Rapid Chloride Permeability Testing's Suitability for Use in Performance-Based Specifications

Concerns about variability can be mitigated

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Performance-based specifications are becoming increasingly more common for infrastructure projects. The National Ready Mixed Concrete Association is committed to making performance-based specification the industry standard with its P2P Initiative (Prescription to Performance specifications). It's important, however, to have acceptance tests that correlate to performance criteria such as durability. For example, ASTM C39, "Standard Test Method for Compressive Strength of Cylindrical Concrete Specimens," is an accurate test for compressive strength but is not an indicator of concrete durability.[1]

Some concrete professionals believe that the rapid chloride permeability (RCP) test—AASHTO T 277-07 or ASTM C1202-07, both titled "Standard Test Method for Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration"—is a valid method for estimating concrete's permeability to chloride ions and, therefore, its ultimate durability with regard to reinforcing bar corrosion and concrete delamination. Many in the industry, however, are skeptical of its validity as it's not a direct test, unlike chloride ponding, which is. Others feel that the RCP test is too variable to be a quality acceptance test. Unfortunately, due to this ongoing debate, many have chosen to do no testing for concrete permeability.

The Port Authority of New York and New Jersey (PANYNJ) is a bi-state agency that builds, operates, and maintains a range of large infrastructure projects, from bridges and tunnels to port and airport facilities in the New York City metro area, in addition to redeveloping the World Trade Center site. PANYNJ has experience with a variety of concrete applications and has been using performance-based specifications for just over a decade. Each application has its own performance criteria, which can include compressive strength, flexural strength, bond strength, or permeability.

The introduction of RCP testing in the early 1990s and the success of the laboratory results and trial projects led to an overall adoption of the method by PANYNJ in 1998. The analysis performed by PANYNJ staff on the RCP test results of contract concrete illustrates that the concerns about RCP testing are overstated and that the quality and durability of our infrastructure concrete can be improved by specifying the RCP test as a quality acceptance measure where appropriate.

COMPARISON WITH CHLORIDE PONDING

A major cause of durability issues for concrete in areas that use chloride-based deicing agents or are located in a saltwater environment stems from chloride intrusion into concrete. Chlorides provide the necessary electrolytes in concrete for steel reinforcement to corrode, causing oxidation products that expand and destroy the surrounding concrete. An accepted test method used to evaluate the permeability of concrete is chloride ponding (AASHTO T 259).

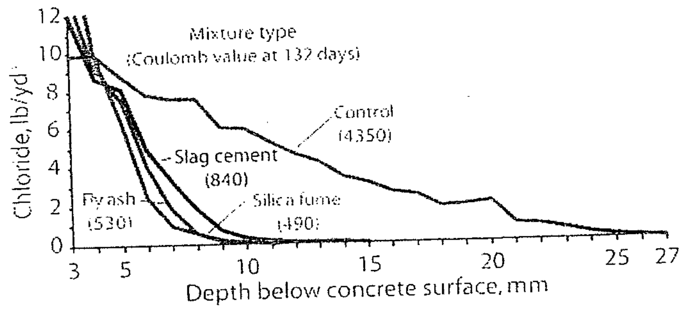

Fig. 1: AASHTO T 259 laboratory results. Numbers in parentheses are corresponding RCP results in coulombs (1 mm = 0.039 in.; 1 lb/yd³ = 0.593 kg/m³)

TABLE 1:
Mixture proportions and RCP values for concrete batches prepared for comparison of chloride ponding and RCP tests

Mixture proportions	Control	Fly ash	Slag	Silica fume and fly ash
Cement, lb	600	470	420	560
Fly ash, lb	—	190	—	100
Slag, lb	-	—	240	—
Silica fume, lb	—	—	—	45
Sand, lb	1200	1000	1050	1000
Stone, lb	1700	2050	2050	1930
w/c	0.50	0.40	0.40	0.40
HRWR/MR, oz	—	62	78	90
RCP test results at 132 days	4350	530	840	490

Note: 1 lb = 0.45 kg; 1 oz = 29.57 mL

In this test, a 3% sodium chloride solution (NaCl) is kept continuously ponded on the surface of the concrete slab. At specified test dates, concrete samples are drilled from the specimen and chloride is determined at various depths.

