National Cooperative Highway Research Program

NCHRP Synthesis 220

Waterproofing Membranes for Concrete Bridge Decks

A Synthesis of Highway Practice

Transportation Research Board
National Research Council

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Synthesis of Highway Practice 220

Waterproofing Membranes for Concrete Bridge Decks

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Transportation Research Board
National Research Council

Research Sponsored by the American Association of State Highway and Transportation Officials in Cooperation with the Federal Highway Administration

NATIONAL ACADEMY PRESS
Washington, D.C. 1995

Subject Areas
Materials and Construction;
Bridges, Other Structures, and
Hydraulics and Hydrology; and
Maintenance

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NCHRP SYNTHESIS 220

Project 20-5 FY 1993 (Topic 25-09)
ISSN 0547-5570
ISBN 0-309-05863-5
Library of Congress Card Catalog No. 95-61638

Price: $18.00

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Published reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from:

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Printed in the United States of America

PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis will be of interest to research, specifications, materials, design, and construction engineers; contract and specification administrators; agency project managers and staff; and concrete bridge deck construction contractors. This synthesis describes the state of the practice with respect to the development and present status of waterproofing membranes for concrete bridge decks.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

This report of the Transportation Research Board describes the use of waterproofing systems applied to new bridge decks and the rehabilitation of deteriorated concrete bridge decks. In addition, this synthesis describes current practice with regard to methods for assessing the effectiveness of membranes, criteria for use, installation practices, and factors that affect the performance of waterproofing systems in new construction and rehabilitation. Suggestions for future research are also included.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments.

A topic panel of experts in the subject area was established to guide the research in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

CONTENTS

ACKNOWLEDGMENTS

David G. Manning, Ph.D., P.E., Contract Management Office, Ministry of Transportation, Ontario, Canada, was responsible for collection of the data and preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of Ronald I. Frascoia, Research and Development Supervisor, Vermont Agency of Transportation; Frederick D. Hejl, Engineer of Materials and Construction, Transportation Research Board; James R. Hoblitzell, Structural Engineer, Federal Highway Administration; James F. Rush, Regional Construction Engineer, New Jersey Department of Transportation; Robert Travis, Section Chief, Maintenance Design and Research, California Department of Transportation; Y. Paul Virmani, Research Chemist, Federal Highway Administration; Richard E. Weyers, Professor of Civil Engineering, Department of Civil Engineering, Virginia Polytechnic Institute and State University; and John Wojakowski, Concrete Research Engineer, Kansas Department of Transportation.

The Principal Investigators responsible for the conduct of this synthesis were Sally D. Liff, Manager, Synthesis Studies, and Stephen F. Maher, Senior Program Officer. This synthesis was edited by Linda S. Mason, assisted by Rebecca B. Heaton.

Scott A. Sabol, Senior Program Officer, National Cooperative Highway Research Program, assisted the NCHRP 20-5 staff and the topic panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance were most helpful.

The provision of Figures 15–19 and 21–23 by Ronald I. Frascoia, Vermont Agency of Transportation, was also most helpful.

WATERPROOFING MEMBRANES FOR CONCRETE BRIDGE DECKS

SUMMARY

Waterproofing membranes are used to protect the concrete in a deck slab from freeze-thaw induced deterioration and to protect the embedded reinforcement against corrosion. States, particularly those in New England, with a long history of membrane use began using membranes to prevent deterioration of concrete beneath asphalt surfacing. Elsewhere in the United States, the use of membranes resulted largely from a 1972 Federal Highway Administration (FHWA) requirement that bridge decks be protected against corrosion.

Surveys over the past 20 years have shown a sharp decline in the number of agencies using waterproofing membranes in new construction. In 1994, 25 percent of state agencies reported using membranes on new decks. By contrast, the number of agencies using membranes in rehabilitation work has remained about the same for the last 20 years. About one-half of the states use membranes in deck rehabilitation work, although their use may be limited to specific types of structures. In 1992 (the latest year for which figures are available), the area of membranes installed in rehabilitation was about six times that installed on new decks.

Agencies are sharply divided over the merits of waterproofing decks. Reasons given for not using membranes include the inability to inspect the top surface of the deck slab, poor performance of experimental installations, and short service life of asphalt overlays. Conversely, other jurisdictions report that membranes are cost-effective in new construction, especially in rehabilitation.

Although membranes provide the waterproofing integrity, they are but one component of a complex waterproofing system that includes primers, adhesives, protection board, tack coats, and asphaltic surfacing. The waterproofing system's performance is determined by the complex interaction of material factors, design details, and the quality of construction. The waterproofing integrity of membranes is determined by the bond to the deck and the amount of damage to the membrane. Even a damaged membrane will slow the flow of water if it remains well bonded. The bond of the membrane to both the deck slab and the surfacing is essential for the good performance of asphalt surfacing. A loss of bond is often a precursor to cracking, slippage, or break-up of the surfacing.

The survey for this synthesis identified 22 different proprietary waterproofing products used in the United States in 1992. Most of the membranes are preformed products, with the marketplace being dominated by the same three products for almost 20 years. The situation in the United States is in marked contrast to Canada where hot-rubberized asphalt membranes are used widely, and to Europe where a large number of resin-based and bitumen-based liquid membranes, as well as sheet membranes, are in use.

Developments in waterproofing systems have been hampered by the low-bid process and by the absence of performance specifications, that generally recognize life-cycle costs. The lack of a quantitative definition of performance requirements, the absence of realistic prequalification test procedures, and inadequate quality assurance tests are major obstacles to the development of specifications. Waterproofing concrete bridge decks has also been a neglected area of research, with only one major national study completed 20 years ago.

Field studies have shown that the performance of waterproofing systems has been extremely variable. Many of the systems installed in the 1970s failed after only a few years service, and some had to be removed before being opened to traffic. More recent studies have shown generally satisfactory performance, especially by agencies with a lengthy experience in installing membranes. Several studies have shown that the thickness of the asphalt surfacing is important in reducing damage to the membrane from both traffic loading and thermal effects.

The application of a membrane will not stop corrosion in an existing deck, but may be a cost-effective means of extending the life of the deck slab, nonetheless. The riding quality of the deck will be improved and spalling of the concrete delayed. Future corrosion activity is determined by the proportion of salt-contaminated concrete removed and the extent to which corrosion products are removed from the reinforcing steel. In practice, corrosion cells will inevitably develop in a rehabilitated deck slab.

Research is suggested to examine field performance, prequalification testing, and quality assurance procedures with the objective of developing a performance specification for waterproofing systems. Further research is also suggested in the development of methods to investigate the condition of waterproofing systems in service.

CHAPTER ONE

INTRODUCTION

BACKGROUND

Premature deterioration of bridge decks was recognized as a serious problem for highway agencies in the 1960s (*1*). Investigations at that time identified the role of moisture and deicing salts in aggravating freeze-thaw deterioration in concrete and initiating the corrosion of embedded reinforcement. This led to improvements in the quality of concrete used in highway structures, an increase in specified concrete cover, and modifications in quality assurance procedures to ensure the specified changes were achieved in the field. Some agencies were already requiring additional protection for bridge deck surfaces. Concrete sealers and waterproofing membranes with a bituminous wearing course were used most widely.

As the durability of concrete bridge decks continued to receive considerable attention in research and performance studies, a number of new approaches for increasing durability, such as coated reinforcement, concrete overlays, corrosion inhibitors, and the use of polymers, were introduced in the late 1960s and the 1970s (*2*). The Federal Highway Administration (FHWA) encouraged states to evaluate different protective systems on an experimental basis. The National Experimental Evaluation Program (NEEP) Project No. 12 was initiated in 1970 to encourage the use of membranes, polymer concrete, and dense portland cement concrete. In 1972, FHWA introduced a policy that required application of a deck protective system to all structures on the federal-aid system likely to be subjected to potentially damaging applications of deicing salts. This had a dramatic effect on the use of waterproofing membranes because states had only a few protective systems from which to choose. Products now commonly used, such as epoxy-coated reinforcement, were not available in 1972. The market for waterproofing membranes expanded as new products were introduced and agencies with no experience in specifying and constructing membranes began to use them. Several agencies initiated studies into the construction and performance of membranes. Much of the North American literature on membranes relates to systems installed in the early and mid 1970s.

There was also a significant increase during the 1970s in the number of bridges requiring rehabilitation, especially the need to repair corrosion-damaged decks. Many of these bridges had been built only a few years earlier as part of the interstate highway network construction. The premature deterioration was the focus of national attention and a considerable research effort to identify effective repair methods. However, ensuring durability in a structure already contaminated by salt is much more difficult than providing effective corrosion protection in new construction. The performance of a rehabilitated structure is influenced strongly by the proportion of chloride-contaminated concrete removed, and the quality of construction, as well as the choice of the method of rehabilitation (*2, 3*). As in the case of new construction, the availability of membranes, their relatively low cost, and the need for their immediate implementation were major factors in their selection by states that had not previously used them.

There are two principal reasons to use a waterproofing membrane: to protect the concrete in the deck slab and to protect the reinforcing steel against corrosion (*4–6*). In deicing areas, bituminous surfacings should not be used on decks without a membrane, except as a temporary measure to improve ride quality. Bituminous surfacings used on bridge decks in North America and most of Europe are both porous and permeable. This results in salt-laden water being trapped on the deck surface, which can initiate corrosion of the reinforcement and accelerate deterioration of the concrete through freeze-thaw action (*7–9*). Additional reasons for using a waterproofing membrane are to prevent dripping on roads below, to avoid unsightly staining or efflorescence on deck soffits (*5*), and to delay carbonation of the concrete (*6*).

Waterproofing membranes are also used widely in other types of structures such as parking decks, roofing decks, and water-retaining structures. While some of the materials used are the same, much of the technology is not transferable to bridge decks. Some of the most demanding requirements for service on bridge decks are the ability to resist damage from paving equipment, hot asphalt, and traffic loading—conditions that do not apply to other structures.

USE OF MEMBRANES ON BRIDGE DECKS

Current Usage

States that reported using membranes in the survey for this synthesis are shown in Figure 1, which applies to new construction, and Figure 2, which applies to rehabilitation. A copy of the survey is given in Appendix A; a detailed summary of responses can be found in Appendix B. Replies to the survey were received from 48 states, the District of Columbia, and six Canadian provinces. For reasons that are unclear, and that cannot be explained adequately by climate, membranes have been used in the North East for decades. Elsewhere in the United States, membrane use is sporadic. The geographic distribution of membrane use illustrates the widely divergent viewpoint with respect to the effectiveness and performance of the membranes.

States are also divided sharply on the merits of placing bitu-

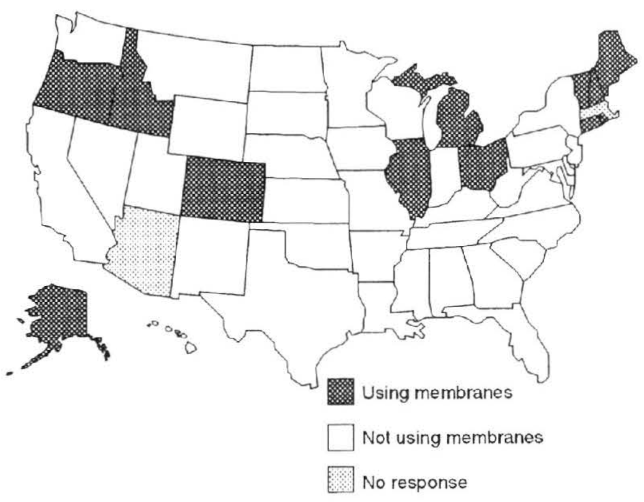


FIGURE 1 States using waterproofing membranes in new construction.

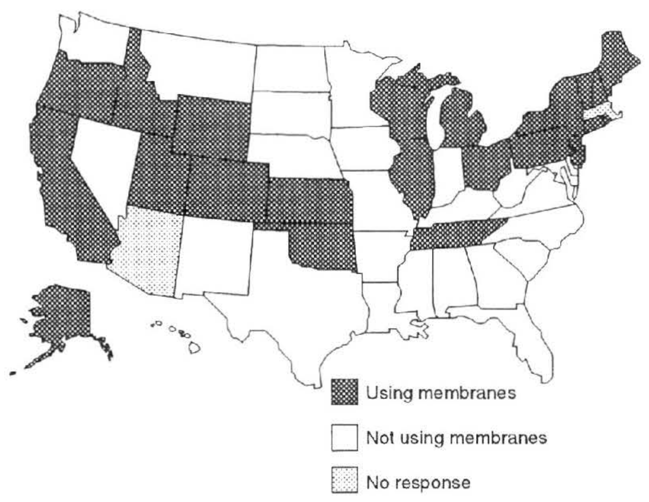


FIGURE 2 States using waterproofing membranes in rehabilitation.

minous wearing surfaces, which is a major factor in determining whether membranes are considered for use. States opposed to placing bituminous overlays on decks argue that the overlays perform poorly and hide deterioration in the deck slab. Other states express satisfaction with the performance of bituminous overlays, and achieve the same service life on decks as adjacent sections of bituminous pavement. Some jurisdictions actually prefer to use a bituminous surfacing on bridge decks because of dissatisfaction with the riding quality and skid resistance of an exposed concrete surface (*4*).

The use of membranes is much more widespread in Canada than in the United States. All six (of ten) provinces responding to the survey reported using membranes in both new construction and rehabilitation.

Estimating the quantity of membranes being used by states is difficult because not all states responded to the survey and others were unable to provide data on quantities installed. Appendix B shows that 58,000 m^2 (620,000 ft^2) of membrane was installed on new decks in the United States in 1992, and 309,000 m^2 (3,330,000 ft^2) of membrane was installed in rehabilitation. A further 49,000 m^2 (530,000 ft^2) was installed in either new construction or rehabilitation. The corresponding figures for Canada were 23,000 m^2 (250,000 ft^2), 18,000 m^2 (190,000 ft^2), and 95,000 m^2 (1,021,000 ft^2), respectively. It was estimated that plans called for the installation of 740,000 to 930,000 m^2 (8 to 10 million ft^2) of membrane on bridge decks in the United States in 1985 (*10*).

While membrane use has declined from 1986 to 1992, the total of 416,000 m^2 (4,480,000 ft^2) reported for the United States in 1992 underestimates the quantity being used. It also represents only applications to state-owned bridges and therefore grossly underestimates the total market. There is no reason to anticipate from the survey responses that the market for membranes will continue to decline. While five states reported declining usage, six estimated that the use of membranes was static, and eleven indicated that the use of membranes is increasing.

Recent History of Usage

A number of surveys with questions on the use of membranes have been conducted over the past 20 years. The survey for this synthesis, as well as the one conducted in 1977 for *NCHRP Synthesis of Highway Practice 57: Durability of Concrete Bridge Decks* (*2*), documented the use of membranes in new construction and rehabilitation. NCHRP Project 12-32, "Evaluation of Bridge Deck Protective Strategies," research results of which were published as *NCHRP Report 297*, examined the use of membranes in new construction in 1986 (*11*). A study by the Strategic Highway Research Program (SHRP), "Concrete Bridge Protection and Rehabilitation," included a survey of rehabilitation techniques in use in 1989 (Chamberlin, W.P., "Summary of the Field Survey Questionnaire," unpublished report, June 1989). An even earlier survey was undertaken in 1974 as part of NCHRP Project 12-11, "Waterproof Membranes for Protection of Concrete Bridge Decks," a two-phase study. Research results of Phase I were published as *NCHRP Report 165* (*12*). Although the project's objectives were primarily concerned with the use of membranes in new construction, it is not clear from the report whether the survey responses also included data on the use of membranes in rehabilitation.

Responses to the five surveys undertaken in the period 1974 to 1994 are summarized in Table 1. Only data from state agencies are included in the table. Although the number of responses differed and some inconsistencies exist in individual responses, several interesting trends emerge.

During the 20-year period, the number of states using membranes in new construction declined considerably. It should be noted that the figures included the use of membranes as part of multi-protection systems. The 1977 and 1986 surveys asked agencies to distinguish between the use of membranes as a standard procedure and their use on an experimental basis. While the use as a standard procedure remained about the same, the experimental use of membranes decreased from 29 to 15

TABLE 1
STATE AGENCY RESPONSES TO VARIOUS SURVEYS ON USE OF MEMBRANES IN DECK CONSTRUCTION AND REHABILITATION

	New Construction				Rehabilitation		
	1974[1]	1977[2]	1986[3]	1994[4]	1977[1]	1989[5]	1994[4]
Membrane use, %	74	69	53	25	58	51	46
As a standard, %	—	40	38	—	46	47	—
Experimentally, %	—	29	15	—	12	4	—
No. of responses	42	48	45	48	48	47	48

[1] From Table 1 (*12*). The report does not state explicitly that responses apply only to new construction.
[2] From Table A-1 (*2*).
[3] From Table F-2 (*11*), but including 3 states shown in Table F-4 as making limited use of membranes.
[4] From Appendix B.
[5] From Chamberlin, W.P., "Summary of the Field Survey Questionnaire," unpublished report, June 1989.

percent. This is not to imply, however, that the same states continued to use membranes as a standard procedure from 1977 to 1986. Analysis of the individual responses reveals that seven states began using membranes as a standard procedure while eight terminated their use.

The number of states using membranes in rehabilitation has also declined, but much less dramatically than in new construction. In the 1989 survey, only two states responded that membranes were being used experimentally in rehabilitation, indicating that most states use membranes in rehabilitation as a standard procedure, or not at all. Almost one-half of the states responding to the latest survey do use membranes in rehabilitation (though not necessarily on all decks), representing a major change in the use of membranes over the years. In 1977, many more states were using membranes in new construction than rehabilitation. By 1994, the situation had reversed.

TABLE 2
PREFERRED PROTECTIVE SYSTEM BY STATE AGENCIES IN DECK CONSTRUCTION AND REHABILITATION

	Preferred System, % of Responses		
	1977[1]		1986[2]
Protective System	New Decks[3]	Rehabilitation[4]	New Decks[5]
Epoxy-coated bars	54	—	82
Concrete overlay	14	61	0
Membrane	19	25	11
Others	13	14	7

[1] From (*2*).
[2] From (*11*).
[3] 37 states responded.
[4] 36 states responded.
[5] 45 states responded.

In September 1977, the U.S. General Accounting Office (GAO) surveyed the states and asked for information on the preferred methods of deck construction and rehabilitation (*2*). The 1986 survey also asked states to indicate the preferred method of protection for new decks. The results are summarized in Table 2. In 1977, only 19 percent of the respondents indicated membranes were the preferred protective system on new decks (54 percent selected epoxy-coated bars), and only 11 percent selected membranes as the first-choice option for the repair of decks (61 percent selected concrete overlays). By 1986, the popularity of membranes for use on new decks had dropped slightly, but more than 80 percent of the responses indicated a preference for use of epoxy-coated bars, which explains why the number of agencies using membranes in new construction has declined. However, the rehabilitation field is not dominated by one option, and the number of states using membranes has remained about the same.

The data in Tables 1 and 2 support observations that membranes were widely used in the 1970s because states were required by federal policies to provide positive deck protection. Membranes were selected because of their availability and low cost, but they were never popular outside of a few areas with a long history of usage.

TYPES OF MEMBRANES

The original reason for the use of membranes in several jurisdictions was a response to the common experience of discovering badly deteriorated concrete concealed beneath bituminous overlays (*1,8*). Attempts to waterproof the concrete deck slab surface using concrete sealers such as linseed oil or silicone were largely unsuccessful. In some cases this led to changes in the methods of constructing bare decks (*4*) and, in others, to the development of more effective waterproofing barriers. The built-up membrane became popular in the 1960s although other approaches, such as reducing the permeability of bituminous pavement through adding asbestos fibers, were also investigated (*13*). The concept of waterproofing the bituminous concrete rather than using a separate membrane has been of renewed interest, and a commercial product using polymer additives in the paving mixture is now available in the marketplace (*14,15*).

The most common type of built-up system consisted of layers (usually two) of glass fabric mopped with alternate coats of coal-tar pitch emulsion (*1,16*). This system is still used in Illinois and is permitted in Connecticut, but was discontinued in most other places. It was found to be labor intensive and slow to construct because of the curing time required for each layer (*17*). Condition surveys also showed evidence of rotting of the glass fabric. Oregon permits the use of a different type of built-up system consisting of a polypropylene fabric rolled into a hot rubber-asphalt membrane, which is made by mixing ground rubber and asphalt cement on site.

During the 1960s, a number of new types of membranes became available. Research for *NCHRP Report 165: Waterproof Membranes for Protection of Concrete Bridge Decks—Laboratory Phase* was initiated because of the number of membranes in the marketplace. Phase I of the study investigated the effectiveness of 147 waterproofing systems available at the time the work commenced in 1970 (*12*). Following laboratory testing, five systems were selected as the most promising for detailed evaluation under service conditions. It is not coincidental that all five systems consisted of preformed sheets, which will almost certainly perform better than liquid membranes in simple screening tests. All five systems required the application of an adhesive to attach the membrane to the deck surface.

In Phase II of the above-mentioned study, field experience with these systems showed that installation was labor intensive and difficult. Blisters were common, large sheets were unwieldy in windy conditions, and performance was extremely vulnerable to the quality of workmanship, especially at critical locations such as curbs, expansion joints, and deck drains (*18*). The self-adhesive preformed membranes in use today were developed to overcome the high costs and difficulties in installing the sheet membranes used in the early and mid 1970s.

The surveys carried out in May 1986 for *NCHRP Report 297: Evaluation of Bridge Deck Protective Strategies* and for this synthesis showed a definite preference for the use of preformed membranes. Responses to the 1986 survey, which dealt only with new construction, showed that 11 states were using preformed membranes, four were using liquid membranes, and one was using both. Figures from the current survey were similar: 14 states use preformed membranes, and five use preformed and liquid membranes. Of the three remaining states, one uses a built-up system exclusively, one permits the built-up system as an alternative to preformed membranes, and the other permits the use of built-up, preformed, and liquid systems.

Despite the popularity of preformed membranes, some jurisdictions prefer to use liquid membranes, and more so in Canada than the United States. The most common liquid membrane in North America is a hot-applied rubberized asphalt, which has been in use since the early 1970s. Liquid membranes based on polymer resins are common in Europe but their use in North America has been very limited. Only Oregon and Alberta reported using resin-based liquid membranes.

A classification of the materials used in membranes and a more complete discussion of the effect of material characteristics on performance are given in Chapter 3.

OTHER COMPONENTS OF WATERPROOFING SYSTEMS

Waterproofing membranes cannot be used by themselves—other components must be used to protect the membrane and, in many cases, to improve adhesion of the membrane to the deck and the surfacing. This means that the membrane is only one component of a waterproofing system that may consist of several components (see Figure 3). The characteristics and reasons for using the various components are summarized next.

Primers

Primers are used to penetrate and coat the concrete deck surface to improve adhesion of the membrane to the deck slab. In the past, primers were usually bitumen dissolved in an organic solvent but, due to environmental and safety reasons, these have been largely replaced by emulsions. Synthetic rubber, sometimes combined with a resin and dissolved in a solvent, is used as a primer with some proprietary sheet membranes. Resinous primers are normally used with resin-based liquid systems.

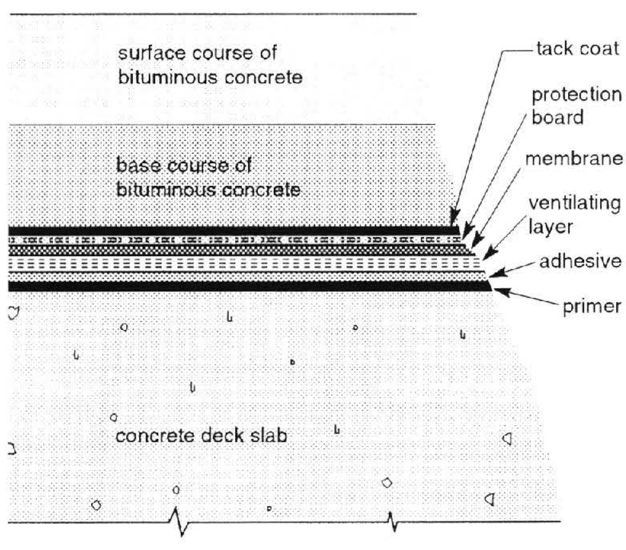


FIGURE 3 Schematic of possible components of a waterproofing system.

Adhesives

Some sheet systems require a separate adhesive to bond the membrane to the deck. The most common adhesive is oxidized bitumen, which is sometimes modified by the addition of polymers. Many of the proprietary sheet membranes have a self-adhesive, pressure-sensitive, bituminous backing.

Ventilating Layers

In situations where blistering is anticipated, a ventilating layer may be used between the deck surface and the membrane to dissipate vapor pressures. This layer may consist of a thin lift of sand asphalt (nominally 13 mm or 0.5 in. thick), which also serves as a levelling course on rough deck surfaces, or a perforated sheet of prefabricated material, which is usually felt or other non-woven fabric. Although ventilating layers have been used in Europe (*5,19,20*), they have been scarcely used in North America.

Protection Board

Protection board, typically consisting of a sandwich of asphalt and mineral filler between layers of asphalt-impregnated felt, is sometimes used between the membrane and the bituminous surfacing. Alternatively, a single layer of felt (often roofing felt) has been used.

The primary purpose of protection board is to prevent damage to the membrane from construction equipment. It also serves to protect the membrane against penetration by large aggregate particles under traffic loading once the deck is open to traffic. Protection board is often used in conjunction with liquid membranes, but rarely with preformed systems.

Tack Coats

A tack coat may be used to improve adhesion between the membrane (or protection board) and the surfacing. The binder content of bituminous surfacings is too low to "wet" the contact surface. Asphalt emulsions have typically been used because most membranes are damaged by organic solvents.

Bituminous Surfacings

While some agencies use only a single protective layer of bituminous concrete over membranes, two layers are more common. The bottom layer is known as the base course, and the second layer as the surface or wearing course. In the United Kingdom and in the state of Illinois, a layer of sand asphalt is used to protect the membrane from damage during application of the base course.

Except for resinous primers and some modest benefits from unpunctured protection board, the membrane is the only component of the waterproofing system that contributes to the waterproofing integrity of the system (*9*). However, it is the complex interaction of all the components that determines the waterproofing system's performance. Factors affecting the performance of waterproofing systems are described in detail in Chapter 3.

PURPOSE AND SCOPE OF SYNTHESIS

Waterproofing membranes have been used for many years to prevent deterioration of concrete bridge decks, but with mixed success. Some states have had good experience with membranes, while adjacent states will not use them, and some states have had a mixture of good and bad performance.

A wide variety of membranes has been used and continues to be available in the marketplace. All membranes must be protected by a wearing course, which is a major factor affecting the service life of the waterproofing system.

This synthesis reports on the use of waterproofing systems applied to new bridge decks, and in conjunction with the rehabilitation of deteriorated concrete bridge decks. It includes a review of domestic and foreign literature and a survey of current practices in North America. This synthesis describes methods for assessing the effectiveness of membranes, criteria for use, installation practices, and factors that affect the performance of waterproofing systems in new construction and rehabilitation. Suggestions for future research are also included.

CHAPTER TWO

EVALUATION TECHNIQUES

INTRODUCTION

There are three circumstances under which waterproofing membranes must be evaluated: as part of a product approval process, as part of quality assurance testing, and to determine the performance of waterproofing systems in the field. This chapter is divided into three sections. The first describes techniques that have been used in the laboratory, usually as part of the prequalification of membranes. The second discusses procedures that have been used in outdoor exposure plot testing, followed by the final section, which presents procedures that can be used to evaluate field performance, including tests conducted in the laboratory on field specimens.

LABORATORY TEST PROCEDURES

A multitude of laboratory tests have been developed to evaluate the performance of waterproofing systems, though most of the tests apply only to the membrane. The tests can be divided into two categories: materials characterization tests and performance tests.

A useful way to present available information on laboratory testing of waterproofing systems is to examine the procedures used in the study for NCHRP Project 12-11 (research results of Phase I were published as *NCHRP Report 165* (*12*)) and in a study carried out in the late 1980s at the Transport and Road Research Laboratory (now TRL, the Transport Research Laboratory) in the United Kingdom (*9*). The research for *NCHRP Report 165* was undertaken in the mid 1970s and represents the most intensive study of waterproofing membranes in North America. The findings significantly influenced the specifications and type of membranes used in the United States, which continues to this day. The U.K. study was the largest and most recent study reported in the literature and represents the state of the art. A comparison of the procedures used in the two studies shows progress that has been made in defining performance requirements for waterproofing systems and in developing test procedures to measure those requirements.

The study for *NCHRP Report 165* included the following materials characterization tests:

- Ultimate tensile strength and elongation at break (ASTM D412, D638, and C190)
- Hardness (ASTM D2240)
- Water absorption (ASTM D570)
- Glass transition temperature (modified ASTM D648)
- Pot life
- Thin-film set time
- Resilience (ASTM D2632)
- Stain test.

For liquid membranes, the tests were performed on specimens cut from sheets cast or fabricated to the same thickness as that specified for field use. The only exceptions were where the test method required a particular thickness of material.

The purposes of material characterization tests are to ensure that high quality materials are used, and to provide a benchmark for future quality assurance testing to verify that the quality of the product is maintained. Because of the wide range of materials used in waterproofing systems, acceptance requirements are specific to the material and do not necessarily correlate with field performance. For example, the tensile strength and elongation of a vulcanized sheet of rubber would be very different from those of a liquid membrane, but both could perform satisfactorily in the field.

The performance tests used in the study for *NCHRP Report 165* are summarized in Table 3. Most of the test procedures were developed as part of the study and were applied as part of a test cycle. Four specimens were fabricated by applying each membrane to a concrete base and subjected to a different series of tests.

Tests intended to simulate field performance are useful in establishing a ranking of membranes, but only under the specific test conditions. Even when the same products are tested, rankings are likely to differ from study to study because of differences in test procedures. Further, for most of the tests, a correlation with field performance has not been established. Test conditions may be too harsh, in which case acceptable membranes could be rejected, or not sufficiently demanding, with the result that membranes that pass the laboratory testing fail in service.

