DO NOT

Evaluation of Concrete Overlays for Bridge Applications

WA-RD 137.1
Final Report
October 1987

Washington State Department of Transportation
Planning, Research and Public Transportation Division
Research Office
in cooperation with the
United States Department of Transportation
Federal Highway Administration

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO WA-RD 137.1	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
4. TITLE AND SUBTITLE EVALUATION OF CONCRETE OVERLAYS FOR BRIDGE APPLICATIONS		5. REPORT DATE October 1987
		6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Khossrow Babaei		8. PERFORMING ORGANIZATION REPORT NO
9. PERFORMING ORGANIZATION NAME AND ADDRESS Washington State Transportation Center (TRAC) 135 More Hall, FX-10 University of Washington Seattle, Washington 98195		10. WORK UNIT NO. 11. CONTRACT OR GRANT NO Y 3399 Task 2
12. SPONSORING AGENCY NAME AND ADDRESS Washington State Department of Transportation (WSDOT) Transportation Building, KF-01 Olympia, Washington 98504		13. TYPE OF REPORT AN PERIOD COVERED Final 14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

This study was conducted in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

16. ABSTRACT

This report documents performance of 12 concrete bridge decks that were rehabilitated and/or protected with latex-modified concrete and low-slump dense concrete overlays in order to prevent future de-icing salt penetration and reinforcing steel corrosion.

Regardless of concrete deterioration caused by rebar corrosion, the overlaid bridge decks will require maintenance in the form of resurfacing in the future. This maintenance may be due to traffic action and a severe environment causing surface distress such as scaling, rutting, and a lack of skid resistance, or stripping of the overlays from the decks.

There are indications that the continued corrosion of reinforcing steel in the salt contaminated underlying decks is less extensive in the absence of overlay surface cracking.

17. KEY WORDS bridge decks, reinforcing steel, corrosion, salt, deterioration, latex-modified concrete, low-slump dense concrete	18. DISTRIBUTION STATEMENT

19. SECURITY CLASSIF (of this report) Unclassified	20. SECURITY CLASSIF. (of this page) Unclassified	21. NO. OF PAGES 104	22. PRICE

DOT FORM 310-022 (11-86) 1216

EVALUATION OF CONCRETE OVERLAYS FOR BRIDGE APPLICATIONS

by

Khossrow Babaei
Research Engineer

Washington State Transportation Center
135 More Hall, FX-10
University of Washington
Seattle, Washington 98195

Washington State Department of Transportation
Technical Monitor
Robert H. Krier
Bridge Operations Engineer

Final Report

Research Project Y-3399
Task 2

Prepared for

Washington State Transportation Commission
Department of Transportation
and in cooperation with
U.S. Department of Transportation
Federal Highway Administration

October 1987

ACKNOWLEDGEMENTS

This work was sponsored by the Washington State Department of Transportation (WSDOT), in cooperation with the Federal Highway Administration, and was conducted by the Washington State Transportation Center (TRAC) at the University of Washington.

WSDOT technical monitor for the project was Robert H. Krier, bridge operations engineer. Other members of WSDOT Bridge and Structures Branch professional staff who participated in the project include Ed Henley, engineer of bridge technology development, and Willis Whitney, bridge condition engineer.

The testing phase of the project was conducted by Ronald Schultz, special projects engineer, and Keith Anderson, research specialist, both from WSDOT Materials Laboratory. Robert Dubois, research assistant from University of Washington, assisted collection of field test data.

The valuable comments offered by the WSDOT participants on the draft final report are acknowledged.

DISCLAIMER

The contents of this report reflect the views of the author, who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Washington State Transportation Commission, Department of Transportation, or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

SUMMARY

The protection of existing reinforced concrete bridge decks against salt infiltration through the application of overlays has been a major effort for the Washington State Department of Transportation (WSDOT). A report by WSDOT (1) indicated that as of April 1986 1,681 bridges in the state highway network still needed deck protection systems. These bridges were constructed according to older design practices, which did not require protection from salt infiltration. Since the application of salt on unprotected bridge decks during the winter can cause embedded reinforcing steel to corrode and consequently concrete to deteriorate internally, some of the concrete in the unprotected decks has developed corrosion-induced deterioration and requires rehabilitation prior to being protected. Another objective of protecting existing decks through the application of overlays is to retard any continuing corrosion of the reinforcing steel by preventing moisture and oxygen from reaching the reinforcing steel.

Because of the results from evaluations of the constructability, cost-effectiveness, and performance of early experimental installations of various bridge deck protective systems in the United States, WSDOT adopted three overlay protective strategies in the mid- and late-1970s. The adopted strategies were (1) asphalt concrete-membrane (ACM), (2) latex-modified concrete (LMC), and (3) low-slump, dense concrete (LSDC). ACM was used as WSDOT's primary protective system on existing bridge decks from 1975 through 1983. In 1984 WSDOT implemented criteria for the selection of protective systems for existing bridge decks, based on its experience and the findings from its bridge deck membrane research. Because LMC had a potential for better durability and promised to retard corrosion in existing salt contaminated decks more effectively, it became the primary system in Washington, followed by ACM. The use of LSDC, however, was discontinued in 1984 due to WSDOT's concerns about its chloride permeability. As of April 1986 the number of protective systems installed on the state's bridges were 487 ACM, 128 LMC, and 35 LSDC.

WSDOT initiated this research project to see if its expectations about the performance of bridge deck concrete overlays were being met. These expectations included satisfactory durability, chloride impermeability, and an effectiveness in retarding continued corrosion of the rebar in decks already contaminated with salt. This research was also aimed at recommending modifications to design and construction procedures, if unforeseen problems had occurred in the overlays' performance. To pursue the goals of the research, the project team selected six LMC and six LSDC sites on which to conduct detailed field and laboratory studies to evaluate the overlays' performance. The project team attempted to select sites with the longest service periods. The average age of the selected sites was five years when the tests were conducted in the summer of 1986.

SURFACE WEAR AND FRICTION RESISTANCE

The surface wear of both LMC and LSDC overlays was not considerably different from the wear of conventional concrete subject to the same traffic exposure. In some of the overlays the transverse texturing was worn completely away. While the friction resistance of the LMC overlays was satisfactory, the friction resistance of the LSDC overlays was marginal. The higher friction resistance of the passing lanes as compared to that of the driving lanes showed the sensitivity of the overlays' skid qualities to traffic.

SURFACE CRACKING

Many overlays were cracked extensively. However, a few crack-free overlays of both LMC and LSDC existed. The characteristics of the cracking suggested that the cracks resulted mainly from initial shrinkage of the concrete in its construction stage and that they later lengthened and deepened when the structures flexed and when the concrete temperature and moisture fluctuated. Precautions to minimize the occurrence of cracking are especially important.

OVERLAY BOND

LMC overlays generally bonded more strongly with the underlying decks than did the LSDC overlays. Although no significant debonding of any of the overlays had occurred up to the summer of

1986, the weak bond found in some areas of both the LMC and LSDC installations indicated their susceptibility to debonding and stripping from those portions of the decks. A quality control procedure that includes a test for bond strength before the construction is accepted may be needed. However, this will require a "performance" type of specification rather than the "product specification" currently adopted by WSDOT.

CHLORIDE PERMEABILITY

LMC overlays of 1-1/2 inches and 2-inch LSDC overlays have largely prevented chlorides from intruding into the underlying decks. With the decreased amount of salt presently applied on Washington bridge decks, a significant amount of post-overlay chloride will probably not build up at the rebar level in the foreseeable future. However, cracks in the overlays have permitted higher levels of chlorides to intrude into the concrete, and they can contaminate the underlying decks in the long run. Therefore, the cracks should be sealed for preventive maintenance.

CORROSION-INDUCED DETERIORATION

One-third of the decks overlaid with LMC and two-thirds of the decks overlaid with LSDC had developed internal concrete deterioration associated with rebar corrosion. The deteriorated decks had been contaminated with salt prior to being overlaid. The extent of overlay cracking seemed to have influenced the extent of post-overlaying deterioration. Sealing of the overlay cracks would probably mitigate this type of deterioration.

PROTECTIVE SYSTEM SELECTION

The findings of this study support WSDOT's selection of LMC over LSDC for protecting bridge decks with rigid overlays.

SERVICE LIFE EXPECTANCY

Regardless of concrete deterioration caused by reinforcing steel corrosion, overlaid bridge decks will require future maintenance in the form of resurfacing. This maintenance will be needed because traffic action and a severe environment will cause surface distress or debonding and stripping of protective overlays from the decks.

FINDINGS

The following findings appear warranted based on the discussions presented in this report.

FREEZE-THAW SCALING

- Although the test overlays did not show signs of freeze-thaw scaling, scaling has been detected in some Washington bridges overlaid with either latex-modified concrete (LMC) or low-slump, dense concrete (LSDC). The problem has been especially acute in gutter areas.
- The scaling resistance of LMC installations in the United States has generally been better than the scaling resistance of LSDC installations.

WEAR AND FRICTION RESISTANCE

- The surface wear of LMC and LSDC overlays was about the same and not considerably different from the wear of conventional concrete. Transverse texturing, approximately 3/16-inch deep, was worn completely away after about seven years of exposure to an average daily traffic (ADT) of about 8,000, with trucks comprising about 10 to 15 percent of the traffic. WSDOT has even noticed higher rates of wear during its regular inspection. In one LMC overlay, the texturing was worn out in only six months under an ADT of about 30,000.
- The LMC overlays showed better friction resistance than the LSDC overlays. In the driving lanes the average friction number was 45 for the LMC overlays as compared to 34 for the LSDC overlays. The friction resistance of the passing lanes was on the average 7 units higher than that of the driving lanes.

OVERLAY CRACKING

- In the sample tested, many overlays were cracked. However, a few crack-free overlays of both LMC and LSDC were also present.
- The cracking in the LMC overlays was relatively less extensive than the cracking in the LSDC overlays. The maximum amount of cracking in the LMC overlays was 40 percent of the deck

area as compared to 89 percent for the LSDC overlays. However, some LMC overlays recently placed in Washington have cracked more extensively than the LMC overlays tested in this work.

- The cracking patterns suggested that the cracks resulted mainly from initial plastic shrinkage in the overlays and that they later propagated as a result of repeated structure flexing, thermal cycling, and wetting and drying.
- After an average service period of about five years, the depth of cracks either reached the overlay bond interface or exceeded that into the underlying deck.

OVERLAY BOND

- The LMC overlays generally bonded more strongly with the underlying decks than did the LSDC overlays. Using pull-out tests, the average overlay bond tensile strength was 203 psi for the LMC overlays and 141 psi for the LSDC overlays. The shear bond strength should be roughly equal to three times the measured tensile bond strength.
- Although no significant debonding of any overlay had occurred by the summer of 1986, the weak interface bond found in some areas of both the LMC and LSDC installations was alarming to note.

CHLORIDE AND WATER PERMEABILITY

- The chloride permeability of 1.5-inch, crack-free LMC and 2.0-inch, crack-free LSDC seemed to be satisfactory. No chlorides seemed to have penetrated the underlying decks after about five years of service.
- A prediction for 1.5-inch, crack-free LMC or 2.0-inch, crack-free LSDC is that at the Washington State Department of Transportation's (WSDOT) current level of bridge deck salt application (assuming a maximum of 5 tons per lane-mile per year), the chloride content at the rebar level may increase 0.13 lb/c.y. per ten years, which is insignificant. Higher chloride accumulation rates can be expected if the rate of salt usage increases.

- Cracks had permitted the intrusion of larger amounts of chlorides into the overlays than crack-free areas. Cracks had also contaminated concrete with chlorides 3 inches from the crack in each horizontal direction, mainly in the regions close to the surface.
- Although chloride intrusion from the cracks into the underlying decks did not seem to be significant after about five years of service, long-term exposure, such as ten to 15 years, could contaminate 16 percent of the underlying deck if the extent of cracking reaches 90 percent of the deck area, the maximum detected in the overlays.
- For crack-free concrete, the water permeability of the LSDC overlays was greater than that of the LMC overlays. At crack-free areas, decks under LSDC overlays had an average of 1 percent by weight of concrete more water than decks under LMC overlays.
- Since the crack-free overlays had not permitted chloride intrusion into the underlying decks, the conclusion can be drawn that concrete overlays are possibly able to screen out chlorides while permitting some water to seep.

CORROSION AND DELAMINATION

- One-third of the decks overlaid with LMC and two-thirds of the decks overlaid with LSDC showed delaminations or concrete deterioration associated with rebar corrosion.
- The post-overlaying delamination rates for some LMC and LSDC covered decks were higher than their pre-overlaying deterioration rates.
- All of the delaminated decks were contaminated with chlorides before they were overlaid. However, not all of the contaminated/overlaid decks were delaminated.
- An important characteristic of the contaminated/overlaid decks without delaminations or with insignificant delaminations was that they either did not have cracks in their overlays or their cracking was insignificant. Cracking can contribute to corrosion-induced delamination by periodically facilitating the intrusion of water and oxygen into the originally contaminated decks upon their drying.

- Delaminations also increased as the pre-overlaying rehabilitated areas increased. Rehabilitations may cause deterioration in the areas adjacent to them. They also can deteriorate within themselves if they are patched with inferior materials.
- A prediction based on the limited data available is that when overlay cracking exceeds 50 percent of the deck area, originally contaminated underlying decks may develop delaminations at a rate of about 1 percent of the deck area per year, or 7 percent of the rehabilitated areas per year, whichever is larger.

PROTECTIVE SYSTEM SELECTION

- The findings of this study on the durability and impermeability of concrete overlays support WSDOT's selection of LMC over LSDC for bridge deck protection.

RECOMMENDATIONS, APPLICATIONS

The following applications, which are based on the discussions presented in the body of this report, are recommended for improving and enhancing future LMC or LSDC work, if the applications are different from WSDOT's current policies.

Improve scaling resistance by

- providing effective bridge deck surface drainage;
- avoiding overworking and sprinkling the surface of concrete during concrete placement (mainly LSDC);
- avoiding delays between concrete placement and its curing; and
- providing a sufficient air drying period before the first application of de-icing salts. A two-month period may be designated as a minimum; otherwise the surface may be sealed temporarily. New York DOT has used this procedure.

Increase wear resistance by

- avoiding overworking and sprinkling the surface during concrete placement (mainly LSDC);
- curing promptly after concrete placement (the elapsed time may be limited to 30 minutes); and
- increasing the concrete's wet-cure period (at least 48 hours for LMC).

Increase friction resistance by

- incorporating the maximum possible fine aggregate into the mix;
- incorporating crushed aggregate into the mix;
- incorporating polish-resistant aggregate into the mix; and
- building deeper traction grooves, at least 1/4-inch deep, by saw-cutting the grooves in the hardened concrete. New York DOT has experimented with this procedure.

This recommendation is subject to further data on this procedure's performance, cost and impact on traffic control.

Minimize overlay cracking by

- allowing a maximum evaporation rate of 0.15 lb/ft^2/hr while placing the overlay, or
    - erecting wind barriers,
    - keeping aggregate cool by shading it,
    - using cold mixing water, possibly by incorporating ice,
    - using fog nozzles to maintain a sheen of moisture on the concrete surface before curing. This recommendation is subject to the results of field trials to support its feasibility,
    - curing promptly after concrete placement (the elapsed time should be below 30 minutes),
- prolonging the wet-cure period to at least 48 hours (for LMC), and
- allowing the wet-cure cover to remain without wetting after the specified wet-cure period and before the dry-cure period (for LMC). The period of time between wet-curing and dry-curing may be such that it results in natural drying of the wet-cure cover. The duration of this intermediate curing, however, will depend on its impact on traffic control, and its effectiveness needs to be further explored.

Improve bond durability by

- providing a bond coat for the overlay by applying a grout made of the overlay ingredients. This procedure is better than scrubbing a portion of the overlay mix onto the deck and removing the coarse aggregate as it is broomed out. The superiority of this procedure needs to be verified in the field.
- coring the concrete and conducting a laboratory shear bond test on the core samples through the bond interface before accepting the construction. An initial bond strength of 500 psi may be specified as the minimum acceptable strength using Iowa

Test Method Number 406. This quality control procedure can supplement WSDOT's current procedure, chain dragging of the overlay. However, this procedure requires a "performance" type specification rather than the "product specification" currently adopted by WSDOT.

Reduce chloride and water permeability by

- sealing the cracks in concrete overlays, possibly by using polymer materials. Minnesota DOT and Kansas DOT have sealed cracks using polymers.

Minimize the occurrence of post-overlay delaminations by

- designating the perimeter of the concrete removal areas a few inches away from the perimeter of the pre-overlaying delaminations detected by chain dragging;
- saw-cutting the perimeter of the concrete removal area and restricting the size of the concrete removal hammers to 30-pound jackhammers above the reinforcing steel and 15-pound chipping hammers below the reinforcing steel;
- testing any patching materials that fill the concrete removal areas for initial strength, durability, and alkalinity so that properties comparable to the conventional portland cement concrete are utilized; and
- sealing cracks in the overlays of originally chloride-contaminated decks against penetration of moisture. Sealing may be achieved effectively by using polymer materials. Minnesota DOT and Kansas DOT have sealed cracks using polymers.

NEEDED RESEARCH

This research documented the performance of six LMC overlaid bridge decks, supported WSDOT's use of LMC, and made a number of recommendations involving numerous operations within the department to enhance the WSDOT's bridge deck program. In view of WSDOT's commitment to a program involving extensive use of the LMC overlay, evaluation of only six overlays is rather minimal for projecting the long-range performance of LMC in the bridge deck network. Furthermore, supplementary information is needed to implement some of the recommendations of this research. Thus, additional testing and evaluation as well as information assimilation is certainly warranted. Below are presented recommendations for the needed research.

ISSUES NEEDING FURTHER STUDIES

The issues needing further study can be divided into two broad categories: (a) those associated with the life expectancies of LMC overlaid bridge decks, and (b) those associated with the tentative recommendations of this report involving the design and construction of LMC overlays.

Life Expectancies of LMC Overlaid Decks

The limited test data obtained in this study on life expectancy should be verified and/or modified by testing at least six more LMC installations. Attempts should be made to select the sites with the longest service periods to accurately project LMC overlaid deck's long-range performance.

The test sites should be those with chloride contaminated underlying decks. The knowledge gained from the current study allows the analysis of test data from this type of bridge deck to reveal both the durability of the LMC overlays as well as their corrosion mitigation characteristics. The findings of the current study indicate the role of two factors in the development of corrosion-induced deterioration. These are the intensity of overlay cracking and the magnitude of pre-overlaying deck repairs. Thus, the test sites should be selected to document more clearly the significance of these two factors on performance. For this reason the six test sites should be divided into two classes: (1) low magnitude repair decks (preferably less than 2 percent of the deck area repaired), and (2) high magnitude repair decks (preferably more than 5 percent of the deck area repaired). Each class of bridge deck should then be divided into three groups: (1) low intensity cracked deck (preferably less than 5 percent of the deck area cracked), (2) medium intensity cracked deck (preferably between 5 percent and 30 percent of deck area cracked), and (3) high intensity cracked deck (preferably more than 30 percent of deck area cracked).

Recommendations Involving Design and Construction

Certain recommendations of this report require further data assimilation and analysis from various sources nationwide and/or require the results of experimental field projects in order to verify their feasibility, prepare design and construction guidelines for them, and implement them. Those recommendations are the following:

- increase the wet-cure period of LMC to increase its wear resistance and to minimize its cracking,
- saw-cut traction grooves in the hardened concrete to increase friction resistance,
- use fog nozzles when placing LMC to minimize the occurrence of cracking,
- use a grout made of the overlay ingredients to increase bond strength, and
- seal cracks using polymer materials to prevent chloride intrusion and to retard continuing corrosion of the rebar.