PANYNJ performed a study that correlated chloride ponding test values to RCP test values. Four specimens—one with fly ash, one with slag cement, one with silica fume and fly ash, and a cement-only control—were prepared and allowed to cure for approximately 4 months, in accordance with ASTM C31. Each specimen was ponded with an NaCl solution for 1 year. The RCP test was performed on all four specimens prior to ponding. The mixture proportions and RCP values are given in Table 1.

After 1 year, 3 in. (76 mm) diameter cores were taken from the concrete specimen and cut on a lathe in 0.04 in. (1 mm) increments to produce powdered concrete samples for chloride analyses. The top 0.16 in. (4 mm) was discarded from each sample due to irregularities in the surface profiles. The remaining samples were then analyzed for chloride content using the acetic acid method (AASHTO T 260). As can be seen in Fig. 1, after 1 year of ponding, the concrete specimens that had an RCP test value of less than 1000 coulombs had little to no chlorides present at a depth of 0.39 in. (10 mm), indicating a concrete with low permeability to chloride ions.

Chloride ponding and RCP testing provide results for most mixtures in a similar time frame; however, the RCP test provides results in as little as 28 days for mixtures containing silica fume, a significant time savings over chloride ponding. There is also an accelerated method for the RCP test, developed by the Virginia Transportation Research Council, that can be used on any type of concrete: after 7 days of moist curing (according to ASTM C31 at 73°F [23°C]), the specimens are cured in a heated water bath (100°F [38°C]) for 21 days. PANYNJ has found that this accelerated method approximates the maturity of concrete specimens with Type F fly ash to 125 days and specimens with slag cement to 200 days. Occasionally, PANYNJ uses this accelerated method.

FIELD TEST VARIABILITY

Mixture proportions for projects where the RCP test was used as the quality acceptance test are shown in Table 2. Table 3(a) summarizes the field RCP production results, about 500, for the mixtures given in Table 2. Mixture proportions with slag cement, fly ash, and silica fume were analyzed. The mean, standard deviation, and coefficient of variation within tests and between batches, or overall, were calculated for both the RCP and compressive strength data. It should be noted that an RCP test result is the average of two tests performed on the same sample, as is a compressive strength test result. The summary of the results is presented in Tables 3(a) and (b).

The ASTM C1202-07 precision statement is the major argument against using this test for quality acceptance. It states that the "single operator coefficient of variation of single test results has been found to be 12.3%," but PANYNJ data show the within-test variation to be about 4.05%.[4] It should be noted that this precision statement has remained the same for the last 12 years, even as the accuracy of the testing equipment has improved, as indicated by PANYNJ test results. The test method is sensitive to changes in batching—PANYNJ data show an overall (weighted average) coefficient of variation of 29.3%. This variation should not be a deterrent to using this test, however, provided the performance-based specification takes this sensitivity and testing variability into account by raising the upper limit in the acceptance criteria or allowing a higher percentage of concrete with RCP test results higher than specified.

Table 4 illustrates ACI's standards for concrete quality control.[2] Using this chart and applying it to the PANYNJ data presented in Tables 3(a) and (b) allows for comparison between the RCP test results and compressive strength data. If the standards of comparison given in Table 4 are used for the RCP and compressive strength data, it can be seen that the within-test variations for compressive strength tests and RCP are excellent and good, respectively. Because within-test variability is an indication of sampling and testing error, these results indicate that there is more variability in the RCP test, but not to the extent that this test could not be used for acceptance. The overall coefficient of variation is 16.8% for compressive strength results and 29.3% for the RCP test. Both are considered poor by the standard given in Table 4. This would indicate that the variability in the production of these 11 concrete mixtures was high, and the quality control at the batch plants should be improved. The RCP test is more sensitive to this batching variability. The data in Tables 3(a) and (b) indicate that the within-test variances are small when compared to the overall coefficient of variation.

