APPENDIX D -- CHLORIDE PROFILE DATA AND ANALYSIS

APPENDIX D -- Chloride Profile Data and Analysis

D.1 ODOT POWDER SAMPLING APPARATUS FOR DETERMINING CHLORIDE ION CONCENTRATION IN CONCRETE

D1.1 Vacuum Collection Apparatus -- This system is designed to collect pulverized concrete powder from the hole produced by a rotary hammer in concrete. The powder is drawn though a 5/8-inch dia hollow bit by vacuum and collected in a #6 size cone coffee filter apparatus. See Figure 3.2.

Rotary hammer (large) -- For example, Bosch 11232EVS, Model 0-611-232-739, 8.8 amp, 950 watt; 450 RPM at 3750 BPM (beats per minute); a drill that produces powder more rapidly may plug the air hole in the drill bit.

Anchor Bore Air Bit -- Part No. AA62518, 5/8-inch dia., 16 1/2 inch usable length, 18 1/2 inch overall length rotary hammer drill bit; a conical secondary cutting head contains a vacuum hole at the tip for drawing powdered concrete out of the hole.
Anchor Bore Air System Adapter -- Part No. AA71368
Vacuum Cleaner Connector -- Part No. AA82543
(All manufactured by Heller Anchor Bore, Fraser MI 48026 (313-294-6066))

Wet/Dry Vacuum -- Shop Vac; use the standard vacuum hose end (1 1/4 inch dia.)

#6 Size Cone Coffee Filter Apparatus -- The powder filter apparatus connects the vacuum source to the Plastic Air Vacuum Head (included on Anchor Bore Air System Adapter, but ordered separately as Part No. AA10256) on the rotary hammer and collects the powder sample in a #6 standard cone-type coffee filter. The length of the 1/2 inch dia. hose should be as short as practical; this facilitates cleaning of the hose between samples and improves the performance of the vacuum system.

The powder filter requires the following items: 12 to 18 inches of 1/2 inch ID reinforced Tygon hose, one nylon 1/2 inch hose to 1/2 inch pipe adapter, one 1/2 inch SS hose clamp, two 1/2 inch O-rings (1/8 inch thick), two 1/2 inch conduit lock nuts, two 1 inch x 1/2 inch conduit reducing washers.

The filter container should have a top lip of 16 to 20 inches in circumference. This is the vacuum seal for the #6 cone-type coffee filter. A snap seal will facilitate removal of the filter containing the sample. Use a 1 to 1.6 quart Rubbermaid Servin' Saver Canister. Make a 13/16 inch hole in the center of the snap top and a 1 5/8 inch hole in the center of the container bottom for hose connectors.

Connection from the filter container to the vacuum hose requires the following items: one 1 1/2 x 1/4 NFS-dwv adapter (plastic drain pipe), one sink overflow washer, one 2 inch x 1 1/4 inch conduit reducing washer. A standard Shop Vac vacuum cleaner hose will fit into the drain pipe adapter. Place the threaded adapter end with the compression nut inside the container and washers outside, and tighten the nut to form a vacuum seal.

Spacers -- Spacers for drilling concrete to incremental depths are **NOT** made using PVC pipe (PVC contains chloride and abraded fragments can contaminate the powder sample). Use instead 3/4-inch dia. polypropylene pipe (it contains no halogens). This type of pipe is made by Simtek PolyPro, SI 34PP150, and is available from Familian Northwest, Industrial Plastics Div., Washougal WA, (360-835-2129). A graduated series of spacers consists of polypropylene pipe sections each shorter in length from the previous spacer by ½ inch. Spacers go over the drill bit during concrete powder sampling. The impact hammer is allowed to drill into the concrete until the spacer snugly fits between the hammer and the concrete. At this point the ½ inch deep sample has been taken. The next sample will use the next shorter spacer.

Dust removal snoot -- This is a 24 inch long piece of 1/4-inch dia SS tube attached by duct tape (and possibly a tubing fitting to give a better fit to the vacuum line) to a Shop Vac vacuum cleaner. It is used to suck out any debris remaining in the drill hole between samples to prevent cross-contamination of samples.

D.1.2 Sampling and Analytical Procedures

Sample collection -- The powder filter apparatus/rotary hammer/hollow drill apparatus is used in conjunction with spacers to incrementally removed pulverized concrete samples from the concrete. Take samples at 1/2 inch deep increments using the graduated series of spacers the positions the drill bit from 0 to 15 inches into concrete structures. Typically, pulverized concrete powder samples are collected from 3 side-by-side holes to increase the volume of the sample for chemical analysis. The powder samples are collected on the #6 size coffee filters. Using a powder funnel, the samples in the coffee filters are emptied into clear vials with thumb tab caps (for example, U.S. Plastics Part No. 81006, 1.24 inch dia x 2 7/8 inch long) for submission to the chemistry laboratory for analysis.

The last sample or two at the bottom of a hole, as the hole breaks through the backside of the beam, can result in incomplete sample collection. Typically, as the concrete breaks away, only a small sample is collected . Because of this, a series of samples is taken from the opposite (back) side of the beam, overlapping the original hole by 1 1/2 inches (3 to 6 samples). In this way, the frontside and backside sample results can be pieced together into a seamless chloride profile with good sampling practice for all samples collected. All samples designated as backside samples are drilled in a direction counter to that of the frontside samples.

Elimination of sample cross-contamination -- Cross contamination between successive samples is eliminated by cleaning the vacuum line, the hollow drill, the powder filter apparatus, and the drill hole between samples to remove any powder remaining form the prior sample. This is done by tapping the drill to shake dust out of the hollow tube, tapping the vacuum line to the powder filter apparatus and the powder filter apparatus (while open after removing the prior sample) to shake out dust or powder. The dust removal snoot is inserted into each drilled hole between sampling and the hole is vacuumed out to remove any remaining powder before the next sample is collected (drilled).

Sample analysis -- The powder sample is analyzed for water soluble (Cl_w) and acid soluble (total Cl_t) chloride and for calcium (Ca). The techniques for Cl and Ca analysis are given in AASHTO T 260-94, "Sampling and Testing for Chloride Ion in Concrete and Concrete Raw Materials," (*AASHTO, 1995b*). Calcium concentrations are also determined for each powder sample and used to correct the Cl values for the amount of aggregate contained in the powder sample. The chloride ion detection limits were 0.12 kg/m^3 (0.2 lb/yd^3) for total chloride content and 0.06 kg/m^3 (0.1 lb/yd^3) for the water-soluble chloride content.

