EVALUATION OF SEVERAL TYPES OF CURING AND PROTECTIVE MATERIALS FOR CONCRETE

Part IV — Final Report on Performance

by

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(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

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SUMMARY

Various curing and/or protective coatings were evaluated under three conditions: (1) accelerated laboratory freezing and thawing of specimens in 2 percent sodium chloride solution, (2) exposure in an outdoor area of slabs subjected to controlled application of deicers, and (3) exposure of some of the materials on three bridges. The performance of the outdoor slabs and bridge decks has been observed over the interim since the last report (Newlon 1973).

Based upon observations after exposure of the outdoor slabs and the field test sections for five winters, the conclusions from the three previous parts of this report were confirmed.

The following conclusions and recommendations are presented.

(1) Properly entrained air is overwhelmingly the most effective defense against scaling caused by deicing chemicals. The fact is evident from the excellent performance of the outdoor exposure slabs after intensive deicing for five years and the absence of scaling on the bridge decks, which also were built with concrete that was uniformly and adequately air entrained.

(2) When insufficient entrained air is obtained, linseed oil treatments delay the onset of scaling but do not prevent it.

(3) Materials of the type studied that are designed to cure and protect concrete in a single application are not effective since the two functions are mutually exclusive (one requires the retention of water while the other requires keeping it out) and they should be thought of as two separate operations. Some of the materials may meet the requirements and be useful for either or both functions, but not simultaneously.

(4) Linseed oil treatments applied after curing with a white pigmented, resin based compound of the type specified by the Virginia Department of Highways & Transportation are effective without prior removal of the curing compound.

(5) Under intensive and controlled applications of deicing salts, chloride contents at depths 2" (50 mm) below the surface approached the threshold level (about 0.05 percent by weight) for steel corrosion after five years in properly air entrained concrete. In the non-air entrained concrete, the chloride content at the same depth was about double that value. The chloride content was not influenced by curing or protective treatments.

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BACKGROUND

Concern for the premature deterioration of concrete in bridge decks, which became increasingly apparent during the 1960s, prompted the promotion of a variety of products intended to provide improved curing, subsequent protection, or both. These products were formulated from a variety of materials — some new or exotic and some more conventional or with long histories of use. Among the new materials were those containing epoxy resins, chlorinated rubber, or other polymers. Old materials were represented by renewed interest in organic oils, such as linseed oil.

In 1966, as part of its defense against deck deterioration, particularly deicer scaling, the Virginia Department of Highways adopted as a general practice the use of linseed oil treatments for all superstructure concrete and pavement surfaces. Most of such concrete is cured with a membrane curing compound, and with the advent of the general use of linseed oil several questions arose as to the need to remove the curing compound prior to application of various protective treatments. A number of these questions were studied in limited scope laboratory and field evaluations in Virginia. Results from a variety of research studies by other agencies were also published. In some cases, the results from these studies were in conflict with each other while in other cases they were confirmatory. These studies were summarized in Part I of this report (Newlon 1970a).

Faced with the need for information on a large number of proprietary formulations, the Highway Department requested the Research Council to evaluate the major generic classes of materials in field trials. Prior to the field trials preliminary screening and laboratory tests were to be made to select the most promising materials as outlined in the Working Plan (Newlon 1968). The results of the laboratory and outdoor exposure studies conducted preliminary to field trials were given in Part I of this report (Newlon 1970a). Part II (Newlon 1970b) contained information on the installation and initial performance of the field test sections. Part III (Newlon 1973) presented the results from five winters' observation on the slabs exposed out-of-doors and performance information from the bridge decks after three winters' exposure.

The conclusions from Parts I, II, and III are included in the Appendix. The project included evaluation under three conditions: (1) accelerated laboratory freezing and thawing of specimens in 2 percent sodium chloride solutions, (2) exposure in an outdoor area of slabs which were subjected to controlled applications of deicers, and (3) exposure of some of the materials on three bridges constructed as a part of an interstate project. Observations have continued so as to provide information on performance for five winters' exposure of all specimens and decks.

MATERIALS

Curing and/or Protective Materials

The curing and/or protective coatings used in various combinations were (1) white polyethylene sheeting (WPS), (2) pigmented liquid membrane curing compound (LMS), (3) chlorinated rubber sealers (CRS) from four sources, two of which were used at each of two levels of solids content, (4) monomolecular film (MEF) developed to reduce early evaporation (Cordon and Thorpe 1965), and (5) linseed oil "anti-spalling" solution (LOT). The combinations of materials used and the numerical designations employed in presenting the data are given in Table 1. In cases where linseed oil solutions were applied to concretes cured with liquid membrane curing compound, they were applied directly without any effort to remove the compound. This was based upon previous research, discussed in Part I, which showed that the curing membrane was penetrated by the linseed oil solution and that the freezing and thawing resistance was thereby increased.

Materials which would function as curing media were tested in accordance with the Virginia modification of AASHO T 155. The moisture losses are shown in Table 2 along with the values specified at the time by the Virginia Department of Highways and other specifying agencies such as ASTM and AASHO. It should be noted that all materials easily complied with the ASTM and AASHO requirements but two chlorinated rubbers (Codes 9 and 13) did not conform at either age to the more restrictive VDH requirements, and one did not conform to these requirements at 24 hours.

Table 1

Combinations of Curing and Protective Coatings Used

Number	Condition[a]
0	No Cure
1	LMS
2	WPS
3	(LMS) + LOT
4	(WPS) + LOT
5	MEF + (LMS) + LOT
6	(MEF) + (WPS) + (LOT)
7	(MEF) + (LMS)
8	CRS_1 - H (High Solids)
9	CRS_2 - L (Low Solids)
10	CRS_2 - LP (Low Solids-Pigmented)
11	CRS_3 - L (Low Solids)
12	CRS_3 - H (High Solids)
13	CRS_4 - L (Low Solids)

(a) Notations

LMS Liquid Membrane Seal

WPS White Polyethylene Sheeting

LOT Linseed Oil "Anti-Spalling" Solution

MEF Monomolecular Film

CRS_1 Chlorinated Rubber - Source #1

CRS_2 Chlorinated Rubber - Source #2

CRS_3 Chlorinated Rubber - Source #3

CRS_4 Chlorinated Rubber - Source #4

Table 2

Results of Tests of Curing Materials

Material	Code	Moisture Loss, gms/in^2 [a] AASHO T 155 (Va. Modification) Average of 3 Specimens		Solids Content, percent
		24 hours	72 hours	
VDH Specs. — Maximum	-	.075	.150	—
LMS	1	.036[b]	.085[b]	—
WPS	2	.004	.009	—
CRS_1 - H	8	.078[c]	.115[b]	31.2
CRS_2 - L	9	.103	.170	25.0
CRS_2 - LP	10	.078[c]	.125[b]	27.6
CRS_3 - L	11	.090	.136[b]	21.4
CRS_3 - H	12	.063[b]	.096[b]	31.0
CRS_4 - L	13	.137	.235	22.2
AASHO Specs. — Maximum	—	—	.355	—

a. Expressed in terms of VDH requirements of gm/in^2. Conversion to more conventional gm/cm^2 requires division of the above values by 6.45.

b. Conforms.

c. Essentially conforms.

The linseed oil solution was supplied as solvent reduced, boiled linseed oil. The analysis of the boiled linseed oil is given in Table 3. No tests were run on the monomolecular film. It was supplied by the manufacturer, who markets it as a proprietary product.

Table 3

Analysis of Boiled Linseed Oil

Acid Value	4.8
Color (Gardner)	12-
Specific Gravity 77°F.	0.9296
Viscosity (Gardner)	A
Set to Touch	4½ hours
Iodine Value	184
Ash	0.2%

OUTDOOR SCALING SLABS

Concretes

The concretes used in all specimens exposed out-of-doors were fabricated to represent that intended for use in the field and contained a water reducing-set retarding admixture. All of the concrete materials have provided excellent service. The nominal proportions were as shown in Table 4. The important characteristics of the individual batches were given in Part I. For the slabs exposed out-of-doors both air entrained and non-air entrained slabs were used as described later.

Table 4

Nominal Concrete Characteristics

Property	Value
Cement Content, lbs/yd^3 (kg/m^3)	658 (392)
Air Content, percent (where used)	6½ ± 1
Slump, inches (mm)	2½ ± ½ (64 ± 13)
Intended Strength, f'_c, psi (MPa)	4000 (27.6)

Cement — Type II

Fine Aggregate — Natural Siliceous Sand: Specific Gravity 2.60; F. M. 2.83.

