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Laboratory Comparison of Several Tests for Evaluating the Transport Properties of Concrete

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Abstract

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The chloride diffusion coefficient is an important input in service-life models for reinforced concrete. ASTM C 1585 measures the rate of absorption of water into the capillary pore system at a standard degree of saturation and thus provides a measure of fluid ingress and movement in concrete subject to drying conditions.

These methods more accurately and completely describe the means of transport in concrete and should help improve the understanding and assessment of these important characteristics.

FINAL REPORT

LABORATORY COMPARISON OF SEVERAL TESTS FOR EVALUATING THE TRANSPORT PROPERTIES OF CONCRETE

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Virginia Transportation Research Council (A partnership of the Virginia Department of Transportation and the University of Virginia since 1948)

Charlottesville, Virginia

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ABSTRACT

The transport properties of concrete are a primary element in determining the durability of concrete. In this study, several new test methods that directly measure aspects of fluid and ionic transport in concrete were examined. ASTM C 1543 and ASTM C 1556 provide the means for determining the apparent chloride diffusion coefficient, which is the controlling parameter for chloride ion migration in saturated pore systems.

The chloride diffusion coefficient is an important input in service-life models for reinforced concrete. ASTM C 1585 measures the rate of absorption of water into the capillary pore system at a standard degree of saturation and thus provides a measure of fluid ingress and movement in concrete subject to drying conditions.

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INTRODUCTION

The ability of fluids and ionic species to enter and move within concrete is a major factor in determining its durability. As a consequence, transportation agencies focus on using concretes having low transport properties to enhance service life. Although not always evident to the traveling public, this is nonetheless contrary to the agencies' prime objective: facilitating movement.

Several mechanisms are involved in the transport of fluids within concrete. Movement into and through unsaturated concrete, a common state for concrete with surfaces exposed to the atmosphere, is largely controlled by absorption of the capillary pore system. Where the pore system is saturated, diffusion becomes the primary mechanism driving the movement of ionic species. Pressure-driven permeation is not a major factor regarding concrete durability in typical transportation system applications, but it may play a larger role in deeply submerged elements such as piles and tunnel linings where pressure heads are large enough to drive flow through the concrete.

The Rapid Chloride Permeability Test (AASHTO T 277 [American Association of State Highway & Transportation Officials, 2003] and ASTM C 1202 [ASTM International, 2003a]), an electrical test, has become a primary measure of concrete transport properties since its development in the 1980s (Whiting, 1981), largely because of the relative ease and speed of the measurement with respect to the actual measurement of chloride penetration. The growing interest in service-life prediction models for concrete has created interest in methods that more closely reflect the actual processes, absorption and diffusion, primarily involved in transport within concrete.

PROBLEM STATEMENT

The commonly used method for assessing the transport properties of concrete relative to its durability, the Rapid Chloride Permeability Test, does not reflect the actual mechanisms, absorption and diffusion, that are principally involved. However, several new methods have recently been developed that directly measure these important properties. Experience with these test methods is needed to develop an understanding of the potential applications of the methods and the interpretation and use of their results.

PURPOSE AND SCOPE

As a part of its standards development activities, ASTM Subcommittee C09.66 has conducted an inter-laboratory testing program to study the precision of methods related to concrete permeability. The Virginia Transportation Research Council (VTRC) was a participant in the program that examined ASTM C 1202 and a draft electrical method that measures concrete conductivity; two chloride penetration tests, ASTM C 1543, Determining the Penetration of Chloride Ion into Concrete by Ponding, and ASTM C 1556, Determining the Apparent Chloride Diffusion Coefficient of Cementitious Mixtures by Bulk Diffusion; and an absorption test, ASTM C 1585, Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes. This report discusses only the results by VTRC, focusing on the tests that involve direct measures of transport properties. A previous report (Lane, 2005) discusses in detail the ASTM C 1202 and conductivity tests.

