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## **Standard Method of Test for**

# **Predicting Chloride Penetration of Hydraulic Cement Concrete by the Rapid Migration Procedure**

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**AASHTO Designation: T 357-22<sup>1</sup>**

Technically Revised: 2022

**Technical Subcommittee: 3c, Hardened Concrete**



**American Association of State Highway and Transportation Officials  
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## 1. SCOPE

- 1.1. This procedure is for the rapid evaluation of chloride penetration resistance of concrete, from non-steady-state migration experiments.
- 1.2. *The quality of the results produced by this standard are dependent on the competence of the personnel performing the procedure and the capability, calibration, and maintenance of the equipment used. Agencies that meet the criteria of R 18 are generally considered capable of competent and objective testing/sampling/inspection/etc. Users of this standard are cautioned that compliance with R 18 alone does not completely assure reliable results. Reliable results depend on many factors; following the suggestions of R 18 or some similar acceptable guideline provides a means of evaluating and controlling some of those factors.*
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## 2. REFERENCED DOCUMENTS

- 2.1. *AASHTO Standards:*
- < M 339M/M 339, Thermometers Used in the Testing of Construction Materials
  - < R 18, Establishing and Implementing a Quality Management System for Construction Materials Testing Laboratories
  - < R 39, Making and Curing Concrete Test Specimens in the Laboratory
  - < R 100, Making and Curing Concrete Test Specimens in the Field
  - < T 24M/T 24, Obtaining and Testing Drilled Cores and Sawed Beams of Concrete
  - < T 277, Electrical Indication of Concrete's Ability to Resist Chloride Ion Penetration
- 2.2. *ASTM Standards:*
- < D1193, Standard Specification for Reagent Water
  - < E1, Standard Specification for ASTM Liquid-in-Glass Thermometers
  - < E230/E230M, Standard Specification for Temperature-Electromotive Force (emf) Tables for Standardized Thermocouples
  - < E2877, Standard Guide for Digital Contact Thermometers
- 2.3. *International Electrotechnical Commission Standard:*
- < IEC 60584-1:2013, Thermocouples - Part 1: EMF Specifications and Tolerances
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### 3. TERMINOLOGY

#### 3.1. *Definitions:*

- 3.1.1. *chloride penetration depth*—the distance between the surface exposed to chloride solution and the chloride penetration front where the color changes from white to brown after spraying of 0.1*N* silver nitrate solution.
- 3.1.2. *diffusion*—the movement of molecules or ions under a gradient of concentration, or more strictly speaking, chemical potential, from a high concentration zone to a low concentration zone.
- 3.1.3. *migration*—the movement of ions under the action of an external electrical field.

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### 4. SUMMARY OF TEST METHOD

- 4.1. This test method uses electrical migration to accelerate the movement of chloride ions into a concrete specimen and a colorimetric indicator to measure the extent of chloride penetration. An external potential is applied axially across the specimen to force the chloride ions to migrate into the specimen. After a defined test duration, the specimen is axially split and a silver nitrate solution (colorimetric indicator for chloride) is sprayed on one of the fresh split surfaces. The chloride penetration depth is measured from the extent of the visible white silver chloride precipitate. From this penetration depth, the rate of chloride ion penetration is determined and used to rate the concrete.

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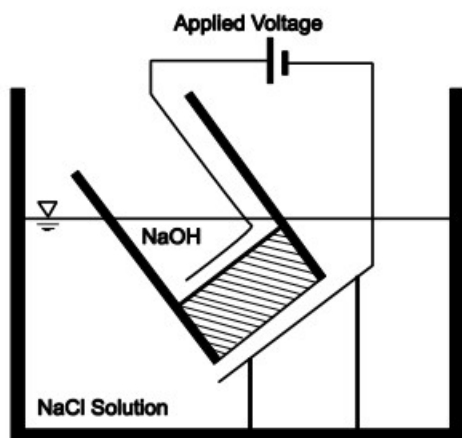
### 5. SIGNIFICANCE AND USE

- 5.1. The results of this test can be used to rate concrete according to the relative ease with which chloride ions can penetrate into the concrete. This in turn gives an indication of the potential for corrosion of reinforcing steel due to chloride intrusion.

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### 6. APPARATUS

- 6.1. Water-cooled diamond saw, capable of making cuts perpendicular to the axis of 100-mm diameter concrete cylinders or cores.
- 6.2. *Conditioning Equipment:*
  - 6.2.1. *Vacuum Desiccator*—250-mm diameter or larger (capable of containing at least three specimens), allowing two hose connections, each of which must be equipped with a stopcock.
  - 6.2.2. *Vacuum Pump*—Capable of maintaining a pressure of less than 5 kPa (37 mmHg) in the desiccator.  
**Note 1**—Because the vacuum will be drawn over water, the pump should be protected with a cold trap, or the pump oil should be changed after each use.
  - 6.2.3. *Vacuum Gauge or Manometer*—Capable of reading vacuum levels as low as 1 kPa (5 mmHg).
- 6.3. Migration apparatus shown schematically in Figure 1 (Note 1). Detailed drawings may be found in Annex A1.



