

Acceptance Criteria for Durability Tests

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Introduction

As we make the shift toward performance-based specifications, it becomes necessary to identify durability tests and criteria that can be used to define performance. Strength-based criteria for mixture proportioning, jobsite acceptance and referee testing for low strength situations are well established. These concepts are statistically based and balance the 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 the water to cementitious materials ratio (w/cm) and a concomitant specified compressive strength level that serves for acceptance purposes. For almost all cases, the specified w/cm is intended to control the permeability of concrete to fluids and chemicals in solution that cause durability problems. Strictly speaking, w/cm is a prescriptive limitation intended to control a performance property, permeability. However, with current mix design technology, which includes the use of a variety of supplementary materials and admixtures, there is a wide variation in permeability properties at the same w/cm based on how the mixture is proportioned. One commonly used alternative to specifying maximum w/cm for concrete designed to withstand aggressive environments (chlorides, sulfates etc.) is to specify performance criteria based on ASTM C 1202, *Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration*, commonly referred to as the Rapid Chloride Permeability (RCP) test. Figure 1 illustrates a typical setup of the RCP test. While the method has its detractors, it is one of the only standardized tests that provides a reasonably good indicator of the permeability of concrete. One of the problems is that the developers of the test intended it for

more controlled use in laboratories rather than for acceptance of concrete from samples obtained at the jobsite.

Many state transportation agencies and other engineers are using ASTM C 1202 in their specifications primarily for mixture qualification and some even include it for concrete acceptance. There seems to be a greater desire among agencies to use this test for concrete acceptance purposes. Before this is widely practiced, we believe that certain knowledge and understanding is required in order to use this test in an appropriate manner. This article discusses acceptance criteria based on ASTM C 1202 as an indicator of permeability. The concepts will also be applicable to other performance tests that are not currently in common use.

