

TIME TO CORROSION OF REINFORCING STEEL IN CONCRETE SLABS

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The purpose of this investigation is to provide administrators and designers with factual data on which to base decisions as to the type of protection to provide for bridge decks constructed in corrosive environments. The specific study objective is to determine the relative time to corrosion of reinforcing steel embedded in concrete slabs that are fabricated from various mix designs and construction procedures and subject to periodic wetting with a 3 percent sodium chloride solution. Constructed and tested were 124 reinforced concrete slabs 4 by 5 by 0.5 ft. Data obtained from tests of the effect of portland cement concrete mix design, concrete cover over the reinforcing steel, and consolidation of the fresh plastic concrete are discussed in this paper. A brief description of slab fabrication and testing procedures is also presented.

• ONE OF THE most severe problems facing the highway industry is reinforcing steel corrosion induced by chloride de-icer and the subsequent deterioration of concrete bridge decks. The Offices of Research and Development in the Federal Highway Administration consider elimination of bridge deck deterioration one of their highest priority efforts. The problem and approach to the solution of the problem are defined in Task 4B1 of the Federally Coordinated Program of Transportation Research. One work unit within that task is the FHWA staff research study, "Time-to-Corrosion of Reinforcing Steel in Concrete Slabs Versus Various Parameters of Design and Construction." The purpose of that work unit is to provide administrators and designers with factual data on which to base decisions as to the type of protection to provide for bridge decks constructed in corrosive environments. The specific study objective is to determine the relative time to corrosion of reinforcing steel embedded in concrete slabs fabricated from various mix designs and construction procedures and subject to periodic wetting with a 3 percent sodium chloride solution.

Interim findings have been published in 2 interim reports (1, 2). The first report documents the effect of mix designs, construction techniques, and special treatments on chloride migration and reinforcing steel corrosion in 124 reinforced concrete slabs 4 by 5 by 0.5 ft (1.22 by 1.52 by 0.15 m). Although the data obtained indicate the relative resistivity of the various concretes to de-icer penetration, the relative number of salt applications in this test is not considered to be suitable for estimating bridge deck service life or the time to corrosion of reinforcing steel in a concrete bridge deck subjected to a specific de-icer exposure. An evaluation of the corrosion detection device is also presented. The second report presents data on the half-cell potential versus time (with increased de-icer applications) in the form of plots for each of the 124 reinforced concrete slabs.

Data obtained from the portion of the test slabs used to document the effect of portland cement concrete mix design, concrete cover over the reinforcing steel, and consolidation of the fresh plastic concrete are discussed in this paper. A brief description of slab fabrication and testing procedures is also presented.

FABRICATION AND TESTING

The test slabs in the outdoor exposure yard are shown in Figure 1. The 20-ft² (1.86-m²) slabs were molded in watertight molds, and a grid of No. 4 reinforcing bars was positioned at the required depth. The concrete was vibrated to 99 ± 1 percent of the rodded unit weight; a direct transmission nuclear density apparatus was used to control consolidation. The nuclear apparatus was a commercially available moisture-density gauge of the type commonly used to monitor soil compaction. Screeding was accomplished by a reproducible manual finishing process. The appropriate curing procedure was applied immediately after loss of surface sheen and remained on the concrete for 7 days.

After slabs were removed from the molds, the sides were coated with epoxy resin to prevent water loss during testing. A small dike was placed around each slab to permit ponding of the sodium chloride solution. After 7 days of on-ground curing, the slabs were placed and leveled in the outdoor exposure yard. The surfaces were wire-brushed to remove the membrane curing compound before the initial sodium chloride application (at 6 weeks of age).

The top surface of each slab was subjected to ponding to a depth of 1/16 in. (1.6 mm) in a 3 percent sodium chloride solution each afternoon. Three evaluation techniques are used to determine the ability of each variable in preventing chloride migration to the level of the reinforcing steel and its subsequent corrosion.