Correction of Cl values for the aggregate in powder samples – Concrete powder samples contain varying amounts of pulverized aggregate that dilute the cement paste in the sample. Chlorides in the concrete are contained only in the cement paste. Therefore, in converting the amount of chloride in a specific powder sample to its concentration in a cubic meter (or yard) of concrete, it is necessary to adjust the chloride value for the dilution resulting from the powdered aggregate. Normally this is done using the value of soluble calcium in the concrete and present only in the cement paste as a reference. [Type 1 Portland contains approximately 22 weight pct soluble Si and 46.5 weight pct soluble Ca.] An alternative procedure when the concrete contains limestone aggregate is to use the soluble silica (expressed as Si) also present only in the cement paste.

The adjustment of the chloride values using soluble Ca is made in the following way. The soluble Ca values for all of the powder samples taken from the original concrete are averaged. This gives a fairly good estimate of the weight fraction of soluble Ca in the concrete. All of the chloride values are then adjusted to a concrete containing this weight fraction of soluble Ca. This is done by multiplying the measured chloride concentration in a specific sample by the ratio of the average soluble Ca weight fraction to the weight fraction of soluble Ca in the specific sample, i.e., (avg soluble Ca/soluble Ca in the specific sample). This then is the adjusted weight fraction of chloride in the concrete. Multiply this number by the density of concrete (2380 kg/m^3 or 4005 lb/yd^3) to get the concentration of chloride (in kg/m^3 or lb/yd^3) in the concrete.

D.2 CHLORIDE PROFILE DATA – "As-received" Beam.

Patch Concrete, concentration in weight pct in powder sample

Sample	Location	54A(west to east)			56A(west to east)			Average values(west to east)		
range, in.	inches	Ca	Cl(total)	Cl(sol)	Ca	Cl(total)	Cl(sol)	Ca	Cl(total)	Cl(sol)
0.0-0.5	0.25	5.18	0.216	0.220	5.08	0.264	0.262	5.13	0.24	0.24
0.5-1.0	0.75	5.22	0.281	0.285	5.37	0.444	0.414	5.30	0.36	0.35
1.0-1.5	1.25	7.68	0.504	0.504	4.95	0.341	0.357	6.32	0.42	0.43
1.5-2.0	1.75	8.20	0.479	0.468	6.30	0.382	0.393	7.25	0.43	0.43
2.0-2.5	2.25	11.30	0.205	0.205	6.21	0.329	0.327	8.76	0.27	0.27
2.5-3.0	2.75	3.19	0.192	0.183	7.06	0.262	0.260	5.13	0.23	0.22
3.0-3.5	3.25	4.91	0.138	0.139	7.61	0.212	0.212	6.26	0.18	0.18
3.5-4.0	3.75	6.20	0.098	0.107	5.91	0.125	0.116	6.06	0.11	0.11
4.0-4.5	4.25	3.06	0.048	0.051	5.27	0.067	0.067	4.17	0.06	0.06
4.5-5.0	4.75	4.25	0.040	0.033	5.23	0.032	0.035	4.74	0.04	0.03
5.0-5.5	5.25	5.70	0.029	0.035	4.68	0.015	0.013	5.19	0.02	0.02
5.5-6.0	5.75	2.35	0.011	0.011	4.75	0.003	0.011	3.55	0.01	0.01
6.0-6.5	6.25	5.90	0.014	0.019	5.79	0.003	0.006	5.85	0.01	0.01
6.5-7.0	6.75	7.07	0.015	0.016	4.82	0.003	0.005	5.95	0.01	0.01
7.0-7.5	7.25	7.36	0.006	0.005	6.89	0.003	0.005	7.13	0.00	0.01
7.5-8.0	7.75	5.84	0.003	0.005	3.78	0.016	0.015	4.81	0.01	0.01
8.0-8.5	8.25	6.55	0.014	0.012	7.18	0.010	0.008	6.87	0.01	0.01
8.5-9.0	8.75	5.89	0.005	0.005	4.87	0.035	0.035	5.38	0.02	0.02
9.0-9.5	9.25	5.80	0.010	0.006	2.97	0.010	0.007	4.39	0.01	0.01
9.5-10.0	9.75	6.35	0.011	0.005	2.89	0.015	0.016	4.62	0.01	0.01
10.0-10.5	10.25	7.21	0.022	0.008	4.30	0.010	0.007	5.76	0.02	0.01
10.5-11.0	10.75	5.43	0.037	0.035	6.01	0.020	0.019	5.72	0.03	0.03
11.0-11.5	11.25	4.75	0.062	0.060	7.89	0.052	0.052	6.32	0.06	0.06
11.5-12.0	11.75	7.65	0.167	0.158	4.89	0.050	0.053	6.27	0.11	0.11
12.0-12.5	12.25	7.75	0.163	0.175	5.32	0.080	0.078	6.54	0.12	0.13
12.5-13.0	12.75	7.00	0.218	0.214	5.43	0.075	0.083	6.22	0.15	0.15
13.0-13.5	13.25	4.66	0.178	0.175	6.25	0.182	0.180	5.46	0.18	0.18
13.5-14.0	13.75	4.51	0.230	0.234	5.70	0.190	0.196	5.11	0.21	0.22
14.0-14.5	14.25	5.58	0.318	0.327	9.82	0.212	0.207	7.70	0.27	0.27
14.5-15.0	14.75	4.22	0.257	0.264	6.39	0.040	0.020	5.31	0.15	0.14
15.0-15.5	15.25	5.25	0.104	0.104						
Average:		5.87	0.131	0.131	5.65	0.116	0.115	5.77	0.124	0.124