METHODS

Test specimens were fabricated from four concrete mixtures (C1, C2, C3, and C4) by Degussa Admixtures, Inc., and distributed to the participating laboratories. All concretes were moist cured for 28 days prior to specimen preparation for the individual tests. The mixture proportions are shown in Table 1. The specimens were subjected to three test methods.

- ASTM C 1543 (ASTM International, 2003b). Three 200 by 200 by 90 mm concrete slabs for each concrete mixture were ponded with a 3% by mass NaCl solution for 90 days. The vertical sides of the slabs were coated with epoxy prior to ponding. Following the ponding, three 30-mm-diameter holes were drilled using a bit to obtain powder samples from 12.5-mm intervals at centered depths of 12.5, 25, 38, and 51 mm. The chloride content of each sample and the background chloride content of the concrete were determined in accordance with ASTM C 1152 (ASTM International, 2004a). The reported chloride content thus represents the chloride that migrated into the concrete (transported chloride) from the ponding solution.
- 2. ASTM C 1556 (ASTM International, 2003c). Three 100 by 100 mm concrete cylinders for each mixture were submersed in 15% by mass NaCl solution. The cylinder wall and the unfinished end of each cylinder were coated with epoxy; after the epoxy had cured, they were conditioned by immersion in lime-saturated water for 6 days prior to submersion in the NaCl solution. Specimens for C1 were submersed for 35 days, specimens for C2 for 42 days, and specimens for C3 and C4 for 49 days to ensure measurable chloride penetration into the specimens. Following removal from the solution, the specimens were frozen to arrest chloride migration until they could be sampled for chloride analysis. Samples for chloride analysis were obtained in 2-mm increments from the exposed surface to a depth of 18 mm by repeated passes of a 12.5-mm gang of masonry point-tuck blades across the specimen surface in 1-mm-deep intervals. This is a somewhat time-consuming process, estimated to take about 4 hours per specimen. The chloride content of each sample and the background

chloride content of the concrete were determined in accordance with ASTM C 1152. These chloride contents were then used to calculate a surface chloride concentration and the apparent diffusion coefficient of the concrete.

3. *ASTM C 1585 (ASTM International, 2004b).* Three 100-mm-diameter cylinders, 50 mm in length from each mixture were tested. Following curing, the specimens were conditioned in an environmental chamber at 50°C and 80% relative humidity for 3 days followed by 2 weeks storage in individual sealed containers in the laboratory to allow equilibration of the internal moisture condition within the specimen. The specimen sides were then sealed with tape, and a plastic bonnet was placed over the cut end, leaving the finished end exposed for immersion in water for an 8-day period. Prior to immersion and periodically throughout the immersion period, the specimens were weighed. The change in mass of the specimen over time is used to calculate the initial and secondary rates of absorption of the concrete.

					C4 (6% Silica
Component	Units	C1	C2	C3	Fume)
Cement	(lb/yd^3)	517	592	748	703
Silica Fume	(lb/yd^3)	0	0	0	45
Coarse Aggregate (CA)	(lb/yd^3)	1825	1812	1731	1721
Fine Aggregate (FA)	(lb/yd^3)	1227	1219	1164	1157
Water	(lb/yd^3)	300	284	284	284
FA/CA		0.42	0.42	0.42	0.42
W/CM		0.58	0.48	0.38	0.38
28-day strength from trials	psi	4260	5280	6920	7530

Table 1. Mixture Proportions

W/CM = water to cementitious materials ratio; $psi - lb/in^2$.

