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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM
REPORT

165

**WATERPROOF MEMBRANES FOR
PROTECTION OF CONCRETE BRIDGE DECKS
LABORATORY PHASE**

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**WATERPROOF MEMBRANES FOR
PROTECTION OF CONCRETE BRIDGE DECKS
LABORATORY PHASE**

C. J. VAN TIL, B. J. CARR, AND
B. A. VALLERGA
MATERIALS RESEARCH AND DEVELOPMENT
OAKLAND, CALIFORNIA

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

In recognition of these needs, the highway administrators of the American Association of State Highway and Transportation Officials initiated in 1962 an objective national highway research program employing modern scientific techniques. This program is supported on a continuing basis by funds from participating member states of the Association and it receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board of the National Research Council was requested by the Association to administer the research program because of the Board's recognized objectivity and understanding of modern research practices. The Board is uniquely suited for this purpose as: it maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; it possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; its relationship to its parent organization, the National Academy of Sciences, a private, nonprofit institution, is an insurance of objectivity, it maintains a full-time research correlation staff of specialists in highway transportation matters to bring the findings of research directly to those who are in a position to use them.

The program is developed on the basis of research needs identified by chief administrators of the highway and transportation departments and by committees of AASHTO. Each year, specific areas of research needs to be included in the program are proposed to the Academy and the Board by the American Association of State Highway and Transportation Officials. Research projects to fulfill these needs are defined by the Board, and qualified research agencies are selected from those that have submitted proposals. Administration and surveillance of research contracts are responsibilities of the Academy and its Transportation Research Board.

The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs

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The members of the advisory committee selected to monitor this project and to review this report were chosen for recognized scholarly competence and with due consideration for the balance of disciplines appropriate to the project. The opinions and conclusions expressed or implied are those of the research agency that performed the research, and, while they have been accepted as appropriate by the advisory committee, they are not necessarily those of the Transportation Research Board, the National Research Council, the National Academy of Sciences, or the program sponsors. Each report is reviewed and processed according to procedures established and monitored by the Report Review Committee of the National Academy of Sciences. Distribution of the report is approved by the President of the Academy upon satisfactory completion of the review process.

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FOREWORD

*By Staff
Transportation
Research Board*

This report is recommended to bridge design engineers, construction engineers, materials engineers, maintenance engineers, research engineers, and others concerned with the preservation of concrete bridge decks. It describes and presents the findings of a comprehensive assessment of the protective capabilities of all bridge deck waterproofing membrane systems known to be available when the project started. An extensive program of laboratory testing and a more limited program of field study were applied to aid in selecting those for which the expectation of success appeared to be the highest. The work led to eventual selection of five systems as the most promising for more extensive field evaluation. Materials and construction specifications were prepared for these five systems, as was also a plan for in-service evaluation.

During the past several years, the problem of premature deterioration of reinforced concrete bridge decks has appeared prominently in almost every listing of major problems facing highway transportation agencies. Although the problem has been the subject of numerous researches and much has been learned, no universally acceptable solution has been found and the search for systems that offer positive protection continues.

NCHRP Synthesis 4, "Concrete Bridge Deck Durability" (1970), places first awareness of the severity of the problem in the late 1950's. Surveys of the extent and severity of the problem subsequent to that period identified cracking, scaling, and spalling as the most common deck defects. Spalling was found to be the most serious defect, and experience has shown it to be the least susceptible to control. Spalling is now generally agreed to be caused mainly by corrosion of the reinforcement steel in the presence of moisture and a chloride salt.

Although high-quality concrete, air entrainment, and a good thickness of concrete cover over the steel reinforcement have been found to improve the resistance of bridge decks to deterioration, it is generally agreed that additional control measures are required. Waterproofing barriers have become the most favored means for providing the added control. However, experience shows that most of those used to date have not provided the desired degree of protection. The project with which this report is concerned was undertaken to discover improved waterproof membrane protective systems. Concurrently, alternative approaches to protection, including reinforcement steel coating, cathodic corrosion protection, and polymer impregnation to waterproof concrete, are being investigated elsewhere. Recognition that even the best of waterproof membrane systems can be effective only where decks are relatively free from chloride contamination adds impetus to the search for alternative systems.

In the research reported herein, personnel of Materials Research and Development subjected 147 known membrane systems to preliminary examination. Twenty-five systems in place on existing bridge decks were inspected during the course of the preliminary examination. Seventy-eight of the initial 147 systems showed sufficient promise to be selected for more detailed study. A comprehensive series

of laboratory characterization and performance tests, many of which were devised in the project effort, produced nine candidates for a field application test. Permeability, crack-bridging capability, durability, resistance to impact damage, and structural serviceability were among the principal characteristics examined in the laboratory. Ease of application was tested in the field. As a result of the testing, five systems were selected as the most promising for further evaluation in the in-service environment. The surviving membranes consist of vulcanized, cured, or crosslinked elastomers, all of which appeared to provide good dimensional stability on exposure to asphaltic concrete placed at normal application temperature, to water, to solar heat, and to freeze-thaw conditions. All of the surviving systems require a protective coat of asphaltic concrete to serve adequately, and all but one appear to require the application of an intermediate protective layer to avoid damage during construction operations following membrane installation.

The in-service evaluation of the five survivor systems is being conducted by Materials Research and Development as a follow-on to the present study. Until the results of this work become available, some discretionary judgment must be applied in the adoption of any of the systems in general practice. However, the chance seems good that any one of these systems will serve markedly better than applications represented by the 25 systems examined in the field survey of existing installations during the study.

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Serving the project as consultants in the areas of their special experience were Robert Gaul, of Adhesive Engineering Company, and Dr. Fritz S. Rostler, of MR&D; John L. Beaton, of the California Division of Highways, also served the project in an advisory capacity.

Special thanks are extended to the many representatives of

highway agencies who cooperated in the field study and in the information search; and to the materials manufacturers who contributed of their knowledge of properties of materials and performance of systems, and furnished samples of materials for evaluation.

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WATERPROOF MEMBRANES FOR PROTECTION OF CONCRETE BRIDGE DECKS

LABORATORY PHASE

SUMMARY

The general objective of this two-phase study was to develop or discover an effective waterproof membrane system (or systems) for use in protecting concrete bridge decks against premature deterioration. This report presents the results of research carried out in Phase I to define the service requirements and significant properties of membrane waterproofing systems and to devise an experimental program for evaluating the performance of candidate membrane systems under service conditions. Phase II is to include field evaluation of selected membrane systems.

The information required to initiate the study was developed by means of a comprehensive search of the literature, supplemented by inquiries to selected representatives of highway agencies and materials manufacturers. The literature search and review enabled the preparation of an extensive annotated bibliography consisting of 335 items by United States authors and 48 items by foreign authors.

A method was developed for classification of membrane systems into fairly well-defined classes with similar characteristics. The basic method consists of a five-digit code number that is determined by decisions about whether the system is a pre-formed sheet or an applied-in-place (built-up) type; thermoplastic or thermosetting in nature; unmodified or modified by the addition of appreciable amounts of other materials; fiber-reinforced or nonreinforced; and one that does or does not require a separate wearing-course overlay.

Representative systems that had already been applied to bridge decks were selected for field investigation. Field data obtained for 49 installations of 25 different membrane systems included measured electrical resistance as an indicator of membrane permeability, and the results of bond tests. Electrical resistance tests indicated that most of the membranes were far from impermeable, no slippage failures were noted in the field, indicating that bond was sufficient in all installations investigated.

A comprehensive list of 147 membrane systems that had been used or proposed for use was compiled from the information search. Of this number, 69 were eliminated in a preliminary screening. The remaining 78 systems were subjected to a series of laboratory characterization and performance tests. The results of three of the laboratory performance tests (electrical resistance, crack bridging, and water absorption) were the primary means of screening the membrane systems. Minimum requirements for acceptable performance in terms of the results of these tests were established. These requirements were selected on the basis of tentative requirements established by other tests, and by comparing the results accumulated from tests on systems evaluated in this project. The latter procedure is considered valid because the project objective is to select the "most promising" membrane system rather than to separate each system on the basis of being "satisfactory" or "unsatisfactory." An additional 51 systems were eliminated from further consideration at this stage because of failure to meet these requirements.

To make the final selection of the most promising systems, the 21 surviving systems were subjected to additional laboratory tests to evaluate adhesion, hot air exposure, fatigue, and moisture-temperature exposure. An additional 12 systems were eliminated in this step. The remaining nine were evaluated by a field application test, which resulted in five systems being recommended for inclusion in the Phase II field evaluation.

Materials and construction specifications were prepared for the five recommended systems. Specific types of systems meeting the requirements of the materials specifications were preformed sheets (applied-in-place systems passing all other requirements did not form water-impermeable films on placement) consisting of vulcanized, cured, or crosslinked elastomers that provided dimensional stability on exposure to water, to solar heat, to freeze-thaw conditions, and to hot asphalt concrete during construction.

CHAPTER ONE

INTRODUCTION AND RESEARCH APPROACH

BACKGROUND

Regardless of the type bridge structure, most bridge decks on streets and highways in the United States are constructed of portland cement concrete. The majority of these decks were designed to perform as both a structural unit and a wearing surface. Thus, deterioration in the deck concrete by scaling and spalling affects not only the riding characteristics of the surface but also reduces its structural strength, and, if allowed to continue, may render the bridge unsafe for traffic. Scaling is defined as the flaking or peeling away of surface mortar caused by freeze-thaw conditions and the presence of deicing salts. Spalling is a depression caused by separation and removal of the surface concrete due to rust pressures from steel corrosion.

Although the rate at which deterioration occurs varies widely from place to place, the mechanism is generally the same. Chemicals carried by water, particularly where high concentrations of sodium or calcium chloride are used in deicing, act on the steel-reinforced deck to cause spalling and disintegration. Corrosion of the reinforcing or prestressing steel results initially in expansion because of the greater volume occupied by the rust produced, followed by fracture of the concrete, spalling, and disintegration. Eventually this process, together with reduction in the cross-section of the steel, results in loss of structural integrity. The cost of replacing a disintegrated bridge deck commonly runs to twice the original cost of construction. The corrosion mechanism and its effect on bridge decks is described in *NCHRP Synthesis 4 (1)*. There are approximately 563,000 bridges in the combined highway systems,

and it has been estimated that about 88,900 bridges are "critically deficient," many because of salt damage (2).

Because the major cause of damage is related to the ability of rainwater to penetrate the deck from the surface, attempts have been made to devise methods for prevention of such penetration. These methods have included use of waterproofing admixtures in the concrete (3), use of surface-penetrating sealers (4), and placement of an impermeable membrane over the deck surface (4). Other approaches to solving the problem have been the search for noncorrosive deicing chemicals (5), use of protective coatings for the reinforcing steel (6), and use of corrosion inhibitors in concrete (7). The research effort in the present project is directed exclusively to the discovery or development of an effective waterproofing membrane system to be placed on the portland cement concrete bridge deck surface. The system may be either a single layer, serving as both a waterproofing membrane and a wearing surface, or a composite comprised of a waterproofing membrane covered by a wearing surface.

Although many agencies (8, 9, 10) have worked toward evaluating the effectiveness of such waterproof bridge deck membranes, most studies have, from necessity, been limited in extent both as to the number of systems included and as to the range of severity of service conditions. Difficulties also have resulted from the lack of generally accepted criteria for performance of systems and the lack of convenient means for measurement of the effectiveness of membranes in the field.

A wide variety of materials have been used, or proposed for use, as waterproof bridge deck membranes. A majority

of the systems have included a covering layer, usually asphalt concrete, to protect the membrane from the action of traffic, and, in some cases, to provide the necessary skid resistance that the membrane may lack. A measure of success has been reported for some of these materials in limited applications; however, no generally accepted waterproof membrane system for concrete bridge decks currently exists. Surface-penetrating sealers, such as linseed oil, are specifically excluded from consideration in this study.

OBJECTIVES

The general objective of this study is to develop, or discover, an effective waterproofing membrane system (or systems) for use on portland cement concrete bridge decks. The study consists of two separate phases, as follows:

Phase I: Define the service requirements and significant properties of membrane waterproofing systems and devise an experimental program for evaluating the performance of candidate membrane systems under service conditions.

Phase II: Conduct the field evaluation of selected membrane systems.

This report includes the results of Phase I only, although consideration is given to ultimate conditions and constraints imposed by the Phase II portion of the study. Under the general objective stated previously, the Phase I portion of the study was guided by the following more specific objectives:

1. To critically review and evaluate current theories and practices used in design and construction of waterproof membrane systems and to develop a classification method.
2. To conduct a field condition survey of various waterproof membrane systems and materials currently in service, with special emphasis on evaluating performance, service requirements, and benefit/cost ratios.
3. To study materials and membrane systems at laboratory scale to relate significant test properties with service requirements and, thus, to establish performance criteria.
4. To select existing waterproof membrane systems, or modifications thereof, or entirely new systems, and to devise an experimental program for evaluating field performance of systems under service conditions.

RESEARCH APPROACH

To initiate the research, a form letter requesting information and references was directed to highway agencies in all states and a selected number of foreign countries, to all manufacturers and suppliers known to be active in the field, and to other governmental agencies and trade associations. This was followed by a literature search including use of the information retrieval systems of the Highway Research Information Service (HRIS) and the Defense Documentation Center (DDC). Personal contacts and visits also were made with the Transport and Road Research Laboratory (United Kingdom), the Laboratoire Central des Ponts et Chaussées (France), and with various other groups active in membrane research, including the project consultants and advisers. Current waterproofing practice in other fields, such as roofing and hydraulic linings, was considered relevant to this study.

After a review of the published literature and all other information obtained, the approach to meeting the project objectives included a field survey of existing membranes and a series of laboratory characterization and performance tests. The results of both the characterization and the performance tests were initially used to screen the great variety and number of systems available, and to eliminate those that were judged to have little or no chance of serving as a satisfactory membrane under application and service conditions encountered in the field. Membranes surviving this initial screening were compared with field survey information, where applicable, with the findings reported by others; and on the results of further series of laboratory experiments and of field test installations. Aids used in the screening and selection process were a generic physiochemical classification system, a quantified set of performance criteria, and a procedure for estimating benefit/cost ratios, all of which were developed for this purpose during the course of this study.

The results of the study are presented in the form of materials and construction specifications for five waterproofing membrane systems selected on the basis of the foregoing research approach. A recommended experimental program for evaluating the field performance of these five systems is presented for implementation in Phase II of this research program.

CHAPTER TWO

FINDINGS

INFORMATION SEARCH

The initial study effort was directed toward obtaining information developed from previous research relative to this study, and toward assembling a complete list of all membrane systems that have been applied to bridge decks or that

have been proposed for this purpose. The list of membrane systems was assembled from the literature review, from replies to letter requests to user agencies, and from manufacturers by solicitation and volunteer submissions. The number and variety of systems exceeded original expectations, and additional suggestions from manufacturers continued to

arrive during the latter part of the study; many arrived too late to evaluate. These additional suggestions from manufacturers were primarily in the form of modifications and improvements of previously submitted systems. Thus, it is important to note that the results of this study apply to the systems as of the time samples were obtained, and that significant modifications may have been made to some systems since that time. A summary of highway agency replies is given in Table 1, and a summary of membrane systems installed by highway agencies is given in Table 2.

During the initial review of the published literature, annotations were prepared stating briefly the subject matter covered. In addition to serving as a valuable tool in the process of synthesizing and evaluating the wide variety of collected information for use in this study, the resulting annotated bibliography (App A*) should also be helpful to other researchers. The literature search uncovered many items which, after initial review, were found to contain no information directly related to the scope of this study. These items were, however, included in the bibliography as a record of the scope of the search and for possible assistance to others in search of information for related studies.

For convenience, the items in the annotated bibliography have been separated into two groups: articles by United States authors (No. 1 to 335), and articles by foreign authors (No. 336 to 383). Items within each group are alphabetized by the author's name. No attempt was made to include the information obtained from manufacturers, because most such information was in the form of special brochures, data sheets, or letters that generally are unavailable from library sources.

In addition to the specific information obtained on membrane systems, the results of the review of the published literature and other information obtained may be briefly summarized as follows.

1. The practice of applying a penetrating sealer to bridge decks, based on 50-percent linseed oil in solution, is widespread. This sealer appears to inhibit scaling of the portland cement concrete (10), but is ineffective for preventing reinforcing steel corrosion.

2. Although a few membrane systems (particularly those in items No. 34 and 99) have been adopted as "standard" by several user agencies, there is little published factual information about the performance of these systems.

3. A considerable research effort has been directed toward the problem of deterioration of concrete bridge decks, notably in delineating the mechanism of deterioration, in assessing the extent of the problem, and in developing repair methods for damaged decks (11). However, until a few recently initiated projects, little effort has been devoted to evaluating or developing waterproof membranes.

4. Several European countries, notably the United Kingdom, France, and West Germany, have used membrane systems for protection of bridge decks and have research underway for evaluating and improving membrane systems. For example, a standard performance specification and a qualified products list have been published in the United

Kingdom (12) and are used for new bridge deck construction.

5. The increasing awareness of the extent of damage to bridge decks caused by deicing salts has led to attempts by many manufacturers to develop satisfactory membrane systems. These efforts have resulted in many new membrane systems of a variety of types being proposed to user agencies, particularly in the last few years. Included are many systems of the prefabricated type that previously have received little attention in the United States.

6. No user agency has expressed complete satisfaction with any membrane system it has evaluated, although some agencies reported that certain systems show promise.

7. An FHWA notice issued early in 1971 provides for federal fund participation in application of bridge deck membranes. This is expected to accelerate the evaluation and use of membrane systems.

8. In 1970, FHWA Research and Development Demonstration Project #15 began to demonstrate to state highway agencies a method for measuring the effectiveness of membranes via the electrical resistance test, and corrosion of the reinforcing steel via the halfcell potential test.

9. The Organization for Economic Cooperation and Development (OECD) road research program (Research Group C3, "Protection of Bridge Decks in Reinforced and Prestressed Concrete") initiated a project in January 1970 to review and appraise the methods used in various countries to waterproof bridge decks. The United States is represented in the group by the FHWA. Results and recommendations are contained in the OECD publication, "Waterproofing of Concrete Bridge Decks," Paris, July 1972.

CLASSIFICATION METHOD

As information on membrane systems was collected, a method was developed for their classification into fairly well-defined classes with similar characteristics. The primary purpose of this classification was to assist in this study by simplifying the comparison and evaluation of systems and to serve as a clear and concise presentation in the study report. The method selected consists of an initial division accomplished by making five rather simple decisions regarding basic characteristics of the systems. These decisions are based on whether or not the membrane waterproofing system in question is basically:

- A preformed sheet or an applied-in-place (built-up) type.
- Thermoplastic or thermosetting in nature.
- Unmodified or modified by the addition of appreciable amounts of other materials.
- Fiber reinforced or nonreinforced.
- A system that does or does not require a separate wearing-course overlay.

Where a further breakdown may assist in the evaluation or comparison of systems within a class, a secondary division is made indicating the generic type of material. Provisions were included for expansion of this secondary division as new systems and materials are introduced into the classification method. A detailed description of the method,

* Appendix A, an annotated bibliography, is not published herein but may be obtained on a loan basis or for the cost of reproduction from the Program Director, NCHRP, Transportation Research Board, 2101 Constitution Ave. N.W., Washington, D.C. 20418

TABLE 1

SUMMARY OF HIGHWAY AGENCY REPLIES TO LETTER REQUEST FOR INFORMATION ON WATERPROOF MEMBRANE PROGRAM

Highway Agency	Status of Membrane Program	Overall Performance of Membranes Evaluated	Comments
Alabama	Limited	--	Experimented with seals, primarily as deck repair.
Alaska	None	--	Recent use of linseed oil and kerosene, effectiveness not determined
Arizona	None	--	Do not use salt.
Arkansas	None	--	Treat all new decks with linseed oil.
California	Active		
Colorado	Experimental	Good	
Connecticut	Active	Satisfactory to Poor	
Delaware	Experimental	Poor	
Florida	Experimental	--	Not in use long to evaluate
Georgia	None	--	
Idaho	Limited	--	
Illinois	Active	--	Work not advanced sufficiently to warrant formal reporting.
Iowa	Experimental	--	
Kansas	Limited	--	Used chip and slurry seals, doubt membranes economic advantages.
Kentucky	None	--	Used mostly surface seals, favor linseed oil.
Louisiana	Limited	--	
Maryland	Active	Good	Use linseed oil on new bridges.
Massachusetts	Active	Good to Poor	
Michigan	Active	Good to Poor	Occasional problems in application, e.g., poor quality control, poor bond, slow cure in cold weather.
Minnesota	Active	Good to Poor	
Mississippi	None	--	Have used linseed oil.
Missouri	Experimental	--	No system of sufficient age to evaluate.
Montana	None	--	Have not used waterproof membranes.
Nevada	None	--	Use an asphalt tack coat under AC surfacing.
New Hampshire	Active	Good	
New Jersey	Active	Satisfactory	
New Mexico	None	--	Have not used waterproof membranes, but considering.
New York	Active	Good to Poor	
North Dakota	None	--	Use light application of linseed oil on new decks
Ohio	Active	Satisfactory	
Oklahoma	Experimental	Poor	Used AC, asphalt surface treatments, and linseed oil.
Oregon	Limited	--	
Pennsylvania	Experimental	Poor	
South Carolina	Experimental	--	Also use linseed oil.
South Dakota	None	--	Use linseed oil and kerosene mixture
Tennessee	Active	--	Use linseed oil with mineral spirits on new decks
Texas	Experimental	--	
Utah	Experimental	Satisfactory to Poor	
Vermont	Active	Satisfactory to Poor	
Virginia	Active	Satisfactory to Poor	
Washington	Experimental	Poor	
Wyoming	Active	--	Used linseed oil with AC overlay.
E. Hudson P'hw'y Auth.	Standard	--	Use New York State standard.
Ill. St. Toll H'w'y Auth.	Limited	--	
Mass. TP Auth.	Active	--	
N. J. TP Auth.	Active	--	
N. Y. St. Thruway Auth.	Active	Satisfactory to Poor	Research program planned for 1971.
Texas TP Auth.	Active	Satisfactory	
Del. River & Bay Auth.	Active	Limited Success	
TP Auth. of Kentucky	None	--	Have considered use of membrane systems, no applications to date.
Wash. Toll Br. Auth.	None	--	Toll bridges maintained by Dept. of Highways.
Texas A & M Univ.	Active	Poor	Lab. research on several systems, mostly penetrants.
Univ. of Utah	Active	--	Preliminary research, no conclusions as yet.
Dept. of the Army Cold Regions Res. and Eng. Lab.	Limited	--	Discussed properties of several types of membranes.
Dept. of the Army Waterway Exp. Sta.	Limited	--	Sent a summary of information on membrane systems.
Canada	Active	Good	Ontario and Toronto have done considerable work in this field.

9

9

	Waterproof Membranes for Concrete Bridge Decks, System Number ^a																												
Highway Agency	3	8	12	14	17	21	25	26	27	28	29	30	33	34	35	41	43	45	46	47	48	50	51	52	53	60	63	65	66
Alberta, Canada																													
Arkansas																													
California			1-70		1-70									15-70				X											
Calif., Bay Toll Crossings																								P					
Colorado			1-70																										
Connecticut														8-67/68			1-65									1-68			
Delaware									1-63																				
Del., River & Bay Auth																													
District of Columbia																	1-62												
Idaho																													
Illinois				1-68	1-69	1-70	S		P	P	P		1-68	S		3-68/69							P						
Ill., Toll Hwy Auth.														4-68/70															
Indiana																													
Iowa														1-65															
Kansas			2-70											2-70			2-60								P				
Kentucky																					1-70					2-68			
Louisiana																X	X												
Maine																													
Maryland																													
Massachusetts	2-69	1-69			1-69			S		1-68				S					1-68				2-69/70				1-68	1-68	
Mass. TP Auth.																													
Michigan	1-70													44-63/66	29-63/66								P		4-69/70			2-65	
Minnesota																													
Mississippi																													
Missouri														L												1-60			
Nebraska																													
Nevada																													
New Hampshire							S	S																					
New Jersey								L																					
N.J. TP Auth.	2-7													L															
New Mexico																													
New York	1-68				1-70				1-69						1-61			1-69		3-65/67							1	3-65/67	1-68
N.Y., Port Auth.														S															
N.Y., Thruway Auth								L		L				S	L														
Ohio				1-70						2-67/68																			
Oklahoma																													
Ontario, Canada						5-67/69	11-7			P												226-68/69	5-64/69						
Oregon				1-69																									
Pennsylvania				1-69																									
Rhode Island								1-66	1-69				26-67/69																
Saskatchewan, Canada																													
South Carolina																													
Tennessee														L															
Texas	X													X															
Texas, TP Auth											L																		
Toronto, Canada							S																		P				
Utah	P		P							P	P			1-68	S			P											
Vermont																													
Virginia														L			1-68												
Washington																									3-71				
Wyoming																										P			

TABLE 2 (Continued)

[illegible]

Key to Notation

S -- in standard use
L -- in limited use
X -- in experimental use
P -- proposed for use in 1971
1-70, 3-71, etc -- number of membranes used
in indicated year
M -- many, 1950 to 1960

*A short description of the system represented by each number is given in Table 9

including the numerical and alphabetical codes assigned, is presented in Appendix B.

The classification method served its intended purpose, and proved a valuable tool in the orderly comparison and evaluation of the various dissimilar systems considered. For example, it enabled systems that were essentially similar to be recognized, thus avoiding the effort that would be required to evaluate each one individually. Despite the proved usefulness of the classification method in this study, it is not suggested that this method would necessarily be feasible or practical for use in preparation of standard materials or construction specifications for membrane systems.

FIELD INVESTIGATION

A representative number of membrane systems that had previously been applied to bridge decks were selected for field investigation. The initial selection was based primarily on such factors as type of membrane, geographic area, climatic conditions, level of traffic, and length of time in service. The location of bridges included in this investiga-

tion is shown in Figure 1. Final selection was made with the assistance of the cooperating highway agency involved, with priority given to those considered representative of a particular system for which the most complete construction and service records were available, and which could be tested with the least delay and hazards to traffic. Field data were obtained for 49 installations, which included 25 different membrane systems.

For each installation, available information recorded on the field data sheet included structural details of the bridge (span lengths, width, number of lanes, shoulders, grade, cross-slope, curvature, etc.); traffic loads, volumes, and speed; and the specific type of membrane, with details of construction. Data obtained included a description of the present condition of the bridge based on a visual inspection (with particular attention to the deck pavement and the underside of the deck), and results of electrical resistance and bond tests of the membrane. A sample of the form used to record this field data is given in Appendix C. Data collection was supplemented by photographic records, and intact core samples were taken for examination in the lab-

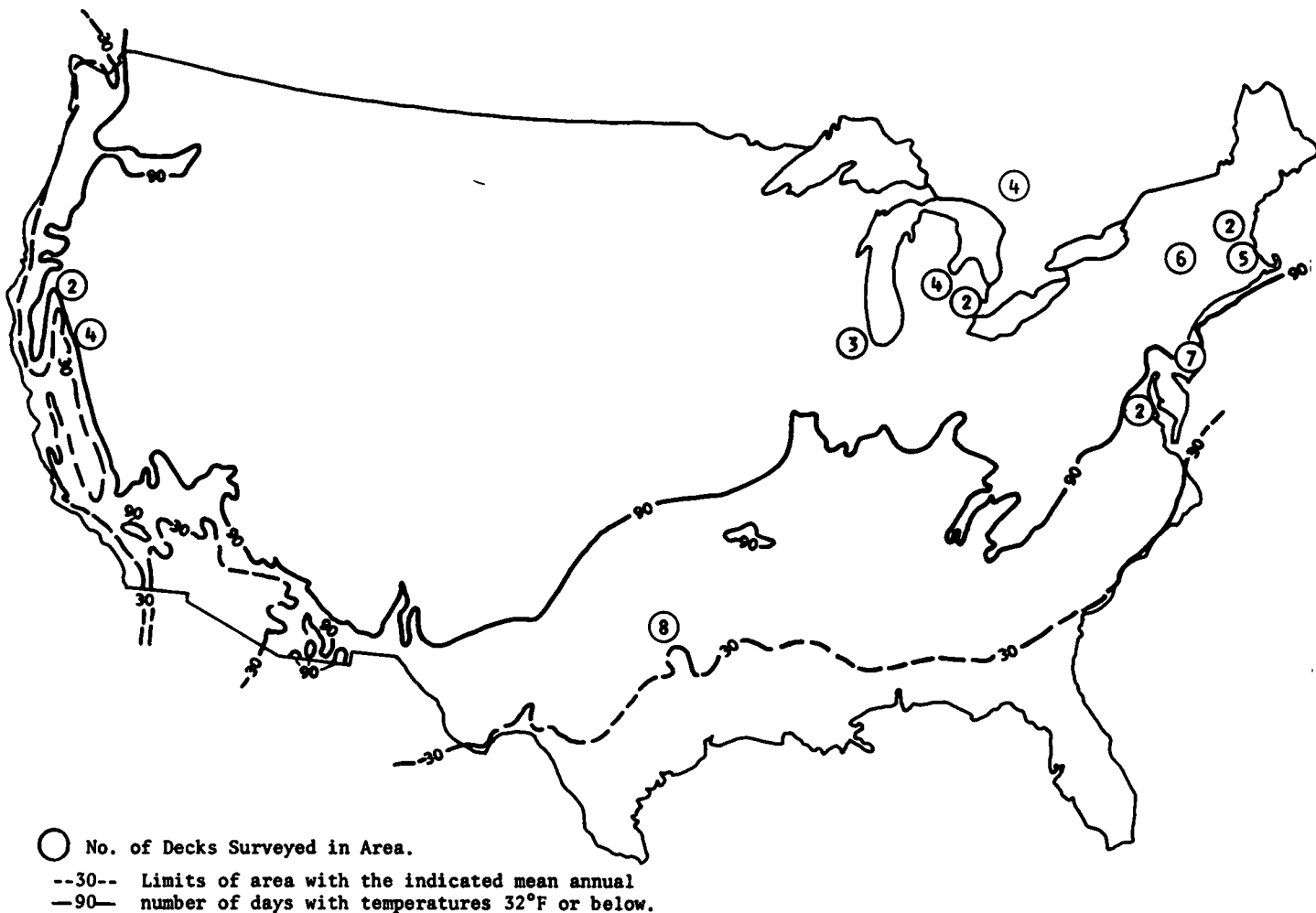


Figure 1. Location of bridges in field survey in relation to climatic areas (Source Climatic Atlas of the United States, U S Dept of Commerce, Environmental Science Services Admin. June 1968.)

oratory. Laboratory tests for chlorides content were performed on the portland cement concrete portion of core samples taken from those decks where records indicated no deicing salts had been applied before placing the membrane.

The techniques used in the electrical resistance test were adapted from the test method developed by Stratfull (13). This test was used as a measure of the water permeability of the membrane, and was the primary means of evaluating its condition at the time of survey. Details of the test method, the equipment used, and the manner in which the results were summarized are presented in Appendix C.

Two rows of resistance measurements were performed for each membrane installation studied—one row was selected to represent the most heavily traveled portion of the bridge deck, and the other was selected to represent the least traveled portion. One row was usually in the right wheelpath of the right lane, and the other was in the shoulder area or, if there was no shoulder, between the wheelpaths in the right lane. The results of measurements in each row were analyzed separately to evaluate the possible effects of traffic on the condition of the membrane. (See App. C for a description of the method of analysis.) Figure 2 shows graphically the results for two such installations, one in which the measured resistance was substantially lower in the line of heaviest traffic, and a second in which little difference was observed between measurements in the heaviest and least traveled rows. From comparisons between rows of measurements, it was concluded that certain membrane installations were damaged by operation of repeated heavy traffic loads on the asphaltic concrete wearing course. Other membrane installations showed essentially no difference between heavy traffic and light traffic, and in some instances heavy traffic was beneficial.

Although these conclusions are believed to be generally valid with respect to the membrane installations observed, they should not be considered necessarily applicable to every individual membrane installation, because resistance measurements were not made at the time of construction, and effects of possible "built-in" variations could not be eliminated.

To compare field-membrane installations with each other, the selection of a representative resistance value for each was necessary. In each installation, the row of reading with the lowest mean was selected for comparison, on the assumption that this would represent the potential damage to the bridge deck regardless of somewhat lower permeability in other areas. To account for variations within each series of measurements, the mean less one standard deviation was selected as the representative value.