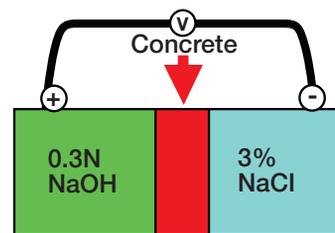
Testing Variation

The first and foremost aspect that needs to be

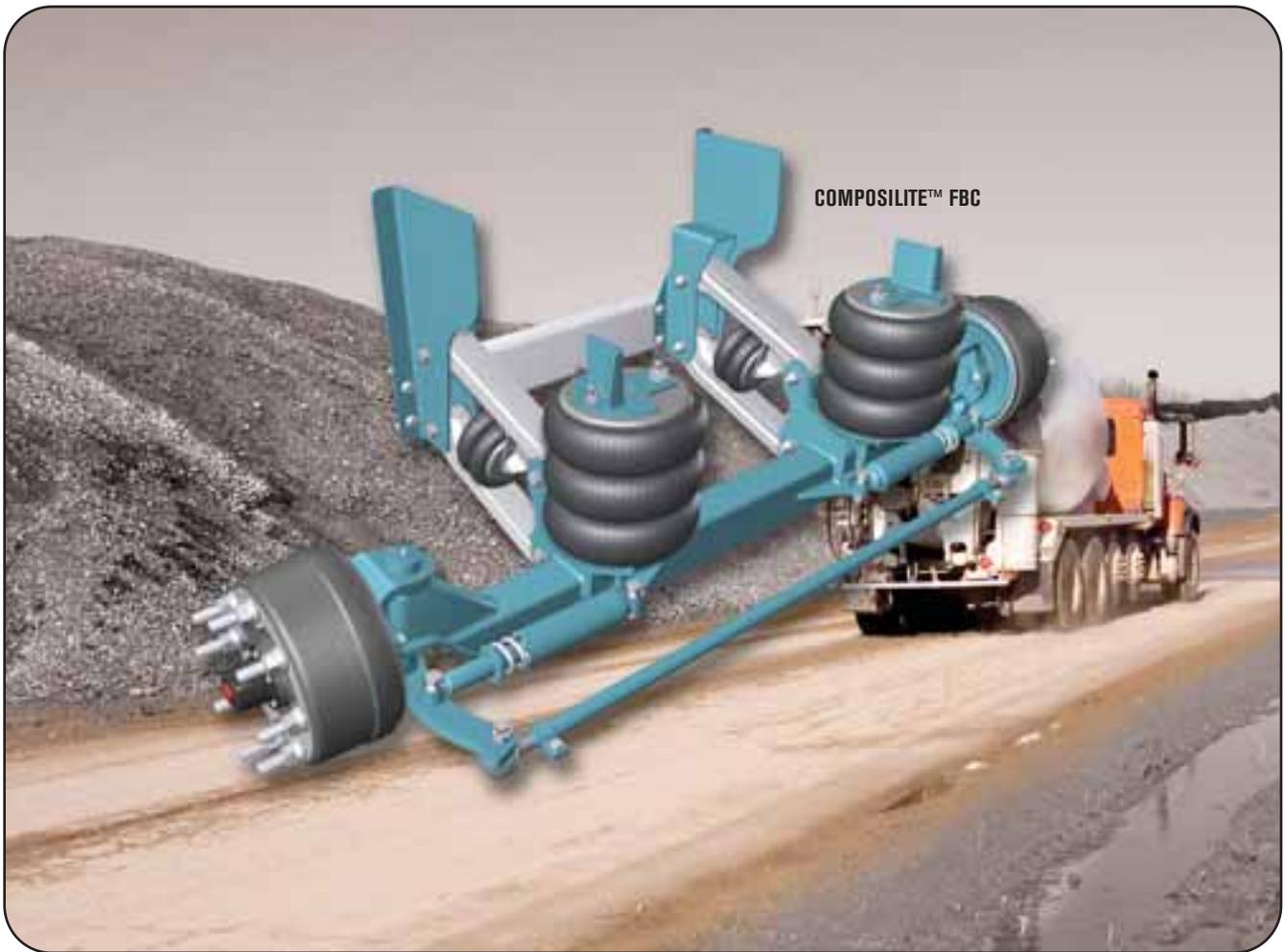
kept in mind when selecting a test for qualification or acceptance of concrete is a consideration of the precision of the test method and the associated risk to the producer and purchaser of rejecting or accepting acceptable or defective product, respectively. Compared to the strength test (ASTM C 39), the RCP test (ASTM C 1202) tends to have a larger testing variability. In ASTM C 39, the precision statement indicates that the within test coefficient of variation (V) of companion 6 x 12-inch cylinders prepared in field conditions is 2.9%. It states that the acceptable range of individual cylinder strengths prepared from the same sample of concrete and tested by one laboratory should not differ by more than 8.0%. In comparison, ASTM C 1202 reports a single operator coefficient of variation of test results (measured in triplicate) to be 12.3%



Figure 1 – ASTM C 1202 (RCP) test setup.



Chloride Ion Penetration	
Charge Passed	Chloride Penetrability
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2000-4000	Moderate
1000-2000	Low
100-1000	Very Low
<100	Negligible



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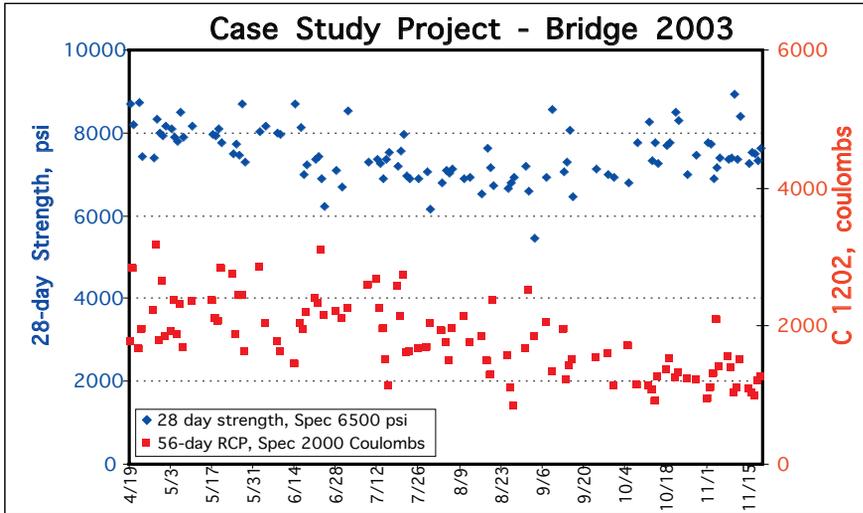
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ASTM C 1202 Results Average = 1800 coulombs Standard Deviation = 540 coulombs C. of Variation = 30%	ASTM C 39 (Strength) Results Average = 7480 psi Standard Deviation = 632 psi C. of Variation = 8.4%
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Figure 2: Strength and RCP test data for a bridge project illustrating differences in test result variability.

with an acceptable range of 42%. While the precision estimates are not directly comparable due to the method used in developing

them, they serve to illustrate that the variability of C 1202 test results can be on the order of six times higher than that of the

strength test results.

