors. In some regions, aggregate characteristics make it very difficult to obtain low RCP test values even with very durable concrete mixtures. Finally, in regions where this test is not currently performed, it will take a while for laboratories to achieve the proficiency necessary to perform this test for acceptance of concrete. Current laboratory inspection and personnel certification programs don't qualify a facility to perform RCP tests. In such cases, the alternative is to use the current specification and acceptance criteria with *w/cm* and strength or to use RCP as a prequalification test with acceptance based on strength tests.

POINTS TO PONDER

Some users of RCP tests feel that the variability of the method is not as high as the precision statement indicates. The ASTM International Subcommittee on Fluid Penetration has recently completed a round-robin test program that included several of the nation's most experienced laboratories, and it would certainly be interesting to see whether this study indicates an improvement in the precision.

Besides the precision of the method, there is a strong need for field test data to evaluate the production variability that should be used to establish the producer's target average values. Projects in which both strength and RCP tests have been conducted on the same batches of concrete are of interest, as it would be valuable to compare the variability of both test results to develop rational acceptance criteria.

Initial curing procedures need to be examined to determine whether they should be more stringent than those used for strength cylinders. For example, ASTM C 31 has tighter temperature limits of 68 to 78 °F (20 to 26 °C) during the initial curing at the job site for concrete strength over 6000 psi (41.4 MPa), as opposed to the 60 to 80 °F (16 to 27 °C) for lower strength concrete. Similar requirements for initial curing may be required to address the sensitivity of RCP test specimens to curing.

The approach proposed in this article is a first stab at establishing statistically based criteria for tests other than strength tests. The approach can be improved as more experience is gained and the variability of the test and that associated with the production process is quantified.

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Selected for reader interest by the editors.

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