Patch Concrete, concentration in pounds per cubic yard of concrete

Sample	Location	54A(west to east)			56A(west to east)			Average values(west to east)		
range, in.	inches	Ca	Cl(total)	Cl(sol)	Ca	Cl(total)	Cl(sol)	Ca	Cl(total)	Cl(sol)
0.0-0.5	0.25	231.2	9.6	9.8	231.2	12.0	11.9	231.2	10.8	10.9
0.5-1.0	0.75	231.2	12.4	12.6	231.2	19.1	17.8	231.2	15.8	15.2
1.0-1.5	1.25	231.2	15.2	15.2	231.2	15.9	16.7	231.2	15.5	15.9
1.5-2.0	1.75	231.2	13.5	13.2	231.2	14.0	14.4	231.2	13.8	13.8
2.0-2.5	2.25	231.2	4.2	4.2	231.2	12.2	12.2	231.2	12.2	12.2
2.5-3.0	2.75	231.2	13.9	13.3	231.2	8.6	8.5	231.2	11.2	10.9
3.0-3.5	3.25	231.2	6.5	6.5	231.2	6.4	6.4	231.2	6.5	6.5
3.5-4.0	3.75	231.2	3.7	4.0	231.2	4.9	4.5	231.2	4.3	4.3
4.0-4.5	4.25	231.2	3.6	3.9	231.2	2.9	2.9	231.2	3.3	3.4
4.5-5.0	4.75	231.2	2.2	1.8	231.2	1.4	1.5	231.2	1.8	1.7
5.0-5.5	5.25	231.2	1.2	1.4	231.2	0.7	0.6	231.2	1.0	1.0
5.5-6.0	5.75	231.2	1.1	1.1	231.2	0.1	0.5	231.2	0.6	0.8
6.0-6.5	6.25	231.2	0.5	0.7	231.2	0.1	0.2	231.2	0.3	0.5
6.5-7.0	6.75	231.2	0.5	0.5	231.2	0.1	0.2	231.2	0.3	0.4
7.0-7.5	7.25	231.2	0.2	0.2	231.2	0.1	0.2	231.2	0.1	0.2
7.5-8.0	7.75	231.2	0.1	0.2	231.2	0.1	0.2	231.2	0.1	0.2
8.0-8.5	8.25	231.2	0.5	0.4	231.2	1.0	0.9	231.2	0.7	0.7
8.5-9.0	8.75	231.2	0.2	0.2	231.2	0.3	0.3	231.2	0.3	0.2
9.0-9.5	9.25	231.2	0.4	0.2	231.2	1.7	1.7	231.2	1.0	1.0
9.5-10.0	9.75	231.2	0.4	0.2	231.2	0.8	0.5	231.2	0.6	0.4
10.0-10.5	10.25	231.2	0.7	0.3	231.2	1.2	1.3	231.2	1.0	0.8
10.5-11.0	10.75	231.2	1.6	1.5	231.2	0.5	0.4	231.2	1.1	0.9
11.0-11.5	11.25	231.2	3.0	2.9	231.2	0.8	0.7	231.2	1.9	1.8
11.5-12.0	11.75	231.2	5.0	4.8	231.2	1.5	1.5	231.2	3.3	3.1
12.0-12.5	12.25	231.2	4.9	5.2	231.2	2.4	2.5	231.2	3.6	3.9
12.5-13.0	12.75	231.2	7.2	7.1	231.2	3.5	3.4	231.2	5.3	5.2
13.0-13.5	13.25	231.2	8.8	8.7	231.2	3.2	3.5	231.2	6.0	6.1
13.5-14.0	13.75	231.2	11.8	12.0	231.2	6.7	6.7	231.2	9.3	9.3
14.0-14.5	14.25	231.2	13.2	13.5	231.2	7.7	8.0	231.2	10.4	10.7
14.5-15.0	14.75	231.2	14.1	14.5	231.2	5.0	4.9	231.2	9.5	9.7
15.0-15.5	15.25	231.2	4.6	4.6	231.2	1.4	0.7	231.2	3.0	2.7

Original Concrete, concentration in weight pct in powder sample

Sample	Location	54F(west to east)			55F(west to east)			Average value(west to east)		
range in.	inches	Ca	Cl(total)	Cl(sol)	Ca	Cl(total)	Cl(sol)	Ca	Cl(total)	Cl(sol)
0.0-0.5	0.25	11.70	0.259	0.255	12.50	0.356	0.322	12.10	0.31	0.29
0.5-1.0	0.75	12.10	0.233	0.232	5.55	0.136	0.124	8.83	0.18	0.18
1.0-1.5	1.25	9.85	0.165	0.166	9.01	0.146	0.082	9.43	0.16	0.12
1.5-2.0	1.75	11.20	0.138	0.138	8.79	0.099	0.085	10.00	0.12	0.11
2.0-2.5	2.25	11.00	0.091	0.095	7.67	0.056	0.049	9.34	0.07	0.07
2.5-3.0	2.75	7.10	0.002	0.002	6.57	0.023	0.016	6.84	0.01	0.01
3.0-3.5	3.25	7.99	0.002	0.002	7.11	0.016	0.010	7.55	0.01	0.01
3.5-4.0	3.75	7.84	0.020	0.016	9.61	0.017	0.008	8.73	0.02	0.01
4.0-4.5	4.25	6.99	0.007	0.006	8.28	0.013	0.008	7.64	0.01	0.01
4.5-5.0	4.75	4.41	0.005	0.005	7.93	0.012	0.006	6.17	0.01	0.01
5.0-5.5	5.25	6.92	0.015	0.011	8.84	0.013	0.007	7.88	0.01	0.01
5.5-6.0	5.75	9.40	0.015	0.010	8.70	0.013	0.007	9.05	0.01	0.01
6.0-6.5	6.25	8.85	0.017	0.009	8.26	0.012	0.007	8.56	0.01	0.01
6.5-7.0	6.75	6.88	0.017	0.008	5.70	0.012	0.007	6.29	0.01	0.01
7.0-7.5	7.25	5.21	0.014	0.007	7.22	0.015	0.009	6.22	0.01	0.01
7.5-8.0	7.75	5.54	0.011	0.007	5.15	0.012	0.007	5.35	0.01	0.01
8.0-8.5	8.25	3.79	0.010	0.005	8.90	0.013	0.008	6.35	0.01	0.01
8.5-9.0	8.75	5.11	0.014	0.005	4.53	0.009	0.007	4.82	0.01	0.01
9.0-9.5	9.25	6.94	0.014	0.006	5.27	0.008	0.007	6.11	0.01	0.01
9.5-10.0	9.75	7.53	0.015	0.007	8.55	0.013	0.007	8.04	0.01	0.01
10.0-10.5	10.25	5.83	0.011	0.006	5.68	0.011	0.006	5.76	0.01	0.01
10.5-11.0	10.75	2.45	0.010	0.006	8.83	0.013	0.007	5.64	0.01	0.01
11.0-11.5	11.25	1.63	0.010	0.004	8.61	0.024	0.016	5.12	0.02	0.01
11.5-12.0	11.75	2.70	0.022	0.017	9.13	0.050	0.038	5.92	0.04	0.03
12.0-12.5	12.25	6.56	0.070	0.054	4.28	0.042	0.039	5.42	0.06	0.05
12.5-13.0	12.75	7.98	0.123	0.105	7.87	0.167	0.108	7.93	0.15	0.11
13.0-13.5	13.25	8.41	0.154	0.139	4.72	0.175	0.089	6.57	0.16	0.11
13.5-14.0	13.75	3.26	0.054	0.047	6.67	0.218	0.206	4.97	0.14	0.13
14.0-14.5	14.25	5.78	0.259	0.250	10.10	0.395	0.371	7.94	0.33	0.31
14.5-15.0	14.75	12.40	0.532	0.507	11.50	0.453	0.432	11.95	0.49	0.47
Average:		7.11	0.077	0.071	7.72	0.085	0.070	7.41	0.081	0.070