Coarse Aggregate — Crushed Granite Gneiss: Specific Gravity 2.83; artificially graded as follows:

-1 + 3/4	20%
-3/4 + 1/2	37%
-1/2 + 3/8	33%
-3/8 + #4	10%

Procedures

Twelve slabs each 2' x 2' x 4" (0.61 m x 0.61 m x 51 mm) were cast in the laboratory for exposure to deicing tests in the outdoor area. The surface of each slab was divided into four quadrants, each of which received a different treatment. One-quarter of each block thus represented a given curing-treatment condition. Six of the slabs were made of air entrained concrete and six were made of non-air entrained concrete. Air entrained concrete was used because it represented the normal condition. The non-air entrained concrete was used to accelerate the anticipated deterioration. The distribution of the various curing and/or treatment conditions is shown schematically in Figure 1. In order to estimate variability from slab to slab the white pigmented membrane seal followed by linseed oil was included on each slab and several randomly selected materials were replicated.

5	3
6	4

Slab 1 N and 1 A

3	12
9	10

Slab 2 N and 2 A

5_R	1
7	3

Slab 3 N and 3 A

13	10_R
0	3

Slab 4 N and 4 A

0_R	3
2	8_R

Slab 5 N and 5 A

11	12_R
3	8

Slab 6 N and 6 A

Figure 1. Distribution of curing-treatment conditions on the outdoor scaling blocks.

During fabrication of the slabs in the laboratory, oscillating electric fans were used at the lowest speed to create a gentle movement of air (less than 5 mph (8 km/h)) over their surfaces. This was intended to simulate actual construction conditions. This air movement was continued for 24 hours. Concrete for each slab was taken from a separate batch. The important characteristics of each batch were given in Part I.

The concrete was placed in wooden forms and screeded with a metal faced screed. This was followed by minimal wood floating. After the surface was finished, polyvinyl chloride waterstops were inserted to form a dike to hold water during deicer exposure. Liquid curing materials were applied by brushing at a rate of 200 sf./gal. (5 m^2/dm^3), and sequences were as recommended by the manufacturer for the sequences given in Table 1. The air entrained and non-air entrained specimens were made on separate days. The curing materials were applied when the sheen disappeared. The slabs, elevated to simulate bridge deck exposures, were placed in an outdoor exposure area adjacent to USWB Station Charlottesville 1-W at an age of one month. The initial freeze occurred when the concrete was 60 days old and had been in the outdoor exposure area for 30 days. Eight specimens are shown in Figure 2. The slabs were not retreated with linseed oil during the five winters during which they were exposed.

Figure 2. Slabs in outdoor exposure area.

The deicing procedure used was as follows:

(1) Cover slab with approximately 300 ml/sf (3225 ml/m^2) of water.

(2) Following freeze, distribute NaCl in an amount to give 2 percent by weight of water in (1).

(3) Allow the salt-water solution to freeze and thaw one time.

(4) Rinse surface and repeat.

Note: NaCl was used rather than $CaCl_2$ or a mixture so as to increase the number of freezes, some of which would be prevented in the $CaCl_2$-water system.

Thus one cycle involved a freeze in water, thawing in the presence of NaCl, a subsequent freeze in salt water and thawing in the presence of NaCl. Freezing and/or thawing were judged by daily visual observation rather than according to temperature and in some cases the ice remained on the surface for several days.

The slabs were periodically observed for changes in surface appearance. Evaluation of the changes in surface appearance was based on the rating system shown in Table 5.

Table 5

Rating System Used for Evaluation

Condition	Surface Appearance
0	No scaling
1	Very slight scaling (1/8" (3 mm) maximum depth — no coarse aggregate visible)
2	Slight to moderate scaling
3	Moderate scaling (some coarse aggregate visible)
4	Moderate to severe scaling
5	Severe scaling (coarse aggregate visible over entire surface)

Results

Scaling

The slabs were placed in the exposure area in the fall of 1968. During the exposure through five winters, the slabs were exposed to 123 cycles as defined earlier, 51 of which lasted longer than 24 hours. Detailed information on the cycles is given in Table 6.

The scaling ratings for the slabs after one, two, and five winters are shown in Figure 3. In Part I, which included data for the slabs after two winters of exposure and the results from accelerated laboratory freezing and thawing tests after 300 cycles, it was concluded that non-air entrained specimens representing conditions 2, 3, 4, 5, and 6 and all air entrained specimens performed significantly better than did those representing the remaining conditions. Specimens for conditions 3, 4, 5, and 6 received linseed oil treatments. These treatments were particularly effective during the early exposure as evidenced by the results after 100 cycles of laboratory testing or one winter of exposure in the outdoor scaling tests. In all testing the several chlorinated rubber compounds performed poorly when compared with various curing methods followed by a treatment with linseed oil.

Table 6

Characteristics of Freezing and Thawing Exposure

Period	Cycles[a]	Cycles Longer Than 24 Hours	Longest Continuous Freeze, Days
Nov. 68	3	3	4
Dec. 68	5	3	6
Jan. 69	5	4	7
Feb. 69	6	6	5
Mar. 69	4	2	2
Total 1st Winter	23	18	—
Nov. 69	4	3	7
Dec. 69	5	4	8
Jan. 70	6	4	6
Feb. 70	6	6	4
Mar. 70	4	2	3
Total 2nd Winter	25	19	—
Nov. 70	3	1	2
Dec. 70	5	1	2
Jan. 71	9	3	3
Feb. 71	5	2	5
Mar. 71	7	0	0
Total 3rd Winter	29	7	—
Nov. 71	2	0	0
Dec. 71	3	1	2
Jan. 72	5	1	3
Feb. 72	7	2	4
Mar. 72	4	0	0
Total 4th Winter	21	4	—
Nov. 72	4	0	0
Dec. 72	5	1	3
Jan. 73	6	1	5
Feb. 73	7	1	5
Mar. 73	3	0	0
Total 5th Winter	25	3	—
TOTAL 5 WINTERS	123	51	—

[a] As defined on page 8.