Although no minimum value of resistance had been established for satisfactory service for bridge deck membranes, the wide range of values obtained, together with tentative indications by others (13), indicated that some grouping into comparative categories could be made. Thus, a decision was made to rate those installations with a representative resistance value of more than 10^8 ohms/ft² as "good," those between 10^8 and 10^4 as "fair," those between 10^4 and 10^2 as "poor," and those below 10^2 as "very poor." A graphic representation of these ratings for each membrane installation is shown in Figure 3, and numerical val-

ues and geographical location are given in Table 3. It should be understood that these ratings refer to the membrane system as it was tested, with no assurance as to whether lower ratings indicate a basic fault of the system or whether they are a result of faulty placement or of damage after placement. However, it does point out that although a few field systems are essentially impermeable, most of them are apparently far from impermeable.

Details of the methods and equipment used to perform a bond test conducted during the field survey are also given in Appendix C. Paving experience has shown that a lack of bond between any layer near the surface may result in slippage during construction or slippage under the action of heavy traffic. This is particularly important in areas of high horizontal stresses represented by high-speed curves, grades, or wherever heavy braking is required. Although no standard minimum requirement for the bond of membrane-to-deck or of asphaltic concrete-to-membrane has been established, experience has shown that a satisfactory bond usually exists where asphalt tack coats are used between portland cement concrete slabs and asphaltic concrete overlays.

It has also been postulated that a bond between a membrane and the bridge deck serves the beneficial purpose of localizing the effects of water and salt that may penetrate a small defect or break in the membrane. The bond tests were performed to obtain a numerical value for comparison among membrane systems placed under field conditions. The results of the field bond tests are given in Table 4. Field observations revealed no slippage of the asphalt concrete surfacing, indicating the bond was sufficient in all installations investigated.

Although the electrical resistance test was selected as the primary means of evaluating the permeability of membranes in the field because it is both rapid and nondestructive, the penetration of water and deicing salts through the membrane may also be evaluated by determining the quantity of chlorides deposited in the deck concrete. This procedure requires sampling of the deck concrete for testing in the laboratory. Because the core samples obtained included a portion of the concrete immediately beneath the membrane, it was decided to determine the chlorides content of the concrete from those samples obtained from bridge decks to which no deicing salts had been applied before installation of the membrane. The results of these laboratory tests on samples from 14 such bridge decks is given in Table 4.

LABORATORY CHARACTERIZATION TESTS

To characterize the various materials used in the membrane systems selected for study, their basic physical properties were determined. Because little of the desired information was available in the manufacturer's literature in a form suitable for comparison, a series of standard tests were performed in the laboratory. The tests were selected on the basis of past experience of the project staff and from information obtained by review of the literature. These tests included determinations of ultimate tensile strength and elongation at break, hardness, water absorption, glass transition temperature (heat deflection temperature), pot life, thin film set time, resilience, and plasticizer migration.

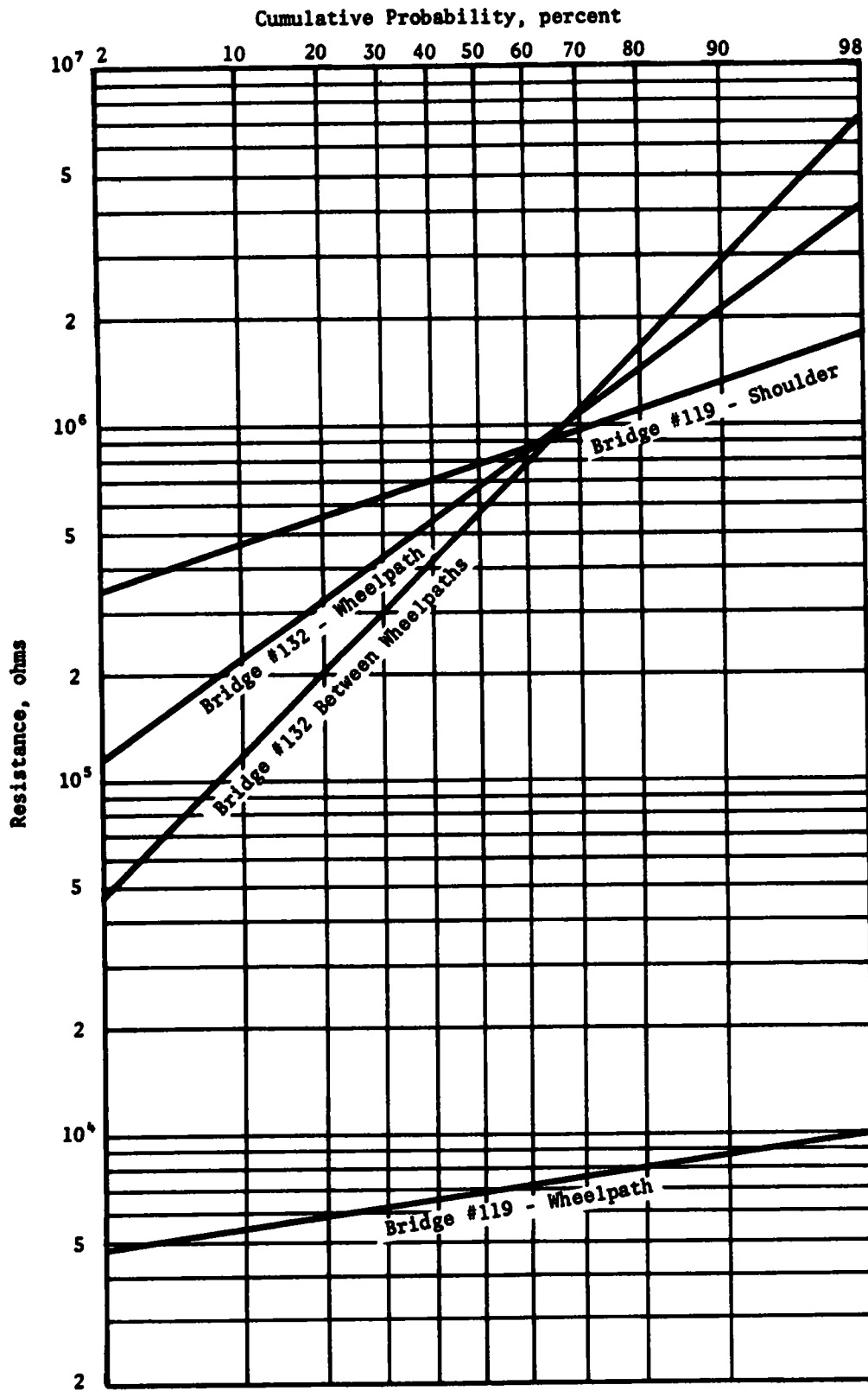


Figure 2. Resistance measurements on two representative bridge decks with system 34.

(stain). A description of each of the test methods used is given in Appendix C, Part II Characterization test results are given in Table 5.

LABORATORY PERFORMANCE SCREENING TESTS

To assist in selecting the most promising systems from among the large number available, another series of tests was developed to evaluate, at laboratory scale, the potential performance of the systems under field conditions. These performance tests were intended to simulate the ability of the membrane systems to:

1. Form a complete and impervious barrier to penetration of water.
2. Bridge, without rupture, those cracks that appear in portland cement concrete bridge decks during the shrinkage of the concrete while curing, and periodically change in width with thermal or moisture cycles
3. Form a sufficient bond between the membrane system and the portland cement concrete deck to resist slipage during construction and under traffic.
4. Withstand without deterioration the elevated temperature resulting from placement of a hot asphaltic concrete wearing course on the membrane system.
5. Resist the normal action of construction equipment during placement of an asphaltic concrete wearing course over the membrane system.
6. Resist the slow penetration of the asphaltic concrete aggregate (creep damage) resulting from traffic on the wearing course.

To evaluate the potential performance of membrane systems on a laboratory scale, a set of four specimens (designated A, B, C, and D) of each was prepared by applying them to the surface of standard concrete building blocks approximately $8 \times 16 \times 1\frac{1}{2}$ in. sealed with a cement grout. Performance tests conducted in the laboratory on these specimens consisted of:

1. A visual check of the bond of the membrane to the concrete block.
2. A high-temperature cycle (250 F) to simulate the effects of application of a hot asphaltic concrete wearing course over the membrane.
3. An "impact damage" test, at both room temperature and 140 F, to simulate damage that might be caused by construction equipment and loose rock during the placement of a hot asphaltic concrete wearing course over the membrane.
4. Two "creep damage" tests of differing severity, both at 140 F, to simulate damage that might result from the action of traffic on the asphaltic concrete wearing course
5. A "crack bridging" test, at both room temperature (77 F) and a lower temperature (0 F), to simulate the effect of opening of cracks in the portland cement concrete bridge deck after the membrane system has been placed.
6. Electrical resistance tests (as a measure of water permeability) following placement of the membrane, after the heat cycle, and after each of the impact damage and creep damage tests

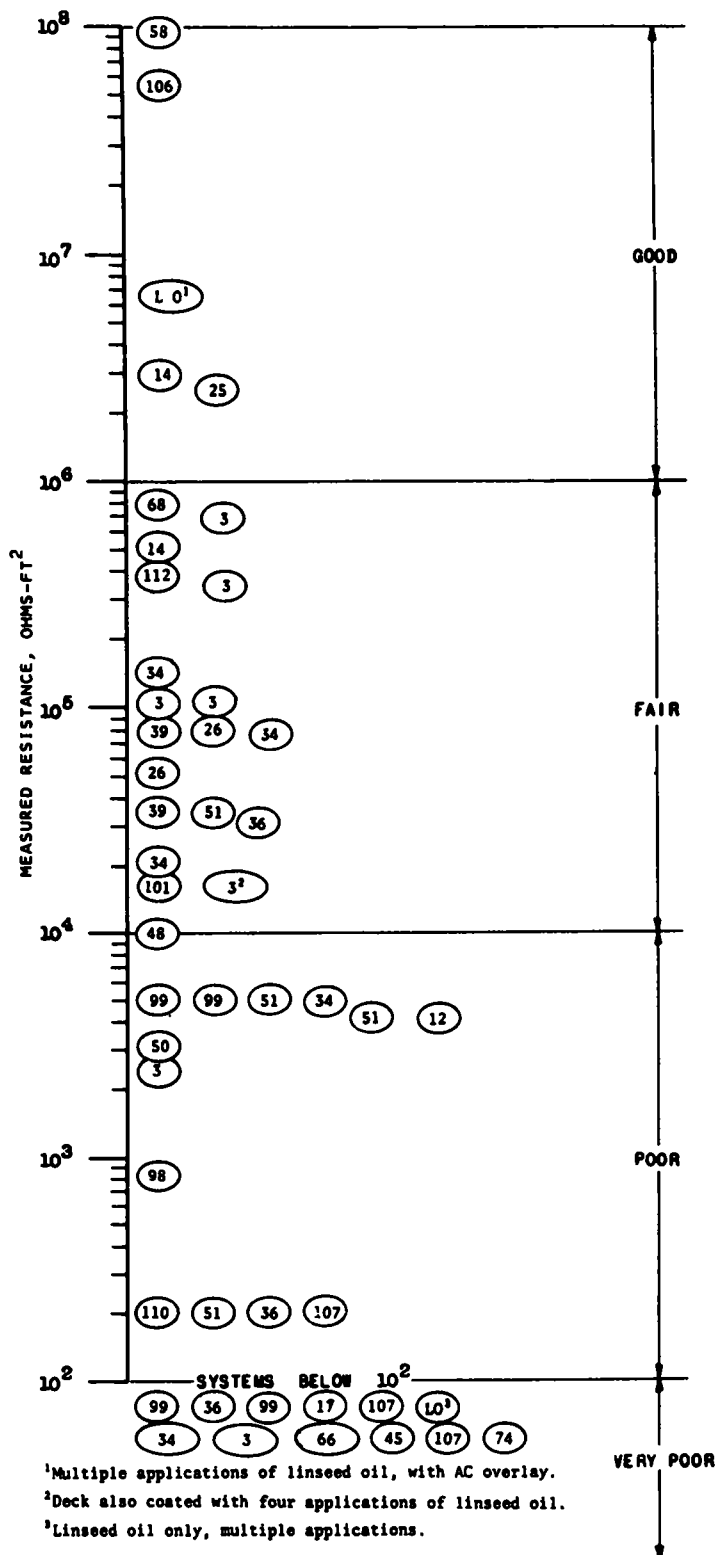


Figure 3. Summary of field electrical resistance measurements on selected bridge decks.

TABLE 3
SUMMARY OF FIELD ELECTRICAL RESISTANCE MEASUREMENTSON SELECTED BRIDGE DECKS

System Number	Classification	Location	Climatic Exposure ⁶	Age, Years	Field Survey Number	Electrical Resistance, $\times 10^4$ ohms-ft ²				R a n k i n g			
						In traffic areas		In non-traffic areas		In traffic areas		In non-traffic areas	
						Mean	- σ^1	Mean	- σ^1	Mean	- σ^1	Mean	- σ^1
3	1/1c/1/2/1	Michigan	>90	2	136	653	158	73.9	33.4	9	8	20	14
3	1/1c/1/2/1	New Jersey	30-90	4	108	474	95.0	195	10.4	11	10	13	19
3	1/1c/1/2/1	New Jersey	30-90	--	110	315	65.1	815	281	14	13	9	8
3 ²	1/1c/1/2/1	Texas	30-90	3	121-A	44.6	1.58	4225	2670	23	27	4	4
3	1/1c/1/2/1	New Jersey	30-90	4	105	137	44.9	79.1	10.5	19	16	19	18
3	1/1c/1/2/1	Massachusetts	>90	2	116	0.57	0.26	1.52	0.76	34	33	38	34
3	1/1c/1/2/1	New York	>90	3	127-B	0.02	<0.01	0.02	<0.01	42	39	44	42
12	1/1a/2/1d/1	California	>90	1	112	79.0	2.48	2.58	0.41	21	25	36	38
14	1/1b/2af/2/1	New Jersey	30-90	4	107	800	429	686	294	8	7	10	7
14	1/1b/2af/2/1	New Jersey	30-90	4	106	1010	614	309	49.5	6	6	12	12
17	1/1a/2/2/1	Massachusetts	>90	2	118	<0.01	<0.01	13.1	8.54	44	39	29	20
25	2/1b/1/1a/1	Ontario	>90	7	144	5260	2720	422	247	4	4	11	9
26	2/1b/1/1a/1	New Hampshire	>90	17	146	2795	1875	68.9	9.15	5	5	21	22
26	2/1b/1/1a/1	New Hampshire	>90	12	145	256	21.4	133	5.05	17	20	14	25
34	2/1a/2b/1a/1	Michigan	>90	5	139	297	120	55.5	13.6	15	9	22	16
34	2/1a/2b/1a/1	Illinois	>90	4	132	30.7	13.0	25.6	7.47	24	21	26	23
34	2/1a/2b/1a/1	California	>90	1	102	7.50	1.95	28.4	5.14	28	26	25	24
34	2/1a/2b/1a/1	Michigan	>90	5	140	3.00	0.48	111	46.5	29	31	15	13
34	2/1a/2b/1a/1	Massachusetts	>90	2	119	<0.01	<0.01	35.1	23.4	44	39	24	15
34	2/1a/2b/1a/1	Illinois	>90	0	134	---	---	109	8.23	--	--	16	21
50	2/1b/2fj/2/1	Ontario	>90	4	142	456	23.7	3.56	0.32	12	19	34	39
50	2/1a/2b/2/1	Michigan	>90	4	138	278	60.1	14.6	3.59	16	14	28	27
36	2/1a/2b1/2/1	Michigan	>90	6	137	135	32.4	16.2	3.02	20	18	27	28
36	2/1a/2b1/2/1	California	>90	1	103	0.40	0.02	80.2	13.1	36	36	18	17
36	2/1a/2b1/2/1	California	>90	1	113	<0.01	<0.01	<0.01	<0.01	44	39	47	42
51	2/1b/2bf/2/1	Ontario	>90	3	143	25.8	3.59	1250	228	25	23	8	10
51	2/1b/2bf/2/1	Massachusetts	>90	2	115	0.52	0.41	1.12	0.90	35	32	39	33
51	2/1b/2bf/2/1	Massachusetts	>90	1	117	0.79	0.50	3.48	1.86	33	30	35	29
51	2/1b/2bf/2/1	Michigan	>90	1	135	0.39	0.02	>9310	>9310	37	36	1	1
48	2/1b/2f/2/1	Texas	30-90	<1	120	2.06	1.00	5.05	3.90	32	28	31	26
45	2/1j/2n/2/1	New York	>90	2	128	0.05	<0.01	4.03	1.30	40	39	33	31
110	2/2a/2d/2/1	Washington, D. C.	30-90	8	148	552	52.9	0.44	0.02	10	15	41	41
58 ³	2/1b/2a1/2/2	Ontario	>90	7	141	>9310	>9310	>9310	>9310	1	1	1	1
68	2/2a/1/2/1	Texas	30-90	3	122	925	77.5	1845	207	7	12	7	11
74	2/2b/1/2/1	Illinois	>90	4	133	9.88	4.11	0.07	<0.01	27	22	42	42
66	2/2c/1/2/1	New York	>90	3	127-C	0.06	<0.01	0.01	<0.01	39	39	45	42
106	2/2a/2m1/2/1	Texas	30-90	3	125	6410	5430	6640	5780	2	2	3	3
112	2/2a/2e/2/1	California	>90	3	101	445	37.7	2785	482	13	17	6	6
99	2/2a/2c1/2/1	California	>90	1	114	<0.01	<0.01	0.96	0.75	44	39	40	35
99	2/2a/2c1/2/1	New Jersey	30-90	4	104	176	84.8	6.00	0.52	18	11	30	36
99	2/2a/2c1/2/1	Texas	30-90	3	123	22.0	0.57	42.5	0.51	26	29	23	37
99	2/2a/2c1/2/1	New Jersey	30-90	--	109	2.69	0.04	<0.01	<0.01	30	39	47	42
98	2/2a/2e1/2/1	Texas	30-90	3	124	2.30	0.08	2.26	0.08	31	35	37	40
107	2/2a/2e1/2/1	New York	>90	1	130	0.24	0.02	4.23	1.25	38	34	32	32
107	2/2a/2e1/2/1	New York	>90	2	129	0.03	<0.01	0.03	<0.01	41	39	43	42
107	2/2a/2e1/2/1	New York	>90	3	127-A	0.01	<0.01	0.01	<0.01	43	39	45	42
101	2/2a/2lm/2/1	Washington, D. C.	30-90	--	147	56.2	3.31	90.5	1.66	22	24	17	30
LO ⁴	---	Texas	30-90	5	121-B	5310	3785	3185	661	3	3	5	5
LO ⁵	---	Texas	30-90	8	126	<0.01	<0.01	<0.01	<0.01	44	39	47	42

¹Mean less one standard deviation.²Deck also coated with 4 applications of linseed oil.³Does not include cracked areas, where resistance was very low.⁴Multiple applications of linseed oil, with AC overlay.⁵Linseed oil only, multiple applications.⁶Mean annual number of days with temperatures 32°F or below.

Note See Table 9 for description of systems

Given in Appendix C, Part III, are details of the method of preparation of the laboratory performance test specimens; the order in which the cycle of tests was performed on each set of specimens; and a description of each method of test. The results of the laboratory performance tests on 79 systems are given in Table 6.

On the basis of the results of the screening tests, a number of systems were eliminated from consideration for selection as the "most promising." Systems that survived the screening process were subjected to additional laboratory tests for further evaluations and comparisons. These additional tests (as described in App C) included:

- 1 Adhesion of the system to concrete by both tensile and overlap shear methods.
- 2 Age hardening by exposure of the system in air at 140 F for 30 days
3. Fatigue testing by repeated cycles of tensile elongation on the membrane materials at 0 F
4. Exposure of the membrane materials to repeated cycles of changes in moisture and temperature, each cycle consisting of: (a) water at 140 F; (b) water at 0 F; (c) water at room temperature; and (d) air at 140 F.

The results of these tests on the 21 membranes that survived the initial screening are presented in Table 7.

The relative ease with which systems may be placed on a portland cement concrete surface, and problems associated with construction (e.g., bubbling; blistering, or difficulty in application caused by high viscosity, short working life, or long curing time) are important practical aspects in the comparison of systems. Preparation of the specimens for the laboratory performance tests enabled such comparisons to be made only at laboratory scale. To further evaluate the practical aspects of placement, those nine systems which were judged as having survived the laboratory screening tests and the additional comparative testing, were observed during field application of test sections.

The field application of test sections consisted of placing a 10 × 12-ft section of each of the nine "surviving" membrane systems on the concrete deck of a bridge closed to traffic. Each system was placed essentially according to manufacturer's recommendations, with minor modifications as necessary to meet project limitations. For systems 6, 20, 21, and 135, this consisted of applying the adhesive to the deck surface and to the reverse side of the membrane sheet with a roller, and rolling the membrane into place. System 24 was placed by pouring the hot adhesive onto the deck and simultaneously rolling the membrane sheet into the hot adhesive. For system 10a, a perforated sheet (antibubbling device) was placed on the deck surface without adhesive; the hot adhesive was then poured onto the surface of this sheet, and the membrane sheet rolled into the hot adhesive. System 94 was applied with a metal squeegee after application of a primer with a roller. System 63 was placed similar to system 94, except that a rubber squeegee was used for the liquid membrane. System 67 was also placed with a rubber squeegee, but without primer. Systems 63, 67, and 94 were lightly brushed with a stiff-bristle brush shortly after application in an attempt to eradicate the bubbles that were forming. Four-in. minimum lap joints were used in

TABLE 4

RESULTS OF FIELD BOND TESTS AND LABORATORY TESTS FOR CHLORIDES IN DECK CONCRETE

Bridge Deck Survey No	System No *	Field Bond Test		Chlorides in PCC, lbs/yd ³ PCC
		Test No	Force**at Break, psi	
104	99	a	>32	2 30
		b	19	
105	3	a	11	2 01
106	14	a	24	1.44
		b	27	
107	14	a	25	1 73
		b	>32	
108	3	a	13	1.66
109	99	--	--	3 44
110	3	a	27	1.50
		b	25	
112	12	a	2	--
		b	3	
113	36	--	--	0 43
114	99	a	3	0 43
		b	29	
115	51	a	25	--
		b	21	
117	51	a	>32	--
		b	>13	
119	34	a	14	--
		b	14	
132	34	a	25	--
133	74	a	8	--
		b	11	
134	34	a	22	
135	51	a	>11	--
		b	24	
137	36	a	8	--
138	39	a	>32	--
		b	>32	
139	34	a	25	--
		b	8	
142	50	--	--	0 86
143	51	a	>32	18 91
144	25	a	>32	0 50
145	26	a	>32	0 22
		b	24	
146	26	a	>32	0 14
		b	>32	
148	110	a	21	--
		b	>32	

*See Table 9 for description of systems

**2 inch diameter core used in test

placing all preformed membrane systems.

After placing and curing, the initial permeability of each system was evaluated visually and by the electrical resistance test. Five of the prefabricated sheet membranes (systems 10a, 20, 21, 24, and 135) were judged to be essentially impermeable as placed and were selected as the most promising.

Some penetration of water was indicated for system 6 (4650×10^4 ohms/ft²). One or two ¼-in.-diameter bubbles per square foot remained in system 63, and the measured resistance, if bubbles were included in the area tested, was 1395×10^4 ohms/ft², indicating some penetration of water through the membrane at these points. Many small bubbles remained in systems 67 and 94, and some penetration of water was also indicated by a measured resistance of 22.7×10^4 ohms/ft² for system 67 and 2320×10^4 ohms/ft² for system 94. After these initial permeability measurements, a protective course * was placed on systems 6, 20, 21, 24, 63, 67, and 135. From laboratory test data, systems 10a and 94 had been judged to require no such protection. Two inches of dense-graded hot asphaltic concrete was then placed as a wearing course over all nine test sections.

Low and erratic readings were obtained when resistance

* APOC Board, 4 × 8-ft panels, ½ in. thick, manufactured by Asphalt Products Oil Corp., Long Beach, Calif., and bonded with 0.05 gal per sq yd application of SS-1h asphalt emulsion

TABLE 5

RESULTS OF LABORATORY CHARACTERIZATION TESTS ON MEMBRANE MATERIALS

System Number	TENSILE PROPERTIES						HARDNESS SHORE		WATER ABSORPTION, % wt. gain (34 weeks)	DEFLECTION TEMP., °F	POT LIFE, Minutes	THIN FILM SET TIME, Minutes	IMPACT RESILIENCE	Stain Number
	Ultimate Strength, psi			Elongation at Break, %			after 1 and 15 sec.							
	@ 140°F	@ 77°F	@ 0°F	@ 140°F	@ 77°F	@ 0°F	A	D						
1	1070	1390	1970	60	60	45	88, 83	39, 31	21.5	-8	NA	NA	23	0
2	1970	3090	3660	0	5	10	91, 89	--	33.1	28	NA	NA	29	4
3	56	61	510	150	130	310	26, 11	--	1.60	-57	NA	NA	18	21
5	760	1930	2680	>260	520	>430	72, 68	--	4.37	-52	NA	NA	36	0
6	1680	2920	5350	410	310	80	96, 92	49, 40	0.96	4	NA	NA	22	0
7	610	1560	2570	320	520	250	87, 84	--	12.79	-23	NA	NA	39	1
9	440	320	1470	>590	580	25	46, 38	--	2.36	-44	NA	NA	11	9
10	760	1080	5270	250	150	40	89, 83	--	8.91	-9	NA	NA	16	30
10a	(Same materials as used for system No. 10, greater thickness.)													
11	880	1300	2980	60	58	30	88, 84	--	10.90	-14	NA	NA	12	7
12	750	940	1980	170	53	30	57, 51	--	3.99	-23	NA	NA	5	29
13	500	540	860	>400	570	250	68, 64	--	3.4	-48	NA	NA	19	7
15	1610	1680	3010	270	220	12	93, 91	46, 39	1.18	1	NA	NA	27	0
16	830	1020	2160	70	360	219	89, 87	--	17.1	-13	NA	NA	34	0
17	940	1080	2430	370	670	4	98, 97	47, 45	0.12	-16	NA	NA	35	30
19	1460	2080	3170	>270	390	350	66, 64	--	15.01	-38	NA	NA	21	7
20	1580	2140	3170	>250	290	300	60, 58	--	3.35	-51	NA	NA	41	0
21	1320	1460	2230	290	340	360	62, 60	--	1.43	<-70	NA	NA	10	0
22	1580 ¹	2970 ¹	5610 ¹	150 ¹	30 ¹	0 ¹	97, 94	48, 39	11.9	28	NA	NA	31	1 ⁸
23	1240 ¹	2640 ¹	4800 ¹	300 ¹	80 ¹	30 ¹	95, 92	47, 38	9.54	7	NA	NA	28	1 ⁸
24	730 ³	1140 ³	1990 ³	340	1280	440	91, 89	36, 29	20.91 ¹	35 ⁸	NA	NA	10	7 ⁸
25	"	1390	2050	"	--	0	70, 49	--	20.2	22	NA	NA	20	6 ¹⁰
26	"	690 ⁸	2010 ⁸	"	6 ⁸	25 ⁸	70, 55	--	11.6 ⁷	8	NA	NA	15	2
27	>560	1210	1450	>460	550	150	78, 63	--	19.2 ⁷	-34	indef.	--	8	1
28	(Severe bubbling, unable to make suitable specimens)						94, 83	40, 24	38.7 ⁷	--	indef.	--	28	1
34	290	3030 ⁸	7610 ⁸	0	--	0	83, 74	--	6.37	33	NA	NA	8	30
40 ¹	"	78	--	--	--	--	83, 65	--	>0.45	10	NA	NA	6	7 ¹⁰
50	(Insufficient material to make specimens)													
51	"	"	"	"	"	"	71, 22	--	1.02 ⁷	3	NA	NA	7	6 ¹⁰
52a	"	970 ⁸	1940 ⁸	"	40	45	81, 71	--	4.02 ⁷	-19	NA	NA	15	7 ¹⁰
52b	"	1110 ⁸	1900 ⁸	"	75	45	49, 40	--	2.02 ⁷	-12	NA	NA	5	6 ¹⁰
52c	"	750 ⁸	1960 ⁸	"	70	40	31, 25	--	18.2 ⁷	-17	NA	NA	7	8 ¹⁰
52d	"	1020 ⁸	1860 ⁸	"	50	25	70, 49	--	2.00	-8	NA	NA	12	8 ¹⁰
58	--	--	--	--	--	--	--	--	--	--	--	--	--	--
61	(Foamed to sponge-like consistency, unable to test)													
63	600	1240	3210	320	410	320	77, 70	80, 74	1.49 ⁷	-39	>50	--	21	0
67	250	350	710	125	150	250	55, 53	--	1.90	<-70	300	--	48	30
68	(Clear liquid, did not set up, unable to test)													
72a	120	990	9210	15	55	0	95, 93	48, 38	2.16	42	35	indef.	9	2
72b	(Same materials as used for system No. 72a)													
73	74	440	1400	--	--	--	--	--	3.11 ⁷	54	--	indef.	--	--
77	320	410	560	160	140	150	75, 64	--	-0.12	<-70	indef.	--	6	4
78	380 ⁸	1940	3870 ⁸	21 ⁸	80	20 ⁸	30, 23	--	9.97	-27	45	>120	10	25
79	(Same materials as used for system No. 99)													
80	82	97	520	110	>210	>360	26, 15	--	10.1	-43	83	15	19	30
88	430	6040	10,600 ⁸	33	2	0	--	78, 76	1.69	105	26	--	40	0
93	60	80	>260	190	290	>380	20, 17	--	1.15 ⁷	<-70	210	--	42	30
94	280	640	1240	400	410	220	68, 57	--	0.92	<-70	90	240	42	8
98	135	1240	3540	40	30	0	97, 97	55, 49	1.25	32	54	330	8	3
99	130	580	5900	12	30	0	96, 93	51, 29	0.99	39	37	330	0	16
100	(Clear liquid, did not set up, unable to test)													
102	180	260	350	280	>710	>380	21, 20	--	4.71	-60	210	3 days	28	30
103	190	180	290	>425	>770	>400	7, 5	--	5.49	-44	>480	--	11	30
104	210	2930	6600	40	13	0	100, 99	88, 61	2.24	89	6	120	20	5
105	71	670	4500	10	40	7	95, 83	46, 27	1.40	16	14	--	27	5
106	1240	7510	3010	25	0	0	99, 99	90, 88	2.01	127	30	45	9	3
107	80	600	2170	27	80	4	96, 81	52, 24	3.14	34	29	120	8	30
110	52	210	2980	46	>230	132	38, 20	--	0.78	-8	NA	NA	7	--
112	100	1640	5380	27	100	0	99, 97	65, 47	2.79	50	15	180	13	27
115	240	1250	1660	--	--	--	--	--	1.95 ⁷	100	--	--	--	--
117	160	840	1550	--	--	--	--	--	0.91 ⁷	96	--	--	--	--
119	440	920	1020	--	--	--	--	--	5.73 ⁷	--	--	--	--	10
121	--	--	--	--	--	--	--	--	--	--	--	--	--	--
127	(Unable to prepare laboratory specimens for testing)													
128	220	360	980	>375	>600	310	51, 40	--	4.01	<-70	60	180	21	6
129	90	440	2240	20	100	2	81, 71	--	-4.04 ⁷	12	>360	>360	19	0
130	>536	>710	>1160	>500	>850	>410	59, 53	--	147.0	-39	4 days	9	41	1
131	(Foamed to frothy consistency, unable to test)													
132	230	370	980	50	120	240	66, 64	--	10.4	<-70	4	11	40	0
133	220 ⁸	650 ⁸	920 ⁸	5 ⁸	8 ⁸	3 ⁸	60, 33	--	2.42	-22	NA	NA	15	4
134	460 ⁸	470 ⁸	740 ⁸	0 ⁸	4 ⁸	8 ⁸	51, 31	--	1.39	-5	NA	NA	11	4
135	1130	1470	2330	>300	400	340	61, 58	--	1.40	<-70	NA	NA	9	0
136	165	2770	9570	38	60	0	99, 99	70, 65	2.71	78	68	>420	12	2
137	80	1400	10,320	20	80	4	98, 93	62, 41	2.58	43	33	360	18	0
138	100	970	7200	20	70	0	99, 93	64, 42	2.39	52	20	180	6	1
139	130	650	2560	7	62	18	86, 79	--	2.55	-8	>180	960	7	30
141	200	300	1110	140	210	120	53, 44	--	12.3 ⁷	-23	210	--	8	30
142	(Same materials as used for system No. 10)													

¹Vinyl reinforcement failed²Vinyl side was 0³Too soft for testing⁴Includes felt⁵Value for 26 or 29 weeks⁶Elongation not measured on briquette specimens -- Tests not performed⁷Felt reinforcement failed⁸Value for foil reinforcement⁹Test not applicable to non-setting materials¹⁰Value for fiber reinforcement¹¹Value for adhesive-saturated felt