CHAPTER 1
INTRODUCTION

The protection of existing reinforced concrete bridge decks against salt infiltration through the application of overlays has been a major effort for the Washington State Department of Transportation (WSDOT). A report by WSDOT (1) indicated that as of April 1986 1,681 bridges in the state highway network still needed deck protection systems. These bridges were constructed according to older design practices, which did not require protection from salt infiltration. Since the application of salt on unprotected bridge decks during the winter can cause embedded reinforcing steel to corrode and consequently concrete to deteriorate internally, some of the concrete in the unprotected decks has developed corrosion-induced deterioration and requires rehabilitation prior to being protected. Another objective of protecting existing decks through the application of overlays is to retard any continuing corrosion of the reinforcing steel by preventing moisture and oxygen from reaching the reinforcing steel.

In the past two decades, various bridge deck protective strategies have been developed nationwide to prevent salt from infiltrating into concrete bridge decks. Because of the results from evaluations of the constructability, cost effectiveness, and performance of early experimental installations of various protective systems in the United States, WSDOT adopted three overlay protective strategies in the mid- and late-1970s. The adopted protective strategies were asphalt concrete/membrane (ACM) overlay, latex-modified concrete (LMC) overlay, and low-slump, dense concrete (LSDC) overlay. ACM was used as WSDOT's primary protective system on existing bridge decks from 1975 through 1983 (1). In 1976 WSDOT installed its first experimental concrete overlay on a bridge deck, an LMC overlay. But it was not until 1979 that LMC and LSDC were bid as alternative protective strategies on bridge decks. In 1984 WSDOT implemented criteria for the selection of protective systems for its existing bridge decks, based on its experience and the results from its bridge decks membrane research (2, 3). The WSDOT's protective system selection criteria are shown in

Table 1. Because LMC had a potential for better durability and promised to retard corrosion in existing salt-contaminated decks more effectively, it became the primary system in Washington, followed by ACM. The use of LSDC, however, was discontinued in 1984 due to WSDOT's concerns about its chloride permeability. As of April 1986 the number of protective systems installed on the state's existing bridges were 487 ACM, 128 LMC, and 35 LSDC (1).

The WSDOT initiated this research project to see if its expectations about the performance of bridge deck concrete overlays were being met. These expectations included satisfactory durability, chloride impermeability, and an effectiveness in retarding continued corrosion of the rebar in decks already contaminated with salt. This research was also aimed at recommending modifications to design and construction procedures, if unforeseen problems had occurred in the overlays' performance.

To pursue the goals of the research, the research team visited 47 concrete overlaid bridge decks in the state of Washington in the summer of 1985 and reviewed information about their construction. The research team then selected six LMC and six LSDC sites on which to conduct detailed field and laboratory studies to evaluate the overlays' performance. The ages of the selected installations ranged from two to seven years, with an average of five years. Subsequently, further background information on the design, construction, rehabilitation, and protection of the 12 selected sites was collected from different sources within WSDOT to assist with the performance evaluation. Finally, the researchers designed a comprehensive experiment to reveal any distress which might have affected the performance of the decks. Detailed information on the process of selecting the test bridges can be found in Appendix A. During the summer and fall of 1986 the research team completed the detailed field testing of the 12 selected decks and the pertinent laboratory studies.

Table 1. WSDOT's Bridge Deck Repair Priority and Protection System Selection Matrix

Group	Rating	Code	cl>2#/cy[a]	Deterioration[b]	Priority No. – Protection System Traffic Category >10,000 ADT	 2,000 - 10,000 ADT	 <2,000 ADT
1	slight	8	none	None	3(LMC)[c]	4(LMC-AC)[d]	8(LMC-AC)
		7	none	None			
2	moderate	6	<20%	<2%	6(LMC)	7(LMC-AC)	9(LMC-AC)
		5	20-40%	2-5%			
3	severe	4	40-60%	>5%	1(LMC)	2(LMC)	5(LMC)
		3	>60%	>5%			

a. Percent of chloride samples exceeding 2#/c.y.

b. Deterioration is defined as the percent of the total deck area that has spalls and/or delaminations.

c. Protection method: latex-modified concrete overlay.

d. Protection method: latex-modified concrete overlay or asphalt concrete and waterproofing membrane.

CHAPTER 2
INTERPRETATION, APPRAISAL, AND APPLICATION

General information on the condition of each test bridge is tabulated in Table 2 for the six LMC overlays and in Table 3 for the six LSDC overlays. The information includes both the decks' pre-protection conditions and their present conditions. The test area on each bridge generally comprised the driving lane and the adjacent shoulder.

In the following sections the research findings pertinent to each bridge deck distress category are analyzed and interpreted so that the present condition of the test bridges can be appraised. Recommendations are also made for predicting and prolonging the service lives of concrete overlaid bridge decks.

FREEZE-THAW SCALING

Findings

None of the 12 test bridge decks showed signs of freeze-thaw scaling. However, freeze-thaw scaling has been detected in some Washington installations of both LMC and LSDC (2). The problem has been especially acute in gutter areas.

Discussion

Bridge decks are subject to saturated freezing conditions, more freeze-thaw cycles and higher rates of salt application than roadways; thus they are more susceptible to concrete freeze-thaw scaling. For LSDC, air-entrainment is the primary means of controlling freeze-thaw damage. The air content of LSDC is generally about 6.5 ± 1.0 percent. Air-entrained LSDC, because of its low specified water/cement ratio of about 0.32, is able to resist freeze-thaw and de-icer scaling very well. However, research has shown that adequate air-entrainment in LSDC is not always achieved (4). Depending on the characteristics of the mix and air-entraining agent, sometimes up to ten times the normal dose of air-entraining agents may be needed to produce the desired air content (4). Thus, the effectiveness of

Table 2. Latex-Modified Concrete Test Overlays, General Information

Bridge No. & Name	Year Built	Type of Structure	Length (ft.) --- Width (ft.)	Year Overlaid	(1) $\overline{\text{Cl}}$ contamination before overlaid	(2) Conc. repair before overlaid (% of test area)	Type of Conc. repair	ADT (1983)	Present Condition (1986)								
									Avg. Friction No. Driv. Lane .... Pass Lane	(3) Cracking (% of test area)	Pull-out Bond (psi) Max. / Avg. / Min.	Debonding (% of test area)	Half-Cell (% of readings) (4)			Delamination (% of test area)
													<0.20 (V)	0.20-0.35 (V)	>0.35 (V)	
90/96.5 Denny Cr. Rd O-xing	1972	3-Span prestressed beams, (part. cont.)	244 --- 52-67	June, 1980	0% (5)	None	None	8,150	41 55	0%	191 115 8	0%	100%	0%	0%	0%
90/174 S Renslow Br.	1968	2-Span prestressed beams, (part. cont.)	211 --- 38	June, 1984	25% (7)	1.1%	Set-45	5,050	43 51	8%	326 172 95	0.04%	100%	0%	0%	0%
90/510 S Medical Lake Rd OC	1966	3-Span prestressed beams, (cont.)	130 --- 36	June, 1982	50% (1-3-80)	14.97%	Monolithic	5,850	53 58	40%	382 251 >159	0%	69%	30%	1%	4.38%
90/512 S N.P. Ry OC	1966	3-Span prestressed beams, (part. cont.)	150 --- 38	June, 1982	30% (1-3-80)	1.7%	Monolithic	8,750	52 54	35%	>199 165 127	0%	77%	22%	2%	3.88%
20/211 S Swinomish D. Berentson Br.	1972	16-Span prestressed beams & 5-span steel beams	3,259 --- 33	(6) Aug., Sept. 1981	83% (8-19-80) (test section)	1% (overall)	Monolithic	7,950	40 46	2%	>398 185 8	0%	100%	0%	0%	0%
2/311 Pine Cr.	1949	3-Span conc. T beam (cont.)	209 --- 26	June, 1979	80% (5)	9.9%	Monolithic	1,380	43 44	14%	462 329 >159	0.01%	100%	0%	0%	0%

(1) Percent of concrete samples having more than 2 lb/cy chloride content
(2) Estimated for bridges 90/174 S and 20/211 S
(3) Percent of cracked grid squares
(4) Negative sign eliminated
(5) Found in this study, no previous data
(6) 300 ft. test section over partially continuous prestressed beams starting from span 15 from WPS
(7) Modified in this study

Table 3. Low-Slump, Dense Concrete Overlays, General Information

									Present Condition (1986)										
Bridge No. & Name	Year Built	Type of Structure	Length (ft.) --- Width (ft.)	Year Overlaid	(1) $\overline{\text{Cl}}$ contamination before overlaid	(2) Conc. repair before overlaid (% of test area)	Type of Conc. repair	ADT (1983)	Avg. Friction No. Driv. Lane	Avg. Friction No. Pass. Lane	(3) Cracking (% of test area)	Pull-out Bond (psi) Max.	Pull-out Bond (psi) Avg.	Pull-out Bond (psi) Min.	Debonding (% of test area)	Half-Cell (4) (% of readings) <0.20 (V)	Half-Cell (4) (% of readings) 0.20-0.35 (V)	Half-Cell (4) (% of readings) >0.35 (V)	Delamination (% of test area)
90/91 N South Fork Snoqualmie River	1975	3-Span prestressed beams, (part. cont.)	313 --- 73-79	Sept. - Oct. 1983	0% (6-30-82)	0.03%	Monolithic	7,890	38	49	50%	201	143	81	0.04%	100%	0%	0%	0%
90/106 N Gold Cr.	1973	3-Span concrete slab (cont.)	139 --- 38	Sept., 1979	100% (5-14-79)	None	None	7,890	39	43	0%	>382	84	24	0%	100%	0%	0%	0%
90/124 S Lake Valley Rd OC	1962	3-Span prestressed beams, (simple)	104 --- 38	Aug., 1979	100% (5-14-79)	13.4%	Monolithic	5,950	34	44	28%	446	233	143	0%	100%	0%	0%	1.04%
90/150 S Taneum Cr.	1965	1-Span prestressed beams, (simple)	108 --- 38	June - Aug., 1983	90% (12-9-81)	9.73%	Duracal	7,550	29	32	84%	326	143	8	0%	53%	46%	1%	2.00%
90/160 S Reeser Cr.	1967	3-Span concrete slab (cont.)	120 --- 38	July, 1981	0% (5)	1.16%	Monolithic	7,650	31	38	89%	111	30	8	0%	100%	0%	0%	0.05%
90/162 N Wilson Cr.	1967	3-Span concrete slab (cont.)	118 --- 38	Oct., 1981	50% (10-22-80)	17.75%	Monolithic, Set-45 & Gilcrete over piers	7,650	32	42	65%	>428	210	111	0%	64%	34%	2%	5.86%

(1) Percent of concrete samples having more than 2 lb/cy chloride content
(2) Estimated for bridges 90/91 N and 90/124 S
(3) Percent of cracked grid squares
(4) Negative sign eliminated
(5) Modified in this study

air-entraining agents in LSDC mixes should be examined before they are used in the field. Also, because it is stiff, the LSDC mix may be inadequately consolidated, resulting in large amounts of entrapped air rather than entrained air. The water absorption of LSDC mixes can be used to evaluate their scaling resistance. A water absorption rate less than 4.5 percent by weight of the concrete is desirable (5). That absorption rate reflects the combined effects of the degree of consolidation and the actual water/cement ratio.

LMC does not entrain air, but it provides voids, which generally comprise 6 percent or less of the volume. Voids help the mix resist scaling, in conjunction with LMC's low specified water/cement ratio of about 0.32 and latex particles. Latex particles reduce the absorption of water and increase freeze-thaw and de-icer scaling resistance. The scaling resistance of LMC installations in the United States has generally been better than that of LSDC installations.

Elements involved in the design and construction of concrete overlays that adversely affect the overlays' freeze-thaw durability include

- ineffective surface drainage, which results in ponding and, ultimately, saturation of the concrete,
- overworking and sprinkling of the surface (mainly LSDC), which can alter the concrete surface air void structure and decrease the surface concrete strength as well,
- delays between concrete placement and its curing, and
- an insufficient air drying period before the first application of de-icing salts (4). A two-month period may be designated as a minimum amount of time; otherwise, the surface may be sealed temporarily. New York DOT has used this procedure.

SURFACE WEAR AND FRICTION RESISTANCE

Findings

The surface wear of both LMC and LSDC test overlays was not significantly different from the wear of conventional concrete subject to the same environment. With enough traffic, transverse texturing (approximately 3/16-inch deep) that had been tined into the overlays in their plastic stage were worn completely away after about seven years of exposure. For example, on Bridge 90/106 N (LSDC), the grooves had disappeared in the driving lane after seven years of exposure to an average daily traffic (ADT) of about 8,000. The percentage of trucks on this route was estimated to be 10 to 15 percent of the total traffic volume. WSDOT has even noticed higher rates of wear on some recently installed overlays. For example, in the case of the LMC on the Chehalis River Bridge, 101/115, which had an ADT of about 30,000, the grooves were worn out in about six months (2). For conventional concrete, about 1/2 inch of wear or more can be expected in urban areas after about 20 years of service when studded tires are allowed (2). Studded tires are permitted on Washington roadways between November 1 and April 1.

Friction resistance numbers (tested at 40 miles per hour) for the LMC and LSDC test overlays are given in Table 2 and Table 3, respectively. After an average of five years of service the mean friction number for the driving lanes was 45 for the six LMC overlays as compared to 34 for the six LSDC overlays, a difference of 11 units. The mean friction number for the passing lanes, which carry less traffic, was an average of seven units more than that for the driving lanes for all 12 overlays. Testing was performed with a locked-wheel friction tester that met ASTM E 274-79 specifications.

The friction resistance information in Table 2 and Table 3 is further summarized in Table 4. As shown in Table 4, the best and worst friction resistance performances for the LMC overlays were consistent with their age and traffic volume, or the total traffic on the overlays during their service periods. However, this consistency was not noticed for every overlay, probably because of the many design and construction factors that contribute to the friction resistance. For example, a three-year-old LSDC overlay had substantially less friction resistance than a seven-year-old LSDC overlay, even though their traffic volumes were about the same (see Table 4).

Table 4. Friction Resistance of Six Latex-Modified Concrete and Six Low-Slump, Dense Concrete Overlays (adapted from Tables 2 and 3)

Type of Overlay	Friction Resistance (Driving Lane)	Bridge Number	Age of Overlay (years)	ADT	(Age) x (ADT) x 365 [1]	Avg. Friction Number (Driving Lane)
LMC	Best	90/510 S	4	5,850	8,541,000	53
	Worst	20/211 S	5	7,950	14,508,250	40
LSDC	Best	90/106 N	7	7,890	20,158,950	39
	Worst	90/150 S	3	7,550	8,267,250	29

[1] Index representing the total traffic on the overlays during their service periods

Discussion

Theoretically, LSDC should have better wear resistance than conventional concrete because its lower water/cement ratio and higher cement factor should result in more strength. However, its performance showed that its wear resistance is about the same as that of conventional concrete. The construction of LSDC involves many factors that influence its wear resistance. For example, during finishing, the stiffness of the mix may require the surface to be either overworked or sprinkled with water, both of which reduce the surface strength of concrete. Also, rapid construction policies, generally used during the reconstruction of existing bridges so that they can be opened to the public as soon as possible, involve shorter curing periods, which may reduce the wear resistance of the concrete. The wear resistance of LMC overlays, on the other hand, is not as sensitive to construction procedures, but LMC's strength is about the same as conventional concrete. Shorter curing periods may also influence the wear resistance of LMC. The wear resistance of both LMC and LSDC is decreased if the curing process is not started immediately following concrete placement.

The friction resistance of concrete surfaces is provided by two types of surface texture, fine texture and coarse texture. The fine texture provides the contact area with the tire; the coarse texture mainly helps water escape from the surface, reducing the potential for hydroplaning (6). The amount of fine aggregate in the mix plays an important role in providing the fine texture. LMC incorporates more fine aggregate in the mix than LSDC. This may account for the higher friction resistance of the LMC overlay, as discussed earlier. For the fine texture to be durable, the fine aggregate should be polish resistant, or the surface may become slippery.

According to WSDOT specifications, the coarse texture in a concrete surface is built by tining the plastic concrete. The transverse texturing built into the surface in this manner allows surface water to escape. However, as the concrete surface wears under traffic, the coarse texture, and the fine texture as well, can disappear. When this stage is reached, the coarse aggregate in the mix contributes to friction resistance. Crushed, coarse aggregate and polish-resistant aggregate provide better friction resistance. ASTM D3319, a method for testing the accelerated polishing of aggregates using the British Wheel, may be used to evaluate the polish susceptibility of the aggregates.

Extensive wear causes rutting in the wheeltracks, which can create ponding of the surface water. Ponding increases the potential for cars to hydroplane or skid when the water freezes into ice. Ponding also accelerates deterioration of the concrete. Presently there are no standard methods for partially patching ruts in concrete surfaces. Thus, the repair of rutting requires resurfacing.

CRACKING

Findings

In the sample tested, many overlays were cracked. However, a few crack-free overlays of both LMC and LSDC were also found. These were Bridge 90/96.5 (LMC, six years old, Table 2) and Bridge 90/106 N (LSDC, seven years old, Table 3). The LMC overlays were less cracked than the LSDC overlays. The extent of cracking on each deck was determined quantitatively by designating any 5-foot by 5-foot grid square on the deck as a cracked area when cracking occurred in it. Following this procedure, the worst cracking of an LMC overlay was 40 percent of the deck area of Bridge 90/510 S (Table 2), and the worst cracking of an LSDC overlay was 89 percent of the deck area of Bridge 90/160 S (Table 3).

The pattern of the cracking (a combination of random, transverse, and/or longitudinal cracking) suggested that the cracks probably resulted from initial plastic shrinkage in the overlays and that they later lengthened as a result of repeated structural flexing, thermal cycling, and wetting and drying. The exceptions to this were the cracks in Bridge 20/211 S (LMC, 2 percent cracking) and Bridge 2/311 (LMC, 14 percent cracking). The first bridge had only a few shallow transverse cracks over a support, possibly caused by the negative live load moment in the continuous deck slab. The second bridge also had only transverse cracks, but they were oriented directly along the uppermost transverse rebar in the monolithic patch areas. These cracks reached the rebar and were most likely caused by settlement of the plastic LMC around the rebar, possibly because of the shallow rebar depth in these areas combined with the relatively high slump of the LMC mix. Coring showed that the cracks in the remaining decks generally either reached the bond interface or exceeded that.

Discussion

The major contributing factor to cracking in LMC and LSDC overlays is shrinkage of the concrete in its plastic stage. Both concretes typically have low water/cement ratios of about 0.32, resulting in a limited amount of bleed water that can rise to the surface after the concrete is placed. Under this condition, the surface evaporation rates are likely higher than the bleed rates in an arid and hot environment. Thus, shrinkage results. Since the shrinkage in the upper layer is restrained by the concrete mass, it causes random, transverse, and/or longitudinal cracking. The following material and environmental factors promote plastic shrinkage in concrete:

- high concrete temperature,
- high air temperature,
- low air humidity, and
- high wind velocity.