1. The electrical half-cell potential of the reinforcing steel is monitored by weekly measurement of its potentials at 6 predetermined positions on the surface of each slab. Analysis yielded the following meaning of the potentials (referenced to the copper-copper sulfate half-cell, CSE): (a) potentials consistently greater than 0.35 V CSE—high probability of corrosion; (b) potentials consistently less than 0.20 V CSE—high probability of no corrosion; and (c) potentials in the range of 0.20 to 0.35 V CSE—uncertain area with regard to the condition of the reinforcing steel, i.e., may be active or passive, and use of another detection technique is indicated.

2. The chloride content at the level of the reinforcing steel is determined at select times by dry-coring and analysis according to the procedure described by Berman (3). Work by Lewis and studies in the FHWA laboratories have shown the chloride content corrosion threshold (i.e., the minimum quantity of chloride required to initiate reinforcing steel corrosion in a bridge deck of portland cement concrete when sufficient moisture, oxygen, and other necessary factors are present) to be approximately 0.20 percent of Cl⁻ per gram of cement or 330 parts per million of chloride on a concrete basis, i.e., 1.3 lb of chloride ion per 1 yd³ of concrete (3, 4). All chloride contents presented in this paper are in parts per million, ppm, chloride ion (by weight) in the concrete. For conversion to pounds of Cl⁻ per cubic yard of concrete, multiply Cl⁻ ppm by 0.003915.

3. Visual and delamination surveys are made to locate cracking, rust stains, and hollow planes. To date no cracking or delamination is present although surface rust stains are present on many slabs.

MIX DESIGN PARAMETERS

Water-Cement Ratio—The effect of water-cement ratio on water permeability of concrete is widely documented. Since a similar effect has been suggested with respect to chloride migration, water-cement ratios spanning the feasible range were included. Specifically, water-cement ratios of 0.4, 0.5, and 0.6 by weight (i.e., 4.5, 5.6, and 6.8 gal/bag; 17, 21, and 26 litres/bag) were studied by using mix designs with a constant cement content of 658 lb/yd³ (390 kg/m³).

Cement Content—Cement contents of 564, 658, and 752 lb/yd³ (335, 390, and 446 kg/m³) were included to ascertain the effect of changes in quantity of portland cement. Water-cement ratio was constant at 0.5.

Aggregate Proportions—The ratio of coarse aggregate to fine aggregate may have an effect on the movement of chloride within the concrete. The standard mix design for concrete with a water-cement ratio of 0.5 and cement content of 658 lb/yd³ (390 kg/m³) used a sand-stone ratio of 0.822 by volume (i.e., 55 percent coarse aggregate

and 45 percent fine aggregate). In selected instances, the sand-stone ratio was changed to 0.429 (i.e., 70 percent coarse aggregate and 30 percent fine aggregate) with the other major variables remaining constant, i.e., water-cement ratio = 0.5, and cement content = 658 lb/yd³ (390 kg/m³).

The mix designs are given in Table 1, and the consistency of each mix is illustrated by the slump tests shown in Figure 2.

Cover Over Reinforcing Bars

Numerous bridge deck surveys have linked the incidence of spalling with the depth of concrete cover over the reinforcing steel. Therefore, the depth of the reinforcing mat was included as a variable. Concrete covers used were 1, 2, and 3 in. (25, 51, and 76 mm).

Consolidation

The in-place density was believed to be a prime determinant of concrete permeability. Therefore, the normal placement procedure included vibration to 99 ± 1 percent of the rodded unit weight. However, several slabs were not properly consolidated during fabrication; therefore, we were able to determine the effect of improper consolidation on the chloride permeability of the concrete.

The majority of the 20-ft² (1.85-m²) reinforced concrete slabs have received more than 300 daily salt applications. Approximately 35,000 electrical potential measurements indicative of the reinforcing steel condition in the 124 slabs have been obtained. In addition, 203 concrete samples at the reinforcing steel level have been subjected to chloride content determination. Severe surface rust stains are present on a portion of the slabs, and severe corrosion of the reinforcing steel is apparent in some instances. Although no delamination has yet occurred, the above data have been used to formulate the interim conclusions discussed below.

EFFECT OF CONCRETE MIX DESIGN ON CHLORIDE-INDUCED CORROSION

As documented earlier, a portion of the 20-ft² (1.85-m²) slabs was used to determine the effect of water-cement ratio, cement content, and aggregate proportions on chloride-induced corrosion of the reinforcing steel. Figure 3 shows the effect of concrete mix design on chloride content at the level of the reinforcing steel (1 in., 25.4 mm) after approximately 330 daily salt applications. The data are given in Table 2.