**Figure 1**—Schematic of Migration Apparatus

- 6.3.1. *Silicon Rubber Sleeve*—Inner/outer diameter 100/115 mm, about 150 mm long.
- 6.3.2. *Two Stainless Steel Clamps*—20 mm wide with diameter range of 105 to 115 mm. (See Figure 2.)
- 6.3.3. *Plastic Container (Catholyte Reservoir)*—370 by 270 by 280 mm (*L* by *W* by *H*).
- 6.3.4. Plastic support with 0.5-mm thick stainless steel plate (cathode) attached. (See Figures A1.1 through A1.5.)
- 6.3.5. *Stainless Steel Mesh or Plate (Anode)*—With holes, about 0.5 mm thick. (See Figure A1.5.)  
**Note 2**—Other designs are acceptable provided that temperatures of the specimen and solutions during the test can be maintained in the range of 20 to 25°C. Test cells for T 277 have been used successfully in this procedure. Use of T 277 cells requires test specimens to be coated as specified in T 277 before conditioning.
- 6.4. Power supply capable of supplying 0- to 60-V direct current (DC)-regulated voltage with the accuracy  $\pm 0.1$  V.
- 6.5. *Ammeter*—Capable of displaying current to  $\pm 1$  mA.
- 6.6. *Thermometer or Thermocouple*—With readout device capable of reading to  $\pm 1^\circ\text{C}$ .
- 6.7. Any device suitable for splitting the specimen longitudinally, e.g., compression testing machine with split tensile test apparatus.
- 6.8. *Slide Caliper*—With 0.1-mm resolution and ruler for measuring.

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## 7. REAGENTS AND MATERIALS

- 7.1. *Purity of Reagents*—Reagent-grade chemicals shall be used in all tests. Unless otherwise indicated, all reagents shall conform to the specifications of the Committee on Analytical Reagents of the American Chemical Society, where such specifications are available. Other grades may be used provided it is first ascertained that the reagent is of sufficiently high purity to permit its use without lessening the accuracy of the determination.

- 7.2. *Purity of Water*—Unless otherwise indicated, water shall be reagent-grade water as defined by Type III of ASTM D1193.
- 7.3. *Reagents:*
- 7.3.1. *Sodium Chloride Solution, 10 Percent by Mass*—dissolve 100 g sodium chloride (NaCl) in 900 g tap water.
- 7.3.2. *Sodium Hydroxide Solution, 0.3 N*—dissolve approximately 12 g sodium hydroxide in 1 L distilled or deionized water.
- 7.3.3. Silver nitrate (AgNO<sub>2</sub>) solution, 0.1 M.
- 7.4. *Sealant:*
- 7.4.1. Five-minute epoxy or other suitable sealant for coating specimen sides, if required by the test apparatus. (See Note 2.)

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## 8. SAMPLING, TEST SPECIMENS, AND TEST UNITS

- 8.1. The method requires cylindrical specimens with a diameter of 100 mm and a thickness of 50 mm, sliced from cast cylinders or drilled cores with a minimum original length of 100 mm. The cylinders or cores should meet the requirements described in R 39, R 100, or T 24M/T 24. Three specimens should be used in the test.
- 8.2. *Obtaining Test Specimens:*
- 8.2.1. If a drilled core is used, an outer (i.e., closest to the original surface) layer of the concrete (approximately 10–20 mm thick) should be cut off (Note 3), after which a  $50 \pm 2$  mm thick slice should be cut from the remaining core length to be used as the test specimen. The end surface of the test specimen that was closest to the original surface (i.e., the end surface that was adjacent to the discarded outer layer) should be exposed to the chloride solution (catholyte).
- 8.2.2. If a cast cylinder is used, an outer (i.e., closest to the troweled surface) layer of the concrete approximately 25 mm thick should be cut off (Note 3), after which a  $50 \pm 2$  mm thick slice should be cut from the remaining length of the cylinder to be used as the test specimen. The end surface closest to the original troweled surface should be exposed to the chloride solution (catholyte).
- 8.2.3. The thickness should be measured to the nearest 0.1 mm with a slide caliper at four locations equally spaced around the specimen. All four thickness measurements shall be  $50 \pm 2$  mm.  
**Note 3**—The term “cut” here means to saw perpendicularly to the axis of a core or cylinder by means of a water-cooled diamond saw.

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## 9. CONDITIONING

- 9.1. Brush and wash away any burrs from the surfaces of the specimen. Wipe excess water from the surfaces of the specimens.
- 9.2. Coat specimen sides with 5-min epoxy or other suitable sealant if required.
- 9.3. *Preconditioning (Vacuum Saturation):*
- 9.3.1. Place surface-dry specimens in the vacuum desiccator. Both end surfaces must be exposed.