Original Concrete, concentration in pounds per cubic yard of concrete

Sample	Location	54F(west to east)			55F(west to east)			Average value(west to east)		
range, in.	inches	Ca	Cl(total)	Cl(sol)	Ca	Cl(total)	Cl(sol)	Ca	Cl(total)	Cl(sol)
0.0-0.5	0.25	297.0	6.6	6.5	297.0	8.5	7.6	297.0	7.5	7.1
0.5-1.0	0.75	297.0	5.7	5.7	297.0	7.3	6.6	297.0	6.5	6.2
1.0-1.5	1.25	297.0	5.0	5.0	297.0	4.8	2.7	297.0	4.9	3.9
1.5-2.0	1.75	297.0	3.7	3.7	297.0	3.3	2.9	297.0	3.5	3.3
2.0-2.5	2.25	297.0	2.5	2.6	297.0	2.2	1.9	297.0	2.3	2.2
2.5-3.0	2.75	297.0	0.1	0.1	297.0	1.0	0.7	297.0	0.6	0.4
3.0-3.5	3.25	297.0	0.1	0.1	297.0	0.7	0.4	297.0	0.4	0.2
3.5-4.0	3.75	297.0	0.8	0.6	297.0	0.5	0.2	297.0	0.6	0.4
4.0-4.5	4.25	297.0	0.3	0.3	297.0	0.5	0.3	297.0	0.4	0.3
4.5-5.0	4.75	297.0	0.3	0.3	297.0	0.4	0.2	297.0	0.4	0.3
5.0-5.5	5.25	297.0	0.6	0.5	297.0	0.4	0.2	297.0	0.5	0.4
5.5-6.0	5.75	297.0	0.5	0.3	297.0	0.4	0.2	297.0	0.5	0.3
6.0-6.5	6.25	297.0	0.6	0.3	297.0	0.4	0.3	297.0	0.5	0.3
6.5-7.0	6.75	297.0	0.7	0.3	297.0	0.6	0.4	297.0	0.7	0.4
7.0-7.5	7.25	297.0	0.8	0.4	297.0	0.6	0.4	297.0	0.7	0.4
7.5-8.0	7.75	297.0	0.6	0.4	297.0	0.7	0.4	297.0	0.6	0.4
8.0-8.5	8.25	297.0	0.8	0.4	297.0	0.4	0.3	297.0	0.6	0.3
8.5-9.0	8.75	297.0	0.8	0.3	297.0	0.6	0.5	297.0	0.7	0.4
9.0-9.5	9.25	297.0	0.6	0.3	297.0	0.5	0.4	297.0	0.5	0.3
9.5-10.0	9.75	297.0	0.6	0.3	297.0	0.5	0.2	297.0	0.5	0.3
10.0-10.5	10.25	297.0	0.6	0.3	297.0	0.6	0.3	297.0	0.6	0.3
10.5-11.0	10.75	297.0	1.2	0.7	297.0	0.4	0.2	297.0	0.8	0.5
11.0-11.5	11.25	297.0	1.8	0.7	297.0	0.8	0.6	297.0	1.3	0.6
11.5-12.0	11.75	297.0	2.4	1.9	297.0	1.6	1.2	297.0	2.0	1.6
12.0-12.5	12.25	297.0	3.2	2.4	297.0	2.9	2.7	297.0	3.0	2.6
12.5-13.0	12.75	297.0	4.6	3.9	297.0	6.3	4.1	297.0	5.4	4.0
13.0-13.5	13.25	297.0	5.4	4.9	297.0	11.0	5.6	297.0	8.2	5.3
13.5-14.0	13.75	297.0	4.9	4.3	297.0	9.7	9.2	297.0	7.3	6.7
14.0-14.5	14.25	297.0	13.3	12.8	297.0	11.6	10.9	297.0	12.5	11.9
14.5-15.0	14.75	297.0	12.7	12.1	297.0	11.7	11.2	297.0	12.2	11.6

D.3 FITTING CHLORIDE PROFILE DATA TO COMPUTE C_o AND D

The determination of chloride concentration at various depths in reinforced concrete structures has been performed in the field for many years. These data have shown that the near-surface chloride concentration can vary widely due to washing effects of precipitation. However, the chloride concentration at greater depths changes slowly in accordance with Fick's second law of diffusion, Equation 4.1, and the one-dimensional solution for concrete, with either a background chloride ion concentration or initially free of chloride ion, exposed to a constant surface concentration of chloride ion, C_o, at time zero, Equation 4.2. The effective diffusion constant for chloride ion in concrete in this equation is D. Values of these parameters are given in Table 4.7.

Since the chloride concentration below the near-surface region is well behaved, and sufficient data points are often available from field measurements, it is possible to estimate values for C_o and D from the chloride ion profile and the age of the structure. C_o and D are "effective" values since many factors affect the values of these parameters that are not considered in equation D.2. As noted, the actual C_o at any time is affected by precipitation washing of the concrete surface and the leaching of Cl ions from the near-surface region. In addition, during periods of dryness when there is not intervening precipitation washing, Cl ions can concentrate on the concrete surface as the result of prolonged dry deposition of salt. D values are affected by the porosity of the concrete, the size distribution of the aggregate, and reactions with aggregate and other minerals.

However, the values of C_o and D obtained by fitting the Cl ion profiles can be considered representative of the structure and the environment to which the structure has been exposed. C_o can be considered a measure the severity of the environment and conditions at the concrete surface. D can be considered a measure of concrete durability since, in addition to its mechnical properties, the concrete must serve as an effect barrier to chloride diffusion to maintain the integrity of the structure. Furthermore, if detailed Cl profile data are taken before a structure shows visible distress due to chloride-induced corrosion of the rebar and are fitted to equation D.2 to give values of C_o and D, an estimate of the time to distress can be made and preventative measures taken before the structure is at risk to corrosion damage.

To obtain values for C_o and D from **equally-spaced chloride profile data**, a BASIC program was written to estimate the values based on the least-squares criteria for the residuals. The program works as follows:

- Input the duration of the concrete exposure to the chloride environment, in years; usually the structure age.
- Input depth spacing of the equally-spaced chloride samples, in **inches**. The program converts this value to cm. It then computes the location of each sample as the mid-point of the sample interval, i.e., half the sum of the maximum and minimum sample depth. The location of the first sample is computed as half the sample spacing.
- Input sequentially, from the first sample to the last sample taken, the concentration of chloride ion in each sample, in any units desired. The programs provides the opportunity to correct the input chloride ion concentrations. The series of input chloride ion

concentration data can be truncated later to limit the series to those values where the chloride ion concentration is changing significantly or to those values unaffected by near-surface washing effects.