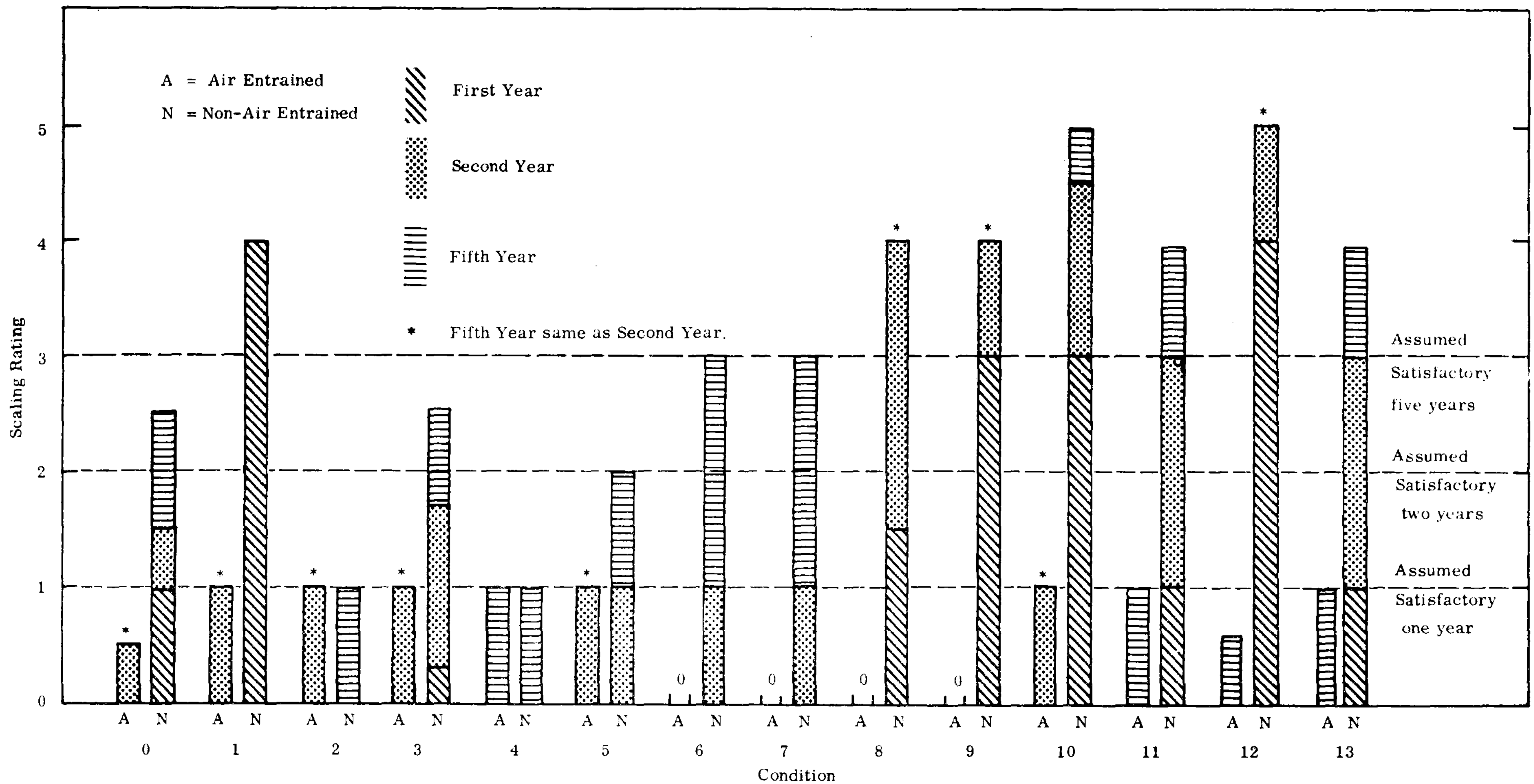

Figure 3. Scaling ratings of slabs in outdoor exposure. Average values are given for multiple occurrences of a test condition.

Despite the differences attributable to the curing and/or protective coatings, the overwhelming factor with regard to scaling was the presence of entrained air. The use of a monomolecular film also appeared to improve resistance to scaling. This is still a valid statement of the results as reflected by additional exposure.

In addition to the quantitative evaluation in Figure 3, a qualitative comparison could easily be made, as seen in Figure 4, which permits a comparison based upon appearance after three and five winters of slabs that received the same treatments. The differences shown are typical of all slabs that were shown in Part III.

As discussed in Part III, the major portion of the scaling appeared on the non-air entrained slabs during the first or second winter. The progression of scaling then slowed. The obvious influence of the surface treatments placed upon different quadrants was particularly evident. But by far the most dramatic comparison is between the performance of the air entrained and non-air entrained slabs (B and C in Figure 4). On slab C and the remaining air entrained slabs, many of the protective treatments were still intact after five winters, which reconfirms the well documented fact that the best defense against deicer scaling is properly proportioned air entrained concrete.

The project anticipated that observations of the field sections would continue for five winters. Since the outdoor slabs had achieved this length of exposure in 1973, testing of them was terminated.

Chloride Analyses*

Following completion of exposure and observations of the slabs stored out-of-doors, samples were taken for chloride analyses using the sampling and testing procedures described by Clear (1974). Initially, samples were taken from both the air entrained and non-air entrained blocks designated as Number 2, the appearance of which was illustrated in Figure 4. As was indicated in Figure 1, the curing treatment combinations represented on Block 2 were Conditions 3 (LMS + LOT), 9 (CRS_2 - L),10 (CRS_2- LP) and 12 (CRS_3-H).

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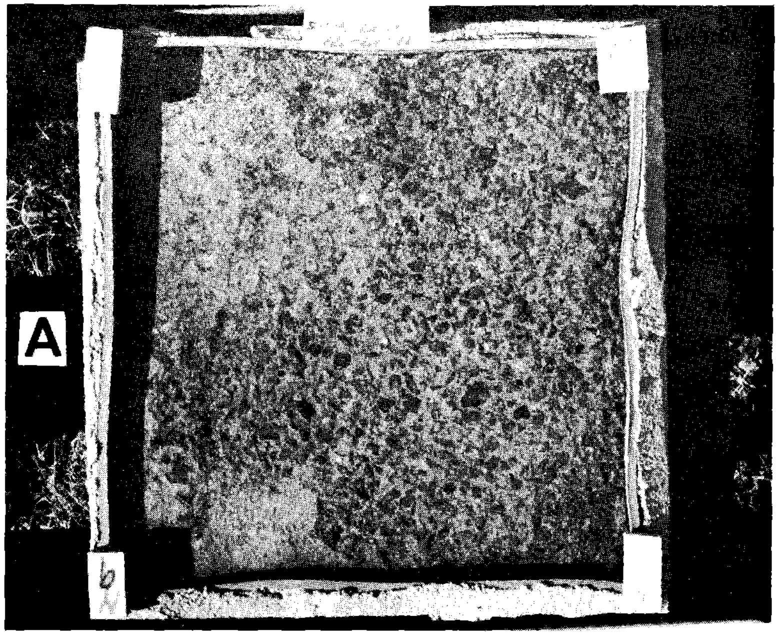
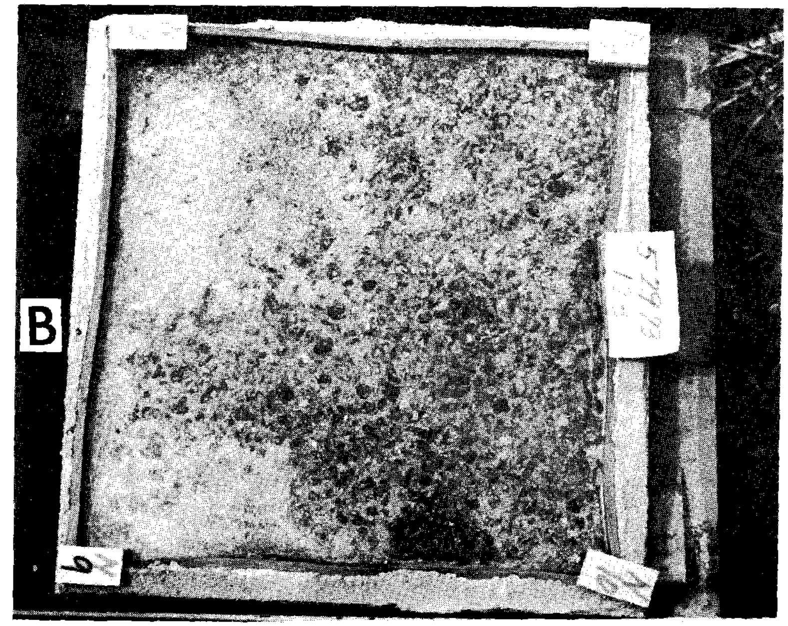
*Chloride analyses were done by the Council's Chemistry Laboratory under the guidance of John Reynolds.





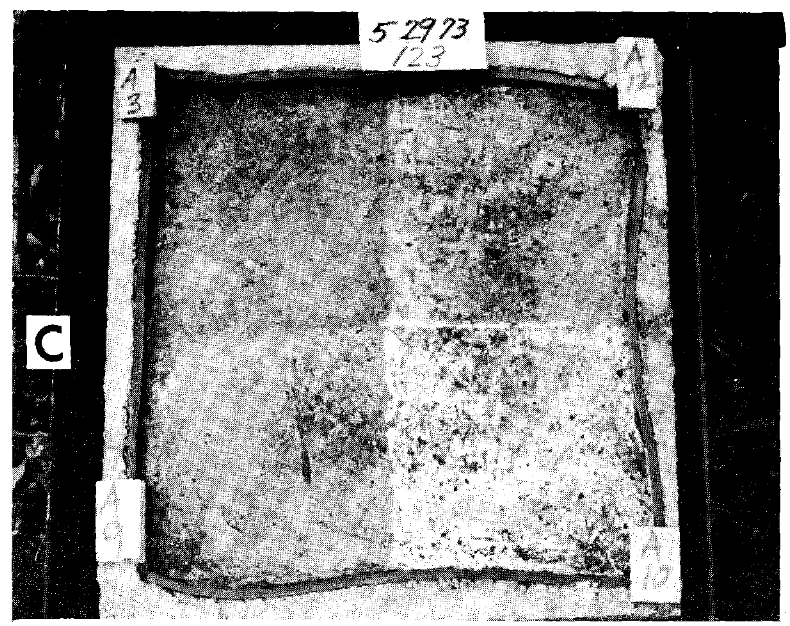


Figure 4. Appearance after deicing of conditions 3 (LMS + LOT), 9 (CRS_2 - L), 10 (CRS_2(LP)), and 12 (CRS_3 - H).