Let us try to put these numbers in some perspective. An acceptable range of 42% for the RCP test suggests that if we get two results from the same sample, one of 800 coulombs and the other of 1200 coulombs, they are still within the acceptable range of testing error. However, if we get two strength test results of 4000 psi and 6000 psi, clearly that is not within the range of testing error. Let us consider a project scenario with a specified strength of 5000 psi and a specified RCP test value of 1000 coulombs. Clearly the 4000 psi strength test result is a low break and is a cause for inquiry. Does a RCP test result of 1200 coulombs deserve an inquiry as well? Given that the acceptable testing range is 42%, it is quite possible that the 1200 coulomb result is due to normal testing variability. A retest of another set of specimens made from the same batch of concrete may very well yield a value lower than 1000 coulombs. In this case the test result of 1200 coulombs should not be a cause for inquiry. To avoid these problems, one must develop a rational, statistically-based acceptance criteria for the

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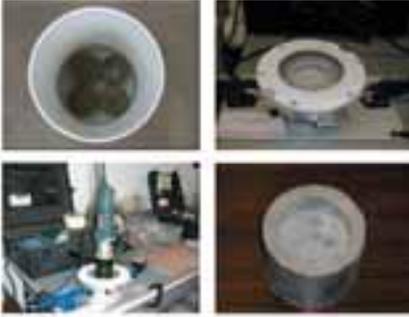


Figure 3. Test set up for ASTM C 1556 test to measure apparent diffusion coefficient of concrete.

RCP test. We propose to use the same widely accepted concepts as the current provisions for submittals and acceptance established for compressive strength. This discussion assumes that RCP test results during the course of a project follow a normal probability distribution, like strength test results.

Establishing Statistically-Based Acceptance Criteria

If the specified strength, f'_c , is greater than 5000 psi, ACI 318 Section 5.6.3.3

states that the strength of concrete shall be considered satisfactory if the test results, defined as the average of at least two cylinder strengths, meet both the following criteria:

1. Arithmetic average of any three consecutive cylinder test results equals or exceeds specified strength (f'_c)
2. No individual test result should be less than $0.90f'_c$

For simplicity in this article, let us define terminology for specified “permeability” based on ASTM C 1202 test results as p'_c where the test result is the average of at least two specimens. Based on strength provisions, it is proposed that the RCP test results of concrete shall be considered satisfactory if both the following criteria are met:

1. Arithmetic average of any five consecutive test results is equal to or lower than specified permeability, p'_c
2. No individual test result should be above $1.30 p'_c$

When the permeability acceptance criteria are compared to the strength acceptance criteria, two things become obvious:

1. The concrete producer has to design mixtures for a required average RCP test value, p'_{CR} , to be lower than the specified permeability, p'_c , unlike the case of strength where required average strength, f'_{CR} , is designed to be higher than specified strength, f'_c . This is because with permeability measures, a lower value is more resistant to fluid ingress (and therefore more durable) than a higher value.
2. The proposed permeability criteria using the RCP test are slightly more lenient. This is a reasonable approach to accommodate the five to six times higher testing variability of the RCP test as compared to the strength test. Taking the arithmetic average of five consecutive tests instead of three is proposed to reduce the influence of the higher testing variability and reduce the risk of rejecting acceptable concrete. The higher allowance proposed for an individual test result compared to the specified permeability is to accommodate the larger acceptable range of single operator

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results. It is these authors opinions that the allowance of 30% higher RCP test result compared to the specified value is a conservative approach to address the testing variability. Other more robust criteria can be established when a better measure of jobsite sample test variability can be determined.

Case Study

What target average permeability is required for a specified permeability, p'_{cr} , of 1500 coulombs?

Assume an overall coefficient of variation of RCP test results (includes testing and batch to batch variation) to be in the range of 30% for general construction testing. This is a reasonable number for good quality control and is based on actual data for a particular project communicated to the authors. The strength and RCP test results for an actual bridge project for a given class of concrete are illustrated in Figure 2. ACI 214R, *Evaluation of Strength Test Results for Concrete*, reports an overall coefficient of variation of 9% to 11% for

strength test results as “good” control in general construction testing.

This case is evaluated by three approaches.