- The initial point in the series of chloride ion concentrations to be fit can be selected. The program assumes the series is to begin with the first point. However, if washing or concentration effects are present in the near-surface region to distort the profile, a sampling point deeper in the concrete can be selected to begin the fitting algorithm by simply specifying the number of the point in the series, e.g., point 3 in a series of 12 values.
- The initial estimate of C_o is assumed by the program to correspond to the chloride ion concentration of the initial point in the series to be fit. However, the program allows this value to be changed to any desired value. The initial C_o could be estimated by inspection of the chloride ion concentration data. However, using the default initial value, the algorithm will converge to the least-squares best estimate fairly efficiently. The usual sumof the squares error (or residual) term measures the agreement between the input value of the measured chloride concentration, C_m, and the fitted value, C_f, i.e.,

$$\varepsilon^2 = \sum(C_m - C_f)^2 \qquad \textbf{(D.3)}$$

- The program will execute the least-squares fitting algorithm, showing the changing values of C_o and D on the screen.
- The program will refine the estimate for D by incrementing for the current value of C_o. It will compare the magnitude of the sum of the square of the residuals for the current step, $\varepsilon^2{}_n$, with that for the previous step, $\varepsilon^2{}_{n-1}$. Delta is the sum of the square of the residuals for the current step compared to the previous step. When delta ceases to converge for the current value of C_o, the value of C_o is incremented and D again found for the minimum in the sum of the square of the residuals. This two step process is continued until the sum of the square of the residuals is a minimum for both C_o and D within a specified error value selected by the program.
- At convergence to a solution, values of C_o and D will be printed on the screen. **The units of C_o are those of the input chloride concentration data, and those for D are in cm^2/s.**
- The option is then given to look at a plot of the fitted chloride profile computed using equation D.2 and the measured profile produced from the input data. The fitted values of C_o and D, along with a few statistics, are printed on the graph.
- The program stops if the operator is finished. Continuation will permit a complete new data set to be entered or the previous set to be reused for refinement of the data set by choice of the initial point in the input series or of the initial C_o.

The flow diagram for the computer program follows in Figure D.1.

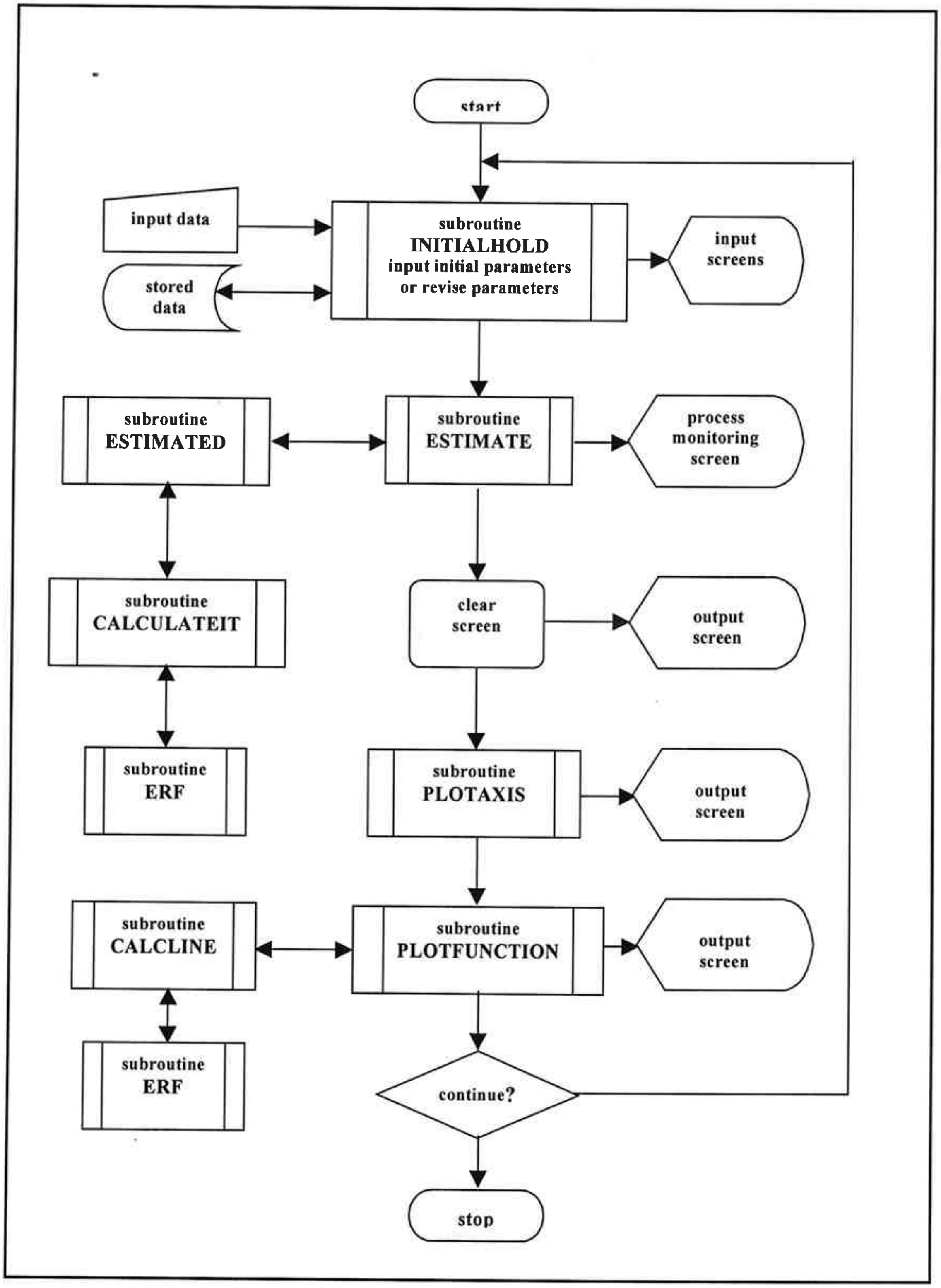

Figure D.1: Flow diagram for BASIC computer program to determine diffusion coefficient, *D*, and surface chloride ion concentration, C_0, from chloride profile in concrete.

D.4 BASIC CODE FOR FITTING CHLORIDE PROFILE DATA AND COMPUTING C_o AND D

The code was written in a basic Microsoft (R) BASIC Professional Development System, Version 7.00,C) Copyright Microsoft Corporation, 1989. The code follows. An executable copy of this program is available from the Oregon Department of Transportation, Research Group, 200 Hawthorne Avenue SE, Salem, OR 97301-5192, telephone 503-986-2700. Refer to the "Evaluation of Rocky Point Viaduct Concrete Beam" final report, Project No. SPR 381.

