TECHBRIEF

Surface Resistivity Test Evaluation as an Indicator of the Chloride Permeability of Concrete

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Introduction

Many agencies have adopted the standard tests for electrical indication of concrete's ability to resist chloride ion penetration (AASHTO T 277 and ASTM C1202), commonly known as the rapid chloride permeability test (RCPT), in their specifications for qualification and acceptance and as a means of indirectly assessing the permeability of concrete mixtures. (See references 1–5.) Nevertheless, the RCPT is labor-intensive and costly and presents high variability.[3,6,7]

Research studies have shown that the surface resistivity (SR) test (AASHTO TP 95) is a promising alternative to the RCPT. (See references 3, 6, 8, and 9.) Recently, some agencies have shown interest in replacing the RCPT with the SR test and have started implementation efforts.[3,8] However, none of the studies have included high-volume fly ash (HVFA) mixtures or mixtures containing fly ash and fine limestone powder.

Objective

The purpose of this study was to investigate the correlation of the SR test with the widely used RCPT in evaluating concretes' ability to resist chloride penetration, including HVFA mixtures.

Experimental Program

In this study, a total of 25 concrete mixtures were prepared. They covered a variety of mix designs, including plain portland cement mixtures (Type I/II cement), fly ash mixtures (Class F and Class C fly ashes), and ternary mixtures containing HVFA and fine limestone powder (0.3 mil). The water-to-binder ratio varied from 0.37 to 0.50, and the cementitious content varied from 423 to 643 lb/yd^3. Natural sand with specific gravity of 2.61, absorption of 1.1 percent, and fineness modulus of 2.76 was used. Different coarse aggregates were used, including gravel, limestone, granite, and diabase, with maximum size varying from ¾ to 1½ inches.

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Table 1 shows the proportions of plain portland cement mixtures with different cement content, water-to-cement ratios, and aggregate types and gradation. In the mixture ID, the first number represents the AASHTO M 43 aggregate size designation (size numbers 57, 67, and 467), the following letter represents the type of aggregate (L for limestone, DB for diabase, and GV for gravel), and the last number represents the water-to-cement ratio.[10] For example, mixture 57DB47 is a mixture with a No. 57 diabase and a 0.47 water-to-cement ratio.

Table 2 shows the mixture proportions of the binary and ternary mixtures. In the mixture ID, PC stands for Type I/II portland cement, F for Class F fly ash,

Table 1. Mixture proportions of plain portland cement mixtures.

ID	Cement (lb/yd^3)	Coarse Aggregate (lb/yd^3)	Type of Coarse Aggregate	AASHTO M 43 Gradation	Maximum Size (inches)	Coarse Aggregate Specific Gravity	Coarse Aggregate Absorption (percent)	Fine Aggregate (lb/yd^3)	W/C	WR (oz/cwt)	AEA (oz/cwt)
57LS42	643	1,790	Limestone	57	1	2.86	0.3	1,262	0.42	2.0	0.18
57GV47	643	1,699	Gravel	57	1	2.58	1.9	1,089	0.47	—	0.30
57DB37	643	1,699	Diabase	57	1	2.97	0.6	1,481	0.37	6.0	0.15
57GV40	564	1,750	Gravel	57	1	2.58	1.9	1,444	0.40	7.7	—
57DB42	643	1,699	Diabase	57	1	2.97	0.6	1,397	0.42	5.8	0.58
57DB47	643	1,699	Diabase	57	1	2.97	0.6	1,315	0.47	—	0.30
467LS37	521	1,790	Limestone	467	1.5	2.71	0.5	1,464	0.37	12.0	0.05
467LS42	521	1,790	Limestone	467	1.5	2.71	0.5	1,398	0.42	3.2	0.20
467LS47	521	1,790	Limestone	467	1.5	2.71	0.5	1,331	0.47	1.7	0.28
67GV42	564	1,750	Gravel	67	0.75	2.57	1.6	1,265	0.42	3.2	0.05
67GV45	564	1,750	Gravel	67	0.75	2.57	1.8	1,223	0.45	—	0.20
67LS37	564	1,750	Limestone	67	0.75	2.83	0.6	1,506	0.37	10.0	0.05
67LS42	564	1,750	Limestone	67	0.75	2.83	0.6	1,434	0.42	1.5	0.23
67DB37	564	1,750	Diabase	67	0.75	2.97	0.6	1,581	0.37	11.0	1.00
67DB42	564	1,750	Diabase	67	0.75	2.97	0.6	1,509	0.42	1.8	0.20
67DB45	564	1,750	Diabase	67	0.75	2.97	0.6	1,465	0.45	0.8	0.22