Current Approach

Currently, there are no industry-recommended statistically-based acceptance criteria for the RCP test. Consequently, the test result above the specified permeability is considered a “failure” and a cause for inquiry. Using fundamental statistical concepts that assume a normal distribution of RCP tests, a concrete producer will have to choose a level of risk and design mixtures 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 by ACI 318), the required average permeability for the mixture can be calculated as follows:

$$p'_{cr} = p'_c - 2.33 (V \times p'_{cr})$$

Where V is an estimate of the coefficient of variation (standard deviation

expressed as a percentage of the average) of test results obtained during the course of a project.

This can be expressed as follows:

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

Assuming a coefficient of variation, V, of 30%, and $p'_c = 1500$ Coulombs, one gets $p'_{cr} = 882$ Coulombs.

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

Approach Identical to ACI 318

In this case, equations identical to Equation 5.1 and Equation 5.3 in ACI 318 Code are considered

$$p'_{cr} = p'_c - 1.34 (V \times p'_{cr}) \quad \text{results in} \\ p'_{cr} = 1070 \text{ coulombs}$$

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$$p'_{cr} = 1.1 \times p'_c - 2.33 (V \times p'_{cr})$$

results in $p'_{cr} = 971$ coulombs

This will cause the producer to design for an average permeability, $p'_{cr} = 971$ coulombs.

Clearly this approach, while better than the current approach, is still conservative since it does not account for the higher testing variability of ASTM C 1202 compared to ASTM C 39. Note that the value of 1.34 in the first equation in this approach derives from $(2.33/\sqrt{3})$ and is tied to the acceptance criteria that the average of three consecutive tests should equal or exceed the specified value.

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

Proposed Approach

The approach that was proposed earlier in this article can be mathematically expressed as the following two equations:

$$p'_{cr} = p'_c - (2.33/\sqrt{5}) \times (V \times p'_{cr})$$

results in $p'_{cr} = 1143$ coulombs

$$p'_{cr} = 1.3p'_c - 2.33 (V \times p'_{cr})$$

results in $p'_{cr} = 1147$ coulombs

This approach will allow the producer to design the mixture for an average permeability, p'_{cr} of 1143 coulombs.

This is the most reasonable approach that takes into account the higher testing variability of the RCP test as compared to the strength test. The Table below summarizes the p'_{cr} determined by the three differ-

ent approaches:

For a specified RCPT=1500 coulombs
Clearly the 1143 coulombs is a lot easier to design for than the 882 coulombs. The most conservative approach will result in concrete mixtures with a much lower w/cm and much higher cementitious paste content thus resulting in a greater tendency for cracking. Cracked concrete will lead to poorer durability even though the RCP test results in the lab are very low.

Acceptance Criteria

A comparison of the acceptance criteria for tests performed from samples obtained at the jobsite can be summarized as follows:

(continued on page 49)

Comparing Target Values of P'_{cr} When Proportioning Concrete

Approach	p'_{cr} Coulombs
Current (no single test result below specified)	882
Approach similar to Current ACI 318 Strength Provisions	970
Proposed approach	1143

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Comparison of Acceptance Criteria

Approach	Acceptance criteria
Current	Individual tests $\leq p'_c$
Similar to ACI 318 Strength Provisions	Individual test $\leq 1.1p'_c$ Avg. of 3 tests $\leq p'_c$
Proposed approach	Individual test $\leq 1.3p'_c$ Avg. of 5 tests $\leq p'_c$

Referee Testing

ACI 318 includes provisions in the event of strength test results that fail to meet the criteria. The criteria for cores obtained from the structure are that the average of three cores should be equal to or greater than $0.85f'_c$ and each individual core should not be less than $0.75f'_c$. These criteria allow for non-standard curing conditions of concrete in the structure and the process of removing core specimens. The criteria are more lenient than standard cured strength tests.

The same concepts for referee testing are appropriate for RCP tests on cores removed from the structure. Tests on these cores cannot be expected to comply with the specified

permeability, p'_c . These criteria need to be established to be acceptable at a higher permeability level and this relationship probably needs to be developed by a research program similar to that used to establish the criteria for strength of cores.