REM FIND C_o AND D USING LEAST SQUARES FITTING

```
    DIM realc(25), calcc(110), delta(1000)
    CONST pi = 3.14159
    DECLARE SUB Initialhold (title$, t, depth, realc(), n, Co, nx)
    DECLARE SUB Esitmate (t, depth, realc(), n, Co, D, nx, calcc(), SSR, SST)
    DECLARE SUB EstimateD (t, depth, realc(), n, Co, nx, D, calcc())
    DECLARE SUB Calculateit (t, depth, n, Co, D, nx, calcc(), z, erfz)
    DECLARE SUB Erf (z, erfz)
    DECLARE SUB PLOTAXIS (title$, t, Co, D, SSR, SST)
    DECLARE SUB PLOTFUNCTION (t, depth, Co, D, calcc(), realc(), n)
    DECLARE SUB Calcline (t, Co, D, calcc(), z, erfz)
500 CLS
    SCREEN 8, 1
    CALL Initialhold(title$, t, depth, realc(), n, Co, nx)
    CALL Esitmate(t, depth, realc(), n, Co, D, nx, calcc(), SSR, SST)
    CLS
    CALL PLOTAXIS(title$, t, Co, D, SSR, SST)
    CALL PLOTFUNCTION(t, depth, Co, D, calcc(), realc(), n)
    PRINT "again? y/n  "
      y$ = INPUT$(1)
    IF y$ = "y" THEN GOTO 500
    CLOSE #1
END SUB
```

SUB Initialhold (title$, t, depth, realc(), n, Co, nx)

```
    VIEW
    WINDOW
    CLS
    COLOR 15, 1
    REM using cgs units
    IF t = 0 GOTO 91      REM coming from start t = 0,
    CLOSE #1
    LOCATE 3, 15
    PRINT "Reuse current data? y/n"
      data$ = INPUT$(1)
    IF data$ = "n" THEN GOTO 91
```

```
CLS
FOR i = 1 TO n
        ii = i + 2
        LOCATE ii, 15
        PRINT "sample # "; i, "concentration = "; realc(i)
NEXT i
LOCATE ii + 1, 20
PRINT "is everything as you want it? y/n"
  ok1$ = INPUT$(1)
IF ok1$ = "y" THEN GOTO 93
89  PRINT "Which sample # needs changing?"
INPUT sno
PRINT "Enter the new value"
INPUT realc(sno)
PRINT "change another? y/n"
  ok2$ = INPUT$(1)
IF ok2$ = "y" GOTO 89
GOTO 93
91  CLS
LOCATE 1, 15
INPUT "Data Identification?  ", title$
LOCATE 2, 15
INPUT "Enter the age of the structure in years  ", age
  day = 24 * 60 * 60#
  t = day * 365 * age
LOCATE 3, 15
INPUT "Enter the sampling increment in inches  ", depth
  depth = depth * 2.54
LOCATE 4, 15
PRINT "Enter the chloride concentration in descending order"
LOCATE 5, 20
PRINT "Hit enter to end   "
   nx = 1
     i = 1
92  LOCATE 5 + i, 20
INPUT realc(i)
  n = i - 1
IF realc(i) = 0 THEN GOTO 93
  i = i + 1
GOTO 92
93  Co = realc(nx)
CLS
FOR i = 1 TO n
ii = i + 3
    LOCATE ii, 15
```

```
        PRINT "sample # "; i, "concentration = "; realc(i)
    NEXT i
    LOCATE ii + 2, 20
    PRINT "is everything correct? y/n"
      ok1$ = INPUT$(1)
    IF ok1$ = "n" THEN GOTO 91
    CLS
94  LOCATE 4, 20
    PRINT "Co = "; Co
    LOCATE 6, 20
    PRINT "no. of points = "; n, "starting point = "; nx
    LOCATE 10, 15
    PRINT "Do you want to change the starting point?  y/n"
      ok2$ = INPUT$(1)
    IF ok2$ = "n" THEN GOTO 95
    LOCATE 12, 15
    INPUT "enter new starting point"; nx
      Co = realc(nx)
    LOCATE 14, 15
    PRINT "the new starting point is"; nx; ", new Co is"; Co
95  LOCATE 16, 20
    PRINT "Do you want to change Co?  y/n"
      ok3$ = INPUT$(1)
    IF ok3$ = "n" THEN GOTO 96
    LOCATE 19, 15
    INPUT "enter new Co"; Co
96  CLS
    'LOCATE 3, 15
    'PRINT "do you wish to adjust the sensitivity on Co? y/n"
    'LOCATE 4, 22
    'PRINT "the value to be input is in Co units"
    'LOCATE 5, 22
    'PRINT "for example, .05 "
    'LOCATE 7, 22
    'PRINT "Do you want hardcopy of the results? y/n"
      'x$ = INPUT$(1)
    'IF x$ = "n" THEN GOTO 98
    'OPEN "c:\chloride\fitdata.dat" FOR APPEND AS #1
98  END SUB
```

SUB Esitmate (t, depth, realc(), n, Co, D, nx, calcc(), SSR, SST)

```
    DIM testsumdeltac(300)
    FOR i = 1 TO 300
        testsumdeltac(i) = 0
    NEXT i
```

```
     CLS
       j = nx - 1
110    j = j + 1
     CALL EstimateD(t, depth, realc(), n, Co, nx, D, calcc())
       sumdeltac = 0
     FOR i = nx TO n
          absdelta = (calcc(i) - realc(i)) ^ 2
          sumdeltac = sumdeltac + absdelta
     NEXT i
       testsumdeltac(j) = sumdeltac
       Co = Co + .1
     IF j = nx GOTO 110
     LOCATE 14, 33
     PRINT USING "D = ##.##^^^^"; D
     LOCATE 12, 33
     PRINT USING "Co = ##.## "; Co
     LOCATE 16, 33
     PRINT USING "Delta = ###.#### "; testsumdeltac(j)
          IF testsumdeltac(j - 1) < testsumdeltac(j) THEN GOTO 111
     GOTO 110
111    Co = Co - .25
     FOR i = 1 TO 300
          testsumdeltac(i) = 0
     NEXT i
     CLS
       j = nx - 1
112  j = j + 1
     CALL EstimateD(t, depth, realc(), n, Co, nx, D, calcc())
       sumdeltac = 0
     FOR i = nx TO n
          absdelta = (calcc(i) - realc(i)) ^ 2
          sumdeltac = sumdeltac + absdelta
     NEXT i
       testsumdeltac(j) = sumdeltac
       Co = Co + .01
     IF j = nx GOTO 112
     LOCATE 14, 33
     PRINT USING "D = ##.##^^^^"; D
     LOCATE 12, 33
     PRINT USING "Co = ##.## "; Co
     LOCATE 16, 33
     PRINT USING "Delta = ###.#### "; testsumdeltac(j)
          IF testsumdeltac(j - 1) < testsumdeltac(j) THEN GOTO 113
     GOTO 112
113  Co = Co - .01
```

```
    LOCATE 19, 26
    PRINT "hit any key to display the graph"
      x$ = INPUT$(1)
      SSR = 0
      SST = 0
    FOR i = 1 TO n
         delta = (calcc(i) - realc(i)) ^ 2
         SSR = SSR + delta
         totaldelta = realc(i) ^ 2
         SST = SST + totaldelta
    NEXT i
END SUB
```