— Admixture was not used.
W/C = Water-to-cement ratio.
WR = Water-reducing admixture.
AEA = Air-entraining agent.

Table 2. Mixture proportions of binary and ternary mixtures.

ID	Cementitious Material (lb/yd^3)	Fly Ash Content (percent)	Limestone Powder Content (percent)	Type of Coarse Aggregate	AASHTO M 43 Gradation	Coarse Aggregate Specific Gravity	Coarse Aggregate Absorption (percent)	Coarse Aggregate (lb/yd^3)	Fine Aggregate (lb/yd^3)	W/CM	WR (Type A) (oz/cwt)	AEA (oz/cwt)
69PC31F	491	31	0	Gravel	57	2.56	1.9	1750	1444	0.46	3.90	—
68PC23F9L	499	23	9	Gravel	57	2.56	1.9	1750	1444	0.45	3.90	—
65PC35C	522	35	0	Gravel	57	2.56	1.9	1750	1444	0.43	3.00	—
65PC26C9L	522	26	9	Gravel	57	2.56	1.9	1750	1444	0.43	3.00	—
50PC50F	454	50	0	Gravel	57	2.56	1.9	1750	1444	0.50	3.90	—
48PC37F15L	467	37	15	Gravel	57	2.56	1.9	1750	1444	0.48	3.90	—
45PC55C	501	55	0	Gravel	57	2.56	1.9	1750	1444	0.45	3.00	—
45PC41C14L	502	41	14	Gravel	57	2.56	1.9	1750	1444	0.45	3.00	—
75PC25F	564	25	0	Granite	57	2.80	0.5	1823	1264	0.45	1.75	0.77

— Admixture was not used.
W/CM = Water-to-cementitious materials ratio.
WR = Water-reducing admixture.
AEA = Air-entraining agent.
Note: The nominal maximum size of all coarse aggregate was 0.75 inches.

C for Class C fly ash, and L for fine limestone powder (0.3 mil), which was used as a portland cement replacement. The number preceding the letters represents the percentage of that material in relation to the total mass of cementitious material. For example, mixture 68PC23F9L is a mixture that contains 68 percent portland cement, 23 percent Class F fly ash, and 9 percent fine limestone on a mass basis.

Mixtures were prepared and cast following ASTM C192.[11] A minimum of six cylinders were cast, three for 28-day compressive strength tests and three for SR tests as well as RCPT. In some cases, three extra specimens were cast for testing at different ages. Specimens were protected from moisture loss for the first 24 h, then demolded, placed in a standard lime water tank, and cured at 73 ±3 °F until tested.

Slump tests (ASTM C143/143M), air content tests (ASTM C231/C231M), unit weight tests (ASTM C138), 28-day compressive strength tests (ASTM C39/C39M), SR tests (AASHTO TP 95), and RCPT (ASTM C1202) were carried out. (See references 2, 9, and 12–15.) SR tests and RCPT were carried out by a single operator.

A four-point Wenner probe with 1.5-inch probe spacing was used for the SR tests (see figure 1). A total of eight readings per specimen were taken. The readings were averaged and a correction factor of 1.1 was applied to take into account the lime water curing condition.

Immediately after the SR test, the specimens were cut, prepared, and tested according to ASTM C1202, so the same specimen was used for both the SR test and the RCPT. The SR test was carried out at 28 days on plain mixtures and at 56 days on binary and ternary mixtures. In a few cases, binary and ternary mixtures were also tested at 28 days.

Figure 1. SR test using a four-point Wenner probe.

Table 3. Fresh properties and compressive strength results.