The water-cement ratio of the concrete appears to be the primary determinant of the ability of portland cement concrete to resist chloride intrusion. The maximum chloride content at a 1-in. (25.4-mm) depth within the concrete with a water-cement ratio of 0.40 after 330 salt applications with a 3 percent NaCl solution was 437 ppm chloride on a concrete basis. Conversely, for water-cement ratios of 0.5 and 0.6, the maximum chloride contents were 1,555 and 1,701 ppm chloride respectively.

The resistance of the air-entrained portland cement concrete with water-cement ratios of 0.4, 0.5, and 0.6 to 100 cycles of freezing and thawing was studied by using 14- by 10- by 3-in. (356- by 254- by 76-mm) specimens tested in accordance with ASTM C 672-72T. All 3 concretes were resistant to scaling, exhibiting a maximum rating of 3 on a 0 to 10 visual rating scale (5). That rating signifies light scale over one-half of the surface. No differences in scaling with variation in water-cement ratio were evident for the air-entrained concretes.

Variation in the cement content of the concrete (at a constant water-cement ratio of 0.5) had little effect on chloride migration. As shown in Figure 3, for cement contents of 564, 658, and 752 lb/yd³ (335, 390, and 446 kg/m³), average chloride contents of 904, 912, and 1,147 ppm at a 1-in. (25.4-mm) depth were found after approximately 330 salt applications. Data overlap was large and statistical analysis (assuming normality) showed that, at the 95 percent confidence level, cement contents in the range of 564 to 752 lb/yd³ (335 to 446 kg/m³) did not affect chloride intrusion when the water-cement ratio was constant at 0.5.

Figure 1. Test slabs.



Table 1. Mix designs.

Mix	Water-Cement Ratio	Cement Content (lb/yd ³)	Sand-Stone Ratio	Slump (in.)
1	0.5	564		2.1
2	0.5	658	0.822	3.3
3	0.5	752		6.9
4	0.4	658		1.0
5	0.6	658		8.1
6	0.5	658	0.429	4.4

Note: 1 lb = 0.45 kg; 1 yd³ = 0.76 m³; and 1 in. = 25.4 mm.

Figure 2. Slump tests.

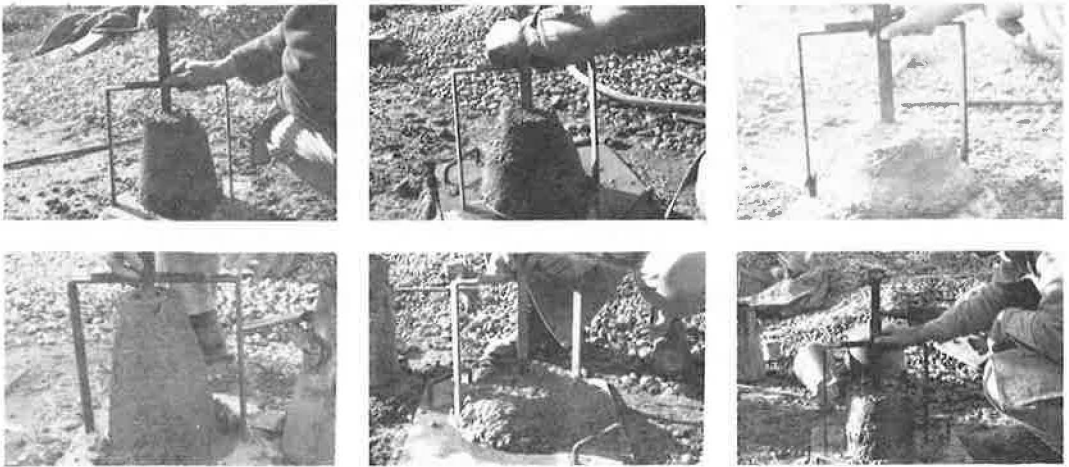


Figure 3. Effect of mix design parameters.