(A) Non-air entrained — 77 cycles (two winters)
(B) Non-air entrained — 123 cycles (five winters)
(C) Air entrained — 123 cycles (five winters)

Using the rotary hammer percussion bits described by Clear (1974), powder samples were removed at the points indicated in Figures 5 and 6 at depths of 1" (25 mm) and 2" (50 mm) below the surface. This procedure provided 12 samples from each depth for each block: 5 from Condition 3, 5 from Condition 10, and 1 from each of the other two conditions. The results expressed as percentages of chloride by weight of powdered concrete sample are also shown in Figures 5 and 6.

Based upon the Research Council's experience with this method and that from other studies (Stratfull et al, 1975), a coefficient of variation for samples taken from concretes representing the same set of conditions of the order of 30 percent to 35 percent was expected. Stratfull and his co-workers (1975) suggest that the main variable is the inconsistent distribution of chlorides through the concrete rather than differences in sampling. For variations of this magnitude, differences of average chloride levels of about 50 percent would be necessary to indicate significant differences.

The data in most cases represent insufficient replications but by judicious grouping of the data according to major generic class, several relationships are probably worthy of elaboration. These are indicated in Table 7. As expected, the chloride content at the 2" (50 mm) depth is significantly less than at 1" (25 mm). It is also evident that the chloride contents at both depths are significantly lower in the air entrained concrete as compared with those in the non-air entrained concrete.

As described earlier, the air entrained slab was free from scaling and surface mortar deterioration whereas this type of deterioration occurred early for the non-air entrained slab. The higher levels of chlorides in the latter case suggest migration of the chlorides through various channels and cracks associated with this type of deterioration, in addition to the ion migration through the apparently sound concrete. The water-cement ratio of the non-air entrained concrete was 0.43 while that of the air entrained concrete was 0.40. The lower water-cement ratio would be expected to retard penetration but not to the extent indicated by the results. As seen in Table 7, the chloride contents were also more variable in the deteriorated than in the sound concretes. In 11 of the 12 sampling locations on the air entrained slab, the chloride level at the 2" (50 mm) depth was substantially (more than 50 percent) lower than that at 1" (25 mm). For the remaining location there was essentially no difference. For the non-air entrained block, the differences at the two depths were less significant but still evident.

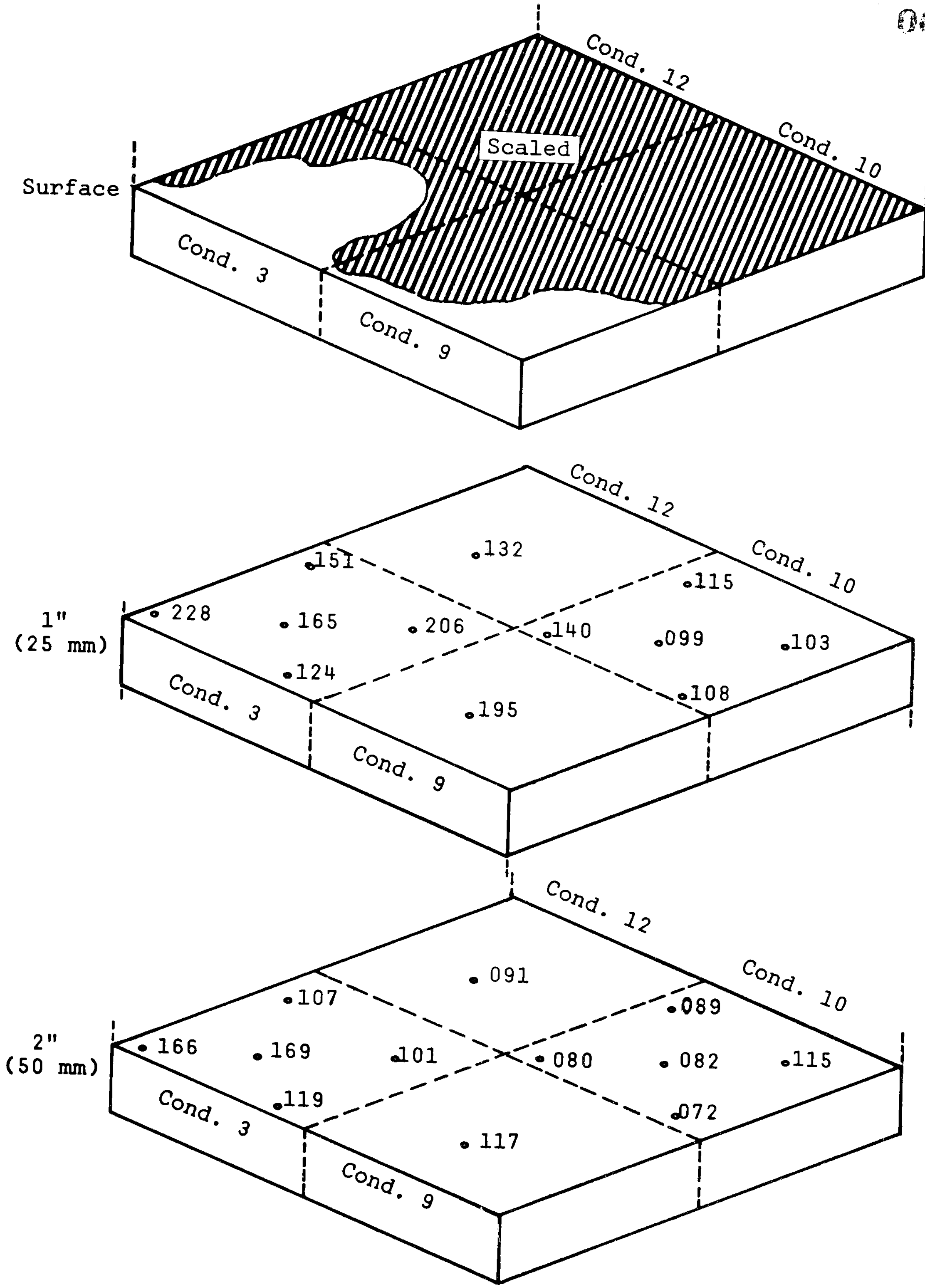


Figure 5. Location of samples and results of chloride analyses for slab 2N (Non-air entrained).