The difficulty of using laboratory tests to predict performance can be illustrated by the crack bridging test. In developing the crack bridging test reported in *NCHRP Report 165*, investigators identified ten test procedures that had been developed in the period 1962 to 1971. The developers of the test procedures all identified what appeared to be a "reasonable" simulation of field conditions. However, there were significant differences in specimen preparation, the method and rate of loading, and definition of acceptance requirements. Consequently, the test procedures could be expected to produce vastly different rankings without it being known whether any ranking correlates with field performance or where the division between acceptable and unacceptable performance should be drawn.

In contrast with the study for *NCHRP Report 165*, the TRL study (*9*) included very few materials characterization tests and a large number of performance tests. The laboratory test program was part of a much larger study that included outdoor

TABLE 3
LABORATORY PERFORMANCE TESTS REPORTED IN NCHRP REPORT 165 (*12*)

Property	Basis of Test Method
Bond	a) Qualitative, by lifting the membrane from a concrete block b) Measuring shear and tension, by gluing dollies to the membrane
Water penetration	Electrical resistance
Impact damage	Repeated drops of a round chisel at room and elevated temperatures
Creep damage	Pressure on aggregate particles at elevated temperature; damage measured by electrical resistance
Crack bridging	Flexural loading at room temperature; loading rate 0.25mm/min (0.01 in./min) to a crack width of 2.5mm (0.1 in.), then 1.3mm/min (0.05 in./min) to 6.4mm (0.25 in.)
Aging	Measure change in weight, tensile strength, elongation, and hardness after 30 days at 60°C (140°F)
Fatigue	Cycles in tension at -18°C (0°F)
Freeze-thaw resistance	Measure change in tensile strength, elongation, and hardness, after 10 cycles of immersion at 60°C and -18°C (140°F and 0°F)

trials of waterproofing systems (*21*) and investigation of site practices and failures (*22*).

Test procedures were developed that were relevant to the performance of membranes during installation of the membrane, after installation of the membrane and before placement of asphalt, during asphalt placement, and in-service. Eighteen tests were used in the investigation, and these are summarized in Table 4.

A quantitative, or semi-quantitative, procedure was developed for assessing the membranes' performance using a seven-point scale. For some tests, membranes were placed on the scale according to observations of damage or response; in other tests, rankings were assigned on the basis of physical measurements. In some cases, it was possible to establish values that relate to satisfactory field performance. For example, water absorption is an important property of membranes because of the risk of damage from freezing. Membranes that absorbed less water than 7 percent of their mass over an 8-month period showed no signs of distress or dimensional change. Above this value, the distress was related to the type of material and its initial thickness. Establishing acceptance criteria that relate directly to field performance represents a significant advance toward the development of a performance specification for waterproofing systems.

Other European countries have developed performance-based tests for waterproofing membranes. A compilation of test procedures used on preformed membranes in nine countries has been prepared (*6*) under the auspices of the Committée European Normalisation (CEN) as the first step in preparing a standard for preformed membranes in the countries of the European Economic Community.

OUTDOOR EXPOSURE PLOT TESTS

Laboratory testing is very useful as a screening and ranking procedure in evaluating membranes, but some of the factors with the greatest effect on field performance cannot be simulated adequately in the laboratory. These factors include the condition and moisture content of the concrete, the range of weather conditions that could prevail during installation, and the method of application and compaction of the surfacing.

As an intermediate step between the laboratory and actual field installations, exposure plot testing can fulfil a very useful role. Exposure plot studies involve testing specimens, which are either custom-fabricated or removed from service under natural, outdoor conditions. Environmental exposure conditions that accelerate natural deterioration are appropriate, but conditions that may change the mechanism of deterioration are not. Exposure plot testing is expensive and no standard procedures exist. The literature contains only a few reports of exposure plot studies. The most extensive study was conducted by TRL (*21*) prior to the laboratory testing program described in the previous section.

A concrete slab 24 × 6 × 0.15 m (79 × 20 × 0.5 ft) was cast and divided into 48 equal bays. Different waterproofing systems were installed on 47 of the bays, with the remaining bay serving as a control with no waterproofing system. The concrete surface was cleaned by water blasting and manufacturers installed membranes. The manufacturers had the option of performing additional surface preparation and of deferring installation if weather conditions were considered unsuitable.

The test was designed to allow for the evaluation of individual components of the waterproofing system and several

TABLE 4
LABORATORY TESTS FOR THE TRL STUDY (9)

Property	Temperature Range (°C)	Basis of Test Method
1. Properties Relevant During Installation of Membranes		
i) flexibility and dimensional stability	-10 to +35	examined for evidence of stiffness at low temperatures and softening at high temperatures
ii) resistance to unrolling*	-10 to +10	examined for effect of upright storage of rolls and ease of unrolling
iii) recoil on unrolling*	-10 to +10	examined for ability to lay flat
iv) resistance to uplift at the edges on rolling*	-10 to +10	measurement of edge curl on unrolling
v) bend test*	-10 to +10	examined for cracking on bending 90°
vi) tear resistance*	-10 to +35	observed resistance to tearing by hand
vii) ease of cutting*	-10 to +35	observed ease of cutting with a hand held razor knife
viii) knife blade penetration	-10 to +35	observed resistance to penetration of a dropped razor knife
ix) viscosity of primers	-20 to +35	measured viscosity with a Brookfield viscometer
2. Properties Relevant to Membranes After Installation and Before Placing Asphalt		
x) resistance to penetration by loose aggregates	-10 to +35	measured penetration by a ball-ended probe
xi) resistance to impact of dropped objects	18	measured penetration caused by chisel dropped from various heights
xii) reflectivity	25	measured reflectivity using a photoelectric light meter
xiii) resistance to fuel spillage	15	observed damage caused by ponding and evaporation of gasoline and diesel fuel
3. Properties Relevant to Membranes During Application of Asphalt		
xiv) resistance to hot asphalt	75 to 200	observed effect of exposure to thermal shock
xv) resistance to hot aggregate	75 to 200	observed damage caused by rolling a sharp aggregate particle on the membrane
4. Properties Relevant to Waterproofing Integrity		
xvi) water absorption	20	measured absorption over an 8 month period, followed by assessment of damage after freezing for 24 hours; some membranes were also tested over a 100 day period after performing test (xiv)
xvii) water transmission	20	measured increase in weight of encased slabs over a 12 month period and made observations with respect to deterioration or debonding; test repeated on primers, adhesives, protection board and asphalt surfacings; also carried out with selected materials using two coats and with concrete slabs treated with isobutyl silane
xviii) chloride transmission	20	similar to test (xvii) except ponded in 3% chloride solution for 8 months

* For sheet membranes only.

combinations of components. Sections of each membrane were covered with mineral dressed protection sheet, even when manufacturers claimed that their system did not need protection. Pieces of silicone-treated release paper were placed underneath the membrane and pieces of bituminized release paper were positioned under the surfacing to facilitate forensic examination of membrane. A piece of unbonded protection board was also placed to evaluate the degree of protection provided by this type of product.

The membranes were left exposed for about 4 weeks before the surfacing was placed. During this time they were exposed to direct sunlight and limited pedestrian traffic. Prior to placing the surfacing, the membranes were observed for evidence of damage, debonding, pinholes, blisters, and degree of cure.

Two parallel strips of asphaltic surfacing, approximately 3 m (10 ft) wide, were placed on all the membranes at the same time. One strip consisted of base course asphalt and the other was a sand asphalt carpet. The surfacings were compacted using standard paving equipment. Temperatures and pressures at the interface between the membranes and the asphalt were measured during placement of the asphalt.

Portions of the surfacing were removed 1 month to 3 years after they had been placed. Observations of the condition of the various components were recorded, and a number of tests performed. Bond of the membrane was assessed periodically by peeling membrane from the concrete and surfacing periodically over the 3-year test period. After 3 years, the bond of the membranes to the concrete was measured using a pull-off test. Waterproofing integrity was measured by applying a standard head of water over a period of 80 days. The principal findings from this study are summarized in Chapter 3.

EVALUATING WATERPROOFING SYSTEMS IN THE FIELD

Because waterproofing membranes must be protected by a bituminous surfacing, determining the condition of the membrane is difficult. Evaluation before placing the surfacing is of limited value because most types of membrane are susceptible to damage during paving operations. The property of primary interest is the watertightness of the membrane. Two approaches for evaluation are possible: methods that measure properties of the membrane directly and those that measure properties of the concrete in the deck slab from which the effectiveness of the membrane can be inferred. This section is primarily concerned with methods used in the field (visual inspection, electrical, embedded devices, physical sampling), but some techniques that have been used in the laboratory on field specimens are also described (ultrasonic, air permeability, and others).

Planning a Field Condition Survey

A condition survey to evaluate the effectiveness of a membrane is expensive; therefore, careful planning to optimize the information collected is important. The scope of the survey is normally determined by decisions that must be made from the findings. For example, at the operational level if a choice must be made between replacing or rehabilitating a deteriorated deck, the survey will focus on the condition of the concrete rather than on the membrane. For a deck exhibiting less deterioration, it may be necessary to determine the extent of concrete repairs prior to applying a new membrane or, for a deck in good condition, whether the membrane must be replaced. In such cases, the testing must yield sufficient information so that all necessary work can be included in the rehabilitation contract. If this is not done, and the contractor is required to undertake extra work, delays often result, contract administration is difficult, and excessive costs may be incurred. In some cases, the method of rehabilitation may be less than the optimum.

For research or performance studies, the objective is often to formulate policy on the future use of individual products, or membranes in general, on the basis of only a short performance history. This type of investigation is very difficult and the use of a number of the more sophisticated techniques described in this section may be necessary. As with all condition surveys, planning activities should include a study of the structural drawings and inspection reports, arrangements for traffic control, staff and equipment needs, a work plan detailing the sequence of operations, and standard forms for recording observations and data. For structures with a complex geometry (such as a large skew angle, large curvature, or variable width), it is good practice to lay out a reference grid on the site plan to save time and avoid mistakes in the field (*2*).

Visual Inspection

The condition of membranes cannot be assessed by direct visual observation and experience is required to search out clues as to their effectiveness. The most direct evidence is available from inspecting the deck soffit after a period of rain. Wet spots and moisture associated with cracks in the concrete indicate the membrane is leaking. Because of grades and crossfalls, the point of leakage may be some distance from the location of the symptoms, especially for a poorly bonded membrane. Under dry conditions, efflorescence is evidence of water seepage through cracks and joints. Rust stains from corroding reinforcing steel are also direct evidence of membrane failure in new decks that have been waterproofed. For membranes applied after the deck was placed in service, inspection records must be consulted to determine whether the deterioration has increased. It may be possible to infer whether the membrane has failed but, depending on the condition of the structure at the time the membrane was installed, corrosion could have continued even though the membrane remained watertight. It is also important to establish that any corrosion is the result of seepage through the membrane and not from sources such as leakage at expansion joints, splash from deck drains, seepage through parts of the deck such as a sidewalk not protected by the membrane, run-off through open railings, or salt spray directly on the soffit.

In cases where the deck soffit is inaccessible, or covered by permanent steel forms, the recourse is to use techniques applied to the top surface.

Visual inspection of the asphalt surfacing may offer clues as to the condition of the membrane. Cracks, especially wide cracks, may be an indication of defects in the membrane, but there are many examples of bridges where the surfacing has exhibited extensive cracking and the membrane remained watertight. Radial cracks, wet spots, or staining associated with cracks in the asphalt are more reliable indicators of deficiencies in the concrete deck slab, and, by extension, that the membrane is not effective.

Experience has shown that membranes fail most frequently in one of three areas: leakage at the edges where the membrane meets the curb or expansion joint, leakage beneath poorly constructed joints in the surfacing, or puncture in the wheel path areas. While visual observations of the deck surface cannot identify puncture failures, moisture associated with gaps at the perimeter of the surfacing or with ravelling at construction joints is a good indication that the membrane is either leaking or susceptible to leakage in the future.

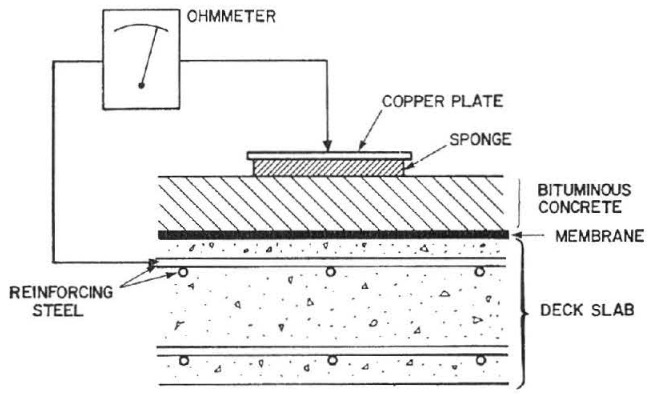


FIGURE 4 Circuit for measuring the electrical resistance of membranes.

Electrical Methods

A number of test methods that measure electrical properties of either the membrane or the underlying concrete are available for field use. These methods are based on measurement of the resistance of the membrane, or the potential or polarization resistance of embedded reinforcing steel. High frequency capacitance measurements for determining moisture content have been investigated in the laboratory but not developed for field use (*23*).

Resistance Measurements

A non-destructive method for evaluating the permeability of concrete sealers was developed in California and its use was extended to waterproofing membranes with an asphalt overlay (*24*). The procedures were based on the use of electrical resistance measurements to determine the effectiveness of coatings on buried pipelines.

The method assumes that where a dielectric material is used to seal concrete, its electrical resistance is a measure of its waterproofing ability. Thus, if the sealer or membrane is porous or punctured, water can pass through, and the greater the number of holes or interconnected pores, the lower the resistance. Conversely, if the sealer or membrane is impermeable to water, the resistance will be infinite. The method is applicable to any sealer or coating that is not conductive and to any structure in which the reinforcing steel is electrically continuous.

The procedure consists of connecting one lead of an ohmmeter to the reinforcing steel and the other lead to an electrode on the deck surface, which consists of a copper plate and wet sponge (see Figure 4); the electrical circuit is not completed until wetting solution from the sponge percolates through the asphalt to the membrane. A full description of the equipment and a standard test procedure have been published by the American Society for Testing and Materials (ASTM D3633).

The permeability of asphalt wearing courses varies considerably, and it may take several hours of periodic wetting at the test locations before testing can begin. A representative, well-compacted test location is chosen as a checkpoint. Resistance readings are taken at intervals until the resistance stabilizes, which indicates that the wetting solution has reached the surface of the membrane. A wetting period of 30 minutes is often sufficient, but where the resistance readings remain infinite, measurements should continue for at least 4 hours.

The test site location has to be chosen carefully. If the test is intended to measure the average condition of the membrane, resistance readings are usually selected by a random location system or made on a regular grid. If the purpose is to determine whether the membrane is leaking, readings will usually be concentrated near the perimeter and in the wheel paths.

A number of difficulties have been experienced in applying resistance measurements mainly because of variations in pavement porosity, moisture in the surfacing, and short circuits to the reinforcing steel (*25–28*). Some of the problems that can occur are illustrated in Figure 5. As originally conceived, the test method involved placing a sponge directly on a sealed concrete surface, in which case the contact area was known and the "resistivity" of the sealer could be calculated. (The units of electrical resistivity are ohm/m. The literature refers to the quotient of the resistance and the contact area of the sponge in ASTM D3633 as "resistivity," which has the units ohm/m^2.) When testing a membrane beneath a bituminous overlay, the area of contact between the wetting solution and the membrane is not the same as the area of the sponge but is a function of the time of soaking, the permeability of the asphalt, the moisture content of the asphalt, and the longitudinal grade and crossfall of the deck. If water is ponded on the top of the membranes, as is often the case, a short circuit to the reinforcing steel may occur through embedded hardware such as a deck drain or steel expansion joint. A note in ASTM D3633 suggests checking for excessive moisture in the asphalt by attaching the ohmmeter to the reinforcing steel and two probes on the deck surface. Immediate low readings (of the order of 10 000 Ω) indicate excessive moisture and further testing should be postponed.

When using a direct current ohmmeter, problems of drift and non-reproducible values resulting from the galvanic coupling of the copper plate to the reinforcing steel are often experienced. Approximate readings can sometimes be made by

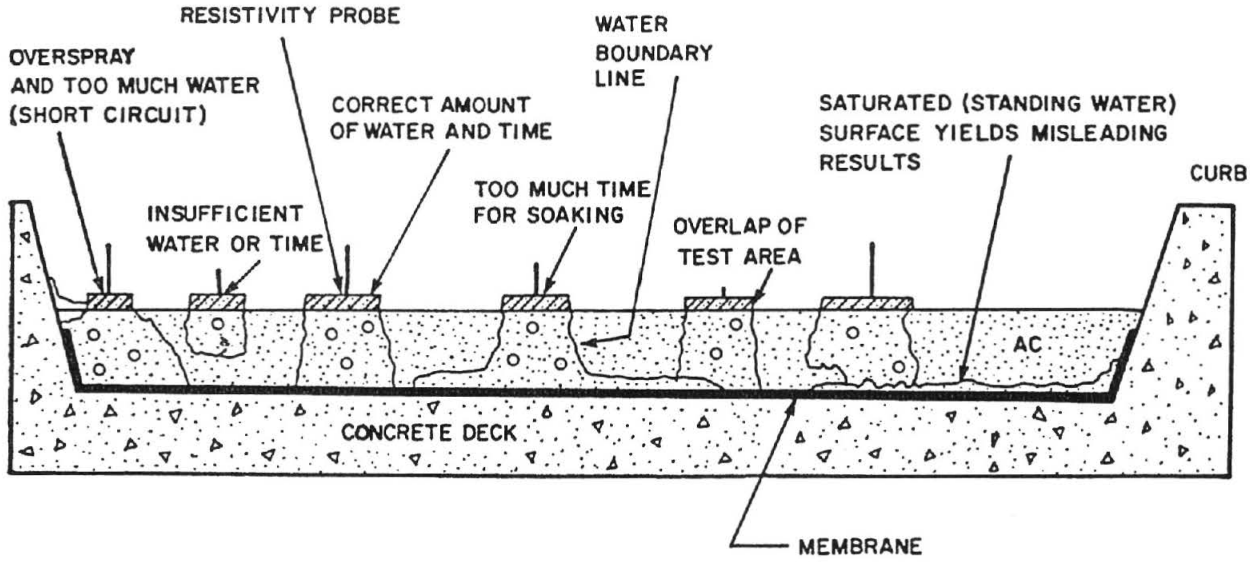


FIGURE 5 Possible problems in "resistivity" measurements (*26*).

reversing the leads by means of a double-pole switch. For greater accuracy, an alternating current ohmmeter is preferred.

Experience in the use of the electrical resistance test led to the development of subjective criteria to describe the effectiveness of sealers and membranes. Spellman and Stratfull (*24*) originally suggested that an excellent waterproofing material would have an average electrical resistivity greater than 50kΩ/m² (500kΩ/ft²) whereas a poor or perforated membrane would have an average resistivity of less than 10kΩ/m² (100kΩ/ft²). These values were also quoted in a report published by the Organization for Economic Cooperation and Development (OECD) in 1976 (*29*). In the course of extensive laboratory and field measurements as part of the study for *NCHRP Report 165* and Phase II of NCHRP Project 12-11 (*12,18*), the following criteria were adopted:

- >100kΩ/m² (>1 MΩ/ft²) —good
- 1 kΩ/m² to 100 kΩ/m² (10 kΩ/ft² to 1MΩ/ft²)—fair
- 10 Ω/m² to 1 kΩ/m² (100 Ω/ft² to 10kΩ/ft²)—poor
- 10 Ω/m² (<100 Ω/ft²) —very poor

Other investigators have established different criteria, some of which are based on resistance values rather than resistivity (*30,31*). Some states developed criteria that did not rely simply on average values. For example, Oregon considered a membrane to be satisfactory if 80 percent of the resistance readings were greater than 500kΩ and 100 percent were greater than 100kΩ (*28*). A membrane was deemed unsatisfactory if 50 percent of the readings were less than 100kΩ. The performance of membranes with readings between the two criteria was considered doubtful.

The factors affecting resistivity measurements in the field were the subject of a detailed investigation in California (*30*). The study showed that while there is a relationship between holes in a membrane and resistance, there is also an effect of hole size. Several small holes, having a total area equal to a single large hole, will offer greater resistance. The study also investigated the effect of probe size. It was expected that resistivity calculated by dividing resistance readings by the area of the probe would produce consistent results. This proved not to be the case. The wetted areas of the membrane under the asphalt surfacing were unknown, but presumably not in the same ratio as the probe areas. Thus, investigators concluded that resistivity values had little meaning, and only resistance readings should be reported.

Repeated surveys on the same decks over a period of years confirmed this conclusion and caused the investigators to question the usefulness of the procedure (*32*). Readings taken over a period of 5 hours rarely stabilized because as the wetted area of the membrane increased, the resistance decreased. Because investigators also experienced difficulties in interpretation because of moisture in the surfacing, they placed greater reliance on visual observations and on measurements taken directly on the membrane after the surfacing was removed at selected locations.

The Vermont Agency of Transportation demonstrated a relationship between resistivity readings and chloride penetration through sealants and membranes (*33*). In 1975 and 1976, resistance readings and core samples were taken at 131 locations on 51 bridges (*27*). The cores were analyzed for chloride content. When 500 kΩ was used as the criterion for an effective waterproofing, there was a correlation between resistance readings and chloride intrusion data in approximately 60 percent of the measurements. In other words, high resistance readings were associated with no chloride intrusion and low resistance readings were associated with chloride intrusion about 60 percent of the time. Varying the acceptance criterion above and below 500 kΩ did not significantly affect the reliability factor of the test.

The results of a field survey of 76 bridges in Ontario in 1974 (*31*) showed a lack of correlation between resistance readings, half-cell potential measurements, chloride ion contents, and visual observations. The survey concluded that many of the readings from the resistance test were false negative values, i.e., low resistance readings were not necessarily associated with defects in the membrane. It was suggested they were probably the result of moisture in the surfacing.

The lack of good correlation between resistance readings and chloride intrusion indicates the limitations of both the resistivity test and the sampling procedures for chloride determinations. The resistivity test measures the average value of the resistance over the area wetted by the contact solution, and the extent of this area is unknown. The chloride sample is, however, taken from a point that may or may not coincide with an imperfection in the membrane.

Because of its limited use as a quality assurance test when readings can be taken directly on the membrane, the electrical resistance test, which was widely used in the 1970s, has diminished. Interpretation of results taken through an asphalt surfacing is much more difficult. High results after several hours soaking are a good indication of an impermeable membrane but low results, especially uniformly low results, require more detailed examination to ensure they were not the result of a short circuit or moisture in the surfacing. Where sufficient readings are taken, it is good practice to plot equal resistance contours and investigate anomalous areas more closely.

Potential Measurements

The method of measuring the half-cell potential of steel in concrete for the purpose of determining the corrosion activity of the steel was also developed in California (*34*). A full description of the equipment and procedure has been published by ASTM (ASTM C876 "Standard Test Method for Half-Cell Potentials of Uncoated Reinforcing Steel in Concrete").

When steel corrodes in concrete, a potential difference exists between the anodic half-cell areas and the cathodic half-cell areas along the reinforcing bar. The potential of the corrosion half cells can be measured by comparison with a standard reference cell, which has a known, constant value. A copper-copper sulfate electrode (CSE) cell is normally used in field work because it is rugged, inexpensive, and reliable. The potential difference between the steel reinforcement and the reference cell is compared by connecting the two through a high-impedance voltmeter. This is done by connecting one lead of the voltmeter to the reinforcing steel. The other lead is connected to the reference cell, enabling electrode potentials to be measured at any desired location by moving the half cell over the concrete surface in an orderly manner.

The reinforcement in bridge decks is usually in good electrical contact so that only one electrical connection to the reinforcement is needed. It is, however, necessary to check that a good connection has been made and that the reinforcing steel is continuous by measuring the resistance to the reinforcing steel at another location or to exposed metal fixtures that are connected to the reinforcing steel. A separate connection is required wherever the steel is not continuous as, for example, in sections of a bridge deck separated by expansion joints.

Convention dictates that the potentials of steel relative to the CSE be reported as negative values. The reason for this is that iron is more negative than copper in the electrochemical series.

An appendix to ASTM C876 states that for testing of above ground, reinforced concrete structures, the significance of measured values is as follows:

- Less negative than -0.20 V (CSE) greater than 90 percent probability of no corrosion,
- Between -0.20 and -0.35 V (CSE) corrosion activity uncertain
- More negative than -0.35 V (CSE) greater than 90 percent probability that corrosion is occurring.

If positive readings are obtained, it generally indicates that there is insufficient moisture in the concrete and the readings should not be considered valid.

The above criteria have been applied widely, and often indiscriminately, though the standard states that potential measurements should be interpreted by experienced engineers or technical specialists, often using corroborating data from other test procedures.

There are two types of surveys in which potential measurements have been used in evaluating the effectiveness of membranes: when a membrane is applied to a new deck, the detection of active corrosion potentials indicates that chloride ions have penetrated the membrane; and when a membrane is applied to a deck in service, or during rehabilitation, the periodic measurement of corrosion potentials has been used to try to determine the effect of the membrane on corrosion activity in the deck slab.

ASTM C876 states specifically that the criteria for corrosion activity should not be used to formulate conclusions concerning changes in corrosion activity with time on a rehabilitated structure in which the rehabilitation caused moisture or oxygen content or both at the embedded steel to change with time, such as when a membrane is applied to a chloride-contaminated deck, unless either experience or destructive examination validates the criteria.

To ensure that the electrical circuit is completed, holes must be drilled through the asphalt and the membrane at the test locations. Typically, a 13-mm (0.5-in.) diameter bit is used and drilling is stopped when concrete dust is visible on the deck surface. Drilling into the concrete deck slab by a small amount (no more than 13 mm or 0.5 in.) also eliminates the effect of junction potentials, which can have a significant effect on recorded values (*35*). If the asphalt contains significant amounts of water, potential measurements will detect the presence of corrosion activity (including exposed hardware connected to the reinforcing steel) but not necessarily its location. The holes are filled with wetting solution prior to taking measurements, and later dried and caulked to seal the deck.

Rate of Corrosion Measurement

Whereas potential measurements provide information on the presence of corrosion activity, they give no information about the rate of corrosion (*36,37*). Corrosion rates of steel in highway structures are primarily controlled by the resistivity of the concrete and the availability of oxygen at the steel surface. Consequently, it is possible to have high potential measurements but low corrosion rates. This is particularly applicable on asphalt-covered decks constructed without a membrane, or with one that is ineffective, because the asphalt traps moisture in the concrete. This restricts the availability of oxygen at the steel surface and can result in "black" corrosion in which the corrosion products occupy no more than the original volume of the steel, resulting in deep pitting of the steel without delamination of the concrete.

There are several different methods of measuring the rate of corrosion of steel in concrete (*38*), though linear polarization and frequency response appear to be most suitable for field applications (*39*). Commercial instruments are available and three devices were evaluated as part of a SHRP study on inspecting and assessing the physical condition of concrete structures (*40*). Two of the devices operated on the principle of linear polarization. The procedure involves measuring the potential of the reinforcement and then measuring the current required to cause a small cathodic polarization of the steel, which enables the polarization resistance to be calculated. The polarization resistance is inversely proportional to the corrosion current, which in turn is directly proportional to the rate of corrosion. One of the linear polarization devices included a guard electrode, which is used to confine the current to the area of reinforcement directly below the counter electrode.

The third device operated on the principle of superimposed current pulses of high and low frequency. The higher frequency provides a measure of the concrete resistance. The lower frequency measures the sum of the concrete resistance and polarization, and the polarization resistance can therefore be calculated.

All three devices were found to give comparable qualitative results for actively corroding structures. The linear polarization device with current confinement was found to give corrosion currents most closely matching true values, especially for very small corrosion currents.

The electrical circuit for making rate of corrosion measurements is the same as for potentials, but the membrane must be removed over an area of approximately 150 mm × 150 mm (6 in. × 6 in.) at each test location so that the electrodes are in direct contact with the concrete surface. A single measurement with the simplest device takes about 3 minutes, and the other devices require more time.

Measuring the rate of corrosion is not likely in making operational decisions about waterproofing membranes. Given that the technology is relatively new and that field experience is limited, rate of corrosion measurements are likely to remain a research tool for some time. They do, however, offer the possibility of providing a more definitive answer to questions surrounding the effectiveness of membranes applied to corroding decks and are likely to be used in research studies on this topic.

Embedded Devices

In the early 1970s, the Arizona Department of Transportation developed a procedure for improving the interpretation of measurements taken in the electrical resistance test (*26*). Two 300-mm (1-ft) square aluminum foil sheets were placed on top of the membrane prior to placing the asphalt surfacing. Electrical connections were made to the sheets so that the time needed for wetting the deck could be established and the problem of substantially increasing the wetted area avoided. Measurements of resistance between the two sheets could also be used to indicate whether moisture was present on the surface of the membrane.

In field evaluation studies conducted as part of Phase II of NCHRP Project 12-11, moisture detectors made from copper foil were placed on the deck surface prior to placing the membranes. Each detector consisted of two strips of copper foil each 13 mm (0.5 in.) wide and 2.7 m (9 ft) long and spaced 50 mm (2 in.) apart, fastened to the deck with duct tape (*18*). Leads were connected to each strip and left accessible for testing. Measurements of the resistance between the strips were made at 6-month intervals over a 2-year period. The resistance between the strips dropped substantially during the period of observation. This was interpreted as an indication of moisture accumulation beneath the membrane. However, resistance values were higher than would have been anticipated if salts were also present, and this was taken as evidence that deicing salts did not penetrate the membrane.

Copper foil strips were placed at 40 locations on 23 bridges in Vermont (*27*). Difficulties were experienced with installing liquid membranes because the thickness of the membrane had to be increased over the strips, which also acted as a bond breaker. The strips were monitored over a period of 2 to 5 years, during which several failed. There was a lack of correlation with chloride penetration data, and it was concluded that the strips were not an effective way of monitoring membrane performance. Moisture sensing electrodes made from copper foil were also included in a study in New Jersey (*41*). The readings were found to be difficult to interpret, and most of the junction boxes housing the terminal connectors were destroyed by vandals over a 5-year period.