PANYNJ SPECIFICATIONS AND CONTRACT PAYMENTS

For PANYNJ projects where the RCP test is used for quality acceptance, the contractor must submit mixture proportions supported by laboratory test data with an RCP value of less than 1000 for mixtures without a corrosion inhibitor and less than 1500 for mixtures with calcium nitrite used as a corrosion inhibitor, at a specified age. PANYNJ's performance specification acceptance criteria stipulate that a percent within limit (PWL) of 90% for all test lots be below an RCP value of 1500 without a corrosion inhibitor or 2000 with a corrosion inhibitor, at a specified

TABLE 2:
CEMENTITIOUS MATERIAL AND CORROSION INHIBITOR CONTENTS FOR MIXTURES ON PROJECTS USING THE RCP TEST FOR ACCEPTANCE TESTING

Mixture number	Cement, lb	Fly ash, lb	Slag, lb	Silica fume, lb	Corrosion inhibitor
2306	350	—	210	—	Yes
2413	482	206	—	—	No
2430	275	—	413	—	No
2450	490	210	—	—	Yes
2465	420	—	280	—	No
2581	350	—	210	—	Yes
2603	483	207	—	—	No
2615	445	195	—	—	No
Precast (Mixture 1)	450	—	208	25	No
Precast (Mixture 2)	650	—	—	45	No
Precast (Mixture 3)	517	—	208	34	Yes

Note: 1 lb = 0.45 kg

TABLE 3(a):
RCP test results for mixtures summarized in Table 2

Mixture	Age of test specimens	Number of tests	Mean	Within-test SD	Within-test CV	Overall SD	Overall CV
2306	28*	43	1419	56	3.9	343	24.2
	120	45	1448	92	6.3	342	24.6
2413	28*	32	1238	44	3.5	449	40.3
2430	28*	114	706	18	2.6	192	27.1
2450	28*	57	774	21	2.7	305	39.4
2465	120	16	1770	49	2.8	553	31.2
2581	120	20	1484	87	5.9	545	36.7
2603	120	26	590	49	8.2	203	34.5
2615	120	77	579	32	5.5	134	23.1
Precast (Mixture 1)	28	39	473	12	2.4	126	26.7
Precast (Mixture 2)	28	12	1113	35	5.2	405	36.4
Precast (Mixture 3)	28	13	307	14	4.5	90	29.2
Weighted average	**—**	**494**	**899**	**38**	**4.1**	**263**	**29.4**

*The RCP test results are based on a 28-day accelerated cure, 7 days at 73 F (23 C) and 21 days at 100 F (38 C)

Note: SD stands for standard deviation; CV stands for coefficient of variation

TABLE 3(b):
Compressive strength test results for mixtures summarized in Table 2

Mixture	Age of test specimen	Number of tests	Mean	Within-test SD	Within-test CV	Overall SD	Overall CV
2306	28	43	8520	274	3.2	1004	11.8
2413	28	32	6430	125	1.9	1319	20.3
2430	28	114	7820	177	2.3	1145	14.6
2450	28	56	5550	123	2.2	773	13.9
2465	28	15	7950	190	2.4	896	11.3
2581	28	20	8830	318	3.6	1101	12.5
2603	28	28	7570	267	3.5	1422	18.8
2615	28	171	6290	191	3.0	1434	22.8
Mixture (1)	28	39	8200	—	—	878	10.7
Mixture (2)	28	12	11,050	—	—	1215	11.0
Mixture (3)	28	13	8710	—	—	909	10.4
Weighted average	**—**	**543**	**7230**	**170**	**2.4**	**1179**	**16.8**

Note: SD stands for standard deviation; CV stands for coefficient of variation

TABLE 4:
Standards of concrete control*, Table 3.3 from ACI 214R-02

Overall variation					
	Coefficient of variation for different control standards, %				
Class of operation	Excellent	Very Good	Good	Fair	Poor
General construction testing	Below 7.0	7.0 to 9.0	9.0 to 11.0	11.0 to 14.0	Above 14.0
Laboratory trial batches	Below 3.5	3.5 to 4.5	4.5 to 5.5	5.5 to 7.0	Above 7.0
Within-test variation					
	Coefficient of variation for different control standards, %				
Class of operation	Excellent	Very Good	Good	Fair	Poor
Field control testing	Below 3.0	3.0 to 4.0	4.0 to 5.0	5.0 to 6.0	Above 6.0
Laboratory trial batches	Below 2.0	2.0 to 3.0	3.0 to 4.0	4.0 to 5.0	Above 5.0

* f'_c 34.5 MPa (5000 psi)

age. For concrete mixtures with fly ash or slag cement, the RCP test is performed at 120 days; for concrete mixtures with silica fume, the RCP test is performed at 28 days.