Note: See Table 9 for description of systems

¹²Values for binder, except tensile strength ¹³Stain spreads

TABLE 6
RESULTS OF LABORATORY PERFORMANCE TESTS

Membrane System Number	Side 1 - Resistance			Side 2 - Resistance			Crack Bridging, Room Temp.	Side 1 Resistance		Side 2 Resistance		Crack Bridging, 0°r	Side 1 - Resistance			Side 2 - Resistance			
	Init	After Impact	After Heat	Init	After Heat	After Impact		Init.	After Heat	Init.	After Heat		Init	After Impact	After Heat	Init	After Heat	After (recp) Mod	Severe
1	"	1 39	0 10	"	"	0 22	Pass	"	112	"	175	Pass	"	0 34	0 24	"	7 31	"	66 8
2	"	0 60	-0-	"	"	0 05	0 06	"	3 06	"	3 31	--	"	0 12	0 005	"	5,000	---	---
3	5,000	26 1	97 3	5,000	164	9 81	Pass	825	100	1,000	250	Pass	975	0 20	0 13	687	17 6	1.85	5 94
5	"	53 6	51.7	"	"	0 55	Pass	"	"	"	"	Pass	"	18 6	13 2	"	2,500	4,375	4 31
6	"	1 25	1.89	"	"	0 51	Pass	"	"	"	"	Pass	"	0 62	1.20	"	"	"	"
7	"	0 11	0 12	"	"	0 02	Pass	"	"	"	"	Pass	"	0 50	0 28	"	9 81	13 6	3 08
9	"	0 02	0 35	"	"	1.17	Pass	"	"	"	"	Pass	"	-0-	4.69	"	"	3,750	3 94
10	"	"	"	"	"	925	Pass	"	"	"	"	Pass	"	875	2,000	"	"	"	200
10a	"	"	"	"	"	2500	Pass	"	"	"	"	Pass	"	870	2,500	"	"	"	---
11	"	"	"	"	"	"	Pass	"	"	"	"	Pass	"	"	"	"	No Reading	"	0 56
12	"	0 21	0 44	"	"	0 63	Pass	"	"	"	"	-0-	"	0 89	2 79	"	1,750	"	295
13	"	0 30	0 42	"	"	0 20	Pass	"	"	"	"	Pass	"	0 15	0 38	"	"	"	3 44
15	"	0 46	14.4	"	"	1.17	Pass	"	"	"	"	Pass	"	0 17	0 48	"	"	"	"
16	"	0 06	0 95	"	"	0 14	Pass	"	"	"	"	Pass	"	0 37	475	"	"	6 31	18 8
17	"	0 17	0 11	"	"	0 61	Pass	"	27.3	"	36.1	0.055	"	1 39	"	"	"	"	2 17
19	"	2.71	6.12	"	"	74.8	Pass	"	112	"	175	Pass	"	7 51	7 69	"	"	"	"
20	"	3.69	29.8	"	"	50 4	Pass	"	"	"	"	Pass	5,000	437	30 4	1,250	1,875	2,500	3,750
21	11 2	5 06	11.4	11 3	10 8	0 90	Pass	19 9	150	18 2	212	Pass	8 44	1 20	0 41	8 81	0 44	1.00	55 6
22	"	0 34	0 22	"	"	0 47	Pass	"	"	"	"	0 060	"	0 42	0 16	"	20 9	"	8 4
23	"	0 67	0 62	"	"	3 06	Pass	"	"	"	"	0 24	"	1 81	0 31	"	"	"	400
24	"	10.7	52 5	"	"	1.42	Pass	"	"	"	"	Pass	"	2 87	3 84	"	11 2	"	3 56
25	0 03	-0-	-0-	0 01	-0-	0 03	Pass	0 09	-0-	0 05	-0-	--	0 07	0 05	0 10	0 09	0 08	---	---
26	"	"	"	"	"	9 31	Pass	"	"	"	"	0 11	"	0 52	1,000	"	"	6 93	2 0
27	"	0 02	0 06	1,375	137	0 09	Pass	5 81	3 31	2,000	3 81	0 032	11 1	0 32	0 33	244	191	41 1	1 72
28	0 15	---	---	0 74	---	---	--	1 04	---	0 41	---	--	6 44	---	---	2 31	---	---	---
34	-0-	-0-	-0-	-0-	0 08	-0-	0 115	-0-	-0-	-0-	-0-	0 015	-0-	0 26	0 06	0 08	0 05	0 01	-0-
40	"	"	"	"	"	"	Pass	"	"	"	"	-0-	"	"	"	"	"	"	5 31
50	"	4 19	10 1	"	"	"	0 057	---	---	---	---	--	---	---	---	---	---	---	---
51	"	0 27	2 22	"	"	0 32	Pass	"	"	"	"	-0-	"	0 02	0 29	"	"	37 4	1.16
52a	16 4	0 16	0 25	3 19	"	0 01	Pass	"	200	"	375	--	3 19	0 12	0 29	"	"	---	---
52b	0 67	0 66	"	0 27	"	0 13	Pass	3 19	"	72 3	"	--	0 30	0 06	26 6	5 12	"	---	---
52c	3 04	0 17	0 70	2 01	1.96	0 02	Pass	4.20	2 44	1 75	2 06	--	32 8	0 01	16 3	37 7	"	---	---
52d	0 21	0 25	0 90	500	4 92	0 30	Pass	"	2,500	"	750	--	1 15	0 11	"	1 49	"	---	---
58	"	---	---	---	---	---	Pass	"	---	---	---	-0-	---	---	---	---	---	---	---
61	1,125	1 45	8 06	2,125	650	325	Pass	1,000	375	1,067	412	Pass	1,375	1.22	9 81	1,100	362	300	500
63	"	1 17	0 71	"	"	0 99	0 19	"	102	"	3,750	Pass	"	0 87	1 82	"	5,000	"	88 6
67	"	8 80	3 56	"	"	0 73	0 092	"	1,000	"	7,500	0 160	"	4 56	5 94	"	3,750	121	175
68	-0-	---	---	-0-	---	---	--	0 10	---	0 01	---	--	"	---	---	"	---	---	---
72a	1 35	0 24	0 45	0 79	4 06	0 12	0 072	1 42	1 14	0 97	3 44	--	0 54	0 06	0 07	0 36	1 61	---	---
72b	6 19	---	---	5 06	---	---	--	9 31	9 81	7 81	11 1	--	1 51	---	---	4 31	---	---	---
73	0 99	0 95	1 89	0 81	11.6	1.36	0 020	1 57	0 61	2 26	0 30	--	3 79	1 84	0 47	0 84	0 94	---	---
77	0 49	0 22	0 12	0 34	0 74	0 23	0 054	0 32	0 50	0 50	8 31	--	0 28	0 26	0 19	0 23	0 93	---	---
78	44 9	0 08	0 15	47 9	43 6	0 13	Pass	17 7	5 06	14 0	5 25	Pass	41 7	0 16	0 12	23 4	3 75	6 4	18 6
79	"	0 13	0 15	"	"	0 36	0 150	"	"	"	"	0 09	"	0 07	0 12	"	5,000	"	0 09

TABLE 6 (Continued)

Membrane System Number	Side 1 - Resistance			Side 2 - Resistance			Crack Bridging, Room Temp	Side 1 Resistance		Side 2 Resistance		Crack Bridging, °F	Side 1 - Resistance			Side 2 - Resistance			
	Init	After Impact	After Heat	Init.	After Heat	After Impact		Init.	After Heat	Init	After Heat		Init.	After Impact	After Heat	Init	After Heat	After Mod.	After Creep Severe
80	"	0.94	"	"	"	0.39	Pass	287	150	300	181	Pass	"	52.3	101	"	"	5,000	5.06
88	"	"	6.31	"	"	31.7	0.240	"	"	"	"	0.018	"	3.00	7.56	"	"	443	1.05
93	"	"	"	"	"	1,875	Pass	"	"	"	"	Pass	"	57.3	"	"	"	"	3.7
94	"	"	"	"	"	"	Pass	"	"	"	"	Pass	"	"	"	"	"	"	17.6
98	"	3.59	2.37	"	"	0.29	0.017	"	"	"	"	--	"	0.32	0.41	"	"	---	---
99	20.9	0.17	0.17	24.7	"	0.13	0.051	28.7	206	41.1	129	0.007	40.4	0.55	0.13	1,000	112	4,375	0.16
100	0.01	---	---	0.02	---	---	---	-0-	---	-0-	---	--	0.01	---	---	0.005	---	---	---
102	"	"	5,000	"	"	"	Pass	204	162	150	114	Pass	"	812	"	"	"	"	3.2
103	"	"	"	"	"	"	Pass	---	---	---	---	Pass	"	2,500	"	"	"	"	---
104	"	"	4.94	"	"	0.55	0.120	"	"	"	"	0.010	"	512	2,500	"	5,000	"	0.31
105	"	8.56	1.77	"	"	0.86	0.016	"	"	"	"	--	"	51.1	5.31	"	3,750	---	---
106	5,750	0.37	0.16	2,250	"	0.25	0.00	3,125	2,500	1,500	2,500	--	26.7	0.63	0.40	40.	"	---	---
107	400	---	6.06	5,000	"	0.38	Pass	250	350	3,750	812	0.002	"	0.48	350	"	"	"	0.39
110	"	0.04	0.10	"	22.6	0.14	Pass	"	"	"	"	0.020	"	0.19	0.20	"	0.18	0.37	11.56
112	18.2	2.06	6.06	10.8	32.3	0.69	Pass	53.6	13.6	46.1	3.94	0.001	34.2	0.40	0.53	39.8	725	0.61	0.79
115	"	5,000	"	"	"	"	0.014	5,000	1,250	71.1	43.6	--	1,125	2.87	"	26.8	"	---	---
117	"	"	"	"	"	"	0.022	"	"	"	"	--	"	"	"	"	"	---	---
119	0.05	---	---	0.03	---	---	--	0.07	---	0.01	---	--	0.08	---	---	0.02	---	---	---
121	"	---	---	---	---	---	0.080	---	---	---	---	--	---	---	---	---	---	---	---
127	0.04	---	---	0.04	---	---	--	0.05	---	0.05	---	--	0.05	---	---	0.02	---	---	---
128	"	1.19	4.69	"	"	0.42	0.248	"	"	"	"	0.25	"	1.00	6.19	"	"	"	10.06
129	1,125	0.64	0.44	1,250	5,000	0.41	0.067	1,000	"	1,000	"	-0-	1,250	0.13	0.19	1,625	"	---	0.74
130	0.05	---	---	0.09	---	---	--	0.21	---	0.20	---	--	0.03	---	---	0.04	---	---	---
131	157	0.17	0.28	196	52.6	0.16	0.029	121	49.8	287	162	--	137	0.11	0.21	162	97.3	---	---
132	16.9	0.09	0.09	16.1	11.8	0.20	0.038	32.4	46.1	42.3	66.1	--	69.3	0.21	0.49	"	16.7	---	---
133	"	0.35	0.20	"	"	0.21	0.203	"	"	"	"	0.150	"	0.11	0.15	"	"	52.3	1.2
134	"	1.64	1.02	"	"	0.24	Pass	"	"	"	"	0.030	"	0.07	0.07	"	"	"	3.7
135	26.2	5.56	6.94	20.7	7.31	0.56	Pass	151	27.9	119	22.3	Pass	15.2	2.69	3.51	14.3	3.10	1.85	2.9
136	156	0.10	0.26	55.4	156	0.13	0.210	26.2	3.44	41.8	99.8	0.030	56.1	0.31	0.39	86.1	17.6	0.80	0.19
137	275	0.76	0.68	"	2.01	0.71	0.205	"	"	"	"	0.02	"	0.28	0.35	"	"	"	0.21
138	"	1.02	4.44	"	30.1	1.91	0.016	"	"	"	"	--	"	7.56	17.6	"	"	---	---
139	1,062	0.15	0.37	912	41.7	0.11	0.02	587	875	475	---	--	675	0.21	0.19	775	750	---	---
141	225	0.09	0.13	217	181	0.05	0.043	287	375	287	375	0.001	134	2.87	0.74	151	362	338	2.25
142	"	"	"	"	"	"	Pass	"	"	"	"	Pass	"	"	"	"	"	---	2,500

- NOTE 1. All resistance measurements are in ohms-ft², and should be multiplied by 10,000
2. Crack bridging test results are given as the width of the crack in the block, in inches, at time of failure of the membrane. "Pass" indicates no failure of the membrane to the limits of the test (0.25").
3. No entry in any column means that the test was not run
4. See Table 9 for description of systems.

TABLE 7
RESULTS OF LABORATORY TESTS ON 21 SYSTEMS SELECTED FOR FURTHER COMPARATIVE TESTING

System Number	ADHESIVE STRENGTH		FATIGUE		AFTER 140°F AIR EXPOSURE								FATIGUE		AFTER MOISTURE-TEMPERATURE CYCLING								Change in length, %
	in tension, ¹ psi	in shear, ¹ psi	cycles at 0°F to failure	Permanent elongation %	Hardness Shore, 15 sec.		Tensile Strength		Tensile Elongation		Change in length, %	Change in weight, %	Cycles at 0°F to failure	Permanent elongation %	Hardness Shore, 15 sec.		Tensile Strength		Tensile Elongation				
					Value	Change, points	psi	Change, %	%	Change, %					Value	Change, points	psi	Change, %	%	Change, %			
3	26 (ac)	4 (a)	10	7	10A	-1	33	-46	210	+62	+2.2	-1.4	---	---	9A	-2	35	-43	260	+100	+7		
5	75 (m)	100 (a)	10	5	62A	-6	2240	+23	380	-27	-3.4	-4.8	---	---	62A	-6	2100	+8	410	-21	-2		
6	12 (a)	24 (a)	10	6	40D	0	2760	-28	310	0	-0.8	+0.1	10	3	37D	-3	2590	-11	290	-6	-1		
7	57 (a)	35 (a)	10	4	81A	-3	1290	-17	650	+25	-7.5	+0.2	---	---	88A	+4	2160	+38	410	-21	-5		
9	45 (a)	15 (a)	10	8	47A	+9	780	+144	400	-31	-1.7	0	---	---	46A	+8	1080	+238	325	-44	-2		
10	64 (a)	30 (ac)	4	7	86A	+3	1570	+46	140	-8	+0.1	-2.1	---	---	84A	+1	1290	+19	150	0	0		
10a	48 (ac)	14 (a)	10	8	79A	-2	1520	+17	150	-6	+0.1	-2.0	10	5	78A	-3	1330	+2	160	0	0		
11	63 (ac)	48 (a)	2	5	86A	+2	1520	+17	50	-16	-0.6	-1.0	---	---	87A	+3	1410	+8	50	-16	-1		
15	53 (am)	28 (a)	9	2	39D	0	1700	+1	360	+64	+0.6	-0.1	---	---	37D	-2	1610	-4	350	+59	0		
19	105 (ac)	138 (a)	10	1	64A	0	2030	-2	400	+3	+0.1	-0.3	---	---	65A	+1	1910	-8	390	0	0		
20	80 (ac)	133 (ac)	10	3	64A	+6	2060	-4	290	0	-1.3	-3.0	---	---	65A	+7	1820	-15	320	+10	-1		
21	57 (am)	61 (am)	10	3	57A	-3	1400	-4	310	-9	+0.2	-0.4	---	---	58A	-2	1420	-3	350	+3	0		
23	47 (ac)	27 (m)	6	3	38D	0	2660	+0.8	120	+50	-0.3	-1.0	---	---	36D ³	-2	2630 ³	-0.4	90 ³	+12	-2		
24	49 (am)	24 (am)	10	-3 ⁴	25D	+4	620	+9	520	-46 ⁴	-2.2	-0.3	---	---	23D	+2	530	-7	510	-47 ⁴	-3 ⁴		
63	203 (j)	368 (m)	10	0	74A	+4	980	-16	300	-23	0	-1.8	10	2	69A	-1	1180	+0.8	420	-8	0		
67	91 (ac)	130 (ac)	10	2	57A	+3	410	+10	160	0	-1.0	-3.8	10	1	58A	+4	430	+13	180	+13	0		
94	211 (ac)	205 (ac)	10	3	62A	+4	590	+25	320	+7	-1.2	-2.7	10	1	62A	+4	570	+21	310	+3	-1		
102	97 (ac)	92 (ac)	10	3	19A	-3	150	0	660	-3	-0.7	-3.7	---	---	17A	-5	140	-7	740	+9	0		
128	66 (ac)	40 (m)	10	3	32A	+16	240	+56	460	-22	+3.0	-8.1	---	---	21A	+5	140	-7	540	-8	+3		
135	42 (a)	22 (m)	1	4	53A	+20	550	-15	6.5	-19	-0.3	+0.2	---	---	53A	+20	730	+12	3.5	-56	+1		
135	60 (am)	65 (am)	10	0	54A	-4	1510	+3	390	-2	0	-0.4	---	---	53A	-5	1410	-4	440	+1.6	0		

¹Mode of failure indicated in parenthesis, as follows

- (m) - in membrane
- (a) - in adhesive
- (am) - between adhesive and membrane
- (ac) - between adhesive and concrete
- (j) - in jig

Note: See Table 9 for description of systems

²Change from original value (see Table 5)

³Blistered

⁴Anomalous values resulting from felt backing

measurements on the asphaltic concrete wearing course were attempted. Saturation of the rather porous asphaltic concrete by recent rains, in combination with discontinuous test areas, resulted in the current bypassing the membrane. Consequently, each membrane system was cored and re-

sistance measurements were made in the laboratory on the 4-in.-diameter core samples. These measurements were somewhat more conclusive and were used with the laboratory screening test data to make a final selection. These data are given in Table 8.

TABLE 8
RESULTS OF ELECTRICAL RESISTANCE TESTS ON
MEMBRANE SYSTEMS PLACED IN FIELD TEST SECTIONS

MEMBRANE SYSTEM	ELECTRICAL RESISTANCE ($\times 10^4$ OHMS/FT ²)				
	IN THE FIELD		ON CORES		ON MEMBRANE PLACED IN LAB. ON PCC BLOCKS ^a
	ON MEMBRANE SURFACE	ON AC WEARING COURSE	AIR DRIED	OVEN DRIED	
6	4650	3.1	27.7	0.1	∞
20	∞	4.8	166.7	21.1	∞
21 ^b		6.9	166.7		11.2
135 ^b		5.0	83.3	17.4	26.2
10a	∞	4.5	∞	∞	∞
24	∞	46.5	2.3	1.0	∞
94	2320	1.0			∞
67	22.7	3.1	2.9		∞
63	∞ to 1395 ^c	2.1	0.1		∞

^a From laboratory performance test results (Table 6)

^b Membrane material is electrically conductive

^c Areas without and with bubbles

Note See Table 9 for description of systems

CHAPTER THREE

INTERPRETATION OF FINDINGS

GENERAL APPROACH

One of the specific objectives of Phase I of this study was to select those waterproof membrane systems considered to be most promising and to devise, for Phase II, an experimental program for evaluating their performance under service conditions. The general approach to selection of the most promising systems consisted of the following:

1. Preparation of a comprehensive list of all systems that have been used or proposed for use, and classification of these systems.

2. A preliminary objective screening to eliminate proposed systems for such reasons as: they are not waterproof membranes (concrete surface hardeners, etc.); they are surface-penetrating sealers, such as linseed oil, which are outside the scope of this study, they are essentially identical to others; and other reasons discussed in detail later.

3. Further screenings of the remaining systems, based on

the results of the laboratory characterization and performance tests, and of laboratory durability tests. The field survey results assisted in this step by indicating levels of performance that have been experienced in the field, and in selection of laboratory performance tests to be included.

4. A final screening based on further laboratory testing, field installations, judgments regarding relative difficulty of installation in the field, and availability.

Figure 4 shows the steps involved in evaluating the membrane systems and indicates the number of systems surviving at each step of the evaluation process.

Materials and construction specifications were prepared for the five remaining membrane systems that survived the final field trials of the evaluation process. These systems are considered the most effective and were designated as most promising. The materials specifications are based primarily on the results of laboratory characterization and performance tests, and also on information extracted from the

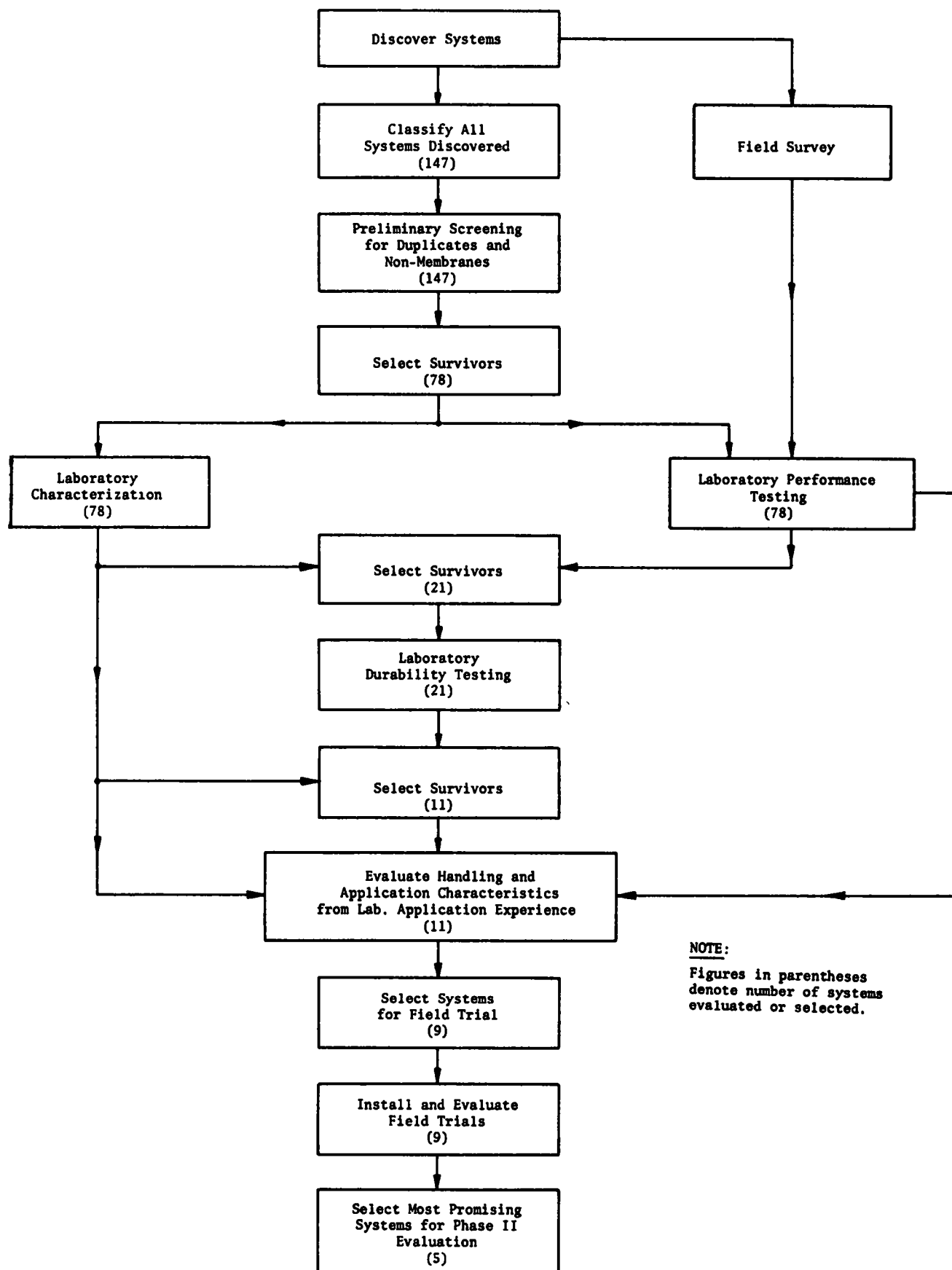


Figure 4. Flow chart of membrane system evaluation procedure.

manufacturers' product data sheets. Construction specifications are based on manufacturers' recommendations, modified or supplemented by project findings.

The experimental program recommended for Phase II implementation was developed from the following basic assumptions:

1. Field performance is to be evaluated on the basis of full-scale installations of the systems on bridge decks under construction in areas where deicing chemicals are used and which are subjected to normal highway traffic under various climatic conditions.

2. The membrane systems are to be financed by the participating highway agency, and installed either by their own forces or by construction contract, at the highway agency's option.

3. The Phase II research agency is to assist the participating highway agency in preparing plans and specifications for the installations and in monitoring the construction; and will conduct both initial and follow-up sampling and testing of the completed installations.

4. The Phase II research agency is to analyze the data obtained from all installations and prepare a final report, including recommendations regarding possible further evaluation of the installations following completion of Phase II.

5. The experimental program should be designed to be of minimum scope. Additional increments may be included should additional funds become available (For example, decks already exposed to salt might be added, in addition to new decks.)

6. The experimental program should provide for progress reports following each complete round of tests.

FIELD SURVEY RESULTS

Electrical Resistance (Permeability) Testing

Although Figure 3 indicates that certain systems fall in the "good" category, these data must be viewed in conjunction with other factors. Following is a brief discussion of systems placed in the "good" and upper range of the "fair" category.

System 58, although providing excellent resistance generally, exhibited cracks. Electrical resistance over these cracks was in the "very poor" category. These readings were not included in the average listed.

Systems 68, 106, and the linseed oil seal with asphaltic concrete (AC) overlay had been placed in a relatively mild climate and apparently had not, at the time of survey, experienced significant freeze-thaw cycling. Laboratory test results indicate that, from the nature of these three systems, they would not be expected to provide significant bridging of cracks in the underlying PCC deck.

Systems 3 and 14 are preformed materials and generally have provided improved water impermeability relative to most applied-in-place systems. System 14 is thick, thus resisting damage, but it is no longer produced, primarily because of high costs of transportation and difficulty in handling the heavy sheets. System 25 had extremely low initial resistance in laboratory performance tests. System 3 showed promise, but was eliminated late in the screening

process. System 112 is a thermoset epoxy resin that has exhibited variable performance in California. This particular installation had a greater-than-normal membrane thickness as judged by the cores removed. System 34 is in general use and, although fiber-reinforced, it is based on a binder that exhibits extreme brittleness at low temperatures, and performance is highly variable.

System 26 deserves special mention because the decks using this system are the two oldest decks surveyed. These two decks have provided 17 and 12 years of satisfactory service. This would not have been predicted by the results of the field electrical resistance tests, where both were rated as fair (Fig 3), or by the results of laboratory testing of the materials that indicated high water absorption, marginal crack bridging ability at 0 F, and potential for damage under traffic if a protective cover is not provided. It is possible that one or more of the following circumstances may have contributed to this service record:

1. Exceptionally good workmanship in placement of the membrane

2. Light applications of deicing salts during the initial few seasons while the concrete was gaining appreciable additional strength.

3. Unusually high quality of deck concrete.

4. Greater than normal depth of cover over the reinforcing steel.

5. Uniformly high density and impermeability of the asphaltic concrete surfacing

Bond Testing

A number of systems exhibited sufficiently low strength in field installations that cores became detached during drilling. Bond tests could not be made in these situations; therefore, the results do not appear in Table 4. A wide range of values (2.2 psi to >32 psi) was obtained, however, no clear relationship of bond test results with membrane performance was observed. No evidence was found of membrane failure as a result of lack of bond.

Intact cores were removed from the remaining bridge decks for possible future bond testing in the laboratory, inasmuch as laboratory testing would provide more accurate results owing to the controlled nature of the test conditions. Because a relationship between bond and field performance did not emerge, and the majority of field membranes did not exhibit low permeability, bond testing was not performed in the laboratory.

Chlorides Determination

A determination of the chlorides content of the deck concrete was made on one sample from each of 14 bridge decks surveyed to which deicing salts had not been applied before placement of the waterproofing membrane. The amount of salt deposited in the position of deck concrete obtained by a core sample depends on many variables, including the quantities of salt applied to the deck, the permeability of the membrane in the area of the core, the density of the concrete sample, the presence or absence of cracks in the concrete sample, and the time during which

the concrete sample has been exposed to salt. Thus, the distribution of chlorides in a bridge is highly variable, and a considerable number of samples would be required to arrive at a reliable estimate of the chlorides content representative of the deck as a whole

The chlorides contents reported in Table 4 were determined from only a single sample from each deck, and the results do not necessarily represent the average level of chlorides present in these decks. However, the results do serve the intended purpose of determining whether or not chlorides were present. The fact that chlorides were found in all the samples indicates that none of these membranes were completely effective in preventing the penetration of deicing salts.

THE SCREENING PROCESS

Pre-laboratory Screening

Table 9 gives all the membrane systems that have been used or proposed for use. Included for each membrane system is an identification number assigned to it for convenient reference in this project, its classification according to the method given in Appendix B, and a brief description. Those systems that were eliminated in the preliminary objective screening process are marked with a single asterisk at the project identification number, and the reason for elimination is given in parentheses following the description. Of the original 147 systems, 69 were eliminated in this preliminary screening

Initial Laboratory Screening

The 78 systems that survived this preliminary screening were subjected to the laboratory characterization and performance tests. The results of the characterization tests are given in Table 5, and the results of the performance tests are given in Table 6. The results of three of the laboratory performance tests (electrical resistance, crack bridging, and water absorption) were the primary means of comparing systems and eliminating those considered less promising. Because minimum requirements for performance in terms of test results have not been standardized, such limits were developed during the initial laboratory screening. These limits were selected on the basis of tentative limits established by other tests, and by comparing the results accumulated from tests on systems evaluated in this project. The latter procedure is considered valid because the project objective is to select the most promising system rather than to separate each system on the basis of being satisfactory or unsatisfactory. The limiting values established as a basis for selection of systems at this stage are given in Table 10. Fifty-seven systems were eliminated from further consideration; the reasons for elimination of each are given in Table 9. The 21 systems that survived the screening process are given in Table 11.

Final Laboratory Screening

The results of the impact and creep damage tests showed considerable increase in permeability (decrease in electrical resistance) for essentially all the systems in one or both

tests. These results, together with evidence from the field investigation, led to the conclusion that unacceptable damage to these membranes would be expected to result from equipment operations during placement of the asphaltic concrete wearing surface, from traffic operations on the wearing surface after placement, or from both. Because few systems would remain if this group were eliminated from further consideration, it was assumed in subsequent evaluations that, before placing the asphaltic concrete wearing course, a suitable protective layer would be provided over all membranes expected to be damaged

To make the final selection of the most promising systems, the 21 surviving systems were subjected to additional laboratory tests to evaluate adhesion, hot-air exposure, fatigue, and moisture-temperature exposure. The test methods are given in Appendix C, and the test results are given in Table 7.

The results of these additional tests, plus all previous test results and other information accumulated, were used as the basis for a comprehensive review and comparison of these 21 systems. An additional 12 systems were eliminated from further consideration for the reasons given in Table 12. The remaining nine systems were retained for further evaluation by a field application test

Field Application Test and Final Screening

In the field application test, a 10 × 12-ft section of each of the nine systems was placed on a concrete bridge deck. The purpose of this test was to evaluate placement of these membranes under actual field conditions, and to compare the membrane sections placed in the field with the specimens fabricated in the laboratory. For the three applied-in-place systems (systems 63, 67, and 94), anticipated problems associated with bubbling during curing were confirmed by this test. Bubbles remained in these systems, even after efforts were made to remove them during placement and initial curing. Visual examination and the low resistance measured on the surface (Table 8) demonstrated that the bubbles resulted in voids in the cured membrane which allowed penetration of water

No difficulties were expected in placing the other six systems, and none were encountered in the field test. Although careful workmanship and attention to detail are necessary, no unusual skills are required for placement of these prefabricated sheet membranes. Five of these systems were found to be essentially impermeable as placed in this field test (systems 10a, 20, 21, 24, and 135) and were selected as the most promising for further evaluation in Phase II.

LABORATORY PERFORMANCE AND CHARACTERIZATION TESTING

As discussed previously, performance testing is designed to simulate, in the laboratory, actual and anticipated field conditions. Characterization testing serves the following two purposes.