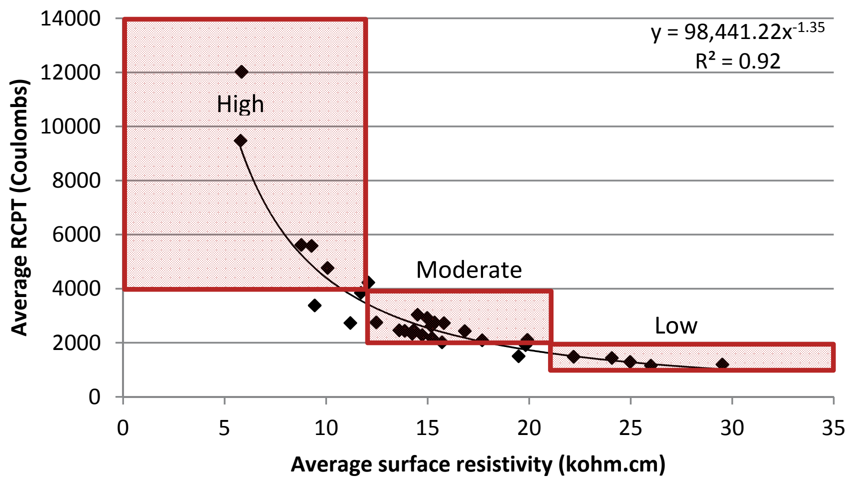
ID	Slump (inches)	Unit Weight (lb/ft^3)	Air Content (percent)	28-day Compressive Strength (lbf/in^2)
57LS42	3.00	145.3	6.0	6,150
57LS47	3.00	144.2	5.5	5,220
57GV37	2.50	139.9	7.0	5,490
57GV40	1.50	144.3	4.0	6,750
57DB42	2.25	148.4	6.9	5,350
57DB47	7.50	145.3	7.0	5,130
467LS37	0.25	144.8	6.0	7,860
467LS42	0.75	142.9	7.0	5,420
467LS47	3.50	142.2	7.9	4,590
67GV42	4.50	141.4	6.6	5,170
67GV45	3.00	142.0	5.5	4,450
67LS37	0.25	147.0	4.5	7,710
67LS42	1.25	146.9	5.0	5,610
67DB37	0.25	155.5	4.7	7,540
67DB42	2.00	149.7	6.8	5,570
67DB45	1.00	152.6	5.0	5,730
57GT45	3.00	149.8	5.1	5,040
69PC31F	0.75	145.0	2.6	3,730
68PC23F9L	1.00	143.9	3.0	4,580
65PC35C	2.00	144.7	3.0	4,031
65PC26C9L	1.25	144.6	3.3	5,470
50PC50F	1.00	143.4	3.1	1,730
48PC37F15L	0.75	143.4	3.0	2,460
45PC55C	5.00	143.3	4.4	1,870
45PC41C14L	2.50	143.1	3.8	3,640

Results

Table 3 shows the fresh property test results and 28-day compressive strength of all the mixtures. The mixtures presented a wide range of results; slump varied from 0.25 to 7.5 inches, air content varied from 2.6 to 7.9 percent, and compressive strength varied from 1,730 to 7,860 lbf/in^2.

Figure 2 shows the relationship between the SR test and the RCPT, where each point represents the average of three tests. According to Broomfield and Millard and Gowers and Millard, the maximum size of the aggregate should not exceed 1 inch for the

Figure 2. Relationship between SR test and RCPT.



probe spacing used in this study (1.5 inches), but there were three mixtures with a 1.5-inch maximum size.[16,17] Nonetheless, these mixtures followed the trend of the other mixtures, and the overall correlation between the two tests resulted in a best-fit line with an R^2 of 0.92. If supplementary cementitious materials other than fly ash or admixtures that could affect the electrical conductance are used, this regression line should not be used without validation.

The SR tests were easier and faster to run and presented lower variability than the RCPT. The coefficient of variation (COV) of the SR tests ranged from 0.9 to 14.9 percent with an average of 5.3 percent, and the COV of the RCPT varied from 2.9 to 19.3 percent with an average of 10.0 percent. The SR test results ranged from about 6 to about 29 kohm-cm, and the RCPT results ranged from about 1,160 to 12,000 C, which represent mixtures with low to high chloride ion penetrability.