Specifications include payment reductions when the concrete has a high RCP value or bonus payments for concrete where the RCP values fall below the specified number. To obtain a bonus payment, the concrete must also test within specification for compressive strength and air and water content. Payment reductions are made for a lot that has a PWL less than 90%, while bonuses are paid for lots with a PWL higher than 95%. These acceptance criteria take into account the higher variability in RCP test results when compared with the compressive strength data (ASTM C39). The PWL for compressive strength is 95% for a specified f'_c.

An analysis was done to determine the percentage of concrete that received reduced payment, full payment, or bonus payment based on the PANYNJ specification for RCP data. Of the concrete that was placed, approximately 11% did not meet PANYNJ specifications and resulted in reduced payments. (between 1 and 50% of the unit price of the concrete). Therefore, 89% of the concrete where the RCP test was the payment criteria in the specification received full payment or a bonus. Of this 89%, 35% exceeded the minimum requirements in the performance specification, allowing the contractor to qualify for a bonus between 1 and 6% of the unit price of the concrete.

EFFECT OF POZZOLANS

The RCP test also provides an indication as to the presence of pozzolans and can detect changes in batching. In our experience, a mixture that contains only portland cement will not produce an RCP value below 1000. PANYNJ had a project that required the substitution of 30% fly ash for cement but the RCP test results called into question its actual presence. An analysis of the tests on the job showed the compressive strength of the concrete met the specifications; however, the RCP results were repeatedly failing.

After a thorough investigation to determine the cause for the high RCP values, it was confirmed that the fly ash that was called for in the mixture and shown on the batch tickets was never batched into the concrete.

TABLE 5:
Comparison of key characteristics for two mixtures (compressive strength values are nearly equal, RCP values are not)

	No fly ash	Fly ash
Compressive strength	6640 psi	6630 psi
Standard deviation	850 psi	1050 psi
Coefficient of variation (within test)	2.2%	3%
Coefficient of variation (overall)	12.8%	15.8%
120-day RCP test results		
RCP value	1970	583
Standard deviation	581	135
Coefficient of variation (within test)	2.2%	5.5%
Coefficient of variation (overall)	29.4%	23%
Percent within limits	85	100

Note: 1 psi = 0.0069 MPa

Once the fly ash was added, the RCP results dropped dramatically to values that were consistent with historical data. Table 5 compares the test results from the job before and after the presence of the fly ash. It's worth noting that the compressive strength test results provided no indication that the fly ash was not incorporated into the concrete delivered to the project.

CONCLUSION

If done properly, specifying the RCP test as an acceptance criterion in a performance-based specification is technically appropriate. The variability of RCP tests is greater than the variability of ASTM C39 tests, but when appropriate limits are specified, the variability can be overcome. The analysis of the payments to contractors further proves that, with a well-written specification, good concrete can be placed, and contractors will be rewarded for providing quality and discouraged from supplying deficient concrete.

For a more sustainable concrete infrastructure, we need to better define and confirm properties of concrete required to extend its service life. This means going beyond the standard tests typically performed.

References

1. Obla, K.H., and Lobo, C.L., "Acceptance Criteria for Durability Tests," *Concrete International*, V. 25, No. 5, May 2007, pp. 43-48.

2. ACI Committee 214, "Evaluation of Strength Test Results of Concrete (ACI 214R-02)," American Concrete Institute, Farmington Hills, MI, 2002, 20 pp.

Received and reviewed under Institute publication policies.

Note: Additional information on the ASTM and AASHTO Standards discussed in this article can be found at **www.astm.org** and **www.transportation.org**.

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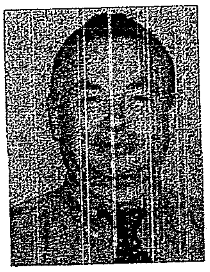

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