1. To define an individual membrane system by its fundamental physical properties in order that promising systems may be specified by potential user agencies.
2. To relate basic mechanical and thermal properties to

TABLE 9
MEMBRANE SYSTEMS USED OR PROPOSED FOR USE

System Number	Classification	Description
1**	1/11/1/1d/1	Preformed sheet of styrene-butadiene rubber (SBR) block copolymer, reinforced with polypropylene mat (resistance after heat cycle, water absorption).
2**	1/1b/1/1bcg/1	Preformed sheet of polyethylene-coated kraft paper, bonded with chopped glass fiber reinforced asphalt (crack bridging at room temperature).
3	1/1c/1/2/1	Preformed sheet of unvulcanized ethylene-propylene rubber.
4*	1/1c/1/2/1	Preformed sheet of vulcanized ethylene-propylene rubber. (Same as No. 135)
5	1/1j/1/2/1	Preformed sheet of unvulcanized, self-curing chloroprene rubber.
6	1/1g/1/2/1	Preformed sheet of polyvinyl chloride (PVC).
7	1/1k/1/2/1	Preformed sheet of unvulcanized chlorosulfonated polyethylene.
8*	1/1c/1/2/1	Preformed sheet of ethylene-propylene rubber. (Similar to No. 3)
9	1/1b/21b/1d/1	Preformed sheet of SBR block copolymer - modified asphalt, reinforced with a polypropylene fiber mat.
10**	1/1g/2ac/1f/1	Preformed sheet of coal tar-modified PVC with chopped fiber filler -- 75 mils thick. (Replaced with thicker sheet of same material, No. 10a)
10a	1/1g/2ac/1f/1	Same as No. 10 -- 125 mils thick.
11	1/1b/2/1d/1	Preformed sheet of asphalt, modified with a thermoplastic resin and reinforced with a thermoplastic fiber mat.
12**	1/1a/2/1d/1	Preformed sheet of coal tar-modified synthetic resins, reinforced with polypropylene fiber mat (crack bridging at 0°F).
13**	1/1b/2f/1c/1	Preformed sheet of asphalt-modified polyethylene, reinforced with polyethylene sheet (heat cycle).
14*	1/1b/2af/2/1	Preformed sheet of rubberized asphalt-asbestos-aggregate mixture. (Withdrawn from production)
15	1/1g/2a/2/1	Preformed sheet of PVC laminated to a sheet of asbestos fiber felt.
16**	1/1k/2g/2/1	Preformed sheet of chlorosulfonated polyethylene rubber laminated to a sheet of asbestos fiber felt (water absorption).
17**	1/1a/2/2/1	Preformed sheet of coal tar-modified thermoplastic resin (resistance after heat cycle, crack bridging at 0°F).
18*	1/2k/1/2/1	Preformed sheet of lead. (Extremely high cost and difficult field application.)
19	1/2d/1/2/1	Preformed sheet of vulcanized chloroprene rubber.
20	1/2d/1/2/1	Preformed sheet of vulcanized chloroprene rubber.
21	1/2e/1/2/1	Preformed sheet of vulcanized butyl rubber.
22**	1/2e/2o/1e/1	Preformed sheet of laminated PVC, nylon fabric, and butyl rubber (crack bridging at 0°F).
23	1/2d/2o/1e/1	Preformed sheet of laminated PVC, nylon fabric, and chloroprene rubber.
24	1/2e/2ad/2/1	Preformed sheet of butyl rubber, laminated to an asphalt-saturated felt.
25**	2/1b/1/1a/1	Applied-in-place, asphalt emulsion reinforced with glass fiber mesh (initial resistance, water absorption).

*Eliminated by preliminary screening process for reasons noted in parenthesis following description.

**Eliminated on the basis of results of laboratory tests or other reason noted in parenthesis following description.

TABLE 9 (Continued)

System Number	Classification	Description
26**	2/1b/1/1a/1	Applied-in-place, asphalt cement reinforced with glass fiber mesh (water absorption).
27**	2/1jk/1/2/1	Applied-in-place, chloroprene-chlorosulfonated polyethylene rubber solution (crack bridging at 0°F, initial resistance, water absorption).
28**	2/1f/1/2/1	Applied-in-place, SBR rubber solution (initial resistance, water absorption).
29*	2/1f/1/2/1	Applied-in-place, SBR rubber solution. (Similar to No. 28)
30*	2/1/21/2/2	Applied-in-place mortar of two-component synthetic resin and aggregate. (Similar in voids to asphalt concrete mixture, not impermeable).
31*	2/1j/1/2/1	Applied-in-place, one-component chloroprene solution. (Similar to No. 28)
32*	2/11/1/2/1	Applied-in-place, solution of SBR block copolymer. (Similar to No. 28)
33*	2/1b/21/2/1	Applied-in-place, sprayed liquid asphalt with aggregate chips. (Not an impermeable membrane)
34**	2/1a/2b/1a/1	Applied-in-place, coal tar emulsion reinforced with glass fiber fabric (initial resistance, crack bridging at 0°F).
35*	2/1a/2b1/2/2	Applied-in-place, coal tar emulsion and slurry of coal tar emulsion and sand. (Not suitable for high traffic volumes without wearing course)
36*	2/1a/2b1/2/1	Applied-in-place, coal tar emulsion and slurry of coal tar emulsion and sand. (Inferior to reinforced version, No. 34)
37*	2/1a/2b1/2/2	Applied-in-place, slurry of coal tar emulsion and special aggregate. (Not suitable for high traffic volumes without wearing course)
38*	2/1a/2bf/2/2	Applied-in-place, slurry of rubberized coal tar emulsion and special aggregate. (Not suitable for high traffic volumes without wearing course)
39*	2/1a/2bf/2/2	Applied-in-place, slurry of rubberized coal tar emulsion and sand. (Not suitable for high traffic volumes without wearing course)
40**	2/1b/2j1/2/1	Applied-in-place, mastic of natural and petroleum asphalt and aggregate (crack bridging at 0°F).
41*	2/1d/2n/2/2	Applied-in-place, chlorinated rubber and epoxy in a solvent. (Not suitable for high traffic volumes without wearing course)
42*	2/1b/2a/2/1	Applied-in-place, asphalt with asbestos fiber filler. (Manufacture of system discontinued)
43*	2/1b/2b/2/1	Applied-in-place, rubberized asphalt emulsion with filler. (Inferior to reinforced emulsion systems)
44*	2/1i/2f/2/1	Applied-in-place, rubber-modified acrylic emulsion. (Inferior to reinforced emulsion systems)
45*	2/1j/2n/2/1	Applied-in-place, rubber modified with plasticizer. (Used as dampproofing only)
46*	2/1e/2/2/1	Applied-in-place, unvulcanized nitrile rubber and resin in a solvent. (Not an impermeable membrane)
47*	2/1h/2c/2/2	Applied-in-place, rubber/vinyl copolymer modified with coal tar. (Not suitable for high traffic volumes without wearing course)
48*	2/1b/2f/2/1	Applied-in-place, asphalt modified with styrene-butadiene random copolymer. (Inferior to reinforced asphalt systems)

*Eliminated by preliminary screening process for reasons noted in parenthesis following description.

**Eliminated on the basis of results of laboratory tests or other reason noted in parenthesis following description.

TABLE 9 (Continued)

System Number	Classification	Description
49*	2/1b/2h1/2/1	Applied-in-place, mastic of asphalt, rubber crumb, and aggregate. (Similar to No. 50)
50**	2/1b/2fj1/2/1	Applied-in-place, mastic of petroleum and natural asphalt, rubber, and aggregate (crack bridging at room temperature).
51**	2/1b/2bf/2/1	Applied-in-place, asphalt modified with rubber and mineral filler, (crack bridging at 0°F).
52a**	2/1b/2i1d/1	Applied-in-place, asphalt modified with rubber and reinforced with polypropylene fiber mat (initial resistance).
52b**	2/1b/2i1d/1	Applied-in-place, asphalt reinforced with polypropylene fiber mat (initial resistance).
52c**	2/1b/2i1b/1	Applied-in-place, asphalt modified with rubber and reinforced with polypropylene fiber mat (initial resistance, water absorption).
52d**	2/1b/2i1d/1	Applied-in-place, asphalt reinforced with polypropylene fiber mat (initial resistance).
53*	2/1f/2fk1/2/2	Applied-in-place mortar of aggregate, portland cement, and rubber. (Not an impermeable membrane).
54*	2/1h/2fk1/2/2	Applied-in-place mortar of aggregate, portland cement, and rubber. (Not an impermeable membrane)
55*	2/1f/2fk1/2/2	Applied-in-place mortar of aggregate, portland cement, and rubber sealed with epoxy. (Not an impermeable membrane)
56*	2/1i/2k1/2/2	Applied-in-place mortar of acrylic emulsion, portland cement, and aggregate. (Not an impermeable membrane)
57*	2/1i/2k1/2/2	Applied-in-place mortar of acrylic emulsion, portland cement, and aggregate. (Not an impermeable membrane)
58**	2/1b/2a1/2/2	Applied-in-place mixture of aggregate, asphalt, and asbestos fiber (crack bridging at 0°F).
59*	2/2b/1/1f/1	Applied-in-place, polyester resin reinforced with chopped glass fibers. (Not an impermeable membrane)
60*	2/2b/1/1b/1	Applied-in-place, polyester resin reinforced with glass fiber mat. (Manufacture of system discontinued)
61**	2/2m/1/2/1	Applied-in-place, one-component, unmodified polyurethane (excessive bubbling).
62*	2/2c/1/2/1	Applied-in-place, two-component, unmodified polyurethane. (Similar to No. 63)
63	2/2c/1/2/1	Applied-in-place, two-component, unmodified polyurethane.
64*	2/2c/2/2/1	Applied-in-place, two-component, modified polyurethane. (Unsuccessful applications in field)
65*	2/2c/1/2/1	Applied-in-place, two-component, unmodified polyurethane. (Similar to No. 63)
66*	2/2c/1/2/1	Applied-in-place, two-component, unmodified polyurethane. (Similar to No. 63)
67	2/2c/2c/2/1	Applied-in-place, two-component, coal tar-modified polyurethane.
68**	2/2a/1/2/1	Applied-in-place, two-component epoxy resin in solvent (initial resistance).
69*	2/2a/1/2/1	Applied-in-place, epoxy resin in solvent. (Similar to No. 68)

*Eliminated by preliminary screening process for reasons noted in parenthesis following description.

**Eliminated on the basis of results of laboratory tests or other reason noted in parenthesis following description.

TABLE 9 (Continued)

System number	Classification	Description
70*	2/2a/2c/2/1	Applied-in-place, epoxy resin modified with coal tar. (Inferior to reinforced version, No. 79)
71*	2/2g/2l/2/1	Applied-in-place, silicone rubber with solvent and aggregate. (Not an impermeable membrane)
72a**	2/2b/1/2/1	Applied-in-place, flexibilized polyester resin (initial resistance, crack bridging at room temperature).
72b**	2/2b/1/2/1	Applied-in-place, flexibilized polyester resin (initial resistance).
73**	2/2b/2l/2/1	Applied-in-place mortar of polyester resin with aggregate (initial resistance, crack bridging at room temperature).
74*	2/2b/1/2/1	Applied-in-place, polyester resin catalyzed with a peroxide. (Inferior to reinforced version, No. 60)
75*	2/2a/1/2/1	Applied-in-place, unmodified epoxy resin. (Designed as bonding agent for PCC, not an impermeable membrane)
76*	2/2i/1/2/1	Applied-in-place, isocyanate reacted with an aromatic amine. (Unsuccessful applications in field)
77**	2/2e/1/2/1	Applied-in-place, two-component butyl rubber (crack bridging at room temperature)
78**	2/2c/2c/1a/1	Applied-in-place, two-component polyurethane modified with petroleum oil and reinforced with glass fiber fabric (initial resistance).
79**	2/2a/2c/1a/1	Applied-in-place, epoxy resin modified with coal tar and reinforced with glass fiber fabric (crack bridging at 0°F).
80**	2/2c/2c/2/1	Applied-in-place, two-component polyurethane, modified with coal tar (relative tensile strength)
81*	2/2c/2c/2/1	Applied-in-place, two-component polyurethane, modified with coal tar. (Similar to Nos. 67 and 80)
82*	2/2c/2c/2/1	Applied-in-place, two-component polyurethane, modified with coal tar. (Similar to Nos. 67 and 80)
83*	2/2c/2c/2/1	Applied-in-place, two-component polyurethane, modified with coal tar. (Same as No. 80)
84*	2/2c/2c/2/1	Applied-in-place, two-component polyurethane, modified with coal tar. (Manufacturer declined request for sample)
85*	2/2c/2c/2/1	Applied-in-place, two-component polyurethane, modified with coal tar. (Same as No. 80)
86*	2/2c/2c/2/1	Applied-in-place, two-component polyurethane, modified with coal tar. (Similar to Nos. 67 and 80)
87*	2/2c/2c/2/1	Applied-in-place, two-component polyurethane, modified with coal tar. (Similar to Nos. 67 and 80)
88**	2/2c/2c1/2/1	Applied-in-place, two-component polyurethane, modified with coal tar, with aggregate (crack bridging at 0°F).
89*	2/2c/2c/2/1	Applied-in-place, two-component polyurethane, modified with coal tar. (Manufacture of system discontinued)
90*	2/2c/2c/2/1	Applied-in-place, two-component polyurethane, modified with coal tar. (Similar to Nos. 67 and 80)
91*	2/2h/2c/2/1	Applied-in-place, two-component polysulfide resin, modified with coal tar. (Similar to No. 103)

*Eliminated by preliminary screening process for reasons noted in parenthesis following description.

**Eliminated on the basis of results of laboratory tests or other reason noted in parenthesis following description.

TABLE 9 (Continued)

System Number	Classification	Description
92*	2/2c/2c/2/1	Applied-in-place, two-component polyurethane, modified with coal tar. (Manufacture of system discontinued)
93**	2/2c/2/2/1	Applied-in-place, two-component, modified polyurethane (very slow curing).
94	2/2c/2d/2/1	Applied-in-place, two-component polyurethane, modified with asphalt.
95*	2/2m/2c/2/1	Applied-in-place, one-component polyurethane, modified with coal tar. (Similar to Nos. 67 and 80)
96*	2/2m/2c/2/1	Applied-in-place, one-component polyurethane, modified with coal tar. (Similar to Nos. 67 and 80)
97*	2/2m/2c/2/1	Applied-in-place, one-component polyurethane, modified with coal tar. (Manufacturer does not recommend for this purpose)
98**	2/2a/2e1/2/1	Applied-in-place epoxy resin modified with petroleum oil, with aggregate (crack bridging at room temperature).
99**	2/2a/2c1/2/1	Applied-in-place epoxy resin modified with coal tar, with aggregate (initial resistance, crack bridging at room temperature).
100**	2/2a/2c/2/1	Applied-in-place two component epoxy resin modified with coal tar, with solvent (initial resistance).
101*	2/2a/21m/2/1	Applied-in-place flexibilized epoxy resin, with aggregate. (Manufacturer does not recommend for this purpose)
102	2/2h/2c/2/1	Applied-in-place, two-component, polysulfide polymer, modified with coal tar.
103**	2/2h/2c/2/1	Applied-in-place two-component polysulfide modified with coal tar (handling).
104**	2/2a/2d1/2/1	Applied-in-place epoxy resin modified with asphalt, with special aggregate (crack bridging at 0°F).
105**	2/2a/2e1/2/1	Applied-in-place two component epoxy resin, modified with petroleum oil, with aggregate (crack bridging at room temperature).
106**	2/2a/2m1/2/1	Applied-in-place modified epoxy resin, with aggregate (crack bridging at room temperature).
107**	2/2a/2e1/2/1	Applied-in-place two-component epoxy resin modified with petroleum oil, with aggregate (crack bridging at 0°F).
108*	2/2a/2m1/2/1	Applied-in-place epoxy resin modified with pine oil, with aggregate. (Manufacturer does not recommend for this purpose)
109*	2/2a/2m/2/1	Applied-in-place epoxy resin modified with pine oil. (Designed as protective coating for PCC, not an impermeable membrane)
110**	2/2a/2d/2/1	Applied-in-place epoxy resin modified with petroleum asphalt (crack bridging at 0°F).
111*	2/2a/2e/2/1	Applied-in-place epoxy resin modified with petroleum oil. (Inferior to No. 112, by field experience)
112**	2/2a/2e/2/1	Applied-in-place epoxy resin modified with petroleum oil (initial resistance, crack bridging at 0°F).
113*	2/2a/21/2/2	Applied-in-place mixture of epoxy resin and aggregate. (Designed as flooring system, not an impermeable membrane)

*Eliminated by preliminary screening process for reasons noted in parenthesis following description.

**Eliminated on the basis of results of laboratory tests or other reason noted in parenthesis following description.

TABLE 9 (Continued)

System Number	Classification	Description
114*	2/2a/21/2/2	Applied-in-place mixture of epoxy resin and aggregate. (Designed as flooring system, not an impermeable membrane)
115**	2/2a/21/2/2	Applied-in-place mixture of two-component epoxy resin and aggregate (crack bridging at room temperature).
116*	2/2a/21/2/2	Applied-in-place mixture of unmodified epoxy resin and special aggregate. (Similar to No. 115)
117**	2/2a/2e1/2/2	Applied-in-place mixture of aggregate and epoxy resin modified with petroleum oil (crack bridging at room temperature).
118*	2/2a/21/2/2	Applied-in-place mixture of aggregate and unmodified epoxy resin. (Similar to No. 115)
119**	2/2a/2k1/2/2	Applied-in-place mixture of emulsified epoxy resin, portland cement, and aggregate (initial resistance).
120*	2/2f/2k1/2/2	Applied-in-place mixture of polysiloxane resin, portland cement, and aggregate. (Manufacturer does not recommend for this purpose)
121**	2/2a/2d1/2/2	Applied-in-place mixture of aggregate and asphalt-modified epoxy resin binder (crack bridging at room temperature).
122*	(unknown)	System described by brand name only. (Unable to further identify.)
123*	2/1/21/2/2	Applied-in-place mixture of aggregate and synthetic resin binder. (Not an impermeable membrane)
124*	(unknown)	System described as low viscosity epoxy only. (Unable to further identify.)
125*	2/2a/21/2/2	Applied-in-place mixture of aggregate and unmodified epoxy resin. (Same as No. 116)
126*	2/2/2k1/2/2	Applied-in-place mixture of aggregate, portland cement, and unidentified additive. (Not an impermeable membrane)
127**	2/2/1/2/1	Applied-in-place unidentified photo-catalyzed polymer (initial resistance).
128	2/2c/1/2/1	Applied-in-place, hydroxyl-terminated polybutadiene, reacted with an isocyanate to form a flexible polyurethane.
129**	2/2a/1/2/1	Applied-in-place unmodified, two-component epoxy resin (crack bridging at room temperature).
130**	2/2m/1/2/1	Applied-in-place one-component polyurethane (initial resistance, water absorption).
131**	2/2m/1/2/1	Applied-in-place one-component polyurethane (crack bridging at room temperature, water absorption).
132**	2/2c/1/2/1	Applied-in-place two-component polyurethane (initial resistance, crack bridging at room temperature).
133	1/1/1/1/1	Reinforced preformed sheet of laminated thermoplastic materials.
134**	1/1/1/1/1	Reinforced preformed sheet of laminated thermoplastic materials (crack bridging at 0°F).
135	1/1c/1/2/1	Preformed sheet of vulcanized ethylene-propylene rubber.
136**	2/2/2/2/1	Applied-in-place modified epoxy resin (crack bridging at 0°F).

*Eliminated by preliminary screening process for reasons noted in parenthesis following description.

**Eliminated on the basis of results of laboratory tests or other reason noted in parenthesis following description.

TABLE 9 (Continued)

System Number	Classification	Description
137**	2/2a/2/2/1	Applied-in-place modified epoxy resin (crack bridging at 0°F).
138**	2/2/1/2/1	Applied-in-place two-component synthetic resin (crack bridging at room temperature).
139**	2/2/2c/2/1	Applied-in-place modified thermosetting resin (crack bridging at room temperature).
140*	2/2h/1/2/1	Applied-in-place two component modified polysulfide resin. (Set up while mixing, unable to prepare test specimens)
141**	2/2/2/2/1	Applied-in-place two-component modified thermosetting resin (crack bridging at room temperature).
142**	1/1g/2ac/1f/1	Same as No. 10, with special ventilating underlayer added (Eliminated as separate system, and ventilating underlayer added as optional feature to No. 10a).

*Eliminated by preliminary screening process for reasons noted in parenthesis following description.

**Eliminated on the basis of results of laboratory tests or other reason noted in parenthesis following description.

TABLE 10

CRITERIA USED IN SCREENING MEMBRANE SYSTEMS

TEST	LIMITING VALUE
Initial electrical resistance	50×10^4 ohms/ft ² , min
Crack bridging at 77 F or 0 F	0.10 in., min
Water absorption, distilled water, 36 weeks at room temperature	10.0 percent, max *

* Certain systems were excepted from this limiting value and subjected to further evaluation because they appeared to be particularly promising in other respects

membrane performance under controlled laboratory conditions, thereby gaining a better understanding of the requirements of effective materials.

The following paragraphs discuss the various tests employed in view of these purposes, including the interrelationship of certain tests.

Crack Bridging

As might be expected, a general correlation was found between tensile elongation of the membrane material and performance of the system in the crack-bridging test. This correlation existed despite the fact that several different adhesives were used to bond preformed membranes to the concrete decks, and that some systems were preformed sheets whereas others were applied-in-place. This correlation is shown in Figure 5. Membrane systems may be conveniently grouped according to their performance in crack-bridging. Three such groups, based on testing at 0 F (which is more stringent than testing at 77 F or 140 F) are as follows:

1. Unreinforced systems of low elongation, which fail

TABLE 11

SURVIVING SYSTEMS SELECTED FOR FURTHER COMPARISON TESTING

System Number	Description
3	Preformed sheet of unvulcanized ethylene-propylene rubber
5	Preformed sheet of unvulcanized, self-curing chloroprene rubber
6	Preformed sheet of polyvinyl chloride (PVC)
7	Preformed sheet of unvulcanized chlorosulfonated polyethylene
9	Reinforced preformed sheet of styrene-butadiene rubber (SBR) block copolymer-modified asphalt
10	Preformed sheet of coal tar-modified PVC with chopped fiber filler --75 mils thick.
10a	Preformed sheet of coal tar-modified PVC with chopped fiber filler --125 mils thick.
11	Preformed sheet of asphalt, modified with a thermoplastic resin and reinforced with a thermoplastic fiber mat
15	Preformed sheet of PVC laminated to a sheet of asbestos fiber felt
19	Preformed sheet of vulcanized chloroprene rubber
20	Preformed sheet of vulcanized chloroprene rubber
21	Preformed sheet of vulcanized butyl rubber
23	Preformed sheet of laminated PVC, nylon fabric, and chloroprene rubber
24	Preformed sheet of butyl rubber laminated to an asphalt-saturated felt
63	Applied-in-place, two-component, unmodified polyurethane
67	Applied-in-place, two-component, coal tar-modified polyurethane
94	Applied-in-place, two-component, asphalt-modified polyurethane
102	Applied-in-place, two-component, polysulfide polymer, modified with coal tar
128	Applied-in-place, hydroxyl-terminated polybutadiene, reacted with an isocyanate to form a flexible polyurethane
133	Reinforced preformed sheet of laminated thermoplastic materials
135	Preformed sheet of vulcanized ethylene-propylene rubber

TABLE 12

RESULTS OF REVIEW AND COMPARISON OF 21 SYSTEMS
SELECTED FOR FURTHER TESTINGSystem
Number

3	Eliminated from further consideration because of significant reduction in tensile strength and increase in elongation after both air exposure and moisture-temperature exposure, and availability of vulcanized version (System 135) without these deficiencies.
5	Eliminated from further consideration because of reduction in elongation after both air exposure and moisture-temperature exposure, and availability of vulcanized version (System 20) without these deficiencies.
6	Retained for field application test.
7	Eliminated from further consideration because of change in elongation after moisture-temperature and air exposure, and extremely high water absorption.
9	Eliminated from further consideration because of reduction in elongation and increase in hardness after both air exposure and moisture-temperature exposure, combined with anticipated problems in placement resulting from extreme difficulty in removal of release paper used on both sides of membrane to prevent sticking together in roll.
10	Eliminated from further consideration because of improved damage resistance of 10a, and failure at fourth cycle in fatigue test.
10a	Retained for field application test.
11	Eliminated from further consideration because of extremely high water absorption, and failure at second cycle in fatigue test
15	Eliminated from further consideration because of failure at ninth cycle in fatigue test, and significant increase in elongation after both air and moisture-temperature exposure.
19	Eliminated from further consideration because of extremely high water absorption, and availability of alternate vulcanized chloroprene with low water absorption (System 20).
20	Retained for field application test.
21	Retained for field application test.
23	Eliminated from further consideration because of extremely high water absorption, failure at sixth cycle in fatigue test, and significant change in elongation after air exposure.
24	Retained for field application test.
63	Retained for field application test.
67	Retained for field application test.
94	Retained for field application test.
102	Eliminated from further consideration because of anticipated difficulty in placement due to high viscosity, and extremely long set time.
128	Eliminated from further consideration because of anticipated difficulty in placement due to high viscosity, and availability of alternate two-component urethanes with lower viscosity and water absorption (Systems 63, 67 and 94).
133	Eliminated from further consideration because of failure at first cycle in fatigue test, and reduction in elongation and increase in hardness after both air exposure and particularly, moisture-temperature exposure
135	Retained for field application test

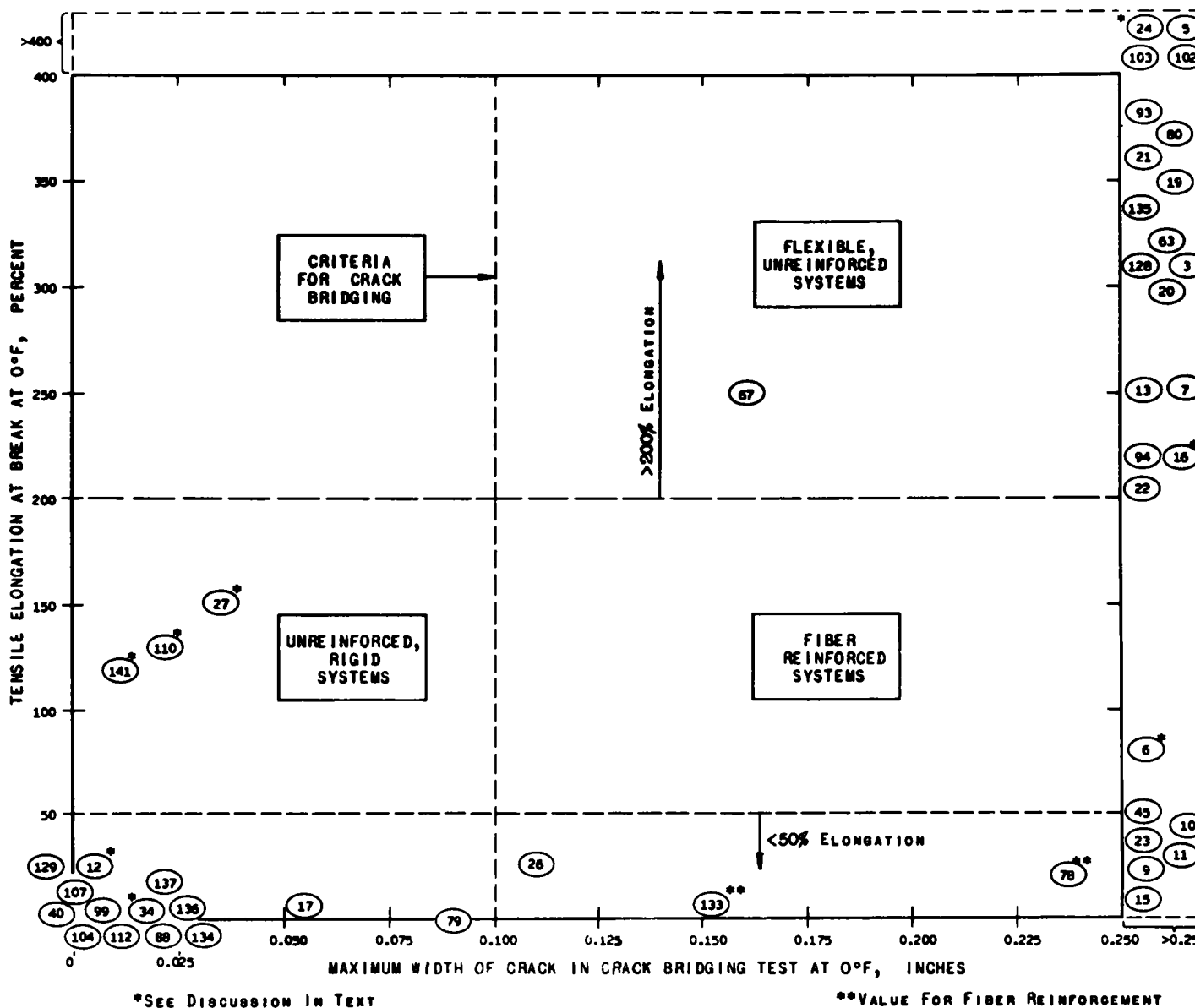


Figure 5 Relationship between crack-bridging ability and tensile elongation at 0 F.

over very fine cracks. These included systems 17, 22, 40, 51, 58, 88, 99, 104, 107, 112, 121, 129, 134, 136, 137 (total of 15, lower left quadrant in Fig. 5).

2. Unreinforced systems with 200 percent or more elongation at 0 F, which bridge wide cracks with ease. These included systems 3, 5, 7, 13, 16, 19, 20, 21, 61, 63, 67, 80, 93, 94, 102, 103, 128, and 138 (total of 18, upper right quadrant in Fig. 5).

3. Fiber-reinforced systems which, despite a low elongation (less than 50 percent at 0 F), have significant crack-bridging ability, presumably because of the fiber action in distribution of stress, thus preventing localized cracking. These include systems 1, 9, 10, 10a, 11, 15, 23, 26, 78, 79, and 133 (total of 11, lower right quadrant in Fig. 5).

Certain exceptions remain, represented by systems 6, 12, 16, 24, 27, 34, 110, and 141, which are discussed subsequently.

1. System 6 exhibited the lowest adhesion in both shear and tension of any system tested and appeared to delaminate, providing additional extensibility, rather than fail by fissuring in the crack-bridging test.

2. Although reinforced, system 12 exhibited little crack-bridging ability at 0 F. This was thought to be caused by a combination of a relatively high-strength bond to portland cement concrete, thus limiting the area over which extension occurs during the crack-bridging test. In addition, the reinforcement in system 12 appeared to be concentrated in a narrow band rather than being dispersed throughout. True stress distribution may not occur under these circumstances.

3. Both systems 16 and 24 were reinforced by a bonded fibrous layer attached to one side of the membrane. Under these circumstances the fiber layer broke early in crack-bridging and tensile testing, and high elongations recorded

were actually values for the unreinforced membranes.

4. Whereas system 27 is highly flexible at 0 F, the limited crack-bridging ability was ascribed to the thinness of the membrane. This material is a rubber solution, and even after application of two coats, a thickness of only $\frac{1}{32}$ in was produced.

5. Although reinforced, the coal-tar binder of system 34 is so brittle at 0 F that the fibers are unable to prevent localized stress build-up and, consequently, cracking occurs.

6. System 110 is apparently designed to cure in the presence of aggregate (i.e., system 121) because a free film remained tacky for 3 weeks and still appeared in a low state of cure when tested 6 weeks after manufacture. The sheets for laboratory characterization were heat-cured in accordance with Corps of Engineers specification CE 807.24 and exhibited good elongation at 0 F. The different cure schedules employed are believed to be the reason for the apparent anomaly.

7. System 141 was more rigid than most two-component urethanes evaluated, but showed good elongation at 0 F. However, the manufacturer supplied an epoxy adhesive primer for the material which produced an exceptionally good bond to portland cement concrete. It is believed the high adhesion restricted the area over which extension could occur during crack-bridging, thus causing an earlier failure than would have been predicted from the tensile elongation.

Water Permeability

Stratfull (13) has shown a direct correlation between the total perforated area of membrane artificially perforated (to simulate damage or pinholes during application) and the electrical resistance. For a typical membrane studied, the relationship derived was:

$$A = 79.6R^{-0.76}$$

in which A = area of holes in membrane, sq in.; and R = resistance, ohms

The correlation coefficient for this equation was -0.989 . In approximate terms, when the hole area is reduced by half, the resistance triples.

An apparently good correlation was obtained in laboratory testing among the observed condition of membranes, a knowledge of their composition, and measurement of electrical resistance. For example, membranes providing poor initial resistance may be categorized as follows.

1. *Membranes based on emulsified binders.* Presumably certain emulsified binders have the potential for reemulsification. Systems 25, 34, 52a, 52b, and 52c fall in this category and are also reinforced.

2. *Reinforced membranes* Fibrous reinforcements may increase permeability because of a tendency to incorporate voids, and, if the fiber is not thoroughly "wetted" by the binder, water may be transmitted over the surface of the fiber. System 78 may exhibit this phenomenon as well as the systems listed in item 1.

3. *Solvent-based systems.* Linseed oil in solvent, as previously discussed, has not generally provided sufficient impermeability in commercial installations unless applied in four or five coats. Similarly, several other systems contain-

ing solvent did not provide satisfactory initial resistance even after two-coat applications. Examples are systems 28, 68, 100, and 127. The type of binder in solution did not appear to significantly affect the result.