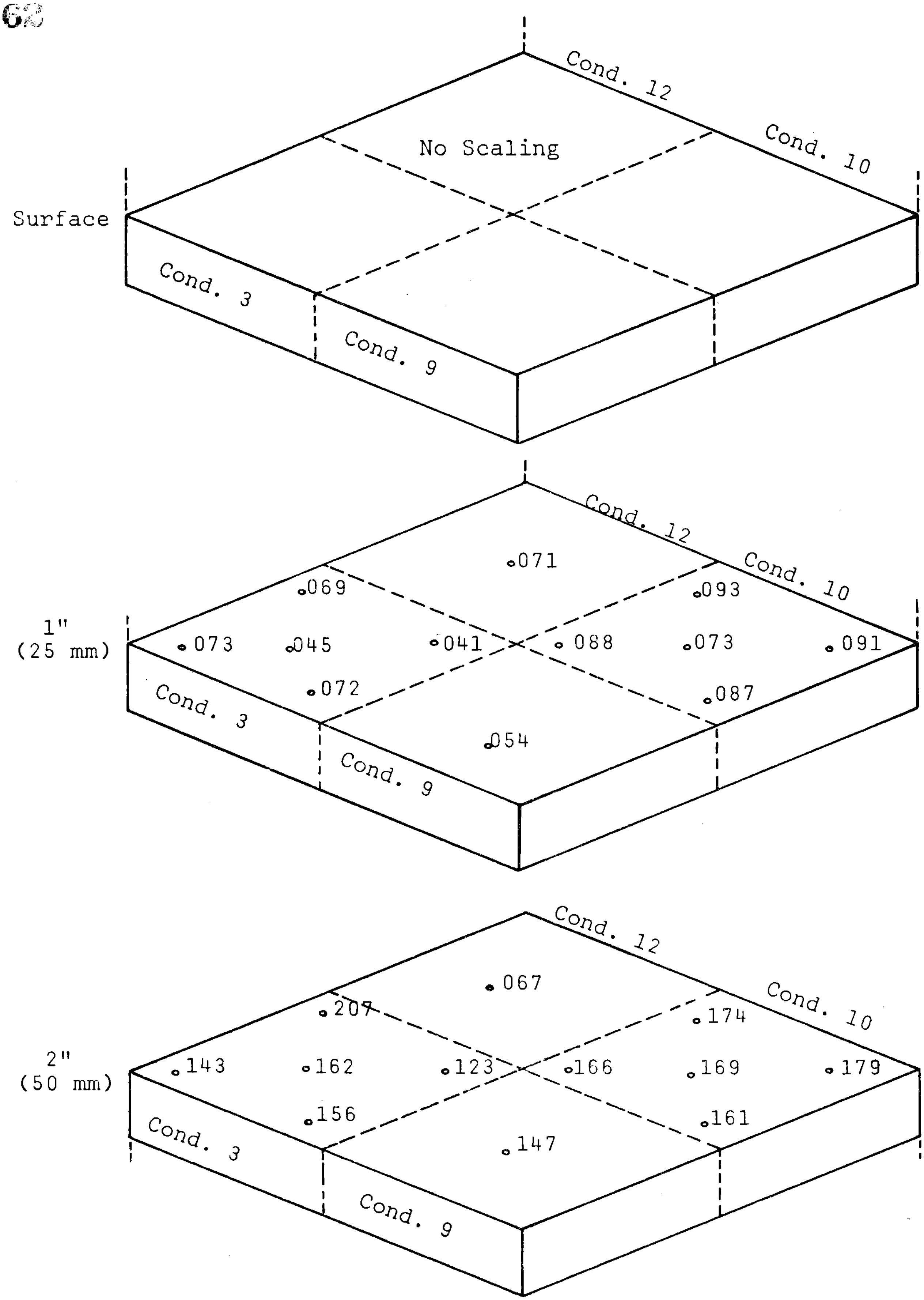


Figure 6. Location of samples and results of chloride analyses for slab 2A (Air entrained).

Table 7

Chloride Contents for Slabs 2N and 2A
(Percentage by weight of powdered concrete sample)

Depth	Both Slabs			Air Entrained			Non-Air Entrained		
	No.	Average $\bar{x}$	Std. Dev., S	No.	Average $\bar{x}$	Std. Dev., S	No.	Average $\bar{x}$	Std. Dev., S
1" (25 mm)	24	0.151	0.038	12	0.154	0.034	12	0.147	.043
2" (50 mm)	24	0.090	0.031	12	0.071	0.017	12	0.109	.031

Chloride contents were determined at the 2" (50 mm) depth for all of the blocks at the locations and with the results shown in Figure 7. As indicated in Figure 7, 52 determinations were made for the non-air entrained and 51 for the air entrained slabs. Because of the variability of the results and the small number of replications, comparisons between the specific treatments are not possible. If, however, all of the results from Condition 3 (LMS + LOT) are compared with the combined results from Conditions 8-12 (CRS), an indication may be gained as to the relative performance of the two generic classes. It must be recognized that the four CRS treatments differ in detail. The results from these measurements are given in Table 8.

Table 8

Chloride Contents at 2" (50 mm) Depth of Blocks
Shown in Figure 7
(Values in percentage by weight of powdered sample)

Condition	Non-Air Entrained			Air Entrained		
	No. of Measurements	Average $\bar{x}$	Std. Dev., S.	No. of Measurements	Average $\bar{x}$	Std. Dev., S.
3 (LMS + LOT)	12	.085	.034	12	.042	.015
8-12 (CRS)	14	.082	.020	12	.045	.023
All Conditions	52	.080	.029	51	.046	.021

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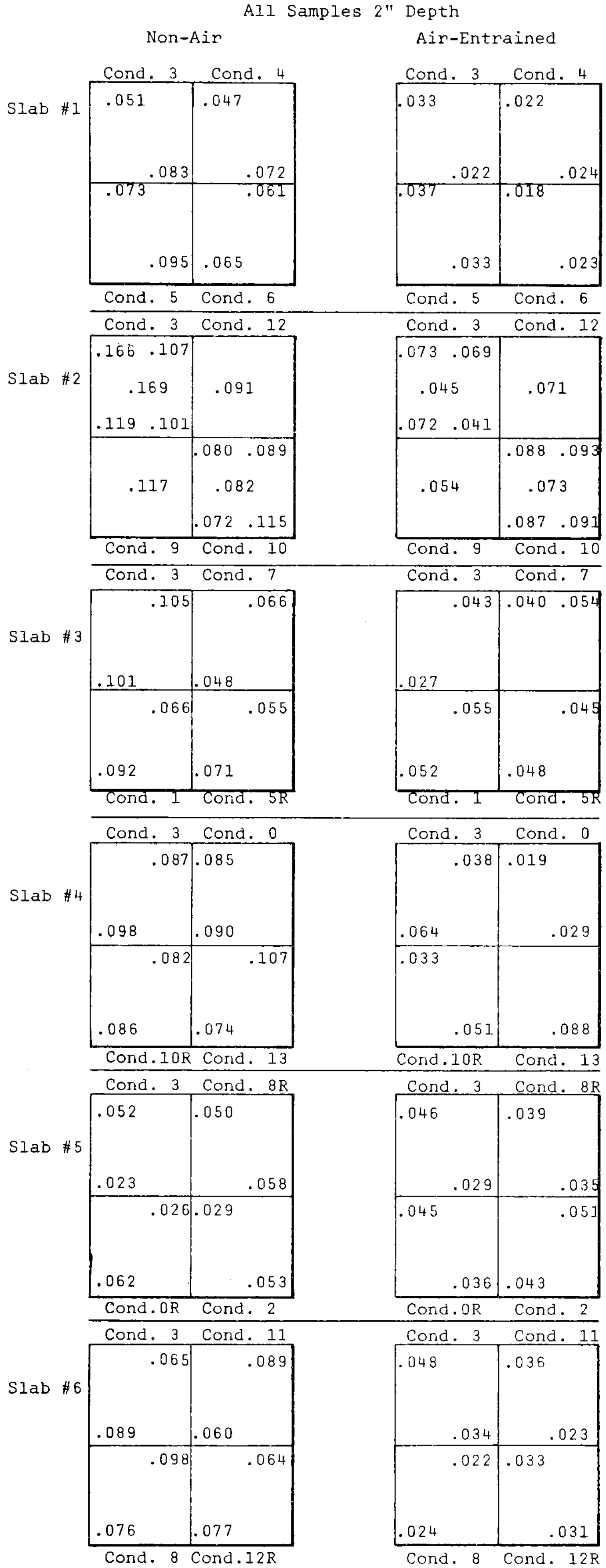


FIGURE 7. LOCATION OF SAMPLES AND RESULTS OF CHLORIDE ANALYSES AT 2" (50 MM) FOR ALL SLABS.

As seen from Table 8, there is no significant difference in chloride contents between the (LMS + LOT) treatment and the several (CRS) materials. The lower amount of chloride in the air entrained concrete for reasons previously discussed is also evident from these data. This reduction held for 44 of the 51 comparative sampling locations.

Within the limitations imposed by the number of replications previously noted, it appears that there is no significant difference in chloride penetration between the (LMS + LOT) and (CRS) treatments. Air entrained concrete, probably because of its increased resistance to surface mortar deterioration due to entrained air and lower water-cement ratios, appears to retard the penetration of chlorides when compared with the non-air entrained concrete.

The concern for penetration of chlorides and consequent corrosion of reinforcing steel has greatly increased since the initiation of this project. It was originally suggested that chloride levels of about 0.05 percent at the depth of the reinforcement were sufficient to initiate corrosion (Clear 1974). More recently a level of 0.025 percent has been suggested (Stratfull et al.1975). These are very small values when compared with the variability of the sampling and testing method. An analysis on stone from the source used in the slabs and decks indicated a chloride content of 0.20 percent by weight of stone, which would translate to approximately 0.1 percent by weight of concrete. Admittedly these types of errors are inherent in the data used to establish threshold levels for corrosion, but the data from the slabs indicate that the threshold level is just being approached in the properly air entrained concrete after five years of intensive salt application. Although the amount and frequencies of deicing applications in the field vary from year to year it is estimated that each year of exposure of the outdoor slabs equals about five years of average field exposure in Virginia. This would translate to about 25 years to reach the threshold level for corrosion in the properly air entrained concrete.