- 9.3.2. Seal the desiccator and start the vacuum pump. The absolute pressure in the desiccator should decrease to a range of 1 to 5 kPa (7.5 to 37 mmHg) within a few minutes. Maintain vacuum for 3 h.
- 9.3.3. With the vacuum pump still running, open the water stopcock and fill the desiccator with de-aired tap water to cover the specimens. Close the water stopcock and maintain the vacuum for an additional 1 h.
- 9.3.4. Close the vacuum line stopcock and turn off the vacuum pump. Reopen the vacuum line stopcock to allow air to reenter the desiccator. Maintain the specimens in this condition for  $18 \pm 2$  h.

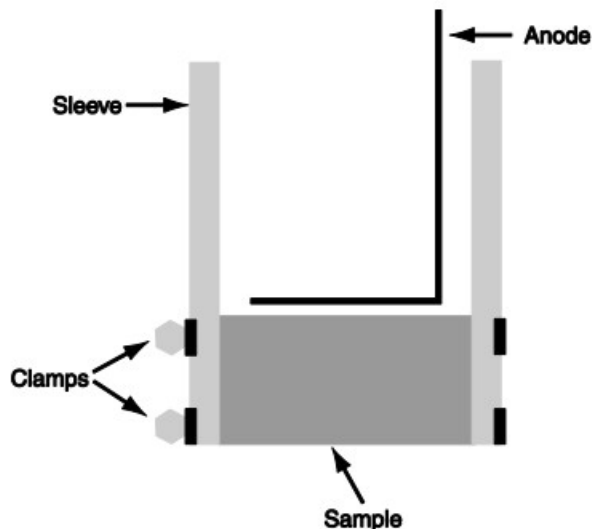
## 10. PROCEDURE

### 10.1. Setup (Note 5):

- 10.1.1. Measure the temperature of the NaOH and NaCl solutions. If the temperatures are not within the range  $23 \pm 2^\circ\text{C}$ , bring the temperatures of the NaOH and NaCl solutions to  $23 \pm 2^\circ\text{C}$  before starting the test. The thermometer for measuring the temperature of the solutions shall meet the requirements of M 339M/M 339 with a temperature range of at least 19 to  $27^\circ\text{C}$  [ $66.4$  to  $80.6^\circ\text{F}$ ] and an accuracy of  $\pm 0.5^\circ\text{C}$  [ $\pm 0.9^\circ\text{F}$ ] (see Note 4).

**Note 4**—Thermometer types suitable for use include ASTM E1 mercury thermometers; ASTM E2877 digital metal stem thermometer; ASTM E230/E230M thermocouple thermometer, Type T, Special; or IEC 60584 thermocouple thermometer, Type T, Class 1.

- 10.1.2. Place the plastic support (cathode) in the catholyte reservoir and fill the reservoir with about 12 L of NaCl solution.
- 10.1.3. For each of the three test specimens, place a rubber sleeve around the specimen as shown in Figure 2 (Note 5). Place clamps as shown in the figure and tighten snugly.



**Figure 2**—Assembly of Specimen in Rubber Sleeve and Placement of Anode

**Note 5**—If using an apparatus different than the one described here (e.g., T 277 cells), set up the apparatus in accordance with the applicable standard or the manufacturer's instructions.

10.1.4. Fill each sleeve with distilled water to check for leaks, and tighten clamps further if necessary (Note 6). Empty the water and place the specimens on the slanted plastic support (cathode) in the catholyte reservoir (Note 7).

**Note 6**—If the curved surface of the specimen is not smooth, or if there are significant defects (e.g., large voids or honeycombs) on the curved surface that may result in significant leakage, apply a strip of silicon sealant to improve the watertightness.

**Note 7**—If the concrete has been allowed to dry substantially after preconditioning, immerse it in tap water for a few minutes to resaturate before placing it on the slanted plastic support (cathode) in the catholyte reservoir.

10.1.5. Fill the sleeve above the specimen with 300 ml of NaOH solution. Immerse the anode in the NaOH solution.

10.2. *Application of Voltage:*

10.2.1. Connect the cathode and anode to the negative and positive poles of the power supply, respectively. Turn on the power, set the power supply to a potential of  $60.0 \pm 0.1$  V DC, and record the initial current (A) through each specimen to the nearest 0.001 A.

10.2.2. Check the current ranges in Table 1 and, if necessary, reset the potential according to the values in the table. If the potential is reset, record new values of initial current for each specimen. If the initial current is greater than 800 mA, do not continue with the test.

**Table 1**—Test Conditions

Initial Current at 60 V (mA)	Applied Voltage (V)	Test Duration (h)
<120	60	18
120–240	30	18
240–800	10	18
>800	Do not test	Do not test

10.2.3. For each specimen, measure and record the initial temperature in the anolyte solution using a thermometer or thermocouple.

