SHRP-M/UFR-91-504

Innovative Materials and Equipment for Pavement Surface Repairs

Volume I: Summary of Material Performance and Experimental Plans

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Strategic Highway Research Program
National Research Council
Washington, D.C. 1991

SHRP-M/UFR-91-504
Contract H-105

February 1991

key words:
asphalt pavement
crack sealing
concrete pavement
data base
joint sealing
maintenance
materials
pavement maintenance
pavement rehabilitation
pavement restoration
performance
pothole repair
spall repair

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Executive Summary

The need for improved materials and procedures for pavement maintenance activities is evident to most people. Methods and materials that last longer and perform better would be a tremendous boon, not only to the traveling public's image of our roads, but also to the already stretched budgets of the maintenance departments. One of the major goals of the Strategic Highway Research Program (SHRP) is to further the state of knowledge in the pavement maintenance area. This goal is being accomplished by research activities that are being sponsored in several key areas. These areas include a study of pavement maintenance effectiveness (SHRP H-101), maintenance measuring equipment (SHRP H-103 and H-104), work zone safety improvement (SHRP H-108 and H-109), and the development of improved maintenance equipment (SHRP H-105 and H-107). Consideration is also being given to the implementation of the findings from SHRP research (SHRP H-110).

The research reported herein was performed under SHRP Project H-105, *Innovative Materials and Equipment for Pavement Surface Repairs*. This study was begun in late 1988, and the research effort was completed in April 1990. The results of this study were used in the development of *Experimental Design and Research Plans (EDRP)*, which formed the basis of a Request for Proposals to conduct a field evaluation of these materials in SHRP Project H-106. The overall goals of this project can be summarized as follows:

- To identify material, procedures, and equipment for patching potholes in asphalt concrete (AC) and repairing spalls in portland cement concrete (PCC) that are more effective and more efficient in preventing pavement deterioration than existing methods.

- To identify materials, procedures, and equipment to use in filling and sealing cracks in both AC and PCC pavements, and resealing joints in PCC pavements, that are more effective in preventing the intrusion of water

into the pavement structure, and that are more efficient than existing methods.

- To develop a set of experimental plans to test new or improved maintenance materials and to develop a set of plans to guide the development of improved maintenance equipment.

The study also sought to identify laboratory tests whose results might be good indicators of field performance. The existence of such "performance-related specifications" would greatly enhance maintenance departments' ability to identify which new or untried materials show the greatest promise and therefore warrant field testing.

The research effort for H-105 was divided into five major pavement maintenance activities:

- AC pothole repair
- AC crack repair
- PCC spall repair
- PCC joint resealing
- PCC crack sealing

For each maintenance activity, information was collected to assist in the evaluation of the performance of materials used for these repairs and the procedure used to prepare the pavement and place the materials.

In this report, the findings from the H-105 research effort pertaining to the evaluation of pavement maintenance materials are presented. Three volumes were prepared under the general heading *Innovative Materials and Equipment for Pavement Surface Repairs.* Volume I, *Summary of Material Performance and Experimental Plans*, includes a discussion of the general methodology used in the conduct of this research study and an analysis of the results from the survey of maintenance materials users. Literature related to the above-noted maintenance activities was also evaluated and incorporated in the study. The result was a list of pavement maintenance materials recommended for further study in field trials and a list of laboratory tests that could be evaluated for their ability to relate to field performance.

The second volume of the report, *Synthesis of Operational Deficiencies of Equipment Used for Pavement Surface Repairs*, describes the deficiencies of the equipment currently used to perform these maintenance activities. The information presented in this volume was collected from questionnaires sent to states, contractors, and other agencies. The data gathered in this part of the study was used to develop the experimental plans for SHRP

Project H-107, which addresses the development or modification of improved pavement maintenance equipment for performing crack sealing and pothole repair.

The third volume of the report, *Data Base Users Guide*, is a user's manual that describes the use and manipulation of the data base used in this project. The data base contains information and performance histories of many patching and sealing materials, as well as performance information on various types of equipment used for pavement maintenance.

Abstract

Pavement maintenance activities generally account for a significant portion of an agency's operating budget. This can be attributed to the high initial costs associated with maintenance activities, the historically poor performance of maintenance repair which often necessitates additional maintenance work, and the exorbitant safety and legal costs associated with the need for traffic control of these activities. As such, any improvements or advancements in this area could result in substantial cost savings.

In an effort to address these areas of concern, the Strategic Highway Research Program (SHRP) has initiated a major research project on the materials and equipment used for five of the more common maintenance activities: portland cement concrete (PCC) crack sealing, PCC joint resealing, PCC spall repair (partial-depth), asphalt concrete (AC) crack sealing and filling, and AC pothole repair. The objectives of the study are to identify materials, procedures, and equipment for these maintenance activities that are more effective and more efficient than past methods.