4. *Combined membrane and wearing course systems* Certain systems proposed as a combined membrane and wearing course provided low initial resistance, apparently because of significant air void content. Such systems allow slow penetration of water in a manner similar to asphaltic concrete or portland cement concrete. Examples are systems 73 and 119.

5. *Bubbling.* Many membrane systems with high viscosity or poor flow exhibit a tendency to bubble. In laboratory preparation this was minimized by:

- a Maintaining a constant temperature to avoid "out-gassing."
- b Application in a minimum of two layers.
- c Bursting bubbles by hand where possible.

Even so, some systems exhibited bubbling with resultant "pinholes," as exemplified by systems 72, 99, 112, and 130.

6. *Electrical conductivity.* One interesting discovery, particularly relevant to both laboratory and field evaluation via resistance testing, was that some membranes are electrically conductive when dry and undamaged. Such systems were carefully identified and their performance judged relative to their dry, undamaged, initial reading rather than on an infinite reading. In systems 21 and 135, electrical conductivity was associated with certain preformed rubbers, presumably those containing a conductive carbon black as reinforcing filler.

Relationship of Permeability to Water-Vapor Transmission

For the purposes of this report, permeability was defined as the gross transmission of liquid water through voids in a membrane as determined by changes in electrical resistance. Water vapor transmission was defined as the diffusion of water vapor through a membrane, as determined by water absorption. This diffusion of molecules of water (water vapor) corresponds to the ability of water to swell the membrane. Swelling may be measured directly by dimensional change or indirectly by weight gain. This latter method was used for convenience. In addition to allowing water vapor transmission, materials with high water absorption are known to exhibit drastic changes in mechanical and thermal properties upon absorption to a point where degradation or damage may occur.

Distilled water was used in preference to tap or salt water in determining absorption because pure water is a stronger solvent than salt solution and represents the more severe condition. Also, bridge decks already contaminated with deicing salts require only water to promote the movement of salt deeper into the deck.

The membrane systems evaluated exhibited a wide range of water absorptions from less than 1 percent to 39 percent, and in one case 147 percent, after 36-week immersion. However, most systems exhibited water absorptions less than 10 percent, a level judged to be a reasonable upper limit for systems designed to provide water resistance for many years in the field.

The distinction between the electrical resistance test for macro-permeability (liquid water) and the water-absorption test of water vapor or molecular transmission was emphasized by the observation that some systems which absorbed 9 to 15 percent water (systems 7, 10, 11, and 19) still provided infinite or near infinite electrical resistance when 36-week-immersed specimens were surface-dried and tested.

Impact (Construction) Damage Resistance

No clear relationship emerged from a comparison of impact damage of a membrane system with its tensile strength, elongation, toughness (as indicated by tensile product), resilience, hardness, and creep (as indicated by the difference between 1-sec and 15-sec Shore D hardness).

The presence or absence of reinforcement did not appear highly significant in relation to impact damage resistance. The majority of systems with good resistance to impact damage were thermosetting, although this may be a coincidence because the systems evaluated ranged from soft vulcanized rubbers through rigid and crosslinked resins. The major factor appears to be membrane thickness, with thick systems, such as 10a, 11, 40, 93, 94, 102, and 103, having the greatest resistance to impact damage. In general, impact strength increases proportionally with thickness, owing to the increasing capacity of the layer to absorb and dissipate energy.

Because a protective overlay may be placed relatively simply to increase membrane thickness and absorb impact damage, the results of the impact damage test were not incorporated into the selection criteria. Based on limited evidence, it was tentatively concluded that, in general, the membrane thickness should be $\frac{1}{8}$ in. minimum to withstand puncture according to the test used in this project. The impact damage test was designed to parallel the one used by the (British) Transport and Road Research Laboratory (TRRL) because of evidence that it approximates the most severe type of construction damage occurring in the field (i.e., heavy equipment tires rolling over loose, sharp aggregates).

Deflection Temperature

This characterization test proved a highly significant indicator of membrane performance. The ASTM Deflection Temperature is an approximation of the glass transition temperature or second-order transition temperature (T_g). This may be defined as the temperature at which a change occurs in an amorphous polymer, or amorphous region of a partially crystalline polymer, from a rubbery to a glassy condition (or vice versa) due to freezing of molecular motion.

The effect of increasing temperature on the polymer state described in terms of transition temperatures is as follows:

	Increasing temperature →			
State:	GLASSY → LEATHERY → RUBBERY → LIQUID ^a			
Description:	(Hard, brittle)	(Stiff, tough)	(Soft, extensible)	
Range:	Below T_g^b	Near T_g	Above T_g	At T_m^c

^a Thermoplastics only

^b Second-order transition temperature

^c First-order transition temperature

Deflection Temperature versus Tensile Elongation

The over-all relationship of T_g to tensile elongation at 0 F for all systems characterized is shown in Figure 6. Of the systems evaluated, only six showed deflection temperature above room temperature (77 F). These are systems 99, 104, 106, 115, 117, and 136, which were glassy, with high hardness, and with tensile elongations close to zero at both 77 F and 0 F.

A second group of 21 systems exhibited deflection temperatures between 0 F and 77 F (systems 2, 6, 15, 22, 23, 24, 25, 26, 34, 40, 50, 72b, 73, 98, 99, 105, 107, 112, 129, 137, and 138). These systems are quite hard but are generally tough at room temperatures, with ultimate tensile elongations more than 30 percent. Exceptions are certain fiber-reinforced systems (systems 2, 26, and 34) where extension of the binder appeared to have been restricted by the fiber. At 0 F, however, all these systems were relatively glassy with elongations generally well below 30 percent with only two exceptions (systems 6 and 24). System 6 has a deflection temperature marginally above 0 F and, thus, may not have undergone complete transition. The deflection temperature specimens of system 24 included felt backing saturated with an adhesive to build up the $\frac{1}{2}$ -in. test bars from the sheet. It is believed the value obtained may reflect the properties of the adhesive-saturated felt combined with the membrane, rather than the membrane only.

The remaining 39 systems, comprising the largest group on which this test was run, showed deflection temperatures below 0 F. The unreinforced systems in this group all exhibited high tensile elongations at 0 F with only two exceptions (systems 17 and 139).

Considering the extremely varied nature of the systems and the layered structure of the test specimens of preformed systems, the derived relationship of T_g to tensile elongation is in excellent agreement with theoretical predictions. With regard to fiber-reinforced systems, a correlation of deflection temperature and tensile elongation would not have been predicted.

Figure 6 shows a wide range of tensile elongations (from more than 100 percent to more than 400 percent) for systems with deflection temperatures below the test temperature of 0 F. This might be expected because the mechanical properties of systems in their elastomeric state (above T_g) would be characteristic of the specific type of polymer involved which, as previously mentioned, were highly diverse.

Deflection Temperature versus Crack-Bridging Ability

The relationship of crack-bridging ability to tensile elongation, and of deflection temperature to tensile elongation has already been discussed. Some correlation might therefore be expected between crack-bridging ability and deflection temperature. This relationship is shown in Figure 7. The chart indicates in general that systems with ability to bridge cracks of 0.100 in. or more have deflection temperatures below the temperature of the crack-bridging test (in this case, 0 F).

Most systems deviating from this behavior have been discussed previously. For example, the seven systems falling

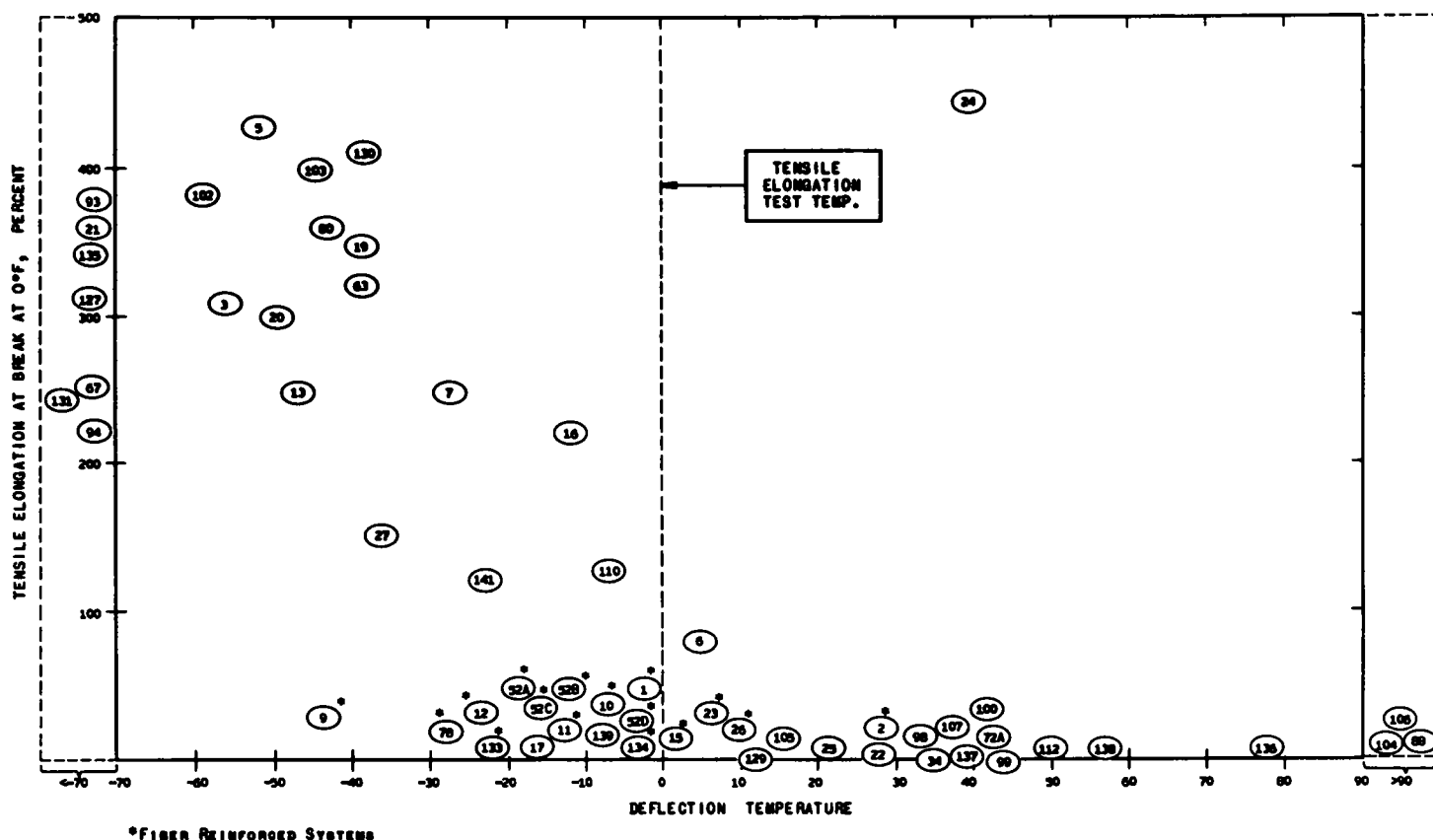


Figure 6 Relationship between deflection temperature and tensile elongation at 0 F.

in the lower left quadrant of Figure 7 (systems 12, 17, 27, 51, 110, 134 and 141) would have been expected to have significantly more crack-bridging ability. However, systems 12 and 134 were reinforced, perhaps in a manner that reduced elongation and crack-bridging, but not deflection temperature. System 134 was based on glass, cloth, and aluminum foil, whereas system 12 was reinforced non-uniformly, as previously discussed.

Systems 27, 110, and 141 were discussed previously; system 27 was thin and system 101 was not cured. System 17 showed much lower tensile elongation than would have been predicted from its deflection temperature of 16 F. Apparently this product becomes quite brittle at temperatures somewhat below its T_g .

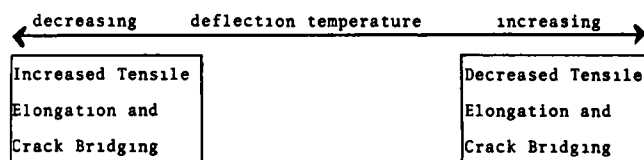
System 51 is very weak, with tensile strength too low to measure. It appeared to fail in crack-bridging at 0 F because of lack of integrity.

In the upper right quadrant, only system 24 fails to follow the general relationship. This system was discussed previously. Its measured deflection temperature represents the laminate of butyl rubber and adhesive-saturated asbestos felt.

Summary of Relationships

In summary, for unreinforced systems, the general inter-relationships between crack-bridging, tensile elongation, and

deflection temperature may be represented schematically:



For unreinforced systems, it appears that in order to bridge 0.100-in. cracks at 0 F, a minimum tensile elongation of 200 percent at 0 F is required and that this property is associated with a deflection temperature of 0 F or less.

For reinforced systems, a high tensile elongation does not appear to be required for crack-bridging ability; however, the binder should be relatively tough and the reinforcement evenly distributed throughout the membrane.

BENEFIT/COST RATIO

Assuming that it has been demonstrated that a membrane system will extend the life of a bridge deck by protecting it from deicing salt damage, the question still remains whether the benefits derived from longer bridge deck life justify the cost of the membrane. This question can best be answered objectively by a comparison of the estimated

cost of the membrane with the estimated monetary benefit derived from the additional bridge deck life resulting from the use of the membrane. Such a benefit/cost comparison will also be useful in selecting the optimum system from among several available systems with differing costs and differing service lives. A procedure for estimating the benefit/cost ratios of waterproof membrane systems was developed to assist in selecting the optimum system for installation on a particular bridge deck. This procedure is detailed in the paragraphs that follow

Definitions

For purposes of this report, the following two basic definitions are assumed:

Cost of membrane—The difference between the original

cost of a bridge deck with a waterproof membrane and the original cost of the same bridge deck without a waterproof membrane.

Benefit—The net saving (difference in costs) that would be realized by the owner agency as a result of installing a waterproof membrane rather than not installing a waterproof membrane.

Also assumed are the following definitions of the costs that are frequently considered in computing the benefits resulting from installation of a waterproof membrane:

Structural deck cost—The total contract price for construction of the structural bridge deck.

Routine maintenance cost—The costs of those minor repairs required to maintain a bridge deck in a safe condition and provide the desired level of service to traffic.

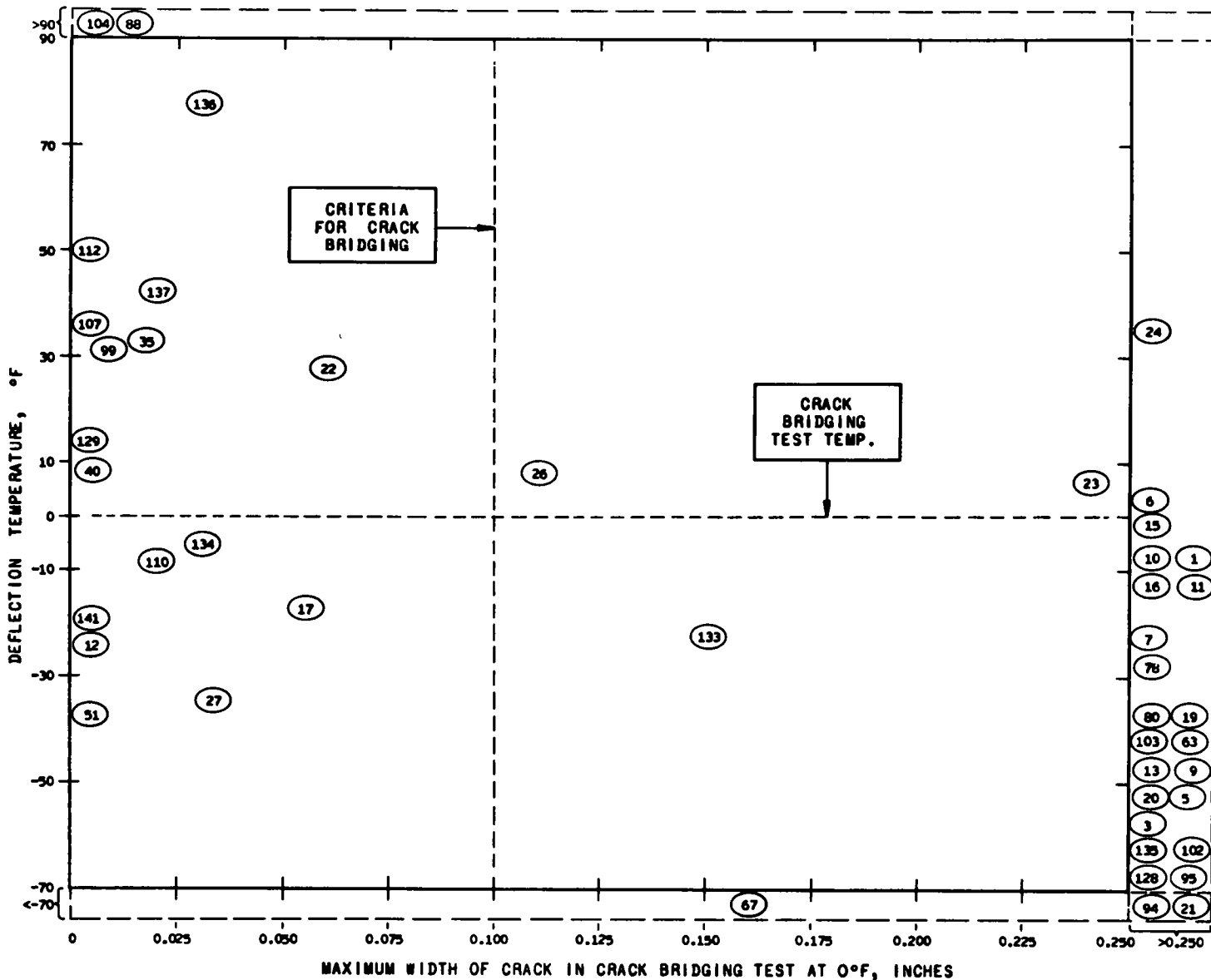


Figure 7 Relationship between crack-bridging ability at 0°F and deflection temperature

Restoration cost—The costs of major repairs, such as partial rebuilding and resurfacing of the structural deck, required as a result of damage by deicing salts.

Traffic delay cost—Additional costs to the traveling public resulting from delays caused by major restoration work.

Accident cost—Additional costs to the traveling public and to the highway agency resulting from accidents caused by unsafe pavement conditions.

Some highway agencies may wish to ignore one cost or another as being irrelevant or too difficult to measure. Others may want to add cost considerations that are significant to a particular decision.

Mathematical Model

A benefit/cost ratio for waterproof membranes on concrete bridge decks may be conveniently expressed by the following mathematical model:

$$B/C = \frac{C_D - C_{DM}}{C_M}$$

in which

B/C = benefit/cost ratio;

C_D = deck cost without membrane as *average annual cost* of the structural deck and its surfacing without a membrane, including all significant costs such as initial construction, maintenance, restoration, traffic delay, accidents, and others;

C_{DM} = deck cost with membrane as *average annual cost* of the structural deck and its surfacing with a membrane including the significant costs for the same items as for the deck without membrane (cost of membrane not included),

C_M = membrane cost as *average annual cost* based on the total contract price to furnish and install the membrane, including any special surface treatment or incremental cost of special surface pavement, if required;

Average Annual Cost = The equivalent uniform annual cost of a nonuniform series of money disbursements where money has a time value.

Obviously a dollar that a highway department spends today is more significant than a dollar it will have to spend 10 years from now. Because of this time value of money, it is necessary to adjust costs and benefits that occur at different times so that they can realistically be compared (14, 15, 16, 17). For this study, this adjustment is made by the average annual cost method; i.e., by calculation of the equivalent annual cost of a series of nonuniform disbursements. The equivalent annual cost is analogous to the amount required annually to repay a loan with interest. No conversion is made of costs, such as for routine maintenance, that can be considered as essentially equal each year.

Current initial construction costs are multiplied by a factor that depends on the life of what the cost buys or saves, and a rate of interest determined by the value of money to those who must bear the cost (14). This factor is called the capital recovery factor (CRF).

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1}$$

in which

i = interest rate;

n = number of years over which the cost is spread.

To consider a one-time cost that will occur in some future year, such as the cost of a major restoration, the cost is first converted to its present worth by multiplying by the present worth factor (PWF)

$$PWF = \frac{1}{(1+i)^n}$$

in which

i = interest rate;

n = year (from present) in which cost is incurred.

The present worth is then multiplied by the CRF to determine its average annual cost. Tables for determining the capital recovery factor and the present worth factor are available in most engineering economy texts.

Because both costs and benefits considered in this study are generally affected to the same degree by inflation, the effect of inflation has been considered negligible. Such a procedure follows current practice for this type economic study (15, 17). Also, for purposes of this study, an interest rate of 6 percent has been chosen.

Use of the Mathematical Model

To determine the benefit/cost ratio for any particular waterproof membrane, all the significant costs must be considered. These include cost of the bridge deck and cost of the membrane, as well as maintenance, restoration, traffic delay, and accident costs. In addition, the expected life of the bridge deck with and without the membrane must be estimated with a reasonable degree of accuracy for the analysis to have meaning.

For example, consider a concrete bridge deck located in a highly corrosive environment. It cost \$12/ft² to construct, and its expected life without a membrane is 10 years, at which time the deck must be completely replaced. However, if a specific waterproof membrane that costs \$1/ft² is installed during original construction, the life of the bridge deck would be 12 years, or an additional 2 years. In this case, maintenance, traffic delay, and accident costs are considered insignificant by the highway agency making the analysis.

$$B/C = \frac{C_D - C_{DM}}{C_M} = \frac{(\$12 \times CRF_{w/o}) - (\$12 \times CRF_w)}{\$1.00 \times CRF_m}$$

in which

$CRF_{w/o}$ = capital recovery factor for 10 years at 6 percent;

CRF_w = capital recovery factor for 12 years at 6 percent;

CRF_m = capital recovery factor for 12 years at 6 percent;

$$B/C = \frac{\$12 \times 0.13578 - \$12 \times 0.11928}{\$1.00 \times 0.11928}$$

$$= 1.66$$

It should be concluded that use of the membrane is clearly necessary because the benefits significantly exceed the costs. If maintenance, traffic delay, and accident costs were significant, their consideration would further favor use of the membrane.

Of course, if the benefit/cost ratio were less than 1.0, use of the membrane would not be favored. If the benefit/cost ratio is only slightly more than 1.0 (in the range of 1.1 to 1.2), it is not clear whether membrane use would be favored, especially considering the assumptions in predicting bridge deck life and the difficulty in making precise estimates of costs.

Because of the difficulty in making precise predictions of bridge deck life, a graph (Fig. 8) may prove helpful in judging the relative value of membranes. For example, from Figure 8 it could be concluded that for a bridge deck cost of \$12/ft² and a life expectancy of 10 years, a membrane costing \$1.25/ft² or less should be seriously considered if it can be expected to extend the life of the deck 2 years or more. If the membrane can be expected to extend the life of the bridge deck 5 years, \$2.50/ft² is clearly not too much to pay for the membrane.

In a similar manner, Figure 9 shows the effect of original bridge deck cost on the consideration of installing a membrane. Using the same assumptions regarding replacement, maintenance, traffic delay, and accident costs, it could be concluded from Figure 9 that if the membrane can be expected to increase deck life from 10 years to 12 years, a \$1.50/ft² membrane would be justified for a \$16/ft² deck,

considered marginal for a \$12/ft² deck, and not justified for a \$8/ft² deck.

A more complex example using the mathematical model might be made for the following conditions. The original bridge deck cost is \$10/ft² for 30,000 ft². If no membrane is used, experience shows that major restoration involving partial replacement and repaving can be expected in 15 years, which will cost \$4/ft² and add 10 years to the life of the bridge deck. Over the years the average yearly maintenance of spalls averages \$0.10/ft² of total deck area. The average cost of accidents caused by spalls resulting from corrosion is \$2,000 per year, or \$0.07/ft² per year. If, however, a waterproof membrane that costs \$1.50/ft² is installed during original construction, the bridge deck will last 25 years with no additional costs required for maintenance, restoration, or accidents as a result of corrosion. However, repaving costs of \$0.20/ft² will be required in 15 years.

The benefit/cost ratio for these conditions would be determined as follows:

Present worth factor for 15 years at 6 percent = 0.4173.

Present worth of restoration = \$4.00 × 0.4173 = \$1.67.

Capital recovery factor for 25 years at 6 percent = 0.07823.

Average annual cost of restoration = \$1.67 × 0.07823 = \$0.13/ft².

Deck cost without membrane = \$10 × 0.07823 = \$0.7823

Average annual cost/ft² without membrane:

\$0.78	Original deck slab
0.13	Restoration
0.10	Maintenance
0.07	Accidents
<u>\$1.08</u>	<u>Total</u>

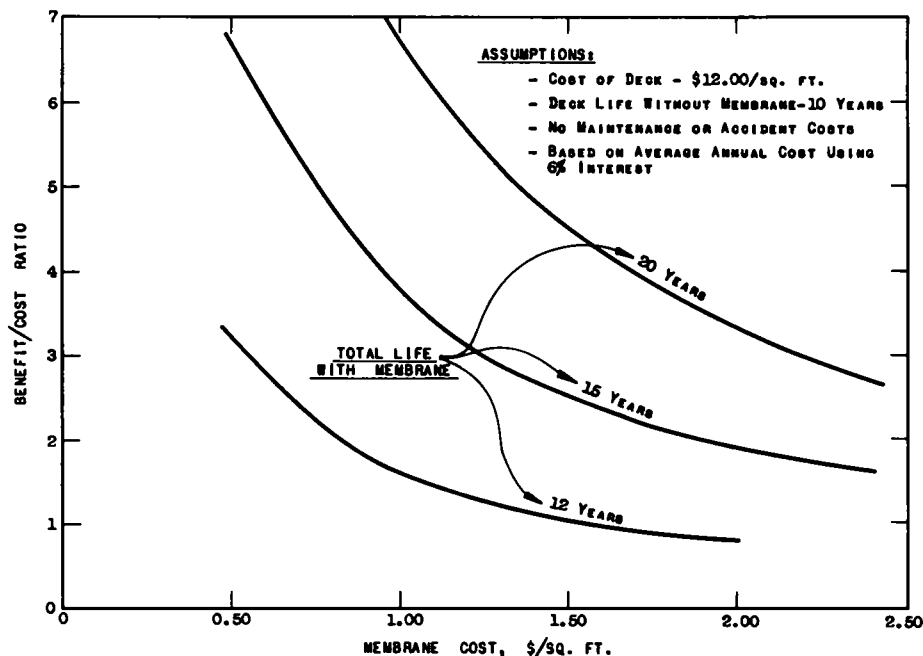


Figure 8. Relationship of benefit/cost ratio to membrane cost for various increased bridge deck life expectancies.

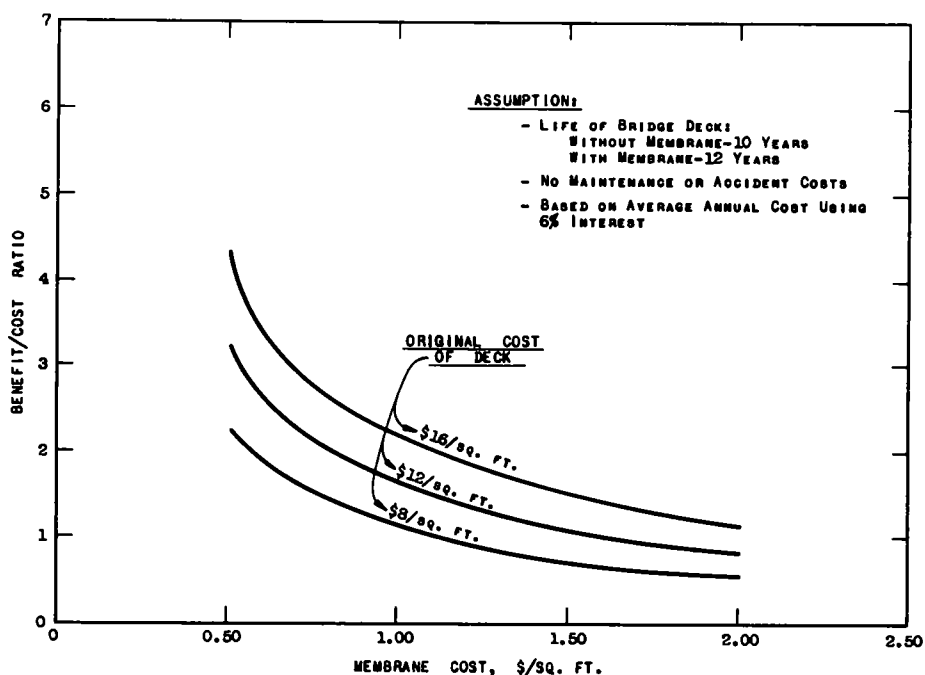


Figure 9 Relationship of benefit/cost ratio to membrane cost for various original costs of deck.

Average annual cost with membrane:

$$\text{Repaving} = \$0.20 \times 0.4173 \times 0.07823 = \$0.0065$$

\$0.78 Original deck

0.0065 Repaving

\$0.79 Total

Average annual cost of membrane:

$$1.50 \times 0.07823 = \$0.11$$

$$\text{Benefit/cost ratio} = \frac{\$1.08 - 0.79}{\$0.11} = 2.6$$

Estimated Membrane Costs

Estimated contract prices were prepared for furnishing and

placing the nine membrane systems that were evaluated by the field application test. Placement cost estimates are based on experience gained by their placement in this test, and on contract prices for other systems with similar handling characteristics. Material costs are based on prices for the general class of materials where no actual prices are available. These estimates are given in Table 13 as ranges of contract prices because actual contract prices depend on such variables as job size, local labor rates, remoteness of site, and contingencies for poor weather conditions in certain locations. These ranges will usually not significantly affect the benefit/cost decision (Figs. 8, 9).

TABLE 13

ESTIMATED CONTRACT COSTS FOR NINE WATERPROOFING MEMBRANE SYSTEMS

	COST (\$/FT ²)		
MEMBRANE NUMBER	MATERIAL	INSTALLATION	TOTAL CONTRACT
(a) Preformed			
6	\$0.29 to 0.35	\$0.25 to 0.50	\$0.44 to 0.85
20	0.82 to 0.95	0.25 to 0.50	1.07 to 1.45
21	0.49 to 0.60	0.25 to 0.50	0.74 to 1.10
135	0.49 to 0.60	0.25 to 0.50	0.74 to 1.10
10a	0.37 to 0.45	0.18 to 0.40	0.55 to 0.85
24	0.32 to 0.40	0.25 to 0.50	0.57 to 0.90
(b) Applied in Place			
94	1.01 to 1.15	0.40 to 0.65	1.41 to 1.80
67	0.40 to 0.45	0.35 to 0.60	0.75 to 1.05
63	0.67 to 0.75	0.35 to 0.60	1.02 to 1.35

Note. Total contract costs include cost of \$0.11 to \$0.15 for protective board placed over membrane before paving, except for systems 10a and 94 which were considered not to require such protection

CHAPTER FOUR

CONCLUSIONS

The comprehensive review of all information obtained from the various sources, together with the analysis of the results of the field survey of selected existing bridge deck membranes and of the laboratory and field test programs, lead to the general conclusions listed in the following paragraphs. It is important to note that all the conclusions of this study, including the selection of the five "most promising" systems, are valid only in regard to the specific materials evaluated and do not apply to new systems or to systems that have been modified since the evaluation was made.

1 A great variety of membrane systems have been installed on bridge decks, many of them in recent years on a trial basis, and large numbers of additional systems have been proposed for use. However, little factual information is available on the ability of these systems to perform effectively by preventing the penetration of deicing salts to the underlying concrete and reinforcing steel for an extended period of time.

2. The field survey and measurements indicated that none of the membrane systems in service is performing this function in a completely satisfactory manner. The major reasons for this generally unsatisfactory performance are.

- a. Use of systems that are not impermeable (even when placed under controlled laboratory conditions) because of defects, such as pinholes or bubbles, in the films or a tendency to emulsify in contact with water.
 - b. Improper construction practices, resulting in damage to the membrane during placement of the asphaltic concrete wearing course over the membrane.
 - c. Inability of membrane systems under service conditions to extend sufficiently to bridge moving cracks in the concrete deck, especially at low temperatures.
 - d. Membrane systems that softened excessively during high ambient temperature service, resulting in lateral movement in the wheelpaths or upward migration into the asphaltic concrete wearing course, thereby leaving insufficient material to function as a membrane.
3. The results of the laboratory test program indicated that.
- a. The electrical resistance test used in this study appears to be a suitable method for assessment of water permeability in both the laboratory and the field. Effective waterproofing membranes should provide near-infinite resistance when placed.
 - b. Impact-damage testing, by the method used in this study, appears to simulate damage to the membrane during construction. Membrane thickness was found to be the major factor in resisting impact damage. With a few exceptions, all systems would require an

additional protective layer covering the membrane to pass the impact-damage test. Damage was effectively assessed by the electrical resistance test.