All the examples of the use of embedded devices date from the early to mid 1970s and no evidence of similar devices being used in later years has been located. There have been some attempts to use other types of humidity devices for measuring moisture content and to use embedded reference cells to detect corrosion activity. With the exception of a study on the World Trade Center in New York City (*42*), none has been reported as being successful.

Physical Sampling

Taking cores or pulverized samples of concrete, or selectively removing pieces of the asphalt surfacing, can provide useful information about the condition of waterproofing membranes.

The removal of samples of asphalt by dry sawing is a well-established technique for examining asphalt-covered decks (*43*). Dry sawing, as opposed to wet sawing, is used to acquire important information about the presence of moisture beneath the waterproofing membrane. Sawn samples are typically not less than 300 mm (1 ft) square and usually taken in areas of suspected deterioration of either the membrane or the deck concrete. Careful removal of the surfacing and membrane permits an assessment of the bond between the asphalt, membrane, and deck. Once the concrete has been exposed, it can be sampled for measurement of chloride ion content. In addition, potential or rate of corrosion measurements can be made to provide more information on the effectiveness of the membrane.

Cores can also be taken to provide information on the condition and effectiveness of membranes. A thin-walled diamond bit should be used, and the minimum core diameter should be 100 mm (4 in.) to reduce the possibility of the asphalt or concrete breaking inside the core bit (*2*). It is also advisable to remove the asphalt from the core bit before drilling the concrete, especially on decks where the bond is poor. Cores taken from wheel path locations should be examined carefully for evidence of penetration of aggregate particles into or through the membrane. Some types of membrane are easily damaged by paving equipment or excessively hot bituminous mixtures and this should be apparent from visual examination. Cores can be used to determine the chloride content of the concrete. Normal practice is to cut the core into slices in the laboratory and measure the chloride ion profile using wet chemical methods of analysis (*23*). A standard method of sampling and testing for chloride-ion content has been published by AASHTO (AASHTO T 260 "Method of Sampling and Testing for Total Chloride Ion in Concrete and Concrete Raw Materials"). The quantity of chloride ion that is sufficient to initiate corrosion is generally accepted to be approximately 0.20 percent by mass of cement (or about 0.03 percent by mass for a typical concrete) when measured by nitric acid extraction on concrete samples taken at the level of the reinforcement. The interpretation of data when "background" chloride ions are present is complex, and guidance is provided by the American Concrete Institute (*44*).

In the early 1970s, agencies began using a percussion drill (sometimes called a rotary hammer) to collect a pulverized sample of concrete in the field and to eliminate sample preparation in the laboratory (*45*).

Research by the Kansas Department of Transportation in the mid 1970s resulted in both a vacuum drilling method for collecting the pulverized sample, and a method of measuring chloride ion content in-situ by inserting a chloride-specific electrode in the deck (*46*). Although the method had advantages of speed and minimal damage to the deck, it was discontinued because of the frequency with which electrodes were being broken in the field.

Several other studies have been undertaken to develop methods of measuring chloride ion content in the field. The most recent study was undertaken by SHRP to inspect and assess the physical condition of concrete structures (*47*). Extensive laboratory and field evaluations resulted in selection of the specific ion probe as the best method, based primarily on technical performance, but also considering cost, speed, and ease of operation. A detailed test procedure was prepared in a format suitable for consideration by ASTM (*48*). The research also investigated methods of obtaining a representative sample of concrete for analysis. The proposed test method recommends use of a heavy-duty rotary hammer fitted with a stop gage and a vacuum bit with a diameter 1.5 times the maximum aggregate size. The concrete powder is drawn through a coaxial hole in the bit and collected by a filter placed in a collection chamber. It was found that grinding the powder so that 99 percent passed a 850μm (No. 20) sieve was sufficiently fine for the results to be reproducible.

In most condition surveys, chloride ion content of the concrete at the level of the reinforcement is of primary interest because of the need to establish whether there is sufficient chloride present to initiate corrosion. In evaluating the effectiveness of membranes, the primary purpose of measuring the chloride ion content of the concrete is to establish whether the membrane is leaking and consequently the surface concrete is of greatest interest. However, care is required in interpreting the data. In cases where the membrane was applied after a deck had been exposed to salt, it may not be possible to assess the effectiveness of the membrane unless data taken at the time of installation is on file or if measured values are very high. Even when the membrane was applied to a new deck, samples should be taken deep in the deck where contamination has not occurred to establish the background chloride concentration.

As noted previously in discussion of the electrical resistivity test, the location of chloride ion measurements may or may not coincide with an imperfection in the membrane. Consequently, chloride ion contents in excess of background levels are a strong indication of membrane leakage (for membranes applied to new decks), but the reverse is not necessarily true. The correlation between chloride ion measurements and the effectiveness of the membrane improves with the number of samples taken.

Ultrasonic Methods

Ultrasonic test methods consist of measuring the travel time of an ultrasonic pulse passing through the material under study. The pulses are generated using electronic circuitry and are transformed to mechanical energy by a transmitting transducer containing piezoelectric crystals. A similar transducer acts as a receiver.

The SHRP study on inspecting and assessing the physical condition of concrete structures included a task to develop a method for evaluating the integrity of bridge deck membranes. Several different approaches were considered and pulsed radar, thermography, and ultrasonic pulse velocity were considered for preliminary examination (*49*). On the basis of screening tests, the pulse velocity method was selected for more detailed evaluation. The surface transmission method had to be used, but this was considered an advantage because when detecting holes in the membrane or debonding between the membrane and the concrete bridge deck or the asphalt, the stress wave had to pass through the defects twice. The equipment used in the evaluation operated at a frequency of 54 kHz.

Preliminary testing on reinforced concrete specimens, with a 65 mm (2.5 in.) hot-mix asphalt layer, showed that a separation of 90 mm (3.5 in.) between transducer and receiver produced the most consistent results when the transducers were placed in different positions relative to the reinforcement. This finding was confirmed on larger, outdoor slabs. The separation of 90 mm (3.5 in.) satisfies the criterion that the separation should be at least 0.9 times the wavelength in the material, which was calculated to be 76 mm (3 in.) (*49*).

Further testing was undertaken on large outdoor slabs, which were constructed with three commercial preformed membranes and asphalt overlays. The membranes were intentionally damaged to different degrees. Two cores were taken from each slab and the condition of the membrane was rated on a scale from 0 to 10 by a single rating representing the number of holes and the degree of bond between the membrane and the concrete and asphalt. A strong correlation between the pulse velocity and the membrane rating was established (the more deterioration, the higher the velocity). It was noted that measurements could not detect small holes in the membrane but were sensitive to bonding. The thickness of the asphalt layer was found to have an insignificant effect on the measurements, but the range of thickness was not reported.

Field validation studies were undertaken in fifteen bridges, five in each of the states of Vermont, New Hampshire, and Maine. The age and condition of the bridges varied, but the membranes were the same as those installed on the outdoor slabs. A sampling plan was developed for each bridge and included taking measurements where the membrane was expected to perform well, where the membrane was most likely to be changed or deteriorated, and at cracks in the surfacing. Cores were taken to represent the range of pulse velocity measurements, including locations where the asphalt surfacing was deteriorated. In some cases, a pulse velocity measurement could not be made. An average of 45 readings and 14 cores were taken from each bridge. Membranes were removed from the cores and rated according to the same procedure used on the slabs. There was a strong correlation between the ultrasonic pulse velocity measurements and the membrane ratings. A statistical model was developed to predict the membrane status. A recommended test procedure for the use of pulse velocity measurements for assessing the condition of preformed membrane systems on bridge decks was prepared (*48*), though it was noted that additional field validation is required to confirm the procedure (*49*). The test method states that the procedure may be used to indicate deterioration and/or debonding of a membrane but cannot be used on a cracked asphalt surface.

Air Permeability Methods

In the course of an investigation of membrane performance on 36 bridge decks in Alberta, air permeability measurements were made on core specimens (*50*). The test procedure was in accordance with the Modified API (American Petroleum Institute) RP-40 method, which is used in the oil industry to measure the permeability of rocks (*51*). Cores 75 mm (3 in.) in diameter were taken through the surfacing, membrane, and at least 50 mm (2 in.) into the concrete deck. The concrete was trimmed to 50 mm (2 in.) in the laboratory, and the permeability was measured by applying air pressure to the surface of the asphalt. The results showed a wide variation in permeability, which was a function of both the type of membrane and the quality of construction. The results correlated well with membranes known to have been damaged at the time of installation. In one case of a hot-applied rubberized asphalt membrane that was damaged because of the use of an ineffective protection board, permeability values were 1,000 times greater than median values from other sites where the same material had been installed.

Other Techniques

Several other techniques have been investigated either for determining the condition of membranes directly, or for measuring properties of concrete deck slabs from which the effectiveness of a membrane could be inferred. None of these techniques is suitable for routine use but the literature is summarized briefly to provide a complete record.

Radar

The principle of ground penetrating radar is that pulses of radio frequency energy are directed into the deck and the reflected signal is captured and analyzed. The pulses are of extremely short duration, approximately one nanosecond. Reflections occur from each interface where there is a change in dielectric constant, or from discontinuities such as voids or cracks.

A number of studies have been carried out on asphalt-covered decks (*52–54*), which demonstrated that radar is capable of identifying anomalous areas in a deck. The practical problem was analyzing the large amount of data collected and relating the different radar signatures to specific types of physical distress. Lack of experience in interpreting the data initially led to a large number of false results. Signal processing techniques have improved considerably (*55, 56*) but commercial systems do not have sufficient resolution to detect defects in membranes. In the SHRP study (*49*), it was found that pulsed radar could identify the asphalt-concrete interface clearly, but could not distinguish the presence of a membrane. More recent work showed that a waterproofing membrane can produce a reflection at the asphalt-membrane interface and another at the membrane-concrete interface. This enables not only the presence of the material to be established but also its thickness to be calculated (*56*). It has been suggested that pulsed radar could be used to detect defects in membranes if a higher frequency and more focused antenna are used to increase spatial resolution (*49*).

Commercial radar equipment can be used to detect debonding of asphalt from some types of membranes and to detect delamination in the deck slab, which in turn may be evidence of an ineffective membrane. It has also been suggested that radar could be used as a measure of the chloride ion content of concrete (*55, 57*), but additional research is needed.

Thermography

Infrared thermography has also been used in investigating the condition of asphalt-covered deck slabs. The method works on the principle that as a bridge deck heats and cools, there is a substantial thermal gradient within the deck because concrete and asphalt are poor conductors of heat. Any discontinuity, such as a delamination or debonding parallel to the surface, interrupts the heat transfer through the deck. This means that in periods of heating, the surface temperature of delaminations or debonded areas is higher than the surrounding concrete. At night the situation is reversed.

Infrared thermography has been shown to be capable of detecting lack of bond and delaminations in asphalt-covered decks (*52*), but the technique is very sensitive to weather conditions and largely impractical at the present time.

Nuclear Methods

The chief application of nuclear methods is in the measurement of density and moisture content in-situ by neutron absorption and scattering techniques. The prime reason for measuring moisture content is to determine if corrosion of embedded reinforcement may occur.

A prototype piece of equipment was developed by the Laboratorie Central des Ponts et Chaussees in France in the mid 1970s to measure the thickness of waterproofing layers by means of a neutron probe (*58*). No further evidence of its use has been uncovered.

In the early 1980s, equipment for measuring the moisture content of concrete by nuclear magnetic resonance methods was constructed and investigated under FHWA contracts (*59,60*). Although the method was feasible, the equipment was expensive, heavy, slow, and required skilled operators. As a result, it was not developed commercially.

A similar fate befell a piece of equipment constructed under a pooled fund study in the late 1970s to measure the chloride ion content of concrete in-situ (*61*). The equipment used neutron beams to bombard the concrete and, following laboratory studies, field trials were undertaken on bridge decks in Texas. The equipment was impractical for reasons of high cost, limited accuracy, and the difficulty of moving it from site to site.

CHAPTER THREE

WATERPROOFING SYSTEMS IN NEW CONSTRUCTION

This chapter describes those aspects of design, construction, and performance that apply to waterproofing systems installed on bridges before they are open to traffic. Aspects of waterproofing systems that apply regardless of whether the system is installed on a new or an existing deck, such as the types of materials used, are also included in this chapter. Other aspects, which are more applicable to the use of waterproofing systems in rehabilitation contracts, are described in Chapter 4.

MATERIALS

This section describes the range and classification of materials used as membranes, performance requirements, and the relationship between materials specifications and performance requirements.

Classification of Membranes

A wide range of materials has been used in the manufacture of waterproofing membranes. The study for *NCHRP Report 165* examined 147 waterproofing systems and developed a classification system based on five characteristics: preformed vs. applied-in-place; thermoplastic vs. thermosetting; unmodified vs. modified; reinforced vs. non-reinforced; and wearing course vs. no wearing course.

A secondary classification was developed for some of the characteristics to indicate the generic type of material.

Thermosetting materials are those that, following the initial permanent set through chemical reaction before or immediately following application, do not change viscosity appreciably with change of temperature. Thermosetting materials include vulcanized rubber sheets and many of the resin-based liquid membranes such as those made from epoxy, polyester, polyurethane, acrylic, or polysulfide resins. Conversely, thermoplastic materials do not set permanently through chemical reaction and will change viscosity in response to changes in temperature. Thermoplastic materials include membranes based on coal tar, asphalt, and rubbers and plastics, which are not cross-linked.

A membrane was considered to be modified if it included an appreciable amount of secondary material to effect a change in properties, such as the addition of coal tar to resins or the use of fillers to asphalt membranes. Materials added for the purpose of promoting setting, or emulsifiers or solvents added for ease of application, were not considered to be modifiers.

Reinforcement was considered to be the incorporation of continuous sheets or fibers in a membrane. Examples are glass fiber, polypropylene or nylon fabrics, and polyethylene sheet. Discontinuous fibers were considered to be modifiers or fillers, rather than reinforcement.

In the 1970s, attempts were made to develop membranes that did not require protection from traffic loading by the application of a separate wearing course. Typically, aggregates were embedded in the surface of the membrane. These products did not perform satisfactorily and are outside the scope of this report.

The distinction between preformed (often called sheet systems) and liquid systems is particularly useful because a number of generalizations can be drawn that are relevant to the evaluation of membranes and their installation (*62*). The relative merits of preformed and liquid systems are listed in Table 5.

An alternative classification system was developed as part of a laboratory and outdoor investigation of 48 waterproofing membranes in the United Kingdom (*9,21*). As in the classification system already described, this method distinguished between sheet and liquid systems and then developed a secondary classification based on material composition. Figures 6 and 7 show the sheet and liquid systems, respectively, that were included in the investigation. The sheet systems were categorized into four types: asphalt-impregnated fabric sheets, polymeric sheets, elastomer sheets, and asphalt-laminated boards.

Asphalt-impregnated fabric sheets consisted of a central core of absorbent material impregnated and coated with asphalt cement. Core materials were either polyester fleece, glass cloth, or woven polypropylene.

Polymeric sheets were extruded blends of various base polymers to which were added other polymers, binders, plasticizers, and inert fillers. Systems used in the trial were based on either bituminized, laminated, or chlorosulfonated polyethylene; ethylene propylene; ethylene vinyl acetate; or polymer plasticized polyvinylchloride.

The elastomer sheets used in the trial were vulcanized butyl or polyisoprene rubber. The butyl type was laminated with asphalt-saturated felt on the underside. Other types of elastomeric sheets, such as those made of polychloroprene, ethylene propylene diene monomer, butyl, and hypalon rubbers, have been used in North America, mainly in experimental installations in the 1970s.

The asphalt-laminated boards, which were also used as protection boards for some systems, consisted of a core of finely crushed aggregate saturated with asphalt-cement between layers of asphalt-saturated felt.

Some sheet systems were self-adhesive, using a pressure-sensitive, asphalt-based adhesive. Others used a separate adhesive, which was normally an oxidized asphalt. A bituminous-based primer was used with most of the systems.

Liquid systems consisted of one- or two-component, mois-

TABLE 5
CHARACTERISTICS OF SHEET AND LIQUID MEMBRANE SYSTEMS (adapted from 2)

Preformed Systems	Liquid Systems
•Tend to perform well in laboratory evaluations	•Tend to perform less well in laboratory evaluations
•Quality of material controlled under factory conditions	•Difficult to ensure consistent quality of materials
•Thickness and integrity controlled at the factory	•Difficult to control thickness of membrane and detect presence of pinholes
•Labor-intensive installation, especially if not self adhesive	•Usually applied in one application by spray or squeegee; built-up systems are labor intensive
•Laps required	•Laps not required
•Difficult to install on curved or rough decks	•Application independent of deck geometry. Thin membranes require a smooth deck
•Vulcanized sheets may be difficult to bond to substrate, protection layer and at laps	•Bonding not usually a problem if substrate prepared properly; self adhesive
•Vulnerable to quality of work at critical locations such as curbs, expansion joints and deck drains	•Less vulnerable at critical locations
•Blisters must be repaired by puncturing and patching	•Blisters and blowholes easily repaired in self-sealing materials, but not in thermosetting materials
•Tend to be more expensive	•Tend to be less expensive

ture or chemically curing solutions. A resin-based primer was normally used.

The coatings were categorized into bituminous and resinous systems. Bituminous systems were subdivided into bituminous solutions or compositions, and mastics. Mastics required heat to convert them to a liquid for application. Similar products, incorporating rubber and polymers for greater flexibility, are used in Canada and in a few states. Resinous types were subdivided into urethane, epoxy, and acrylic resin-based systems.

Bitumen-based systems were either one part blended solutions of various bitumens in hydrocarbon solvents, two part polymer-modified compositions, or refined natural or elastomer-modified mastic asphalts.

The resin-based systems were either one or two part mois-

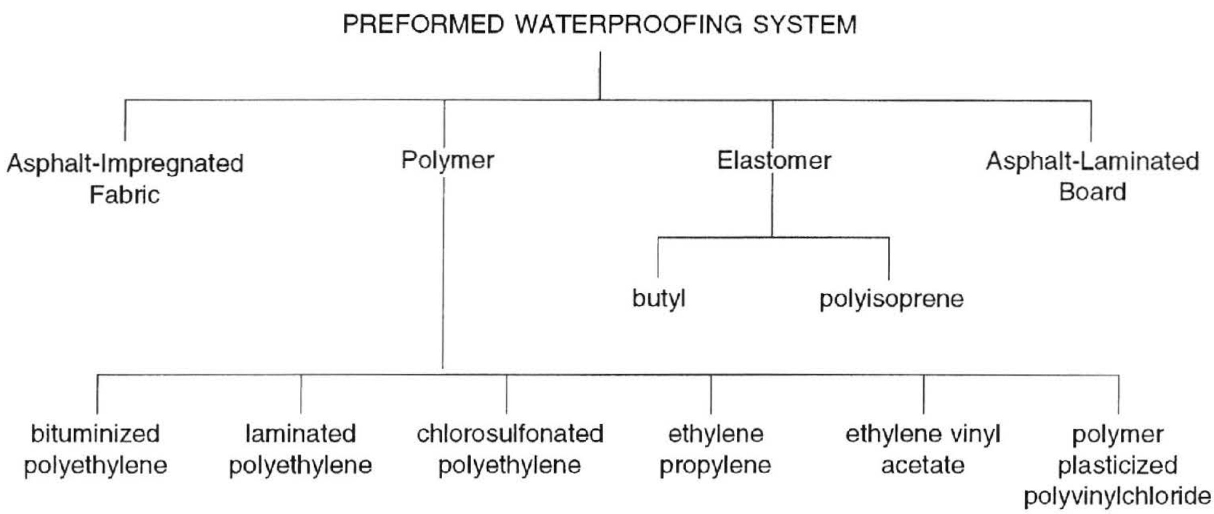


FIGURE 6 Preformed waterproofing systems (adapted from 9).

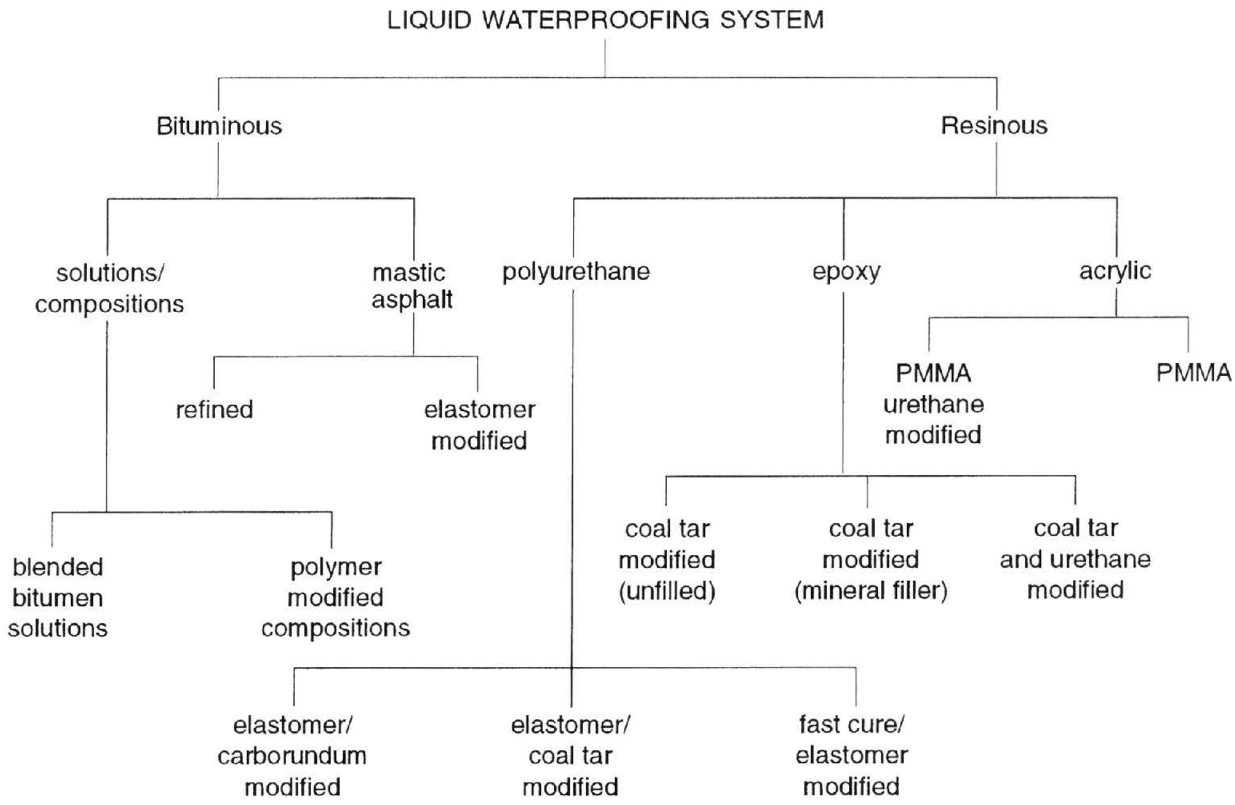


FIGURE 7 Liquid waterproofing systems (adapted from 9).

ture curing or two part chemical curing, based on either urethane, epoxy, or acrylic resins.

Urethane-based systems were all elastomer-modified polyurethanes, some were further modified with either carborundum or coal tar. The latter were referred to as pitch urethanes. Other polyurethane systems were fast curing elastomer- and/or polymer-modified. These normally used generically similar primers but one fast cure system used an epoxy based primer.

All epoxy resin-based systems were modified with coal tar and were referred to as pitch epoxies. Some were mineral filled. One system was further modified with polyurethane and reinforced with a polyester fleece. These systems did not require the concrete to be primed.

Acrylic systems were based on polymethylmethacrylate resin (PMMA) and used a generically similar primer. One system was modified with urethane.

Following an intensive series of outdoor and laboratory tests (which were described in Chapter 2), observations were made on generic relationships between material composition and the performance characteristics of primers, adhesives, and membranes. These observations are summarized in Tables 6 and 7. It must be remembered that the information in the tables relates directly to the membranes that were included in the test program. In some cases, and particularly for polymer sheets, there were widely differing characteristics within the generic group. However, the findings summarized in Tables 6 and 7 are significant because it had generally been accepted that the wide range and quality of materials used in membranes precluded relating materials composition to performance. Where the term "ambient temperature range" is used in Table 7, this refers to the temperature range specified in Table 4 for the relevant property.

The responses to the questionnaire for this synthesis identified 22 different proprietary waterproofing products used in the United States in 1992. Where a product is supplied in several variations, for example supplied in different thicknesses, each variation was counted as a different product. The vast majority of membranes are preformed products and three of the products have dominated the marketplace since the 1970s. The situation in the United States is in marked contrast with Canada, where hot-applied rubberized asphalt membranes are widely used. Seven additional products in this category, which are not used in the United States, were identified.

Requirements for Waterproofing Systems

The requirements for the ideal waterproofing system can be defined simply as the following: watertight after installation, remains watertight during anticipated service life, and economical. These requirements can be expanded, as shown in Table 8, to several more specific requirements, which apply at the time of installation, and during the service life of the waterproofing system.

It is important to note that although many of the requirements apply only to the membrane, the performance of the membrane is determined by the performance of the waterproofing system, which includes all the components illustrated in Figure 3. For example, if the bond between the membrane and the surfacing breaks down in service, resulting in the development of pot holes in the surfacing, then the waterproofing system has reached the end of its service life regardless of the integrity of the membrane.

Two conclusions emerge from consideration of Table 8: the requirements for waterproofing systems are numerous and demanding; and the requirements are largely qualitative.

While it is not difficult to identify the factors that affect the performance of waterproofing systems, it is very difficult to develop quantitative requirements, which would provide reasonable assurance of satisfactory field performance. The reasons for this include the following:

- The requirements are numerous and complex;
- Many different materials are used in waterproofing systems;
- Acceptance tests usually apply to individual components of the waterproofing system, rather than the overall system;
- Correlations between acceptance tests for components and actual field performance have not been developed;
- Service conditions are difficult to define, and even more difficult to simulate in the laboratory or outdoor exposure plot; and
- Waterproofing systems, as with any other material, age in service, but criteria for the end of useful service life have not been defined.

Some of the reasons listed above may appear to be somewhat abstract, and are best illustrated by a few examples taken from the requirements listed in Table 8.

- Waterproofing systems must be "watertight." What does this mean in terms of water transmission through the membrane 1) immediately after installation and 2) after aging? How should it be measured?
- Membranes must not be damaged prior to installation of the surfacing, during paving, or by traffic or environmental loads in service. Absolute requirements such as "no damage" are meaningless, but what constitutes an acceptable level of damage? How should it be measured?
- Waterproofing membranes must be well bonded to the deck and the surfacing. What bond strength is required? Should it be measured in shear or tension? How should aging and loading be simulated? What bond strength is required if a ventilating layer is used?
- Waterproofing systems must bridge cracks in the deck slab, including those that are present at the time of installation and those that develop later. What width of crack should be bridged? What rate of crack movement should be used in simu-

TABLE 6
PERFORMANCE OF GENERIC PRIMERS AND ADHESIVES (adapted from 9)

Type of Material	Positive Attributes	Negative Attributes
Bituminous primers	Workable over ambient temperature range although some unmodified solvented types increased viscosity at low temperatures.	Drying time was temperature and moisture dependent and took from 1 to 48 hours, depending on composition; limited waterproofing ability and poor long term adhesion.
Resinous primers	Workable over ambient temperature range; moderate waterproofing ability and good resistance to chloride penetration.	Pot life limited at high temperatures.
Oxidized bitumen adhesives	Effective barrier to water and chloride transmission when fully bonded and free from blow holes; minimal water absorption.	Significant increase in stiffness at low temperatures; prone to embrittlement and debonding; generally poor long term bond.
Latex adhesives		Very poor adhesion to concrete; ineffective barrier to water or chloride transmission.
Self-adhesive backing to sheet membranes	Bond generally effective when applied at above 10°C.	Below 10°C, bond progressively weaker and almost non-existent below 5°C; poor bond if laitance or contamination of concrete; prone to debonding in the long term.