FIELD TRIALS

Installation

This portion of the project was designed to provide a field evaluation under carefully documented conditions for several of the combinations of the materials studied in the laboratory and on the scaling slabs. Nine combinations of materials were included on 29 test panels on three structures on Interstate Route 64 in Albemarle County.

Two structures (B651 and B652), each with three spans, are on the mainline; and one (B648) carries a secondary route over I-64. Applications on the mainline structures were intended to be duplicated on the secondary structure in order to gain an indication of the effect of differences in traffic volumes and frequencies of deicer application as well as differences in the orientation of the structures.

On the basis of the preliminary screening tests the materials and combinations given in Table 9 were selected for application. When the (LOT) was used, it was applied without any surface preparation other than sweeping. The effectiveness of (LOT) applied without prior removal of the (LMS) had been demonstrated in Part I of this study.

Table 9

Curing and Protective Coating Combinations Used in the Field Tests

Condition	Material
1	Liquid Membrane Seal (LMS)
2	White Polyethylene Sheeting (WPS)
3	LMS plus Linseed Oil Treatment (LOT)
4	(WPS) + (LOT)
5	Monomolecular Evaporation Film (MEF) + (LMS) + (LOT)
6	MEF + WPS + LOT
7	MEF + LMS
7-A[a]	MEF + WPS
8	Chlorinated Rubber (CRS)

[a]Not evaluated in preliminary tests.

Originally, it was proposed to include several other materials but some were eliminated from consideration based upon results developed in the preliminary screening phase and several panels were interchanged to provide minimal inconvenience for the contractor. The final layout of test panels is shown in Figure 8. Within a given span, the numerical sequence of the panels coincides with the order of placing.

The decks were placed during the summer of 1969. B648 was opened to traffic in 1969 and B651 and B652 were opened in 1970.

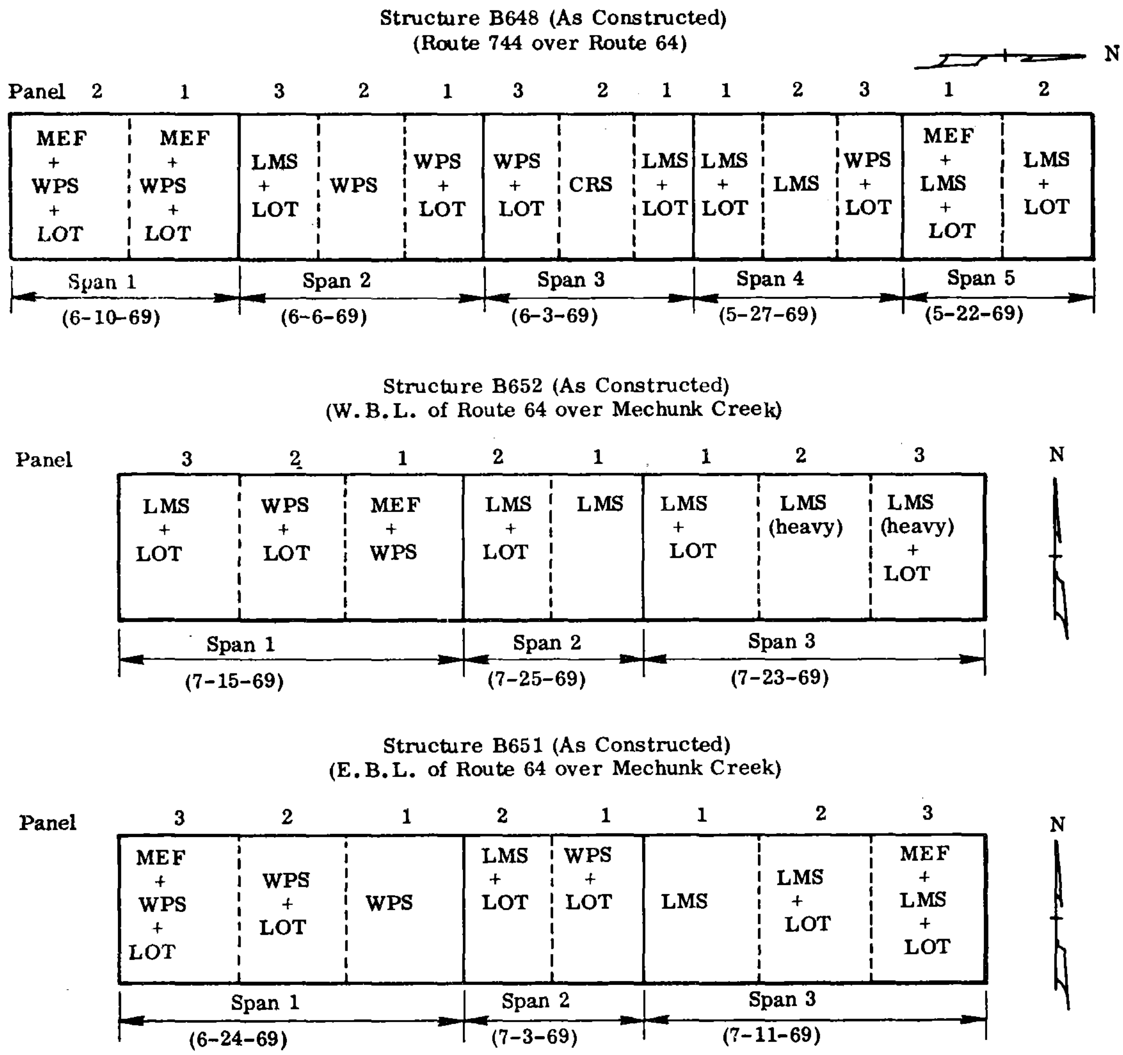
Detailed observations of materials, construction procedures, and atmospheric conditions were described in Part II. As reflected in the conclusions from that report, contained in the Appendix, the most significant findings were:

(1) The uniformly satisfactory air contents indicated a high probability of good performance of the deck surfaces;

(2) the coverage rates of the sprayed curing materials were lower than those specified, even though complete coverage appeared to be achieved, presumably because of the high solids content specified for the materials; and

(3) the performance of the chlorinated rubber was unsatisfactory, apparently because of a combination of factors including characteristics of the material used, those of the concrete on which it was placed, and the atmospheric conditions that existed during the construction.

B648



(WPS) — White Polyethylene Sheeting
(LMS) — Liquid Membrane Seal
(LOT) — Linseed Oil Treatment
(MEF) — Monomolecular Evaporation Film
(CRS) — Chlorinated Rubber Sealant

Figure 8. Test panels for evaluation of concrete curing and protective materials. (0064-002, B648, B651, B652, I 64-2 (55) 93.)

Performance

Condition Surveys

The results from condition surveys made in 1969 and 1970 were presented in Part II. These results were stated as follows:

> Condition surveys were made on all structures in September 1969, and again in September 1970. In the initial surveys, at which time the decks had been exposed to essentially no traffic, the only significant performance characteristic was the very fine surface cracking in the center panel of Span 3 on B648.... After moderate traffic, the cracking was beginning to be obscured by traffic, dust, etc. and was visible only upon close inspection.
>
> At the time of the 1970 survey, B648 had been open to traffic for about one year. B651 and B652 were scheduled to be opened to traffic in three weeks and had been subjected to construction traffic for about one year. On B648 there was some very light scaling in the gutter areas of Panels 2 and 3 of Span 2. These areas appeared to be the result of removal of laitance in the areas hand finished after removal of screed rails. In Span 3 of B648, light scaling is evident over most of Panel 2, which was cured with CRS. This scaling appears to be the result of removal of the CRS and the upper surface of the concrete. Scaling is spotty, but covers about fifty percent of the surface. The southernmost one-third of the panel is less affected than the remaining portion. No defects were observed on the portions of Span 3 cured with WPS and LMS.
>
> The only defects noted on B651 and B652 were transverse cracks over each pier in the negative moment areas. There are five to seven cracks at each pier and their widths vary from very fine to moderate. These cracks apparently formed under construction traffic during paving of the adjacent roadway segments.

Subsequent surveys have been made annually since 1970. The statement from the earlier report quoted above is still a valid description of the performance. There have been very slight increases in the very minor defects noted, but there has been no essential change in condition. This would be expected based upon the excellent control of the concrete during construction, particularly the levels of entrained air. The cracks over the piers noted in 1971 were repaired by sealing with epoxy resin in 1974.