- c. The crack-bridging test developed in this study appears to be effective in simulating the effect on membrane systems of cracks in a concrete bridge deck. In general, unreinforced systems with deflection temperatures at or below the crack-bridging test temperature met the criterion of 0.100-in. minimum crack opening. Such systems exhibited at least 200 percent tensile elongation at the same test temperature. Some fiber reinforced systems met this criterion even though tensile elongation at the same test temperature generally was less than 50 percent. In such systems, the fibers distribute the stress and allow an otherwise too-rigid material to bridge cracks. The majority of systems examined lacked the ability to bridge 0.100-in. cracks at 0 F.
 - d. Many polymers examined as waterproofing membranes were highly swollen by 36 weeks immersion in distilled water. In this condition, polymers exhibit physical properties quite different from the original
 - e. Systems exhibiting good fatigue resistance (repeated tensile elongation) at 0 F generally had deflection temperatures well below 0 F and tensile elongation of 200 percent or more.
4. The results of the laboratory test programs, combined with all other information available, indicate that a membrane system has a good chance of giving satisfactory performance in the field if it meets the requirements of the specifications (see Chapter Five) for any one of these five selected as most promising:
- a. *System 10a*—Preformed sheet of coal tar-modified polyvinyl chloride (PVC) with chopped fiber filler—125 mils thick.
 - b. *System 20*—Preformed sheet of vulcanized chloroprene rubber.
 - c. *System 21*—Preformed sheet of vulcanized butyl rubber.
 - d. *System 24*—Preformed sheet of butyl rubber, laminated to an asphalt-saturated felt.
 - e. *System 135*—Preformed sheet of ethylene-propylene rubber.
5. Specific types of systems meeting the requirements of the materials specifications contained in this study are
- a. Preformed elastomeric sheets Applied-in-place systems passing all other requirements did not form water-impermeable films on placement.
 - b. Vulcanized, cured, or crosslinked elastomers provided dimensional stability on exposure to hot asphaltic concrete (during construction), to water, to solar heat, and to freeze-thaw conditions.

6. No system encountered showed promise of functioning satisfactorily without a separate wearing course, and no evidence was found that any special wearing courses will give substantially better service than conventional dense-graded asphaltic concrete.

7. A procedure was developed for calculating the benefit/cost ratio for waterproof membrane systems for concrete bridge decks, and, under present bridge construction practices, the benefits should far outweigh the costs.

8. If a waterproof membrane system is to perform satisfactorily its function of protecting a concrete bridge deck from premature damage by deicing salts, proper installation of the membrane is vital. The importance of installation warrants special attention to inspection and quality control during construction.

9. Membrane systems in service should be examined periodically for evidence of continued effectiveness. Measurement of permeability by the electrical resistance test and measurement of corrosion of the reinforcing steel by the halfcell potential test are two methods that may be used for this purpose. It should not be assumed that a membrane is performing satisfactorily because no obvious leakage through the deck is observed. Nor should it be assumed that a membrane that has performed satisfactorily in the past will continue to perform satisfactorily under more severe conditions of increased use of deicing salts or higher volumes of traffic, or with less skillful membrane application.

CHAPTER FIVE

RECOMMENDATIONS FOR PHASE II EXPERIMENT

OBJECTIVE

Phase I of this study resulted in selecting, from among waterproof membrane systems that have been used or proposed for use, systems that give an indication of being the most promising. The systems selected have a good chance of giving satisfactory service if placed according to the procedures presented in the specifications. The objective of the Phase II experiment of this study is to evaluate, under actual field conditions, the systems selected in Phase I.

DESCRIPTIONS OF TEST SITES

Six sites are the minimum number recommended to be included within the scope of Phase II. The five systems selected in Phase I are to be installed at each site. Each installation shall consist of a width of at least two lanes plus shoulder (full width of the bridge deck is to be covered) and be at least 50 ft long. (Longer sections are preferable.) Each site is to consist of a single multiple-span bridge, or of two or more similar bridges in proximity on the same highway, so as to be essentially identical with respect to traffic and environmental conditions.

All sites should be selected with the following characteristics in common.

1. *Climatic conditions such that deicing salts are used during the winter months.* Waterproof membranes are considered for use only where such conditions exist.

2. *A deck on a newly constructed bridge, or a new deck on an older bridge.* It is the intent of this requirement that decks be in good structural condition, and that no salt will have been applied to the deck prior to placement of the membrane.

3. *A deck with a reasonably smooth surface.* A texture equivalent to that resulting from machine trowelling makes a good base for membrane system installation. Any irregularities, such as sharply projecting stones or voids left by removal of large stones, should be corrected as required by the specification before the membrane system is installed.

4. *Provision for positive flashing at the juncture of the membrane and the curb.* Joints between membrane and curb that depend on joint-filters to maintain water-tightness are a weak point in the system and require frequent attention by maintenance crews. If no other provision has been made for positive flashing, it is suggested that consideration be given to continuing the membrane up the curb completely over the walkway and covering the membrane in the walkway area with a wearing course of asphaltic concrete or with a portland cement concrete slab.

5. *Provision for closing the bridge to traffic while membrane system and wearing course are placed.* The purpose of this requirement is to permit no traffic to operate on the membrane, except for necessary rubber-tired, slow-moving construction traffic.

6. *A high volume of traffic with a high percentage of heavy trucks.* There was strong indication that some membranes are damaged by the action of traffic, therefore it is recommended that field trials be conducted under heavy traffic conditions.

The major variable to be investigated in the field is climate, with temperature being the most important climatic factor. It was concluded that membrane failures are often related either to their inability to maintain their integrity at small cracks in the deck, particularly during periods of colder temperatures, or to excess softening during higher

temperatures, resulting in lateral movement in the wheel-paths under traffic or upward migration into the asphaltic concrete wearing course.

A second variable to be included in the field trials is superelevation. Inclusion of a bridge deck with appreciable superelevation is intended to serve the purpose of uncovering any problems that might be associated with application of the membrane on a curved surface and with placement of an asphaltic concrete wearing course on a sloping membrane surface. It is also intended to investigate the effects of cross-slope on slippage at interfaces between the deck and the membrane, between the membrane and the asphaltic concrete wearing course, or within the membrane itself, particularly if excessive softening occurs at higher temperatures.

A third variable to be included is temperature during placement of the membrane. Membrane systems should be placed at a temperature that permits ready handling of pre-fabricated sheets, and placement and curing of prime coats and adhesives. For the membranes to be placed in the field trials, a minimum temperature of 50 F is specified. Because of the relatively short construction season in much of the area where membranes are used, and because membranes must often be scheduled for placement late in the construction season, it would be highly desirable to place membranes at lower temperatures.

The field sites are to be selected to provide a measure of the effects of each of these variables at two levels. Thus, in addition to the common characteristics described previously, sites are to have the following special conditions:

1. Sites I and II—less than 1 percent grade and in a moderate climate area. Moderate climate is defined as frequent freezing conditions during winter months, but rarely temperatures below 10 F, and frequent summer temperatures above 85 F.
2. Sites III and IV—less than 1 percent grade and in a severe climate area. Severe climate is defined as frequent winter temperatures below 10 F, and only occasional summer temperatures above 85 F.
3. Site V—on a superelevated curve and in a moderate climate area.
4. Site VI—less than 1 percent grade and in a severe climate area. Membrane is to be placed at a temperature of approximately 35 F to 40 F.

CONSTRUCTION

After selection of the sites, membrane systems will be placed according to the applicable materials and construction specifications, except for modification in application temperature at Site VI. It is recommended that the systems be placed by the cooperating highway agency using either its own crews or a qualified contractor. In addition to construction quality control by the highway agency, construction at all sites should be closely observed and monitored by the Phase II Principal Investigator or a qualified representative. Although it is intended that systems be placed under actual field conditions, it is important that construction result in uniform fabricated systems at all sites.

As far as possible, all systems at a given site should be

placed successively, with a minimum time interval between each placement. This is because it is desirable to place all systems at a site under essentially the same construction conditions, particularly temperature, and to provide for the most efficient and economical use of project personnel in observing and monitoring placement. It is anticipated that placement of the membrane systems at each site, including the asphaltic concrete wearing course, will be completed in approximately 2 weeks.

A record form, to be completed by the foreman at each site, should be prepared covering all significant aspects of construction. Where possible, the record will be supplemented by photographs. As far as possible, the asphaltic concrete surfacing for all installations will be of the same thickness and mix design.

TESTING

A program of field tests will be conducted on the systems as the primary basis for their evaluation. It is proposed that such tests be conducted during a 2-year period from the time of construction. A total of five test rounds will be conducted on each system at each site during the 2-year period. The initial test round will be conducted at the time of placement, and the four additional rounds at approximately 6-month intervals, with actual times to be selected to coincide with the beginning and end of the winter seasons. For example, if placement is in April 1974, the test rounds would be completed approximately as follows:

Round 1—April 1974, at time of placement.

Round 2—October 1974, at beginning of first winter season.

Round 3—April 1975, at end of first winter season.

Round 4—October 1975, at beginning of second winter season.

Round 5—April 1976, at end of second winter season.

The following tests will be conducted on each system during each test round:

1. Electrical resistance test, according to the field method used during Phase I. On the first round, measurements will be made both on the surface of the membrane systems before the asphaltic concrete wearing course is placed and on the surface of the asphaltic concrete wearing course after placement. Subsequent measurements will be made on the asphaltic concrete wearing course only.

2. Resistance measurements using conductive strips at the deck-membrane interface. A series of closely spaced copper tapes will be placed on the deck prior to placing each membrane. Initial measurement of resistance between the two strips in each pair will be made at the time of membrane placement, and measurements will be repeated during subsequent test rounds.

3. Tensile bond test, according to the field method developed and used during Phase I. Core samples immediately adjacent to the bond test locations will also be taken for purposes of visual inspection of the condition of the membrane system and for possible laboratory evaluation of the electrical resistance and adhesion under controlled conditions. Core holes will be carefully patched to fully restore the integrity of the waterproofing.

4. **Determination of chlorides content of deck concrete.** Determination will be made on samples taken from the deck before placement of the membrane and from core samples taken during subsequent test rounds

In addition to the foregoing tests and sampling, a series of photographs will be taken of each system during each test round to serve as a record for later reference and reporting. During the initial test round, the physical characteristics of the deck (including grade, slope, width, structural condition, and surface smoothness) will be recorded. The following information will also be obtained for each site:

- Average daily traffic, with seasonal variations.
- Percent trucks, classified by number of axles
- Traffic speeds.
- Temperature and precipitation records for the study period
- Amount and type of deicing salt used

It is expected that information on traffic and deicing salt use will be available from the cooperating highway agency, and temperature and precipitation data from local weather stations.

REPORTS

It is recommended that Phase II reporting consist of four progress reports—the first to include installation of the test sections and the results of the first test round, and the second, third, and fourth test sections to include the second, third, and fourth test rounds. The final report should be prepared after completion of the fifth test round. In addition to the findings and conclusions regarding the performance of the membrane test sections to that time, the final report should include specific recommendations about whether evaluation of the test sections should be continued, and, if so, a plan should be presented for continued study.

SPECIFICATIONS FOR WATERPROOFING MEMBRANE SYSTEMS

System 10A

Scope

This specification covers materials and construction for a waterproofing membrane system for portland cement concrete bridge decks to provide an impervious barrier to water and deicing salts.

Description

The waterproofing membrane system shall consist of a primer applied to the prepared deck surface, an adhesive, and a preformed sheet of waterproofing membrane. Under conditions where blistering is anticipated, a ventilating layer consisting of a perforated, preformed sheet shall be placed on the primer before application of the adhesive. A tack coat of emulsified asphalt and an asphaltic concrete wearing course shall be placed on the membrane system.

Materials

1. **Primer.** The primer shall be an asphalt meeting the requirements of ASTM D 41.

2. **Adhesive.** The adhesive shall be an asphalt meeting the requirements of ASTM D 312, Type III or Type IV. (Type IV shall be used unless Type III is designated by the Engineer.)

3 Waterproofing Membrane

a. **Description** The waterproofing membrane shall be a preformed sheet, 0.125 ± 0.010 in. in thickness and weighing 6.7 to 7.1 lb/yd². It shall be constructed of a polyvinyl chloride polymer extended with selected coal tar pitch and reinforced with nonwoven natural and synthetic fibers randomly and uniformly distributed throughout the thickness of the sheet. The sheet shall be impermeable, black in color, flexible, non-tacky, and packaged on rolls without release paper.

b. **Tensile strength and elongation.** When tested in accordance with ASTM D 412 (specimens cut from longitudinal direction of the roll using Die C) the ultimate tensile strength shall be 1000 psi to 1500 psi at 77 ± 3 F and 600 psi to 900 psi at 140 ± 3 F, and the elongation at break shall be 130 to 180 percent at 77 ± 3 F and 200 to 250 percent at 140 ± 3 F.

c. **Deflection temperature.** When tested in accordance with ASTM D 648 (specimen prepared by laminating with adhesive, oil bath replaced by isopropanol/dry ice, and using 264 psi load) the deflection temperature shall be -5 F to -15 F.

d. **Water absorption.** When tested in accordance with ASTM D 570, using 1×3 -in. specimens, the absorption after 7 days in distilled water at 77 ± 3 F shall be not more than 2.2 percent

e. **Dimensional stability.** When a 9×9 -in. specimen is exposed in air at 140 ± 3 F for one hour, it shall not change in dimension in either direction by more than ± 0.25 percent.

4. **Ventilating Sheet.** The ventilating sheet shall be a preformed sheet, 0.0500 in. to 0.0625 in. in thickness, meeting the requirements of ASTM D 250, with 0.875-in. to 1.000-in.-diameter holes evenly spaced center-to-center 3.00 in. to 3.25 in. in the transverse roll direction and 6.25 in. to 6.50 in. in the longitudinal roll direction. The surface shall be dusted with a fine sand (approximating 100 percent passing the No. 60 sieve), or other suitable mineral material, to prevent adhesion to the dry primed surface of the concrete; and shall bond to, and be compatible with, the asphalt adhesive.

Construction

1. **Preparation of the Surface** The surface of the deck shall have a smooth, fine-textured finish similar to that obtained by machine troweling. All honeycombed areas and surface cavities shall be cleaned and filled with approved patching materials. All sharp protrusions which, in the opinion of the Engineer, would puncture the membrane shall be removed. The surface shall be clean, dry, and free of laitance, oil, or other contaminants. Residual curing compound need not be removed if, in the opinion of

the Engineer, it will not interfere with adhesion of the primer or adhesive. Immediately before application of the primer, the deck shall be cleaned by brooming and blowing with a compressed-air jet.

2. *Application of Prime Coat.* The primer shall be thoroughly mixed before application. Primer shall not be applied when the air or deck temperature is less than 50 F, or during rain or fog. The primer shall be applied at the rate of 90 to 150 ft/gal to the entire area to which the membrane is to be applied. The primer shall be completely dry and all solvent evaporated before application of the membrane. (Note: This may require up to 24 hours, depending on temperature, humidity, and wind conditions.)

3. *Application of Adhesive and Membrane.* The adhesive shall not be applied when the air or deck temperature is less than 50 F, or during rain or fog. The adhesive shall be preheated in a thermostatically controlled roofing kettle to a temperature no higher than required for application by the method used. The adhesive shall be applied to the primed surface by pouring and distributing by a roofer's mop to the width of the membrane sheet. The membrane shall be immediately rolled and pressed into the adhesive in one continuous operation. An alternative method of application is by means of a roofing machine which mechanically applies the adhesive and membrane in one continuous operation. The adhesive and membrane shall overlap the previously applied membrane by at least 4 in. at the sides and 6 in. at ends. Membrane shall be applied with the longitudinal roll direction parallel to the direction of traffic on the bridge. Application shall begin at the lower points of the deck, in order that the direction of water flow will be over, rather than against, lapped edges and ends.

4. *Application of Ventilating Sheet.* If a ventilating sheet is specified, it shall be placed by unrolling directly onto the cured primer, in the same direction as specified for the membrane. Edges and ends of sheets shall be loosely butt-jointed, without overlap. The adhesive and membrane shall then be applied to the surface of the ventilating sheet in the same manner as specified previously for application to the primed surface.

5. *Application of Wearing Course.* A tack coat of emulsified asphalt and a wearing course of asphaltic concrete shall be applied to the surface of the membrane. No unnecessary traffic shall be permitted on the surface of the membrane, and trucks and paving equipment shall be operated in such a manner as to minimize the possibility of damage to the membrane. Any damage to the membrane shall be repaired before paving will be permitted to proceed.

System 20

Scope

This specification covers materials and construction for a waterproofing membrane system for portland cement concrete bridge decks to provide an impervious barrier to water and deicing salts.

Description

The waterproofing membrane system shall consist of two coats of adhesive, a preformed sheet of waterproofing mem-

brane, an asphalt emulsion bond coat, and a layer of protective board. A tack coat of emulsified asphalt and an asphaltic concrete wearing course shall be placed on the membrane system.

Materials

1. *Adhesive.* The adhesive shall be a general purpose solvent containing neoprene-based contact cement with a drying time of 20 to 60 min at 77 ± 3 F, and providing pressure-sensitive bond to itself after drying for a minimum of 4 hr at 77 ± 3 F. Naphtha or naphtha-like solvents shall not be used.

2. Waterproofing Membrane

a. *Description.* The waterproofing membrane shall be a preformed buffed sheet of vulcanized chloroprene 0.060 in. to 0.065 in. in thickness. The sheet shall be impermeable, black in color, flexible, non-tacky, and packaged in rolls without release paper.

b. *Tensile strength and elongation.* When tested in accordance with ASTM D 412 (specimens cut from longitudinal direction of the roll using Die C) the ultimate tensile strength shall be 1900 psi to 2200 psi at 77 ± 3 F and 1400 psi to 1800 psi at 140 ± 3 F, and the elongation at break shall be 260 to 300 percent at 77 ± 3 F and 230 to 270 percent at 140 ± 3 F.

c. *Deflection temperature.* When tested in accordance with ASTM D 648 (specimen prepared by laminating with adhesive, oil bath replaced by isopropanol/dry ice, and using 264 psi load) the deflection temperature shall be 45 F to 55 F.

d. *Water absorption.* When tested in accordance with ASTM D 570, using 1×3 -in. specimens, the absorption after 7 days in distilled water at 77 ± 3 F shall be not more than 0.65 percent.

3. *Bond Coat.* The bond coat shall be an asphalt emulsion meeting the requirements of ASTM D 977, Grade SS-1h.

4. *Protective Board.* The protective board shall consist of 4×8 -ft sheets, $\frac{1}{8}$ in. in thickness, of APOC Board manufactured by Asphalt Products Oil Corp., or equal.

Construction

1. *Preparation of the Surface.* The surface of the deck shall have a smooth, fine-textured finish similar to that obtained by machine troweling. All honeycombed areas and surface cavities shall be cleaned and filled with approved patching materials. All sharp protrusions which, in the opinion of the Engineer, would puncture the membrane shall be removed. The surface shall be clean, dry, and free of laitance, oil, or other contaminants. Residual curing compound need not be removed if, in the opinion of the Engineer, it will not interfere with adhesion of the adhesive. Immediately before application of the adhesive, the deck shall be cleaned by brooming and blowing with a compressed-air jet.

2. *Application of Adhesive and Membrane.* Adhesive shall not be placed when the air or deck temperature is less than 50 F, or during rain or fog. The adhesive shall be thoroughly mixed before application. One coat of adhesive shall be applied to the entire area to which the membrane

is to be applied and one coat to the entire underside of the membrane sheet. Application shall be by brush or roller at the rate of 120 to 150 sq ft/gal. The adhesive shall be allowed to become dry to the touch before placing the membrane. (Note: A convenient method of application is to unroll a length of membrane immediately adjacent to its intended position, apply the adhesive to the deck and the membrane in one operation, and, after the adhesive has dried, turn and roll the sheet longitudinally into position.) After placing, the membrane shall be lightly rolled with a hand roller or brushed with a stiff-bristle broom to firmly bond the membrane to the deck. The adhesive and membrane shall overlap previously applied membrane by at least 4 in. at the sides and 6 in. at ends. Membrane shall be applied with the longitudinal roll direction parallel to the direction of traffic on the bridge. Application shall begin at the lower points of the deck, in order that the direction of water flow will be over, rather than against, lapped edges and ends.

3. *Application of Protective Board.* A bond coat of asphalt emulsion shall be applied to the surface of the membrane at the rate of approximately 0.05 gal/yd² and allowed to dry until tacky. The sheets of protective board shall then be placed on the bond coat, with edges and ends of boards either loosely butt-jointed or overlapped, at the contractor's option.

4. *Application of Wearing Course.* A tack coat of emulsified asphalt and a wearing course of asphaltic concrete shall be applied to the surface of the protective board. No unnecessary traffic shall be permitted on the surface of the protective board, and trucks and paving equipment shall be operated in such a manner as to minimize the possibility of damage to the protective board and to the underlying membrane. Any damage to the protective board which, in the opinion of the Engineer, indicates the possibility of damage to the underlying membrane shall be investigated by removing the protective board and examining the membrane. If the membrane is damaged, it shall be repaired and new protective board placed before paving will be permitted to proceed.

System 21

Scope

This specification covers materials and construction for a waterproofing membrane system for portland cement concrete bridge decks to provide an impervious barrier to water and deicing salts.

Description

The waterproofing membrane system shall consist of two coats of adhesive, a preformed sheet of waterproofing membrane, an asphalt emulsion bond coat, and a layer of protective board. A tack coat of emulsified asphalt and an asphalt concrete wearing course shall be placed on the membrane system.

Materials

1. *Adhesive* The adhesive shall be a general purpose solvent containing neoprene-based contact cement with a

drying time of 20 to 60 min at 77 ± 3 F, and providing pressure-sensitive bond to itself after drying for a minimum of 4 hr at 77 ± 3 F. Naptha or naptha-like solvents shall not be used.

2. Waterproofing Membrane

a. *Description.* The waterproofing membrane shall be a preformed sheet of vulcanized butyl rubber, 0.0600 in. to 0.065 in. in thickness. The sheet shall be impermeable, black in color, flexible, non-tacky, and packaged in rolls without release paper

b. *Tensile strength and elongation* When tested in accordance with ASTM D 412 (specimens cut from longitudinal direction of the roll using Die C) the ultimate tensile strength shall be 1200 psi to 1500 psi at 77 ± 3 F and 1100 psi to 1400 psi at 140 ± 3 F, and the elongation at break shall be 300 to 350 percent at 77 ± 3 F and 280 to 320 percent at 140 ± 3 F.

c. *Deflection temperature.* When tested in accordance with ASTM D 648 (specimen prepared by laminating with adhesive, oil bath replaced by isopropanol/dry ice, and using 264 psi load) the deflection temperature shall be not greater than -70 F.

d. *Water absorption.* When tested in accordance with ASTM D 570, using 1×3 -in specimens, the absorption after 7 days in distilled water at 77 ± 3 F shall be not more than 0.15 percent.

3. *Bond Coat.* The bond coat shall be an asphalt emulsion meeting the requirements of ASTM D 977, Grade SS-1h.

4. *Protective Board.* The protective board shall consist of 4×8 -ft sheets, $\frac{1}{8}$ in. in thickness, of APOC Board manufactured by Asphalt Products Oil Corp., or equal.

Construction

1. *Preparation of the Surface.* The surface of the deck shall have a smooth, fine-textured finish similar to that obtained by machine troweling. All honeycombed areas and surface cavities shall be cleaned and filled with approved patching materials. All sharp protrusions which, in the opinion of the Engineer, would puncture the membrane shall be removed. The surface shall be clean, dry, and free of laitance, oil, or other contaminants. Residual curing compound need not be removed if, in the opinion of the Engineer, it will not interfere with adhesion of the adhesive. Immediately prior to application of the adhesive, the deck shall be cleaned by brooming and blowing with a compressed-air jet.

2. *Application of Adhesive and Membrane.* Adhesive shall not be placed when the air or deck temperature is less than 50 F, or during rain or fog. The adhesive shall be thoroughly mixed before application. One coat of adhesive shall be applied to the entire area to which the membrane is to be applied, and one coat shall be applied to the entire underside of the membrane sheet. Application shall be by brush or roller at the rate of 120 to 150 sq ft/gal. The adhesive shall be allowed to become dry to the touch before placing the membrane. (Note: A convenient method of application is to unroll a length of membrane immediately adjacent to its intended position, apply the adhesive to the deck and the membrane in one operation, and after

the adhesive has dried, turn and roll the sheet longitudinally into position.) After placing, the membrane shall be lightly rolled with a hand roller or brushed with a stiff-bristle broom to firmly bond the membrane to the deck. The adhesive and membrane shall overlap previously applied membrane by at least 4 in. at the sides and 6 in. at ends. Membrane shall be applied with the longitudinal roll direction parallel to the direction of traffic on the bridge. Application shall begin at the lower points of the deck, in order that the direction of water flow will be over, rather than against, lapped edges and ends.

3. *Application of Protective Board.* A bond coat of asphalt emulsion shall be applied to the surface of the membrane at the rate of approximately 0.05 gal/sq yd and allowed to dry until tacky. The sheets of protective board shall then be placed on the bond coat, with edges and ends of boards either loosely butt-jointed or overlapped, at the contractor's option.

4. *Application of Wearing Course.* A tack coat of emulsified asphalt and a wearing course of asphaltic concrete shall be applied to the surface of the protective boards. No unnecessary traffic shall be permitted on the surface of the protective board, and trucks and paving equipment shall be operated in such a manner as to minimize the possibility of damage to the protective board and to the underlying membrane. Any damage to the protective board which, in the opinion of the Engineer, indicates the possibility of damage to the underlying membrane shall be investigated by removing the protective board and examining the membrane. If the membrane is damaged, it shall be repaired and new protective board placed before paving will be permitted to proceed.

System 24

Scope

This specification covers materials and construction for a waterproofing membrane system for portland cement concrete bridge decks to provide an impervious barrier to water and deicing salts.

Description

The waterproofing membrane system shall consist of a primer applied to the prepared deck surface, an adhesive, a preformed sheet of waterproofing membrane, an asphalt emulsion bond coat, and a layer of protective board. A tack coat of emulsified asphalt and an asphaltic concrete wearing course shall be placed on the membrane system.

Materials

1. *Primer.* The primer shall be an asphalt meeting the requirements of ASTM D 41.

2. *Adhesive.* The adhesive shall be an asphalt meeting the requirements of ASTM D 312, Type III or Type IV. (Type IV shall be used unless Type III is designated by the Engineer.)

3. *Waterproofing Membrane*

a. *Description.* The waterproofing membrane shall be a preformed sheet of vulcanized butyl rubber, 0.030 in.

minimum thickness, laminated to asphalt-saturated asbestos fiber felt, 0.030 in. minimum thickness. The sheet shall be impermeable, black in color, flexible, non-tacky, and packaged in rolls without release paper.

b. *Tensile strength and elongation.* When tested in accordance with ASTM D 412 (specimens cut from longitudinal direction of the roll using Die C) the ultimate tensile strength shall be 1500 psi minimum and the elongation at break shall be 310 percent minimum when tested at 77 ± 3 F.

c. *Deflection temperature.* When tested in accordance with ASTM D 648 (specimen prepared by laminating with adhesive the butyl portion of the sheet only, oil bath replaced by isopropanol/dry ice, and using 264 psi load) the deflection temperature shall be not greater than -77 F.

4. *Bond Coat.* The bond coat shall be an asphalt emulsion meeting the requirements of ASTM D 977, Grade SS-1h.

5. *Protective Board.* The protective boards shall consist of 4×8 -ft sheets, $\frac{1}{8}$ in. in thickness, of APOC Board manufactured by Asphalt Products Oil Co., or equal.

Construction

1. *Preparation of the Surface.* The surface of the deck shall have a smooth, fine-textured finish similar to that obtained by machine troweling. All honeycombed areas and surface cavities shall be cleaned and filled with approved patching materials. All sharp protrusions which, in the opinion of the Engineer, would puncture the membrane shall be removed. The surface shall be clean, dry, and free of laitance, oil, or other contaminants. Residual curing compound need not be removed if, in the opinion of the Engineer, it will not interfere with adhesion of the primer or adhesive. Immediately before application of the primer, the deck shall be cleaned by brooming and blowing with a compressed-air jet.

2. *Application of Prime Coat.* The primer shall be thoroughly mixed before application. Primer shall not be applied when the air or deck temperature is less than 50 F, or during rain or fog. The primer shall be applied at the rate of 90 to 150 sq ft/gal to the entire area to which the membrane is to be applied. The primer shall be completely dry and all solvent evaporated before application of the membrane. (Note: This may require up to 24 hr, depending on temperature, humidity, and wind conditions.)

3. *Application of Adhesive and Membrane.* The adhesive shall not be applied when the air or deck temperature is less than 50 F, or during rain or fog. The adhesive shall be preheated in a thermostatically controlled roofing kettle to a temperature no higher than required for application by the method used. The adhesive shall be applied to the primed surface by pouring and distributing, by a roofer's mop, to the width of the membrane sheet. The membrane shall be immediately rolled and pressed into the adhesive, asbestos-felt side up, in one continuous operation. (An alternative method of application is by means of a roofing machine that mechanically applies the adhesive and membrane in one continuous operation.) The adhesive and

membrane shall overlap previously applied membrane by at least 4 in. at the sides and 6 in. at ends. Membrane shall be applied with longitudinal roll direction parallel to the direction of traffic on the bridge. Application shall begin at the lower points of the deck in order that direction of water flow will be over, rather than against, lapped edges and ends.

4. *Application of Protective Board.* A bond coat of asphalt emulsion shall be applied to the surface of the membrane at the rate of approximately 0.05 gal/sq yd and allowed to dry until tacky. The sheets of protective board shall then be placed on the bond coat, with edges and ends of boards either loosely butt-jointed or overlapped, at the contractor's option.

5. *Application of Wearing Course.* A tack coat of emulsified asphalt and a wearing course of asphaltic concrete shall be applied to the surface of the protective board. No unnecessary traffic shall be permitted on the surface of the protective board, and trucks and paving equipment shall be operated in such a manner as to minimize the possibility of damage to the protective board and to the underlying membrane. Any damage to the protective board which, in the opinion of the Engineer, indicates the possibility of damage to the underlying membrane shall be investigated by removing the protective board and examining the membrane. If the membrane is damaged, it shall be repaired and new protective board placed before paving will be permitted to proceed.

System 135

Scope

This specification covers materials and construction for a waterproofing membrane system for portland cement concrete bridge decks to provide an impervious barrier to water and deicing salts.

Description

The waterproofing membrane system shall consist of two coats of adhesive, a preformed sheet of waterproofing membrane, an asphalt emulsion bond coat, and a layer of protective board. A tack coat of emulsified asphalt and an asphaltic concrete wearing course shall be placed on the membrane system.

Materials

1. *Adhesive.* The adhesive shall be a general purpose solvent containing neoprene-based contact cement with a drying time of 20 to 60 min at 77 ± 3 F, and providing pressure-sensitive bond to itself after drying for a minimum of 4 hr at 77 ± 3 F. Naphtha or naphtha-like solvents shall not be used.

2. Waterproofing Membrane

a. *Description.* The waterproofing membrane shall be a preformed sheet of vulcanized propylene rubber, 0.060 in. to 0.065 in. in thickness. The sheet shall be impermeable, black in color, ethylene flexible, non-tacky, and packaged in rolls without release paper.

b. *Tensile strength and elongation.* When tested in accordance with ASTM D 412 (specimens cut from longitudinal direction of the roll using Die C) the ultimate tensile strength shall be 1300 psi to 1600 psi at 77 ± 3 F and 1000 psi to 1300 psi at 140 ± 3 F, and the elongation at break shall be 380 to 430 percent at 77 ± 3 F and 350 to 400 percent at 140 ± 3 F.

c. *Deflection temperature.* When tested in accordance with ASTM D 648 (specimen prepared by laminating with adhesive, oil bath replaced by isopropanol/dry ice, and using 264 psi load) the deflection temperature shall be not greater than -70 F.

d. *Water absorption.* When tested in accordance with ASTM D 570, using 1×3 -in. specimens, the absorption after 7 days in distilled water at 77 ± 3 F shall be not more than 0.2 percent.

3. *Bond Coat.* The bond coat shall be an asphalt emulsion meeting the requirements of ASTM D 977, Grade SS-1h.

4. *Protective Board.* The protective board shall consist of 4×8 -ft sheets, $\frac{1}{8}$ in. in thickness, of APOC Board manufactured by Asphalt Products Oil Corp., or equal.