ACI 305R-77 provides a chart for determining the surface evaporation rate quantitatively based on these factors. ACI 305R-77 recommends that if the rate of evaporation approaches 0.2 lb/ft^2/hr, precautions against cracking are necessary to minimize plastic shrinkage cracking in conventional concrete. For minimal plastic shrinkage cracking in LMC, WSDOT presently specifies the maximum allowable evaporation rate at 0.15 lb/ft^2/hr. Comparing the water/cement ratio of a conventional concrete, which is usually from 0.45 to 0.50, to the water/cement ratio of LMC or LSDC, which is about 0.32, a maximum allowable evaporation rate of 0.15, rather than 0.20, seems to be prudent for LMC or LSDC overlays.

If evaporation is expected to reach the maximum allowable rate during concrete placement, either the construction should be delayed or precautions to reduce the rate of evaporation should be taken to minimize plastic shrinkage cracking. The most important among these precautions are (7)

- placing the concrete when air temperatures are low, such as at night,
- erecting wind breakers,
- keeping the aggregate cool by shading it,
- using cold mixing water, possibly by incorporating ice,
- using fog (not spray) nozzles to maintain a sheen of moisture between the placement of the concrete and the start of the curing process to minimize surface moisture loss (This recommendation is subject to the results of field trials to support its feasibility.), and
- curing the concrete promptly after placement.

A WSDOT research study suggested that for LMC overlays the length of the uncovered plastic concrete behind the screed should be limited to 10 to 15 feet (8). This work also suggested that for LMC overlays the temperature of the underlying deck should be reduced to at least 85 degrees F and possibly 75 degrees F by continuous wetting for several hours before the overlay is poured. WSDOT specifies that this continuous wetting be two hours.

Aside from plastic shrinkage, concrete is subject to drying shrinkage. After concrete is cured, when it is exposed to the atmosphere, it loses some of its original water to the environment and shrinks. Restraint created by the interior of the concrete causes cracking when this shrinkage occurs. The water content of the concrete mix is the major factor affecting drying shrinkage. Less shrinkage is obtained by decreasing the water content of the mix. Unlike plastic shrinkage, drying shrinkage may not be a problem in an LSDC overlay, since the amount of water in its mix is very small. On the other hand, the long-term shrinkage of LMC is high (9). On two-course, new construction bridge decks, where the overlay is placed on the just-completed underlying deck, the newly constructed underlying concrete deck will also shrink from drying and become compatible with the shrinking overlay. However, this is not the case with overlays placed on existing decks, since the underlying decks have already shrunk. The possibility of long-term cracking in LMC can be reduced by thorough soaking of the substrate before the overlay is placed so that the substrate can also shrink as it dries after the overlay is placed. Soaking periods longer than two hours may be necessary for this purpose. Prolonging the wet cure period from 24 hours to 48 hours (to cure the cement portion) and allowing the wet cure cover to remain without wetting after the specified wet curing period and before the dry curing period may also minimize the incidence of cracking. The period of time between wet-curing and dry-curing may be such that it results in natural drying of the wet-cure cover. The duration of this intermediate curing, however, will depend on its impact on traffic control. This procedure causes the drying shrinkage to occur gradually and employs the creep properties of the overlay concrete, increasing the strain at which the cracking can occur. A gradual shrinkage is especially important for LMC due to its unusually high rate of shrinkage in the first two weeks after construction (9).

Propagation of Cracking. Cores taken by WSDOT from newly placed LMC overlays have revealed that cracks are generally not the full depth of the overlay but are 3/8-inch to 3/4-inch deep (8). This study, however, found that cracks in the sample tested, which had an average service life of about five years, generally either reached the overlay bonded interface or exceeded that into the underlying deck. An explanation is that the initially shallow cracks penetrated through the overlays and the bonded interfaces as a result of deck flexing under repeated live loading or as a result of environmental loading caused by temperature cycling, wetting and drying. These factors make cracks lengthen and deepen. The integrity between the overlay and the underlying concrete provided by the bond allows the cracks to extend through the interface. Researchers in Virginia have documented the propagation of cracks through bare decks as a result of span flexing under live loading (10).

BOND

Findings

The tensile strengths of the overlay bonds were measured by drilling 2-inch-diameter cores past each interface and pulling them out while recording the separation force. Five cores were drilled on each deck. While in some locations on each deck the overlay was separated solely by the drilling action because of a weak bond, in other locations tensile strengths as high as 450 psi were required to separate the overlay. Where the overlay was separated simply by the drilling action, a tensile bond strength of 8 psi, the minimum measurable stress using the test device, was assumed to represent the bond. Occasionally, overlay separation was impossible because the epoxy holding the measuring device to the overlay gave away first. In these circumstances the overlay bond to the underlying deck was recorded as larger than the bond of the epoxy to the overlay.

The maximum, minimum and average pull-out bond strengths for the LMC overlays are presented in Table 2 and for the LSDC overlays in Table 3. The mean bond strength is 203 psi for the six LMC overlays as compared to 141 psi for the six LSDC overlays. The bond strength data in Table 2 and Table 3 are further summarized in Table 5. As indicated in Table 5, the best and worst bond strengths for the LMC overlays were compatible with their age and ADT, or the total amount of traffic on the overlays during their service periods. However, this relationship was not true for every overlay in the sample tested, such as those in Table 5 representing the best and worst bond strengths for the LSDC overlays. This is possibly due to factors involved in the construction of the overlays.

Discussion

One should be cautious when interpreting the significance of the tensile bond. Considerable experimental difficulties exist in determining the true tensile strength of the bond. In direct tension, minor misalignments and stress concentrations in the base of the core can impact the results. Data obtained in previous research on thin polymer concrete overlays (11), indicate that the tensile bond may be roughly equal to one-third of the shear bond. However this correlation greatly depends on the nature of the substrate texture. Shear bond can be obtained with sufficient accuracy in the laboratory from 4-inch-diameter core samples of overlays and their underlying decks. A method for determining the shearing strength of bonded concrete is covered under Iowa Department of Transportation Test Method Number 406, 1978. The minimum acceptable shear bond strength for bridge deck concrete overlays depends on their remaining service lives. This is because repetition of shear stresses in the

Table 5. Tensile Strength of Bond for Six Latex-Modified Concrete and Six Low-Slump, Dense Concrete Overlays (adapted from Tables 2 and 3)

Type of Overlay	Overlay Bond[2]	Bridge Number	Age of Overlay (years)	ADT	(Age) x (ADT) x 365[1]	Avg. Bond Strength (psi)[2]
LMC	Best	2/311	7	1,380	3,525,900	329
	Worst	90/96.5	6	8,510	18,636,900	115
LSDC	Best	90/124 S	7	5,950	15,202,250	233
	Worst	90/160 S	5	7,650	13,961,250	30

1 Index representing the total traffic on the overlays during their service periods

2 Tensile strength of overlay bond, determined by pull-out test

interface caused by traffic loading, differential temperature, and differential moisture tends to decrease the shear strength over time. If 450 psi is assumed as the minimum acceptable shear strength for bridge deck concrete overlays after about five years of service, the corresponding minimum acceptable pull-out bond strength will be roughly 150 psi. By using this relationship and the average pull-out bond strength obtained for each overlay in the sample, the researchers found that five LMC and one LSDC overlays had acceptable bond strengths out of the six LMC and six LSDC overlays tested (see Table 2 and Table 3). However, if the evaluation were based on the minimum bond strength obtained for each overlay, then the number of LMC overlays that would have had acceptable bond strengths would have been two and the number of LSDC overlays with acceptable bond would have been zero. An implication of this evaluation is that in summer 1986 some of the overlays were close to partial debonding.

<u>Effects of Cracking on Debonding</u>. Chain dragging and coring showed that some debonding had occurred on two LMC overlays and one LSDC overlay (see Table 2 and Table 3). One of the debonded overlays (90/174 S, LMC) had begun debonding immediately after curing and had been subsequently patched. In the other two overlays (Bridge 2/311, LMC, and Bridge 90/91 N, LSDC) the debonded areas coincided with slight cracking. Since extensive cracking was inspected in many decks with no signs of debonding, cracking could not have been the sole cause of the debonding.

Cracking changes the pattern of the axial stress in the overlay and the shear stress in the interface caused by liveloading. This condition does not promote bond failure. A pertinent discussion is presented in Appendix B. However, differential shrinkage subjects the interface to shear stress at the perimeter of the overlay. Although cracks act as the perimeter of the concrete, most of the differential shrinkage usually takes place before the concrete cracks, so that cracking results where the tensile stress is at its highest and the shear stress is at its lowest. Therefore, an explanation for the coincidence of cracking and debonding in the two test overlays is that if cracking coincides with a small defect in the interface, it can aggravate the problem and expand it by facilitating the accumulation of moisture in the defective interface. Furthermore, debonding itself can cause cracking because of the lack of composite action between the overlay and the deck, coupled with exposure to traffic impact.

When debonded areas grow, they develop fatigue cracking in the form of interconnected cracking. The debonded areas at this stage may look darker because extensive cracking allows a great amount of water to seep into the separated interface. After this form of distress has developed, overlay stripping can commence at any time. This phenomenon was noticed in the passing lane of Bridge 90/91 N, LSDC.

Minimum Required Bond Strength. WSDOT has noticed some debonding during its regular construction inspections. The problem of debonding is likely related to inadequate construction procedures, which can result in no bond or in an initially low bond strength in the interface. Therefore, provisions to provide a satisfactory initial bond are important. WSDOT currently chain drags its newly constructed bridge deck concrete overlays before accepting them so that it can detect debonding and repair it. This procedure can be supplemented by coring and laboratory shear bond tests. An initial bond strength of 500 psi may be specified as the minimum acceptable strength in order to guarantee the integrity of the interface for 20 years, the service period usually expected of the concrete overlays. Figure 1 illustrates the logic behind this criteria using a hypothetical curve representing the rate of decrease for the smallest acceptable interface shear strength over time. A 100 psi shear strength is assumed to be the minimum allowable strength that will prevent the overlay from debonding when the deck is subjected to AASHTO HS-20 truck loading plus impact.

The procedure for bonding a concrete overlay is to scarify the deck at least 1/4 inch to remove the upper layer of concrete, which is usually contaminated with oil or other foreign material, and to provide a rough texture. The scarified concrete is then sand blasted, followed by an air blast to remove all dust and loose material. Then the deck is thoroughly wetted in preparation for the application of LMC, but it is usually kept dry for the application of LSDC. A wet but surface-dry underlying concrete is preferred for LSDC overlays. A bonding agent is then applied on the damp LMC substrate or dry

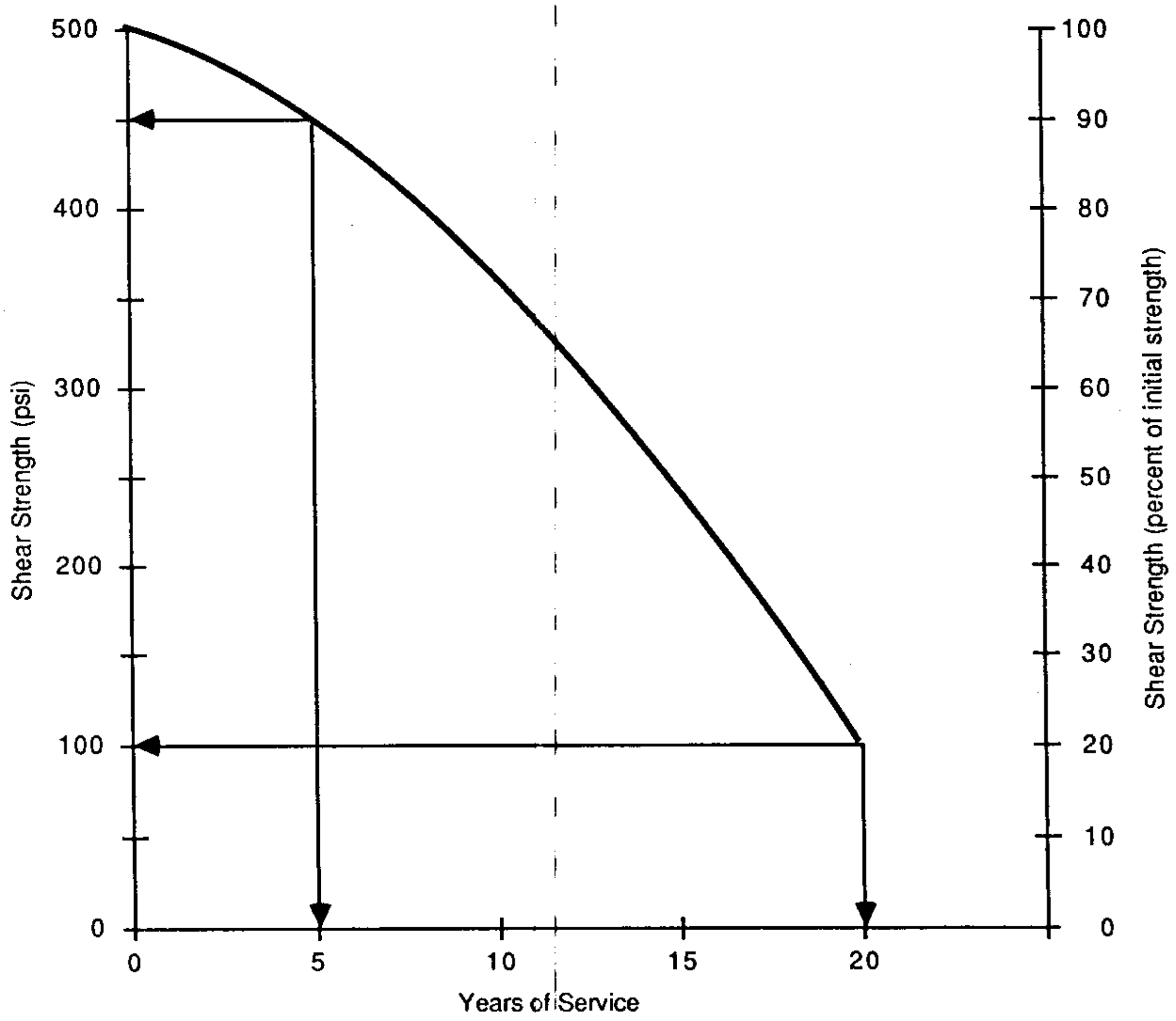

Figure 1. A Hypothetical Curve Representing the Decrease of the Smallest Acceptable Shear Strength in the Interface for Bridge Deck Concrete Overlays

LSDC substrate. To provide a bonding agent, WSDOT requires that a portion of the LMC overlay mix be scrubbed onto the deck and that the coarse aggregate be removed as the mix is broomed out. However, brooming a grout of the overlay mix especially made to provide a bond coat is a better construction practice, since in the former procedure workers may put the excess aggregate back into the overlay instead of wasting it. Also, the former procedure may not provide a sufficient bond coat. In either procedure, it is important that the bond coat does not dry out before the overlay is placed. The effectiveness of applying different types of bonding agents, or applying no bonding agent at all, needs to be further explored.

CHLORIDE INTRUSION PREVENTION

Findings

Concrete samples were taken for laboratory chloride analysis at different locations and depths in each of the overlays to determine their ability to prevent the intrusion of chlorides. Samples were also taken from the underlying decks to use the results for corrosion analysis (see "Corrosion and Delamination"). Concrete samples were taken at crack-free areas, in the cracks, and 3 inches from the cracks so that the contribution of cracking to the chloride permeability of the protective overlays could also be assessed. The results of the chloride content tests are given in Table 6 for the six LMC bridges and Table 7 for the six LSDC bridges. To provide an overall picture of the chloride proofing characteristics of the overlays, plots of average chloride content versus depth are shown in Figure 2 for the LMC overlays and in Figure 3 for the LSDC overlays. These plots correspond to crack-free concrete, cracks, and 3 inches from the cracks. For a meaningful comparison one LMC and one LSDC overlay that did not have cracks were eliminated from the averaging of the chloride content in Figure 2 and Figure 3. The nominal overlay thickness was 1.5 inches for LMC overlays (see Figure 2) and 2.0 inches for LSDC overlays (see Figure 3).

Table 6. Chloride Content (lbs/cu. yd.) in Latex-Modified Concrete Overlaid Test Bridges

Bridge No. and Name	Sample	Free of Cracks								At Cracks		3" from Cracks		Avg. of Samples Free of Cracks
	Number / * Depth	1	2	3	4	5	6	7	8	1	2	1	2	
90/96.5 Denny Cr. Rd. O-xing	0.0 to 0.5	1.57	1.84	0.58	1.86	0.64	1.22	0.86	1.43					1.25
	0.5 to 1.0	0.50	0.57	0.40	0.48	0.42	0.50	0.50	0.46					0.48
	1.0 to 1.5	0.88	0.69	0.14	0.79	0.30	0.46	0.62	0.39					0.53
	1.5 to 2.0	1.07	0.87	0.94	0.65	0.40	0.49	0.52	0.78					0.72
	2.0 to 2.5	0.44	0.53	0.67	0.62	0.94	0.49	0.53	0.50					0.59
	2.5 to 3.0	0.42	0.47	0.86	0.68	0.72	0.55	0.53	0.45					0.59
90/174 S Renslow Br.	0.0 to 0.5	0.69	0.99	0.71	0.71					1.61	0.29	1.20	0.26	0.78
	0.5 to 1.0	0.18	0.34	0.24	0.40					0.66	0.27	0.47	0.19	0.29
	1.0 to 1.5	0.18	0.43	0.28	0.43					0.58	0.19	0.28	0.21	0.33
	1.5 to 2.0	0.11	1.32	1.18	0.72					0.70	0.19	0.14	0.23	0.83
	2.0 to 2.5	0.45	2.09	2.93	0.91					0.21	0.19	0.21	0.18	1.60
	2.5 to 3.0	0.53	0.78	2.74	0.42					0.19	0.20	0.15	0.15	1.12
90/510 S Medical Lake RD O-xing	0.0 to 0.5	2.34	4.30	5.27	5.29					5.90	5.34	7.29	6.67	4.30
	0.5 to 1.0	0.13	0.90	1.40	1.70					2.52	2.45	2.45	1.44	1.03
	1.0 to 1.5	0.23	0.17	0.48	1.22					0.91	2.05	0.28	0.13	0.53
	1.5 to 2.0	0.54	0.42	1.73	2.28					0.71	2.63	1.29	0.14	1.24
	2.0 to 2.5	0.47	1.65	2.31	1.79					1.96	1.69	3.79	0.54	1.56
	2.5 to 3.0	0.19	1.11	1.89	2.48					2.63	2.87	4.84	1.27	1.42

* Depth from ovelay surface (in.)

Table 6. (cont.).