TABLE 7
PERFORMANCE OF GENERIC WATERPROOFING MEMBRANES (adapted from *9* and *21*)

Type of Membrane	Positive Attributes	Negative Attributes
Asphalt-impregnated fabrics	-Fabrics not mineral dressed remained flexible. -Not punctured, but deeply indented, by hot aggregate for membranes with a polyester fleece core, a mineral dressing and a thickness of at least 4mm. -Performance improved by using elastomer/polymer modified bitumens to raise softening point and reduce damage. -Resistant to tearing.	-Mineral dressed membranes stiffen and difficult to unroll below 5°C. -Core materials of asphalt impregnated glass cloth or woven polypropylene easily punctured. -Undressed fabrics liable to damage by cold and hot aggregates. -Damaged by prolonged exposure to fuel. -Oxidized bitumen adhesive had poor long term bond.
Polymer sheets	-Bituminized PE, laminated PE and polymer-plasticized PVC sheets generally remained flexible and less liable to recoil and uplift. -Chlorosulfonated PE (>3mm thick) and polymer-plasticized PVC sheets not punctured by hot aggregate. -Extruded and polymer-plasticized PVC sheets not damaged by site activities. -Most had low water absorption, and good resistance to water and chloride transmission provided fully bonded and not punctured.	-Extruded EP, some chlorosulfonated PE and EVA sheets had progressive stiffening at low temperatures with excessive recoil and uplift at the edges. -Most systems punctured by hot aggregate because of low softening point and thin sheets, even when used with mineral dressed protection sheets. -Extruded PVC sheets susceptible to damage from prolonged exposure to fuel. -Bitumen adhesives or pressure sensitive adhesives prone to debonding.
Elastomer sheets	-Butyl and polyisoprene rubber remained flexible over ambient temperature range and were undamaged by site activities. -Polyisoprene unaffected by high temperatures.	-Both systems debonded. -Butyl system damaged by hot aggregates at temperatures above 150°C. -Butyl system damaged by prolonged exposure to fuel.
Asphalt-laminated boards	-Not damaged by site activities. -Thickness of boards contributed to low chloride transmission.	-Stiffened and cracked on flexing at low temperatures . -Severely damaged by hot aggregate above the softening of the bitumen. -Delaminated at very high asphaltic temperatures. -High water absorption. -Self adhesive systems gave a moderately satisfactory bond.
Bituminous liquid membranes	-Polymer modified compositions remained flexible over ambient temperature range. -Must be used in conjunction with asphalt-laminated board; board and membrane penetrated by hot aggregates but self-sealing nature prevented chloride penetration.	-Bitumen-in-solvent solutions were prone to extensive pin and blow holes and blistering during laying; also prone to embrittlement at low temperatures; penetrated by aggregate at low asphalt application temperatures. Water absorption, water and chloride transmission high.
Mastic asphalts	-Indented by hot aggregates but thickness prevented penetration. -Good waterproofing integrity and low water absorption if fully bonded and undamaged.	-Prone to pin and blow holes, partly because of low reflectivity. -Softened considerably at moderate asphalt temperatures. -Embrittled at low temperatures. -Severely affected by exposure to gasoline. -Minimal bond unless primer used.
Urethane resin system	-All systems had good long term adhesion to concrete, but weaker bond to asphalt. -All systems remained flexible and resistant to fuel damage. -Fast cure systems remained flexible, free from damage by site activities, or hot aggregate; these systems also had good waterproofing integrity and low transmission of chlorides, properties which were assisted by the primer.	-Thin coatings (<2mm thick) prone to damage by asphalt surfacing, irrespective of material composition. -Some cold tar and elastomer modified systems prone to pinholing . -Cold tar modified urethanes liable to damage from site activities and hot aggregate; most had moderate to high water absorption; one system attacked by chlorides and fungal growth.
Epoxy resin system	-Chloride transmission low where no pinholes. -Excellent bond to concrete. -Not affected by fuels.	-Thin cold tar modified systems were severely embrittled at low temperatures and under hot asphalt which lead to damage by aggregate; also prone to pinholing . -Water absorption varied between systems. -Epoxy resins modified with urethane and either reinforced with a fabric scrim or mineral filled to form a slurry were very robust but less flexible; good waterproofing integrity and low chloride transmission.
Acrylic resin systems	-Very good bond to concrete and a moderate bond to asphalt via a tack coat. -Fast cure acrylic systems remained flexible and free from damage from site activities or hot aggregate over normal temperature ranges; good chloride resistance and waterproofing integrity which was assisted by the primer.	-Some softening of fast cure systems after prolonged fuel exposure. -Urethane-modified type cracked over existing crack in the concrete.

EP = ethylene propylene, PE = polyethylene, EVA = ethylene vinyl acetate, PVC = polyvinylchloride.

lation tests? How should aging be simulated? What is the acceptance criterion?

Similar questions can be formulated for most of the requirements identified in Table 8. The exercise shows why it is difficult to formulate acceptance requirements for membranes that could then form the basis for a performance specification.

Materials Specifications

Nearly all the agencies in North America that use waterproofing membranes reported having materials specifications. In some cases, the requirements for the waterproofing materials are part of the construction specifications. In most agencies, membranes are specified by a clause that requires the contractor to use only approved products. Sometimes the products are listed by name and supplier in the specification directly, and in other cases reference is made to a listing in another document. The process by which products are approved varies with the agency but typically consists of a review of information and test results provided by the manufacturer, sometimes supplemented by laboratory testing. The first few installations are usually designated as field trials and, provided that no serious problems are identified, approval follows. Engineering judgment is a key factor in the approval process.

TABLE 8
REQUIREMENTS FOR WATERPROOFING SYSTEMS

During Installation
- Tolerant of variable surface roughness and cleanliness
- Tolerant of changes in temperature and humidity
- Easy to install, independent of deck geometry
- Bonds well to deck, especially at edges
- Resists damage by loose particles, fuel spillage, foot traffic, and dropped objects prior to surfacing
- Not damaged by paving equipment
- Not damaged by asphalt application temperatures up to 180°C (356°F)
- Bonds well to surfacing

In Service
- Unaffected by service temperature, which could be -40 to 60°C (-40 to 140°F)
- Remains watertight and bonded to deck and surfacing during anticipated service life (typically 15 to 30 years)
- Resists puncture by aggregates in surfacing as a result of traffic loads
- Resists shear stresses from traffic loading (including braking and turning stresses)
- Bridges cracks in the deck slab
- Unaffected by salt and water, including traffic-induced hydraulic pressures
- Surfacing can be replaced without replacing membrane

The above situation reflects the difficulty of preparing a materials specification for waterproofing membranes that can be made from several generic groups of materials, and for which satisfactory performance is determined by the interaction of many complex factors. Faced with this dilemma, the usual approach has been to identify products thought to be suitable and then write a specification based on the known properties of the individual products. This approach was taken in the research for *NCHRP Report 165* and has been perpetuated until very recently.

In the study for *NCHRP Report 165*, several tests, listed in Table 3, were used to simulate field performance, and five membranes were selected for field trials. Specifications were written, but the materials requirements made no mention of the performance requirements, only the materials characterization tests. These specifications are summarized in Table 9. The weakness of this approach is readily apparent. The five products were all sheet membranes intended for the same application, yet the requirements had little relevance to the service conditions. For example, the deflection temperature for one product was <-61°C (<-77°F) and for another it was 7 to 13°C (45 to 55°F). Similarly, the tensile strength at elevated temperature ranged from 4.1 to 9.6MPa (600 to 1400 psi), and for one product no strength was specified.

More recently there has been a movement toward generic specifications, partly because of the incentive to develop performance specifications and partly because of the disincentive to specify proprietary products. An example is the specification used by California that applies to preformed, reinforced sheet membranes made from rubberized asphalt or polymer-modified bitumen. The specification requirements are given in Table 10. Despite the progress made, the requirements still rely on materials characterization tests and include different criteria for the softening point of the two materials.

Other agencies are also working toward developing performance specifications. For example, the New England states have prepared a draft specification for sheet membranes that includes requirements for adhesion to the concrete and the surfacing, flexibility, water transmission, water absorption, and resistance to punctures. The hot-applied rubberized asphalt membrane widely used in Canada is covered by a National Standard of Canada (*63*), which is generic and includes several performance requirements. The development of a European specification for preformed membranes was noted in Chapter 2.

In the absence of performance specifications, there is little reason for manufacturers to improve their products because improvement would likely increase costs and reduce sales due to the low bid process. Because of a myriad of agencies, and lengthy and informal approval processes, there is little incentive for other manufacturers to enter the marketplace, especially with new types of membranes. The public sector market does not typically reward superior performance, or innovation, making it very difficult to recoup development costs. These circumstances, which preserve the status quo, are not unique to waterproofing membranes, but are a symptom of the institutional impediments to the introduction of any new products in the highway industry (*64*).

TABLE 9
SPECIFICATION REQUIREMENTS DEVELOPED AS PART OF THE STUDY FOR NCHRP REPORT 165 (*12*)

Membrane	Tensile Strength, MPa@25°C (lb/in²@77°F)	Tensile Strength, MPa@60°C (lb/in²@140°F)	Elongation, %@25°C (77°F)	Elongation, %@60°C (140°F)	Deflection Temperature, °C (°F)	Water Absorption, %	Dimensional Stability, %
Reinforced, modified pvc sheet, 3mm (0.125 in.) thick	7 to 10.5 (1000 to 1500)	4 to 6 (600 to 900)	130 to 180	200 to 250	-20 to -26 (-5 to -15)	<2.2	±0.25
Vulcanized chloroprene rubber sheet, 1.5mm (0.06 in.) thick	13 to 15 (1900 to 2200)	9.5 to 12.5 (1400 to 1800)	260 to 300	230 to 270	7 to 13 (45 to 55)	<0.65	NR
Vulcanized butyl rubber sheet, 1.5mm (0.06 in.) thick	8.5 to 10.5 (1200 to 1500)	7.5 to 9.5 (1100 to 1400)	300 to 350	280 to 320	<-57 (<-70)	<0.15	NR
Vulcanized butyl rubber sheet, 0.8mm (0.03 in.) thick laminated to asphalt-saturated asbestos fiber felt, 0.8mm (0.03 in.) thick	>10.5 (>1500)	NR	>310	NR	<-61 (<-77)	NR	NR
Vulcanized polypropylene rubber sheet, 1.5mm (0.06 in.) thick	9 to 11 (1300 to 1600)	2.5 to 3 (380 to 430)	1000 to 1300	350 to 400	<-57 (<-70)	<0.20	NR

Note: NR = No requirement.

DESIGN

Selection of Waterproofing Systems

As noted in Chapter 1, the reasons for using, or not using, waterproofing membranes in new construction vary from agency to agency. The dominant factors are performance experience and cost, when compared with alternative methods of corrosion protection. The availability, convenience, and perceived satisfactory performance of epoxy-coated reinforcement have resulted in decreased use of membranes in new construction in the United States over the past two decades. In many cases, the need to use a bituminous surfacing has a major influence on the decision not to use waterproofing membranes. The additional dead load, the inability to inspect the deck surface, and poor performance of bituminous surfacings are the reasons given most frequently. In other cases, the objection is focused directly on the membrane. Several agencies tried membranes in the 1970s, but problems were encountered in the installations, and the decision to terminate their use has not been revisited.

TABLE 10
CALIFORNIA SPECIFICATION REQUIREMENTS FOR SHEET MEMBRANES

Property	Test Method	Requirement
Tensile strength	ASTM D882	>8.8kN/m (>50 lb/in.)
Elongation	ASTM D882	>15 %
Pliability	ASTM D146	No cracks
Thickness	—	>1.6mm (>0.065 in.)
Softening point (rubberized asphalt)	AASHTO T53	>74°C (>165°F)
Softening point (polymer modified bitumen)	AASHTO T53	>99°C (>210°F)

NCHRP Report 297: Evaluation of Bridge Deck Protective Strategies (*11*) reported results of the investigation of five strategies for preventing corrosion in new bridge decks: 1) 75 mm (3 in.) or more of concrete cover, 2) a low slump concrete overlay, 3) a latex-modified concrete overlay, 4) a waterproofing membrane and asphalt overlay, and 5) epoxy-coated reinforcing steel. The performance of these strategies was examined through a literature review, a survey of transportation agencies, and field investigations, followed by analysis of the data.

In contrast with the other strategies, the service life of waterproofing membranes is not affected by quantities of salt usage, provided that the membrane is effective. However, the report states that after about 15 years of service, membranes deteriorate because of environmental factors and traffic loading, thus requiring them to be removed and replaced. The life of a bituminous surfacing was also estimated to be about 15

TABLE 11
PRESENT VALUES OF 50-YEAR LIFETIME COSTS FOR BRIDGE DECKS CONSTRUCTED WITH VARIOUS PROTECTIVE STRATEGIES (11)

	Bridge Deck Protection Alternative	Cost[1], $/m² ($/ft²)
Single Protection		
	Cover thickness of 90mm (3.5in)	149.95 (13.93)
	Epoxy-coated top mat	154.47 (14.35)
	Latex-modified or low- slump concrete overlay	176.00 (16.35)
	Waterproofing membrane and surfacing	172.01 (15.98)
Double Protection		
	Epoxy-coated top and bottom mats	160.93 (14.95)
	Epoxy-coated top mat and latex or low-slump concrete overlay	182.45 (16.95)
	Epoxy-coated top mat and waterproofing membrane	178.47 (16.58)

[1] 1986 figures.

years. The cost effectiveness of the five strategies used on their own, and three double protection strategies, was calculated over the 50-year design life of a bridge deck. The results of this are given in Table 11. Waterproofing systems were found to be more expensive than epoxy-coated steel, but slightly less expensive than concrete overlays, in both single and double protection strategies.

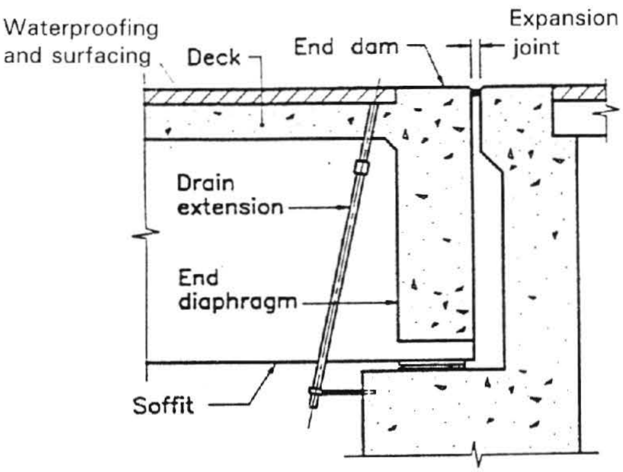
For those agencies using membranes, a number use them only under specific conditions. The most common application is on secondary route bridges. This application implies that membranes have not performed as well under heavy traffic loadings associated with bridges on primary routes. There also appears to be a tacit recognition that membranes may be unsuitable for structures on steep grades, or at locations where heavy vehicles are braking or turning at low speeds. However, the survey did not find evidence of these limitations being stated explicitly. Although certain generic types of membrane are less likely to cause rutting or shoving in the overlay, only one survey respondent had developed criteria requiring that only certain waterproofing systems be used in specific situations. Oregon specifies the maximum slope (longitudinal grade + crossfall) on which each of the approved membranes can be used. All membranes are limited to a slope of 4 or 5 percent, except for a resin system, which can be used on slopes of up to 8 percent. For all other respondents, if a waterproofing membrane was specified, then any product approved by the agency could be used in any situation. This finding is not entirely surprising in view of the fact that most agencies approve only a few products, and often of the same generic type.

Design Details

Design details have a major effect on the performance of waterproofing systems. A prime consideration in any design is to ensure that water is removed quickly from the deck through the provision of adequate longitudinal and transverse (crossfall) grades, and sufficient deck drains. This not only has safety implications but it reduces the opportunity for water to permeate the surfacing and pond on the surface of the membrane.

Deck drains usually extend to just below the top of the asphalt surfacing, and it is therefore important to ensure that the drains are slotted at the membrane-asphalt interface to allow water that reaches the membrane surface to drain away. Maine investigated the use of wick drains between the membrane and the surfacing to speed drainage from the deck, and decrease icing and break-up of the surfacing adjacent to the curbs. The drains consisted of four layers of geotextile material, having a total thickness of 13 mm (0.5 in.), installed 140 mm (5.5 in.) wide along the base of the curb. The performance was monitored for 5 years. Although drainage was more rapid, there was no evidence that the life of the membrane or the surfacing was increased, and it was determined that the cost of the wick drains could not be justified (65).

Deck drains are often not located at the lowest points of the deck slab (in environmentally sensitive locations, there may be no deck drains), and seepage drains should be provided. The purpose of the seepage drains is to remove water from the surface of the membrane, and a typical detail is shown in Figure 8.



NOTE
1. Top of drain to be installed flush with top of concrete deck.
2. Coupler and extension piece not to be installed until after removal of deck framework.
3. Drain to be 40 mm ID rigid PVC tube.
4. All metal parts to be galvanized.

FIGURE 8 Typical seepage drain detail.

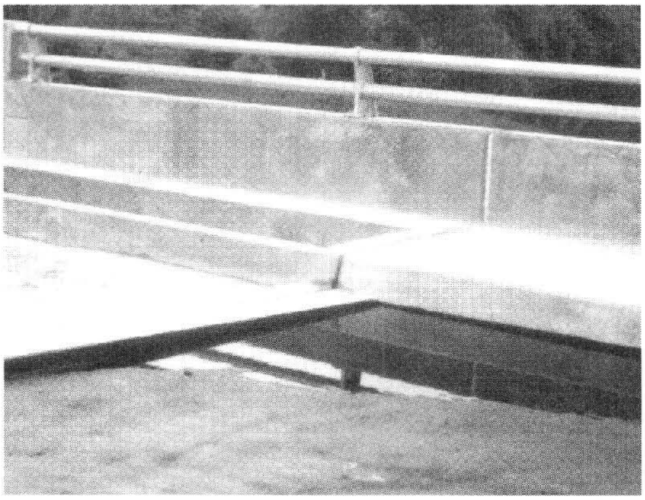


FIGURE 9 Water ponding on a membrane where a seepage drain is not provided.

These drains are also sometimes called bleeder drains. To be effective, the top of the drain must be installed flush with the top of the concrete deck, and waterproofing material must not seal the tube. Figure 9 shows a deck (built without seepage drains) with water ponding on the membrane prior to application of the surfacing. In Europe, proprietary seepage drains that are attached to the formwork prior to placing the deck slab are sometimes used. Some models allow for the escape of vapors from a ventilating layer as well as drainage of the surface of the membrane. Although sometimes used in Europe, ventilating layers are not recommended because of the importance of bond to the overall performance of waterproofing systems. Other precautions, discussed elsewhere in this chapter, can be taken to prevent blistering.

The point of discharge of seepage drains must be designed with care to ensure that salt-laden water is not discharged on other parts of the structure, especially on vulnerable components such as bearings. Seepage drains should not be taken through voids in the superstructure, such as through box beams, because the consequences of leakage could be serious. The volume of water passing through seepage drains tends to be drips, rather than a steady flow, so that if the location of the discharge is acceptable from the environmental standpoint, factors such as erosion are not a consideration.

Waterproofing systems are most vulnerable to leakage at the perimeter of the deck, but there is no consensus as to how or where the membrane should be terminated at curbs, walls, or expansion joints. A number of agencies specify additional measures at the termination points, such as the use of an adhesive with self-adhesive sheets, a double thickness of membrane, or a rubber sheet with liquid membranes. The purpose of all these design and installation details is to prevent water from running down a vertical face and seeping under the waterproofing. This has resulted in several jurisdictions adopting a chase detail to terminate the waterproofing on the theory that if the edge of the membrane is not exposed, the possibility of leakage is reduced.

Two types of chase detail are illustrated in Figure 10. The square chase shown in Figure 10a is easier to form, but has the disadvantage of being difficult to place and compact the surfacing without voids. The sloped chase shown in Figure 10b alleviates the compaction problem but is more difficult to form. Several variations on the details shown in Figure 10 are possible. In the case of a liquid membrane, particularly a viscous material such as rubberized asphalt, the chase may be filled with the membrane. There is no consensus as to the optimum height of a chase. Figure 10 shows the chase ending just below the base course so that it is filled with the first lift of asphalt. It is common practice for the surface course to be placed weeks or months later, and undesirable to leave the membrane exposed to water and contamination. Some agencies extend the chase to the level of the top of the surface course. If the chase is extended further, it is vulnerable to damage by snowplows. Even where a chase is not used, the height at which the membrane terminates differs from agency to agency, though the considerations are essentially the same as those for chases.

There is no agreement that a chase will improve membrane performance. The practice in Vermont is not to apply pre-

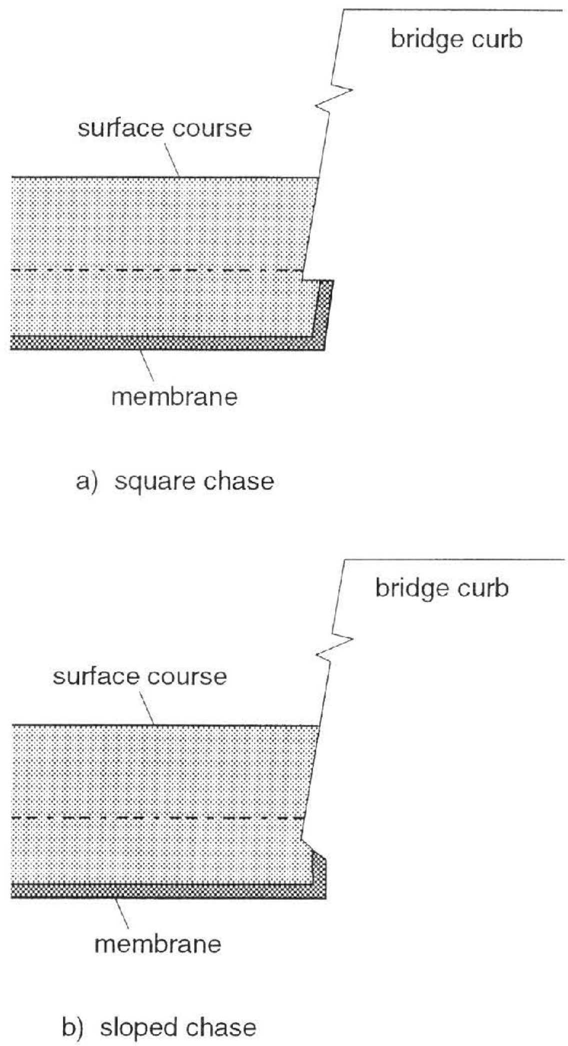


FIGURE 10 Typical chase details.

formed membrane to a vertical face, but to seal the perimeter with a compatible liquid sealant.

Unfortunately, the area of the deck in which the membrane is most prone to leakage coincides with the location where the surfacing is most porous because it is difficult to compact it properly adjacent to curbs, walls, and joints. Rather than rely on a tack coat to bond the surfacing to the vertical concrete surface, some agencies use a detail that involves forming a groove, which is filled with joint sealant. This allows the surfacing to pull away from concrete while still maintaining a watertight seal.

It is difficult to provide a comprehensive reporting of satisfactory edge details because of the wide variation in practice and the fact that the situation is changing constantly as details thought to be performing satisfactorily are discovered to be leaking. The lack of consensus on edge details is perhaps best illustrated by an OECD report (5) that gives examples of a wide range of detailing practices used in member countries. Most of the details used are sound in theory, and the fact that they work at some locations, but not others, suggests that performance may be influenced more strongly by the quality of construction than the actual detail used.

In cases where the sequence of construction requires that the membrane be installed before construction of a barrier wall or expansion joint, sealing the vertical face of the concrete presents a troublesome detail. Either the surfacing must be removed and the membrane lapped, with a termination as described above, or a groove is sawcut full depth through the surfacing adjacent to the concrete and filled with a flexible joint sealing compound.

Another situation vulnerable to leakage is where a deck contains active, wide cracks (typically >2 mm or >0.018 in. wide) or construction joints. The most suitable design detail for dealing with this situation depends on the type of membrane used. For sheet systems, a second strip can be applied as reinforcement. This works better for sheets that are not self-adhesive because, if the strip is bonded only at the edges, the strain in the strip is much less than in the membrane. In some areas, such as New England, the practice is to apply the strip over the crack before installing membrane over the entire deck. For liquid systems, the most common detail is to embed a strip of sheet membrane as reinforcement in the liquid membrane. An alternative approach is to rout and seal the crack or joint before applying the membrane. This only works when the cracks are few and well defined, and the joint sealing material must be compatible with the membrane. These details are illustrated in Figure 11. Figure 12 illustrates an application in which the detail shown in Figure 11b was used at a construction joint in a deck.

CONSTRUCTION

Waterproofing a new bridge deck comprises the following operations:

- Preparing the deck,
- Priming the concrete (where applicable),
- Installing the waterproofing membrane,
- Protecting the membrane with boards or sheets (where applicable),
- Applying a tack coat to the membrane (or protective board or sheet), where applicable, and
- Applying the asphalt surfacing.

This section describes these phases of waterproofing a deck and includes a discussion of construction specifications.

Deck Preparation

A sound, level, uncontaminated, dry, dust-free substrate is essential for a strong and durable bond between the concrete and the membrane. Survey respondents listed sweeping, air

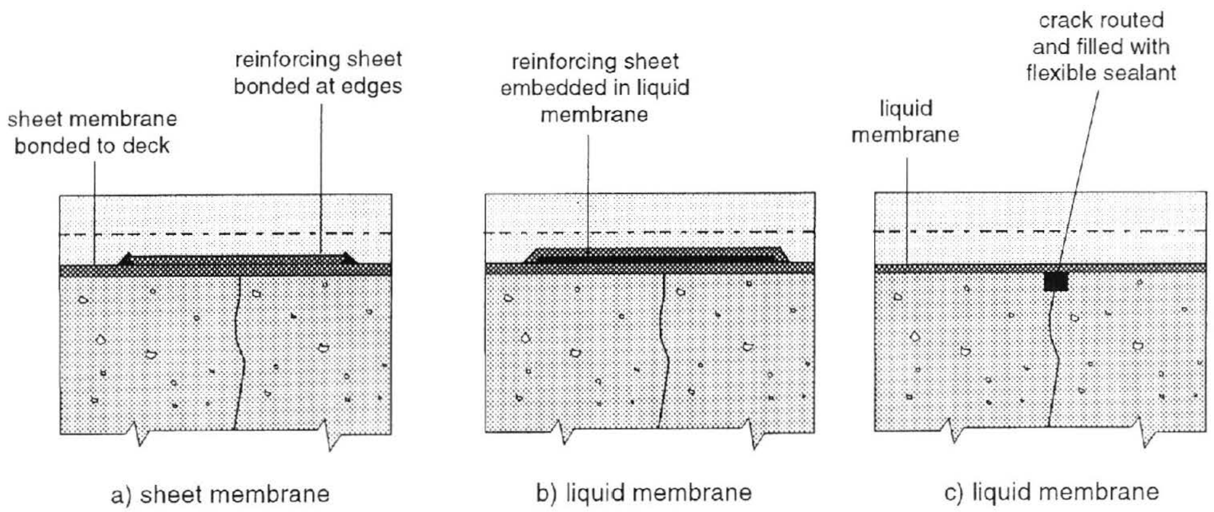


FIGURE 11 Waterproofing details at active cracks and construction joints.

FIGURE 12 Use of a strip of preformed sheet embedded in liquid membrane at a construction joint in the deck.

blasting, abrasive blasting, water blasting, and chemical solvents as methods for deck preparation. Most states using membranes in new construction required air or abrasive blast cleaning of the deck. Sometimes abrasive blasting is used to expose sound, laitance-free concrete, followed by air blasting immediately before application of the tack coat to remove dust and debris from the deck surface. Figure 13 illustrates an example of sand blasting. Note that the compressor should not be on the deck due to the risk of oil drippings.

A number of state specifications require that the deck surface be clean, while leaving the method of cleaning the deck as the contractor's option. Given the importance of good bond to the successful performance of a membrane, and the absence of a definition of "clean," a more specific statement is needed. While industry standards exist for specifying the preparation of steel surfaces, comparable definitions and standards still do not exist for concrete surfaces.

Where a curing compound was used on the concrete surface, it must be removed completely (*66*). This can only be done adequately by water or abrasive blasting. During field trials undertaken in California in the early 1970s, problems were experienced with two different systems because of reactions with

FIGURE 13 Sand blasting a bridge deck prior to waterproofing.

a chlorinated rubber curing compound that was not removed (*67*). In one case, the reaction was with toluene used as the solvent in a primer; in the other, it was with a liquid urethane membrane.

The surface of the deck must also be flat and smooth. Localized depressions can result in water seepage through the surfacing and ponding on the membrane. If this happens to coincide with a wheel-track, the membrane will be subjected to high transient pressures (*68*). A surface tolerance that does not permit a deviation of more than 10 mm over a 3-m gauge length (0.38 in. in 10 ft.) and projections of no more than 3 mm (0.12 in.) has been used in the United Kingdom for many years (*22,68*). Similar tolerances have long been specified elsewhere in Europe (*5*). Surface soundness and cleanliness are much more important to the achievement of a good bond than is surface roughness. A rough surface, particularly one with sharp projections, can contribute to poor membrane performance by causing punctures in sheet membranes and local reductions in the thickness of liquid membranes. Sharp projections can be removed by grinding or by abrasive or water blasting. Localized depressions require patching, though the perimeter of the patch must be saw-cut to avoid feather edges.

Some agencies specify that the deck reach a minimum age, typically 28 days, before being waterproofed to allow for proper curing of the concrete, followed by a period of air drying. The delay between placing concrete and application of the membrane is somewhat arbitrary. Factors such as the weather immediately prior to, and during, application of the waterproofing are likely to have a greater effect on membrane performance.

Application of Primers

A prime coat is used in most waterproofing systems to improve the bond between the membrane and the deck slab. Until the last few years, the most common primer consisted of an asphalt-cement cut back with an equal measure of gasoline solvent. Recent restrictions on volatile organic compounds have led to a much greater use of asphalt emulsions as primers. Resin-based primers are also used. For proprietary sheet membranes, it is common for the primer to be specified and supplied by the manufacturer of the membrane. Most primers are applied by spray, as shown in Figure 14, or squeegee, in one or two coats. Vermont requires that the primer be applied by roller, as shown in Figure 15, to prevent an excessive amount of primer on the deck.

The cure time for primers can range from less than 1 hour for some resinous types to 24 hours or more for solvent-based primers in adverse weather conditions. Blisters can be caused by the vaporization of solvents in inadequately cured primers and products with critical curing times should not be used (*2*).

The membranes should be applied soon after the prime coat has cured. Long exposure results in deterioration of the primer, often accompanied by contamination of the primed surface. In such cases, the surface must be cleaned and an additional primer coat applied. Specifications typically prohibit equipment and foot traffic on the primed surface until the primer has cured completely.

FIGURE 14 Application of an asphalt emulsion primer using a spray.

FIGURE 16 Applying adhesive to the deck and an EPDM rubber sheet. (Courtesy of Vermont Agency of Transportation)

Installation of Membranes

The application technique used for installing the membrane depends on the waterproofing system. Some specifications state simply that the procedures shall be in accordance with the manufacturer's instructions. Others state that the work shall be done by an applicator approved by the manufacturer. A few specifications require that a representative of the manufacturer be present. Most specifications place restrictions on installing membranes in adverse weather conditions. These restrictions vary with the agency and the type of membrane but, under no circumstances, should membranes be applied when the deck is wet or frosty, or if there is precipitation.

FIGURE 15 Application of a proprietary primer using a roller. (Courtesy of Vermont Agency of Transportation)

Sheet Membranes

Many sheet membranes are supplied in rolls approximately 1 to 1.5 m (3 to 5 ft) wide and 10 to 15 m (30 to 50 ft) long. The length is usually limited to a weight that can be handled by one person. A number of sheet membranes introduced in the 1970s were supplied in widths up to 3 m (10 ft). The rolls were heavy and very difficult to handle in windy conditions. Some of the sheets required the application of a contact adhesive to the deck and the membrane. This is illustrated in Figure 16 for an EPDM (ethylene propylene diene monomer) rubber sheet, which was one of the membranes selected in the study for *NCHRP Report 165* for a field trial. The membrane had to be rolled on the deck, as shown in Figure 17, and, once the two surfaces touched, the membrane could not be moved and air pockets were common.