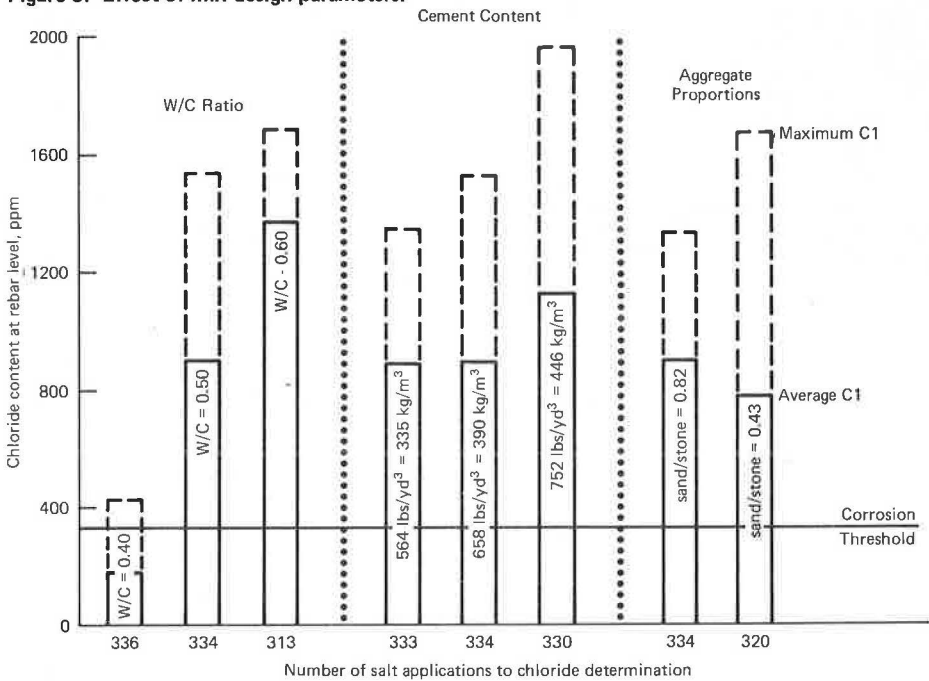


Table 2. Effect of mix design and cover depth on chloride migration.

Description	Number of Slabs	Number of Cores	Cover Depth ^a (in.)	Chloride Content at Level of Reinforcing Steel (ppm of Cl ⁻ on concrete basis)		Number of Salt Applications
				Average	Range	
Water-cement ratio ^b						
0.4	2	10	1.0	179	15 to 437	336
	2	10	2.0	18	13 to 28	337
	2	10	3.0	18	13 to 23	337
	1	3	0.25	2,355	2,289 to 2,450	359
0.5	2	10	1.0	912	386 to 1,555	334
	2	10	2.0	250	23 to 562	348
	2	10	3.0	20	10 to 77	344
	1	3	0.25	3,249	2,437 to 4,332	341
0.6	1	3	1.0	1,407	960 to 1,701	313
	1	3	2.0	1,093	679 to 1,581	354
	2	6	3.0	189	105 to 255	316
	1	3	0.25	3,757	2,965 to 4,666	313
Cement content ^c , lb/yd ³						
563	2	6	1.0	904	235 to 1,369	333
658	2	10	1.0	912	386 to 1,555	334
752	2	6	1.0	1,147	444 to 2,010	330
Sand-stone ratio ^d						
0.822	2	10	1.0	912	386 to 1,555	334
0.429	2	6	1.0	792	309 to 1,693	320

Note: 1 lb = 0.45 kg; 1 yd³ = 0.76 m³; and 1 in. = 25.4 mm.

^aNominal, for example, for a 1.0-in. (25.4 mm) core depth; the actual concrete analyzed was from a 3/4- to 1 1/4-in. (19- to 32-mm) depth.

^bCement content constant.

^cWater-cement ratio = 0.5.

^dWater-cement ratio = 0.5, and cement content = 658 lb/yd³.

Table 3. Time to corrosion of slabs exhibiting potentials consistently greater than 0.35 V CSE.