SUB EstimateD (t, depth, realc(), n, Co, nx, D, calcc())

```
    DIM test1(20), test2(10000)

    FOR i = 1 TO 20
         test1 = 0
    NEXT i
    FOR i = 1 TO 1000
         test2 = 0
    NEXT i
      D = .0001
       j = nx - 1
100   j = j + 1
    CALL Calculateit(t, depth, n, Co, D, nx, calcc(), z, erfz)
      sumdelta = 0
    FOR i = nx TO n
         absdelta = ABS(calcc(i) - realc(i))
         sumdelta = sumdelta + absdelta
    NEXT i
      test1(j) = sumdelta
      D = .1 * D
    IF j = nx GOTO 100
    IF test1(j - 1) < test1(j) THEN GOTO 101
    GOTO 100
101 credit = .1 * D
      k = nx - 1
102  k = k + 1
    CALL Calculateit(t, depth, n, Co, D, nx, calcc(), z, erfz)
      sumdelta = 0
    FOR i = nx TO n
         absdelta = (calcc(i) - realc(i)) ^ 2
         sumdelta = sumdelta + absdelta
    NEXT i
```

```
        test2(k) = sumdelta
      IF k = nx GOTO 102
      IF test2(k - 1) < test2(k) THEN GOTO 103
        D = D + credit
      GOTO 102
103
        D = D - credit
END SUB
```

SUB Calculateit (t, depth, n, Co, D, nx, calcc(), z, erfz)

```
      FOR i = nx TO n
          x = (i - .5) * depth
          dt = D * t
          dt = 2 * ((D * t) ^ .5)
          z = x / dt
          CALL Erf(z, erfz)
          calcc(i) = Co * (1 - erfz)
      NEXT i
END SUB
```

SUB Erf (z, erfz)

```
      REM CALCULATE ERFZ FOR Z
      IF z >= 2 THEN GOSUB 10
      IF z < 2 AND z >= .1 THEN GOSUB 20
      IF z < .1 AND z > 0 THEN GOSUB 30
      IF z <= 0 THEN GOSUB 40
      GOTO 50
10     erfz = 1
      RETURN
20       A1 = .278393
         A2 = .230389
         A3 = .000972
         A4 = .078108
         xxx = 1 + A1 * z + A2 * z ^ 2 + A3 * z ^ 3 + A4 * z ^ 4
         erfz = 1 - (1 / (xxx ^ 4))
      RETURN
30    erfa = 0
      FOR i = 1 TO 10
          n = i - 1
          GOTO 32
31        k = ((2 * i) - 1)
          a = z ^ k
          IF NF <= 0 THEN NF = 1
          delta = ((-1) ^ (i - 1)) * (a / (NF * k))
          erfa = erfa + delta
```

```
        erfz = (2 / (pi ^ .5)) * erfa
        IF ABS(delta) < .00001 THEN RETURN
    NEXT i
    RETURN
32  REM CALCULATES THE FACTORIAL OF N AND RETURNS THE VALUE AS NF
        NF = n
33      n = n - 1
        IF n < 2 THEN GOTO 31
        NF = NF * n
    GOTO 33
40  CLS
    REM IF Z IS LESS THAN OR EQUAL TO ZERO, SET ERFZ = 0"
     erfz = 0
50  REM
END SUB
```

SUB PLOTAXIS (title$, t, Co, D, SSR, SST)

```
        xmin = 0
        xmax = 100
        ymin = 0
        ymax = 100
        ntick = 10
        dx = (xmax - xmin) / ntick
        dy = (ymax - ymin) / ntick
    VIEW (110, 5)-(529, 179), 2, 5
    WINDOW (xmin - dx, ymin - dy)-(xmax + dx, ymax + dy)
    LINE (xmin, ymin)-(xmax, ymin)
    FOR i = 1 TO 10
        LINE (xmin, 10 * i)-(xmax, 10 * i)
    NEXT i
    LINE (xmin, ymin)-(xmin, ymax)
    FOR i = 1 TO 10
        LINE (10 * i, ymin)-(10 * i, ymax)
    NEXT i
    LOCATE 2, 35
    PRINT title$
    WRITE #1,
    WRITE #1, "Title ", title$
    WRITE #1,
    LOCATE 3, 15
    PRINT "40"
    LOCATE 5, 15
    PRINT "wt/"
    LOCATE 6, 15
    PRINT "vol"
```

```
        LOCATE 12, 15
        PRINT "20"
        LOCATE 1, 50
        PRINT USING "  Co  = ##.##     "; Co
        WRITE #1, "  Co  = ", Co
        LOCATE 2, 50
        PRINT USING "  D   = ##.##^^^^ "; D
        WRITE #1, "  D   =  ", D
        LOCATE 3, 50
        PRINT USING "  SSR =###.####    "; SSR
        WRITE #1, "  SSresidual = ", SSR
        LOCATE 4, 50
        PRINT USING "  SST = #####      "; SST
        WRITE #1, "  SStotal = ", SST
          rsquared = ((SST - SSR) / SST) * 100
        LOCATE 5, 50
        PRINT USING "  Rsquared = ###.##% "; rsquared
        WRITE #1, "Rsquared = ", rsquared
          hour = 60 * 60
          day = hour * 24
          year = day * 365
          age = t / year
        LOCATE 6, 50
        PRINT USING "  Structure Age = ## years"; age
        WRITE #1, "Structure Age ", age, "years"
              Lx = .1 * dx
              Ly = .1 * dy
        FOR itick = 0 TO ntick
              concl = xmin + itick * dx
              row = ymin + itick * dy
              LINE (concl, ymin)-(concl, ymin + Lx)
              LINE (xmin, row)-(xmin + Ly, row)
        NEXT itick
              LOCATE 22, 18
              PRINT "0"
              LOCATE 22, 62
              PRINT "20cm"
END SUB
```

SUB PLOTFUNCTION (t, depth, Co, D, calcc(), realc(), n)

```
       FOR i = 1 TO 7
              IF realc(i) < .05 THEN calcc(i) = realc(i)
              test = (calcc(i) - realc(i)) ^ 2
              LOCATE i + 3, 2
              PRINT USING " ###.# "; calcc(i)
```

```
            LOCATE i + 11, 2
            PRINT USING " ##.## "; test
        NEXT i
        WRITE #1, "chloride values"
        WRITE #1, "   depth ", "   real  ", "calculated"
        FOR i = 1 TO n
            x = (i - .5) * depth
            WRITE #1, x, realc(i), calcc(i)
        NEXT i
        CALL Calcline(t, Co, D, calcc(), z, erfz)
        FOR i = 1 TO 100
            LINE (i - 1, 2.5 * calcc(i))-(i, 2.5 * calcc(i + 1)), 5
        NEXT i
          i = 1
200         x = (i - .5) * depth * 5
            y = 2.5 * realc(i)
        CIRCLE (x, y), .5, 0
        IF i = n THEN GOTO 201
          i = i + 1
       GOTO 200
201     END SUB
```

SUB Calcline (t, Co, D, calcc(), z, erfz)

```
       FOR i = 1 TO 100
           x = .2 * i
          dt = 2 * ((D * t) ^ .5)
           z = x / dt
           CALL Erf(z, erfz)
           calcc(i) = Co * (1 - erfz)
       NEXT i
END SUB
```

D5. SPREADSHEET FOR FITTING CHLORIDE PROFILE DATA AND COMPUTING C_o AND D

In addition to the BASIC program in Appendix D.4, C_o and D can be computed using available spreadsheet software and the equation solver that is included in the software. Both approaches are based on the least-square method for minimizing the square of the residuals between measured, C_m, and fitted, C_f, chloride ion concentration profiles.