Skid Resistance*

The skid resistance of the various sections determined in accordance with ASTM E274 prior to and after exposure to one year's traffic were presented in Part II. Data from these tests, as well as measurements made in June 1973 and in June 1975 using the same equipment and techniques, are given in Tables 10 and 11.

Based upon the Council's experience with these procedures for measurements made at the same time under the same conditions, differences of skid numbers greater than 2 are believed to be significant. For measurements made at different times, reflecting conditions such as varying temperatures and seasons of the year, substantially larger variations related to the measuring technique are expected.

With the exception of the low skid resistance of the (CRS) panel prior to opening to traffic, no influence of curing or treatment method was indicated. There was a suggestion that the skid resistance of the (WPS) panels were slightly lower than those cured with (LMS), probably due to the fact that the contact of the sheet covering reduced the asperities of the broomed surface more than did the sprayed compound. After one year's traffic, differences of skid numbers, if significant, are influenced by other factors. As noted in the grand means shown for the three structures, the traffic lanes show slightly lower skid resistance than the passing lanes, as would be expected. For the lightly traveled structure, B648, the skid numbers are intermediate between the traffic and passing lanes of the mainline structures. In all cases, the skid numbers after five winters are well above values generally recognized as satisfactory.

The skid numbers for the last two ages are significantly higher than those measured initially. There appears to have been a reduction after one year's traffic as would be expected. There likewise has been no change from the last two years of traffic. The general and large increase of skid number between one and three (or four) years of traffic is unanticipated and unexplained, but is believed to be related to the fact that the Council's skid testing trailer was undergoing substantial rebuilding during the period 1969-71 when the initial measurements were being made. Thus the relative values made at a given time are valid but comparisons with actual stopping distances are valid only for the last two sets of measurements.

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*The skid resistance measurements were conducted by the Council's Maintenance Section under the guidance of David Mahone.

Table 10

Skid Resistance for B648

Predicted Stopping Distance from 40 mph (64 km/h) Determined in Accordance with ASTM E274

Numerical Designation[a]	Condition	No. of Sections	Skid No. Prior to Traffic		Skid No. After 1 Yr. Traffic		Skid No. After 4 Yr. Traffic		Skid No. After 6 Yr. Traffic	
			NBL	SBL	NBL	SBL	NBL	SBL	NBL	SBL
1	(LMS)	1	57	54	45	44	61	60	62	60
2	(WPS)	1	48	50	47	47	59	56	64	57
3	(LMS + LOT)	4	—	—	45	43	62	58	62	60
4	(WPS + LOT)	3	—	—	44	45	61	57	62	60
5	(MEF + LMS + LOT)	1	—	—	46	41	59	57	61	60
6	(MEF + WPS + LOT)	2	—	—	48	46	63	56	64	57
7	(MEF + LMS)	1	54	54	—	—	—	—	—	—
7-A	(MEF + WPS)	2	50	50	—	—	—	—	—	—
8	(CRS)	1	38	38	44	42	61	57	62	60
Grand Mean			51	50	45	44	61	57	62	60

(a) See Table 9.

Table 11

Skid Resistance for B651 and B652

Predicted Stopping Distance From 40 mph (64 km/h) Determined in Accordance with ASTM E274

Numerical Designation[(a)]	Condition	No. of Sections	Skid Number Prior to Traffic (Age 1 Yr.)		Skid Number After 3 Yr. Traffic		Skid Number After 5 Yr. Traffic	
			TL	PL	TL	PL	TL	PL
1	(LMS)	3	42	45	56	61	59	64
2	(WPS)	1	42	46	56	61	59	64
3	(LMS + LOT)	6	43	45	55	61	56	63
4	(WPS + LOT)	3	42	45	55	60	58	64
5	(MEF + LMS + LOT)	1	40	46	56	60	60	64
6	(MEF + WPS + LOT)	1	42	45	54	61	56	65
7-A	(MEF + WPS)	1	43	46	55	60	58	63
	Grand Mean							
	B651		42	46	55	60	58	64
	B652		44	43	55	61	59	64

Corrosion Potentials

Subsequent to the installation of field test sections, considerable interest developed in a method developed by Stratfull and his associates (1958) for measuring the potential for corrosion of reinforcement. This method, which measures the electrical potential of the steel, was extensively demonstrated by the FHWA (1971) and was used in another Council study (Newlon 1974). In July 1973 potential measurements were made on the decks of two of the three structures. The measurements were made on a five-foot grid over the entire surface of B648 and over the traffic lane of B651. These provided 567 points for B648 and 156 for B651. The results are summarized in Table 12, which is repeated from Part III.

The data in Table 12 show no consistent relationship between potential reading and the type of curing or protective treatment. The results on B651 were more variable than those on B648. This finding probably reflects the fact that B651 had received applications of deicers while B648 had not. Based upon currently accepted criteria, there is no significant potential for corrosion at this time as indicated by this method. The lack of any correlation with type of treatment is consistent with the indication from the outdoor slabs that chloride penetration is not related to the treatments. Because no consistent relationships were observed in 1973, no further field measurements of corrosion potentials were made.

Table 12

Potential Readings[a]
(In Volts)

Condition	B 648 (After 4 Winters' Traffic) Average		B 648 Std. Dev.	B 651 (After 3 Winters' Traffic) Average		B 651 Std. Dev.	Both Bridges Average	Both Bridges Std. Dev.
1 (LMS)	4-2	.065	.041	3-1	.076	.077	.068	.054
2 (WPS)	2-2	.065	.030	1-1	.055	.074	.029	.073
3 (LMS + LOT)	2-3	.063	.047	2-2	.009	.054	—	—
	3-1	.112	.036	3-2	.061	.069	.080	.057
	4-1	.103	.047	—	—	—		
	5-2	.060	.057	—	—	—	—	—
4 (WPS + LOT)	2-1	.063	.034	1-2	.048	.056	—	—
	3-3	.097	.040	2-1	.013	.046	.068	.049
	4-3	.067	.050	—	—	—	—	—
5 (MEF + LMS + LOT)	5-1	.098	.033	3-3	.077	.071	.090	.052
6 (MEF + WPS + LOT)	1-2, 1-1	.091	.045	1-3	.087	.054	.090	.047
7 (MEF + LMS)	—	—	—	—	—	—	—	—
8 (CRS)	3-2	.071	.037	—	—	—	.071	.037
Each Bridge	—	.081	.045		.042	.078	.072	.056

[a] The electrical potential based upon the saturated copper-copper sulfate half cell is negative. The negative sign has been omitted in all cases. All values are negative with respect to the half cell.

CONCLUSIONS

This project was initiated in 1968 in response to a concern for improving the resistance of bridge deck concrete to scaling caused by deicing chemicals. This type of deterioration had been shown by various surveys to be the most prevalent of several types. Also at that time combination curing and sealing compounds were being widely promoted. Since the initiation of the project, subsequent studies in Virginia (Newlon 1974) have shown that the incidence of deicer scaling has been greatly reduced. Nationwide, concern has developed for the effects of corrosion of reinforcement accelerated by the same chlorides that are associated with deicer scaling. While studies in Virginia indicate that the incidences of serious corrosion and spalling are relatively low, where they do occur repairs are very costly and time-consuming.

While the original objective of this project was to evaluate the influence of the various curing and protective treatments, the major conclusion is yet another confirmation of the benefits of proper amounts of air entrainment in eliminating scaling caused by deicing chemicals.

The conclusions from the project have been presented in each of the three previous parts and are included in the Appendix of this report. Although these conclusions were based upon short-term laboratory testing and field exposures, the initial findings have been confirmed by continued exposure and observation.

The conclusions, some of which are repeated from earlier parts of the report on the project, are as follows:

(1) Properly entrained air is overwhelmingly the most effective defense against scaling caused by deicing chemicals. The fact is evident from the excellent performance of the outdoor exposure slabs made with air entrained concrete during five years of intensive applications of deicing salts and the absence of scaling on the bridge decks, which also were built with concrete that was uniformly and adequately air entrained.

(2) When insufficient entrained air is obtained, linseed oil treatments delay the onset of scaling but do not prevent it.

(3) Materials of the type studied that are designed to cure and protect concrete in a single application are not effective since the two functions are

mutually exclusive (one requires the retention of water, while the other requires keeping it out), and they should be thought of as two separate operations. Some of the materials may meet the requirements and be useful for either or both functions but not simultaneously.