Specimen Curing

The type of curing and testing age for the RCP test specimens should be clearly specified. This test being very sensitive, it is imperative that initial curing in the field, if it is proposed to be used, should be in strict accordance to those required for strength tests (ASTM C 31 Section 10.1.2). Subsequently, it is desirable to allow at least 56 to

90 days of moist curing of the test specimens. This allows the slower reacting pozzolans such as fly ash and to some extent slag to be used to attain low RCP test results. If the curing time is limited to 28 days of moist curing this might force the use of more expensive supplementary cementitious materials and preclude the use of fly ash and slag. This is not a desirable approach for specifying concrete. The design professional should evaluate whether using results after a 90-day curing period provides a better indicator of the potential performance of a structure that is intended to have a 50+ year service life. In cases where waiting for 90 days before accepting concrete test results is not feasible, an accelerated specimen curing approach that has been widely tested by the Virginia Transportation Research Consortium (VTRC) can be adopted. This curing method specifies 7 days of moist curing at 73°F, followed by 21 days of immersion in hot water maintained at 100°F. The results obtained by using this accelerated curing procedure have been found to correlate well

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with RCP test results obtained from moist cured specimens at 73°F to later ages of 6 to 12 months.

Another method for evaluating permeability of concrete is ASTM C 1556, *Determining the Apparent Bulk Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion*. In this test, the specimens are subjected to chloride solutions after 28 days of moist curing. After different periods of immersion, the specimens are removed from the salt solution and the penetration of chlorides is measured as a function of depth from a surface. Figure 3 illustrates the test specimens and set up. From the measured chloride contents at different depths, a bulk chloride diffusion coefficient is calculated. Note that ASTM C 1556 is a very involved test that cannot be performed by most commercial laboratories and is not intended for testing samples obtained at the jobsite. However, it can be used to demonstrate the validity of specifying RCP test at 90-day curing period or the 28-day accelerated curing procedure.

The design professional might be concerned with relying on concrete acceptance test results based on later age testing if it is anticipated that the concrete structure will be exposed to a salt environment at an earlier age, such as for marine structures. In order to better answer this, ASTM C 1556 chloride diffusion test was performed on fly ash concrete specimens, which tend to reduce permeability slowly. Fly ash concrete specimens that were subjected to chloride immersion at 28 days showed high chloride diffusion coefficients after 60 days of immersion in solution; but very low diffusion coefficients after one year of chloride immersion. At early ages, fly ash concrete tends to be more permeable and allows the chlorides to penetrate easily. However, beyond 56 days, the permeability of fly ash concrete reduces rapidly and the chloride front cannot easily progress into the concrete. This results in a reduction in chloride diffusion coefficient. Therefore it can be seen that even for the slower acting pozzolans such as fly ash, it is appropriate to

use a 90-day or an accelerated 28-day RCP test requirement for concrete acceptance because these mixtures have been found to attain low long-term chloride diffusion coefficients in spite of the early age chloride exposure.

Readers are cautioned that ASTM C 1202 is not a perfect test and only provides a reasonable indicator of concrete permeability. It does not work well when concrete contains high concentrations of ionic solutions, such as when inorganic corrosion inhibitors are used. In some regions, the aggregate characteristics are such that it is very difficult to obtain low coulomb 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 necessary proficiency to perform this test for acceptance of concrete. Current laboratory inspection and personnel certification programs do not qualify a facility to perform ASTM C 1202. In such cases, the alternative is to use the current specification and acceptance criteria with w/cm and strength.



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Summary

This article presents an approach for using the rapid chloride permeability test, ASTM C 1202, for concrete acceptance for permeability. It illustrates that the current approach of rejecting concrete based on test results that exceed specification limits is not based on sound statistical principles. An approach based on the ACI 318 strength test acceptance provisions, modified to take into account the higher testing variability of ASTM C 1202, is proposed. The advantages of this approach are: 1) It provides a performance measure of the intended performance property for which current w/cm limits are not that reliable; 2) Good quality concrete is not rejected due to the inherently higher testing variability of ASTM C 1202; and 3) The value of the required average permeability, p'_c , is more realistically achievable and avoids high cementitious factors that will be more prone to cracking.

Also it is noted that a single RCP test result should be the average of two specimens. More care is necessary for initial curing of RCP test specimens in the field and

they must be cured for a longer period than 28 days. It is suggested that 90 days of moist curing or an accelerated 28-day curing environment is most desirable. Even though much of the discussion in this article is centered around ASTM C 1202, a similar approach is recommended for other tests such as the shrinkage test (ASTM C 157) or the Air Void Analyzer test, all of which tend to have a higher testing variability than the ASTM C 39 compressive strength test.

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