The values that need to be entered at the beginning of the spreadsheet analysis are underlined in the example in Figure D.2 and are described below.

> **Exposure time** from when the material was placed in service to when the chloride concentration data were collected. The value is entered in years and the spreadsheet computes the time in seconds to use in the diffusion equation.
>
> **Background chloride concentration, C_b,** is determined by inspecting the graphed chloride profile data. That portion of the chloride profile in the center of the beam where diffusion has not yet affected the concrete composition and where the curve becomes flat is the background chloride concentration. A non-zero value indicates the concrete mix contained chloride at the time of construction.
>
> **Effective diffusion coefficient, D,** multiplied by 10^8, is entered as an initial guess. Typical values for cured and aged concrete with various water/cement ratios range from 0.9×10^{-8} to 52×10^{-8} cm²/s. It was found that the spreadsheet used in this analysis (Microsoft Excel) produced erroneous results or error messages when untransformed D values were used. Evidently the equation solver becomes unstable when manipulating very small number. Consequently, D is multiplied by 10^8 (transformed) before entering the value into the spreadsheet. The spreadsheet later calculates the correct D in a separate cell by multiplying the entered value by 10^{-8}. As described below, the calculated D is used in the diffusion equation, Equation 4.2, and the transformed D is used by the optimization algorithm in the equation solver.
>
> **Surface chloride concentration, C_o,** is entered as an initial guess. A reasonable value can be determined by inspection of the chloride.

Measured chloride concentration and position data are entered into the spreadsheet and the chloride profile plotted for inspection. The data shown in the example, Figure D.2, have been truncated to save space. Based on inspection of the chloride profile, the first two measured C values were not incorporated into the analysis because the profile has been affected by precipitation washing in this part of the profile. They do not lie near the projection of the profile in the near-surface region of the beam. Position data in inches are changed to centimeters to accommodate the units used for D in the calculation. The spreadsheet calculates the $C(x,t)$ at each position (column labeled "Fitted C_f") using Equation 4.2 modified to include a background level of chloride, i.e., C_b, and the current values of C_o, D, and t. The error function ERF in Excel is incorporated into Equation 4.2. The residuals and the sum of the squares of the residuals are listed in the last column. The sum of squares is not calculated beyond the location where the chloride profile becomes flat (towards the beam center).

CALCULATION OF EFFECTIVE DIFFUSION COEFFICIENT AND SURFACE CONCENTRATION FROM CHLORIDE ION PROFILE

Location: Patch concrete on west (ocean) side of beam A1

Values:

Exposure time: in years = 25 ; in seconds = 7.88E+08 s

Background chloride ion concentration in concrete (i.e., at time = 0 s), C_b = 0.0 lb/yd^3)

Initial C_o estimate = 22 lb Cl/yd^3

Initial D estimate x 10^8 = 1 cm^2/s

Initial D estimate = 1 E-8 cm^2/s

Data, Fitted Values and Residuals:

Position in beam measured from West face, inches	Measured C_m (lb/yd^3)	Fitted C_f (lb/yd^3)	Residual C_m - C_f
0.25	10.8	not used in fit	
0.75	15.8	not used in fit	
1.25	15.5	16.85	-1.35
1.75	13.8	13.83	-0.03
2.25	12.2	11.10	1.10
2.75	11.2	8.71	2.49
3.25	6.5	6.68	-0.18
3.75	4.3	5.00	-0.70
4.25	3.3	3.65	-0.35
4.75	1.8	2.60	-0.80
5.25	1	1.81	-0.81
5.75	0.6	1.22	-0.62
6.25	0.3	0.81	-0.51
6.75	0.3	0.52	-0.22
7.25	0.1	0.32	-0.22

Sum of squared residuals = 11.80

Calculated Fick's Law Parameters:

Effective chloride diffusion coefficient, D = 3.47 E-8 cm^2/s
Surface Cl concentration, C_o = 25.23 lb/yd^3

Figure D-2. Sample spreadsheet for calculating C_o and D.

The spreadsheet uses an iterative routine that minimizes the value in the sum of squared residuals cell by varying the values in the transformed D (D multiplied by 10^8) and C_o cells. The routine is called solver in Excel. Each iteration produces a new transformed D and/or C_o value, which is subsequently used by the spreadsheet to calculate a new D, new C_f values (column "Fitted C_f"), new residuals, and a new sum of squares. These new values replace the previous values for each iteration. The routine stops when the sum of squares converges to a minimum value resulting in final values for D and C_o, shown in Figure D.2 as "Calculated Fick's Law Parameters".

The BASIC program requires equally spaced data points and assigns the first chloride concentration in the profile to the mid-point of the first interval. All succeeding chloride data are assigned to the mid-points of succeeding intervals equally spaced from first mid-point. Unless the concentration data are first transformed to remove a background level of chloride ion, the program is intended for use where there is no background chloride level. However, small background chloride concentrations will not significantly affect the value of the parameters computed by the program. The program plots measured and calculated profiles. Points at the beginning or end of the data series are readily removed from consideration in the fitting procedure. The program runs in DOS.

The spreadsheet calculations do not require equally spaced data points, although that is the likely format for taking concrete powder samples from drill holes in bridges for measuring the chloride profile. The spreadsheet runs in WINDOWS. Table D.2 shows that there is excellent agreement between C_o values computed by the two procedures. There was less agreement between the D values, with up to a 15 percent difference between the two values. However, these differences are small compared to the variability typically encountered between values measured at different locations on bridges or between values measured for different bridges.

Table D-1. Comparison of C_o and D values calculated using the BASIC program (Appendix D.4) and the spreadsheet (Appendix D.5).

Concrete type and orientation	C_o kg Cl/m³ (lb Cl/ft³)		D cm²/s	
	BASIC program	Spreadsheet	BASIC program	Spreadsheet
Original concrete, west face	5.21 (8.78)	5.25 (8.86)	9.48×10^{-9}	8.21×10^{-9}
Patch concrete, west face	15.00 (25.29)	14.97 (25.23)	3.25×10^{-8}	3.47×10^{-8}
Original concrete, east face	9.58 (16.15)	9.86 (16.61)	1.24×10^{-8}	1.05×10^{-8}
Patch concrete, east face	9.56 (16.12)	9.60 (16.18)	3.14×10^{-8}	3.15×10^{-8}