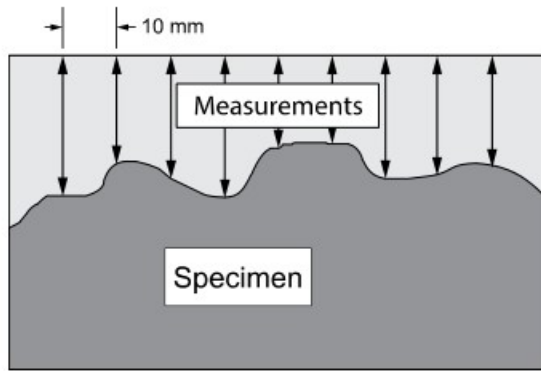
10.2.4. After 18 h, record the final current and temperature for each specimen, and record the temperature of the catholyte solution. Turn off the power supply.

10.2.5. Disassemble the test apparatus and remove test specimens.

10.3. *Measurement of Chloride Penetration:*

10.3.1. Rinse the specimens with distilled water. Wipe excess water from the surfaces of the specimen. Using a suitable device, split the specimen longitudinally into two pieces. Choose one piece for the penetration depth measurement.

10.3.2. Spray 0.1 N silver nitrate solution on the fresh-split surface. When the white silver chloride precipitate on the split surface is clearly visible (after about 15 min), use a ruler to measure the penetration depths at intervals of 10 mm, starting 10 mm from the edge, as shown in Figure 3 (Notes 8, 9, and 10). The depth should be read to the nearest millimeter. At least five valid depth measurements should be obtained.



**Figure 3**—Measurement of Chloride Penetration Depth on Split Face of Specimen

**Note 8**—If the penetration front to be measured is obviously blocked by the aggregate, move the measurement to the nearest front where there is no significant blocking of aggregate, or alternatively, discard this depth if there are more than five valid depths.

**Note 9**—If the presence of a defect in the specimen (e.g., large void or honeycomb) results in a penetration front much larger than the average, measurement(s) should not be made at this location. Note such defects in the test report.

**Note 10**—To eliminate possible edge effects due to non-homogeneous degree of saturation or possible leakage during the test, no depth measurement should be made within 10 mm of the edge. (See Figure 3.)

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## 11. CALCULATIONS

- 11.1. For each test specimen, the depth of penetration is determined by discarding the high and the low value and taking the mean of the remaining measurements.
- 11.2. The rate of penetration is calculated by dividing the depth of penetration (mm) by the product of the applied voltage (V) and the test duration (h).

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## 12. REPORT

- 12.1. *Report the following information:*
- 12.1.1. Name and address of the testing laboratory;
- 12.1.2. Date and identification number of the test report;
- 12.1.3. Name and address of the organization or person who ordered the test;
- 12.1.4. Name and address of the manufacturer or supplier of the tested object;
- 12.1.5. Date of arrival of the tested object;
- 12.1.6. Description of the tested object including sampling, composition, and curing age;
- 12.1.7. Purpose of the test;



- 12.1.8. Test method;
- 12.1.9. Any deviation from the test method;
- 12.1.10. Name and address of the person who performed the test;
- 12.1.11. Date of the test;
- 12.1.12. Test information including the specimen dimensions, applied potential, initial and final currents, and initial and final temperatures;
- 12.1.13. Average (for three specimens) penetration depth and rate of penetration as well as individual penetration depth measurements for each specimen;
- 12.1.14. Any unusual observations, such as significant defects in the specimens or a large penetration front due to a defect or leakage;
- 12.1.15. Inaccuracy or uncertainty of the test results; and
- 12.1.16. Date and signature.

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### **13. PRECISION AND BIAS**

#### 13.1. *Precision:*

13.1.1. *Single-Operator Precision*—The single-operator coefficient of variation of a single test result (where a test result is, as defined in this test method, the average of three separate measurements) has been found to be 8.8 percent according to the results from the Nordic round-robin test between six laboratories.<sup>2</sup> Therefore, results of two properly conducted tests (each consisting of the average of three individual measurements) by the same operator on concrete samples from the same batch should not differ by more than 25 percent.

13.1.2. *Multilaboratory Precision*—The multilaboratory coefficient of variation of a single test result (where a test result is, as defined in this test method, the average of three separate measurements) has been found by Hooton et al.<sup>3</sup> to be 16 percent for plain portland cement concrete or concrete blended with silica fume and by Tang and Sorenson to be 23.6 percent for concrete blended with slag. Therefore, results of two properly conducted tests (each consisting of the average of three individual measurements) should not differ by more than 45 percent for portland cement concrete or concrete blended with silica fume or 67 percent for concrete blended with slag.

13.2. *Bias*—Because there is no accepted reference material suitable for determining the bias in this test method, no statement on bias is made.