Construction

1. *Preparation of the Surface.* The surface of the deck shall have a smooth, fine-textured finish similar to that obtained by machine troweling. All honeycombed areas and surface cavities shall be cleaned and filled with approved patching materials. All sharp protrusions which, in the opinion of the Engineer, would puncture the membrane shall be removed. The surface shall be clean, dry, and free of laitance, oil, or other contaminants. Residual curing compound need not be removed if, in the opinion of the Engineer, it will not interfere with adhesion of the adhesive. Immediately prior to application of the adhesive, the deck shall be cleaned by brooming and blowing with a compressed-air jet.

2. *Application of Adhesive and Membrane.* Adhesive shall not be placed when the air or deck temperature is less than 50 F, or during rain or fog. The adhesive shall be thoroughly mixed before application. One coat of adhesive shall be applied to the entire area to which the membrane is to be applied, and one coat shall be applied to the entire underside of the membrane sheet. Application shall be by brush or roller at the rate of 120 to 150 sq ft/gal. The adhesive shall be allowed to become dry to the touch before placing the membrane. (Note: A convenient method of application is to unroll a length of membrane immediately adjacent to its intended position, apply the adhesive to the deck and the membrane in one operation, and, after the adhesive has dried, turn and roll the sheet longitudinally into position.) After placing, the membrane shall be lightly rolled with a hand roller or brushed with a stiff-bristle broom to firmly bond the membrane to the deck. The adhesive and membrane shall overlap previously applied membrane by at least 4 in. at the sides and 6 in. at ends. Membrane shall be applied with the longitudinal roll direction parallel to the direction of traffic on the bridge. Application shall begin at the lower points of the deck, in

order that the direction of water flow will be over, rather than against, lapped edges and ends.

3. *Application of Protective Board.* A bond coat of asphalt emulsion shall be applied to the surface of the membrane at the rate of approximately 0.05 gal/sq yd and allowed to dry until tacky. The sheets of protective board shall then be placed on the bond coat, with edges and ends of boards either loosely butt-jointed or overlapped, at the contractor's option

4. *Application of Wearing Course* A tack coat of emulsified asphalt and a wearing course of asphaltic concrete

shall be applied to the surface of the protective board. No unnecessary traffic shall be permitted on the surface of the protective board, and trucks and paving equipment shall be operated in such a manner as to minimize the possibility of damage to the protective board and to the underlying membrane. Any damage to the protective board which, in the opinion of the Engineer, indicates the possibility of damage to the underlying membrane shall be investigated by removing the protective board and examining the membrane. If the membrane is damaged, it shall be repaired and new protective board placed before paving will be permitted to proceed.

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APPENDIX B

CLASSIFICATION METHOD

APPENDIX A

ANNOTATED BIBLIOGRAPHY

Appendix A is an annotated bibliography compiled from the review of published literature on membrane systems and includes articles by both United States authors and foreign authors. It is available on a loan basis or for the cost of reproduction from the Program Director, NCHRP, Transportation Research Board, 2101 Constitution Ave., N.W., Washington, D.C. 20418.

GENERAL

The purpose of this classification is to assist in the comparison and evaluation of the various waterproof membrane systems. It is designed to separate all systems into fairly well-defined classes with similar characteristics. The primary separation is accomplished by making five rather simple decisions regarding five basic characteristics. Each decision is expressed by the numbers 1 or 2, and the resulting five numbers are placed in an arbitrarily selected order to form a five-digit classification code. The characteristics selected as the basis for the classification, and the code numbers representing them, are as follows

- First digit - Preformed, 1 vs Applied-in-place, 2
- Second digit - Thermoplastic, 1 vs Thermosetting, 2
- Third digit - Unmodified, 1 vs. Modified, 2
- Fourth digit - Reinforced, 1 vs. Non-reinforced, 2
- Fifth digit - Wearing Course, 1 vs No Wearing Course, 2.

Thus, a membrane which might be described as a preformed sheet of a modified thermoplastic material, with no reinforcing, and requiring a separate wearing course, would be represented by five digits, as follows 1/1/2/2/1.

B-1

DEFINITIONS

For purposes of this classification system, the terms used are defined as follows

a A preformed membrane is one which is plant fabricated into sheets which are shipped to the bridge site either flat or in roll form, for installation on the prepared deck surface. The membrane is installed by bonding to the deck and sealing the joints between the sheets. Prime coats and adhesives may be required for bonding and sealing, or the sheets may be self-bonding.

An applied-in-place (built-up) membrane is one in which the component materials are shipped to the bridge site, and the materials are separately applied to the deck in the proper sequence to form the membrane. Such membranes might vary from a single liquid material applied by spray, brush, roller, or squeegee, to multiple applications of liquids, or liquids and reinforcing sheuts

b Thermoplastic materials are those which, after initial cooling or evaporation of solvents or water following application, do not permanently set through chemical reaction, but will appreciably change viscosity with change in temperature. In service they become softer (more fluid) as the temperature rises, and harder (less fluid) as the temperature decreases

B-2

Thermosetting materials are those which, following the initial permanent set through chemical reaction before or immediately following application, do not appreciably change viscosity with change of temperature in service. Although not thermosetting materials, metals are arbitrarily placed in this category for convenience

c The basic membrane material is said to be modified when an appreciable amount of a secondary material has been added to it in order to effect a change in properties or to serve as an extender. Examples are the modification of resin membrane materials with coal tar or asphalt, or the addition of fillers to coal tar or asphalt membrane materials.

Unmodified membranes are those to which no appreciable amount of such materials have been added. Materials added for the purpose of promoting setting or hardening are not considered modifiers, nor are emulsifiers or solvents added to simplify application considered to be modifications. Aggregates which are embedded in the surface of the membrane for its protection or to provide mechanical bonding action to the wearing course are also not considered to be modifiers.

d. Reinforcement is considered to be the incorporation into the membrane of one or more components

B-3

consisting of continuous sheets or fibers. The addition of fillers or discontinuous fibers (such as asbestos) is not considered to constitute reinforcement. If no such components are used, the membrane is considered to be unreinforced.

e. Membranes which must be protected from the action of traffic by a separate wearing course, such as one or more courses of asphalt concrete, are classed as requiring a "wearing course". If the wearing surface is an integral part of the membrane, it is classed as requiring "no wearing course".

SECONDARY CLASSIFICATION

Where a further breakdown of the primary classes described above may assist in the evaluation and comparison of membranes within the same class, a secondary separation was established for some of the classes, indicating the generic class of material. This secondary separation is expressed by means of a lower case letter placed after the primary classification digit to which it applies. The secondary separation to which the letters have been arbitrarily assigned is presented in the key which follows this section. Provision is made for expansion of this key by assigning letters to additional materials which may be used or proposed for use.

In the example of primary classification given above, a preformed sheet of a modified thermoplastic material,
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2. Thermosetting

- a Epoxy Resin
- b Polyester Resin
- c Polyurethane Resin, two-component
- d Chloroprene (vulcanized)
- e Polyisobutylene (Butyl) Rubber (vulcanized)
- f Polysiloxane Resin
- g Silicone Resin
- h Polysulfide Resin
- i Polyurea Resin
- j Vinyl/Chloroprene (vulcanized)
- k Lead
- l Soft Stainless Steel
- m Polyurethane Resin, one-component, moisture cure

Third Digit

- 1. Unmodified
- 2 Modified
- 0
 - a Asbestos Fiber
 - b Mineral Filler
 - c Coal Tar
 - d Petroleum Asphalt
 - e Petroleum Oil
 - f Styrene-butadiene Random Copolymer Latex
 - g Chloroprene Latex
 - h Vulcanized Rubber Crumb

B-6

with no reinforcing and requiring a separate wearing course was designated as 1/1/2/2/1. If the thermoplastic material was a coal tar ("a" in the key for the second digit) and it was modified with a mineral filler ("b" in the key for the third digit), this further classification would be expressed as follows 1/1a/2b/2/1.

KEY TO CLASSIFICATION

First Digit

- 1 Preformed
- 2 Applied-in-Place (Built-up)

Second Digit

- 1 Thermoplastic
 - a Coal Tar
 - b Asphalt
 - c Ethylene/Propylene/Diene Terpolymer
 - d Chlorinated Natural Rubber
 - e Butadiene/Acrylonitrile (Nitrile) Rubber, uncured
 - f Styrene/Butadiene/Random Copolymer
 - g Polyvinyl Chloride (vinyl)
 - h Polyvinylidene Chloride
 - i Polyacrylate (acrylic) resin
 - j Chloroprene (uncured)
 - k Chlorosulfonated polyethylene (uncured)
 - l Styrene/Butadiene Block Copolymer

B-5

- i Styrene-butadiene Block Copolymer Latex
- j Natural Asphalt
- k Portland Cement
- l Aggregate
- m Plasticizer (e.g. pine oil)
- n Epoxy Resin (uncured)
- o Polyvinyl Chloride

Fourth Digit

- 1 Reinforced
 - a Glass Fiber Fabric (cloth)
 - b Glass Fiber Mat
 - c Polyethylene Sheet
 - d Polypropylene Fiber Mat
 - e Nylon Fabric
 - f Chopped Glass Fibers
 - g Kraft Paper
- 2 Unreinforced

Fifth Digit

- 1. Wearing Course Required
- 2 No Wearing Course Required

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APPENDIX C

METHODS OF TEST

FIELD TESTS

ELECTRICAL RESISTANCE TEST

Equipment

V-O-M meter, Simpson model 269, with leads
 Electrode, Cellulose sponge in metal holder, 7 x 8 3/4
 x 2 in., with small bolt and wing nut attached
 for connecting one lead of V-O-M meter
 Additional cellulose sponges, approximately same size
 as the electrode sponge, for wetting the pavement
 Metal C-clamp, approximately 6 in size, with small
 bolt and wing nut attached for connecting one
 lead of V-O-M meter
 Water container, approximately one gallon capacity,
 with pouring spout and side handle

Materials

Wetting agent, Aerosol OT, 0.38% solution

Procedure

Lay out and mark on the surface of the pavement the
 points at which resistance readings are to be taken (It is
 suggested that at least 2 lines of readings be taken, one in the
 wheelpath area and one in the line of least traffic, such as the

C-1

being careful to maintain all sponges in a saturated condition.
 Continue to make additional rounds of measurements until the
 results of successive rounds remain essentially unchanged,
 except that if readings remain at essentially infinity, measure-
 ments should be continued until at least 4 hours after initial
 placement of the wetting sponges

Recheck the zero reading of the meter before starting
 each measurement round, and when changing from one meter scale
 to another. When using meter scales of 1 K or less, make one
 reading, reverse the leads on the meter, make a second reading,
 and average the two readings

BOND TEST

Equipment

Concrete coring machine, equipped with 2" I D core
 barrel
 Cylindrical wooden blocks, 1 3/4" diameter by about
 2" long, with a screw eye inserted in the center
 of one end (wooden blocks were made by cutting
 lengths from 1 3/4" diameter fir hand-rail stock,
 and screw eyes used were made from 7/32" diameter
 stock with an eye of approximately 7/8" diameter)
 Spring scale, 100 lb capacity x 1 lb divisions (such
 as Chatillon, Type-160, capacity 100 lbs x 1 lb)
 with hook on lower end and pulling handle on the
 upper end

C-4

shoulder area, and that each row consist of at least 10 readings,
 at intervals of approximately 5 to 10 feet, depending on the
 length of the deck area under consideration) Saturate wetting
 sponges with aerosol OT solution, and place one on each marked
 point on the pavement Keep sponges saturated by frequent addi-
 tion of Aerosol OT solution by pouring from the water container.
 Make first resistance readings after sponges have been in position
 approximately one-half hour (See Figure C-1)

To make resistance readings attach the C-clamp to the
 bridge railing in such a manner as to make a good electrical
 contact with the reinforcing steel in the bridge deck (Usually
 simply by tightening the clamp on a nut or bolt of the metal rail
 If railing is entirely of concrete, it may be necessary to chip
 out a small area of concrete to expose the reinforcing steel
 Corrosion on metal should be completely removed by filing or
 scraping before attaching the clamp) Attach one lead from
 V-O-M meter to the connection on the C-clamp Saturate the
 electrode sponge and attach the other lead from the V O-M meter
 to the connection on the metal sponge holder Check zero setting
 of V-O-M meter Pick up one of the saturated wetting sponges
 from the pavement, replace it with the saturated electrode
 sponge, record the resistance indicated on meter, pick up the
 electrode sponge, and replace the wetting sponge on its original
 position on the pavement Repeat this operation until a complete
 round of measurements has been made on all points Make addi-
 tional rounds of measurements at about one-half hour intervals,

C-2

Hammer, 1 to 2 lbs

Cold chisel, 1/2 to 3/4 inch width by any convenient
 length over 6 inches.

Materials

Rapid setting, high strength epoxy adhesive (such as
 Lo Page's 5-minute Epoxy Resin, or Devcon 2-ton
 Epoxy Super Glue).

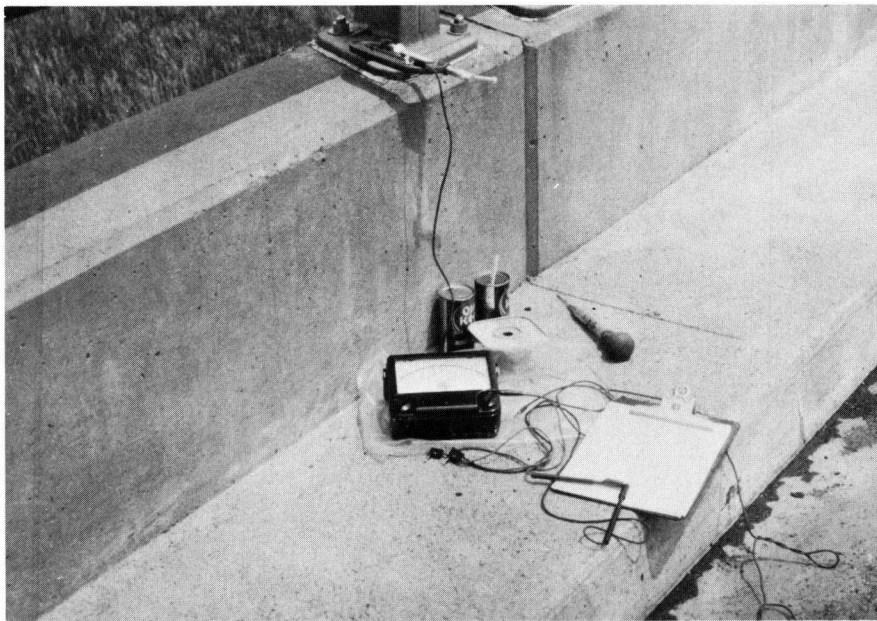
Procedure

With coring machine, core through the asphalt concrete
 wearing course, the membrane, and approximately one inch into
 the portland cement concrete deck Withdraw the core barrel,
 leaving the core in place. (To reduce possibility of binding
 and breaking off the core, operate the coring machine at mode-
 rate speed and do not shut off the cooling water supply while
 withdrawing the core barrel.) Repeat the operation approxi-
 mately 1/4 inch from the first core Thoroughly clean and dry
 the surface of one of the cores, and bond a cylindrical wooden
 block to the center of the core with rapid setting, high
 strength epoxy adhesive. After adhesive has set, insert the
 hook of the spring scale into the screw eye of the cylindrical
 wooden block, and slowly pull straight up on the pulling
 handle until failure occurs in the core Record the maximum
 reading of the spring scale, to the nearest pound, as the bond
 strength. Examine the removed portion of the core, and record
 where failure occurred (See Figure C-2.)

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(a)



(b)

Figure C-1. Electrical resistance test with saturating sponges in place and showing electrode sponge with handle (a) and meter with connections (b).



Figure C-2. Field bond test with cylindrical wooden block in place ready for testing (left). After testing, the core on right is removed by chiseling from the core hole on left.

From the core hole, use hammer and cold chisel to remove the second core by cracking the portland cement concrete horizontally at least 1/2 inch below the membrane. Record the thickness of the membrane and the asphalt concrete wearing course, and the appearance of the portland cement concrete, the membrane, and the asphalt concrete wearing course. (The core so removed may be retained for record or for laboratory testing, if desired.)

LABORATORY CHARACTERIZATION TESTS

ULTIMATE TENSILE STRENGTH AND ELONGATION AT BREAK

(ASTM METHODS D 412, D 638, AND C 190)

Specimens of membranes flexible enough to be cut with a die mounted in a punch press were cut from preformed membranes or cast sheets using ASTM D 412, die C. Specimens of cast sheets of less flexible membranes were machined to the dimensions of ASTM D 638, Type I specimen. Specimens of mortars were cast in ASTM C 190 briquet molds. (All the above specimens are dumbbell-shape.)

The mortar specimens were tested at a loading rate of 600 lb/minute according to ASTM C 190. The machined specimens were tested by ASTM D 638, pulling at a clamp-separation rate of 0.2 inches per minute. The die-cut specimens were tested at room temperature by ASTM D 412, pulling at a clamp-separation rate of 20 ipm. Additional specimens

were tested at 0.2 ipm for those membranes which broke at less than 70% elongation at 20 ipm.

Tests at 0°F and 140°F were run at the speed used for testing the same membrane at room temperature. Values reported are averages of at least three specimens.

HARDNESS (ASTM METHOD D 2240)

Indentation hardness was read instantaneously (1 second) and after 15 seconds creep using the Shore A durometer. Membranes harder than A90 were tested with the Shore D durometer.

WATER ABSORPTION (ASTM METHOD D 570)

Specimens were tested for Long-Term Immersion as specified in ASTM D 570, continuing the immersion until the cutoff date for inclusion of the data in the report.

GLASS TRANSITION TEMPERATURE

Bars 0.5 x 0.5 x 5 inches were tested according to ASTM method D 648, except that the liquid heat transfer medium was methanol, chilled with dry ice. Specimens of preformed membranes were prepared by plying sheets to 0.5 inch thickness; the others were cast in molds.

POT LIFE

Pot life reported for two-component reactive membrane systems is the time at room temperature required

for a filled 100 ml beaker of the mix to become too viscous to pour.

THIN-FILM SET TIME

Thin-film set time reported is the time at room temperature required for the surface of a cast sheet to become substantially tack-free.

RESILIENCE (ASTM METHOD D 2832)

Impact resilience by vertical rebound was measured at room temperature with the Bashore Resiliometer on specimens 0.5 inch thick. Specimens of preformed membranes were prepared by plying sheets to the required thickness, the others were cast in molds.

STAIN TEST

Equipment

- Oven, 140 ± 2°F
- Rigid Steel shelf
- Weights, 1,000 g (one per specimen)
- Punch, hollow, 5/8 inch inside diameter
(No. 9 cork borer)
- Darkroom and ultra-violet light source, or
viewing box as described in ASTM Method D 1328

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different) Record any unusual observations, such as change in dimensions of the specimen

PREPARATION OF PERFORMANCE TEST SPECIMENS

The test specimens for the laboratory performance tests were prepared by applying the membrane system to commercial lightweight portland cement concrete blocks of nominal 16 x 8 x 1 1/2 inch size. The surface to which the system was to be applied was filled with a grout of portland cement and fine sand to prevent excessive absorption of the membrane materials. A 1/8" wide, 1/2" deep transverse groove was sawed at the center of the under side of the block, for the purpose of controlling the location of the crack in the "crack-bridging" test. The blocks were air-dried and the top surfaces were lightly wire-brushed before application of the membrane materials. Manufacturers' suggested application procedures were used as a guide to application of each system (Details of application of each system are presented in Table C-1). Each membrane system was applied to four concrete blocks, designated and labelled as specimen A, B, C, and D. For each specimen the approximately 8" x 8" area on one side of the transverse groove was labelled as "Side 1," and on the other side as "Side 2."

PERFORMANCE TEST CYCLE

A complete cycle of laboratory performance tests consisted of the following

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Materials

Manila folder stock cut to size specified below
Cigarette papers, Washington No. 4 or equal,
nominally 1 1/2 x 2 3/4 inch

Procedure

Prepare specimens 2 cm² in area by cutting from sheet stock with 5/8 inch diameter hollow punch, or by cutting or sawing 1.4 cm squares. Measure and record thickness of specimen. Count out 30 sheets of cigarette paper, fold the stack of 30 sheets once, and place the specimen in the middle of the "book." Cover the steel oven shelf with a clean piece of manila folder stock, place each assembled "book" on the shelf, cover it with a clean 1 1/2 inch square of manila folder stock, and place a 1-kg weight on top of it.

(Note: The oven location must be free of vibration, or the weights may fall. A grid of wires may be used to provide lateral support for the weights but must not support them in such a way that the weight on the specimen is reduced.)

At the end of 120 hours in the 140°F oven, remove the specimens and carefully examine the "books" to determine how many layers of cigarette paper are stained. Record stain under visible light and fluorescence under ultra-violet light, report as "Stain Number" whichever is higher (average the number of stained sheets on each side of the specimen if

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SPECIMEN A

- a) check bond of membrane system to concrete block
- b) electrical resistance measurements on Side 1 and Side 2
- c) impact damage test at room temperature on Side 1
- d) electrical resistance measurement on Side 1
- e) subject entire specimen to heat cycle
- f) check bond of membrane system to concrete block
- g) electrical resistance measurements on Side 1 and Side 2
- h) impact damage test at room temperature on Side 2
- i) electrical resistance measurement on Side 2
- j) crack-bridging test at room temperature

SPECIMEN B

- a) check bond of membrane system to concrete block
- b) electrical resistance measurements on Side 1 and Side 2
- c) subject entire specimen to heat cycle
- d) check bond of membrane system to concrete block
- e) electrical resistance measurements on Side 1 and Side 2
- f) crack bridging test at 0°F
- g) creep damage test (Procedure B) on Side 1 at 140°F
- h) electrical resistance measurement on Side 1

SPECIMEN C

- a) check bond of membrane system to concrete block
- b) electrical resistance measurements on Side 1 and Side 2
- c) impact damage test at 140°F on Side 1

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TABLE C-1. - DETAILS OF APPLICATION OF SYSTEMS TO BLOCKS FOR LABORATORY PERFORMANCE TESTS

System Number	Primer		M e m b r a n e					Comments
	No. of Coats; Application Rate	Dry or Cure Time	Recommended Appl. Rate or Thickness, inches	Component Ratio; Application Temperature	No. of Coats; Time Between Coats	Tack Free Time	Applied Thickness, inches	
1	two, one each to membrane and block; brush coat	2 hrs.	0.036	NA	NA	NA	.0625	Some small air bubbles trapped under sheet; unable to remove by rolling.
2	one; troweled on blocks	15 min.	0.020	NA	NA	NA	.0313	No evidence of trapped air bubbles, good bond.
3	one; brush coat	15 min.	0.063	NA	NA	NA	.0468	Some air bubbles formed under sheet about 45 min. after application.
5	one; brush coat	15 min.	0.063	NA	NA	NA	.0625	Some air bubbles formed under sheet about 45 min. after application.
6	one; troweled on blocks	30 min.	0.055	NA	NA	NA	.0625	Adhesive gummy, difficult to apply; air bubbles trapped under sheet, could not remove.
C-12 7	one; troweled on blocks	30 min.	0.055	NA	NA	NA	.0625	Adhesive gummy, difficult to apply; air bubbles trapped under sheet, could not remove.
9	two; 25 min. interval; brush coat	15 min.	0.095	NA	NA	NA	0.095	Paper backing on sheet difficult to remove.
10	one; brush coat	none	0.078	NA; 425°F	NA	NA	0.078	Blocks heated prior to brushing on adhesive; sheet applied immediately.
10a	one; brush coat	none	0.125	NA; 425°F	NA	NA	0.125	Blocks heated prior to brushing on adhesive; sheet applied immediately.
11	one; brush coat	5½ hrs.	0.062	NA; 425°F	NA	NA	.1875	Used pour and roll method to apply adhesive and membrane.
12	two; brush coats.	45 min.	0.062	NA	NA	NA	.0625	Rolled membrane into adhesive.
13	one; brush coat	1 hr.	0.080	NA	NA	NA	.080	Rolled membrane into adhesive.
15	one; brush coat	1 hr.	0.050	NA; 425°F	NA	NA	.0625	Blocks heated prior to applying adhesive and membrane by pour and roll method.
16	one; brush coat	1 hr.	0.050	NA; 425°F	NA	NA	.0625	Blocks heated prior to applying adhesive and membrane by pour and roll method.

TABLE C-1. - DETAILS OF APPLICATION OF SYSTEMS TO BLOCKS FOR LABORATORY PERFORMANCE TESTS (Continued)

System - Number	Primer		M e m b r a n e					Comments
	No. of Coats; Application Rate	Dry or Cure Time	Recommended Appl. Rate or Thickness, inches	Component Ratio; Application Temperature	No. of Coats; Time Between Coats	Tack Free Time	Applied Thickness, inches	
17	one; brush coat	3½ hrs.	0.040	NA; 315°F	NA	NA	.0625	Blocks heated prior to applying adhesive and membrane by pour and roll method.
19	one; brush coat	15 min.	0.063	NA	NA	NA	.0468	Some air bubbles formed under sheet about 45 minutes after application.
20	two, one each to membrane and block; brush coat	2 hrs.	0.036	NA	NA	NA	.0625	Some small air bubbles trapped under sheet; unable to remove by rolling.
21	one; brush coat	15 min.	0.036	NA	NA	NA	.0625	Some air bubbles formed under sheet about 45 min. after application.
22	one; brush coat	10 min.	0.0625	NA	NA	NA	.0625	Rolled membrane into adhesive with small hand roller.
23	one; brush coat	10 min.	0.0625	NA	NA	NA	.0625	Rolled membrane into adhesive with small hand roller.
24	one; brush coat	3½ hrs.	0.0625	NA	NA	NA	.0625	Blocks heated prior to applying adhesive and membrane by pour and roll method.
25	one; diluted emulsion brush coat	1½ hrs.	0.022 to 0.037	NA	NA	NA	0.313	Applied emulsion, placed glass cloth, and applied second coat of emulsion.
26	none	NA	0.051	NA; 425°F	NA	NA	.0625	Three brush applications of hot asphalt alternated with 3 layers of glass fabric.
27	none	NA	50 ft ² /gal	room temp.	one; 24 hrs.	--	0.031	Some bubbles formed after brushing on last coat, most removed by re-brushing.
28	none	NA	0.1 gal/yd ²	1:1; room temp.	one	20 min.	0.016	
34	one; brush coat	21 hrs.	0.020 to 0.028	NA	NA	--	0.028	Applied adhesive, placed glass fabric and brushed on, and applied second coat of adhesive.
40	none	NA	0.375	NA	NA	NA	0.437	Placed fiber glass sheet on block, applied mastic and troweled to 3/8" thickness.
50	none	NA	0.1975	NA. 425°F	NA	NA	0.187	Blocks heated prior to applying hot membrane material with trowel.

TABLE C-1. - DETAILS OF APPLICATION OF SYSTEMS TO BLOCKS FOR LABORATORY PERFORMANCE TESTS (Continued)

System Number	Primer		M e m b r a n e					Comments
	No. of Coats, Application Rate	Dry or Cure Time	Recommended Appl. Rate or Thickness, inches	Component Ratio, Application Temperature	No. of Coats; Time Between Coats	Tack Free Time	Applied Thickness, inches	
51	none	NA	0.1875	NA; 400°F	NA	--	0.187	Applied hot membrane material.
52a	none	NA	0.35 gal/yd ²	NA	NA	--	0.125	Placed masking tape around edge of block to retain poured emulsion, and placed fabric in fresh emulsion. Fabric wrinkled.
52b	one; 0.03 gal/yd ²	4 hrs.	0.25 gal/yd ²	300°F	one	--	0.125	Blocks heated prior to applying hot asphalt with trowel; immediately applied fabric, some wrinkles.
52c	none	NA	0.40 gal/yd ²	NA	one	--	0.125	Placed masking tape around edge of block to retain poured emulsion, and placed fabric in fresh emulsion. Fabric wrinkled.
52d	none	NA	0.40 gal/yd ²	NA	one	--	0.125	Placed masking tape around edge of block to retain poured emulsion and placed fabric in fresh emulsion. Fabric wrinkled.
61	none	NA	3½ gal/100 ft ²	room temp.	two; 24 hrs.	--	0.078	Brushed on blocks, some air bubbles appeared. Re-brushing after 10 min. removed most bubbles. Second coat same as first.
63	one; brush coat	2 hrs.	20 ft ² /gal	368:910; room temp.	one	--	0.016	
67	none	NA	0.074-0.152	9:1 by wt. room temp.	one	5 hrs.	0.078	Place masking tape around edge of block to retain poured membrane material, spread with brush.
68	none	NA	Apply until puddled	1:1 room temp.	one	--	--	Applied until puddled, penetrated block and dried rapidly.
72a	one; brush coat	35 min.	75 cc/block	0.75:2% MEK Peroxide; room temp.	two; 24 hrs.	Remained tacky after drying	0.125	
72b	one; brush coat						0.140	Broadcast with silica sand after each coat.
73	one; brush coat						0.344	Troweled on blocks, very sticky after 4 days.

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TABLE C-1. - DETAILS OF APPLICATION OF SYSTEMS TO BLOCKS FOR LABORATORY PERFORMANCE TESTS (Continued)

System Number	Primer		Membrane					Comments
	No. of Coats; Application Rate	Dry or Cure Time	Recommended Appl. Rate or Thickness, inches	Component Ratio; Application Temperature	No. of Coats; Time Between Coats	Tack Free Time	Applied Thickness, inches	
77	none	NA	32 ft ² /gal	34:1; room temp.	two; 24 hrs.	--	0.031	
78	one; brush coat	1 hr.	60 mils	10:1; room temp.	--	>24 hrs.	0.063	Applied half of liquid, glass fabric, then remainder of liquid. Some wrinkles remained in glass fabric.
79	none	NA	150 cc/block	50-50 by wt; room temp.	two; 5 min.	--	0.047	Applied half of liquid, glass cloth, then remainder of liquid.
80	none	NA	30-40 ft ² /gal 400 ft ² /gal	NA room temp.	two; 4 hrs.	--	0.094	Applied half of liquid, glass cloth, then remainder of liquid.
88	none	NA	150 cc/block	1:2 room temp.	two; 3 hrs.	--	0.063	Many bubbles in first coat, some in second.
93	none	NA	25 ft ² /gal each coat	231:219 room temp.	three; 24 hrs. - 2nd, 72 hrs. - 3rd	--	0.063	Each coat still very tacky at time of application of next coat.
C-15 94	brush coat	35 min.	0.10 gal/yd ² 0.67 gal/yd ²	100:6.38, 100:14.3; room temp.	two of sealent; 20 hrs., then one of membrane	3½ hrs.	0.125	
98	none	NA	75 cc/block each coat	50-50 by wt; room temp.	two; 4½ hrs.	5½ hrs.	0.047	First coat still very sticky when second coat applied.
99	none	NA	75 cc/block each coat	50-50 by wt; room temp.	two; 2 hrs.	4½ hrs.	0.047	
100	none	NA	--	1:1:¼ by vol. room temp.	one	--	--	Applied until puddled, penetrated into block.
102	none	NA	4 gal/100 ft ²	2:3; room temp.	one	still tacky after curing	0.063	
103	none	NA	1 gal/20 ft ²	1:1 by wt; room temp.	one	indefinite	0.188	Remained soft and sticky since applying.
104	none	NA	75 cc/block each coat	1:1 by vol. 125°F	two; 2 hrs.	>1½ hrs.	0.062	Heated components before mixing, spread with brush.
105	none	NA	75 cc/block each coat					
106	one	2½ hrs.	75 cc/block each coat	1:1 by vol. room temp.	two; 2 hrs.	45 min.	0.062	

TABLE C-1. - DETAILS OF APPLICATION OF SYSTEMS TO BLOCKS FOR LABORATORY PERFORMANCE TESTS (Continued)

System Number	Primer		M e m b r a n e					Comments
	No. of Coats, Application Rate	Dry or Cure Time	Recommended Appl. Rate or Thickness, inches	Component Ratio; Application Temperature	No. of Coats; Time Between Coats	Tack Free Time	Applied Thickness, inches	
107	none	NA	75 cc/block each coat	1:1 by vol. room temp.	two; 2 hrs.	2 hrs.	0.062	Some bubbles formed, most eliminated by rebrushing.
110	none	NA	0.062" min.	14.6:85.5; 250°F	two; 1 hr. 15 min.	--	0.094	Material set very fast, very difficult to get uniform coverage.
112	none	NA	75 cc/block each coat	958.7:838.5; room temp.	two; 2 hrs. 15 min.	3 hrs.	0.062	Some bubbles appeared after application.
115	brush coat	1 hr.	0.375	3½:1 by vol. room temp.	NA (mortar)	--	0.375	Compacted with small hand roller.
117	none	NA	0.375" total thickness	117:100.5; room temp.	NA (mortar)	--	0.375	Compacted with small hand roller.
119	none	NA	0.375" total thickness	1:1:1 room temp.	NA (mortar)	--	0.375	Compacted with small hand roller.
121	brush coat	--	0.875" total thickness	14.6:85.5; 250°F	NA		0.875	Compacted with small hand roller.
127	none	NA	250 ft ² /gal	10:1; room temp.	--	--	--	Absorbed very rapidly into block
128	none	NA	0.062	100:15 by wt; room temp.	two; 2 hrs.	3 hrs.	0.062	Difficult to apply uniformly, very sticky.
129	none	NA	0.0625	600:400; room temp.	two; 22 hrs.	indef.	0.062	
130	none	NA	150 ft ² /gal	NA; room temp.	one	--	--	Penetrated into block.
131	none	NA	25 mil.	NA; room temp.	one	--	0.031	
132	none	NA	25 mil.	100:9.6 by wt; room temp.	one	11 min.	0.031	Set very rapidly, difficult to apply uniformly.
133	brush coat	45 min.	0.084	NA	NA	NA	0.094	
134	brush coat	45 min.	0.071	NA	NA	NA	0.156	
135	none	NA	0.061	NA	NA	NA	0.062	Rolled sheet into adhesive with small hand roller.
136	none	NA	135 ft ² / 1 imp. gal.	3.12:1; room temp.	two; 3 hrs. 40 min.	7 hrs.	0.062	

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TABLE C-1. - DETAILS OF APPLICATION OF SYSTEMS TO BLOCKS FOR LABORATORY PERFORMANCE TESTS (Continued)

System Number	Primer		Membrane					Comments
	No. of Coats; Application Rate	Dry or Cure Time	Recommended Appl. Rate or Thickness, inches	Component Ratio; Application Temperature	No. of Coats; Time Between Coats	Tack Free Time	Applied Thickness, inches	
137	none	NA	75 cc/block each coat	100:70:62; room temp.	two; 2 hrs. 20 min.	6 hrs.	0.062	Blocks and perforated sheet heated before applying adhesive and membrane.
138	none	NA	75 cc/block each coat	6:4 by wt; room temp.	two; 22 hrs.	2½ hrs.	0.062	
139	none	NA	0.031 each coat	155:150	two; 24 hrs.	16 hrs.	0.062	
141	brush coat	24 hrs.	0.06 each coat	61.8:38.2	two; 24 hrs.		0.062	
142	brush coat	4 hrs.	0.125	NA; 375°F	NA	--	0.125	

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- d) electrical resistance measurement on Side 1
e) subject entire specimen to heat cycle
f) check bond of membrane system to concrete block
g) electrical resistance measurements on Side 1 and Side 2
h) creep damage test (Procedure A) at 140°F on Side 2
i) electrical resistance measurement on Side 2.