RESULTS AND DISCUSSION

Chloride Diffusion Tests

The results of the ASTM C 1543 ponding tests are shown in Table 2. ASTM C 1543 is similar to the AASHTO T 259 ponding test but offers a more defined protocol. Distinctions between the two methods include initiation of ponding in ASTM C 1543 at the cessation of moist curing contrasted with a shorter moist-curing period coupled with a drying period prior to ponding in AASHTO T 259; thus the influence of absorption is reduced in ASTM C 1543. Further, ASTM C 1556 anticipates ponding periods extending past 90 days and sampling of thin layers, although for convenience, neither was exercised in this program. Measurable transported chloride was found in the interval centered at a depth of 12.5 mm for all concretes and for C1, C2, and C3 at the 25-mm depth. Chloride contents were negligible for C4, the silica fume concrete at the 25-mm interval, and for all concretes at the 38- and 51-mm intervals. For the 12.5-mm interval, chloride contents for C1, C2, and C3 were comparable, whereas that for C4 was roughly 50% that of the others. At the 25-mm interval, the chloride contents of the four concretes decreased with decreasing water–cementitious material ratios (w/cm) as well as the

Mid-Depth of	Specimen	Chloride Content, % by mass of concrete				
Sample, mm	No.	C1	C2	C3	C4	
12.5	1	0.156	0.205	0.182	0.072	
	2	0.182	0.190	0.160	0.084	
	3	0.175	0.150	0.134	0.072	
	Average	0.171	0.182	0.159	0.076	
	SD	0.013	0.028	0.024	0.007	
25	1	0.081	0.062	0.037	0	
	2	0.081	0.066	0.020	0	
	3	0.069	0.050	0.014	0	
	Average	0.077	0.059	0.024		
	SD	0.007	0.008	0.012		
38, 51	Chloride contents were negligible for all samples at these depths					
Pooled SD for all tests with measurable chloride = 0.0164						

Table 2. Transported Chloride Contents from ASTM C 1543 Slabs

SD = standard deviation.

presence of silica fume in the case of C4. These results are illustrative of limitations resulting from a short (90 day) duration and the sampling of relatively thick (12.5 mm) layers (McGrath and Hooton, 1999; Ozyildirim, 1998). Because of the limited data, diffusion coefficients were not calculated. The pooled standard deviation of the results is 0.016%, an order of magnitude higher than the stated precision of the chloride analysis method, reflecting variations caused by test specimen differences and sampling.

The chloride contents of the samples obtained in the ASTM C 1556 bulk diffusion test are shown in Table 3. Transport properties other than chloride diffusion are negated in this test, and, hence, the results can be used to calculate the apparent chloride diffusion coefficient. This value is referred to as the "apparent" chloride diffusion coefficient, because the chloride contents from which it is calculated include chlorides that have reacted with and become bound to cement hydrates and thus are no longer mobile. The chloride contents for all concretes decrease with depth, and chloride contents at depth decrease with decreasing w/cm and the addition of silica fume. The pooled standard deviation for the ASTM C 1556 chloride contents is higher than that for the ASTM C 1543 tests, reflecting a higher variability associated with the thin-profiling method of sampling, resulting from the natural heterogeneity of concrete.

The chloride data from the ASTM C 1556 and ASTM C 1543 tests are summarized in Figures 1 and 2, respectively. These figures serve to illustrate the differences in the data obtained from the two tests as conducted in this program, with ASTM C 1556 obtaining information from the near-surface concrete, and ASTM C 1543 from deeper within the concrete. A more refined sampling technique similar to that used in ASTM C 1556 could be applied to the ASTM C 1543 specimens to obtain more data points that would permit the determination of the chloride diffusion coefficient. Other distinctions to consider when comparing the data sets are the differences in the concentration of the solutions used, 15% by mass in ASTM C 1556 compared to 3% in ASTM C 1543, and that the reported chloride content for ASTM C 1556 includes the background (initial) chloride content of the concrete whereas the value for ASTM C 1543 does not. In the ASTM C 1556 test, the background chloride content is considered (effectively removed) during the calculations to determine the apparent diffusion coefficient.