Bridge No. and Name	Sample Number / * Depth	Free of Cracks 1	Free of Cracks 2	Free of Cracks 3	Free of Cracks 4	Free of Cracks 5	Free of Cracks 6	Free of Cracks 7	Free of Cracks 8	At Cracks 1	At Cracks 2	3" from Cracks 1	3" from Cracks 2	Avg. of Samples Free of Cracks
90/512 S NP Ry O-xing	0.0 to 0.5	6.14	3.58	2.51	5.68					6.25	5.43	5.80	6.14	4.48
	0.5 to 1.0	3.05	0.69	0.35	2.52					3.31	2.52	2.85	2.21	1.65
	1.0 to 1.5	0.28	1.16	0.72	4.35					2.40	2.20	4.68	5.35	1.63
	1.5 to 2.0	0.52	1.01	1.99	2.36					4.44	3.02	5.14	3.14	1.47
	2.0 to 2.5	0.37	0.67	2.28	2.41					4.24	2.85	5.33	2.92	1.43
	2.5 to 3.0	0.41	0.45	0.31	1.44					3.43	2.00	2.95	2.58	0.65
20/211 S Swinomish-D. Berentson Br	0.0 to 0.5	4.70	2.06	6.19	4.74	4.38	6.83			5.55		3.80		4.82
	0.5 to 1.0	0.45	0.25	0.80	1.04	0.30	1.11			2.77		0.20		0.66
	1.0 to 1.5	2.13	2.27	1.07	4.28	0.22	3.23			2.85		0.71		2.20
	1.5 to 2.0	4.17	2.74	4.60	4.25	3.12	4.50			4.67		3.15		3.90
	2.0 to 2.5	3.03	2.32	5.27	3.03	0.62	4.28			5.20		6.24		3.09
	2.5 to 3.0	2.09	1.87	3.86	2.75	0.53	3.41			5.61		4.89		2.42
2/311 Pine Cr. Bridge	0.0 to 0.5	2.42	2.08	1.06	2.07	1.03	1.86			2.25		2.86		1.75
	0.5 to 1.0	0.34	0.32	0.72	0.73	0.20	0.17			0.49		0.25		0.41
	1.0 to 1.5	0.22	1.87	0.94	2.08	1.49	0.57			0.58		0.20		1.39
	1.5 to 2.0	0.18	2.49	2.49	2.45	2.77	2.27			0.48		0.20		2.11
	2.0 to 2.5	0.15	1.44	2.37	1.73	3.25	1.29			0.30		0.57		1.71
	2.5 to 3.0	0.24	0.71	2.31	1.74	1.66	0.21			0.59		0.70		1.15

* Depth from ovelay surface (in.)

Table 7. Chloride Content (lbs/cu. yd.) in Low-Slump, Dense Concrete Overlaid Test Bridges

Bridge No. and Name	Sample Number / * Depth	Free of Cracks								At Cracks		3" from Cracks		Avg. of Samples Free of Cracks
		1	2	3	4	5	6	7	8	1	2	1	2	
90/91 N South Fork Snoqualmie R.	0.0 to 0.5	6.21	3.41	4.18	5.25					4.56	5.33	5.00	6.32	4.76
	0.5 to 1.0	1.26	0.69	0.60	0.50					3.72	1.55	1.06	0.54	0.76
	1.0 to 1.5	0.55	0.35	0.48	0.52					0.64	1.21	0.22	0.24	0.48
	1.5 to 2.0	2.48	1.10	0.50	2.46					0.40	1.29	0.36	0.30	1.64
	2.0 to 2.5	2.90	3.95	2.47	2.56					1.62	2.30	1.98	2.03	2.97
	2.5 to 3.0	2.30	2.85	2.28	1.66					2.25	2.13	2.67	3.32	2.27
90/106 N Gold Cr.	0.0 to 0.5	3.90	2.87	4.60	4.25	3.37	4.36	4.27	4.46					4.01
	0.5 to 1.0	2.48	1.44	3.32	3.27	2.21	3.04	2.02	1.55					2.42
	1.0 to 1.5	1.29	0.51	3.91	5.89	1.73	3.06	1.94	2.01					2.54
	1.5 to 2.0	1.84	0.67	5.26	5.43	3.54	5.63	2.99	4.32					3.71
	2.0 to 2.5	4.38	1.49	5.55	6.02	4.26	4.46	5.93	6.12					4.78
	2.5 to 3.0	4.90	2.51	4.03	3.25	3.83	3.47	4.95	5.59					4.07
90/124 S Lake Valley RD O-C	0.0 to 0.5	3.21	5.18	3.36	3.70					3.39	4.11	4.56	5.64	3.86
	0.5 to 1.0	1.22	2.69	1.07	1.79					2.92	2.41	2.59	1.97	1.69
	1.0 to 1.5	3.14	2.35	0.95	0.26					0.98	0.93	1.57	0.85	1.68
	1.5 to 2.0	1.54	3.73	1.53	0.17					0.26	0.57	1.56	0.30	1.74
	2.0 to 2.5	3.81	4.76	1.28	0.99					0.25	0.36	2.74	0.20	2.71
	2.5 to 3.0	2.64	4.80	1.23	1.75					0.39	0.65	3.03	0.60	2.61

* Depth from ovelay surface (in.)

Table 7. (cont.).

Bridge No. and Name	Sample Number / * Depth	Free of Cracks 1	Free of Cracks 2	Free of Cracks 3	Free of Cracks 4	Free of Cracks 5	Free of Cracks 6	Free of Cracks 7	Free of Cracks 8	At Cracks 1	At Cracks 2	3" from Cracks 1	3" from Cracks 2	Avg. of Samples Free of Cracks
90/150 S S. Taneum Cr.	0.0 to 0.5	1.55	0.80	2.75	0.88					3.57	3.69	3.92	3.54	1.50
	0.5 to 1.0	0.40	0.24	0.77	0.14					0.95	0.96	0.48	0.25	0.39
	1.0 to 1.5	0.15	0.34	1.74	0.18					0.83	0.79	0.43	0.18	0.60
	1.5 to 2.0	0.30	0.34	4.17	1.11					0.55	0.83	0.25	0.22	1.48
	2.0 to 2.5	1.38	0.61	3.81	0.90					0.52	0.90	0.33	0.18	1.68
	2.5 to 3.0	1.25	1.49	6.27	2.29					0.33	1.11	0.27	0.30	2.83
90/160 S S. Reeser Cr.	0.0 to 0.5	6.70	2.63	1.96	2.08	4.65				6.30	5.46	5.83		3.60
	0.5 to 1.0	1.40	0.23	0.20	0.11	0.70				1.48	1.32	0.58		0.53
	1.0 to 1.5	3.90	0.32	0.26	0.28	0.40				1.24	3.37	0.23		1.03
	1.5 to 2.0	5.81	1.24	0.82	1.04	2.27				2.30	6.00	2.70		2.24
	2.0 to 2.5	5.52	1.55	0.95	1.99	5.63				4.31	4.89	5.00		3.13
	2.5 to 3.0	3.83	1.20	0.96	1.32	5.83				4.63	4.96	3.00		2.63
90/162 N N. Wilson Cr.	0.0 to 0.5	5.40	8.91	3.42	6.52					10.01	10.47	9.72	8.96	6.06
	0.5 to 1.0	1.00	1.83	0.35	1.01					2.64	3.78	2.54	3.42	1.05
	1.0 to 1.5	0.51	1.02	0.21	0.16					0.33	2.95	1.62	1.83	0.48
	1.5 to 2.0	0.48	2.28	1.08	0.28					2.02	3.27	1.92	3.42	1.03
	2.0 to 2.5	1.96	5.29	1.80	0.17					0.86	5.84	1.10	3.42	2.31
	2.5 to 3.0	4.00	5.50	1.68	0.24					0.42	5.87	0.34	6.10	2.86

* Depth from ovelay surface (in.)

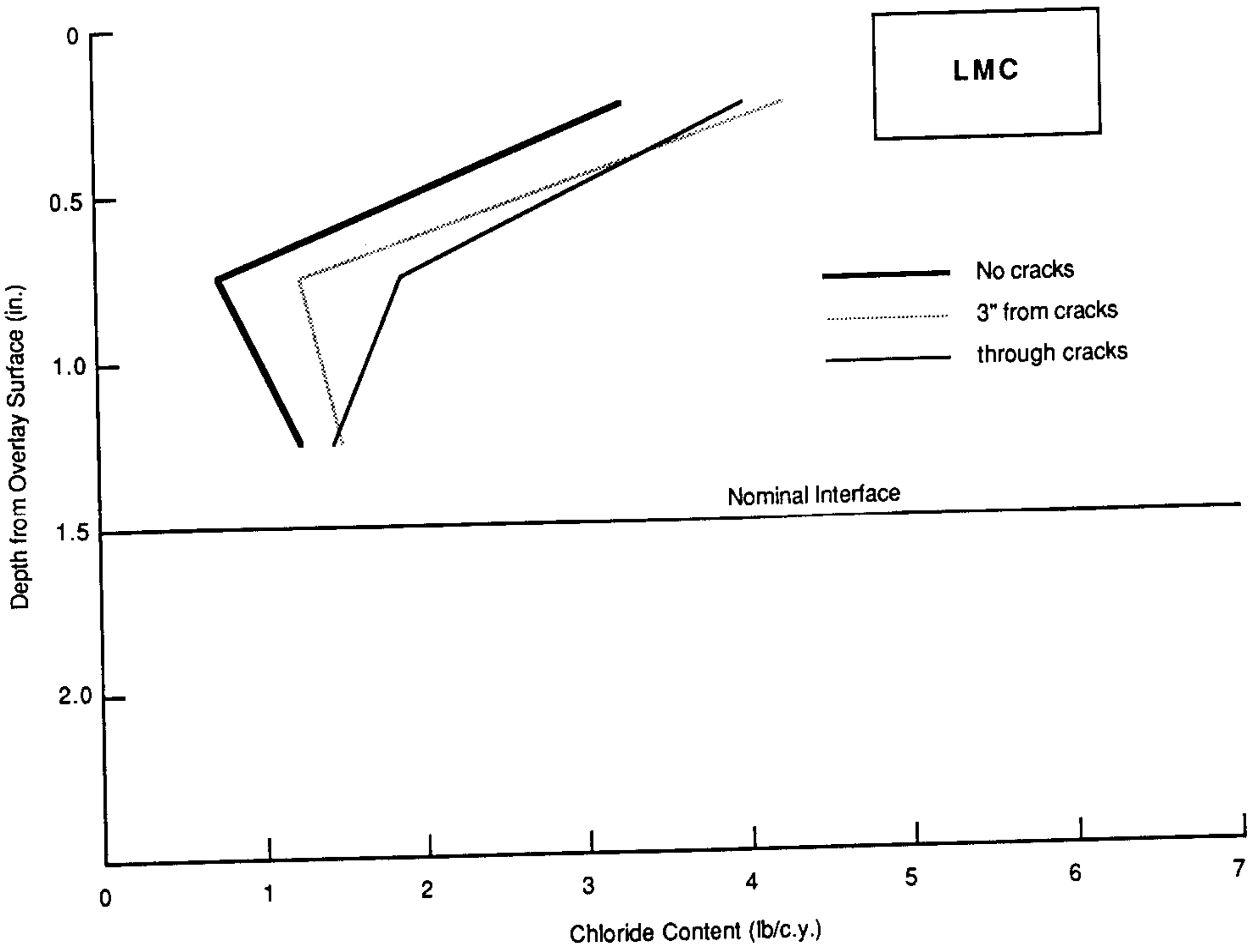

Figure 2. Average Chloride Content of Latex-Modified Concrete Overlays

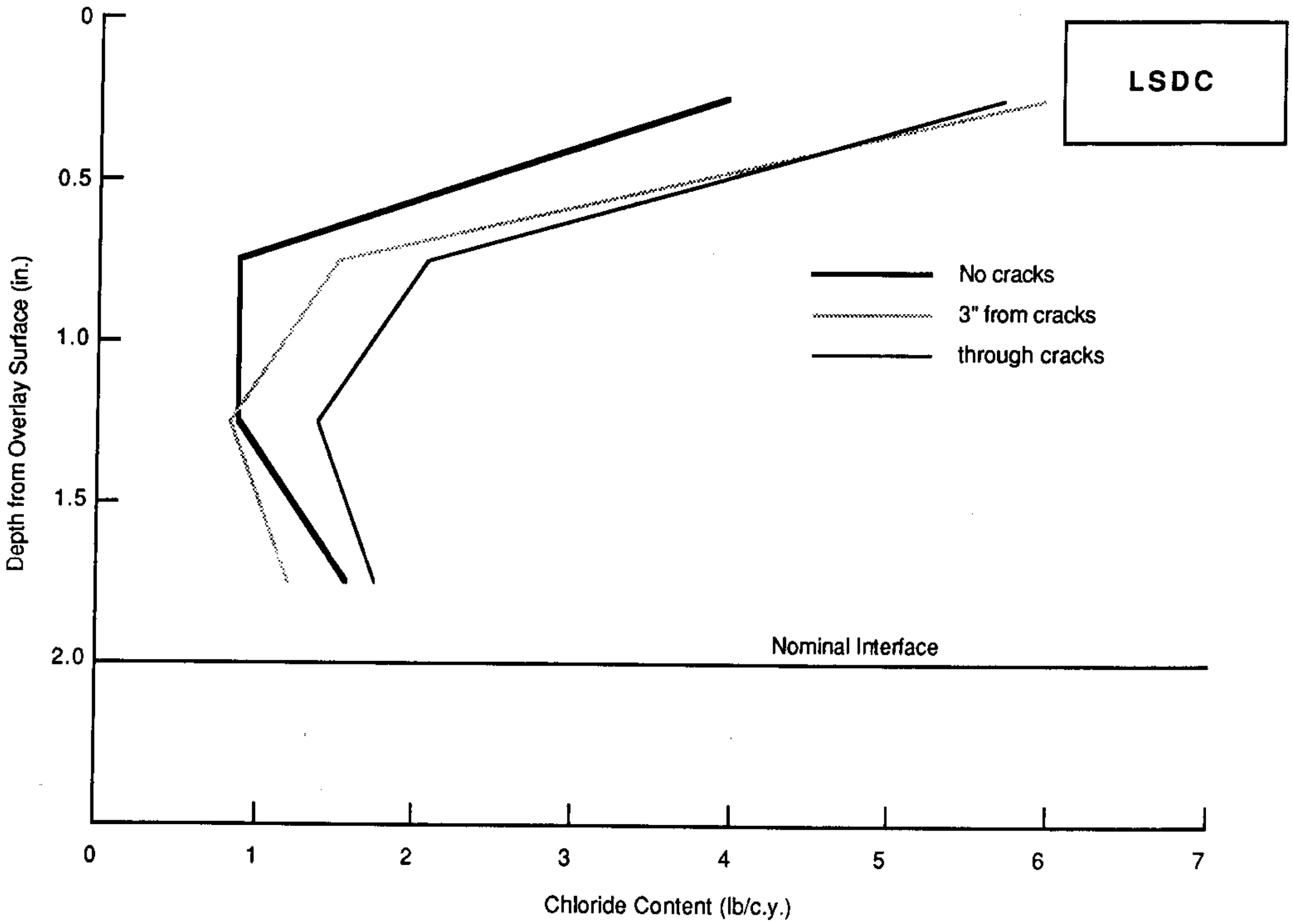

Figure 3. Average Chloride Content of Low-Slump, Dense Concrete Overlays

Discussion

In order to evaluate the degree to which overlays prevent chloride penetration, one needs to know the gradient of chloride content in the overlays with depth. Figure 2 and Figure 3 show that large amounts of chlorides were deposited in the surface and consequently existed in the upper 0.5-inch of the LMC and LSDC overlays. However, the chloride content sharply decreased in the second 0.5-inch layer below the surface. For the LMC decks, the chloride content of the third 0.5-inch layer below the surface may not necessarily represent the chloride content in the overlays. This is because of the possible variation in the overlay's actual thickness as well as difficulties in obtaining powdered concrete samples for chloride analysis at exactly the specified depth. Thus, the third layer below the surface of the LMC overlays may have contained some of the highly chloride contaminated concrete of the surface of the underlying deck. The same is true for LSDC decks, but for the fourth 0.5-inch layer below the surface. This explains a slight increase in the chloride content in the bottom 0.5-inch layer of the LMC and LSDC overlays, as indicated in Figure 2 and Figure 3.

The Chloride Permeability of Uncracked versus Cracked Overlays. The chloride content profile for crack-free LMC in Figure 2 shows that a 1-inch-thick LMC reduced the chloride content of the deck to a level below 1 pound per cubic yard of concrete. This figure is even smaller if the native chloride content in the overlay concrete, usually about 0.30 lb/c.y., is considered. Figure 3 shows that a crack-free, 1.5-inch LSDC overlay had the same chloride proofing ability. Since the LMC overlays were 1.5 inches thick and LSDC overlays 2.0 inches thick, the possibility of post-overlaying chloride contamination of the underlying decks would have been negligible after an average of five years of exposure to salt (if cracks are ignored). Figure 2 and Figure 3 indicate that at the cracks, as well as near the cracks (3 inches from the cracks), the chloride content also decreased as the depth in the overlays increased, a trend similar to crack-free concrete. However, the content of chlorides was higher for a given depth in and near the cracks than for the crack-free concrete. As the depth in the overlays increased, the chloride profile of the concrete in cracked regions converged with that of the sound concrete. The rate of decrease in chlorides with depth was higher for the concrete near the cracks than for the concrete coinciding with the cracks. This discussion shows that although cracks and areas near them have allowed the intrusion of more chlorides into the overlays, mainly in the regions closer to the surface, the chloride intrusion in the underlying concrete decks is not yet sufficient to cause significant contamination after an average of five years of exposure.

Amount of Time until Contamination Occurs in Underlying Decks. LMC and LSDC are not totally impermeable to salt infiltration. Therefore, contamination of the underlying concrete can be expected over time, depending on the rate of salt application. The Department's current maximum salt usage on its roads is about 2.5 tons per lane-mile per year (13). Assuming that bridges, due to their special environment, receive twice as much salt as roads, the maximum amount of salt applied on the WSDOT bridges may be assumed to be 5 tons per lane-mile per year. The question arises that if the underlying decks were originally uncontaminated, how long would it take until chlorides reached the corrosion threshold level in the concrete surrounding the rebar? Or, in general, what would be the rate of chloride increase at the rebar level? The rapid chloride permeability tests conducted on the core samples taken from the overlays and their underlying decks gave clues to the answer.