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### **14. KEYWORDS**

14.1. Concrete; corrosion; chloride penetration; electrical migration.

# ANNEX A

(Mandatory Information)

## A1. APPARATUS DESCRIBED IN SECTION 6

A1.1. This annex contains drawings for the apparatus as described in Section 6 of this standard.

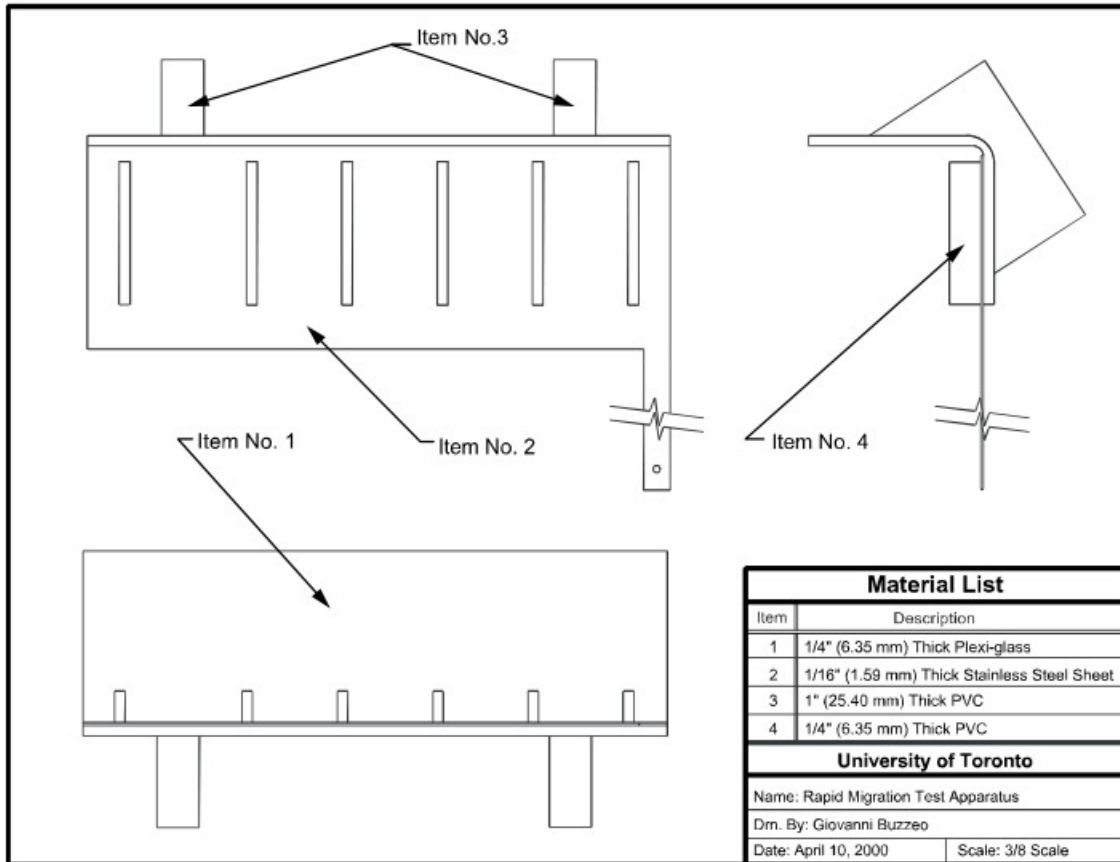
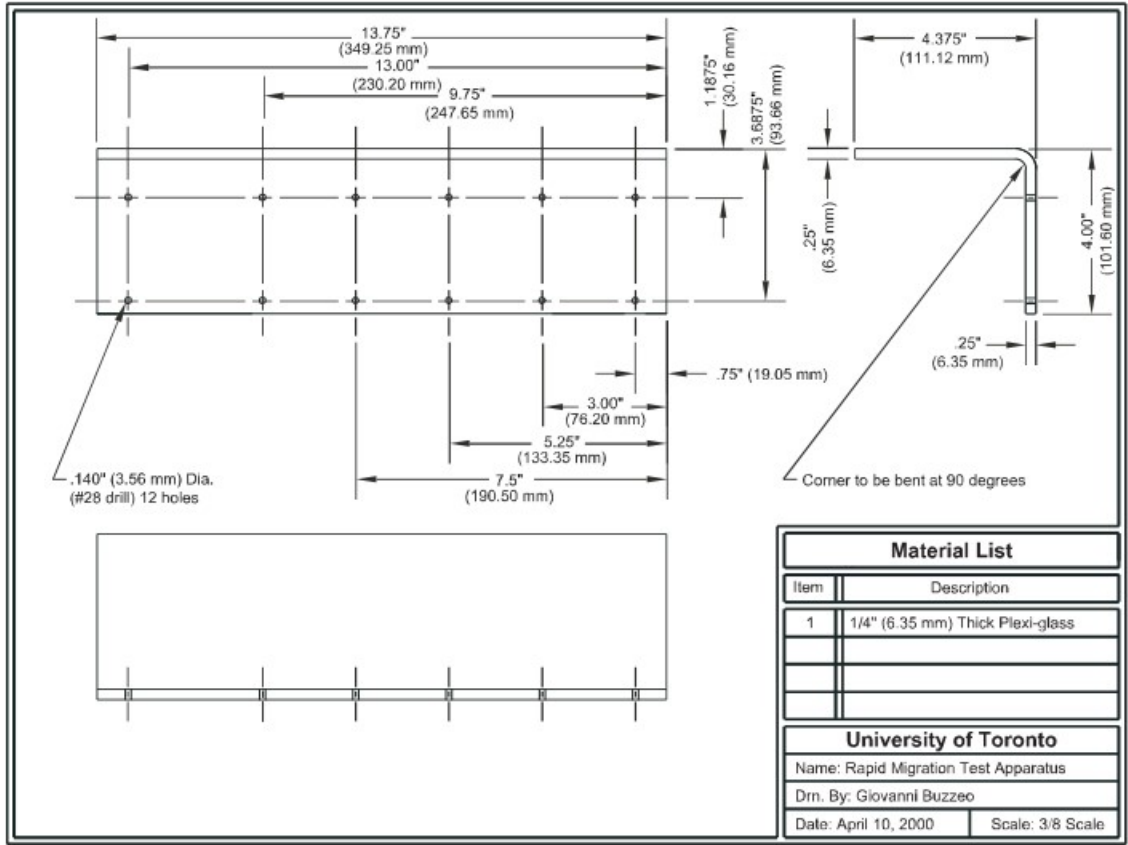
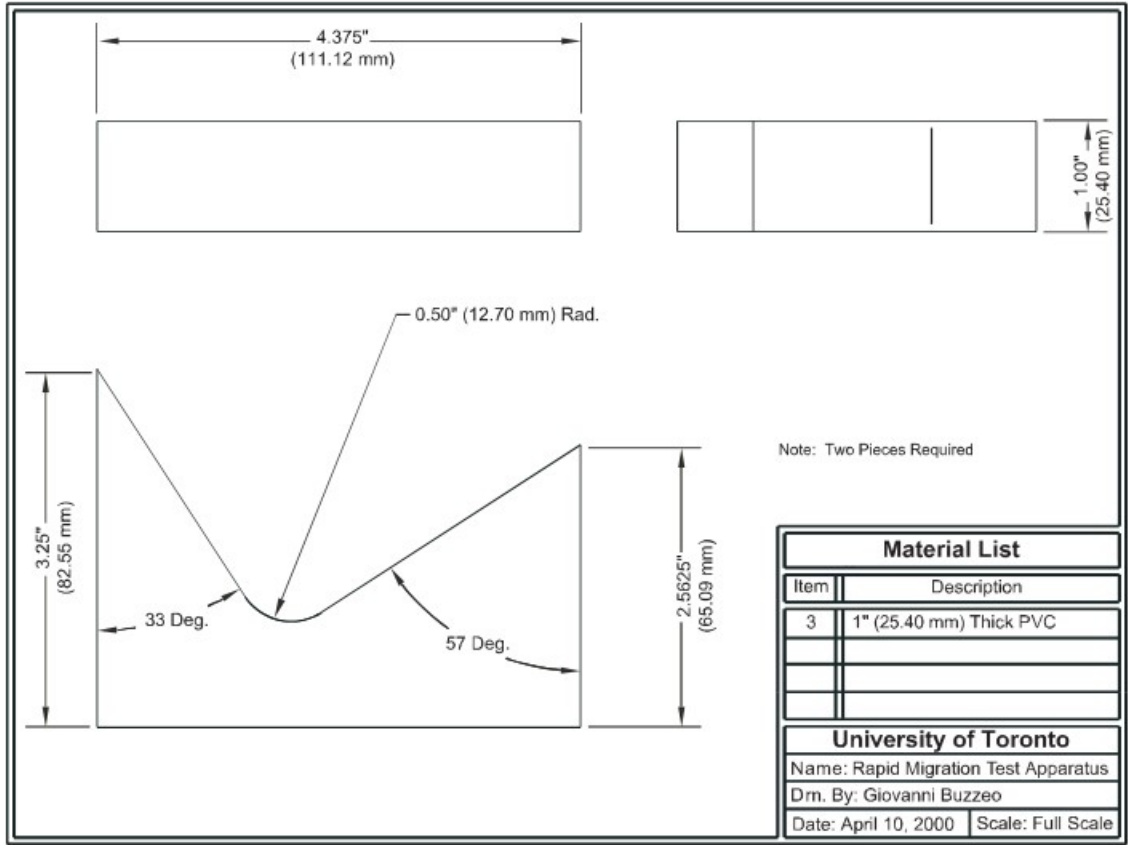