Mid-Depth of	Specimen	Chloride Content, % by mass of concrete					
Sample, mm	No.	C1	C2	C3	C4		
1	1	1.555	0.952	0.687	0.630		
	2	1.211	0.989	0.766	0.658		
	3	1.301	0.0804	0.775	0.673		
	Average	1.355	0.915	0.742	0.653		
	SD	0.178	0.0978	0.0486	0.0215		
3	1	1.275	0.757	0.602	0.365		
	2	0.898	0.713	0.649	0.282		
	3	0.882	0.687	0.556	0.461		
	Average	1.019	0.719	0.602	0.369		
	SD	0.2226	0.0350	0.0463	0.0900		
5	1	0.722	0.473	0.417	0.192		
	2	0.566	0.411	0.408	0.139		
	3	0.537	0.493	0.382	0.178		
	Average	0.608	0.452	0.402	0.169		
	SD	0.0997	0.0359	0.0178	0.0275		
7	1	0.651	0.338	0.304	0.116		
	2	0.413	0.299	0.294	0.070		
	3	0.409	0.383	0.301	0.086		
	Average	0.491	0.340	0.300	0.091		
	SD	0.1386	0.0422	0.0050	0.0233		
9	1	0.577	0.267	0.235	0.089		
	2	0.354	0.245	0.233	0.034		
	3	0.355	0.320	0.197	0.018		
	Average	0.429	0.277	0.222	0.047		
	SD	0.1282	0.0385	0.0215	0.0375		
11	1	0.461	0.222	0.183	0.078		
	2	0.303	0.214	0.192	0.083		
	3	0.318	0.282	0.129	0.078		
	Average	0.360	0.239	0.168	0.080		
	SD	0.0872	0.0371	0.0340	0.0032		
13	1	0.303	0.189	0.144	0.074		
	2	0.271	0.183	0.150	0.072		
	3	0.275	0.254	0.092	0.073		
	Average	0.283	0.209	0.129	0.073		
	SD	0.0173	0.0396	0.0320	0.0010		
15	1	0.210	0.159	0.112	0.074		
	2	0.208	0.152	0.111	0.068		
	3	0.255	0.212	0.073	0.069		
	Average	0.224	0.174	0.099	0.070		
	SD	0.0262	0.0326	0.0221	0.0328		
17	1	0.152	0.130	0.073	0.065		
	2	0.183	0.105	0.072	0.022		
	3	0.208	0.136	0.052	0.070		
	Average	0.181	0.124	0.065	0.052		
	SD	0.0280	0.0166	0.0118	0.0267		
	Pooled SD for all tests = 0.049						

Table 3. Chloride Contents from ASTM C 1556 Specimens

SD = standard deviation.



The diffusion coefficients for the concretes determined from the ASTM C 1556 chloride content data are presented in Table 4. The values obtained for the tested concretes are on the order of 10^{-11} to 10^{-12} m²/sec, which is typical for concrete. The average coefficients for the concretes decrease with decreasing w/cm and the addition of silica fume, but the values for C2 and C3 are influenced by values (C2-3 and C3-1) that appear to be somewhat out of line with the others.

The diffusivity of concrete is of interest for its use in service-life prediction models. It is recognized as being time-dependent (Thomas, 2001), assuming continued hydration reactions of the cementitious materials, so the values for the concretes tested here could be expected to decrease with continued maturity. This time-dependency is of particular interest with respect to concretes containing supplementary cementitious materials, such as fly ash or ground slag, that are known to hydrate more slowly than typical portland cements and silica fume, and thus values obtained at a relatively young age in the expected service life of a concrete may be misleading with respect to the property level that ultimately governs its long-term performance.