Volume I of this three-volume report summarizes the use, performance, and properties of numerous sealing and patching materials used for each of the above maintenance activities. In addition, overviews of four experimental plans developed for testing promising materials are presented. Performance information was compiled through a detailed questionnaire sent to states and other highway-affiliated entities, as well as through published literature reviews and meetings with knowledgeable individuals. Based upon this performance information and information regarding desirable material properties and deficiencies, a set of experimental plans were prepared to test the most promising and innovative materials identified in this study. The results of the experiments are expected to benefit highway agencies by informing them of materials and procedures that can make their pavement surface maintenance programs more cost effective, expedient, and safe.

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Introduction

The decline of the nation's pavement infrastructure is a preoccupation to many. The condition of our highways is referred to frequently in disparaging terms by such groups as politicians, journalists, industry, and the traveling public in general. This is not unexpected, as distressed pavements are one of the most visible and obvious signs of our infrastructure's deterioration as well as one of the major contributors to discontent on the part of the traveling public. These groups, however, are for the most part unable to do anything about the problem besides adding their voices to the general uproar.

The genesis of the problem with the nation's roads has been fairly well-documented. In the late 1950s, the United States launched the construction of the Interstate system. This 40,000-mile-plus construction project was accompanied by a similar boom of supporting roads, primary and secondary networks which linked together to unite remote areas and foster tremendous growth. By the 1970s, the construction associated with the Interstate system was over 90 percent completed, but by then it was clear that the very growth the Interstate was intended to encourage was likely to be its undoing. More traffic and heavier traffic had taken to the roads and the resultant wear and tear on the pavements changed the demands on the Interstate system from new construction to rehabilitation. At the same time, an awareness was growing within the pavement community that better, and more timely, maintenance might help to prolong the life of a pavement.

While the public perception might be that nothing is being done to solve this problem, maintenance activities do constitute a large percentage of the work effort of many transportation departments. Unfortunately, the effectiveness of pavement maintenance activities has generally been less than desired. The reasons for this are varied. Pavement maintenance is often lumped together with other items in the maintenance budget, such as snow and ice removal and vegetation control (mowing and spraying, for example). Repairing pavements is by far the smallest item in such a "lumped-together" maintenance budget, and is often performed when time is available between the more essential winter maintenance and summer maintenance. And, in a year with a lot of snow, there may be little or no money left to repair the roads. Given the low priority that pavement maintenance may receive from the very agencies that perform it, it is not surprising that first-year failures of pavement repairs are quite common, and that the potential benefits of performing regular maintenance activities are not realized.

The need for improved materials and procedures for maintenance activities is evident. Methods and materials that last longer and perform better would be a tremendous boon, not only to the traveling public's image of our roads, but also to the already stretched budgets of the maintenance departments.

One of the major goals of the Strategic Highway Research Program (SHRP) is to further the state of knowledge in the pavement maintenance area. This goal is being accomplished by research activities that are being sponsored in several key areas. These areas include a study of pavement maintenance effectiveness (SHRP H-101), maintenance measuring equipment (SHRP H-103 and H-104), improving work zone safety (SHRP H-108 and H-109), and the development of improved maintenance equipment (SHRP H-105 and H-107). Consideration is also being given to the implementation of the findings from SHRP research (SHRP H-110).

The research reported herein was performed under SHRP project H-105, *Innovative Materials And Equipment For Pavement Surface Repairs*. In this report, the findings from the H-105 research effort pertaining to the evaluation of pavement maintenance materials are presented.

Study Objectives

This study was begun in late 1988 and the research effort was completed in April 1990. The research approach that was followed to obtain the data is discussed and the results from the analysis of that data are shown. All of the results were used in the development of *Experimental Design and Research Plans (EDRP)*, which formed the basis of a Request for Proposals to conduct a field evaluation of these materials in SHRP H-106. The overall goals of this project can be summarized as follows:

- To identify materials, procedures, and equipment for patching potholes in asphalt concrete (AC) and repairing spalls in portland cement concrete (PCC) that are more effective and more efficient in preventing pavement deterioration than existing methods

- To identify materials, procedures, and equipment to use in filling and sealing cracks in both AC and PCC pavements, and resealing joints in PCC pavements, that are more effective in preventing the intrusion of water into the pavement structure, and that are more efficient than the existing methods

- To develop a set of experimental plans to test new or improved maintenance materials, and a set of plans to guide the development of improved maintenance equipment

The major objective of this part of the SHRP research, then, can be restated as *the development of pavement maintenance methods that are more cost-effective and efficient and will therefore contribute to improved performance and to an improvement in safety to both highway users and maintenance personnel.*

The achievement of the objectives of this research will result in significant improvements in the performance of pavements. The use of the most appropriate pavement maintenance materials will mean longer-lasting repairs. This benefit will be reflected in longer-lasting pavements, and pavements that are in better overall condition for a longer period of time. These factors will combine to decrease the overall costs of a pavement over its life, or increase that pavement's cost-effectiveness. Public satisfaction with the condition of pavements might also increase.