The results of the rapid chloride permeability tests of 2-inch standard samples are given in Table 8 for LMC bridges and in Table 9 for LSDC bridges. For the six LMC overlays, the average permeability was 367 coulombs, and for the six LSDC overlays the average permeability was 1,364 coulombs. For the 12 underlying decks (base concrete) the average permeability was 2,494 coulombs, excluding the unusually high permeabilities obtained for the base concrete of Bridge 90/106 N (see Table 9). Figure 4 gives the permeability of different types of concrete made in the laboratory in coulombs (12). By inserting the average permeability numbers obtained for the overlays and underlying decks in Figure 4, one finds that the permeability of the LMC overlays was not higher than that of laboratory-made LMC, the permeability of the LSDC overlays represented the permeability of a

Table 8. Rapid Chloride Permeability Test Results for Six Latex-Modified Concrete Overlaid Bridge Decks

Bridge Number	Permeability (coulombs)			
	Core Sample 1		Core Sample 2	
	Overlay	Base	Overlay	Base
90/96.5	1117	3672	863	2923
90/174 S	240	1865	126	1987
90/510 S	291	1801	273	1897
90/512 S	258	1851	313	1792
20/211 S	284	3860	301	2929
2/311	101	---	236	2342

Table 9. Rapid Chloride Permeability Test Results for Six Low-Slump, Dense Concrete Overlaid Bridge Decks

Bridge Number	Permeability (coulombs)			
	Core Sample 1		Core Sample 2	
	Overlay	Base	Overlay	Base
90/91 N	908	4754	1308	5153
90/106 N	1630	10580	3024	6840
90/124 S	1199	3694	1302	3866
90/150 S	438	1700	930	2437
90/160 S	826	1507	789	—
90/162 N	1684	2970	2326	1862

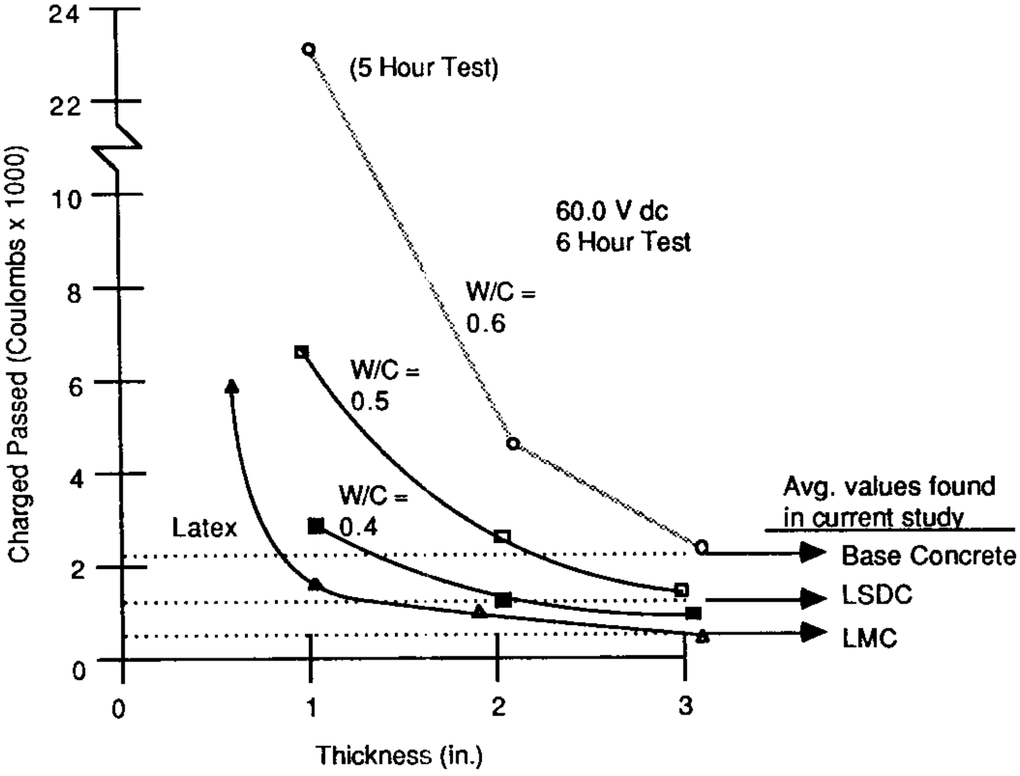

Figure 4. Effect of Core Thickness on Charge Passed in Rapid Chloride Permeability Tests [adapted from Ref.12]

concrete with an approximately 0.40 water/cement ratio, and the permeability of the underlying decks represented the permeability of a concrete with an approximately 0.48 water/cement ratio.

Research has shown that for a system made of 1.5-inch LMC, or a 2-inch LSDC representing a water/cement ratio of 0.40, placed on a concrete deck representing a water/cement ratio of 0.48 and with a specified rebar cover depth of 1.5 inches (a condition similar to WSDOT's existing bridge decks), the number of years until chlorides reach the corrosion threshold level of 1.50 lb/c.y. in 5 percent of deck area may be about 120 if annual salt exposures are about 5 tons per lane-mile (13). This finding is based on the condition that 5 percent of the deck area has a rebar cover depth smaller than the specified value minus 0.65 inch, which generally represents the rebar cover depth distribution in bridge decks. Therefore, LMC and LSDC overlays applied on the WSDOT bridges will probably not permit a post-overlaying increase in contamination in excess of 1.50 lb/c.y. for 120 years. This translates into an average increase in chloride content at the rebar level of about 0.13 lb/c.y. every ten years, which is insignificant. However, higher chloride increase rates can be expected if salt exposures are higher than the assumed figure.

Nevertheless, both LMC and LSDC overlays develop cracks that allow chloride intrusion. Although in the early years of a deck's service small crack widths and depths may prevent the intrusion of chlorides, long-term exposure, such as ten years, negate the influence of crack width in the prevention of chloride intrusion (14). Additionally, cracks can widen, deepen, and lengthen over time. The influence of cracking on chloride intrusion may be noticed in Figure 2 and Figure 3 for the LMC and LSDC overlays after an average service period of only five years. Performance information shows that up to 89 percent of an overlay's area can crack after five years of service (see Table 3 for Bridge 90/160 S, LSDC). This roughly correlates to 312 feet of cracking per 1,000 square feet of deck area with the use of a multiplier of 3.5 found by regression analysis (13). Assuming that each crack can contaminate concrete 3 inches from the crack in each horizontal direction, the total area of the underlying deck that chlorides can contaminate before the effective service life of the concrete overlay is over (usually from 15 to 20 years) is 16 percent of the deck area. Therefore, sealing the cracks as soon as they form is a valuable preventive maintenance measure. Low-modulus polymer materials may be employed to seal the cracks whose widths do not change markedly under environmental loading. Minnesota DOT and Kansas DOT have sealed cracks using polymers.

WATER CONTENT DETERMINATION

Findings

Powdered concrete samples were taken by 1/2-inch-diameter rotary hammer at different locations and depths from each overlay and its underlying deck to determine their water content in the laboratory. The sampling procedure was similar to obtaining concrete samples for chloride analysis. The samples, however, were taken only in crack-free areas. This sampling procedure results in loss of some water from the powdered concrete in the field due to heat generated by the hammer. Nevertheless, the data obtained using this procedure can be considered to represent the relative moisture content of each deck as compared to the other decks in the study. The data from the water content tests are given in Table 10 for the six LMC bridges and Table 11 for the six LSDC bridges.

Discussion

Plots of average concrete water content versus depth for the six LMC bridges and six LSDC bridges are shown in Figure 5. These show that the water content was higher in the cores of the concrete decks than near their surfaces. This is normal since water evaporates from the surface during dry weather. Assuming that conventional concrete of the type used in the underlying decks saturates at about 5.5 percent water by weight of the concrete, the average water content at a depth of 2.75 inches to 4.0 inches was 2.20 percent (or 40 percent of saturation) for decks under LMC overlays and 3.06 percent (or 56 percent of saturation) for decks under LSDC overlays. As discussed previously, these figures do not account for the amount of water lost due to the sampling procedure. As indicated in Figure 5, decks overlaid with LSDC had about 1 percent by weight of the concrete more water than

Table 10. Moisture Content (weight, percent) in Latex-Modified Concrete Overlaid Test Bridges

Bridge No. & Name	Depth (in.)	Shoulder Water Content	Wheel Path Water Content
90/96.5 Denny Cr. Rd O-xing	0.25 - 1.5 1.5 - 2.75 2.75 - 4.0	1.59 2.47 2.06	2.26 2.95 1.97
90/174 S Renslow Br.	0.25 - 1.5 1.5 - 2.75 2.75 - 4.0	2.06 2.53 3.45	2.26 3.23 3.51
90/510 S Medical Lake Rd O-xing	0.25 - 1.5 1.5 - 2.75 2.75 - 4.0	1.73 2.28 1.74	1.62 3.05 2.18
90/512 S N.P. Ry O-xing	0.25 - 1.5 1.5 - 2.75 2.75 - 4.0	1.58 1.41 1.93	1.51 1.98 1.55
20/211 S Swinomish D Barenston Br.	0.25 - 1.5 1.5 - 2.75 2.75 - 4.0	1.49 1.73 2.70	1.51 2.86 2.11
2/311 Pine Cr.	0.25 - 1.5 1.5 - 2.75 2.75 - 4.0	0.91 0.91 1.03	0.39 0.94 2.20
Average of six bridges	0.25 - 1.5 1.5 - 2.75 2.75 - 4.0	1.58 2.20 2.20	

Table 11. Moisture Content (weight, percent) in Low-Slump, Dense Concrete Overlaid Test Bridges

Bridge No. & Name	Depth (in.)	Shoulder Water Content	Wheel Path Water Content
90/91 N South Fork Snoqualmie R.	0.25 - 1.5	2.66	1.98
	1.5 - 2.75	3.35	2.95
	2.75 - 4.0	2.69	3.26
90/106 N Gold Cr.	0.25 - 1.5	2.85	3.00
	1.5 - 2.75	3.37	3.98
	2.75 - 4.0	3.10	3.35
90/124 S Lake Valley Rd OC	0.25 - 1.5	2.79	2.17
	1.5 - 2.75	3.28	3.24
	2.75 - 4.0	3.15	3.66
90/150 S S. Taneum Cr.	0.25 - 1.5	2.34	2.77
	1.5 - 2.75	2.95	2.44
	2.75 - 4.0	2.44	2.86
90/160 S S. Reeser Cr.	0.25 - 1.5	3.30	2.40
	1.5 - 2.75	4.13	3.45
	2.75 - 4.0	3.00	2.46
90/162 N North Wilson Cr.	0.25 - 1.5	3.06	3.58
	1.5 - 2.75	3.90	4.21
	2.75 - 4.0	3.52	3.18
Average of six bridges	0.25 - 1.5	2.74	
	1.5 - 2.75	3.44	
	2.75 - 4.0	3.06	

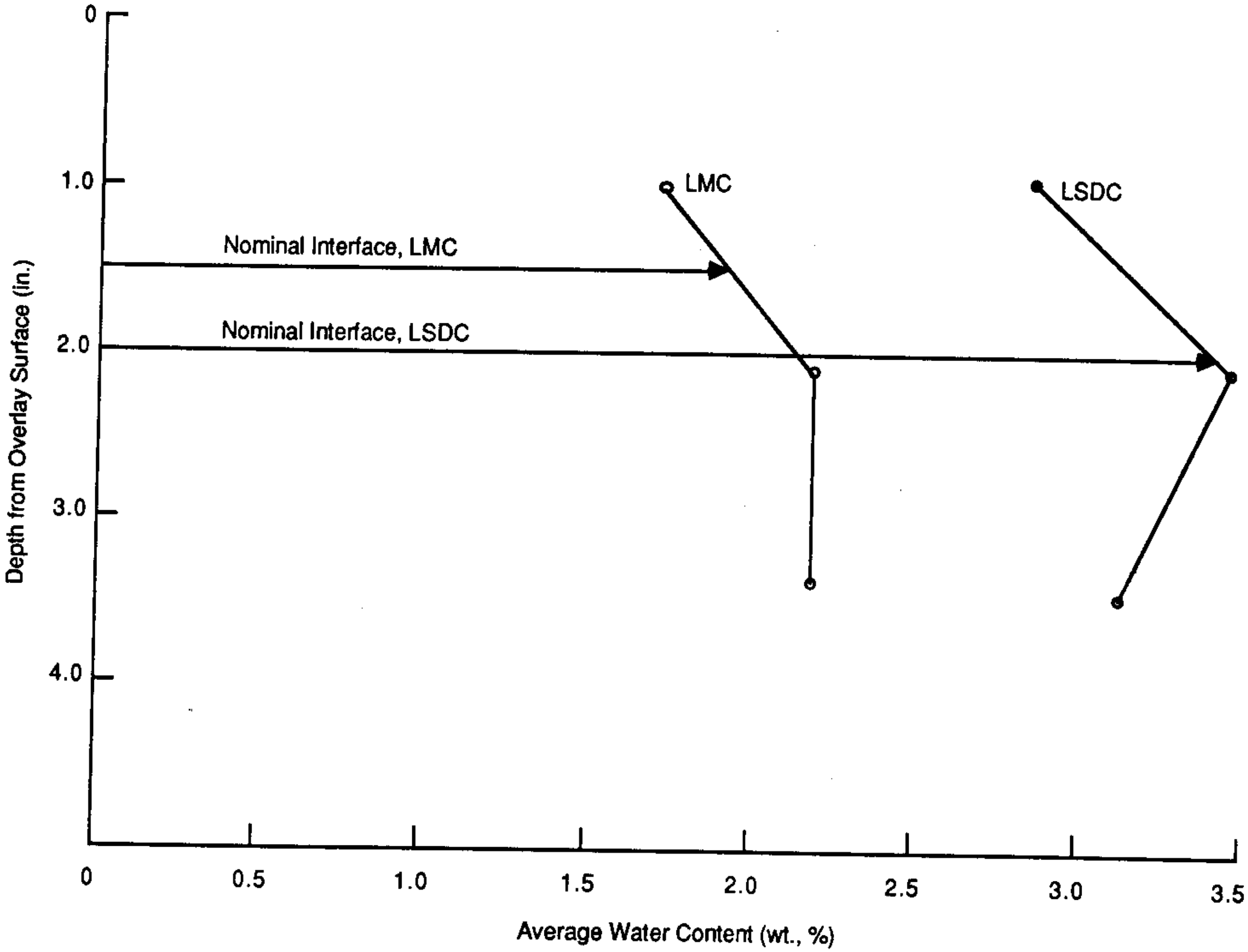

Figure 5. Average Water Content of Six Latex-Modified Concrete and Six Low-Slump, Dense Concrete Overlaid Bridges

those overlaid with LMC. This additional water in LSDC decks was present throughout the depth of the overlays as well as in the underlying decks. The implications of this finding are as follows:

- decks under LSDC overlays are wetter than those under LMC overlays;
- the additional water in the decks under LSDC overlays must have penetrated from the overlay surface. Therefore, the concrete overlays may permit water to intrude into the underlying concrete; and
- since there is no evidence that in the crack-free LSDC chlorides have penetrated the underlying concrete, concrete may be able to screen out chlorides while permitting some water to seep.

CORROSION AND DELAMINATION

Findings

One-third of the decks overlaid with LMC and two-thirds of the decks overlaid with LSDC were delaminated or their concrete was deteriorated in association with rebar corrosion (see Table 2 and Table 3). The delaminations were detected by chain dragging and verified by the half-cell corrosion detection test and spot coring. The largest percentage of delamination among the LMC decks was 4.38 percent of the deck area (Bridge 90/510 S) and the largest percentage of delamination among the LSDC decks was 5.86 percent of the deck area (Bridge 90/162 N). These figures correspond to four years of service for the LMC deck and five years of service for the LSDC deck.

Table 12 compares the average annual pre- and post-overlaying concrete deterioration rates for the delaminated LMC and LSDC decks. The pre-overlaying deterioration rates were obtained by dividing the percent of the rehabilitated area for each deck (see Table 2 and Table 3) by the age of the bridge at the time it was rehabilitated and overlaid. The post-overlaying delamination rates were determined by dividing the percent of the delaminated area of the deck by the age of the overlay at the time it was tested. Table 12 shows that the post-overlaying deterioration rates for two LMC and one LSDC deck were higher than their pre-overlaying deterioration rates.

Table 12. Comparison of Pre- and Post-Overlaying Concrete Deterioration Rates for the Delaminated LMC and LSDC Decks

Type of Overlay	Bridge Number	Average Annual Deterioration (%)	
		Before Overlaying	After Overlaying
LMC	90/510 S	0.94%	1.10%
	90/512 S	0.11%	0.97%
LSDC	90/124 S	0.79%	0.15%
	90/150 S	0.54%	0.67%
	90/160 S	0.08%	0.01%
	90/162 N	1.27%	1.17%

░ Post-overlaying deterioration rate larger than pre-overlaying deterioration rate

Characteristics of Delaminated Concrete. The delaminations in the overlaid decks existed on the roadways and did not extend into the shoulders. The only exception to this was the deck with the worst delaminations among the sample tested (i.e., Bridge 90/162 N, LSDC). This bridge had a small delaminated area on its shoulder. No spalling of the delaminated areas in the overlaid decks was noticed during the testing. Another important characteristic of the delaminated concrete was that its half-cell potential was higher than that of the adjacent areas. Table 13 compares the half-cell potential readings of the delaminated bridge decks obtained at the grid points only and obtained at the grid points and the delaminated locations. As shown in the table, when the half-cell survey includes the delaminated locations, the percentage of questionable potentials (between -0.20 Volts and -0.35 Volts) and active potentials (more negative than -0.35 Volts) increases.

An explanation for the characteristics of the delaminated concrete is that wheel loads greatly contribute to the growth of incipient deterioration induced initially by corrosion. As the amount of the deterioration increases, it in turn promotes more corrosion by facilitating the diffusion of moisture and oxygen into the delaminated concrete. In other words, corrosion and deterioration around the rebar promote each other.

Discussion

The Influence of Chlorides and Surface Cracking on Delamination. All of the delaminated decks were contaminated with chlorides prior to being overlaid (see Table 2 and Table 3). However, not all of the contaminated/overlaid decks were delaminated. Examples are two LMC bridges (Bridge 20/211 S and Bridge 2/311, Table 2) and one LSDC bridge (Bridge 90/106 N, Table 3). An important characteristic of the contaminated/overlaid decks without delamination or with insignificant delamination was that they either did not have cracks in the overlay or the cracking was not significant. Cracking may accelerate corrosion-induced delamination by periodically facilitating the intrusion of new water and oxygen (mixed with water) into the originally chloride-contaminated decks upon their

Table 13. Comparison of Half-Cell Potential Readings of Delaminated Decks Obtained at Grid Points Only and at Grid Points and Delaminated Areas

Type of Overlay	Bridge No.	Half-cell (% of readings) (1)			Delamination (% of test area)
		<0.20 (v)	0.20 - 0.35 (v)	>0.35 (v)	
		Grid Points Only Grid Points and Delaminations			
LMC	90/510 S	69% 59%	30% 35%	1% 6%	4.38%
	90/512 S	77% 66%	22% 30%	2% 4%	3.88%
LSDC	90/124 S	100% 99%	0% 1%	0% 0%	1.04%
	90/150 S	53% 48%	46% 49%	1% 3%	2.00%
	90/160 S	100% 100%	0% 0%	0% 0%	0.05%
	90/162 N	64% 57%	34% 37%	2% 6%	5.86%

(1) Negative sign eliminated

drying. The depth of overlay cracks in the bridges tested, as discussed earlier, was sufficient to allow penetration of water deep into the body of the underlying decks.

With the limited number of test bridges available, attempts were made to correlate the extent of cracking in the overlays with "average annual delamination rates" (i.e., delaminations divided by an overlay service period), as shown in Figure 6. In Figure 6, 15 percent cracking was arbitrarily selected as the limit below which delaminations did not exist and 50 percent cracking was selected as the limit beyond which the "average annual delamination rate" was at its highest in the originally contaminated decks. This information shows that an originally contaminated deck may develop delaminations at a rate of about 1.20 percent of the deck area per year if the overlay cracking reaches or exceeds 50 percent of the deck area. The rate of delaminations for decks with cracking from 15 to 50 percent may be from 0 to 1.20 percent of the deck area per year and may increase linearly. The validity of this finding for beyond seven years of overlay performance cannot be confirmed with the limited data available in this study. In other words, over the long term, originally contaminated decks may still delaminate in the absence of overlay cracking.