Specimen	C1	C2	C3	C4	
Background (initial)	Chloride Content (C_i), %				
1	0.081	0.055	0.055	0.067	
2	0.064	0.060	0.058	0.051	
3	0.075	0.051	0.057	0.066	
Projected Chloride C	Content at Surface (C_s), %		·		
1	1.623	0.997	0.694	0.689	
2	1.273	1.049	0.785	0.789	
3	1.376	0.814	0.811	0.743	
Diffusion Coefficient	$m^2/s \times 10^{-12}$		·		
1	12.58	8.76	9.15	2.21	
2	10.54	6.57	7.68	1.36	
3	8.82	15.21	5.74	2.17	
Average	10.65	10.19	7.52	1.92	
SD	1.89	4.50	1.71	0.48	
CV	17.7%	44.2%	22.8%	25.0%	
Pooled CV	27%				

Table 4. Apparent Chloride Diffusion Coefficients from ASTM C 1556 Tests

SD = standard deviation; CV = coefficient of variation.

The determination of diffusion coefficients for in-service bridge decks that have been exposed to chlorides is challenging because the ingress of chlorides into the concrete is affected by uncontrolled parameters such as the degree of saturation of the concrete (Kirkpatrick et al., 2002a) and variations in the driving concentration. Kirkpatrick et al. (2002b) recognized the strong influence that diffusion coefficients have on time-to-corrosion predictions and emphasized the importance of obtaining accurate values of this property for use in service-life models. ASTM C 1556 provides a means to assess the chloride diffusivity of concretes under controlled conditions, thus affording a closer approximation of the fundamental property value. It can be applied to concretes over various stages of maturity to improve the understanding of the time-dependency of the property and with various solution concentrations to clarify the impact of driving concentrations. The diffusion coefficient of in-service concretes could be assessed by obtaining specimens taken beyond the chloride-ion penetration front and subjecting them to ASTM C 1556. Such applications should help in condition assessments of structures and in refining service-life prediction models.

Absorption Test

The absorption rates from the ASTM C 1585 tests are shown in Table 5. Two values are obtained from each test: an initial absorption rate (C_i) and a secondary absorption rate (C_s) represented in Figure 3 by the slope of initial inflow into the conditioned specimen and the slope after some period of time. Both C_i and C_s decreased with decreasing w/cm and the addition of silica fume. The secondary rates were approximately 50% of the initial rates. The results obtained provided a clear distinction among the four concretes as illustrated in Figure 4. From these data, the rate remains fairly stable after about 1 day, particularly for higher quality concrete, suggesting the test could be terminated earlier than 8 days without loss of significant data.

Specimen	C1	C2	C3	C4		
Initial Absorption, C_i ,	$mm/s^{1/2} \times 10^{-4}$					
1	37.17	24.09	13.57	4.04		
2	33.84	25.35	11.73	5.13		
3	34.50	21.07	12.82	5.34		
Average	35.17	23.50	12.71	4.84		
SD	1.760	2.200	0.927	0.698		
CV	5.01%	9.36%	7.30%	14.43%		
	Pooled $CV = 9.02\%$					
	Expected repeatability range = 25.5%					
Secondary Absorption	, C_s , $mm/s^{1/2} \times 10^{-4}$					
1	15.99	11.09	6.33	2.20		
2	14.56	12.29	6.24	2.46		
3	15.36	10.10	6.88	2.21		
Average	15.30	11.16	6.48	2.29		
SD	0.720	1.100	0.347	0.147		
CV	4.70%	9.83%	5.36%	6.44%		
	Pooled CV = 6.58%					
	Expected repeatability range = 18.6%					

Table 5. Capillary Sorption Results from ASTM C 1585 Tests

SD = standard deviation; CV = coefficient of variation.



Figure 3. Example ASTM C 1585 Results Illustrating Initial (C_i) and Secondary (C_s) Absorption Rates



Figure 4. Absorption Rate of Concretes from ASTM C 1585 Tests

The absorption test measures fluid transport into unsaturated concrete, the condition typical for concrete bridge decks, and thus provides a unique method for assessing this important aspect of concrete quality. Because variations in the degree of saturation will affect the test results, the specimens are brought to a standard reference saturation condition prior to testing to remove this source of variation. Absorption rates have been used in service-life models (Bentz et al., 2001) and may also be coupled with diffusivity to model more realistically the transport characteristics of concretes that are at least periodically exposed to drying conditions. The transport properties of concretes that spend their service lives in the saturated condition, such as submerged columns, can adequately be described by diffusion alone.