Table 4 shows how AASHTO TP 95 and ASTM C1202 classify mixtures by chloride penetrability, depending on resistivity or charge passed, respectively.[2,9] According to the ASTM C1202 criterion, 7 of the 33 sets of tests were classified as low penetrability (< 2,000 C), 20 sets as moderate penetrability (2,000–4,000 C), and 6 sets as high penetrability (> 4,000 C). According to the AASHTO TP 95 criterion, 5 sets were classified as low penetrability (21–37 kohm-cm), 20 sets as moderate penetrability (12–21 kohm-cm), and 8 sets as high penetrability (< 12 kohm-cm).

Table 4. Chloride penetrability classification.

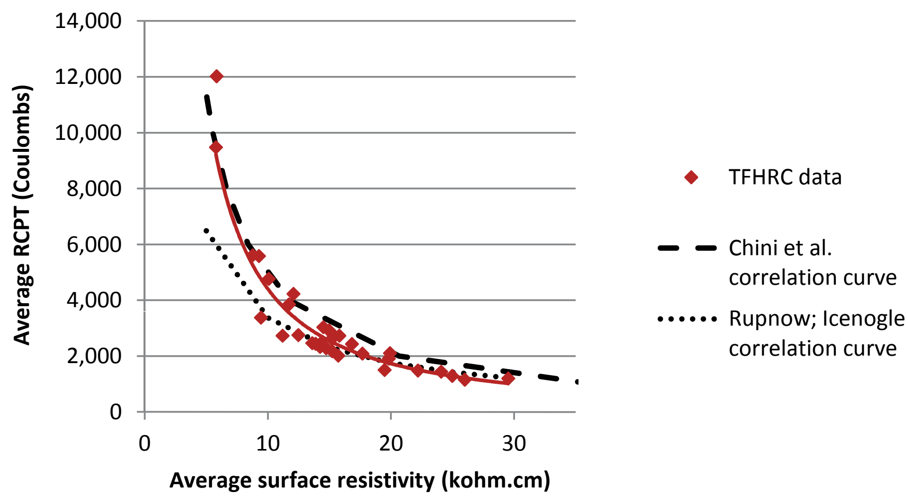
Chloride Ion Penetrability	AASHTO TP 95 (kohm-cm)	ASTM C1202 (Coulombs)
High	< 12	> 4,000
Moderate	12–21	2,000–4,000
Low	21–37	1,000–2,000
Very Low	37–254	100–1,000
Negligible	> 254	< 100

The shaded areas in figure 2 represent the combination of these classifications. Points within the shaded areas receive the same classification by both standards. There were only four points outside of the shaded areas, and they were classified with a higher penetrability by the AASHTO TP 95 criterion than by the ASTM C1202 criterion, indicating that the AASHTO TP 95 classification is more conservative.

Figure 3 shows the data and best-fit curve obtained in this study compared to two other studies. Chini et al. evaluated 508 sets of samples representing a total of 134 mixtures, including plain, binary, and ternary mixtures.[6] Rupnow and Icenogle only evaluated plain and binary mixtures.[3]

As shown, the curve obtained in this study is in agreement with the curve obtained by Chini et al.[6] However, the Rupnow and Icenogle curve yields up to 40 percent lower Coulomb values for resistivities less than 15 kohm-cm.[3] For resistivities of about 15 kohm-cm and higher, the difference between this study's curve and the Rupnow and Icenogle curve is negligible.

Figure 3. Correlation between SR test and RCPT obtained in different studies.



Conclusions

Twenty-five plain, binary, and ternary mixtures containing up to 55 percent class F or class C fly ashes and, in some cases, fine limestone powder and with different aggregate types and maximum sizes were used to evaluate the correlation between the RCPT and the SR test. The results show that the SR test results are highly correlated with the RCPT even for HVFA mixtures and ternary mixtures with finely ground limestone, and a correlation curve was proposed.

The SR test was easier and faster to run compared to the RCPT and did not require any specimen preparation. It also presented lower variability than the RCPT.

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