(4) Linseed oil treatments applied after curing with a white pigmented, resin based compound of the type specified by the Virginia Department of Highways & Transportation are effective without prior removal of the curing compound.

(5) Under intensive and controlled deicing, chloride contents at depths of 2" (50 mm) below the surface approached the threshold level (about 0.05 percent by weight) for steel corrosion after 5 years in properly air entrained concrete. This exposure is estimated to be equivalent to about 25 years of field exposure in Virginia. In the non-air entrained concrete, the chloride content at the same depth was about double that value. The chloride content was not influenced by curing or protective treatments.

RECOMMENDATIONS

Recommendations have been made and implemented throughout the period spanned by this project. These previous recommendations, contained in the Appendix, have been confirmed by subsequent exposure and observations. The major recommendations suggested by this project are:

(1) The currently specified curing procedures for bridge decks followed by linseed oil treatments continue to be the most satisfactory of several alternatives practically available for improved durability.

(2) Continued vigilance to insure proper levels of air entrainment is essential.

(3) The use of monomolecular film should be continued in situations where it is needed. These include (1) days with high evaporation potential, (2) delayed application of curing, and (3) equipment

breakdowns. Its proper use should be carefully monitored to insure that it is not used as a substitute for water that is sometimes undesirably sprinkled on the surface during finishing. Specification of its use for all decks is not desirable.

(4) Unless penetration can be demonstrated materials should not be used as combination curing and protective treatments. Some materials promoted for this combined purpose are effective as either a curing material or protective treatment.

ACKNOWLEDGEMENTS

A field study such as that reported here requires the cooperation of numerous elements of the Department and the construction industry. Appreciation is expressed to the Department's Construction Division for assistance in planning and preparing special provisions for the project, and to the Materials Division for special tests and evaluations. The cooperation of the personnel of the Louisa Residency in coordinating the work with the contractor was invaluable, particularly that of Project Inspector B. D. Conklin.

Special appreciation is expressed to Thomas M. Nunnally, the contractor, who went beyond the requirements of the special provisions to cooperate with the research personnel. Several manufacturers made curing materials available for testing and the project.

The field testing was supervised by Materials Technician Supervisor C. E. Giannini, and the observation of the construction activities and the major portion of the data reduction was made by Highway Engineer Trainees R. A. Parrish and H. E. Harrison, who were assigned to the Council for the summer during which the field work was completed.

During the performance surveys, C. E. Giannini and Material Technicians L. Woodson and B. Marshall, participated in many of the observations and tests. C. E. Smith, Research Engineer, and Celik Ozyildirim, Graduate Assistant (now Research Engineer), assisted in the reduction of corrosion potential data.

As noted in this report, Research Chemist John Reynolds, and the Council's Maintenance Section under the guidance of Senior Research Scientist David Mahone provided chloride analyses and skid resistance data during the follow-up studies.

Appreciation is expressed to all of these people.

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APPENDIX

CONCLUSIONS AND RECOMMENDATIONS

From Part I (Newlon 1970a)

Conclusions

1. Properly entrained air is overwhelmingly the most effective defense against scaling caused by deicing chemicals.

2. When insufficient entrained air is obtained, linseed oil treatments delay the onset of scaling.

3. Linseed oil treatments are effective when applied to concrete previously cured with resin based curing membrane without the necessity for removal of the membrane. Results from these and prior studies indicate penetration of the membrane by the linseed oil treatment, likely through dissolution of the resin film by the mineral spirits.

4. Chlorinated rubber used as a combination curing and protective sealant is not effective on poorly air entrained concrete. It accelerates deterioration over that of such concrete normally cured with or without linseed oil treatment.

5. The monomolecular evaporation retarding film showed some beneficial effects on resistance to scaling of non-air entrained concrete.

6. Based upon compressive strength of cylinders variously cured, the strength of cylinders cured with sprayed on materials is about 75 percent of that from moist curing or various protective coverings, but this strength is not reflected in resistance to scaling.

7. The chlorinated rubber sealer, because of its tenacious film, might accentuate the detrimental effect on skid resistance of a moderate surface texture of the concrete.

Recommendations

1. The number of sections devoted to the chlorinated rubbers in field trials should be reduced below that originally proposed.

2. One-half of each quadrant on slabs exposed outdoors which received initial treatments of linseed oil should be retreated prior to the third winter's exposure.

3. The current practice of the Virginia Department of Highways in treating bridge superstructures with linseed oil should be continued. The treatment of concrete previously cured with membrane without removal of the membrane should continue to be permitted. At the same time, continued emphasis should be placed on the importance of obtaining proper amounts of entrained air. This project has not progressed sufficiently to provide information on the need for retreatment, but the literature reviewed indicates the necessity for periodic retreatment.

4. Since there is some indication that the dissolution of the resin material by the mineral spirits permits penetration of the linseed oil, it might be possible to develop a curing material which, when subsequently dissolved by mineral spirits, would penetrate the surface and offer protection against scaling.

OBSERVATIONS AND CONCLUSIONS AND RECOMMENDATIONS

From Part II (Newlon 1970b)

Observations and Conclusions

1. The operations of the contractor were efficient as reflected in the lack of rejections of concrete, the low coefficients of variation, and the timing of his various operations. The uniformity achieved will greatly reduce the influence of the concrete on the behavior of the performance of the curing and protective treatments.

2. The uniformly satisfactory air contents indicate a good probability of good performance of the deck surfaces.

3. The results of laboratory freezing and thawing tests of concrete specimens made during construction and cured, treated and stored in the field, agreed well with and confirmed the results of similar tests reported in Part I of this report. Specimens treated with linseed oil showed reduced scaling and weight loss as compared to those without the treatment and those cured with chlorinated rubber.

4. Coverage rates of sprayed curing materials were lower than those specified. It is probable that materials meeting the more restrictive requirements of the Virginia Department of

Highways need not be applied at the rates of 150 - 200 ft.^{2} gal. (3.75-5 m^2/dm^3) commonly specified for materials meeting AASHO requirements.

5. Polyethylene coverings were applied later than the sprayed curing materials. The average difference was about 45 minutes.

6. Linseed oil coverage rates were very close to the target value of 0.040 gal/yd.^{2} (1.8 l/m^2). At this coverage rate, the presence of the linseed oil is barely discernible after a month or two.

7. The performance of the chlorinated rubber was unsatisfactory. It developed a very tenacious film which blistered and reduced skid resistance by about 25 percent. It is believed that the bleeding characteristics of the concrete, which contained a water reducing-set retarding admixture, and the severe atmospheric conditions significantly contributed to this behavior; however, these are always present in bridge decks built under Virginia Department of Highways Specifications during the summer when curing requirements are most critical. The conditions did not develop in supplementary tests on a rest area using paving concrete.

8. Desirable benefits of the monomolecular film in extending time available for finishing and for use in emergency situations was qualitatively confirmed. The reduced moisture loss prior to application of curing was also verified although the observed test panels were comparatively few.

9. Difficulties with finishing were associated with days when the computed evaporation rates exceeded 0.10 lb./ft.^{2}/hr.(8.1 g/m^2/sec).

10. High mixture temperatures combined with high air temperatures were reflected in a measurable reduction of compressive strengths and acceleration of setting.

Recommendations

1. The currently specified curing procedures for concrete bridge decks followed by linseed oil treatments continue to be the most satisfactory of the several alternatives practically available for improved durability.

2. Application of the linseed oil treatments following curing with a white pigmented resin based compound of the type specified by the Virginia Department of Highways was once again shown to be satisfactory.

3. Procedures for utilization of the monomolecular film should be initiated so that it can be available in situations where it is needed. These include (1) days with high evaporation potential, (2) delayed application of curing, and (3) equipment breakdowns. Specification of its use for all decks is not desirable.

4. Unless penetration can be demonstrated, no further consideration should be given to materials designed to cure and protect in a single application since the two functions are mutually exclusive (i.e., one requires keeping water in while the other requires keeping it out) and they should be thought of as two separate operations.

CONCLUSIONS

From Part III (Newlon 1973)

1. Properly entrained air is overwhelmingly the most effective defense against scaling caused by deicing chemicals. This fact is evident from the continued good performance of the outdoor exposure slabs that contain entrained air and by the absence of scaling on the bridge decks, which also were built with concrete that was uniformly and adequately air entrained.

2. When insufficient entrained air is obtained, linseed oil treatments delay the onset of scaling.