Relationship of Electrical Conductivity to Transport Properties

The electrical conductivity of the concretes that are the subject of this study has been reported elsewhere (Lane, 2005), where it was noted that the scientific literature shows a good correspondence of conductivity with concrete transport properties. The relationships between electrical conductivity and the transport properties for these concretes are shown in Figure 5 (initial absorption rate), Figure 6 (secondary absorption rate), and Figure 7 (diffusion coefficient). The relationship between the electrical conductivity and the rates of absorption can be described by an exponential function, whereas that of the diffusion coefficient can be described by a logarithmic function.



Figure 5. Relationship Between Electrical Conductivity and Initial Absorption Rate



Figure 6. Relationship Between Electrical Conductivity and Secondary Absorption Rate



Figure 7. Relationship Between Electrical Conductivity and Apparent Diffusion Coefficient

CONCLUSIONS

- The manner in which fluids and ionic species move into and within concrete is largely a function of the saturation state of the concrete, with capillary actions predominating when the pore system is not saturated and ionic diffusion predominating when the pore system is saturated. Several newly standardized test methods are available that directly measure these transport properties of concrete and should be useful in improving service-life models.
- ASTM C 1543 and ASTM C 1556 are methods for measuring the apparent chloride diffusion coefficient of concrete, a property dependent on the maturity of the concrete. The repeatability of the ASTM C 1556 apparent diffusion coefficient measurement was 27%. The diffusion coefficient was not determined from the ASTM C 1543 data, because a simplified sampling procedure was used rather than the incremental profiling necessary for an accurate diffusion calculation.
- Because of the shorter duration and smaller specimen size, ASTM C 1556 offers advantages over ASTM C 1543 for determination of apparent chloride diffusion coefficient, especially where laboratory space is limited.
- ASTM C 1585 measures the absorption rate of water into the capillary pore system of concrete at a standard degree of saturation. The rate of absorption slows after an initial (over several hours) period of absorption and two values, an initial and a secondary rate, are obtained. In these tests, the secondary rate remained stable through the 8-day test period, suggesting the test could be terminated after 1 or 2 days. The repeatability of the initial and secondary absorption rates are 9.0% and 6.6%, respectively.
- The relationship between the electrical conductivity of the concrete and the rates of absorption can be defined by an exponential function. The relationship between the electrical conductivity and the apparent chloride diffusion coefficient can be defined by a logarithmic function.

RECOMMENDATIONS

- 1. VTRC should conduct ASTM C 1556 and ASTM C 1585 tests on typical concrete mixtures to improve the understanding of the relationships between these measures and the electrical conductivity of concretes. Such a program should include maturity over an extended period of time to assess how the relationships hold up over time. It should also include variation in the ASTM C 1556 solution concentration to examine how the driving concentration impacts the diffusion coefficient.
- 2. VTRC should initiate a program to conduct ASTM C 1556, ASTM C 1585, and electrical conductivity tests on concretes that have been in service for an extended period of time. This information would add to the understanding of the transport properties of mature concretes and provide the database necessary to incorporate these methods as quality assessment tools in asset management systems.

3. VTRC should examine the information developed from Recommendations 1 and 2 for possible incorporation into service-file prediction models.

BENEFITS AND COSTS ASSESSMENT

The benefits of the described program are believed to lie in improved knowledge of the behavior of the materials used to construct the transportation system and improvements in the assessment of the quality of the materials and prediction of performance that will enhance asset management. The nature of the work does not lend itself to a quantitative determination of cost, but it is not believed that the testing described will result in significant changes in cost to VDOT.

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