Improvements in repair procedures will also produce many of the same benefits. Over the years, a number of repair procedures have been promoted as being the "right" way to fix a pavement. However, there continues to be an enormous debate over whether the right way (which is usually more expensive and time-consuming) is any better than the quick way. A thorough documentation of what methods work best, and how best to carry out those methods, would be of great use to the pavement maintenance community.

The identification of laboratory tests whose results might be a good indicator of field performance was also sought. The existence of such "performance-related specifications" would greatly enhance maintenance departments' abilities to identify which new or untried materials showed the greatest promise and therefore warranted field testing.

Finally, it is expected that at least some of the improvements in materials and procedures will be realized in the speed and ease with which these repairs are made. That, coupled with the reduced need for repairs to be performed, will result in a major side benefit of the research: a reduction in the amount of time that maintenance workers are exposed to traffic.

Sequence of Report

The research effort for H-105 was divided into five major maintenance activities:

- AC pothole repair
- AC crack repair
- PCC spall repair
- PCC joint resealing
- PCC crack sealing

For each maintenance activity, information was collected to assist in the evaluation of the performance of materials used for these repairs and the procedure used to prepare the pavement and place the materials.

This report discusses the data collection effort followed in this study, presents the results of the research effort for each of these maintenance activities, and provides some preliminary conclusions as well as the recommendations for the SHRP H-106 study.

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Research Approach and Information Sources

The study described herein is the result of the cooperation and input of many individuals, agencies, and materials manufacturers worldwide. A number of different approaches were taken to elicit this input, including the publication of articles in trade magazines, direct mailing of questionnaires, publication of notices in special interest newsletters, presentations at national meetings, as well as more conventional approaches such as literature searches and reviews of recent research and previously published syntheses. The sources of data and the types of data obtained from those sources are described in greater detail in this chapter.

The ultimate goal of this project was to develop a set of experimental plans for each of the five pavement maintenance activities that would guide the performance of a field experiment to be conducted under a later research effort (SHRP H-106). That field experiment would combine the evaluation of the most promising materials and procedures with a complete laboratory testing program. One of the products of such an experiment, then, would not only be the identification of which materials performed best in head-to-head comparisons in the field, but which laboratory tests most closely related intrinsic material properties to actual field performance. The steps employed to achieve this goal included a literature search, a general canvassing of user's opinions, and a more thorough investigation accomplished by telephone calls, personal visits, and field visits.

Research Approach

The initial data collection was intended to identify all of the materials that had been used for pavement maintenance in the past 15 to 20 years, both in conventional and experimental applications. It was also a goal to identify how these materials had performed, and which showed promise and which did not. At the same time, the research work done in the area of correlating lab tests to the performance of these materials, either as part of experimental projects or on a routine basis, was assessed for promising results. The follow-up from this initial paper study consisted of contacting individuals, agencies, and manufacturers which appeared to have promising materials for more information. The results from both the initial data collection effort and the follow-up information provided by a wide range of individuals went into the formulation of the experimental plans for the SHRP H-106 research effort.

Information Sources

Many sources of information were accessed to collect the most recent information available concerning the performance of various patching and sealing materials. The published literature was an excellent starting point, as there have been studies done in many different states examining several or even many different repair products. Information was also usually readily available from the manufacturers, although the performance data may often be idealized. The primary source of performance data for this study, however, was from the results of a comprehensive survey of users obtained through the use of a questionnaire. The various sources of information are described below.

Literature Search

An exhaustive literature search was conducted to identify past research studies and reports that dealt with the performance and effectiveness of various patching and sealing materials specifically for pavements. The Transportation Research Information Service (TRIS) data base was the primary source for providing references in this area. In the search of the TRIS data base, which extended back to 1970, over 500 articles were identified. An additional search on the general topic of sealing and patching materials was performed in a separate data base containing all engineering disciplines (the Engineering Index). Through this search, it was hoped to identify promising or potentially promising materials outside of the transportation field. Products were identified from such areas as aeronautics, hydrology, ceramics, and the chemical field. Over 1000 articles were identified in this search, although only about 125 of these ultimately had any practical application to the transportation field.