Figure 6 shows that the originally uncontaminated decks did not delaminate, regardless of the amount of cracking in their overlays. One of the decks classified as originally uncontaminated in Figure 6 had an insignificant delamination rate (0.01 percent of the area per year) and was slightly chloride contaminated prior to the overlaying (Bridge 90/160 S, LSDC). In this deck, one concrete sample out of ten had more chlorides than 2 lb/c.y., the practical corrosion threshold level. The chloride content of this sample had been 3.65 lb/c.y. and the sampling had been done at a depth of 1-1/2 to 2 inches before the deck was overlaid. In the current investigation a pachometer survey as well as direct rebar exposure showed that the rebar for this deck was about 3 inches down (not including the overlay). This condition suggested that chlorides were almost non-existent at the rebar level for this bridge and supported classifying the deck as originally uncontaminated. The pachometer survey, as well as chloride contents obtained from the underlying decks in this study, helped in

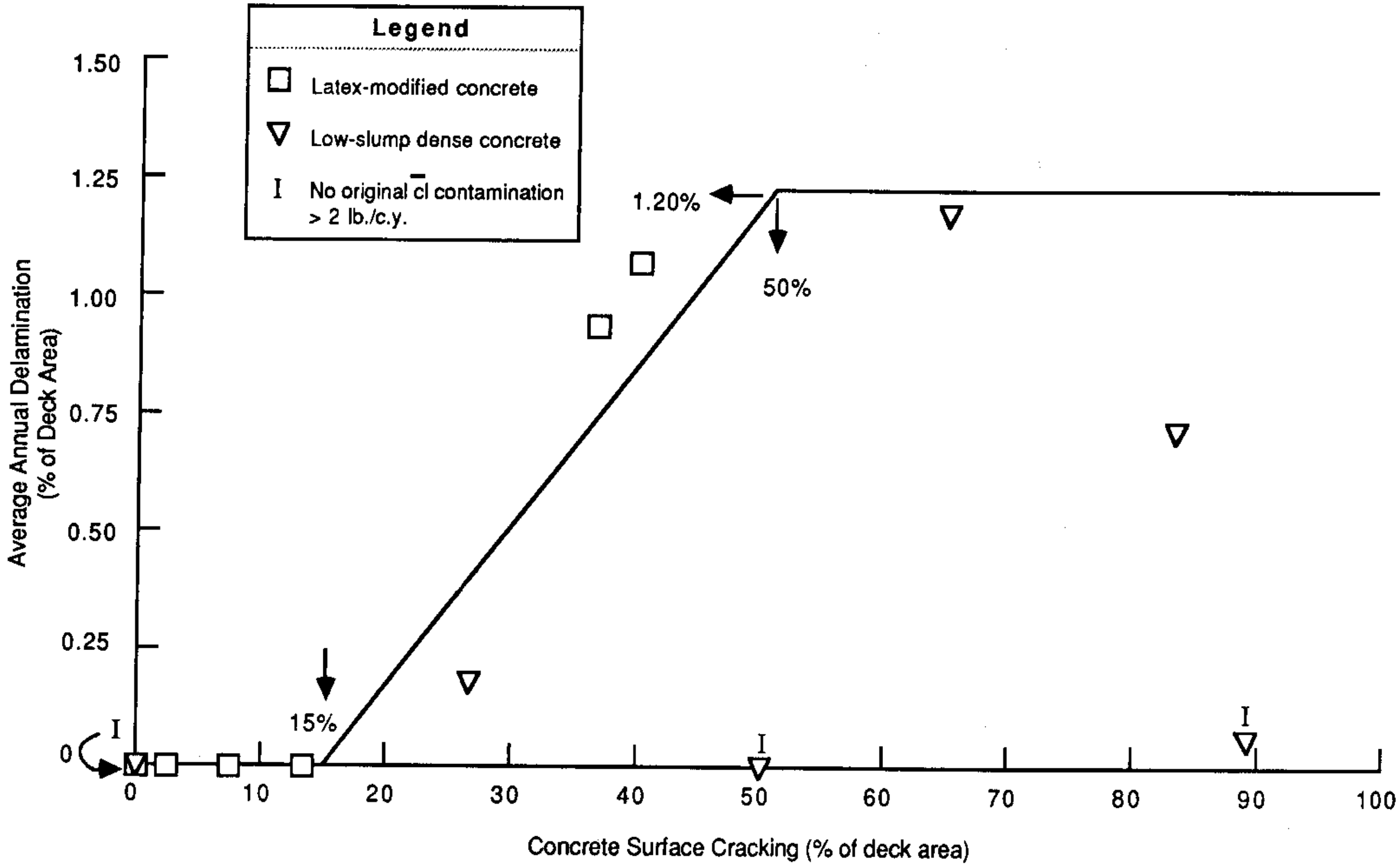

Figure 6. Correlation Between Cracking in Concrete Overlays and Continuing Delamination of Bridge Decks

evaluations of the rest of the test bridges to confirm or modify the state of their original chloride contamination at the rebar level (see Table 2 and Table 3).

Influence of Pre-Overlaying Repair on Delamination. The magnitude of concrete repairs performed before the decks are overlaid can affect the magnitude of delaminations that develop after overlaying. Figure 7 shows this relationship for the delaminated decks of this study. One reason that has been found for this relationship is that the chloride-free repair concrete actually causes rebar corrosion and subsequent concrete deterioration in the adjacent chloride-contaminated concrete (17). This type of deterioration initiates in the adjacent, old concrete, but it later can propagate into the repair area under the impact of traffic. Another reason for this type of deterioration is that removal of the deteriorated concrete may cause damage in the adjacent sound concrete because of the use of heavy hammers or from not saw cutting the perimeter of the removal area. Also, the adjacent rebar may have been initially corroded and may have caused incipient deterioration in the concrete, which might not be detected by chain dragging during inspection. Later, the impact from traffic and further corrosion can expand this incipient deterioration.

Corrosion and/or deterioration may also initiate from the concrete filled in the removal areas. If the removal area is filled with a fast-setting patch material and then overlaid, the patch may deteriorate and the rebar corrode if the patch's characteristics are different from the conventional cement concrete. Any in-place patch material should have strength, durability, and fatigue properties comparable to those of portland cement concrete. The alkalinity of the patch material must also be sufficient to prevent corrosion of rebar embedded in the patch, regardless of whether chlorides are present. On the other hand, if the removal area is filled with the overlay concrete monolithically, the concrete may not be consolidated sufficiently under the paver's screed because of its larger thickness. Extra consolidation with hand vibrators should be employed during monolithic repair to assure adequate strength and bond to the reinforcing steel.

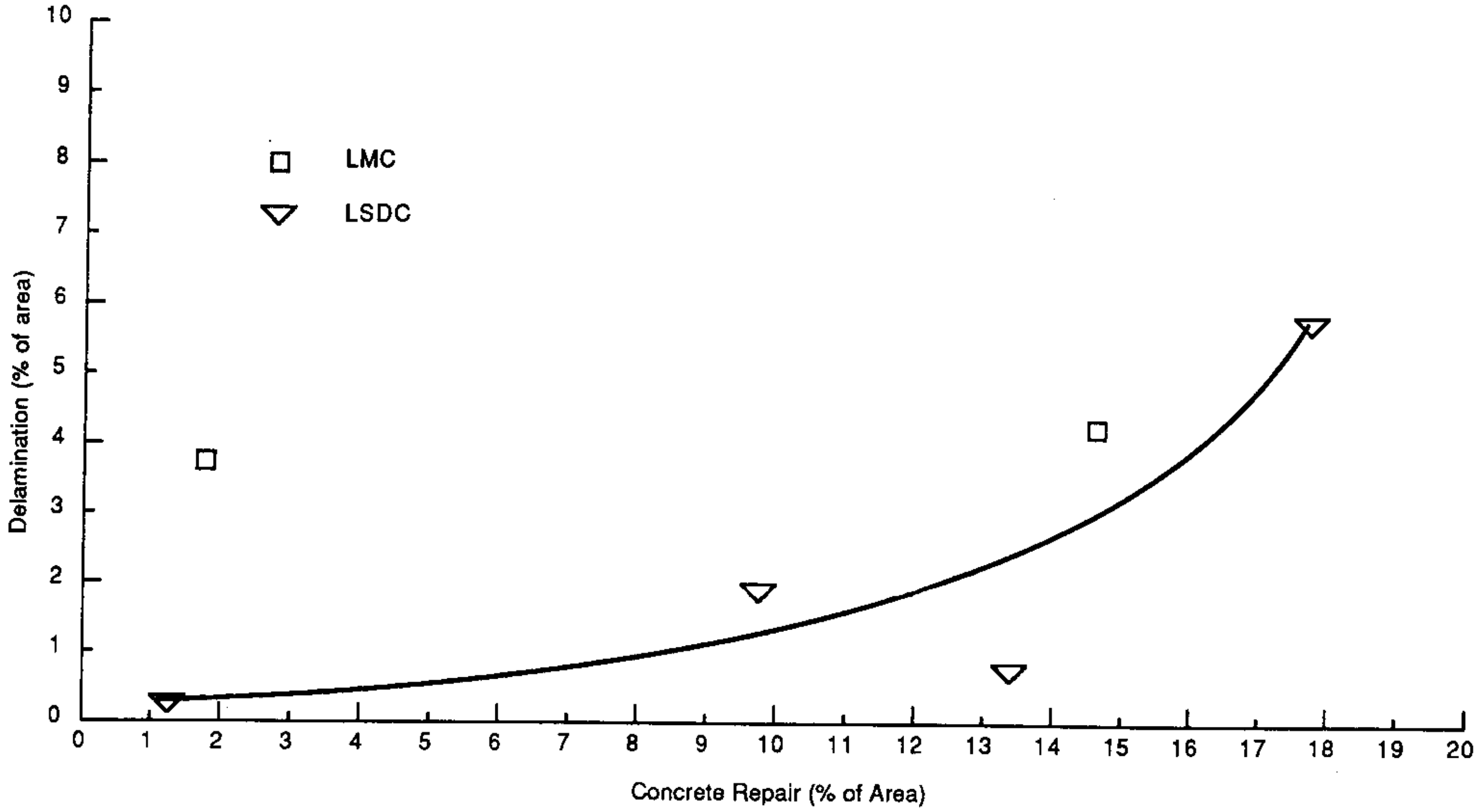

Figure 7. Relation Between Pre-Overlaying Concrete Repair and Post-Overlaying Delamination

In Figure 8 the pre-overlaying repair areas of Bridge 90/162 N (overlaid with LSDC) are superimposed with the delaminated areas detected in the current investigation. The information on the repair areas was obtained from WSDOT District 5 (15). Two types of repair in the underlying deck slab of Bridge 90/162 N can be distinguished: first, those filled monolithically with the overlay; second, those filled with fast-setting patch materials prior to overlaying. The second type of repair was done mainly to minimize construction time and disruption to traffic when deteriorated concrete over the supports of the continuous structure was removed and repaired in sequence. Two types of fast-setting materials were used. These were Gilcrete (P1 in Figure 8) and Set-45 (P2 in Figure 8). As Figure 8 shows, a portion of the delaminated areas was associated with the boundaries of the repair areas, possibly for the reasons described earlier. Also, in the areas repaired with the fast-setting materials deterioration originated from some patches.

This discussion shows that one should consider the magnitude of repair areas when predicting the post-overlaying delamination of a deck. Figure 9 was built to reflect the contribution of the magnitude of repair areas to the occurrence of delaminations. In Figure 9, delaminations of the sample bridges tested are expressed in terms of their percent of the repair area, instead of their percent of the deck area, as used for Figure 6 previously, and are correlated with the amount of overlay cracking. Similar to Figure 6, the limited data available show in Figure 9 that 15 percent cracking may be arbitrarily selected as the limit below which delamination is negligible and 50 percent cracking may be the limit beyond which delamination is at its peak. Figure 9 suggests that an originally contaminated deck may develop delaminations at an average rate of 7 percent of the repair area per year, if the overlay cracking reaches or exceeds 50 percent of the deck area. The rate of delamination for originally contaminated decks with cracking from 15 percent to 50 percent is 0 to 7 percent of the repair area per year and may increase linearly.

Figure 9 supplements Figure 6 for predicting the average annual delamination for a deck. In other words, the amount of delamination in a chloride-contaminated deck can be predicted based on

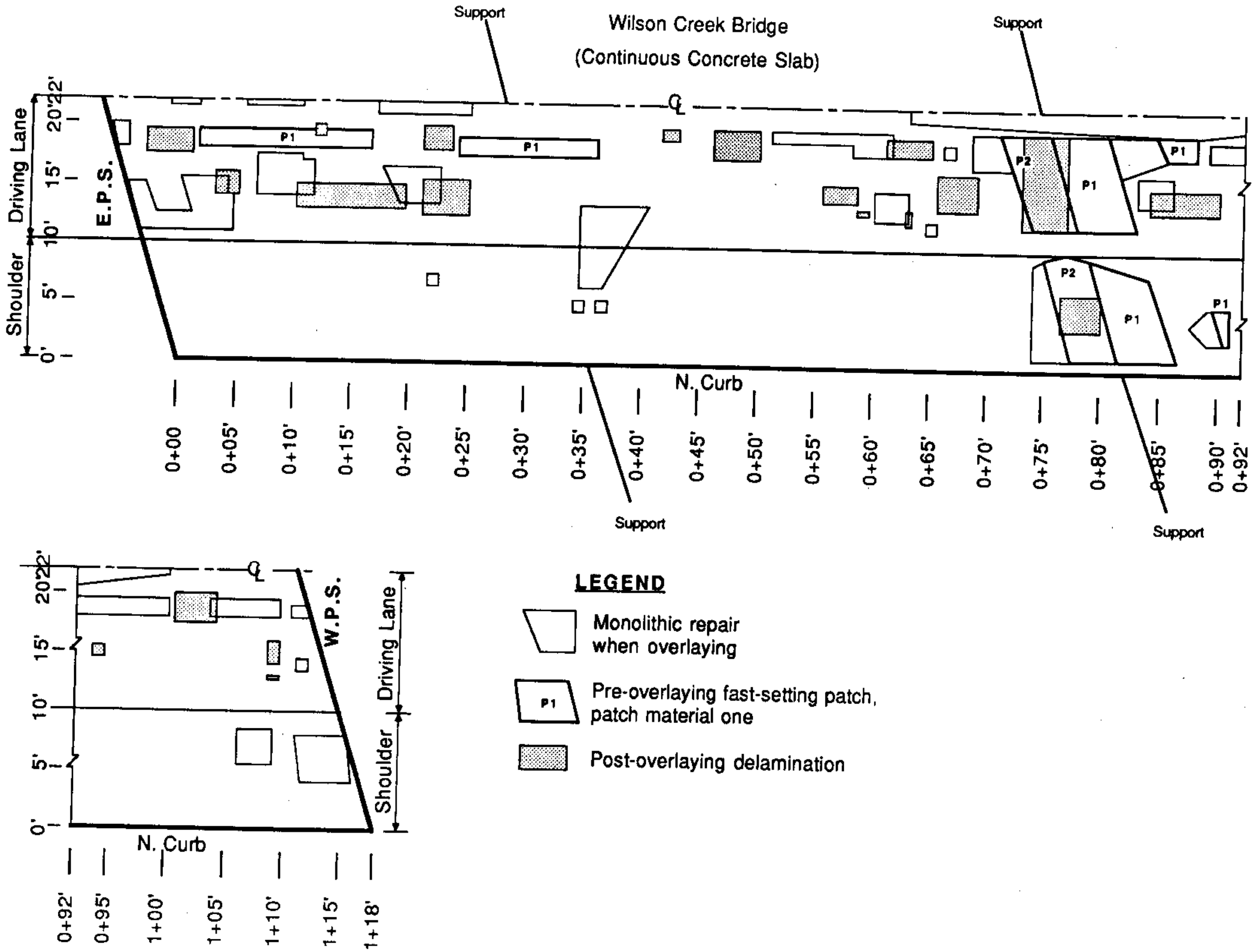

Figure 8. Superimposing Repair Areas Under Low-Slump, Dense Concrete Overlay with Delamination Detected by Chain Dragging the Overlay, Bridge 90/162 N.

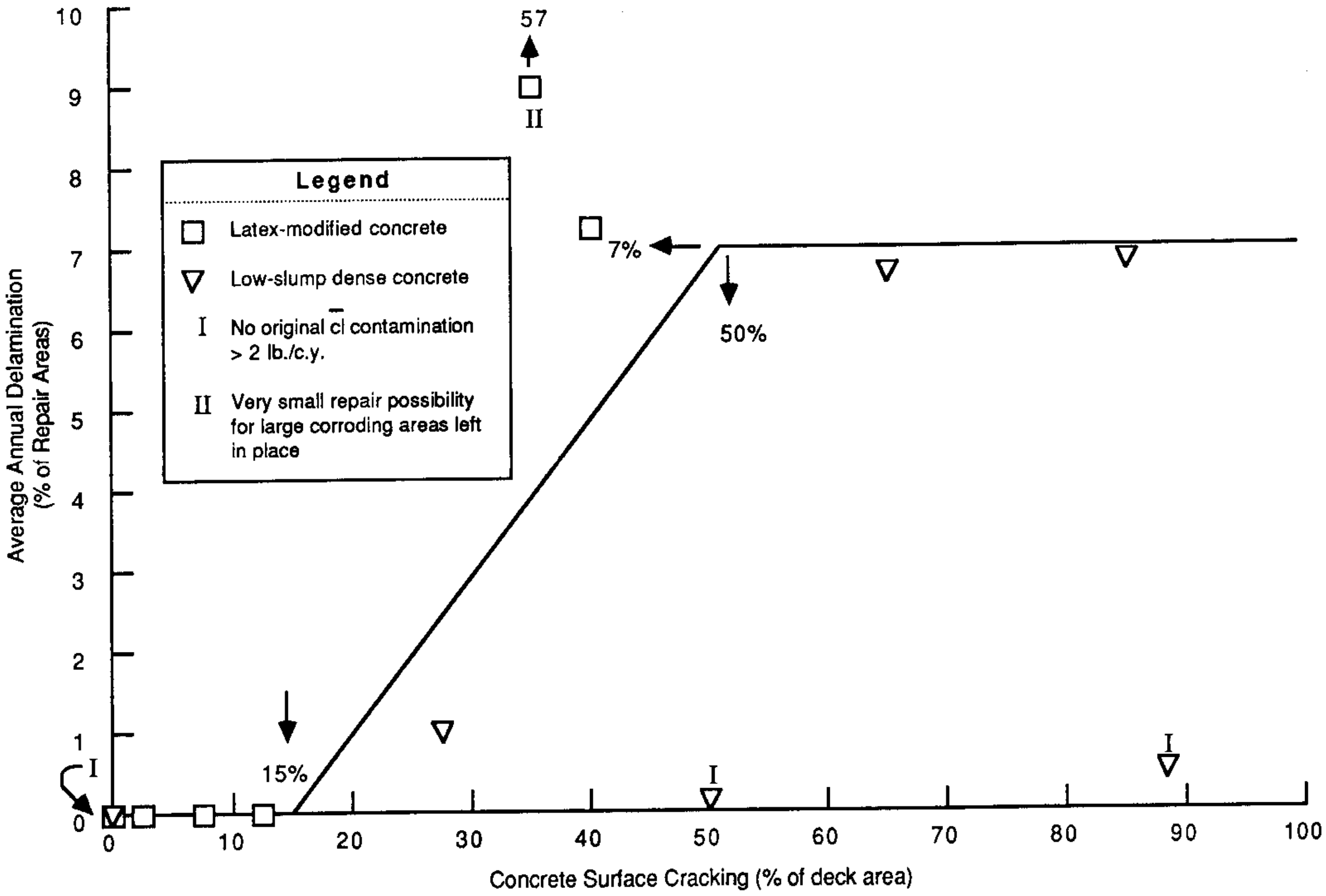

Figure 9. Correlation between Cracking in Concrete Overlays and Continuing Delamination of Bridge Decks and Extent of Repair

the magnitude of cracking (Figure 6), unless the amount of repair in the deck exceeds 17 percent of the deck area (1.2 percent (from Figure 2) divided by 0.07 (from Figure 5) equals 17 percent), in which case the average annual delamination can be conservatively predicted from Figure 9. However, use of Figure 9 is only justified as long as the repair areas do not exceed half of the deck area, as was the case with the sample tested. The increase in size of repair beyond 50 percent of the deck area may decrease the number of repair islands surrounded by the original concrete and may result in less post-overlaying deterioration. For example, when 100 percent of the deck is repaired by removing the old concrete to the rebar level and the overlay is applied on the deck, the possibility of post-overlaying delamination becomes zero. Also, note that if the concrete removal areas are patched with inferior materials, as discussed previously, deterioration within the patch may still occur regardless of whether cracks are present.