Most of the sheet membranes used in North America have a self-adhesive backing. The membranes are unrolled to cover

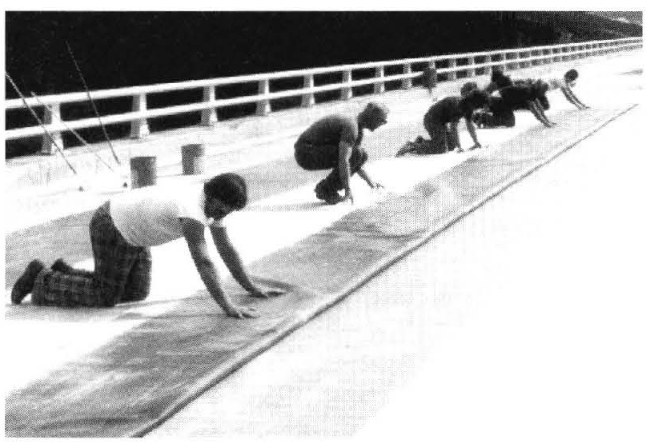


FIGURE 17 Rolling the EPDM rubber sheet on to the deck. (Courtesy of Vermont Agency of Transportation)

the deck in strips, with an overlap of approximately 100 mm (4 in.). The direction of unrolling is usually along the length of the bridge to avoid additional stresses on the lap joint during paving operations. Figure 18 shows a typical installation. Sometimes deck geometry or site conditions dictate laying across the width of the deck. In such cases, the installation should begin at the low end if the deck is on a grade, the analogy being with shingles on a roof. The adhesives are pressure sensitive and a heavy hand roller should be used. The bond strength is also a function of temperature, and the temperature at the time of installation should be 10°C (50°F) or more.

Sheet systems that are not self-adhesive are usually bonded by the pour and roll method. Hot oxidized bitumen is poured on the deck in front of the sheet as it is unrolled and pressed into the bitumen. This is shown in Figure 19, which illustrates another of the membranes installed as a field trial in Phase II of NCHRP Project 12-11. The surplus bitumen squeezed out during application of the membrane is used to seal the lap joints by using a squeegee or similar tool.

FIGURE 18 Application of a self-adhesive preformed membrane. (Courtesy of Vermont Agency of Transportation)

Some sheet systems used in Europe are applied by what is known as the torch-on method. These membranes have a bituminous backing that acts as an adhesive when it is softened by a gas burner as the membrane is unrolled and pressed on the deck.

Liquid Membranes

The most common type of liquid membrane used in North America is a hot-applied rubberized asphalt. The membrane is supplied in blocks to the job site and heated in a mechanically-agitated mixing kettle. The kettle should be of the double boiler type, using oil as the heat transfer medium, for reasons of safety and to prevent overheating of the rubberized asphalt.

FIGURE 19 Application of a preformed membrane into hot bitumen. (Courtesy of Vermont Agency of Transportation)

Hot material is drawn from the kettle, poured on the deck, and spread to the specified thickness (typically 5 ± 1 mm or 0.2 ± 0.04 in.) in a continuous operation, usually by a squeegee. The membrane is also extended up the face of curbs (as shown in Figure 20), barrier walls, and deck drains as specified, usually terminating at the top of the surface course, or in a chase where this has been provided. Where the placing operation is interrupted, by weather or equipment failure for example, the membrane is lapped approximately 150 mm (6 in.) when placing resumes.

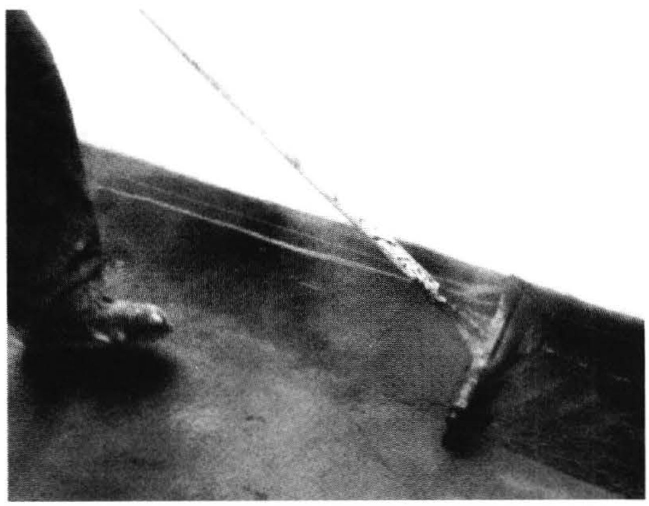


FIGURE 20 Application of a hot-applied rubberized asphalt by squeegee showing extension of membrane up the face of the curb.

FIGURE 21 Extrusion and application by squeegee of a hot-applied PVC membrane. (Courtesy of Vermont Agency of Transportation)

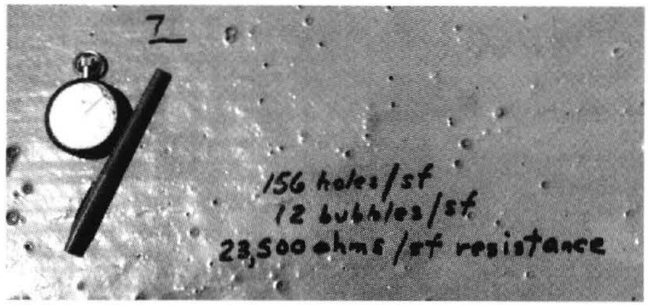


FIGURE 22 Numerous pinholes and blisters in a two-component polyurethane membrane. (Courtesy of Vermont Agency of Transportation)

The method of applying other types of liquid membrane varies with the type of material. They may be applied by spray, brush, or squeegee to form a seamless layer bonded to the deck. Figure 21 shows a hot polyvinyl chloride (PVC) membrane being extruded from the mixer and spread by a squeegee. Spray equipment used to apply some two-component systems is very sophisticated using microprocessor controlled metering and mixing devices. For some systems, a second coat is applied after the first coat has cured. The two coats may be a different color to make it easier for the applicators to gage the thickness of the second coat (*69*).

Blistering

Blistering has been identified as a significant problem in satisfactorily waterproofing a bridge deck (*18*) and affects both preformed and liquid membranes. Blisters are caused by the expansion of air in the concrete after application of the membrane, a phenomenon sometimes known as outgassing. Water or water vapor is not a necessary requirement for blister formation, but is usually a contributing factor (*70*). The vaporization of even a small quantity of water contained in the concrete produces a substantial volume of water vapor and exerts a significant pressure on the membrane. Blisters may take several forms ranging from numerous pinholes (barely visible to the naked eye) (see Figure 22) common in liquid membranes, to large blisters that may cover 0.1 m^2 (1 ft^2) or more in sheet membranes.

A distinction is sometimes drawn between blisters and blowholes (*2,5*). Blowholes, which have the characteristic appearance of small craters, occur at the time of installation of liquid membranes; blisters may develop in any kind of membrane several hours after installation. Blowholes may be formed by the rapid expansion of vapors in the concrete during installation of hot-applied products or during the curing of cold-applied products because of rising ambient temperatures, decreasing atmospheric pressure, or the increase in deck temperature caused by increased absorption of solar radiation upon application of a black or dark-colored membrane. The possibility of blisters or blowholes occurring in any situation is determined by the porosity and moisture content of the concrete (*71*) and the atmospheric conditions during and after installation.

Membranes can be placed without blowing if atmospheric and substrate conditions are favorable. One solution to the blistering problem is to ensure that the deck temperature is higher than ambient temperature at the time the membrane is applied and, where applicable, during the curing period of either the membrane or its adhesives. This would suggest that membranes should be applied in the evening or at night, but there is no evidence of this strategy being employed. Sealing the deck prior to applying the membrane is another possible approach that could reduce the possibility of blister formation. When the membrane is cured, the bond to the deck is usually sufficient to resist vapor pressures from within the concrete. However, the risk of blister formation can be reduced by minimizing the time between membrane and asphalt placement. Except for one unusual case (*19*), a 50-mm (2-in.) thickness of asphalt has been found sufficient to prevent blisters occurring after the hot mix has been placed. The same study found that a 20-mm (0.75-in.) thick layer of sand asphalt was insufficient to prevent the formation of blisters. Figure 23 shows blisters in a membrane after application of a 32-mm (1.25-in.) thick base course. The photograph illustrates the same installation as Figure 19, and is interesting in that it represents one of the few installations of a ventilating layer in North America. As can be seen, the ventilating layer did not prevent the formation of blisters.

The rapid expansion of vapor during placement of the hot mix can also result in blister formation. Unless the asphalt cracks, these blisters are difficult to detect and even more difficult to repair. Air pockets trapped beneath a protection layer will also have the same effect.

FIGURE 23 Blisters in membrane and base course. (Courtesy of Vermont Agency of Transportation)

Repair of Membranes

It is often necessary to repair membranes damaged by site activities or blister formation before installing the protection system and surfacing.

Sheet membranes are normally repaired by cutting out the damaged area using a sharp knife until undamaged, well-bonded membrane is reached. The area is cleaned and dried, and a patch of the original membrane is bonded to the deck with a lap joint over the existing material. Additional bitumen or bonding material may be applied over the joints. Specified lap sizes vary by agency, ranging from 50 to 150 mm (2 to 6 in.). Blisters are treated in a similar manner, except for sheets with a self-adhesive backing where the blister is punctured and pressure applied to bond the sheet to the deck. The hole is then covered with a patch.

The repair of damaged areas of liquid membranes can be difficult and messy if the bond to the concrete is tenacious. Where the membrane must be removed, scraping, chipping, or chemical solvents may be required, depending on the membrane's chemical composition. New material is then applied overlapping the existing membrane.

Where insufficient thickness of material or slight pinholing creates a need for repair, the membrane is often cleaned and overcoated. For hot-applied or thermoplastic materials, blisters, pinholes, and blowholes can sometimes be repaired by applying heat and pressure. Overcoating may be an option for thermosetting materials, but for thermoplastics the extra thickness of material may cause instability. In such cases, the membrane may have to be removed and replaced.

Installation of Protection Boards

Protection boards are used widely in Europe and Canada, but rarely in the United States. In the survey responses only Rhode Island and Utah used a protection board, while Colorado and New Mexico used roofing felt.

In the United Kingdom, protection boards are nominally 1m × 2m (3.3ft × 6.6ft) and available in thicknesses of 3, 6, and 12 mm (0.1, 0.2, and 0.5 in.) (*22*). The boards are normally butt jointed as they are laid directly on a curing liquid membrane and a separate adhesive is not required. The butt joints are sealed with 75-mm (3-in.) wide reinforced tape. At one time, some liquid membranes were protected with a hand dressing of mineral granules. These tended to sink into the partially cured surface, however, reducing the thickness of the membrane, thus the practice was discontinued. Some sheet membranes have integral 3-mm (0.1-in.) boards or a mineral dressing as part of the membrane. Others are protected with mineral dressed bituminized sheets, which are either self-adhesive or bonded with oxidized bitumen using the pour and roll technique. Boards are normally rigid or semi-rigid and laid on horizontal surfaces. Protective sheets are used in conjunction with the boards on other surfaces, notably the vertical surfaces at the perimeter of the deck.

The protection boards used in Canada are typically 1m × 1.5m × 3.6mm thick (3.3ft × 4.9ft × 0.14in. thick) and are used in conjunction with hot-applied rubberized asphalt membranes. The protection boards are laid on the membrane while the surface is still tacky with the length of the board transverse to the deck. The boards are placed with edges overlapping 12 mm (0.5 in.) both longitudinally and transversely, with the longitudinal joints staggered a minimum of 150 mm (6 in.). Boards are cut so that they are placed within 6 mm (0.25 in.) of the perimeter and deck drains. A typical installation is shown in Figure 24.

Ontario requires that the binder course be placed within 1 week of the membrane. While it was always recognized that leaving the membrane exposed increased the risk of damage, the 1-week limit was implemented because in hot weather the protection board was found to curl at the edges, resulting in cracks in the surfacing over the edges of the boards.

As part of the exposure plot study trial in the United King-

FIGURE 24 Protection boards applied over a rubberized asphalt membrane.

TABLE 12
ESTIMATED MEMBRANE TEMPERATURES FROM AMBIENT SHADE TEMPERATURE (condensed from *21*)

Ambient Shade Temp °C	Exposed Membrane °C	Under 50mm Asphalt °C	Under 100mm Asphalt °C
30	70-75	50-55	40-45
20	40-45	25-30	20-25
10	20	10	10
0	0	0	0
-10	-10	-8	-6
-20	-18	-14	-10

dom, described in Chapter 2 (*21*), temperatures on exposed membranes were recorded under ambient conditions. Membrane temperatures were also measured under 50 mm and 100 mm (2 in. and 4 in.) of asphalt surfacing. The highest temperatures recorded on exposed membranes exceeded the softening point of some membranes such that they could be damaged by foot traffic. Asphalt surfacings reduced the maximum temperatures. However, it was still possible for softer membranes, such as rubberized mastics, to exceed their softening point due to solar heating, even when covered by asphalt. These membranes are therefore susceptible to dimensional instability under braking forces in hot sunny weather.

The data were used to prepare a table from which an estimate of the membrane temperature could be derived from a knowledge of the ambient shade temperature. Skies were assumed to be clear and sunny at ambient temperatures above 0°C (32°F), and to be dull and overcast at 0°C (32°F) and below. A portion of the table is reproduced in Table 12. It must be remembered that the shade temperature often exceeds 30°C (86°F) in parts of North America, therefore membranes are even more susceptible to the effects of solar heat.

In addition to the risk of damage and dimensional changes already noted, there are other reasons for leaving the membrane exposed for the shortest possible time after placement. Application of the surfacing is an effective means of preventing the development of blisters. Furthermore, if a membrane surface is left exposed, it may be contaminated and the bond to the surfacing reduced. Some membranes, particularly those containing urethane resins, degrade under ultra-violet light and should not be left exposed.

Application of Tack Coats

A tack coat is used in some waterproofing systems, especially those using a mineral dressing or protection board, to improve the bond between the membrane and surfacing. Bitumen or resin-based tack coats are used in Europe and the choice of material is not necessarily related generically to the membrane. In North America, the tack coat is usually an asphalt emulsion, which may be diluted further with water. The tack coat is applied by spraying and the application of the surfacing follows as soon as the emulsion has cured. An excessive application of tack coat can cause flushing in the surfacing.

Application of Asphaltic Surfacings

As noted elsewhere in this chapter, the timing and application of asphalt surfacing are crucial factors in determining the performance of waterproofing systems. Timing is important because the longer the delay between placing the membrane and the surfacing, the greater the risk of damage, contamination, and blister formation. The method of placement, the bituminous concrete mixture, and the placing temperature are all extremely important because most membranes are more vulnerable to damage during application of the surfacing than at any other time.

Survey responses showed that the thickness of asphalt surfacings used in North America ranged from 25 to 100 mm (1 to 4 in.). Most agencies use 65 to 80 mm (2.5 to 3.25 in.) of surfacing applied in two lifts. While mixture proportions vary from agency to agency, the base course is usually designed to have a high stability and resistance to lateral flow and to incorporate a high proportion of coarse aggregate, whereas the surface course is denser and less harsh and is designed to provide a smooth, skid-resistant riding surface.

Membranes, particularly those made from softer materials or those installed without a protective layer, are easily damaged by the paving equipment, including delivery trucks. It is therefore important that turning movements and sharp braking actions be avoided. A number of agencies require rubber tires on paving equipment and ban the use of vibratory rollers. Work in the United Kingdom demonstrated clearly that, except for some thermosetting resin-based systems, the amount of damage increases as the temperature of the surfacing and the size and sharpness of the coarse aggregate increase (*21*). The sheet and liquid membranes typically used in North America are softened by heat, and control of the delivery and rolling temperatures is important. Delivery temperatures can be as high as 170°C (340°F), but it has been recommended that rolling temperatures be kept below 145°C (295°F) to reduce damage to the membrane. The rolling temperature must be controlled carefully because, if it is too low, the compaction will be inadequate and the bond to the membrane reduced. Most states specify that the membrane not be damaged when placing hot mix, but few states control temperatures. One exception is Maine, which specifies a different placing temperature for each approved sheet membrane. The temperatures range from a low of 120 to 150°C (250 to 300°F) to a high of 155 to 170°C (315 to 340°F).

Only Illinois reported using a protection course, which is employed in conjunction with the state's generic coal tar emulsion and fiberglass fabric waterproofing system. A 12-mm (0.5-in.) thick layer of sand asphalt is placed at a temperature of not less than 143°C (290°F).

Construction Specifications

Most agencies use two specifications for the installation of waterproofing systems. One specification covers placement of the membrane and protection layer (if used); the other covers application of the surfacing. This division of activities is reasonable from the point of view that the membrane is usually installed by a specialized subcontractor and the surfacing by the general contractor. However, it is inconsistent with the objective of achieving an effective waterproofing system because the paving operations have a major influence on a membrane's performance.

All the construction specifications for installing membranes provided in the survey responses were prescriptive. Requirements for deck preparation were qualitative and often vague. Conversely, requirements for the installation of sheet membranes were specified in inordinate detail, to the extent they were often difficult to understand. A number of specifications relied heavily on manufacturer's recommendations. Few respondents attempted to define acceptance requirements beyond the statement that the installation must be "acceptable to the Engineer."

For nearly all of the responding agencies, requirements for placing the asphalt surfacing are contained in the specifications for hot-mix asphalt, which are concerned primarily with the construction of bituminous pavements. As such, the requirements for placing asphalt surfacings on membranes are a minor part of a much larger specification. Further, because the responsibilities for bridges and pavements are split in most agencies, there may be insufficient recognition of the special requirements for paving over membranes on the part of those responsible for hot-mix asphalt specifications.

Acceptance Requirements

In line with the prescriptive nature of construction specifications, acceptance requirements are usually qualitative and based on a visual examination of the membrane after installation. Only Colorado and Idaho required that the membrane be tested for waterproofing integrity after application of the hot-mix surfacing. Colorado uses the electrical resistance test (Colorado Procedure 62) and if the readings are less than 200kΩ, the contractor may be required to repair, or remove and replace, the bituminous pavement and the membrane. The test is not carried out on bridge decks containing epoxy-coated reinforcing steel, or where the presence of moisture in the surfacing prevents testing within a reasonable time after placement. In these circumstances, acceptance is based on inspections and certification by the Engineer that the work was executed in accordance with the specifications. Idaho also uses the electrical resistance test (Idaho Test Method T-113). Areas representing readings less than 500kΩ must be repaired. If more than 30 percent of the readings are less than 500kΩ, the contractor may be required to replace the membrane and surfacing.

Ontario has developed an end-result specification for hot-applied rubberized asphalt membranes, which has been the only type of membrane used in the province since 1972. Poor quality workmanship and inspection resulted in several substandard installations in the 1970s. The main deficiency was that the thickness of membranes was less than specified. In 1983, an interim acceptance plan was introduced for membrane thickness, based on a random sampling of lots and sub-lots. Data gathered under the interim acceptance plan were analyzed and used to develop a statistically based, end-result specification, which was implemented in 1986 (*72*). In 1987, the requirements for quality of the membrane were added to the specification (*73*).

Implementation of the specification forced the manufacturer to be responsible for the quality of the membrane, the contractor to be responsible for the process control during installation, and the agency to perform acceptance testing upon completion of the installation. The general principles applied in developing the specification were as follows: a separation of responsibilities for process control and acceptance, recognition of the inherent variability in materials and testing, allowance for acceptance of material that is slightly less than specified, provision for re-testing of suspect test results, and a reduced payment provision for substandard material or installation.

The quality of material is measured by taking a sample from the contractor's kettle at a random time for each lot, and shipping the samples to the central laboratory for testing. The payment for quality is based on accumulated adjustment points. The maximum reduction in payment is 25 percent. If the accumulated adjustment points exceed 25, the lot is rejected.

The acceptance plan for thickness is based on lots, with a maximum size of 600 m^2 (6,460 ft^2). Each lot is divided into ten equal sub-lots. Three thickness measurements are made at random locations within each sub-lot and the three readings are averaged to constitute one thickness measurement. The average thickness and standard deviation for the lot are calculated. Payment for material thickness is made at the contract-bid price wherever the lot has a mean thickness of 5.0 ± 1 mm (0.20 ± 0.04 in.) and zero percent defective. A reduced payment is applied whenever the mean thickness is greater than 4.0 mm (0.16 in.) and the percent defective is from 0.1 to 5.0 percent. The relationship between price adjustment and percent defective is not linear but elliptical, so that the penalty is low for work that almost meets the specification but becomes increasingly severe until it reaches 50 percent at 5.0 percent defective. Lots outside these limits are rejected. When the mean thickness is greater than 6.0 mm (0.24 in.), the lot could be rejected if the excessive thickness might result in pavement shoving or rutting, e.g., on a steep grade, under high traffic volumes, or subject to braking forces. The final payment to the contractor is calculated by multiplying the adjusted price for thickness by the adjustment factor for quality. These requirements are contained in the construction specification (*74*), and an explanation and worked examples of their application are contained in a field guide (*75*).

Since 1987, the Ontario Ministry of Transportation has published an annual report on bridge deck waterproofing. Each report contains a statistical analysis of the data on material thickness and quality, and a discussion of problems that occurred together with recommended solutions. Figures 25 and 26 are reproduced from the 1992 annual report (*76*).

Figure 25 shows improvement in compliance with the thickness requirements from the introduction of the specification in 1986 to 1992. In 1986, only 80 percent of the lots were accept-

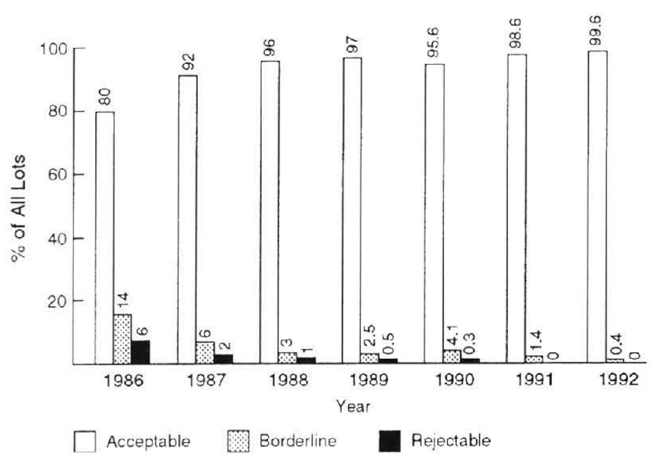


FIGURE 25 Annual thickness compliance for liquid membranes.

able, and 6 percent were rejectable. In 1992, a total of 94 890 m^2 (1,021,000 ft^2) was installed by eight contractors. Of the 257 lots reported, there was only one borderline lot and no rejectable lot. The borderline lot received a price adjustment factor of 0.93.

Figure 26 shows the history of quality tests for the period 1986 to 1992. The requirements were changed in 1986 and the price adjustment for quality was not implemented until 1987. Quality improved steadily until 1991, but in 1992 problems arose that had not been experienced previously. In 1992, 35 percent of samples failed one or more of the six quality criteria.

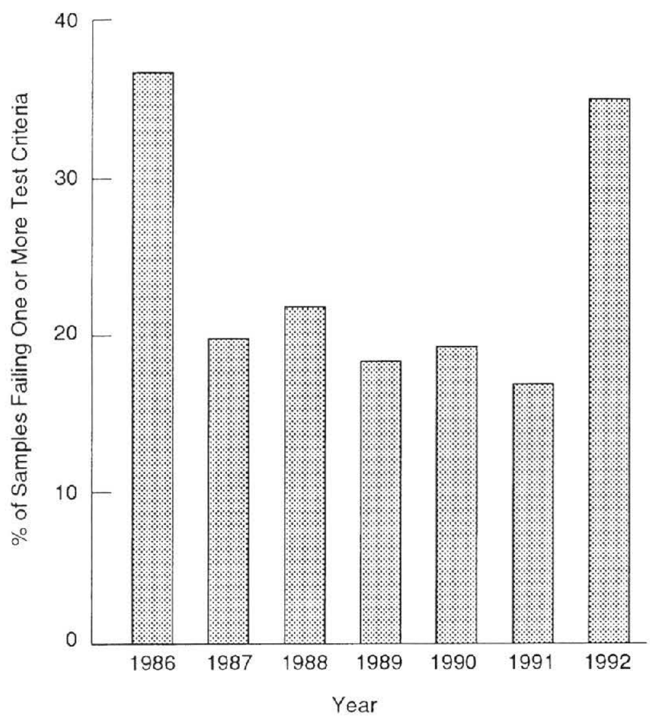


FIGURE 26 Annual material non-compliance for liquid membranes.

All of the samples that failed, failed the toughness/peak load ratio and some samples also failed other criteria. The poor performance was traced to an oil used in the manufacture of the products.

In 1992, the price adjustment factors ranged from 0.786 to 0.995 with an average of 0.938. Six products were removed from the list of approved products, four because of quality problems and two because the product had not been used in Ontario for 5 years.

The data show that the end-result specification has had a continuing impact on improving the quality of bridge deck waterproofing in Ontario. Compliance with the thickness requirement has improved from 80 to almost 100 percent. There has also been a gradual, though less dramatic, improvement in membrane quality, except for 1992, when the acceptance testing was able to identify the effects of a change in the properties of one of the components.

Quality of Construction

The performance of waterproofing systems is very susceptible to the quality of workmanship. Site practice and procedures are improved when the work force is trained, proper supervision is exercised, and inspection is vigilant.

Conditions on site are often less than ideal, and some waterproofing systems are more tolerant of adverse conditions than others. Most site work is carried out to a tight schedule. By the time the deck is ready for waterproofing, the contract may be behind schedule and there is considerable pressure to open the structure to traffic. Consequently, there is a tendency to perform the work hurriedly and to proceed even in adverse weather. All of these factors compromise the quality of the completed installation.

PERFORMANCE

A prerequisite to discussion of the performance of waterproofing systems is a definition of what constitutes a failed waterproofing system, a description of the factors that affect failure, and the mechanisms involved.

A waterproofing system has failed when water or chloride penetrates the concrete, or the surfacing over the membrane has broken up. Under these circumstances, either the system is no longer watertight or the safe passage of vehicles across the deck is impaired.

Break-up of the asphalt surfacing usually has one or more precursors such as debonding of the membrane (at either the concrete-membrane or the membrane-asphalt interface), or extensive cracking, rutting, or shoving of the surfacing. The latter symptoms may result from the use of excessively thick or soft membranes. Deformation of the surfacing is exacerbated under heavy traffic loadings, on grades in excess of about 4 percent, in areas of rapid deceleration, and where the thickness of the surfacing is less than 50 mm (2 in.). Moisture also plays a major role in deterioration of the surfacing. The factors affecting moisture damage, and methods of prevention, are described

TABLE 13
POSSIBLE CAUSES OF ADHESION FAILURES IN WATERPROOFING SYSTEMS (adapted from *22*)

Lack of Adhesion Between the Membrane and the Concrete	Lack of Adhesion Between the Membrane and the Asphalt Surfacing
• Inadequate deck preparation (contamination or poor surface finish) • Adverse weather conditions (too wet or too cold) • Excessive moisture in the concrete • Degradation of primers, especially cut-back asphalt • Embrittlement of oxidized bitumen adhesives (especially if heated to in excess of 230°C or 445°F) • Sheet systems prone to recoil or lift during laying, resulting in air pockets or discontinuous lap joints • Puncturing or impact damage • Displacement of membrane by construction traffic • Blisters or blowholes • Degradation of membrane e.g., by moisture or freezing • Inadequate repair of damage • Delays between application of membrane and surfacing • Poor workmanship e.g., insufficient or excessive coverage of primers or adhesives, improper mixing or proportioning of two component materials, improper thickness of liquid membranes, overheating of primers, adhesives or liquid membranes, gaps between protection boards.	• Poor initial bond, especially with some polymer sheet systems and some resin-based liquid systems • Membrane damaged during application of surfacing, especially for bitumen-based sheets and liquid systems <2mm (0.08in.) thick • Properties of membrane changed by hot asphalt • Moisture on membrane or trapped between membrane and protection boards when paving applied • Rolling temperature of asphalt too cool (<120°C or 250°F) • No tack coat, or tack coat insufficiently cured or over-cured • Contamination of membrane surface e.g. by dust or fuel spillage • Low binder content or poorly compacted asphalt mixture • Asphalt surfacing too thin (<50mm or 2in.) resulting in cracking and lack of thermal protection • Water ponding on the membrane under service conditions especially if present during freezing temperatures.

in *NCHRP Synthesis of Highway Practice 175: Moisture Damage in Asphalt Concrete* (*77*). Once the surfacing begins to break up, the membrane is exposed and easily damaged by traffic.

Waterproofing failures are usually associated with failure of adhesion between the concrete and the membrane (*22*). In some cases, the membrane may leak, and the moisture passing through the membrane may destroy adhesion to the concrete. In other cases, the bond may fail first, eventually leading to failure of the membrane. The possible causes of loss of adhesion are numerous and are summarized in Table 13. The table also summarizes the causes of loss of adhesion between membranes and the asphalt surfacing. While some of these factors involving the surfacing also result in loss of integrity of the membrane, most contribute to failure of the surfacing.

The effect of poor adhesion between the membrane and surfacing on the performance of the surfacing was illustrated on a number of bridge decks in Vermont (*78*). In 1987, a new membrane was installed on nine decks. The membrane was the same as one used in the state for many years with the addition of a high strength polypropylene mesh to the top surface to increase its puncture resistance when applied on rough decks. Pavement failures, in the form of lateral shoving, occurred on four decks within a year of construction. Laboratory tests using a Marshall hammer and confining mold showed excellent bond between the membrane and surfacing over a wide range of mix temperatures, demonstrating that the test procedure did not duplicate the action of the roller in the field. Factors contributing to the failures were identified as the superelevated deck sections, braking action on a grade of 3.5 percent, high summer temperatures, and, in one case, the apparent application of cement dust to the membrane surface to prevent the paving equipment from slipping sideways on the banked deck (*78*). The decks were repaired by removing the surfacing, applying a tack coat to the surface of the membrane, and repaving.