Slab Number ^a	Special Treatment	Time to Corrosion (week) ^b
72-7		1
126-126		1
127-127		1
116-118	2-in. (50.8-mm) reinforcing steel spacing	2
117-119	2-in. (50.8-mm) reinforcing steel spacing	1
78-19	Burlap cure	2
62-22	Poly-sheet cure for 3 days	2
51-24	Poly-sheet cure for 7 days	3
50-69	Permanent metal forms	2
63-70	Permanent metal forms	2
32-73	No rain (cover over slab)	2
106-74	No rain (cover over slab)	1
34-77	Chromate inhibitor	4
71-78	Chromate inhibitor	2
55-89	Monthly NaOH wash	4

^aConcrete for all slabs listed had a water-cement ratio of 0.5, cement content of 658 lb/yd³ (390 kg/m³), and a cover over the reinforcing steel of 1 in. (25.4 mm).

^bOne week is equivalent to 7 daily applications of a 3 percent sodium chloride solution ponded to a 1/8-in. (1.6-mm) depth.

Similarly, the sand-stone proportions (water-cement ratio = 0.5) had little effect on the chloride contents at the 1-in. (25.4-mm) level within the concrete. Both the average chloride content and the range were virtually identical for concrete with sand-stone ratios of 0.82 and 0.43.

TIME TO CORROSION OF TYPICAL BRIDGE DECK CONCRETE

The portland cement concrete with a water-cement ratio of 0.5, cement content of 658 lb/yd³ (390 kg/m³), and 45 percent sand in the total aggregate is typical of much bridge deck concrete. The concrete exhibited a slump of 3 ± 0.5 in. (76 ± 13 mm) and air content of 5 to 7 percent and was placed and cured by using strict quality control. In-place consolidation was controlled by vibrating to 99 ± 1 percent of the rodded unit weight. Standard field construction procedures were used, and the reinforcing steel was positioned to obtain 1 in. (25.4 mm) of clear concrete cover. Electrical potentials were used to determine the number of daily applications of a 3 percent sodium chloride solution required to induce reinforcing steel corrosion.

The time-to-corrosion tests on this bridge deck concrete yielded the most striking (and disturbing) finding of the study. The summary given in Table 3 shows that the time to corrosion for the typical uncracked bridge deck concrete with 1-in. (25.4-mm) reinforcing steel cover was only 1 week (7 applications of a 3 percent NaCl solution) in many instances. The test procedure corresponds to a daily NaCl application rate of only 0.2 lb (0.09 kg) NaCl per 20 ft² (1.85 m²) of concrete surface. Therefore, the total salt applied prior to initiation of corrosion was 1.4 lb (0.64 kg) over the entire 20-ft² (1.85-m²) slab. The maximum time to corrosion for this concrete (in the instances where electrical potentials permitted determination of a valid time to corrosion) was 4 weeks (28 de-icer applications). The total quantity of NaCl applied in this instance was less than 0.3 lb/ft² (1.5 kg/m²) of concrete surface.

This finding shows that uncracked quality concretes, similar to those used in field construction, provide little protection against reinforcing steel corrosion when the reinforcing steel is placed at a 1-in. (25.4-mm) depth. It substantiates the necessity of modifying present bridge deck concrete mix designs and the need to use alternate means of preventing de-icer intrusion. This finding should also lay to rest the misconception that cracks are necessary for de-icer-borne chlorides to get into the concrete.

EFFECT OF CLEAR CONCRETE COVER OVER THE REINFORCEMENT

The tremendous adverse effect of failure to provide sufficient concrete cover over the reinforcing steel is suggested in the discussion presented above. Figures 4 and 5 show the effect of the reinforcing steel cover on chloride migration within quality uncracked portland cement concrete with water-cement ratios of 0.4, 0.5, and 0.6.