Measures to Minimize the Occurrence of Delaminations. The following measures seem to be effective in mitigating the occurrence of post-overlaying delaminations in bridge decks:

- the perimeter of the concrete removal area should be a few inches away from the perimeter of the delamination detected by chain dragging in order to remove possible incipient deterioration in the concrete;
- the perimeter of the concrete removal area should be saw cut to a depth of 1 to 2 inches. The size of concrete removal hammers should be restricted to 30-pound jackhammers above the reinforcing steel and 15-pound chipping hammers below the reinforcing steel;
- if the concrete removal area is patched with a fast-setting material, the material should have initial strength, durability (freeze-thaw and fatigue resistance), and alkalinity comparable to the properties of conventional concrete;

- polymer concrete may be used to patch concrete removal areas because it cures quickly, and because it is dielectric, insulates the steel so that the steel cannot contribute to galvanic corrosion;
- if the concrete removal area is filled monolithically with a concrete overlay, extra hand vibration should be used in the removal area; and
- if the overlay cracks after it is placed on the originally chloride-contaminated deck, the cracks should be sealed against moisture as soon as possible. Sealing may be achieved effectively by using low-modulus polymer materials. Minnesota DOT and Kansas DOT have sealed cracks using polymer materials.

CHAPTER 3

COMMENTS ON WSDOT'S BRIDGE DECK PROTECTIVE SYSTEM SELECTION CRITERIA

The findings of this study concerning the durability and impermeability of concrete overlays supports WSDOT's selection of LMC over LSDC for bridge deck protection. WSDOT's current bridge deck repair priority and protective system selection matrix is presented in Table 1. According to Table 1, decks with traffic volumes higher than 10,000 ADT, decks with chloride contamination exceeding 2 lb/c.y. in 40 percent or more of the sample tested, and decks with deterioration exceeding 5 percent or more of the deck area are protected with LMC overlays only. One reason behind the protective system selection criteria is that LMC overlays are more durable under traffic impact and they may mitigate continued corrosion of the rebar more effectively when applied on highly contaminated/deteriorated decks. Other categories of bridge decks are either protected with LMC or an asphalt concrete/membrane system, depending on each bridge's individual conditions such as the nature of its route, the depth of its rebar cover, or the surface texture on which the system is applied (see Reference 1 for more details).

The performance of the protective strategies indicates that for the same construction quality, LMC is a better choice over an asphalt concrete/membrane system when it is exposed to high traffic volumes, since

- LMC is more resistant to surface wear, rutting, and stripping, and
- LMC delays surface spalling when delaminations originate from the corroding rebar.

However, the performance of the protective strategies does not indicate that LMC can mitigate the continued corrosion of the reinforcing steel more effectively than an asphalt concrete/membrane system does, unless cracks are not present in the LMC overlay. On the other hand, for asphalt concrete/membrane systems, a portion of deck deterioration has been related to the performance of fast-setting materials usually used for patching the underlying decks (16). Therefore, if only the magnitude of contamination and deterioration of the underlying decks influence selection of a protective strategy, and if LMC cracks are to be sealed and conventional concrete (or a fast-setting material with equal properties) is to be used for patching the underlying deck, the choice between LMC and an asphalt concrete/membrane system should not make much difference. In the case of LMC, however, repairs can be done monolithically with the overlay. Table 14, which is based on this discussion, suggests a modification to the WSDOT bridge deck protective system selection criteria.

Note that according to the current WSDOT protective system selection criteria, many decks presently qualified for and protected by asphalt concrete/membranes may have to be protected with LMC after the asphalt concrete/membrane systems have deteriorated and have been removed. The reason for this is that the present procedures for removing asphalt concrete/membranes may result in a rough concrete surface not compatible with a membrane. Generally, bridges of this type will have low ADTs and protecting them with more expensive LMC may not be necessary. A solution to rough surface texture may be to apply a 1/2- to 1-inch asphalt concrete leveling course, followed by the application of a new membrane and an asphalt concrete overlay. The effectiveness of this procedure should be verified through the construction and performance monitoring of an experimental project using this method.

Table 14. Suggested Bridge Deck Protection System Selection Matrix

					Priority No. – Protection System		
						Traffic Category	
Group	Rating	Code	cl>2#/cy[a]	Deterioration[b]	>10,000 ADT	2,000 - 10,000 ADT	<2,000 ADT
1	slight	8	none	None	3(LMC)[c]	4(LMC-AC)[d]	8(LMC-AC)[d]
		7	none	None			
2	moderate	6	<20%	<2%	6(LMC)[e]	7(LMC-AC)[f]	9(LMC-AC)[f]
		5	20-40%	2-5%			
3	severe	4	40-60%	>5%	1(LMC)[e]	2(LMC)[e]	5(LMC-AC)[f]
		3	>60%	>5%			

a. Percent of chloride samples exceeding 2#/c.y.

b. Deterioration is defined as the percent of the total deck area that has spalls and/or delaminations.

---

c. Protection method: latex-modified concrete overlay.

d. Protection method: latex-modified concrete overlay or asphalt concrete and waterproofing membrane.

e. Protection method: latex-modified concrete overlay with cracks sealed.

f. Protection method: latex-modified concrete overlay with cracks sealed or asphalt concrete and waterproofing membrane applied on a deck patched with conventional concrete or fast setting material with equal properties.

REFERENCES

1. Washington State Department of Transportation Bridge and Structures Branch. "Bridge Deck Program." Olympia, Washington, Washington State Department of Transportation (October 1986), 25 pp.

2. Conversations with Willis Whitney, Bridge Condition Engineer, Bridge and Structures Branch, Olympia, Washington, Washington State Department of Transportation (Summer 1986).

3. Babaei, K., and Terrel, R.L., "Performance Evaluation of Waterproofing Membrane Protective Systems for Concrete Bridge Decks," Report No. WA-RD 61.1, Olympia, Washington, Washington State Department of Transportation (August 1983), 43 pp.

4. Whiting, D., and Stark, D., "Control of Air Content in Concrete," NCHRP Report 258 (1983), 84 pp.

5. Newlon, H., and Walker, H.N., "Relationship Between Properties of Hardened Concrete and Bridge Deck Performance in Virginia," Report No. FHWA/VA-85/23, Virginia Department of Highways and Transportation (February 1985), 104 pp.

6. American Association of State Highway and Transportation Officials, "Guidelines for Skid Resistant Pavement Design" (1976), 20 pp.

7. "Control of Cracking in Concrete Structures, ACI 224R-80," ACI Manual of Concrete Practice, Part 3: Use of Concrete in Buildings -- Design, Specifications, and Related Topics (1983), 42 pp.

8. LaFraugh, R.W., and Zinzerling, M.F., "Concrete Overlays for Bridges," Washington State Department of Transportation, Report No. WA-RD 93.1 (May 1986).

9. Bishara, A.G., "LMC Bridge Deck Overlays -- Field Performance Analysis," Report No. FHWA/OH/79/004, Ohio Department of Transportation (October 1979), 96 pp.

10. McKeel, W.T., "Evaluation of Deck Durability on Continuous Beam Highway Bridges," Report No. VHTRC 85-R32, Charlottesville, Virginia, Virginia Highway and Transportation Research Council (April 1985), 25 pp.

11. Sprinkel, M.M., "Thin Polymer Concrete Overlays for Bridge Deck Protection," Transportation Research Record No. 950 (1984), pp. 193-201.

12. Whiting, D., "Rapid Measurement of the Chloride Permeability of Concrete," Public Roads, Vol. 45, No. 3 (December 1981), pp. 101-112.

13. Babaei, K., and Hawkins, N.M., "Evaluation of Bridge Deck Protective Strategies," NCHRP Project 12-32 (April 1987).

14. Beeby, A.W., "Corrosion of Reinforcing Steel in Concrete in Sea Structures -- Application," Proceedings ASCE, Vol. 105, No. ST6 (June 1979), pp. 1155-1166.

15. Information transmitted by Tom Lyon, Location Engineer, Washington State Department of Transportation District 5 (January 1986)

16. Babaei, K., "Effectiveness of Concrete Bridge Deck Asphalt/Membrane Protection," Report No. WA-RD-75.1, Olympia, Washington, Washington State Department of Transportation (February 1986), 49 pp.

17. "Durability of Concrete Bridge Decks," NCHRP Synthesis No. 57, (1979), 60 pp.

APPENDIX A
TEST SITE SELECTION

APPENDIX A
TEST SITE SELECTION

GENERAL INFORMATION AND FIELD OBSERVATIONS OF CANDIDATE CONCRETE OVERLAID TEST BRIDGES

Forty-seven bridges overlaid with latex-modified and low-slump, dense concrete were initially selected as candidate test sites. The most important factor in selecting these sites was the age of the overlays. In order to complete the general information on these sites, the TRAC/WSDOT research team made field trips during the summer of 1985 to observe the conditions of the candidate sites. The tabulated general information on the latex-modified concrete sites (16 sites) and low-slump, dense concrete sites (31 sites) is given in Tables A-1 and A-2, respectively.

DESIGNATION OF TEST SITES

Since the study planned to test 12 bridges (six latex-modified and six low-slump, dense concrete), 35 candidate test sites needed to be screened out. After a careful examination of the past and present conditions of the structures and consideration of factors such as overlay age, traffic volume, and level of contamination/deterioration prior to rehabilitation/protection, the following sites were selected for the testing program:

Latex Overlay Sites

1. 90/96.5, Denny Crk Rd O-xing
2. 90/174 S, Renslow Br
3. 90/510 S, Medical Lk Rd Oc
4. 90/531 N, Abbott Rd Oc
5. 20/211 S, Swinomish D Berentson Br
6. 2/311, Pine Cr

Low-Slump Overlay Sites

1. 90/91 N, S Fk Snoqualmie R
2. 90/106 N, Gold Cr
3. 90/124 S, Lake Valley Rd Oc
4. 90/150 S, Taneum Cr
5. 90/160 S, Reeser Cr
6. 90/162 N, Wilson Cr

The locations of the six latex-modified concrete test sites can be found in Figure A-1 and the six low-slump, dense concrete test sites in Figure A-2.

Table A-1. General Information on Candidate Latex-modified Concrete Overlaid Test Bridges

Bridge No.	Bridge Name	Year Bridge Built	Overlay Age in 1986	ADT (1983)	Length (ft)	Bridge Type	Pre-construction. Condition		Overlay Condition, Summer '85 (visually inspected)
							Deterioration >5%	Samples[1] Contaminated (%)	
90/96.5	Denny Creek RD 0-xing	1971	6	8,150	244	PCB	No	—	Good condition, no distress visible.
90/98.6 N	Upper Snoqualmie R BR	1977	5	8,150	394	CBOX	No	33	Good condition but a few isolated short cracks.
90/174 N	Renslow BR	1968	2	5,050	227	PCB	No	0	Short longitudinal cracks in some areas of driving lane, patches mainly in passing lane, rough finish.
90/174 S	Renslow BR	1968	2	5,050	211	PCB	No	0	Driving lane patched in a few small areas, rough finish on driving lane, some cracking in the deck.
90/403 N	Sprague-Lamona RD OC	1968	5	5,500	85	PCB	No	40	No distress visible.
90/403 S	Sprague-Lamona RD OC	1968	5	5,500	85	PCB	No	40	No distress visible.

(1) Percent of concrete samples having more than 2 lb/cy chloride content

Table A-1. (cont.)

Bridge No.	Bridge Name	Year Bridge Built	Overlay Age in 1986	ADT (1983)	Length (ft)	Bridge Type	Pre-construction. Condition		Overlay Condition, Summer '85 (visually inspected)
							Deterioration >5%	Samples (1) Contaminated (%)	
904/1 OC-SR90	SR904 UC Tyler	—	5	810	223	PCB	No	30	No major distress visible.
90/505 OC-SR90	Salnave RD UC	—	4	small	291	PCB	No	60	No distress visible.
90/510 N	Medical Lake RD OC	1966	4	5,850	130	PCB	No	30	A few transverse cracks over the piers on driving lane.
90/510 S	Medical Lake RD OC	1966	4	5,850	130	PCB	Yes	50	Some short isolated cracks detected in the driving lane.
90/512 N	NP Ry OC	1966	4	8,750	150	PCB	No	50	One longitudinal crack in the driving lane about 3 feet long.
90/512 S	NP Ry OC	1966	4	8,750	150	PCB	No	29	A few short transverse local cracks in driving lane.

(1) Percent of concrete samples having more than 2 lb/cy chloride content

Table A-1. (cont.)

Bridge No.	Bridge Name	Year Bridge Built	Overlay Age in 1986	ADT (1983)	Length (ft)	Bridge Type	Pre-construction. Condition		Overlay Condition, Summer '85 (visually inspected)
							Deterioration >5%	Samples (1) Contaminated (%)	
90/531 N	Abbott RD OC	1962	4	18,200	150	PCB	Yes	64	Good condition, no distress visible.
90/531 S	Abbott RD OC	1962	4	18,200	150	PCB	No	60	No distress visible.
20/211 S	Swinomish-D Berentson BR	—	5	7,950	3,259	SB PCB	No	69	—
2/311	Pine Cr	—	7	1,380	209	CTB	Yes	–	Overlay in good condition (1984 routine survey).

(1) Percent of concrete samples having more than 2 lb/cy chloride content

Table A-2. General Information on Candidate Low-Slump, Dense Concrete Overlaid Test Bridges

Bridge No.	Bridge Name	Year Bridge Built	Overlay Age in 1986	ADT (1983)	Length (ft)	Bridge Type	Pre-construction. Condition		Overlay Condition, Summer '85 (visually inspected)
							Deterioration >5%	Samples (1) Contaminated (%)	
90/91 N	South Fork Snoqualmie River	1975	3	7,890	313	PCB	No	0	A few isolated but developed transverse cracks in shoulder & one lane (5-lane bridge).
90/91.5 N	Homestead Valley Rd OC	1975	3	7,890	104	PCB	No	7	Overlay in good condition, no distress visible (3 lanes & shoulder).
90/92 N	South Fork Snoqualmie River	1976	3	7,890	367	PCB	No	3	Isolated cracks in shoulder. Overlay generally in good condition (3 lanes & shoulder).
90/92.5 N	Garcia Interchange OC	1976	3	7,890	116	PCB	No	8	Overlay in good condition, no distress visible.
90/96 S	South Fork Snoqualmie River	1972	3	7,890	214	PCB	No	57	Overlay in good condition, no distress visible (4-lane bridge).
90/99	SR906 W-W Ramp OC	1969	3	8,150	206	PCB	No	53	No distress visible. One patched area.

(1) Percent of concrete samples having more than 2 lb/cy chloride content

Table A-2. (cont.)

Bridge No.	Bridge Name	Year Bridge Built	Overlay Age in 1986	ADT (1983)	Length (ft)	Bridge Type	Pre-construction. Condition		Overlay Condition, Summer '85 (visually inspected)
							Deterioration >5%	Samples (1) Contaminated (%)	
90/106 N	Gold CR	1973	7	7,890	139	CS	No	100	Overlay in good condition, no distress visible.
90/124 N	Lake Valley Rd OC	1962	7	5,950	104	PCB	—	100	Pattern & longitudinal cracking mainly in driving lane & also approach slab.
90/124 S	Lake Valley Rd OC	1962	7	5,950	104	PCB	Yes	100	Longitudinal & transverse cracks in overlay on driving lane, exp. joint problem.
90/134 N	Cle Elum Rd	1962	3	5,950	297	ST CTB	Yes	100	Pattern cracking mainly on east end of bridge.
90/134 S	Cle Elum Rd	1962	3	5,950	297	ST CTB	Yes	100	Generally in good condition, cracking along two expansion dams.

(1) Percent of concrete samples having more than 2 lb/cy chloride content

Table A-2. (cont.)

Bridge No.	Bridge Name	Year Bridge Built	Overlay Age in 1986	ADT (1983)	Length (ft)	Bridge Type	Pre-construction. Condition		Overlay Condition, Summer '85 (visually inspected)
							Deterioration >5%	Samples (1) Contaminated (%)	
90/150 N	Taneum Cr	1965	3	7,550	108	PCB	Yes	90	Pattern cracking all over driving lane & in approach slab.
90/150 S	Taneum Cr	1965	3	7,550	108	PCB	Yes	90	Extensive pattern cracking all over driving lane & also in approach slab, passing lane w/ hairline cracks.
90/152 N	West Side Canal	1966	3	7,350	31	CS	Yes	100	Pattern cracking all over driving lane & in approach slab.
90/152 S	West Side Canal	1966	3	7,350	38	CS	No	50	Pattern cracking all over driving lane & in approach slab, passing lane w/ hairline cracks.
90/160 N	Reeser Cr	1967	5	7,650	120	CS	—	40	Hairline pattern cracking all over driving lane.
90/160 S	Reeser Cr	1967	5	7,650	120	CS	No	10	Pattern cracking all over, but extension lower in passing lane and shoulder.

(1) Percent of concrete samples having more than 2 lb/cy chloride content

Table A-2. (cont.)

Bridge No.	Bridge Name	Year Bridge Built	Overlay Age in 1986	ADT (1983)	Length (ft)	Bridge Type	Pre-construction. Condition		Overlay Condition, Summer '85 (visually inspected)
							Deterioration >5%	Samples (1) Contaminated (%)	
90/161 N	Damman Rd OC	1967	5	7,650	162	CTB	—	—	Pattern cracking all over driving lane, wide transverse cracks in some locations.
90/162 N	Wilson Cr	1967	5	7,650	118	CS	Yes	50	Pattern & long. cracking all over in driving lane, one location of minor overlay stripping.
90/162 S	Wilson Cr	1967	5	7,650	118	CS	—	—	Cracks in overlay in driving lane, some hairline cracks in shoulder.
90/163 N	BNRR (NP) & SR 97 OC	1968	5	7,650	456	PCB	—	—	Three-lane bridge, most truck traffic in middle lane. Transverse cracks & small patch here.
90/163 S	BNRR (NP) & SR 97 OC	1968	5	7,650	457	PCB	—	—	Slight pattern cracking, some transverse cracking over a pier.
90/180	Columbia R Vantage	—	4	8,155 (both dir.)	2,504	SA SG	No	33	West bound – small patch, east bound – some patches.

(1) Percent of concrete samples having more than 2 lb/cy chloride content

Table A-2. (cont.)

Bridge No.	Bridge Name	Year Bridge Built	Overlay Age in 1986	ADT (1983)	Length (ft)	Bridge Type	Pre-construction. Condition		Overlay Condition, Summer '85 (visually inspected)
							Deterioration >5%	Samples (1) Contaminated (%)	
205/16 E	Burton Rd OC	—	3	17,000	171	PCB	No	0	Good condition.
205/16 W	Burton Rd OC	—	3	17,000	171	PCB	No	0	Good condition.
205/34 E	LP & N RY & 99th St OC	—	3	12,950	237	PCB	No	0	Good condition.
205/34 W	LP & N RY & 99th St OC	—	3	12,950	232	PCB	No	0	Good condition.
205/36 E	St Johns Rd OC	—	3	12,950	212	PCB	No	0	Good condition.
205/36 W	St Johns Rd OC	—	3	12,950	212	PCB	No	0	Good condition.

(1) Percent of concrete samples having more than 2 lb/cy chloride content

Table A-2. (cont.)