In 1992, similar problems were encountered with another preformed membrane on bridge decks in Maine. The planned installation of the same membrane in Vermont caused the Agency of Transportation to measure the bond between the bituminous surfacing and several membranes, using specimens prepared in the field. This led to the development of a 90° peel test and the establishment of a minimum peel strength of 260

N/m (1.5 lb/in.) based on values measured on membranes with a history of satisfactory performance (*79*). An interesting result from the testing was that the bond of one membrane was increased substantially when the compaction roller was delayed for a few minutes, even though the temperature at the membrane surface dropped from 115 to 99°C (240 to 210°F). This suggests that the membrane softened during the delay period, resulting in an increase in bond.

Waterproofing Integrity

The primary requirement of a waterproofing membrane is that it be watertight. The ability of membranes to resist water transmission and the effects of damage and debonding on water transmission were investigated as part of the large exposure plot study undertaken in the United Kingdom (*21*). The test program also included an investigation of the benefit of treating the concrete with isobutyl silane prior to application of the membranes. The test procedures were described in Chapter 2, and the results are illustrated in Figure 27.

The results showed that where a membrane was fully bonded, undamaged, and had low water absorption, there was little or no transmission of water over the 80-day test period. At the other extreme, punctured membranes, which were either unbonded or exhibited high water absorption, were very permeable and passed more water than the untreated concrete because the spread of water was not contained.

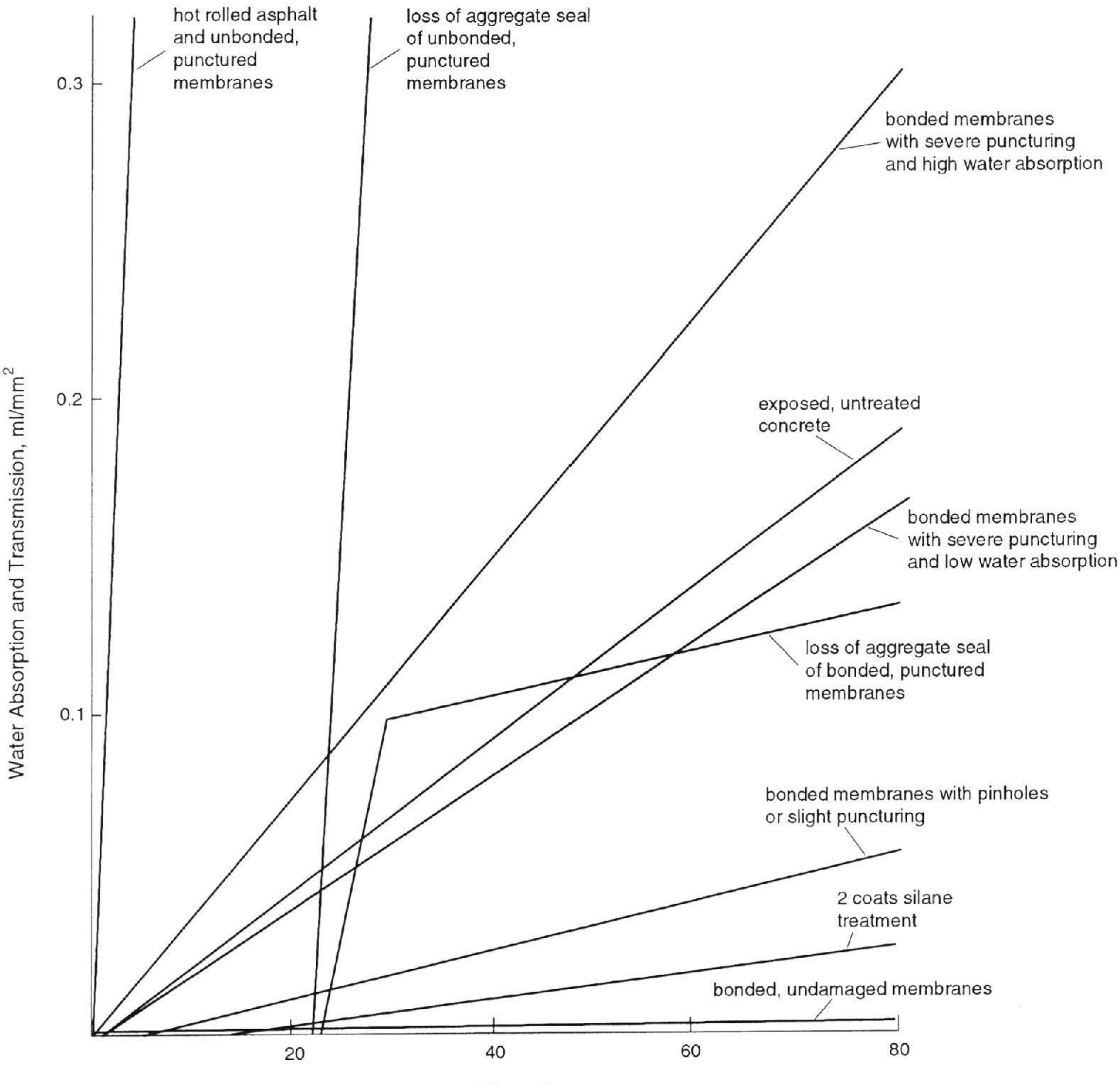


FIGURE 27 Absorption and transmission of water through membranes and surfacing (adapted from *21*).

For other conditions, the amount of water transmitted through the membrane was determined by its water absorption, the amount of damage, and the degree of bond. Even badly punctured membranes slowed the flow of water provided they were well bonded. Some punctured systems had aggregate particles embedded in the puncture, effectively sealing the hole. As the bitumen surrounding the aggregate particle embrittled, the aggregate was loosened and water transmitted through the membrane. This condition was common and likely often occurs in practice.

Two coats of silane were found to reduce the quantity of water transmitted significantly, though the treatment was not as effective as a well-bonded, undamaged membrane.

Asphalt Application Temperature

The temperature of the asphalt surfacing when it is placed on the membrane and the rolling temperature have a significant effect on the amount of damage caused to most types of membrane. In outdoor trials in the United Kingdom, membranes were overlaid with a base course having a maximum coarse aggregate size of 20 mm (0.8 in.), and with a sand asphalt carpet (*21*). Both mixtures conformed to BS 594 "Specification for Rolled Asphalt (Hot Process) for Roads and Other Paved Areas," and were supplied at 180°C (356°F). The base course was rolled at 160°C (320°F) and the sand asphalt at 120°C (248°F). The pressure on the membranes resulting from laying and compacting the asphalt was also measured and found to be 17.5 MPa (2500 lb/in^2) under the action of a 10 tonne (11 ton) road roller for a compacted thickness of 50 mm (2 in.).

When applying the base course, the hot aggregate in the asphalt, in combination with the compaction and rolling operation, tended to rupture, deform, or severely reduce the thickness of some membranes, particularly where their softening temperature was exceeded. Bitumen and polymer-based membranes were highly susceptible to this form of damage. Polymer sheets were generally punctured unless their thickness exceeded 3 mm (0.12 in.). Most of the thin liquid systems, particularly those with a thickness of less than 2 mm (0.08 in.), were ruptured. The only undamaged membranes were polyisoprene rubber sheeting and some fast curing modified polyurethane and acrylic systems (with a thickness between 2.2 and 3 mm or 0.8 and 0.12 in.) and a 5-mm (0.2-in.) thick modified, reinforced epoxy system.

The study also investigated the protection afforded by mineral-dressed protection sheets and asphalt-laminated boards. These were both softened in a similar manner to bitumen membranes with the result that the board or sheet was ruptured or severely reduced in thickness by the hot aggregate. Where the sheet or board was protecting a sheet membrane that had been softened by application of the hot asphalt, the membrane was also ruptured unless its thickness exceeded 2.5 mm (0.10 in.). However, the protection did reduce the severity of the damage. The damage to liquid membranes was also reduced considerably, except for membranes less than 1.5 mm (0.06 in.) thick.

The damage to membranes caused by placing the sand asphalt was substantially less. Some bituminous, polypropylene or polyethylene-based polymer sheets and all the mastic asphalt systems showed signs of melting but were otherwise undamaged. Thin liquid membranes were damaged by high points in the concrete surface during passage of the roller but, again, the sand asphalt reduced the amount of damage.

Damage was found to increase significantly if membranes were not fully bonded.

Temperatures were measured at the interface between the membrane and the asphalt during the placing operation and are shown in Figure 28. The temperature of the membranes rose rapidly and reached a maximum 3 to 4 minutes after the asphalt was placed. For membranes less than 1.5 mm (0.06 in.) thick, the peak temperature occurred almost immediately. The temperature then dropped slowly as the asphalt cooled to the ambient temperature, which took about 5 hours.

Figure 28 also shows the range of softening temperatures for generic classes of membranes. It can be seen that temperatures on the membranes often exceeded their softening points for a lengthy period, especially for bitumen and polymer-based materials. This was a major cause of aggregate indentation and penetration.

Temperatures measured under protective sheets and boards were found to reduce the temperature of the membranes by 15 to 25°C (27 to 45°F). This was sufficient, in some cases, to prevent softening of the membranes, thereby reducing considerably the damaging effects of the hot aggregate.

The substantial reduction in damage that occurred when sand asphalt was used led to a decision in the United Kingdom to require the application of a sand asphalt carpet as an additional protection, prior to application of the base course (*22*). Red oxide is sometimes added to the sand asphalt to assist in identifying the layer so that surfacings can be removed without damaging the membrane. The reduced damage results from the absence of large aggregate particles and the lower placing temperature. The disadvantage is that the bond between the membrane and the asphalt is reduced because of the presence of a sand-rich layer on the surface of the membrane. Damage could also be reduced by lowering the application temperature for the base course, but this also reduces the bond and makes the surfacing difficult to compact.

Field Performance

United Kingdom

The results of an extensive study of site practice and the nature and reasons for the failure of waterproofing systems in the United Kingdom were reported in 1991 (*22*). The investigation was based on survey data, reports from users, laboratory tests, field trials, and observations.

A summary of the results is given in Table 14. Since 1975, waterproofing systems used in the United Kingdom have been required to have a Roads and Bridges certificate issued by the British Board of Agrément. The certificate is issued upon successful completion of a series of checks and tests specified by the Department of Transport. Despite this rigorous prequalification process, many of the waterproofing systems were

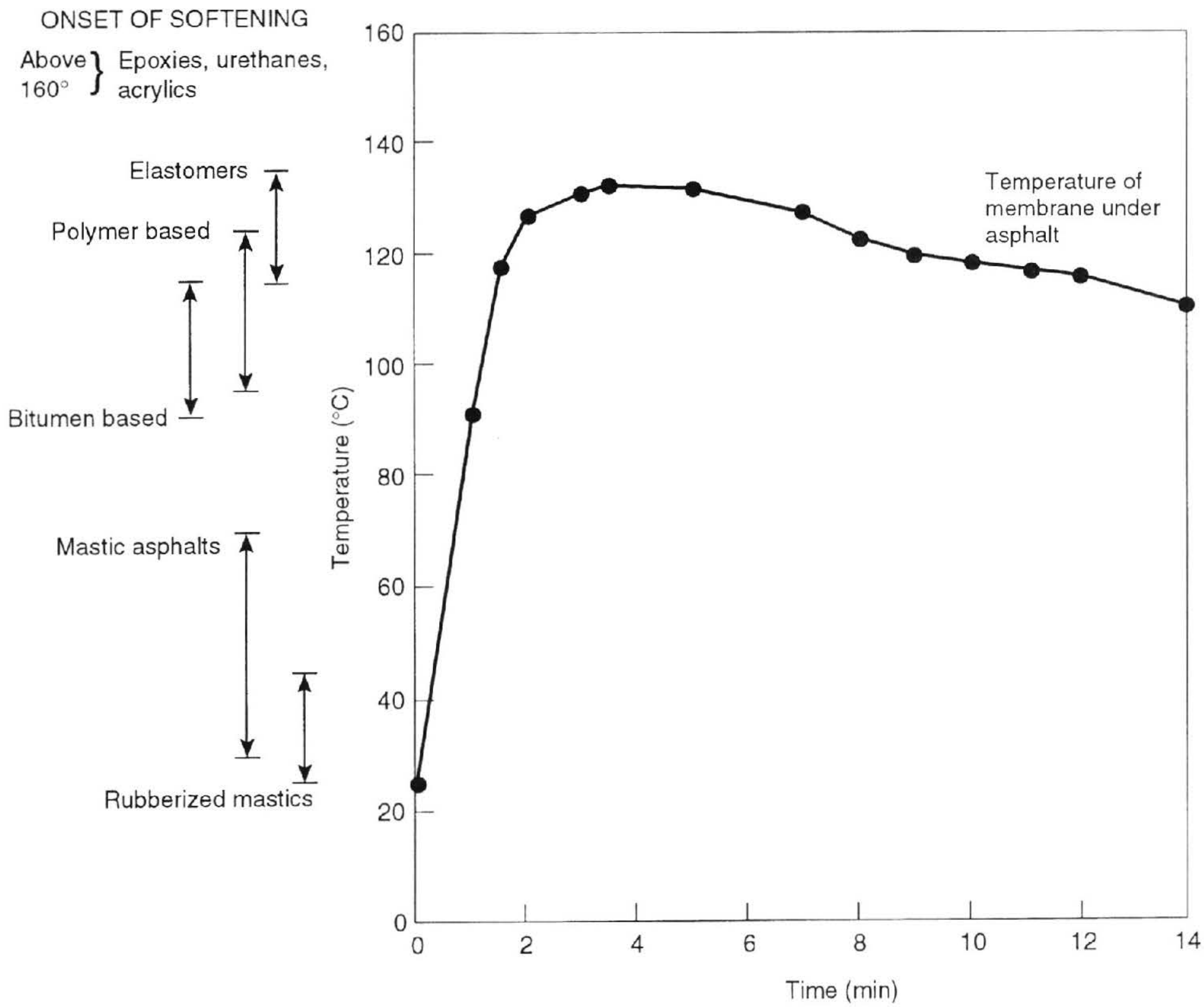


FIGURE 28 Typical asphalt application temperature on membranes, and softening temperatures of generic membranes.

found not to be performing effectively in service. Table 14 also shows that some types of membranes are more susceptible to certain types of failure than others.

Procedures and practices followed during installation and repair of defects were found to have a significant effect on the long-term performance of membranes. Site conditions were rarely ideal, and membranes were often applied to decks that failed to meet the specified surface finish. Conditions during installation and in service were often more severe than the certification tests with the result that the study identified the need to revise the test procedures.

Many of the membranes failed in adhesion at the concrete-membrane interface, for reasons listed in Table 13. Frequently, no single factor was responsible, but adhesion loss was the result of a complex interaction of several factors. Once adhesion has been lost, a perforation in the membrane allows moisture and salts in solution to migrate beneath the membrane, resulting in a failed waterproofing system.

Deficiencies in bond at the membrane-asphalt interface were also recorded, for reasons summarized in Table 13. In some cases, adequate bond was never established and in others, the bond deteriorated in service. Inadequate bond was a precursor to failure of the surfacing rather than the integrity of the membrane, except where the membrane was damaged during installation of the surface course.

United States

The field experience with membranes in the United States has covered the whole spectrum from satisfactory performance (*27*) to dramatic failures where the membrane has had to be removed (*28,80*), sometimes before the deck was open to traffic. A number of agencies have conducted field studies of the performance of membranes, some of which have been undertaken over a period of years. This section summarizes the major findings from several of the studies reported in the literature. Where it is not stated in the report, nor apparent from the context, whether the membrane was applied to a new or a rehabilitated deck, the results are reported in this chapter. Performance studies of membranes applied to existing decks are described in Chapter 4.

Vermont began a program for field evaluation of membrane systems in 1971 as part of NEEP No. 12. Thirty-three systems on 69 new bridge decks were evaluated during the first 11 years of the study (*27,33,81–84*). The products included 15 preformed systems, seven epoxies, five thermoplastics, four polyurethanes, and two tar emulsion systems. The preformed systems included three membranes approved for use in Vermont in 1973 in non-experimental installations, the five systems identified in the study for *NCHRP Report 165*, and seven miscellaneous membranes.

Field testing during the first 2 years included electrical resistivity and half-cell potential measurements, and the determination of chloride ion content in the concrete. A lack of correlation between the three procedures resulted in a decision to rely only on chloride determinations. Measurements were taken close to the curb, in the shoulder, and in the wheel-path area, and concentrated at the lowest part of the deck. Concrete samples were considered contaminated when the chloride ion content was 50 ppm more than the chloride content measured immediately following construction. It was noted that this criterion did not indicate complete failure of the membrane, but that some leakage was occurring.

The findings of the study are summarized in Table 15. The table reports the average results within identifiable groups, though in some cases there were considerable differences in performance between individual products within the same

TABLE 14
PRINCIPAL PROBLEMS WITH WATERPROOFING SYSTEMS IN SERVICE IN THE UNITED KINGDOM
(condensed from *22*)

	Waterproofing System								
Deficiency	A	B	C	D	E	F	G	H	I
Poor adhesion - primer to concrete	o	-	x	o	x	o	x	-	-
Poor adhesion - adhesive to concrete	o	-	x	o	x	o	n	-	-
Poor adhesion - membrane to concrete	o	i	x	o	x	o	x	-	i
Poor adhesion - membrane to asphalt	o	-	o	i	o	i	o	-	x
Poor adhesion - edges/lap joints	o	-	x	o	o	o	n	-	i
Voids under membrane	o	i	x	x	o	x	i	-	-
Moisture under membrane	o	i	x	o	x	o	x	-	i
Moisture under asphalt	i	-	o	-	i	i	o	-	i
Moisture within system	-	-	-	-	-	o	o	-	-
Movement of membrane (traffic loading)	o	-	i	-	i	o	o	-	-
Damage to membrane (traffic loading)	o	-	-	-	-	o	o	-	i
Softening at ambient temperatures	-	-	-	-	-	o	x	-	-
Softening under asphalt temperatures	o	i	x	x	x	x	x	-	-
Embrittlement of adhesive with age	i	x	x	x	x	-	n	-	-
Embrittlement of membrane with age	i	d	-	-	-	-	x	-	-
Puncture by site activities	o	-	-	-	-	i	x	-	-
Puncture/indentation by hot aggregate	o	i	x	o	o	o	x	-	-
Pin/blow holes	n	n	-	-	-	-	x	i	i
Blisters	x	-	x	i	o	o	x	-	-
Damaged by fuel spillage	d	-	i	-	i	o	x	-	-
Degradation with time	-	d	-	-	o	o	x	-	-

A - bituminized woven polypropylene sheet
B - bituminized polyester fleece, mineral dressed
C - ethylene propylene polymer sheet
D - chlorosulfonated polyethylene sheet
E - butyl felt laminated elastomer sheet
F - self-adhesive bituminized laminated board
G - mastic asphalt
H - fast cure polymethylmethacrylate*
I - fast cure polyurethane*

x - frequent problem
o - occasional problem
i - isolated problem
- - no problem noted
n - not applicable
d - no data

*Approved for use after 1988 and limited service data.

TABLE 15
SUMMARY OF MEMBRANE CHARACTERISTICS AND PERFORMANCE IN VERMONT (condensed from *83*)

	Waterproofing System						
Characteristic	A	B	C	D	E	F	G
%Cl^- readings contaminated[1]	19	28	30	17	26	50	60
Average contamination[1], ppm Cl^-	125	120	125	209	83	116	163
Ease of application	e	h	e	h	e	e	v
Blisters	y	y	y	n	n	n	n
Pinholes	n	n	n	y	y	y	n
Bond at curb	f	f	p	f	x	f	p
Membrane-deck bond	f	g	f	g	g	g	g
Pavement-membrane bond	g	g*	f	g	p	p	g
Problems in paving	o	y	y	o	o	n	n
Overall performance	g	fg	fg	g	fg	p	p
Recommendation	c	nr	s	s	s	nr	nr

[1] 0 to 25mm (0 to 1 in.).
* With protection boards.

A - Standard preformed
B - NCHRP preformed
C - Miscellaneous preformed
D - Thermoplastic
E - Polyurethane
F - Epoxy
G - Tar emulsion

e - easy
h - hard
v - very easy
y - yes
n - no
o - occasionally
x - excellent
f - fair
p - poor
fg - fair to good
c - continue use
s - consider selective use
nr - not recommended

group. The figures for the average level of chloride contamination include only data from the samples that were found to be contaminated.

It was concluded that the standard, preformed sheets provided the best overall performance. Two problems were recognized: leakage at the curb and the formation of blisters. The curb detail was modified to include the application of a liquid polyurethane sealant between the membrane and the vertical face of the curb. In some cases, blisters developed at the time of installation of the membrane and after paving, but the occurrences have not been considered a problem (*83*).

The five membranes identified in *NCHRP Report 165* were considered to be performing satisfactorily, although they were vulnerable to leakage at the curb line. They were also expensive and difficult to install, and were not recommended for further use.

Four of the seven miscellaneous preformed systems gave good results, including two that prevented any contamination. Two products were manufactured with small perforated holes and were successful in eliminating blistering, but not in preventing chloride contamination.

The performance of the thermoplastic systems was generally satisfactory. The best performance was from a hot rubberized asphalt system, though it was recommended that future applications include protection board and be limited to grades less than 3 percent because of potential instability under traffic. An application of Gussasphalt (a pourable, mastic type paving mixture developed in Germany) had to be removed after the second winter because of extensive full-depth cracks.

Two of the polyurethane systems showed no contamination, and the other two exhibited widespread leakage. Pinholing was a problem and it was recommended that multiple coats be applied and that the systems be used with protection board or roofing felt.

With the exception of one product, the epoxy systems performed poorly relative to the other groups. One-half of the chloride determinations indicated contamination. The worst performance was recorded by the tar emulsion systems, which were the standard treatment in Vermont during the period 1960 to 1971. A seven-layer system reinforced with glass fabric performed somewhat better than the two-coat, unreinforced system, but was still unsatisfactory.

The chloride measurements showed most of the leakage occurred at the curbs. There was little difference between readings taken in the shoulder and wheel paths, suggesting that puncture by aggregates under traffic loading is not a significant factor in Vermont. It was concluded that, overall, the membranes performed well, with the better ones offering the potential for 50 years of service before corrosion of embedded reinforcement became a serious problem.

A further study in Vermont, which included the replacement of nine experimental membranes installed under NEEP No. 12, was completed in 1993. The average age of the membranes was 18 years and included four of the products selected in the study for *NCHRP Report 165* for field trials. Replacement was made necessary because of pavement distress resulting from lack of bond between the surfacing and the membrane or, in two cases, because of leakage detected at cracks in the soffit.

The decks were examined after removal of the membranes and their condition varied widely. In one case, numerous delaminations were recorded. The distance of the delaminations from the curb was consistent, suggesting that the membrane had been damaged by the paver tracks possibly as a result of aggregate spilling on the deck from the haul trucks. Concrete repairs carried out prior to replacing the membranes ranged from 0.1 to 11.2 percent, and the average was 2.9 percent of the deck area.

Oklahoma also participated in NEEP No. 12. During the period 1973 to 1975, the state installed nine different membranes on 35 new bridges. Five of the membranes were preformed sheets, three were liquid membranes, and one was a built-up system. The thickness of surfacing was 40 mm (1.5 in.) except where 25 mm (1 in.) of sand asphalt was added as a protective layer.

A report chronicles a litany of construction problems that included wrinkles, blisters, fish mouths along lap joints, water beneath membranes, membranes and roofing paper being picked up by paving equipment, and unbonded sand asphalt (*80*). Three different membranes had to be removed within a few days of installation, either because of water under the membrane or damage during the paving operation. A fourth membrane had to be replaced after 18 months because the overlay disbonded and broke up under traffic. It had been reported that workmanship at the time of installation was poor with aggregate under the membrane and fish mouths at laps, which caused cracks in the surfacing.

In 1972, the Minnesota Department of Transportation initiated a study to evaluate corrosion protection treatments on new and rehabilitated decks (*85*). It was concluded, from measurements taken over a 7-year period, that membrane systems were effective in preventing chloride penetration in new decks but that the durability of the surfacing was poor. Cracking and debonding at the interface between the membrane and the surfacing appeared on several decks, in some cases after only 3 years of service. Debonding was a serious problem on decks with high traffic volumes because the action of traffic broke up the surfacing.

Louisiana installed six waterproofing systems in 1975, also as part of an experimental investigation (*86*). Five of the membranes were proprietary sheet membranes and the sixth was a hot-applied elastomeric PVC polymer used with a heavy roofing paper. All six systems were installed on the same bridge, and two of them on a ramp bridge nearby. Difficulties were experienced with the installation of most of the systems ranging from bubbles forming in primers, blisters under the membranes, and shoving and tearing under the paving equipment. Two of the membranes had to be replaced within a few months because lack of bond between the membrane and the surfacing resulted in shoving of the surfacing. The thickness of surfacing was 40 mm (1.5 in.). Resistivity tests were taken before and after placement of the surfacing and after the decks were open to traffic. The readings indicated the membranes were not waterproof and this, together with the poor experience during construction, led to a recommendation not to use waterproofing systems in Louisiana.

Service Life of Membranes in New Construction

Agencies were asked in the survey to state the anticipated service life of membranes and indicate whether the response was based on field performance data. Some agencies skipped the question, while a number of others indicated that performance data existed but made no reference to its source. It appears that most estimates of anticipated service life are based on engineering judgment.

The responses ranged from 10 to 30 years. The higher figures were given by the New England states where there is the longest history of membrane use, and by several contractors with many years of experience. This infers the importance of quality of construction in determining the service life of waterproofing systems.

An interesting aspect of the responses was that most agencies using membranes in new construction and rehabilitation anticipated the same service life in both situations. This reinforces the viewpoint, expressed by a number of agencies, that the service life is determined by the asphalt surfacing rather than by the membrane. Bituminous pavements are typically resurfaced every 15 to 20 years and it is common practice to include repaving of the bridge decks within the limits of the paving contract. In rural areas, and particularly for smaller bridges, there is often no alternative. Knowing that materials and paving equipment will not be available in the vicinity for another 15 to 20 years, agencies will usually make whatever repairs are necessary to the structure while the contractor is on site. This usually includes removal and replacement of the waterproofing system. In these situations, the service life of the waterproofing system is determined by economic and practical considerations, and a more sophisticated approach is not warranted. If the service life of the waterproofing system cannot be extended to the next repaving contract (a total of 30 to 40 years), then the length of time by which the service life would exceed the first repaving contract (15 to 20 years) is of little importance.

CHAPTER FOUR

WATERPROOFING SYSTEMS IN BRIDGE DECK REHABILITATION

This chapter describes those aspects of waterproofing systems that apply specifically to their use in the rehabilitation of existing decks, or as a second stage of construction after a deck has been placed in service and exposed to salt. The principal differences from new construction are in the selection criteria for the use of waterproofing systems, traffic control, deck preparation, and the influence of existing corrosion on future performance.

DESIGN

Selection Criteria Relating to the Use of Waterproofing Systems

Many agencies have developed criteria, sometimes expressed in manuals and sometimes retained in the collective wisdom of design or maintenance staff, for selecting the most appropriate method of rehabilitation at the project level. The decision criteria often have two components: technical and economic. The technical criteria may consist of a list of factors, such as those shown in Table 16 (*87*). Similar criteria were included in the decision methodology developed under a SHRP study on methodology for protecting and rehabilitating existing reinforced concrete structures (*88*). The alternative treatments, such as waterproofing systems, concrete overlays, and cathodic protection, are screened against the factors to identify from the technical standpoint which of the treatments are feasible. An economic analysis is then made of the suitable treatments to identify the most cost-effective solution for the bridge under consideration.

The technical factors that are usually considered include traffic volumes, proportion of truck traffic, dead load considerations, the existing deck surface, deck geometry, and the presence of active cracks. The nature and extent of the deterioration present in the deck also have an important influence on selecting the method of rehabilitation. Waterproofing membranes tend to be unsuitable on badly corroded decks because extensive patching is required and they do not stop corrosion; and on badly scaled decks, because the rough surface is unsuitable for membranes unless a levelling course is applied (*87*). Waterproofing systems are also unsuited to decks with steep grades or crossfalls, especially if the volume of truck traffic is high.

One of the survey questions asked respondents to identify criteria for the use of membranes in rehabilitation. A number of states responded that membranes are not used in some situations because the asphaltic surfacing is a non-structural component, which adds significant dead load. Another common criterion is related to the existing surfacing on the deck or approaches. For example, on bridges in California where an existing asphalt overlay must be replaced and the cost of modifying the approach pavement and joints to accommodate a polyester concrete overlay (the preferred option) is too high, a waterproofing membrane plus asphaltic overlay may be used. There was also evidence of membranes being used for short-term repairs. For example, Michigan reported that a membrane would be installed if a structure was scheduled for repairs within 2 years. Kansas stated that a membrane might be installed to restore a riding surface until permanent repairs with a concrete overlay could be made.

Selection Criteria Relating to Types of Waterproofing Systems

Another survey question asked if criteria have been developed that exclude the use of some types of waterproofing systems if certain factors such as grades, braking, speed of construction, and anticipated service life are applicable. Only Oregon and Alberta responded positively to the question. The criterion in Oregon, which related to the slope of the deck, was discussed in Chapter 3. The criterion in Alberta had as much to do with load carrying capacity as with material properties. Alberta uses hot-applied rubberized asphalt membranes, which are overlaid with 75 mm (3 in.) of bituminous surfacing and resin-based liquid membranes, which are used with 50 mm (2 in.) of bituminous surfacing. For some older bridges in the network, dead load limitations require that only the resin-based membranes be used.

For all other jurisdictions using membranes in rehabilitation, no distinction is drawn between the products approved for use. This is, perhaps, not surprising given that many states only use sheet membranes, for which differences in performance are likely to be minor.