SPECIMEN D (epoxy)

DESCRIPTION OF PERFORMANCE TESTS

BOND (QUALITATIVE METHOD)

Before running any other tests on the specimens, check the bond of the membrane to the concrete block by gently lifting, or attempting to lift, the edges of the membrane. Record any absence of bond, curled edges, bubbles, wrinkles, etc.

After the heat cycle, make a 1 x 1 inch L-shape cut through the membrane on Side 1, avoiding holes made by the impact damage test, and lift the corner of the cut with a knife point. Record a subjective evaluation of the bond and the nature of failure if bond is poor.

ELECTRICAL RESISTANCEEquipment

V-O-M meter, Simpson model 269, with leads

Electrode, cellulose sponge in metal holder,

6 x 6 x 1 in.

C-19

Materials

Wetting agent, Aerosol OT, 0.38% solution

Procedure

Place specimens to be tested in a metal pan. Fill the pan with water to a level 0.25 inch below the bottom of the membrane. Saturate sponges with Aerosol OT solution and place them on the areas to be tested. Allow to soak 20 minutes. Avoid wetting at least 0.5 inch of the outside edges of the membrane.

Saturate electrode sponges with Aerosol OT solution. Connect one lead wire to edge of metal pan. Check zero setting of meter by touching the other lead to the pan. Place electrode sponge in position, connect lead and record resistance. Rotate electrode 180° and repeat the measurement when using the 10² or 10³ scale, reverse the leads and repeat measurements. Average the values if different.

IMPACT DAMAGE TEST METHODEquipment

Oven, circulating air, or controlled temperature cabinet, approximately 30" x 30" x 48" high, controlled at 77 ± 2°F and 140 ± 2°F, with shelves for conditioning specimens and with transparent front and access ports so that manipulations can be performed without opening door.

C-20

Round chisel (punch), 90° conical point of tool steel, head approximately 3 inch x 1 inch diameter plus shaft approximately 30 inch x 1/2 inch diameter, with adjustable slip ring with thumb screw, total weight 1000 ± 1g

Chisel guide, rigidly mounted on arms extending 8 inch from inside wall of cabinet, consisting of 5/8 inch inside diameter brass tube lined with teflon so that the chisel can fall with a minimum of friction, and a quick-release catch to support the chisel

Carriage for specimens, consisting of a heavy wooden base of the same dimensions as the specimen blocks, with metal slides on the bottom, one untreated concrete specimen block on top, and hardboard guides extending above this block to locate test specimen blocks

8 inch (200 mm) rule or spacer

Procedure

Condition test specimens at the test temperature (77 or 140°F) Place a specimen block on top of the concrete block on the carriage, check that it rests solidly without rocking. Adjust the slip ring on the chisel shaft so that the chisel, in its "up" position, is 200 ± 1 mm above the surface of the specimen. Release the catch to drop the chisel on the specimen

C-21

Template, wood, 7 5/8 x 7 5/8 x 3/8 inch with centered 5 inch square opening

Rubber pads, hardness (Shore A) 62 ± 2, 6 x 6 x 1/8 inch

Plywood blocks, 6 x 6 x 1/2 to 3/4 inch

Weights 12 inch x 6 inch diameter concrete cylinders. (Select cylinders and blocks so that the total weight of cylinder, plywood block, and rubber pad is 30 lb ± 1 oz. Add sheet lead if required.)

Materials

Watsonville granite chips passing 3/8 inch sieve (9 51 mm) and retained on #3 sieve (6 73 mm)

Metal jackstones

Procedure A

Place the test specimen (1/2 of the block specimen) on the oven shelf and center the template on it. Distribute by hand, within the template opening, 130 g of granite chips (approximately 150 stones) to form a continuous single layer of stones. Remove the template and carefully place the rubber pad, plywood block, and weight in position. After all test assemblies are in place, close the oven and turn on the fan and heat. Twenty hours after the oven temperature reaches 140°F, carefully remove the weights, blocks, and pads, and tilt or invert the test specimen to dump off those granite chips

C-24

Raise the chisel, move the carriage approximately one inch, and drop the chisel again. Repeat this operation for a total of 36 drops approximately one inch apart within a 5 x 5 inch square, at least one inch from sides, end, and transverse centerline of the specimen. (Note: A marked grid of dots or lines on the bottom of the cabinet is convenient for locating the carriage at the 36 positions.) Check the chisel point frequently for dulling or burring, and sharpen as required. Clean the chisel point as required. Frequent dusting of the chisel point with talc helps to avoid excessive fouling by sticky membranes. (See Figure C-3.)

Record the nature and extent of visible damage to the membrane. Measure electrical resistance of the specimen

(Reference: Road Research Laboratory Technical Memorandum (Bridges) No. BE 27, Appendix B.)

HEAT CYCLE

Place specimens in a forced-draft laboratory oven, preheated to 300°F. Leave heat and fan on until the temperature has returned to 250°F (12 to 15 minutes), then shut off. When the oven has cooled to 100°F (about 4 hours), remove the specimens and allow to cool to room temperature.

CREEP DAMAGE TEST METHODS

Equipment

Oven, circulating air, 140 ± 2°F

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which do not adhere to the specimen. Record whether stones adhere or are imbedded, and any visible damage. Measure electrical resistance.

Procedure B

Place the test specimen on the shelf and center the template on it. Place 4 jackstones on the membrane, one near each corner of the template opening. Remove the template and carefully place the rubber pad, plywood block, and weight in position. After all test assemblies are in place, close the oven and turn on the fan and heat. Twenty hours after the oven temperature reaches 140°F, carefully remove the weights, blocks, and pads, and tilt or invert the test specimen to dump off those jackstones which do not adhere to the specimen. Record whether jackstones adhere or are imbedded, and any visible damage. Measure electrical resistance.

Reference: Bell & Yoder paper "Plastic Moisture Barrier for Highway Subgrade Protection"

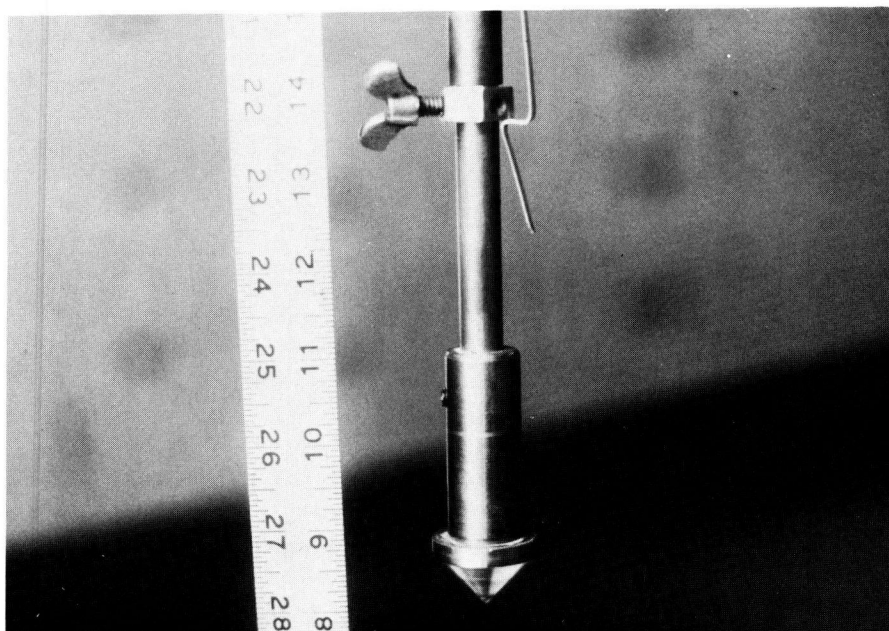
CRACK-BRIDGING TEST METHOD

Equipment

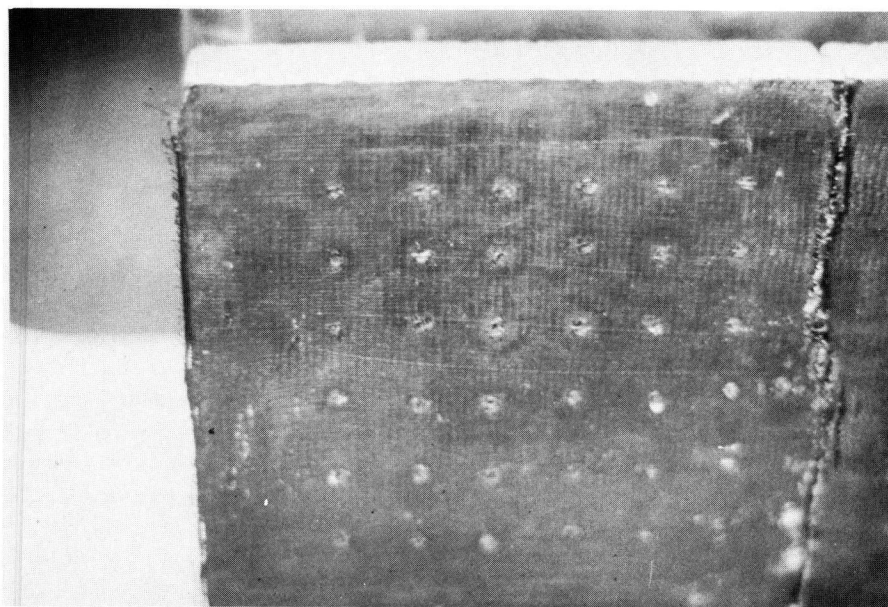
Jack and frame as shown in Figure C-4

Dial gauge, 1 inch capacity, 0.001 inch graduations, 0.1 inch per turn of dial, spindle accessible at either end, and rotating dial ("adjustable zero")

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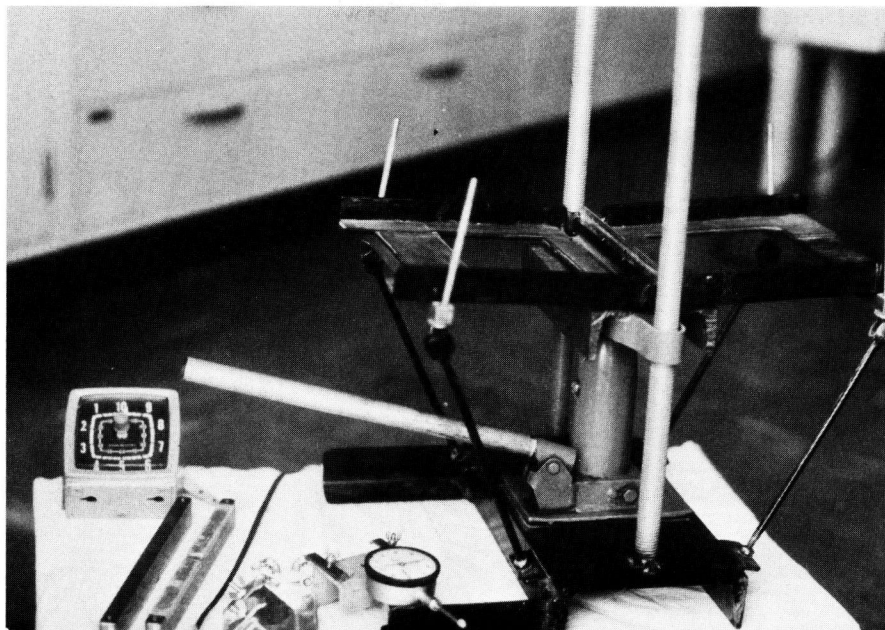


(a)

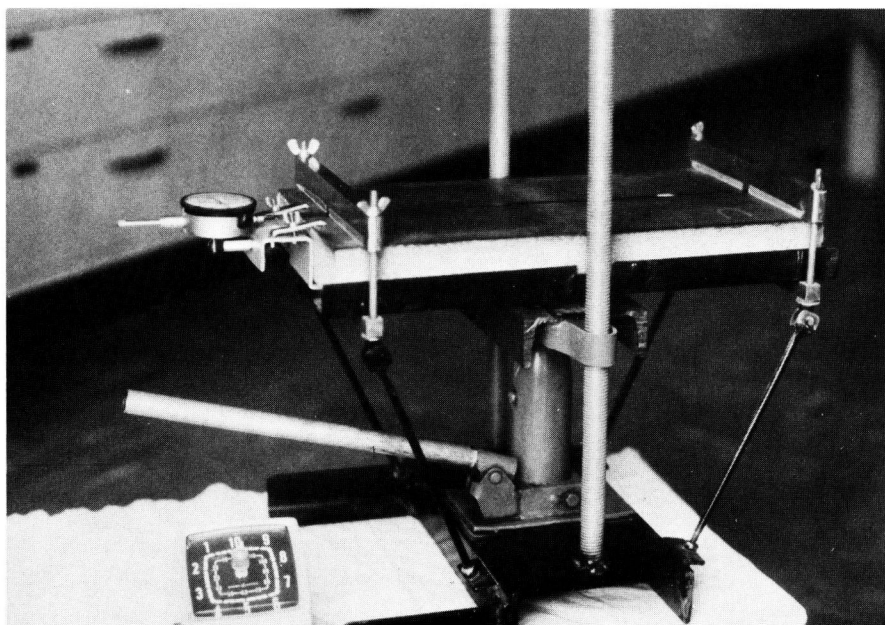


(b)

Figure C-3. Chisel used in impact damage test (a), and one of the membrane specimens after the total of 36 "drops" of the chisel (b).



(a)



(b)

Figure C-4. Crack bridging test equipment ready to receive test specimen (a), and with specimen in place ready for testing (b).

Gauge clamp to fasten on end of block and hold gauge in position with spindle end level with top of membrane and approximately 1 inch away from edge of block

Flexible steel tape 20 x 0.25 x 0.004 inch, with fitting at one end to engage end of gauge spindle

Tape clamp to fasten on end of block opposite the gauge, and to grip tape

Hold-down clamps notched to permit free movement of tape, with bottom edges covered with teflon tape

Timer, with hand making one revolution per 10 minutes

Procedure

Mount a test specimen in the loading frame with the 1/8 x 1/2 inch saw cut in the block fitted onto the tee bar on top of the jack. Install the hold-down clamps and tighten the wing nuts, so that the frame fits snugly up under the block. Thread the flexible tape through the notches in the undersides of the hold-down clamps. Attach the gauge clamp to the near end of the block, and attach the tape to the gauge spindle (Gauge must be mounted so that the spindle can be pulled freely by the tape). Attach the tape clamp to the far end of the block, pull the tape through the tape clamp until the tape is taut and it moves the gauge needle about one-quarter turn of the dial. Tighten the clamp on the tape. Set the gauge dial to zero

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Steel tabs, cold drawn, 5 x 1 x 1/8-inch, with 0.25-inch diameter hole near one end, and the other end cleaned with acid or abrasive for 2-inch length (for shear tests)

Testing machine, constant-rate-extension, capacity at least 200 lb, and speed 0.10 inch per minute

Adapter for crosshead, threaded for 5/8 x 11 bolts

Adjustable clamping frame or table with C-clamps, attached to base of testing machine, to hold 8 x 8 x 2-inch specimens in horizontal position

Adapter for crosshead, with 0.25-inch diameter bolt, to pull tabs while keeping them aligned in the direction of pull

Adjustable clamping frame attached to base of testing machine to hold 8 x 8 x 2-inch specimens in vertical position

Materials

2-component epoxy adhesive (such as Adhesive Engineering Co. Aerobond 2119)

Polyethylene film, 0.004-inch thick

Procedure

Cut the membrane to separate into half-blocks the "A" blocks previously tested at room temperature for impact-damage resistance and crack bridging. Clean the surface of the

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Start the timer and operate the jack so that the membrane surface is lengthened at the rate (as indicated on the dial gauge) of 0.01 inch per minute. Examine the membrane continuously while continuing to elongate the surface at the rate of 0.01 inch per minute until the total elongation is 0.10 inch, or until a single fracture 1/2 inch in length, or multiple fractures with a total length of 3/4 inch occur, disregarding any cracks or fractures in the membrane within 1/2 inch of the edges of the specimen. Continue elongating the surface at the rate of 0.05 inch per minute until the total elongation is 0.25 inch or until a 1/2 inch fracture or multiple fractures totalling 3/4 inch occur.

Report elongation at failure, and the nature and location of the fracture(s). Record observations of other types of failure such as chipping or flaking, debonding, breaking at locations not coinciding with the fracture in the concrete, etc. (Table C-2 summarizes the basic elements of some other crack bridging tests.)

METHOD OF TEST FOR STRENGTH OF ADHESIVE BOND IN TENSION AND IN SHEAR

Equipment

Round die, 1 1/2-inch diameter

Bolts, hex-head, 5/8 inch diameter x 11-thread, with heads machined flat and cleaned with acid or abrasive (for tension tests)

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membrane by wiping with solvent (acetone, unless otherwise specified), rubbing with fine sandpaper, and wiping again with solvent.

Using a 1 1/2-inch diameter die (1.00 in² area), carefully cut through the membrane around areas selected to avoid inclusion of damage test punctures or previous qualitative bond tests. Trim away the membrane for at least 0.25 inch all around the selected test area for all specimens, and for at least 0.75 inch in the direction of pull for the shear test specimens.

Clean the contact surfaces of the bolt heads and the steel tabs by pickling with 1:1 diluted hydrochloric acid or by rubbing with fine sandpaper and wiping with acetone. Attach the bolts and tabs to the test areas with epoxy adhesive, following the manufacturer's instructions for mixing. Support the tabs so that they cannot move from position during curing. Cure all specimens at 140 ± 2°F for 15 hours and cool them to room temperature before testing.

Place the block in position in the testing machine but do not tighten clamps. Align a bolt or tab under the load cell. Carefully position the specimen so that the assembly will remain aligned in the direction of pull during the test and fasten it to the adapter. (Any misalignment will result in low values due to "peeling".) Tighten the clamps on the specimen and pull the bolt or tab at 0.10 ipm. Record maximum load

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TABLE C-2. - SUMMARY OF SOME ELEMENTS OF VARIOUS CRACK BRIDGING TESTS

Agency	Year Developed	Loading Method	Description of Specimen	Material Support
ASTM (C497-65T)	1962	Compressive	Hollow tubing, various sizes.	PCC or tile
Swedish Cement and Concrete Research Institute	1966	Flexural	Flat block 31" x 22" x 4", slot in center.	PCC with re-bar
Shell Research N.V., Amsterdam, Netherlands	1967	Tensile	Flat block, 10" x 0.8" x 0.8", saw cut in center, 0.7" deep	PCC, no re-bar, coating on all surfaces without membrane
Road Research Laboratories, England	1969	Flexural	Flat block, 27½" x 9" x 3"	PCC with re-bar and a horizontal steel stress-raiser
Ministère de L'Équipement, France (Confirmatory Test)	1969	Flexural	Large block, dimensions unknown	PCC with re-bar
Ministère de L'Équipement, France (Screening Test)	1968	Tensile	Square dumbbell with flat test side, 2½" x 2½" x 5" (overall length - 10")	PCC with one ½" dia. re-bar notched in middle and protruding 3" at each end
British Paints Ltd., England (Confirmatory Test)	1970	Flexural	Flat block, 20" x 4" x 4"	PCC with ½" re-bar
British Paints Ltd., England (Screening Test)	1970	Tensile	Small flat plate, dimensions unknown	Steel
State of California (Confirmatory Test, Maxi-cracker)	1971	Tensile	Flat block, 3" x 18" x 24"	PCC with one re-bar to grip
State of California (Screening Test, Mini-cracker)	1971	Tensile	Flat block, 2" x 6" x 12"	PCC with no re-bar, bonded with adhesive to a steel jig split in the center

required, and where failure occurred (e.g., in concrete, between concrete and adhesive, within adhesive, between adhesive and membrane, within membrane)

PROCEDURE FOR AGING TEST (AIR EXPOSURE)

Cut three specimens of each test material from sheet, using dumbbell die C. Mark identification on each specimen. Punch 1/8-inch diameter hole near one end of each specimen. Weigh specimens to nearest 0.001 g and record weight. Measure thickness of center portions of dumbbells. Hang specimens on hooks on rotating shelf of oven, and age them 30 days at $140 \pm 2^\circ\text{F}$. Condition specimens overnight at room temperature ($73.4 \pm 1.8^\circ\text{F}$). Weigh specimens and calculate weight change. Measure tensile strength, elongation at break, and hardness.

PROCEDURE FOR FATIGUE TEST

Cut specimens of each membrane from sheet, using dumbbell die C, and mark 1.00 inch bench marks. Cool specimens to $0 \pm 1^\circ\text{F}$ and test on Constant-Rate-Extension tester at $0 \pm 1^\circ\text{F}$. Grip specimen at bench marks with A-5 flat-face abrasive-lined grips, elongate 0.25 inch at 0.10 ipm and return at 0.50 ipm, releasing lower clamp during return. Allow specimens to relax at least one hour at room temperature between cycles. Record maximum load and number of cycles to failure.

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PROCEDURE FOR FREEZE-THAW TEST (MOISTURE-TEMPERATURE EXPOSURE CYCLE)

Cut three specimens of each test material from sheet, using dumbbell die C. Mark identification on each specimen. Punch a 1/8-inch diameter hole near each end of each specimen. Assemble specimens on 1/8-inch diameter glass or wooden rods, with the specimens at least 1/4-inch apart. Each freeze-thaw cycle consists of the following four steps:

- 1 Immerse specimens in distilled water at room temperature, and place covered containers in $140 \pm 2^\circ\text{F}$ oven overnight (15 hours)
- 2 Transfer specimens to cold (40°F) distilled water, and place in freezer at $0 \pm 2^\circ\text{F}$ during day (9 hours)
- 3 Allow frozen specimens to thaw and to remain immersed at room temperature overnight (15 hours)
- 4 Remove specimens from water and place in $140 \pm 2^\circ\text{F}$ oven during day (9 hours)

After ten complete cycles as above, condition the specimens at room temperature overnight and measure tensile strength, elongation at break, and hardness. Record any unusual changes in the specimens, e.g., distortion, bubbling, ply separation, etc.

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RECORDING FIELD DATA

A special set of data sheets was prepared to record data obtained and observations made during the conduct of the field survey of bridge deck membranes systems. The purpose of these data sheets was to assist in the orderly recording of the test results and other information obtained, and to serve as a "check-list" of information to be obtained. Following is a reproduction of the data sheets used.

FIELD SURVEY DATA SHEET
NCHRP Project 12-11

Date _____ Time _____ Surveyed by _____ Survey Reference No. _____
Owner Agency _____ Bridge No. _____
Highway Route No. _____ Bridge Location _____
Agency Contact: Name _____
Address _____ Phone No. _____

Part I - BACKGROUND INFORMATION

CONSTRUCTION DATA

Bridge Completion Date _____ Date Membrane Placed _____
Weather during membrane placement _____
Reconstruction or Major Repair _____
Date _____ Description of Work _____
1. _____
2. _____
3. _____
4. _____

Bridge type _____

No. Spans _____ Span Lengths _____ Total Length _____
No. of Lanes _____ Width: Lanes _____ Shoulders _____ Total paved _____
Grade, % _____ X-slope _____ Crown _____ Deck thickness _____
Decl. span (distance between supports) _____ X _____
Traffic: up- _____ or down- _____ grade, accelerating _____
decelerating _____ neither _____ Alignment: tangent _____
curvature _____
Decl Concrete Air-entrained, yes _____ no _____ strength _____
Remarks _____

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Membrane: Classification / / / Description _____
Specifications (reference or attach) _____
Manufacturer & address _____
Data sheets or brochures (reference or attach) _____
Equipment Used for Placing AC Wearing Course: Rubber-tired paver _____
tracked _____ Trucks on membrane yes _____ no _____ Hand-placed: yes _____
no _____ Remarks _____
Comments on construction (weather, unusual problems, etc.) _____
TRAFFIC DATA:
Period covered _____ ADT _____ % Trucks _____
Equivalent _____ -kip single axle loads _____
Extent of studded tire or chain use _____
Remarks _____
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PREVIOUS SURVEY OR TEST DATA

Part II - VISUAL EXAMINATION

[illegible]

WEARING COURSE

Condition (continued):

Field Survey Data Sheet
Job No. 0320 Page - 5

Ref. No. _____

	<u>Open</u>	<u>Average</u>	<u>Closed</u>	<u>Comments</u>
Surface Texture (permeability)	-----	-----	-----	_____
	<u>Poor</u>	<u>Acceptable</u>	<u>Good</u>	
Drainage	-----	-----	-----	_____
Riding Quality	-----	-----	-----	_____
Overall Evaluation	-----	-----	-----	_____
Remarks	_____			

USE OF DEICING CHEMICALS

Type used _____

Extent of Use Spread rate _____ Approximate applications/yr _____

No. of yrs. used _____ Use rating Heavy _____ Moderate _____ Light _____

Evidence of Damage

Condition of PCC Approach Slabs _____

Condition of Curbs, Walkways, Railings _____

Other damage _____

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Field Survey Data Sheet
Job No. 0320 Page - 6

Ref. No. _____

CONDITION OF UNDERSIDE OF DECK

Extent of leakage: None _____ slight _____ moderate _____ severe _____

Location of leakage _____

Comments _____

APPEARANCE OF MEMBRANE

At curbs _____

At expansion joints _____

As exposed by coring _____ or sawing _____:

Other _____

OTHER COMMENTS ON VISUAL EXAMINATION

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Ref. No. _____

Part III - SAMPLE RECORD

[illegible]

Remarks

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Ref. No. _____

Part IV - FIELD TESTING

TENSILE ADHESION TEST

[illegible]

PERMEABILITY TEST

[illegible]

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Job No. 0320 Br. No. _____ Survey Ref No _____

Part V - LOG OF PHOTOGRAPHS

[illegible][illegible]

ANALYSIS OF FIELD RESISTANCE TEST DATA

Resistance measurements on bridge deck membranes in the field were recorded as the reading on the meter, in ohms, for each point in two series of points on the surface - one series in the outer wheel path, and the other on the shoulder (or between the wheel paths if there was no shoulder). These two sets of measurements obtained were treated separately in the analysis. On each bridge deck, a "base" resistance measurement of the deck was made by inserting the electrode in a water-filled hole cored through the membrane. The resistance of the electrode sponge was also measured.

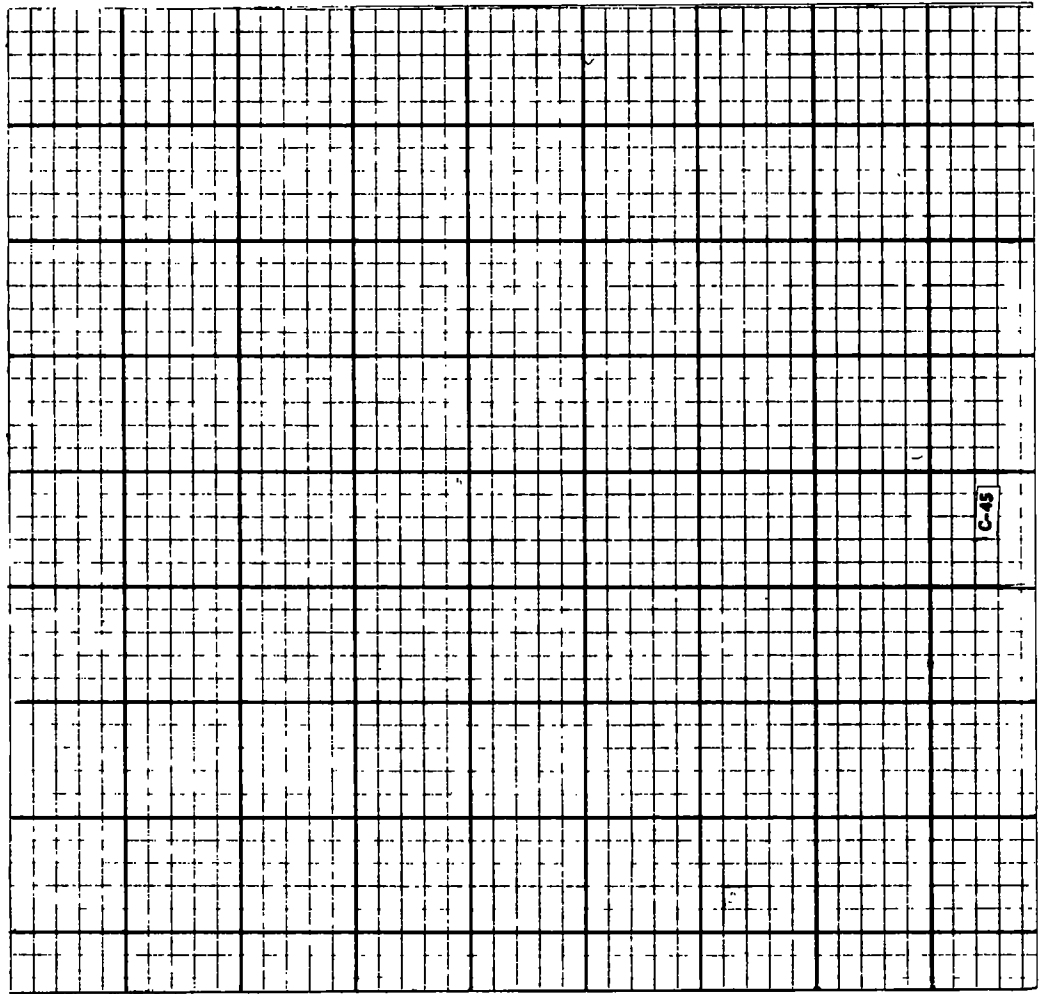
The following calculations were then performed to arrive at measurements for comparison of the resistance of membranes in the field, and between resistance measurements made in the field and those made in the laboratory.

- 1 All recorded values were converted to "net" values by subtracting the measured base resistance of the deck and the resistance of the electrode sponge to arrive at a value for the membrane.
- 2 The net values were converted to ohms-ft² by multiplying by the area of the electrode sponge (Although the same sponge was used for all field measurements, converting to a unit value facilitated comparison with laboratory readings using smaller sponges.)
- 3 Each set of "net" readings was averaged and the standard deviation determined. The lowest value of the mean less one standard deviation was selected as representative of each bridge deck membrane.

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Field Survey Data Sheet
Job No. 0320 Page - 10
Ref. No. _____

Part VI - SKETCH OF SITE PLAN



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