Bridge No.	Bridge Name	Year Bridge Built	Overlay Age in 1986	ADT (1983)	Length (ft)	Bridge Type	Pre-construction. Condition		Overlay Condition, Summer '85 (visually inspected)
							Deterioration >5%	Samples (1) Contaminated (%)	
205/42 E	Salmon Cr & Ave OC	—	3	9,150	294	PCB	No	0	Good condition, one lane with superplasticized section.
205/42 W	Salmon Cr & Ave OC	—	3	9,150	288	PCB	No	0	Good condition.

(1) Percent of concrete samples having more than 2 lb/cy chloride content

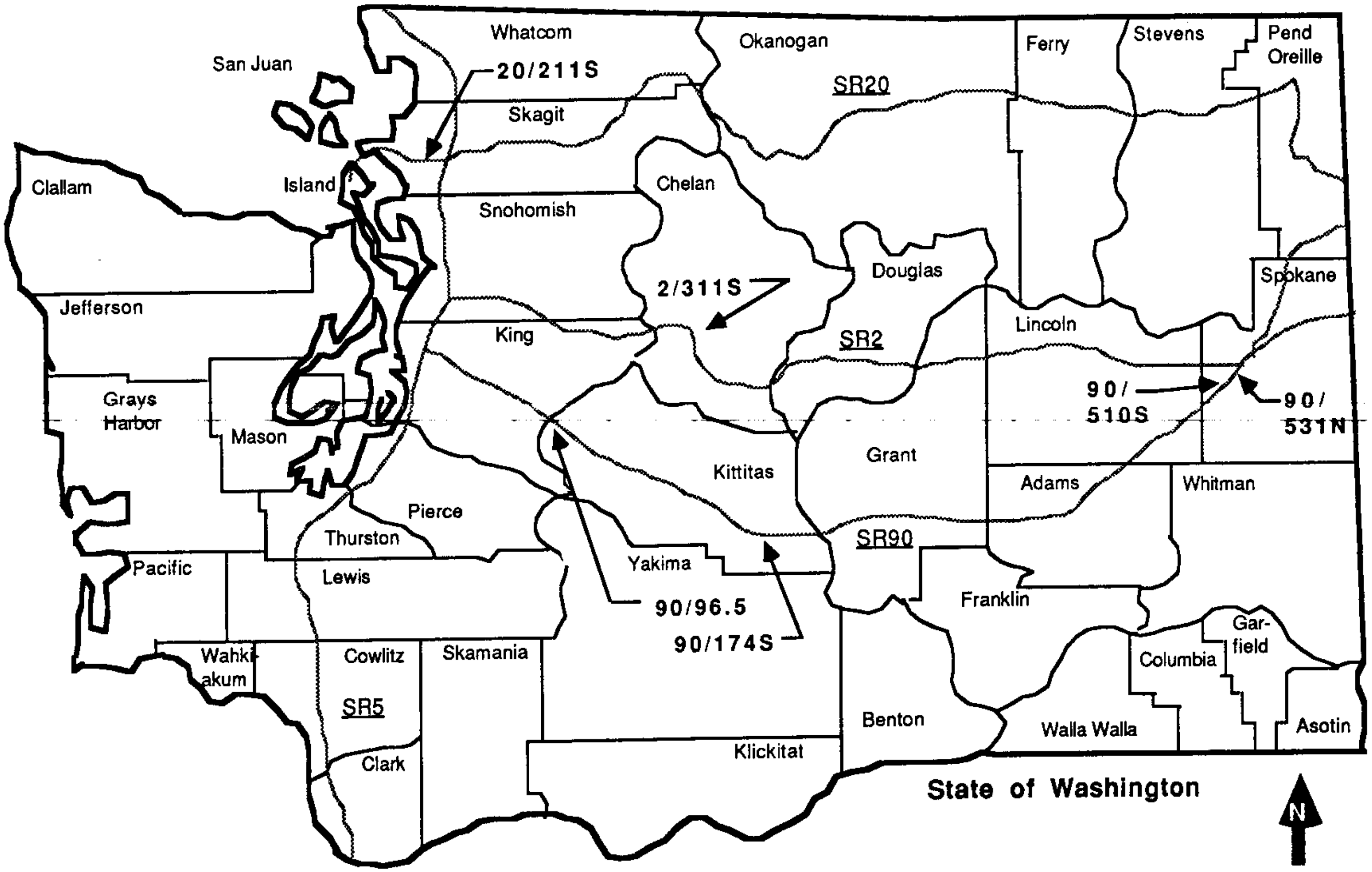

Figure A-1. Location of Latex-modified Concrete Test Sites

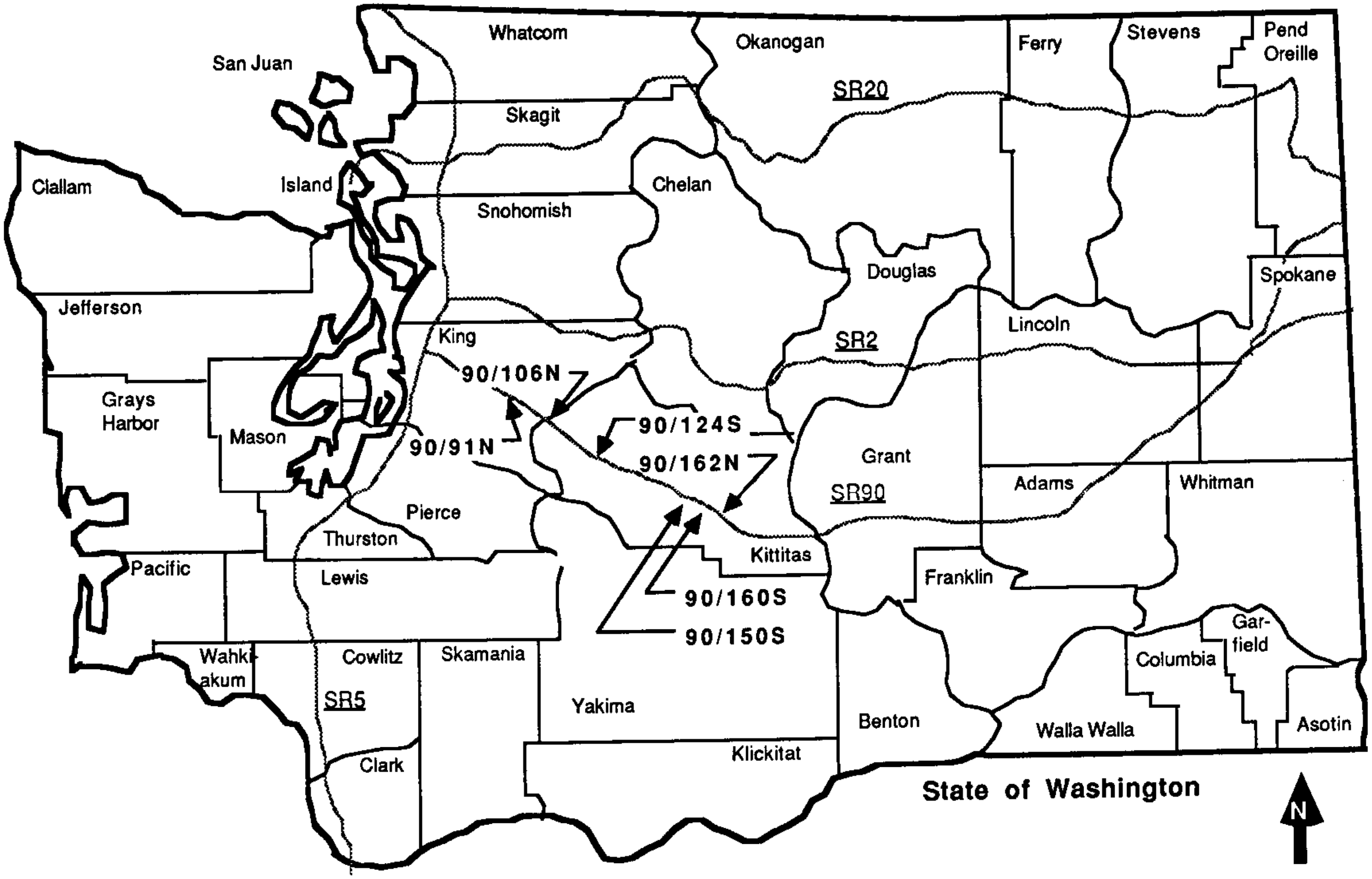

Figure A-2. Location of Low-Slump, Dense Concrete Test Sites

APPENDIX B
DISCUSSION OF BRIDGE CONCRETE OVERLAY INTERFACE SHEAR STRESS

APPENDIX B
DISCUSSION OF BRIDGE CONCRETE OVERLAY INTERFACE SHEAR STRESS

Below is discussed the nature of shear stress in a concrete overlay interface under live loading. This discussion applies to both the longitudinal and transverse flexibility of the bridge superstructure.

Uncracked Overlay

For an uncracked overlay, the interface shear stress can be determined as shown in Figure B-1. In a small element of the overlay, the shear force is equal to the change in the axial forces (tension or compression).

$$(\upsilon)(\Delta x) = (\Delta f_t)(h) \tag{1}$$

or

$$\upsilon = \frac{(\Delta f_t)(h)}{(\Delta x)}$$

in which

υ = shear stress
Δf_t = difference in axial stress (tension in this case)
h = thickness of overlay
Δx = a small length of overlay

Equation (1) can be further expanded as follows.

$$\Delta f_t = \Delta\left(\frac{MY}{I}\right)$$

in which

M = bending moment
Y = distance from neutral axis to the overlay, and
I = moment of inertia of the section (overlay and supporting system)

therefore:

$$\upsilon = \frac{\Delta\left(\frac{MY}{I}\right)(h)}{(\Delta x)} = \frac{(\Delta M)\,(Y)(h)}{(\Delta x)(I)} \tag{2}$$

The term $\frac{(\Delta M)}{(\Delta x)}$ in Equation (2) is the vertical shear force, ν and

the term $\frac{(Y)(h)}{(I)}$ is equal to $\frac{Q}{Ib}$ in which:

Q = statical moment of the overlay about the neutral axis, and
b = the effective width in the composite section

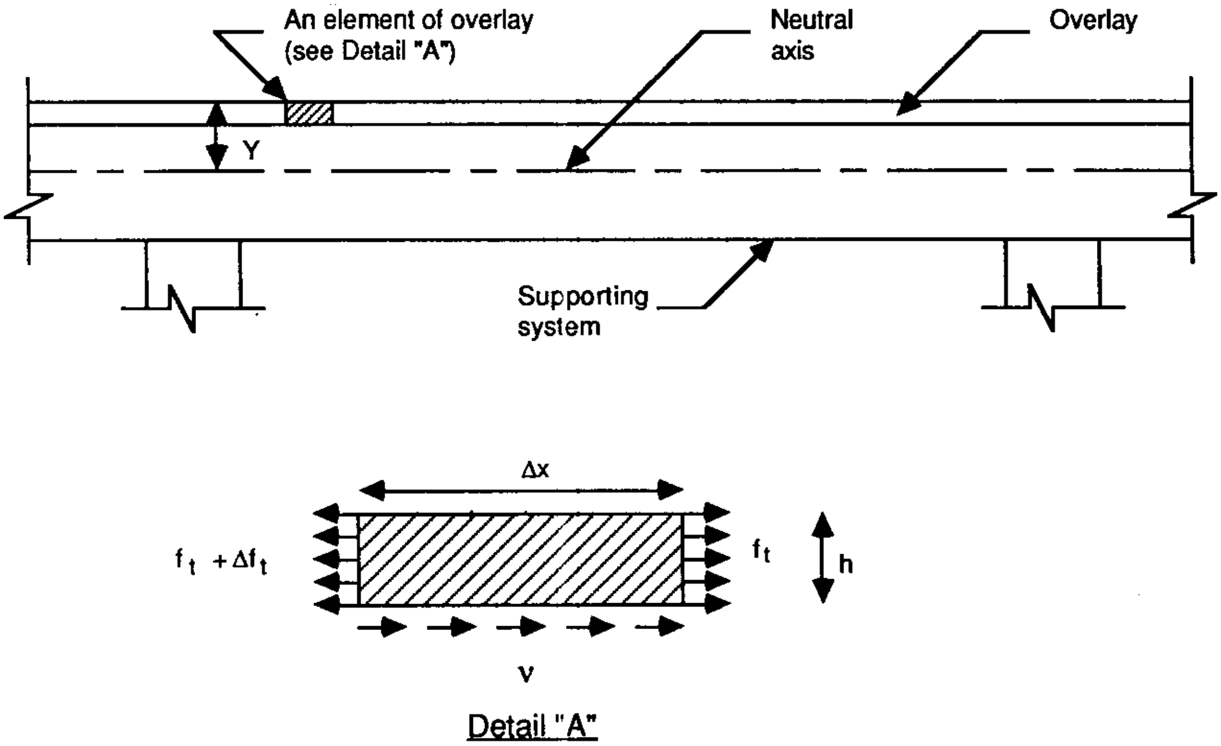

Figure B-1. Interface Shear Stress in Uncracked Overlay

Thus Equation (1) can be alternatively shown as the following, which is the popular form.

$$\upsilon = \frac{V\,Q}{Ib} \tag{3}$$

Cracked Overlay

Shrinkage cracking in the overlay may either occur in the compression zone of the deck or in the tension zone. In the compression zone (areas close to mid-span), overlay segments separated by the cracks will mobilize each other and transmit the axial compression stress. Thus the system will behave almost like the uncracked overlay, as discussed earlier. However, in the tension zone (areas close to supports) the system will behave differently. The location of the neutral axis in the cracked tension zone differs from that of the uncracked concrete, as shown in Figure B-2. Directly at each crack, the neutral axis is located further away from the interface than is the neutral axis of the uncracked section. Midway between cracks it shifts upward to a location closer to the uncracked section, with a gradual transition between these two extremes. The pattern of the transition of the neutral axis follows the pattern of variation of the tensile stress in the cracked segment of the overlay, with the tensile stress being zero at the cracks and at its maximum midway between the cracks. According to this pattern, Δf_t (the difference in tensile stress in a small element) becomes zero at the cracks and midway between the cracks. According to Equation (1), under this condition υ (shear stress) is zero at the cracks and midway between the cracks.

This concept can also be expressed differently. In a cracked overlay, the distribution of interface shear stress is as shown in Figure B-2. The equilibrium of forces requires that the shear stress along the cracked segment change direction, since there is no transmittal of axial stress at the cracks. Therefore, shear stress midway between the cracks is zero. Shear stress is also zero at the cracks, since vertical shear stress is not transmitted along the cracks. The equilibrium of forces requires that the shear force in half of the cracked segment be equal to the axial force midway between the cracks, as shown in Figure B-2. This equilibrium will give the average shear stress in the interface as follows:

$$(\upsilon)(L/2) = (f_t)(h)$$

or

$$\upsilon = \frac{2(f_t)(h)}{L} \tag{4}$$

in which

υ = average shear stress
L = length of cracked segment
f_t = maximum tensile stress in cracked segment
h = overlay thickness

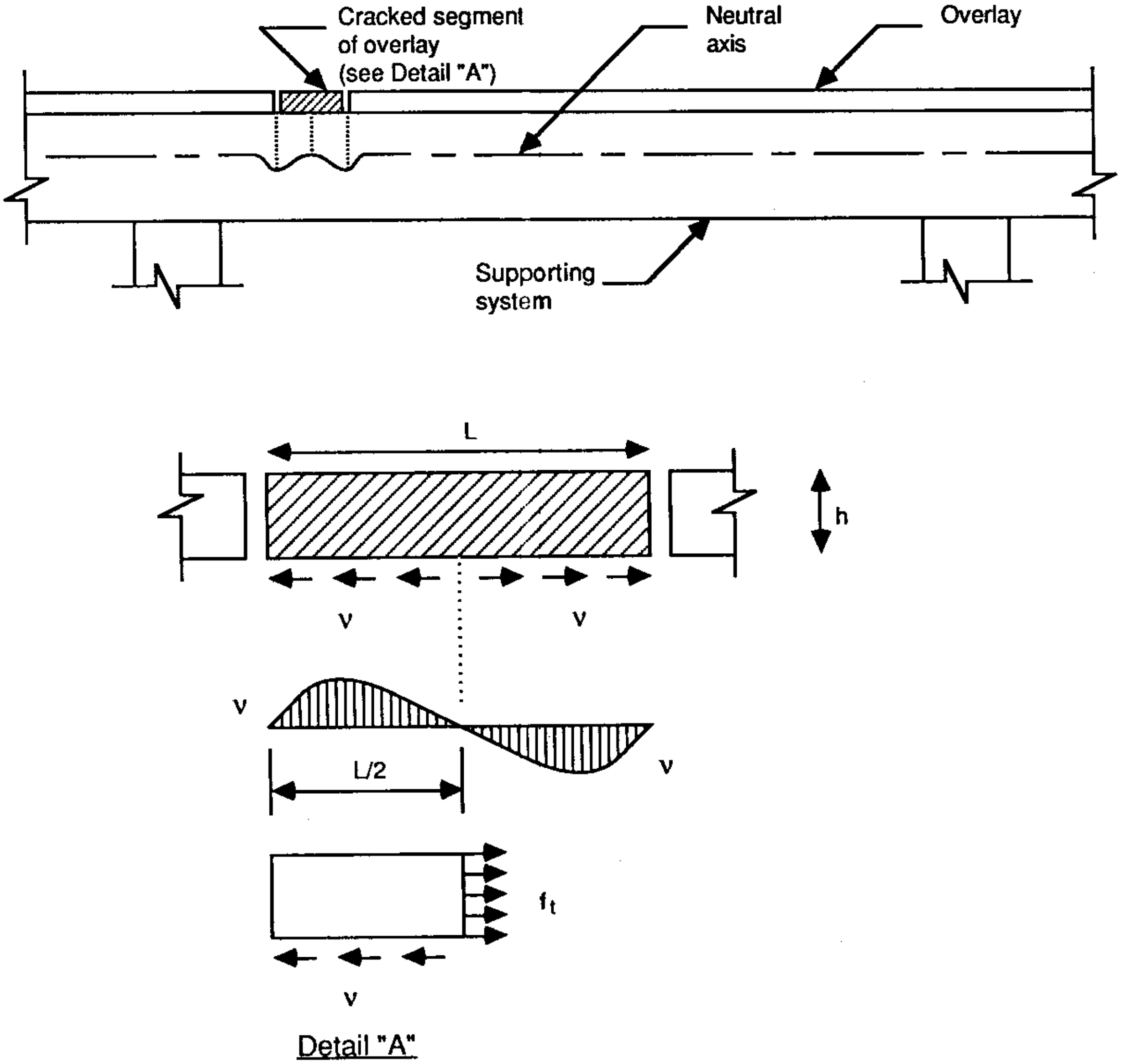

Figure B-2. Interface Shear Stress in Cracked Overlay

The magnitude of h is 1.5 inches for LMC and the magnitude of L may be assumed to be 3 feet for an extensively cracked overlay. Substituting these values in Equation (4) will result in

$$\upsilon = 0.08\ (f_t)$$

Under service conditions ft in a cracked overlay is smaller than that in an uncracked overlay and is well below the overlay's tensile capacity. However, if one assumes that at the extreme ft reaches the tensile capacity of the overlay (say 500 psi), then the corresponding υ will be about 40 psi, which is well below the bond strength of the overlay. The implication of this finding is that before any bond failure can occur in the cracked region, the overlay will fail in tension.