CONSTRUCTION

The sequence of operations in installing a waterproofing system as part of the rehabilitation of an existing deck is the same as in new construction. The major difference in construction activities is that the preparation of the deck surface is often the most time-consuming and expensive operation. Where the existing deck has a bare concrete surface, the work necessary to modify the expansion joints, pad the approach pavement, and sometimes modify the curb height can have a significant effect on the duration and cost of the project. Most contracts are completed while traffic is maintained on the structure, so that traffic control is also a consideration in rehabilitation work.

TABLE 16
DECISION MATRIX FOR SELECTION OF DECK REHABILITATION METHOD (87)

Criterion	Concrete overlay	Membrane + surfacing	Cathodic protection	Rationale
Delamination and spalls exceeding 10% of the deck area		No	No	Where extensive patching is required it becomes more economical and more durable to construct a concrete overlay
Corrosion potential more negative than -0.35V over more than 20% of the deck area		No		Patch repairs and waterproofing rarely reduce corrosion activity and may accelerate it
Moderate or heavy scaling exceeding 10% of the deck area		No	No	The amount of patching becomes too expensive and consequently uneconomical
Active cracks in deck slab	No			Cracks active under live load or temperature change are reflected in a concrete overlay
Remaining life of structure less than 10 years	No		No	Additional cost of concrete overlay or cathodic protection is not justified
Concrete not properly air entrained			No	Application of bituminous surfacing (without waterproofing) may accelerate deterioration of the concrete
Complex deck geometry. Skew exceeding 45°, curvature exceeding 10°, or changing superelevation	No			Concrete finishing machines (especially those used for low-slump concrete) have difficulty accommodating complex geometry
Limited load capacity of structure[1]		No	No	Bituminous overlay is a non-structural component. Concrete overlay can be especially useful where the span/thickness ratio of the deck slab exceeds 15
Electrical power available			No	Power required for rectifier (unless mains, solar, wind or battery power can be provided economically)
Epoxy injection repairs previously performed and will not be removed			No	Epoxy insulates underlying reinforcement from cathodic protection

[1] Capacity after rehabilitation must be verified. Additional strengthening may be necessary.

Traffic Control

The survey also asked a number of questions relating to traffic control during the installation of waterproofing systems. With the exception of Connecticut and Pennsylvania, all states reported that traffic is maintained on the deck during construction. Several states imposed limits on the speed of traffic, although speed limits varied with location and site conditions. Many states also placed limits on the duration of lane closures, which is a means of reducing user delays and increasing safety by minimizing exposure times.

Waterproofing systems are very tolerant of lane-by-lane installation and consequently traffic control considerations are not as demanding as for other methods of rehabilitation. For example, the width of the finishing machine used in the application of a concrete overlay may require additional lane closures or reduced lane widths. Similarly, decks with complex geometry such as variable widths or superelevation may influence lane closures because of the location of the crownline. The application of cathodic protection may also dictate staging because of the need to position hardware in specific locations or to avoid splices. By contrast, waterproofing membranes are easy to lap and the equipment used to install the surfacing can be accommodated in little more than one lane width.

The time of construction is not a major factor in influencing the method of rehabilitation, even in locations where traffic control considerations are paramount. All the methods of rehabilitation in common use involve the same activities, such as concrete removal, concrete placement, and curing. Further, the duration of construction staging is often determined by activities such as joint replacement or modification of approach pavement, which must be done regardless of the method of rehabilitation selected.

Deck Preparation

In most situations where a waterproofing system is used in rehabilitation, the deck will have an asphalt surfacing, and sometimes a membrane, which must be removed before the concrete deck surface can be prepared to receive the new membrane.

Where no membrane is present, the asphalt surfacing is unlikely to be bonded to the deck surface. It is removed easily by planing off the surface using equipment fitted with a blade or, more usually, a bucket.

Where there is an existing membrane on the deck, the difficulty of removal is a function of the bond to the deck. If the bond is weak, the membrane can be planed, sometimes in the same operation as removing the asphalt surfacing as illustrated in Figure 29. In situations where the membrane is tightly adhered to the concrete, removal can be very difficult. Eleven responding agencies reported that they had experienced difficulties in removing existing membranes and eight agencies reported experiencing no difficulties. Other agencies reported no experience because it had not been necessary to remove membranes. The methods of removal varied, although planing or scraping, often followed by abrasive or water blasting, were most common. Some agencies use milling equipment, and Colorado reported using heat to soften the membrane so that it can be removed by scraping. The softer, liquid membranes are especially difficult to remove because they remain tacky; they are also not easily removed by blasting. Recognizing these difficulties, several agencies reported that the contractor is allowed to leave remnants of membrane in place provided that they are tightly bonded to the deck surface. This does not appear to have caused problems in North America because of the limited range of membranes used. The issue of compatibility of materials is much larger in Europe because of the greater diversity of materials used in waterproofing systems. Where a bituminous system is being replaced by a resinous waterproofing system, very thorough preparation is necessary because of the incompatibility of many bitumens and resins (*22*). The deck also needs to be examined for evidence of applications of a sealer. Some silane treatments have been found to reduce the adhesion of membranes (*66*).

FIGURE 29 Use of a bucket to remove surfacing and poorly bonded membrane.

If the concrete deck surface is in good condition, the method of deck preparation is the same as for new construction. More usually, upon removal of the surfacing, the deck will exhibit scaling as a result of freeze-thaw action on the concrete, or corrosion-induced delaminations and spalls.

In the case of a deck with slight to moderate scaling, abrasive (or water) blasting is normally used to remove the unsound surface layers and expose sound clean concrete. The finished surface is considerably less than the ideal surface for the application of a membrane. However, the only way to prepare the surface properly is to install a concrete levelling course, but this is not usually done because no provision has been made within most contracts and the cost of the contract would more than double. Liquid membranes, especially those applied at a thickness of 5 mm (0.2 in.) or more, are more tolerant of a rough concrete surface than sheet membranes. Self-adhesive sheet membranes cannot be bonded satisfactorily to a rough surface without the application of a bituminous adhesive.

In situations where the deck surface is heavily scaled, milling or blast cleaning operations cannot produce a surface suitable for application of a membrane. The removal operations reduce the concrete cover and overly roughen the surface. A thin, concrete levelling course is unlikely to be durable because it will crack and disbond. Two alternatives are normally considered: either a concrete overlay is constructed or a sand asphalt levelling course is placed on the deck.

It is rarely practical to construct a concrete overlay unless need for the overlay was identified at the planning stage and included in the contract documents. In such cases, an increase in the thickness of the deck and the effect on finished elevations will have been considered in the design process. If severe scaling was not anticipated, factors such as cost, delay of contract, contractor expertise, and the effect of dead load and changed elevations must all be considered before a decision can be made to install a concrete overlay. Usually, the expedient alternative of placing a bituminous levelling course will be taken. While this approach is advantageous for being quick, cheap, and providing a smooth, level surface, the life expectancy of the deck slab is short. If the membrane leaks, the water is not confined to the location of the leak. The water cannot escape and will cause rapid deterioration in the concrete, which is known not to be resistant to frost action.

In decks exhibiting corrosion damage, the practice is to remove unsound concrete and to place concrete patches to produce a sound, level deck surface. While the extent of removing the concrete and cleaning the exposed reinforcement have only a minor effect on the quality of the surface for waterproofing, they are major factors in determining the cost of the rehabilitation (*89,90*) and in determining the service life of the waterproofed deck (*3*). These effects are discussed in more detail in the section on the performance of membranes.

The first step in placing concrete patches is that the existing concrete must be removed to sound concrete. Some agencies require removal to below the top mat of reinforcing steel but practices vary widely. In areas of very bad deterioration, full-depth removal may be necessary. In such cases, forms must be attached to the deck soffit. Unless all of the patch is full depth, the concrete should be placed in two lifts to prevent cracking around the perimeter of the full-depth removal. The top of the first lift should be level with the bottom of the other area of the patch. Feather edging of the patch material should always be avoided (*2*). Sharp edges, at least 25 mm (1 in.) deep, should be formed by jackhammers or, preferably, by saw-cutting. Further information on equipment and practices for removing concrete is contained in *NCHRP Synthesis of Highway Practice 169: Removing Concrete from Bridges* (*3*).

After the concrete is removed, the exposed reinforcements must be cleaned by wire brushing or blasting with water or an abrasive. If blast cleaning is used, the concrete surfaces of the patch are cleaned at the same time. A bonding material is applied and the repair material is placed, screeded level with the existing deck surface, and cured. Several agencies use proprietary patching materials for this type of repair, although the cost of the materials becomes significant if quantities are large. Conversely, site mixed concrete is generally unsuitable if small volumes are needed because it is difficult to produce a high quality, air-entrained concrete under these conditions.

The performance of the interface between the parent concrete and the repair material is crucial to the future performance of the deck slab should the membrane leak, and chlorides gain access to the interface. Intense anodic sites can form on the steel at the interface and rapid corrosion can occur (*91*). After the patches have cured, the entire deck surface must be prepared using the same procedures as for new construction. However, while it is common practice to wait 28 days before waterproofing a new deck, construction schedules dictate that waterproofing is frequently applied to a patched deck after only 3 days of curing. The concrete is more porous, and has a higher moisture content than more mature concrete with the result that the membrane is more susceptible to blisters or blowholes.

Numerous factors contribute to the quality of construction of waterproofing systems installed on existing decks being inferior to that on new decks. The deck surface is unlikely to be as clean, level, or as free from irregularities as a new deck, which reduces the bond of sheet membranes and the local thickness of liquid membranes. Working conditions are more difficult because of traffic on the deck, which may influence blast-cleaning operations and the use of some equipment. Removal of debris and dust is more difficult, and contamination more likely. Time constraints are inevitable, and seams in the membrane and construction joints in the overlay may be at less than the optimum locations.

PERFORMANCE

As noted above, the quality of construction for membranes installed on an existing deck is likely to be inferior to that on a new deck because of a rougher deck surface and more difficult working conditions. Both factors tend to impair the performance of the waterproofing system. However, the single biggest factor affecting the performance of a membrane on a deck exhibiting corrosion is the effect of the repairs on continuation of the corrosion activity.

Because moisture is necessary for corrosion, it has sometimes been presumed that the application of a membrane will stop corrosion in a bridge deck. The membrane cuts off the availability of water and it might be argued that corrosion will cease as the concrete dries out, or the available moisture is consumed in the corrosion reactions. Even if corrosion does not stop, the membrane might be expected to ameliorate ongoing corrosion by reducing the moisture content of the concrete, which would increase the resistivity of the concrete and reduce the corrosion currents. These presumptions have not been supported by the results of field surveys (*31,85,92–96*) which have indicated a continuation of corrosion activity if all the chloride-contaminated concrete is not removed.

The effectiveness of membranes in stopping or reducing corrosion was investigated as part of a laboratory study undertaken in the United Kingdom (*97*). Specimens were fabricated and the top surface exposed to alternate drying and ponding with salt solution until the embedded steel was corroding. The surface was waterproofed and the effect on the corrosion monitored for more than a year. Several parameters were measured, including corrosion current, potential of the steel, and resistivity of the concrete. The membrane had no significant effect on the corrosion activity, as recorded by both the current and potential measurements. The treatment also had little effect on the resistivity of the concrete, which suggests that the membrane did not reduce the moisture content of the concrete, even though the bottom of the slab was unsealed and exposed to relatively dry air in the laboratory. The results were consistent with measurements of the weight change of the specimens.

A very similar laboratory investigation was undertaken as part of a SHRP study (*98*). Specimens were fabricated and the sides sealed with epoxy to simulate the boundary conditions anticipated in a bridge deck. A membrane and bituminous overlay were applied after the steel began to corrode, and the corrosion current density was measured using a commercial linear polarization device. The corrosion current decreased by more than 50 percent during the first few weeks after application of the membrane, and remained reasonably constant for the remainder of the monitoring period of 1 year. However, the current density did not drop below the level of 2.15mA/m^2 (0.20mA/ft^2) normally associated with a cessation of corrosion activity. The decrease in corrosion was attributed to the reduction in the moisture content of the concrete as a result of applying an impervious overlay.

An earlier study in the United Kingdom (*99*) investigated the effectiveness of three procedures for cleaning steel reinforcement. Effectiveness was measured in terms of whether the reinforcement continued to corrode after completion of the repairs to the concrete. Manual and power wire brushing were not effective in cleaning locally corroded steel. Grit blasting was usually effective in cleaning steel with coarse pits but not fine corrosion pits. However, it was noted that the grit blasting treatment was performed and inspected more thoroughly in the experiment than would be possible in the field. It is especially difficult to clean the underside of bars exposed in a deck because the blast must be applied by rebound, which destroys much of the energy. For most practical situations, it can be concluded that sufficient corrosion products remain on the steel for corrosion to continue.

The effects of a membrane on corroding reinforced concrete were also investigated in the parking garage of the New York World Trade Center (*42*). Rate of corrosion probes were installed in the concrete and currents were measured for periods up to 3 years. In general, the corrosion continued after application of the membrane. In some cases the corrosion currents were relatively unaffected, sometimes there was a sharp increase followed by a slight decrease, and in others there was a sharp decrease for a few months followed by a significant increase. The last mentioned situation was most common in former areas of delamination. The bars in the repair areas were cleaned by wire brushing, which was almost certainly a contributing factor to the corrosion continuing.

The effect of patches on corrosion activity in a salt-contaminated bridge deck was explained as a result of an investigation of methods of repairing deteriorated decks, which was initiated in California in 1969 (*89,100*).

Corrosion of reinforcement is the electrochemical degradation of steel in concrete. It occurs when there are sufficient chloride ions at the steel surface to destroy the passivity of the steel and an electrochemical cell develops. Four basic elements are necessary for an electrochemical cell to function: an anode where ions go into solution and corrosion takes place; a cathode, which does not corrode but maintains the ionic balance of the corrosion reactions; an electrolyte, which is a solution capable of conducting current by ionic flow; and a conductor, which permits the flow of electrons between the anode and cathode. In the case of steel in concrete, the anodes and cathodes occur on the reinforcing steel, which also acts as the conductor, and moist concrete serves as the electrolyte. This is illustrated schematically in Figure 30.

The major factors that determine the rate of corrosion are the size of the anodic and cathodic areas, the distance between them, the availability of oxygen and moisture at the cathode, the polarization of the cell, and the resistivity of the electrolyte.

As the steel corrodes, it expands, usually resulting in a delaminated piece of concrete separated from the parent concrete by a fracture plane parallel to the concrete surface, often located at or near the level of the reinforcement.

When repairs are made, the delaminated concrete is removed. Future corrosion activity is determined by the amount of concrete removed and the extent to which corrosion products are cleaned from the reinforcing steel. If the concrete is removed from around the perimeter of the bars, and the corrosion deposits removed from the bars before (chloride free) patching material is placed, the steel in the patch area will become cathodic with respect to the steel outside the patch. Thus, a former anodic area becomes a cathode. In many cases, a greater potential difference exists across the perimeter of the patch than before the original concrete was removed. The steel outside the patch becomes the anode, and rapid corrosion of the steel surrounding the patch may occur.

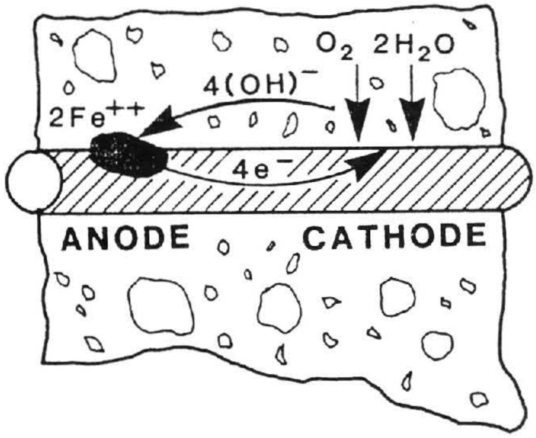


FIGURE 30 Simplified model of steel corrosion in concrete (*101*).

If the steel is exposed in the patch but remains partly surrounded by the original concrete and partly by the patching material, corrosion will continue. The same situation prevails if corrosion products remain on the bars.

Attempts have been made to eliminate the patching effect by insulating the steel in the patched area from further corrosion activity (*100*). This strategy was used in California by applying an epoxy coating to the steel just prior to placing the patching material. The technique was not completely successful because corrosion was found subsequently in patches where the steel was coated (*89*). It is extremely difficult to clean and coat the underside of bars with a liquid epoxy in the field and voids in the epoxy presumably accounted for the continuing corrosion activity.

Even if all the anodic areas are removed from a deck and the areas patched after insulating the steel, the steel outside the patch does not need the participation of the steel inside the patch for it to become active. If potential differences exist along the steel, as they invariably do, corrosion can begin elsewhere in the deck slab. It is common to measure a significant reduction in corrosion activity immediately after repairs have been made. As the new cells become established, corrosion activity increases regardless of the effectiveness of the membrane. It is important to note that the effect of patches on corrosion activity is not specific to membranes but applies to any other non-electrochemical method of rehabilitation, such as the construction of a concrete overlay.

The effect of patch repairs was observed in a recent study in Vermont. Two decks were rehabilitated in 1986 by repairing delaminations and applying a membrane. The membranes were removed in 1993 and the results of potential and delamination surveys were compared with measurements taken at the time of rehabilitation. A number of new delaminations had developed, mainly around areas that had been patched, or at areas with a potential more negative than -350 mV (CSE) in 1986. The average corrosion potential was less negative in 1993 than before the repairs were made despite the fact that chloride levels at the reinforcement exceeded the corrosion threshold value. The state considered the treatments to be effective in slowing corrosion activity in the decks.

A reduction in corrosion activity (as measured by potential readings) has been reported for other chloride-contaminated bridge decks in Vermont following application of a membrane (*102*). In a study of six decks, potential readings on five of the decks became less active by an average of 105 mV during the first year, with a further reduction of 34 mV during the second year. One of these decks was monitored for 49 months and there was no significant increase in corrosion activity. In the case of the sixth deck, there was little change in the average potential reading, which remained in the active range during 3 years of monitoring after application of the membrane. The difference in performance between this deck and the other five decks was ascribed to corrosion of the bottom mat of reinforcement. As noted in Chapter 2, potential measurements are difficult to interpret if not supported by collaborating data.

Four bridges in Vermont were studied as part of an investigation by SHRP to determine service life of rehabilitation techniques (*96*). The bridges had all been rehabilitated through the application of a membrane 4 or 5 years prior to the investigation. (The SHRP study report notes that the membranes were 4 to 15 years old at the time of the investigation. Data from the Vermont Agency of Transportation show the bridges were rehabilitated 4 or 5 years prior to the investigation.)

The test procedures involved cutting 0.6m × 0.6m (2ft × 2ft) sections of surfacing and membranes from the deck. Measurements were then made of depth of cover, chloride content, concrete resistivity, and corrosion current density. The rate of corrosion measurements were made with two commercial devices, though only the readings from the instrument with the lower coefficient of variation were used in interpreting the remaining service life. None of the rate of corrosion measurements indicated a passive condition. For two membranes, 50 percent of the readings were in the range associated with corrosion damage within 2 years, and the remaining 50 percent within the 2- to 10-year range. For another membrane, 100 percent of the readings were in the range associated with damage in 2 to 10 years, and for the fourth membrane, 78 percent of the readings were in either the less than 2 year or the 2- to 10-year range. The resistivity values were generally low, indicating a relatively high moisture content in the concrete. It was reported that no accurate estimate of the service life could be determined from the field evaluation, although the life predicted by the rate of corrosion measurements was reasonably consistent with the 10- to 15-year range reported in the expert opinion survey conducted as part of the study.

California began its program of investigating membranes in the early 1970s. In 1971, three liquid membranes and three sheet membranes were installed, four of them on bridges with a 5.4 percent grade. Various degrees of difficulty were encountered in all the installations (*67*). Problems encountered included the following:

- Blistering (in all six systems),
- Incompatibility with chlorinated rubber curing compound (2 systems),
- Sagging,
- A roofing paper was applied too early to a urethane membrane with the result that it did not cure,
- Tack coat stuck to paving equipment and lifted the membrane,
- The release paper was difficult to remove from one sheet system,
- Another sheet system debonded from the curb, and
- Membranes were damaged during the paving operation, especially those applied to the bridges on the steep grade.

The investigation was expanded and several installations were evaluated for periods up to 8 years (*103*). The evaluation consisted of resistance measurements taken before and after paving, and at intervals after the deck was opened to traffic. These measurements were supplemented by selective removal of the surfacing and visual observations of the membrane and protection board or roofing felt (where used).

Seven preformed membranes were evaluated at 20 installations, and five of the membranes were considered acceptable. The biggest problem identified was the occurrence of blisters. The two membranes considered unacceptable had low resistance readings from the time of construction. The use of protection board was not considered necessary with the preformed membranes, though it was recommended that the base course consist of 10 mm (0.38 in.) maximum size uncrushed aggregate to minimize damage to the membrane.

The study also evaluated seven liquid membranes at 16 installations, and considered two of the seven acceptable. Those rated unacceptable exhibited excessive permeability or were damaged by the paving equipment. Blistering was a problem with all of the membranes. The results of the study, summarized in a final report (*32*), led to the preparation of a list of approved products and revisions to the specifications for waterproofing decks.

Monitoring of a number of the installations was continued as part of a consolidated study of several experimental features on bridges (*104*). The deck waterproofing systems were reported as performing satisfactorily on the basis of visual observations, although the asphalt surfacing had to be replaced on three bridges 5 to 9 years after the installation because of break-up of the surfacing.

California recognized at the program's outset that a membrane would not stop corrosion, but the life of the deck would be extended in a cost-effective manner (*67,103*). All of the membranes were overlaid with 75 mm (3 in.) of asphalt surfacing for protection and for maintaining an adequate riding surface even after delaminations developed in the deck slab.

Four waterproofing systems were placed on existing decks in Kansas during the period 1970 to 1974 and investigated in 1982 or 1983 (*105*). Two of the systems were polypropylene-reinforced sheets and the other two were coal-tar modified liquid membranes. On the basis of visual examination and resistivity measurements, the installations were reported to be performing well. The only exception was a heavily trafficked deck, located on a grade with a traffic signal at the low end of the deck. Where the membrane was subjected to braking forces, it failed in less than 9 years. The remaining membranes were investigated again in 1991 (*106*). Resistivity measurements indicated that the membranes had failed, suggesting that the useful life of a waterproofing system in Kansas is 15 to 20 years.

Another early example of the use of membranes was an installation on the I-74 bridges in Iowa in 1973. A preformed membrane was installed as part of a deck replacement of the northbound bridge. The membrane was replaced in 1976 because of blisters and bond failure between the protection board and the membrane. The southbound bridge, which had a different sheet membrane, was still in service after 12 years although the surfacing had required extensive patching and the deck was programmed for a concrete overlay. Installations on four bridges on I-380 also had to be replaced after only a few years of service. These experiences caused Iowa to discontinue using membranes, even in experimental installations.

The experience in Missouri was similar to that in Iowa. Missouri initiated a study of several protective systems that included two preformed and two liquid waterproofing systems (*107*). Each system was installed on two existing bridges located on interstate highways in North Kansas City in 1976 or 1977. All of the surfacing installations were subjected to heavy truck traffic. The thickness of the asphalt surfacing was 50 mm (2 in.). Although the membranes were effective in preventing additional chloride penetration of the deck, resistance readings on all of the membranes dropped sharply after the first year. Of greater concern, however, was that the maintenance-free life of the surfacings was found to be about 5 years. This experience caused Missouri to discontinue using waterproofing membranes. Existing membranes are being replaced by polymer or concrete overlays as they reach the end of their service life.

Minnesota also experienced short service lives from surfacings placed over membranes (*85*). Measurements taken over several years on rehabilitated decks revealed extensive debonding of the surfacing and delamination within the deck slab. The state concluded that applying a membrane does not halt the deterioration of a corroding deck.

Five waterproofing systems, three preformed and two liquid systems, were installed on existing decks in New York in 1976 as part of the National Experimental Evaluation Program (NEEP) No. 12 (*108*). The asphalt surfacing was 60 mm (2.5) in. thick. The maximum aggregate size in the base course was 10 mm (0.38 in.). The membranes were evaluated over a 13-year period by visual observation, and resistance and potential measurements. A two-coat bituminous epoxy system exhibited low resistance readings from the time of construction. The resistance values of the three preformed membranes dropped substantially after about 5 years. The hot-applied, polyvinyl chloride-based liquid membrane maintained consistently high readings for 8 years, when the deck was rehabilitated "permanently." The study concluded that four of the membranes had an effective life of about 8 years, which was reported to be about the service life of a 60 mm (2.5 in.) asphalt overlay.

Illinois evaluated the performance of 20, chloride-contaminated decks over a 3-year period ending in 1980. The decks were repaired by patching spalled and delaminated areas, followed by the application of Illinois' standard built-up waterproofing system. For all of the structures, more than 50 percent of the deck area contained chloride in excess of the corrosion threshold value and at least 30 percent of the deck area exhibited active corrosion potentials. The decks were monitored annually by visual inspection, for delaminations (using the Delamtect device), membrane permeability, and corrosion potentials. By the conclusion of the study, no significant trends were identified (*109*). A second phase was initiated in 1982 for a further 3 years. The same test procedures were used excepting permeability measurements, which were not taken because the test method (ASTM D3633) was considered unreliable, and copper strips embedded in the deck were damaged beyond repair. After 6 or 7 years the majority of the decks were reported to be in generally good condition (*110*). Blisters developed on 15 of the structures and difficulties were encountered in distinguishing between the blisters and delaminated areas. The average area of delamination was estimated to be less than 1 percent, and the maximum to be 2.4 percent. During the period of the study, no maintenance was performed on 13 of the decks; cracks in the surfacing were sealed on 4 decks, and delaminated areas were patched on three decks. An economic analysis comparing the cost of patching and waterproofing with deck replacement showed that repairs were cost effective if they lasted more than 4.5 to 9.8 years, depending on the assumptions made in the analysis.

New Jersey installed nine waterproofing systems as part of a study to investigate the cost effectiveness of several alternative strategies for rehabilitating bridge decks (*95*). The systems comprised seven preformed membranes, one liquid rubberized asphalt, and one system described as a "tack coat" membrane. The waterproofing systems were monitored over a period ranging from 4 to 14 years.

Although there was some deterioration of the surfacing, and corrosion continued in the deck slab, it was concluded that the waterproofing systems were effective in extending the life of the deck slabs. It was shown, through a life-cycle cost analysis, that membranes are effective in New Jersey if they provide 10 years of service. A life of 10 to 15 years was projected from the field measurements. The study also developed recommended criteria for the use of protective systems. Membranes were recommended for consideration for all structures where the deck deterioration is not extensive. Membranes were the only system recommended for use where the remaining life of the structure is projected to be less than 10 years, because they were the least expensive of the options considered.

In the early 1970s, it was recognized that a permanent repair could only be made if all the concrete containing sufficient chlorides to cause corrosion was removed (*45,89*). It is now recognized that all of the corrosion products must also be removed from the reinforcing steel, a task which is virtually impossible in practice. It follows that applying a membrane to a salt-contaminated deck will not stop corrosion, but nevertheless may be an appropriate method of extending the deck life by providing a smooth riding surface and preventing the development of potholes in the deck slab for a number of years. The decision should be based on a cost/benefit analysis for each of the schemes under consideration. While costs can usually be determined reasonably accurately, the extension of service life is much more subjective, and most agencies rely on past performance histories in comparable situations.

Service Life of Membranes in Bridge Deck Rehabilitation

One of the survey questions asked agencies to provide data on the anticipated service life of membranes applied to existing decks. A supplementary question asked whether the anticipated life was based on actual performance data and, if not, how it was established.

The responses ranged from 3 to 30 years. Most answers were in the range of 10 to 20 years. Although several agencies stated that service life was based on actual field performance, no supporting data were supplied. It appears that, in most cases, the anticipated service life is based on engineering judgment.

The survey responses do not imply that membranes last for 3 years in some parts of the country and 30 years in others. Those agencies, such as Kansas and Michigan, that reported short service lives only use membranes as part of repairs to maintain an adequate riding surface on a deck until more permanent repairs can be made. As noted previously, actual service life is determined primarily by the deck preparation procedures and the quality of workmanship. Many of the longer estimates of service life were in the New England states, where there is a long tradition of membrane use.

A study of the service life of several corrosion protection systems was undertaken in Alberta (*111*). Based on field data, and expert opinion, it was estimated that the average service life of a waterproofing membrane and bituminous surfacing applied to an existing deck is 16 years to the optimum time for the next rehabilitation. Adjustments ranging from -5 to +7 years were suggested to account for factors such as type of structure, traffic volume, drainage conditions, and the number of freeze-thaw cycles.

TABLE 17
SERVICE LIFE OF REHABILITATED DECKS (condensed from *112*)

		Service Life, years		
System	Source	Ave.	Low	High
Membrane + surfacing	L	9.7	3.7	15.0
Membrane + surfacing	Q	11.8	4.5	20.0
Concrete overlay	L	17.9	13.6	25.0
Concrete overlay	Q	15.5	10.0	22.5

L = from literature survey; Q = from responses to questionnaire.

The service life and cost of various methods of deck rehabilitation were reported in a literature survey undertaken as part of a SHRP study (*112*). Information was collected from two sources: the literature and a questionnaire. The average service life, and the range of service lives reported for a membrane and bituminous surface, and a concrete overlay, are given in Table 17. Data from the two sources are reasonably consistent, and data for membranes are within the range of the responses reported in Appendix B. Data on the costs of membranes and concrete overlays are given in Table 18. While the data are reasonably consistent for concrete overlays, there is an unexplained disparity between the two sources with respect to the cost of waterproofing membranes. The range of costs is so large as to make a meaningful discussion of costs difficult, and emphasizes the importance of basing calculations of cost effec-

TABLE 18
INITIAL AND LIFE-CYCLE COST OF REHABILITATED DECKS (condensed from *112*)

		Initial Cost, $/m²		Present Value Total Cost[1], $/m²	
System	Source	Average	Range	Over 25 years	Over 50 years
Membrane + surfacing	L	60.81	18.57-161.99	114.70	147.36
Membrane + surfacing	Q	29.45		51.24	66.26
Concrete overlay	L	99.52	13.38-344.16	123.35	156.63
Concrete overlay	Q	104.59		151.99	192.29

L = from literature survey; Q = from responses to questionnaire.