After 330 daily NaCl applications, extremely large chloride contents were encountered near the concrete surface. For example, for concrete with a water-cement ratio of 0.5, the maximum chloride content found at a $\frac{1}{4}$ -in. (6.4-mm) depth was 13 times that required to induce corrosion of the reinforcing steel. With depth, the chloride contents decreased rapidly to negligible values for the concrete with water-cement ratios of 0.4 and 0.5. The importance of water-cement ratio is also demonstrated in this instance. Figure 5 shows that for the uncracked portland cement concrete with a water-cement ratio of 0.4, 2 in. (50.8 mm) of clear concrete cover over the reinforcing steel are required to ensure against chloride-induced corrosion for at least the field equivalency of 330 salt applications in this test. For the typical bridge deck concrete with a water-cement ratio of 0.5, the cover requirement is increased to a minimum of 3 in. (76.2 mm); and for the concrete with a water-cement ratio of 0.6, a clear concrete cover significantly greater than 3 in. (76.2 mm) is probably necessary to prevent chloride intrusion to the reinforcing steel. The importance of concrete cover is further demonstrated by the finding that, for the typical uncracked bridge deck concrete, corrosion of reinforcing steel was initiated after 7 salt applications when the cover was 1 in. (25.4 mm). With 3 in. (76.2 mm) of clear concrete cover, the reinforcing steel in the uncracked concrete does not corrode after 330 de-icer applications.

Figure 4. Average chloride content versus depth.

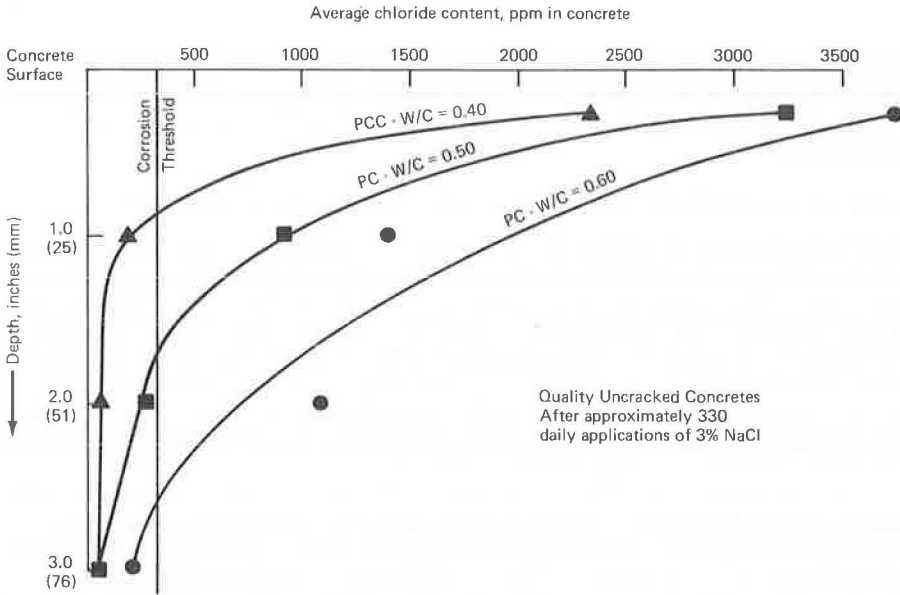


Figure 5. Maximum chloride content versus depth.

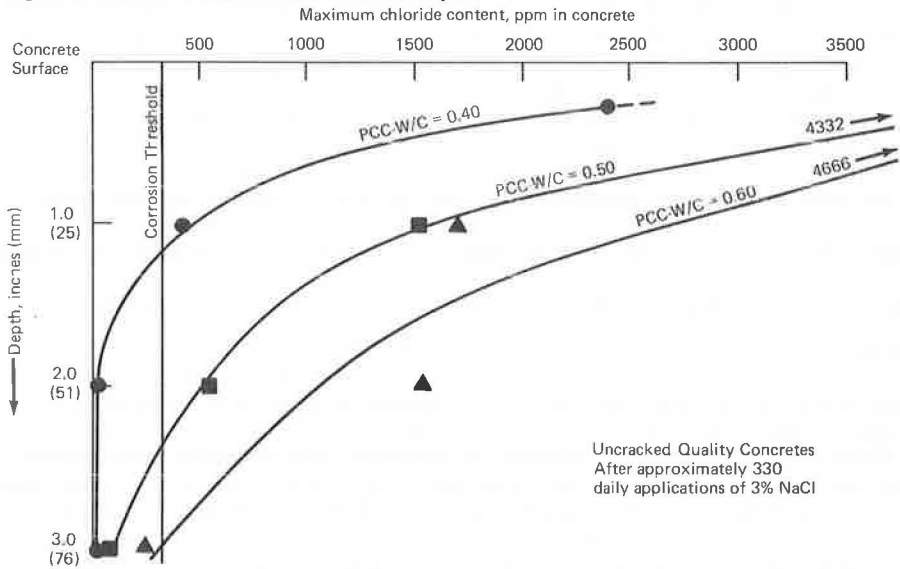
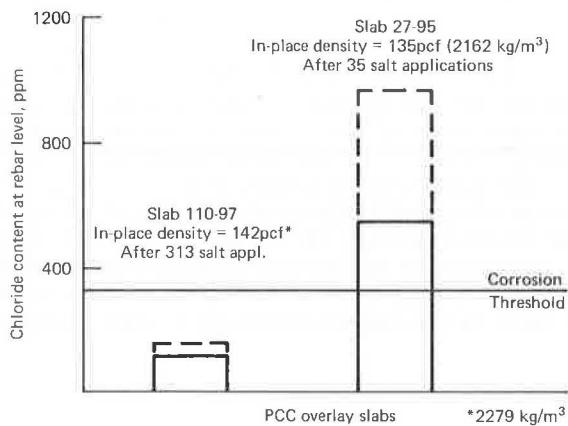