Figure A1.1—Cathode Assembly



**Figure A1.2**—Cathode: Detail of 3-in. Plexiglas™ Sheet



**Figure A1.3**—Cathode: Detail of 1-in. PVC

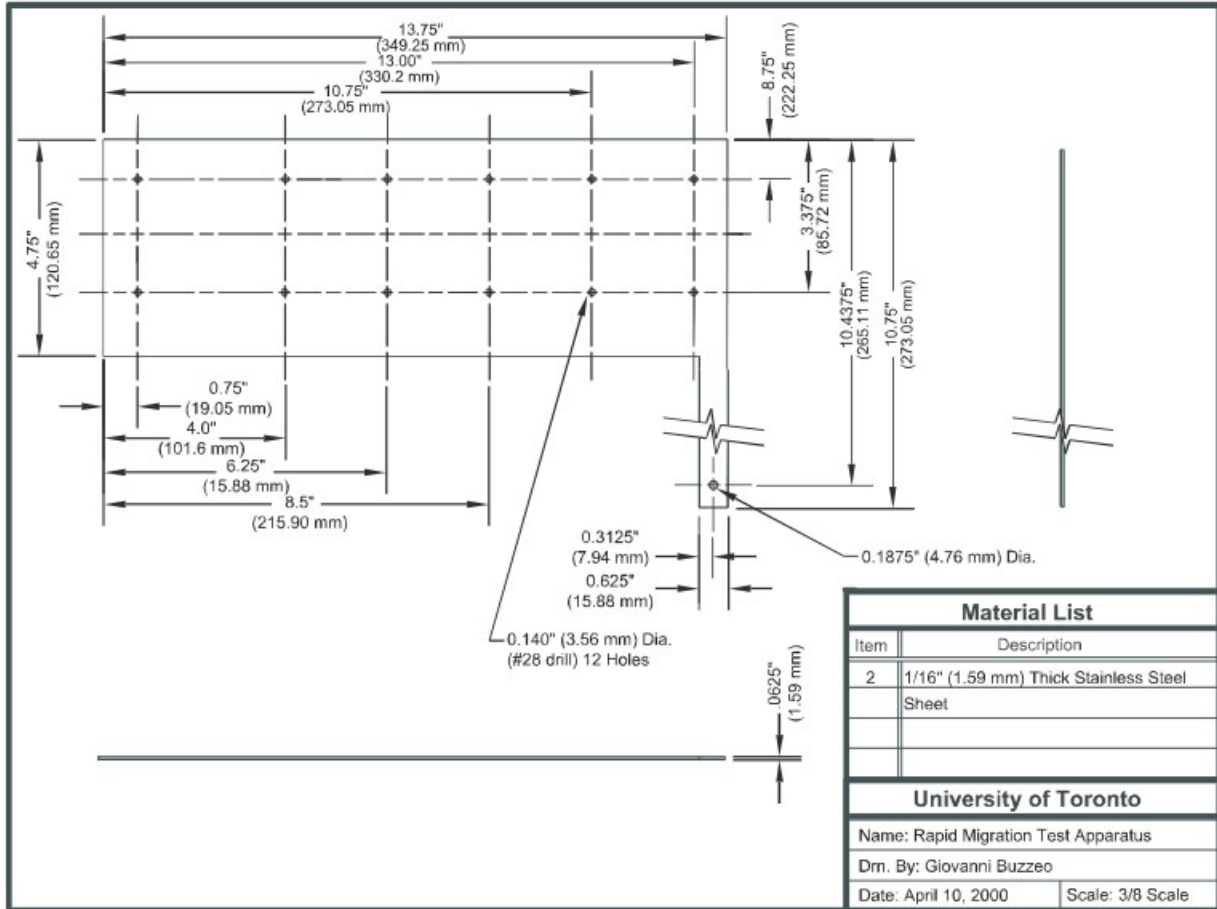


Figure A1.4—Cathode: Detail of Stainless Steel Sheet

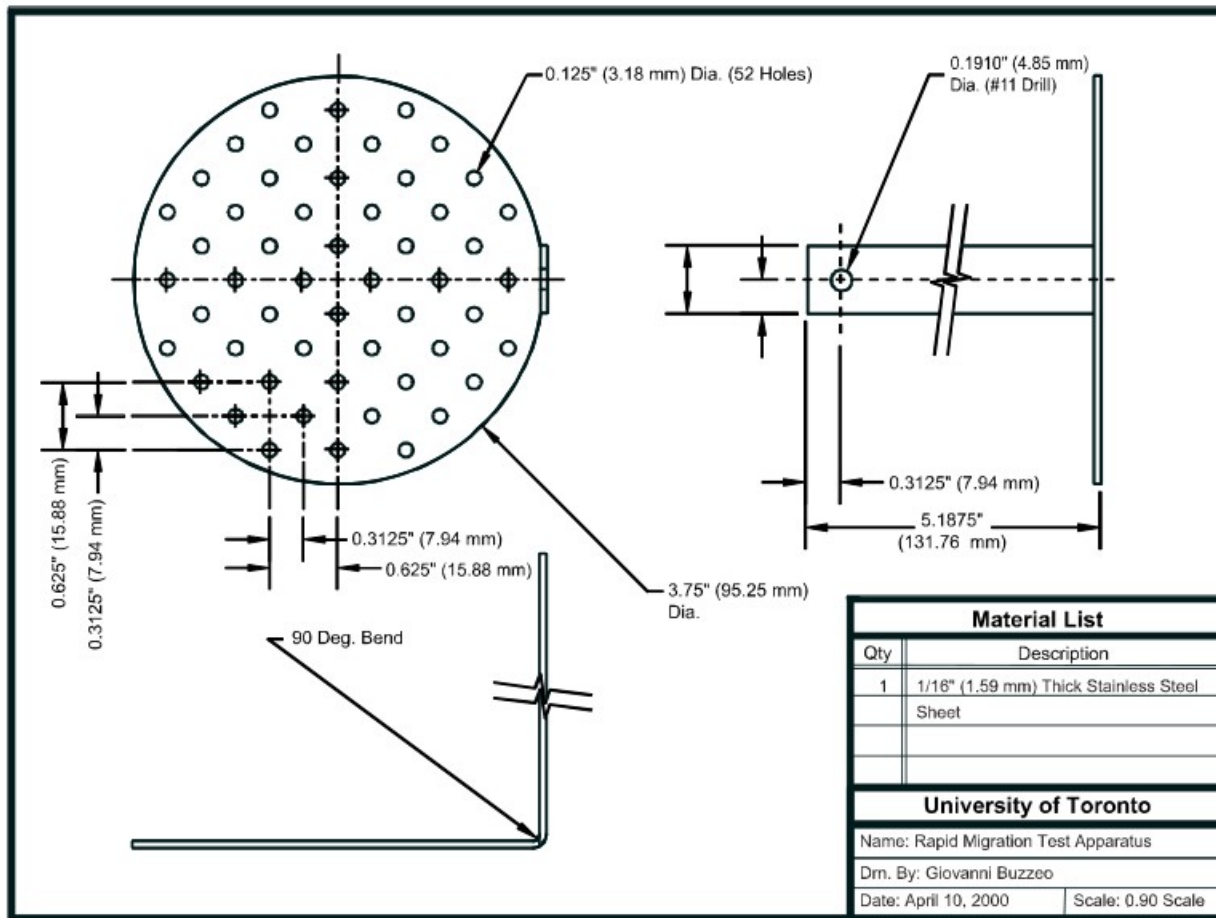


Figure A1.5—Anode

## APPENDIX

(Nonmandatory Information)

### X1. INTERPRETATION OF RESULTS

- X1.1. Table X1.1 shows recommended ranges of the rate of penetration measured by this test method (mm/V-hr) corresponding to different grades of high-performance concrete (HPC) proposed by Goodspeed et al.<sup>4</sup> The recommended ranges for the rapid migration test are based on laboratory research by Hooton et al.<sup>3</sup> in which the rapid migration test was compared to the T 277 test. The rapid migration test result limits shown below correspond to ranges of charge passed in T 277 used to define HPC grades based on chloride penetration. Those ranges are: Grade 1—2000 to 3000 coulombs, Grade 2—800 to 2000 coulombs, and Grade 3—less than 800 coulombs.

**Table X1.1**—Recommendations for Chloride Penetration Rate Corresponding to FHWA HPC Performance Grades

Rate of penetration (mm/V-h)	FHWA HPC Performance Grade		
	1	2	3
	$0.034 \geq x > 0.024$	$0.024 \geq x > 0.012$	$0.012 \geq x$

<sup>1</sup> Formerly AASHTO Provisional Standard TP 64. First published as a full standard in 2015.

<sup>2</sup> Tang, L. and H. E. Sorensen. *Evaluation of the Rapid Test Methods for Chloride Diffusion Concrete*, *NORDTEST Project No. 1388-98*. SP Report 1998: 42, SP Swedish National Testing and Research Institute. Bords, Sweden, 1998.

<sup>3</sup> Hooton, R. D., M. D. A. Thomas, and K. Stanish. *Prediction of Chloride Penetration in Concrete*, FHWA-RD-00-142. Federal Highway Administration, U.S. Department of Transportation, Washington, DC, 2001.

<sup>4</sup> Goodspeed, C. H., S. Vanikar, and R. A. Cook. "High-Performance Concrete Defined for Highway Structures." *Concrete International*, Vol. 18, No. 2, February 1996, pp. 62–67.