[1] Based on 10% interest rate, 5% inflation rate, and a maintenance cost of 10% of initial cost.

tiveness on local figures rather than on national averages. Despite the wide range of values, the costs do indicate that membranes are less expensive than concrete overlays, both initially and over a life cycle of 25 to 50 years.

Taking the results of the performance data and expert opinion reported in this chapter, it appears reasonable, in the absence of local experience to the contrary, to assume a service life for membranes used in the rehabilitation of decks to be no more than 5 to 10 years, if only minimal repairs are made or the surfacing is less than 75 mm (3 in.) thick, and 10 to 20 years if deck repairs are more extensive and a surfacing of more than 75 mm (3 in.) is used.

CHAPTER FIVE

CONCLUSIONS

There are two reasons for using a waterproofing membrane on a bridge deck: to protect the concrete in the deck slab from freeze-thaw induced deterioration, and to protect the embedded reinforcement against corrosion. It is known that in Vermont, waterproofing membranes were used in response to observations of badly deteriorated concrete when bituminous surfacings were removed. The deterioration was most prevalent adjacent to curbs and expansion joints where water could pond on the deck slab. Beginning in 1960, two coats of tar emulsion were specified, and this subsequently led to the use of more effective membranes in the early 1970s. The other New England states likely followed a similar path because the use predates the recognition of corrosion as a dominant mechanism in the deterioration of bridge decks. Elsewhere in the United States, the use of membranes was largely the result of a 1972 federal requirement that bridge decks be protected against corrosion. The history of membrane use in Canada parallels that in the New England states. Prior to 1960, sealers were used to counteract deterioration of concrete beneath asphalt surfacings; however, when these measures were unsuccessful, membranes were introduced.

Data gathered in surveys conducted over the past 20 years show a consistent decline in the number of state agencies using waterproofing membranes in new construction. In 1994, 25 percent of agencies reported using membranes on new decks (though not necessarily on all decks in the state). The major reason for the decline has been the development of alternative strategies for corrosion protection, particularly epoxy-coated reinforcing bars. Epoxy-coated bars are relatively inexpensive, easy to use, and are perceived by most agencies to be performing satisfactorily in bridge decks. The states are sharply divided over the merits of waterproofing decks. Reasons given for not using membranes include the inability to inspect the top surface of the concrete deck slab, the poor performance of experimental installations, and the short service life of asphaltic overlays.

In contrast with new construction, the number of state agencies using membranes in conjunction with the rehabilitation of bridge decks has remained about the same over the past 20 years. About one-half of the states use membranes in rehabilitation work, though in some cases the use is limited to specific types of structures, or for keeping a deck in service for only a few years. While several states were using membranes on an experimental basis in the 1970s, most jurisdictions had removed the experimental designation and either adopted membranes as a standard treatment or terminated their use by the late 1980s. The greater use of membranes in rehabilitation than new construction reflects the fewer options available for protection of existing decks. Data from the 1994 survey showed that, in 1992, the area of membranes installed in rehabilitation was approximately six times that installed in new construction. Several agencies reported that membrane use in rehabilitation was increasing.

The survey identified that 22 different proprietary waterproofing products were used in the United States in 1992, including variations of the same product. The vast majority of the membranes are preformed products and three of the products have dominated the marketplace for almost 20 years. The situation in the United States is in marked contrast with Canada, where hot-applied rubberized asphalt membranes are widely used, and with Europe, where resin-based liquid membranes are used as well as sheet membranes and bitumen-based liquid membranes.

It is interesting to examine the current situation in the United States in the context of the recent history of membrane usage. Bridge deck deterioration was not recognized as a serious problem by highway agencies until the late 1960s. When the federal requirement for corrosion protection was issued in 1972, four acceptable treatments were available. A number of inexpensive proprietary membranes were available. Many more were introduced, often without adequate testing, in an attempt to capture a rapidly expanding market. Some of these membranes were accepted by state agencies, without a definition of performance requirements and often without a formal evaluation. They were installed by inexperienced contractors and accepted by inspectors with little or no relevant training. Many of the installations were designated experimental and several states instituted performance studies. Much of the U.S. literature dates from this period and chronicles the problems with field installations, which were all too common. Based on this experience, a number of agencies abandoned the use of membranes and the decision does not appear to have been revisited.

The study reported in *NCHRP Report 165: Waterproof Membranes for Protection of Concrete Bridge Decks* was initiated in the early 1970s in response to the proliferation of membranes in the marketplace. The study evaluated 147 products and, on the basis of simple laboratory screening tests, identified five products as being suitable for field evaluations. All five products were sheet membranes requiring the application of an adhesive to bond the membrane to the deck. Three of the five products were sheets of vulcanized rubber. These types of membrane inevitably perform well in laboratory tests, which cannot duplicate field conditions adequately. The membranes proved to be very difficult to install without creating blisters because the adhesive acted as a contact cement. The self-adhesive, reinforced polymer sheets became popular during this period, and have remained essentially unchanged for almost 20 years.

The current static situation is a consequence of both public agency specifications and lack of incentive for product improvement in the private sector. Most agencies use prescription specifications, many of which date from the 1970s and are based on manufacturers' recommendations. Most states using membranes maintain a list of approved products. The approval process, which varies from state to state, is not well defined in most states and relies on trial installations and engineering judgment. The actual membrane used in any situation is determined by the low bid process.

While there has been progress toward the development of performance specifications, significant improvements in waterproofing systems cannot be expected until specifications that will challenge and reward manufacturers are written. In current bidding practices for membranes, there is an emphasis on first costs with little consideration of life-cycle costs. In the United States, development of performance specifications has been hampered by lack of research. Except for minor expenditures in several SHRP studies, there has been only one nationally funded study (NCHRP Project 12-11), which was completed 20 years ago.

The lack of a quantitative definition of performance requirements for waterproofing systems, the absence of prequalification test procedures that will simulate the requirements, and inadequate quality assurance tests are major obstacles to the development of specifications. Research in the United Kingdom has shown that conditions on site are often more demanding than current prequalification tests.

Although the membrane provides the waterproofing integrity, it is one component of a waterproofing system that includes primers, adhesives, protection board, tack coat, and bituminous concrete surfacing. The overall performance of the system is determined by the complex interaction of material factors, design details, and quality of construction. Failure occurs when the membrane is no longer watertight or the surfacing breaks up.

The waterproofing integrity of membranes is determined primarily by two properties: bond and the amount of damage. A good quality, undamaged, fully bonded membrane is watertight. Conversely, damaged, unbonded membranes transmit large quantities of water because the water is not confined to the location of the leak. For conditions between these two extremes, performance is governed by the amount of damage and the degree of bond. Even a membrane that is badly punctured will slow the flow of water if it remains well bonded. The application of two coats of silane to the concrete deck slab has been found to reduce the quantity of water transmitted significantly, although the treatment is not as effective as a well-bonded, undamaged membrane. Some silanes can also reduce the bond of membranes to the deck slab.

Loss of adhesion between the membrane and the deck slab eventually leads to failure of the membrane. Some self-adhesive sheet membranes have very poor bond when applied at temperatures below 5°C (41°F). Ventilating layers reduce the bond to the deck slab and are not advised for use. Loss of adhesion between the asphalt surfacing and the membrane is usually a precursor to failure of the surfacing.

Many of the membranes in current use are susceptible to damage by paving equipment and hot aggregate at the time of installation of the surfacing. Protection boards are used in Canada and in Europe to prevent damage from these sources, but only a few states require them. However, studies have shown protection boards to be effective in reducing damage during placement and compaction of the surfacing, and after the deck is opened to traffic. Construction specifications place few controls on the contractor's operations when placing and compacting the surfacing, yet any damage that occurs is very difficult to detect afterwards.

Several studies have shown the importance of the thickness of the asphalt surfacing in reducing damage to the membrane from both traffic loading and thermal effects. It has also been shown that thicker membranes are more tolerant of surface finish and more resistant to damage from site activities, paving operations, and traffic loading; however, where grades exceed 4 percent or the deck is subject to braking forces or turning movements by heavy truck traffic, rutting or shoving are likely to occur.

Field studies have also shown that the performance of membranes has been extremely variable, and most investigations have revealed decks in which the waterproofing system was not performing satisfactorily. Many of the studies that revealed poor performances were undertaken in the early 1970s. More recent studies, and especially those by agencies with lengthy experience in the installation of membranes, have tended to show generally satisfactory performance. The application of a membrane will not stop corrosion in an existing deck, but the strategy can still be cost effective in extending the life of a deck. The major benefit is in providing a smooth riding surface and in slowing the deterioration of the deck slab by preventing the development of potholes for a number of years. Some field studies have also suggested a reduction in corrosion activity. Future corrosion performance is determined by the amount of salt-contaminated concrete removed from the deck, and the extent to which corrosion products are cleaned from the steel. In practice, it is virtually impossible to prevent new corrosion cells from developing in the rehabilitated deck. The typical service life for waterproofing systems in current use is 15 to 20 years when applied to a new deck. On rehabilitated decks, the service life is typically in the range of 5 to 10 years if only minimal repairs are made or if the surfacing is less than 75 mm (3 in.) thick, and 15 to 20 years if deck repairs are more extensive and the thickness of surfacing is 75 mm (3 in.) or more. In many cases, the service life is determined by the surfacing rather than by the membrane.

There is no proven and reliable method for determining the condition of a waterproofing system either immediately after construction or in later performance studies, or in condition surveys for making project level decisions concerning the rehabilitation of waterproofed decks. Visual inspections, combined with chloride ion content measurements of the concrete, and selective removal of the surfacing are the most satisfactory methods of investigating bridges in service. The electrical resistivity test that was used widely in the 1970s has so many serious limitations that its use has been largely discontinued. Half-cell potential tests are more difficult to interpret than when used on bare decks, especially when a membrane is applied to a deck already contaminated by salt. For the detailed investigations, or for research studies, ultrasonic and rate-of-corrosion measurements show promise but require additional field validation. Other techniques such as radar, thermography, and nuclear techniques have been investigated but are not currently practical.

While there is no doubt that waterproofing systems can be a very cost-effective method of bridge deck protection, the conclusions show that waterproofing practices in the United States, which have been almost static for the past 20 years, can stand some improvement. Materials, prequalification procedures, design details, and construction practices are not as refined as European, and especially U.K., practice. It appears that the common practice to obtain the lowest first costs is retarding development, and that a modest increase in the price paid for the supply and installation of waterproofing systems may result in a more than commensurate increase in performance. Some procedures to improve the practice can be suggested for immediate consideration, while others must wait for the results of research.

The following are materials considerations for membranes that may improve the practice:

- Prequalification tests and acceptance criteria could be reviewed to determine if the reasons for current approval practices are valid. Many jurisdictions accept only a handful of proprietary products and there have been few changes in many years.
- The softer and thicker membranes are likely to cause rutting or shoving in the surfacing where grades exceed 4 percent or the deck is subject to braking forces or turning movements by heavy truck traffic. Either membranes resistant to these forces or another method of deck protection should be used.
- Liquid membranes should be more than 2 mm (0.08 in.) thick, and preformed membranes more than 2.5 mm (0.10 in.) thick.
- Ventilating layers reduce the bond of the membrane to the deck and are not advised for use.

Design considerations that may enhance practice are as follows:

- Drainage from the bridge deck should be properly provided. Water should drain quickly from the deck and seepage drains should be provided at the lowest points to drain water passing through the asphalt from the surface of the membrane.
- Most of the membranes in current use are susceptible to damage at the time of installation of the asphalt surfacing. Protection board or a layer of sand asphalt are effective in resisting punctures and either one should be considered when writing specifications and developing drawing details.
- Several studies have shown that the thickness of the asphalt surfacing has a major influence on the performance of waterproofing systems. A minimum thickness of 75 mm (3 in.) is suggested when specifying thickness.

To help in the construction process, thorough consideration of the activities that have a significant effect on the performance of waterproofing systems should be incorporated in the construction specifications. The items to be thoroughly considered when writing specifications include the following:

- The definition of a clean, sound, and dry deck surface;
- Weather conditions (temperature and precipitation) at the time of installing the membrane;
- Maximum elapsed time between installing the primer, membrane, protection board, tack coat, and base course of the surfacing; and
- Controls on the equipment, placing temperature, and rolling temperature of the surfacing to prevent damage to the membrane.

In the process of collecting information for this synthesis, three current research studies involving waterproofing membranes were identified. Alaska is undertaking a study of the performance of membranes. Oklahoma is conducting a field study of construction practices of membranes with the objective of rewriting its materials and construction specifications. Vermont is continuing a long-established program of monitoring the field performance of membranes, and is also revising its construction specifications.

With regard to future research needs, it appears that the highest priority need is the development of a performance-based specification for waterproofing systems. An integral component of the specification should be a provision for life-cycle costing so that systems that offer superior performance can compete on an equitable basis with systems that have low initial cost, but a short service life. To achieve this goal, research studies are needed to examine field performance, prequalification testing, and quality assurance procedures.

There have not been performance studies in North America equivalent in depth and scope to the U.K. studies cited extensively in this synthesis. While many of the findings are applicable, differences in materials, construction practices, and climate mean that detailed performance studies need to be undertaken in the United States. These studies would need to include a review of the reasons for the current practice and to determine whether the conclusions reached in the research studies undertaken in the 1970s are still valid in the 1990s. The logical product of the field studies would then be a quantitative definition of the performance requirements for waterproofing systems.

Once performance requirements are established, a suite of prequalification tests, together with quantitative acceptance criteria, would be a necessary development. The objective is to develop tests that will ensure that products meeting the requirements will perform satisfactorily in the field, while not being so stringent that satisfactory products are rejected. Finally, quality assurance requirements would require definition, which would necessitate the development of test methods that can be applied immediately following installation of the components of the waterproofing system. This approach is consistent with a public sector definition of requirements and product development in the private sector.

The second area of needed research continues to be in the development of methods for investigating the condition of waterproofing membranes in the field. Despite the progress in recent years, further research is needed to develop measures of the effectiveness of waterproofing systems under service conditions.

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GLOSSARY

Blister—a pocket of air or vapor between a membrane and the deck surface.

Blowhole—a perforation in a liquid membrane resulting from the escape of vapors from the concrete before the membrane has cured.

Membrane—a continuous sheet of material, either preformed, cured from a liquid, or cooled from a hot melt, which is applied to the surface of a concrete bridge deck, and protected from the action of traffic by a wearing course.

Pinhole—a perforation in a membrane barely visible to the naked eye.

Protection board—a layer of material placed between the membrane and the bituminous surfacing to prevent damage to the membrane by construction traffic.

Seepage drains—a tube or hole through the membrane and deck slab for the purpose of draining moisture from the surface of the membrane.

Ventilating sheet—a permeable, preformed sheet of material, applied between the membrane and the deck surface for the purpose of preventing blisters.

APPENDIX A

SURVEY OF CURRENT PRACTICE

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
Project 20-5, Topic 25-09

Waterproofing Membranes for Bridge Decks

Questionnaire

Name of respondent: ______________________
Agency: ______________________
Title: ______________________
Phone No.: ______________________

NOTE: For the purpose of this survey, a membrane is defined as a continuous sheet of material, (either preformed, cured from a liquid, or cooled from a hot melt), applied to a bridge deck surface, and protected from the action of traffic by a wearing course. Concrete overlays, polymer overlays, and concrete sealers are not included.

1. **USE**

Does your agency use waterproofing membranes for:

a) New Construction?
Yes ☐ go to questions 2 to 10
No ☐ go to questions 10 and 11

b) Rehabilitation?
Yes ☐ go to questions 2 to 10
No ☐ go to questions 10 and 11

2. **PRODUCTS AND QUANTITY INSTALLED**

FOR THE TWO TABLES WHICH FOLLOW ON PAGE 2, PLEASE RESPOND BY KEEPING i) THROUGH iv) IN MIND:

i) List membranes (Product) used in:
a) New Construction and b) Rehabilitation

ii) Give commercial product names (Commercial Names) of membranes where possible.

iii) Are any of these products considered experimental? (Please indicate Yes or No)

iv) Give total area installed (broken down by product if available) in 1992 for:
a) New construction and b) Rehabilitation

NCHRP Project 20-5, Topic 25-09
Agency: ______________________

a)

New Construction			
Product	Commercial Name	Experimental?	1992* Area (sq.ft.)
		Total	

b)

Rehabilitation			
Product	Commercial Name	Experimental?	1992* Area (sq.ft.)
		Total	

* If 1992 data are not available for a) or b), please give the most recent data and indicate the year the data is provided for.

v) Is the use of membranes:

a) increasing ☐

b) decreasing ☐

c) static ☐

3. SELECTION CRITERIA

i) Do criteria exist for when membranes are used instead of another method of corrosion protection (such as existing surfacing, corrosion potentials, deck condition, anticipated life) in:

a) New Construction? Yes ☐ No ☐

b) Rehabilitation? Yes ☐ No ☐

(If the answer to either of the above is Yes, please attach details)

ii) Are some products used only in specific situations (such as grade, braking forces, speed of construction, anticipated life)? Yes ☐ No ☐

(If the answer to the above is Yes, please attach details)

iii) What are the anticipated service lives of membrane systems in:

a) New Construction? ______________________________

Is the anticipated life based on actual service life? Yes ☐ No ☐

If the answer to the above was NO, how was the anticipated life established?

____

b) Rehabilitation? ______________________________

NCHRP Project 20-5, Topic 25-09
Agency:______________________

Is the anticipated life based on actual service life? Yes ☐ No ☐

If the answer to the above was NO, how was the anticipated life established?

____

4. DESIGN DETAILS

Have standard design details been developed for:

a) installing membranes? Yes ☐ No ☐

b) terminating edges? Yes ☐ No ☐, If the answer to b) is Yes:

curbs? Yes ☐ No ☐

barrier walls? Yes ☐ No ☐

joints? Yes ☐ No ☐

(If the answer to any of the above is Yes, please attach details)

5. DECK PREPARATION

i.) How are decks prepared prior to applying membranes in:

a) New Construction?

____

b) Rehabilitation?

____

ii.) How are the existing membranes removed?

____

iii.) Is the contractor permitted to leave tightly-adhering remnants of membrane in place? Yes ☐ No ☐

If YES, how is this specified? ______________________

iv.) Has removal been difficult? Yes ☐ No ☐

If the answer to iv.) is YES, please explain: ______________________

(Please attach details, if necessary)

6. ASSOCIATED PRODUCTS

Are other products used in conjunction with membranes?

venting layers: Yes ☐ No ☐

seepage drains: Yes ☐ No ☐

protection board: Yes ☐ No ☐

other:__________ Yes ☐ No ☐

(If the answer to any of the above is Yes, please attach details)

7. SPECIFICATIONS

Are copies of the following specifications available:

a) material specifications? Yes ☐ No ☐

b) construction specifications? Yes ☐ No ☐

(Please supply example specifications if the answer is Yes to either of the above)

8. SURFACING

What thickness and type of surfacing is used with membranes?

____

(Please attach details, if necessary)

9. TRAFFIC CONTROL AND LANE CLOSURES

i.) Is traffic maintained while waterproofing a deck? Yes ☐ No ☐

ii.) What limits are placed on the contractor (e.g. time of lane closures)?

____

iii.) What limits are placed on the traffic (e.g. speed)?

____

10. PERFORMANCE

Has your agency conducted field studies or research on the performance of membranes?

Yes ☐ No ☐

Please supply copies of reports or the name(s) of an individual to contact regarding this work:

Name______________________ Phone No.______________________

Name______________________ Phone No.______________________

NCHRP Project 20-5, Topic 25-09
Agency:________________________

11. **REASON FOR NON USE**

Please explain why your agency does not use membranes for bridge deck protection. Include details of unsuccessful experiences and reasons, if applicable.

____
____
____
____
____
____

(Please include any further explanation on an attached sheet)

****

Thank you for your assistance!

Please Respond To:

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

Attn: Sally D. Liff/Stephen F. Maher
NCHRP Research Syntheses

If you have any questions, please call either of the above on (800) 424-9818 or (202) 334-3242. If you would like to submit your questionnaire response by facsimile, please do so on (202) 334-2527.

We would appreciate your response by February 18, 1994

APPENDIX B

SUMMARY OF RESPONSES TO SURVEY OF CURRENT PRACTICE

The survey for this synthesis (Appendix A) was mailed in January 1994 to highway agencies in the United States and Canada to ascertain the current state of the practice of waterproofing bridge decks. Replies were received from 48 states, the District of Columbia, and six Canadian provinces. Responses are summarized in the table on the following pages.

FOOTNOTES IN TABLE

Y = Yes, N = No

NEW CONSTRUCTION

[1]Area Installed	Area installed in 1992, X 1,000 m^2 (except for Saskatchewan—1993 figures) *Connecticut and Ontario—Includes area installed in rehabilitation (not included in totals for U.S. or Canada)
[2]Deck Preparation	A = air blasting, B = abrasive blasting, C = chemical solvent, S = sweeping, O = contractor's option, L = levelling course, W = water blasting, G = grinding

REHABILITATION

[3]Method of Removal	B = abrasive blasting, O = contractor's option, H = heat, M = melting, P = planing or scraping, W = water blasting
[4]Restrictions	P = pilot cars, S = speed of traffic, T = time of construction, V = varies with site

NEW CONSTRUCTION AND/OR REHABILITATION

[5]Type of Membrane	P = preformed, H = hot applied, L = liquid, B = built-up system
[6]Associated Products	S = seepage drains, P = protection board, R = reinforcements, F = roofing felt
[7]Approved Products	Does the agency maintain a list of approved products?
[8]Trend in Use	I = increasing, D = decreasing, S = static
[9]Reason for Non-Use	A = alternative corrosion protection system used, C = cost, D = deck protection not required, P = poor performance

AGENCY	NEW CONSTRUCTION						REHABILITATION											NEW CONSTRUCTION AND/OR REHABILITATION									AGENCY
	MEMBRANES USED	AREA INSTALLED[1] (X 1,000 m^2)	USE CRITERIA	PRODUCT CRITERIA	SERVICE LIFE (in years)	DECK PREPARATION[2]	MEMBRANES USED	AREA INSTALLED (X 1,000 m^2)	USE CRITERIA	PRODUCT CRITERIA	SERVICE LIFE (in years)	DECK PREPARATION	METHOD OF REMOVAL[3]	REMOVAL DIFFICULT	REMNANTS LEFT	TRAFFIC MAINTAINED	RESTRICTIONS[4]	TYPE OF MEMBRANE[5]	SURFACING THICKNESS (in mm)	ASSOCIATED PRODUCTS[6]	MATERIALS SPECS.	CONSTRUCTION SPECS.	APPROVED PRODUCTS[7]	PERFORMANCE STUDIES	TREND IN USE[8]	REASON FOR NON-USE[9]	
AL	N						N																	N		D	**AL**
AK	Y	5	Y		15	AB CS	Y		Y	N		O	O	Y	Y	Y	PV	P	50		N	Y	Y	Y	I		**AK**
AR	N						N																	N		D	**AR**
CA	N						Y	3	N		10-15	ALS	BW	Y	N	Y		P	75	S	Y	Y		Y	D		**CA**
CO	Y	38	Y	N		AW	Y		Y	N		AW	HP	Y	N	Y	V	HP	65	F	Y	Y		Y	I		**CO**
CT	Y	49*	N	N	30	O	Y		N	N	30	O	MP	Y	N	N		BP	65	S	Y	Y	Y	N	I		**CT**
DE	N						N																	N		A	**DE**
FL	N						N																	N		D	**FL**
GA	N						N																	Y		CP	**GA**
HI	N						N																	N		D	**HI**
ID	Y	1	N	N		O	Y	2	N	N		B		N	N	Y		HP	30-60		Y	Y		N	I		**ID**
IL	Y	1	Y	N	10-12		Y	12	Y	N	10-12		P	N	Y	Y	V	B	55-65			Y	Y	N	D		**IL**
IN	N						N																	Y		P	**IN**
IA	N						N																	Y		P	**IA**
KS	N						Y	n/a	Y		3-5		M			Y	V	P	50		N	N		N	S		**KS**
KY	N						N																	N		A	**KY**
LA	N																										**LA**
ME	Y	2	N	N	25	O	Y	45	N	N	15	AS	S	Y	Y	Y	ST	P	75	S	Y	Y	Y	Y	S		**ME**
MD	N																										**MD**

	AGENCY	MI	MN	MS	MO	MT	NE	NV	NH	NJ	NM	NY	NC	ND	OH	OK	OR	PA	RI	SC	SD
NEW CONSTRUCTION	MEMBRANES USED	Y	N	N	N	N	N	N	Y	N	N	N	N	N	Y	N	Y	N	Y	N	N
	AREA INSTALLED[1] (X 1,000 m^2)	2							n/a						6		n/a		n/a		
	USE CRITERIA	Y							N						N		N		N		
	PRODUCT CRITERIA	N							N						N		Y		N		
	SERVICE LIFE (in years)								20						15		10-15		10-15		
	DECK PREPARATION[2]	AS							O						SA						
REHABILITATION	MEMBRANES USED	Y	N	N	N	N	N	N	Y	Y	N	Y	N	N	Y	Y	Y	Y	Y	N	N
	AREA INSTALLED (X 1,000 m^2)	20							n/a	1		50			9	3	n/a	7	n/a		
	USE CRITERIA	Y							N	Y		Y			N	Y	N	Y	N		
	PRODUCT CRITERIA	N							N	N		N			N	N	Y	N	N		
	SERVICE LIFE (in years)	5							20	10-15		11			15	20	10-15	5-10	10-15		
	DECK PREPARATION	AS							O	B		ABW			AS	BG					
	METHOD OF REMOVAL[3]	OP							P	M		MP			PW	M		O	P		
	REMOVAL DIFFICULT								Y	N		N			Y				N		
	REMNANTS LEFT	N							N	N		N			Y	N	Y		N		
	TRAFFIC MAINTAINED	Y							Y	Y		Y			Y	Y	Y	N			
	RESTRICTIONS[4]	SV							V	V		ST			V	VS		V			
NEW CONSTRUCTION AND/OR REHABILITATION	TYPE OF MEMBRANE[5]	P							P	P		PH			P	P	BH LP	P	HP		
	SURFACING THICKNESS (in mm)	25-50							50	50-100		50			65	75	40-50	40-75	75		
	ASSOCIATED PRODUCTS[6]								S	S		FS						S	P		
	MATERIALS SPECS.	Y							Y	Y		N			Y	Y	Y	Y	Y		
	CONSTRUCTION SPECS.	Y							Y	Y		Y			Y	Y	Y	Y	Y		
	APPROVED PRODUCTS[7]	Y							Y	Y		Y			Y		Y	Y			
	PERFORMANCE STUDIES	N	Y	N	Y				Y	Y	N	Y	Y	N	N	Y	N	N	N		
	TREND IN USE[8]	S							S	D		I			I	I	S	I	D		
	REASON FOR NON-USE[9]		P	D	P						A		P	A							
	AGENCY	MI	MN	MS	MO	MT	NE	NV	NH	NJ	NM	NY	NC	ND	OH	OK	OR	PA	RI	SC	SD

AGENCY	NEW CONSTRUCTION						REHABILITATION											NEW CONSTRUCTION AND/OR REHABILITATION									AGENCY
	MEMBRANES USED	AREA INSTALLED[1] (X 1,000 m^2)	USE CRITERIA	PRODUCT CRITERIA	SERVICE LIFE (in years)	DECK PREPARATION[2]	MEMBRANES USED	AREA INSTALLED (X 1,000 m^2)	USE CRITERIA	PRODUCT CRITERIA	SERVICE LIFE (in years)	DECK PREPARATION	METHOD OF REMOVAL[3]	REMOVAL DIFFICULT	REMNANTS LEFT	TRAFFIC MAINTAINED	RESTRICTIONS[4]	TYPE OF MEMBRANE[5]	SURFACING THICKNESS (in mm)	ASSOCIATED PRODUCTS[6]	MATERIALS SPECS.	CONSTRUCTION SPECS.	APPROVED PRODUCTS[7]	PERFORMANCE STUDIES	TREND IN USE[8]	REASON FOR NON-USE[9]	AGENCY
TN	N						Y	7	Y	N	10-15	A	SM	Y	N	Y	VS	P	80	S	Y	Y	Y	Y	I		TN
TX	N						N																			A	TX
UT	N						Y	4	Y	N	10-20	AB	PB	N	N	Y	V	HP	75	P	Y	Y		Y	D		UT
VT	Y	3	N	N	30		Y	26	N	N	20-30		PS	N	Y	Y	VS	P	65		Y	Y	Y	Y	S		VT
VA	N						N																	Y		P	VA
WA	N		Y				N						M	N	N									Y		AP	WA
WV	N						N																	Y		P	WV
WI	N						Y	119	Y	N	12-15	B	M			Y	VS	P	50		Y	Y		Y	I		WI
WY	N						Y	1	Y	N	20	B	SB	Y	N	Y		P	60		Y	Y	Y	N	I		WY
DC	N						N																			A	DC
TOTAL		58						309																			
CANADA																											
AB	Y	9	Y	N	20	B	Y	2	Y		20	B	BM		N	Y	ST	HL	50-80	PS	Y	Y	Y	Y	D		AB
NB	Y	11	N	N	15	O	Y	13	N	N	15	O	P	Y	Y	Y	S	HP	65	PS	Y		Y	N	S		NB
NF	Y	2	N	N	15	AB	N											H	50	P		Y		N	I		NF
NS	Y		N	N	20	AB	Y		N	N	>10	AB				Y		H	55	P	Y	Y		N	S		NS
ON	Y	95*	Y		15	AB	Y		Y		15	AB	PW	Y	Y	Y		H	80	PR S	Y	Y	Y	Y	S		ON
SK	Y	1	N		10-20	AB	Y	3	Y	N	10	AB				Y	S		80	PR	Y	Y	Y	N	S		SK
TOTAL		23						18																			

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