Figure 6. Effect of insufficient consolidation.



EFFECT OF INSUFFICIENT CONSOLIDATION

Failure to achieve at least 98 percent of the rodded unit weight of the concrete during placement resulted in extremely poor resistance to de-icer penetration. The adverse effect of failure to consolidate the concrete is shown in Figure 6. Slab 27-95, which is a portland cement concrete overlay with a water-cement ratio of 0.32, a cement content of 823 lb/yd³ (486 kg/m³), and a 1-in. (25.4-mm) reinforcing steel cover, was not properly consolidated during fabrication even though the slab received extensive internal vibration and appeared to have adequate density. The direct transmission nuclear density apparatus indicated the final in-place density was 135.0 lb/ft³ (2162 kg/m³), i.e., 92.5 percent of the rodded unit weight, whereas the unit weight of the concrete was 146.1 lb/ft³ (2340 kg/m³). Sufficient chloride to induce corrosion had migrated to the level of the reinforcing steel within this concrete after only 28 salt applications as determined by electrical potential measurements. Actual chloride determinations made after 35 salt applications confirmed this finding (965 ppm chloride). Slab 110-97, on the other hand, which was fabricated by using the same concrete mix design, cover, and construction techniques but was properly consolidated, had little chloride at the level of the reinforcing steel after 313 salt applications. The in-place density was 142.3 lb/ft³ (2279 kg/m³), i.e., 97.5 percent of the rodded unit weight. Maximum Cl⁻ was 161 ppm. No reinforcing steel corrosion is occurring in this concrete.

These data indicate that proper consolidation of the concrete is a prerequisite to achieving a chloride-resistant bridge deck concrete. An in-place density of approximately 98 percent of the rodded unit weight of the fresh concrete appears to be a necessity.

CONCLUSIONS

The study findings presented above show that conventional bridge deck concrete, placed with strictest quality control, is not impermeable to chlorides. Redefining "quality" concrete will yield a more chloride-resistant (although not impermeable) portland cement concrete. Other considerations may dictate alternate means of protecting a deck from de-icer penetration and subsequent damage. But if the decision has been made to use a bare concrete bridge deck in an area where significant de-icer exposure occurs, interim findings of this study indicate that

1. The water-cement ratio of the bridge deck concrete should be as close to 0.4 by weight (4.5 gal/bag, 1.5 litre/bag) as is feasible;
2. Some method such as a direct transmission nuclear density apparatus should be used to control consolidation of bridge deck concrete to ensure a minimum in-place density of 98 percent of the rodded unit weight of the concrete; and
3. Minimum clear concrete cover over the reinforcing steel should be 2 in. (50.8 mm) for concrete with a water-cement ratio of 0.4 and 3 in. (76.2 mm) for concrete with a water-cement ratio of 0.5.

These cover depths are recommended on the basis of interim findings and should be considered minimum. Data to be obtained after additional de-icer treatments may or may not indicate that greater cover depths over the reinforcing steel are required. Also, these recommendations are based solely on chloride-penetration data and do not consider the design or construction problems that may be inherent in their use.

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