From the beginning of the study, it was felt that the key to evaluating the performance of the multitude of materials on the market was user feedback. Early in the project, a one-page questionnaire was placed in *Roads & Bridges*. This questionnaire was aimed at the users of the various patching and sealing products, as well as at manufacturers. Unfortunately, there were very few responses received from this questionnaire.

In addition, a very detailed questionnaire was prepared and sent to all state DOTs, Canadian Provincial Highway Agencies, and SHRP's international participants to learn of their current equipment, materials, and procedures for patching and sealing. A second mailing went to selected cities, counties, and all members of the maintenance committee of the International Bridge Turnpike and Toll Road Association (IBTTA). These questionnaires were designed to obtain very complete and extensive information on the performance of all materials used for pavement surface repair. Performance information was requested on both equipment and materials used for sealing and patching activities in different applications. In recognition of the difference in performance of many materials under different climatic conditions, several categories were established. These included life expectancy when applied in both wet and dry conditions at temperatures both below and above freezing. In addition to life expectancy information, the number of years of experience with each material was requested. Over 120 responses were ultimately received. Agencies replying included 39 states, 9 Canadian provinces, various cities and toll road authorities, and several foreign countries.

Although they have the potential for providing information on specific questions in a relatively short time, questionnaires are not always the best means of soliciting useful information. Lengthy questionnaires that create the impression of requiring a good deal of time to complete will often be set aside or given only casual attention. Also, in a survey such as this, there is no way to ensure that the recipient of the questionnaire is the most knowledgeable individual within the organization. And, there may be different experiences within an organization that can not be easily synthesized by one individual's response. For this reason, perhaps, many of the respondents did not feel comfortable providing performance data without ample opportunity to qualify their answers. For example, one State noted that "performance varies with type of preparation, condition of pavement, and Average Daily Traffic (ADT)." An example of the materials questionnaire sent to the states is given in Appendix A.

It can not be overemphasized that the questionnaires, which form the backbone of the product evaluation effort, represent a collection of opinions rather than a reporting of observed, repeatable fact. While this is a limiting factor, it is felt that the efforts made to compile data from other sources has at least partially overcome the drawbacks of a research report based on subjective questionnaires.

The problems with the questionnaire approach to data collection continue when the results are evaluated. Not only have the questionnaires been completed by individuals with a range of experience and available time, they come from a wide range of environmental regions and are even using different products that have been referred to by the same name. Averaging the responses will tend to obscure large differences, without providing the real reason for those differences.

Additional publicity and interest in the research effort was sought through several other initiatives. Publication of a notice on the goals of the project was requested from all of the State Technology Transfer (T^2) newsletters, which are distributed quarterly in most states to maintenance practitioners. A favorable response was received from many of these, although the number of responses to the published notices was not overwhelming. A note about the research was also published in the newsletter of the International Joints and Bearings Research Council (IJBRC) newsletter, and presentations were made to several Transportation Research Board (TRB) committees as the project was starting. Elements of the research progress were also published in SHRP's newsletter, *FOCUS*, and in an issue of *Roads & Bridges*.

Manufacturers

Product manufacturers provided literature on their products and, in some cases, more extensive information. Generally, a product listing and various test specifications were available for most materials. Follow-up interviews, agency visits, and field surveys of product installations were conducted to yield additional information on the various products.

Follow-up

Following the initial data collection effort, the collected data was reviewed for relevancy and to identify what sources appeared to be most promising. Some of the questionnaires were followed up by telephone calls for further information or clarification. However, most of the follow-up work was done in the form of field visits to agencies or materials manufacturers. These visits enabled the researchers to visit actual field experiments, to talk with the users and discuss problems, and to visit a number of lab facilities for materials evaluation. It was these visits, as much as anything else, which clarified those materials that appeared to be promising.

Types of Information

All available information was sought for the various patching and sealing materials. This included various test specification data, performance data, and any other data which may be of interest. For patching materials, the following information was pursued:

- Performance data (years, traffic)
- Adhesiveness
- Allowable temperature ranges for application
- Durability
- Stiffness
- Allowable moisture conditions
- Hole preparation required
- Special handling/mixing requirements
- Cure time (PCC)
- Opening to traffic (PCC)
- Environmental effects

For sealing materials, the properties and information sought included:

- Performance (years, traffic)
- Adhesiveness
- Applicable temperature ranges
- Durability
- Stiffness
- Moisture conditions
- Joint/crack preparation required
- Special handling/mixing requirements

Data Base Development

The enormous amount of information collected for this project required a systematic means of storing and retrieving the data. Given the volume of data and its primarily subjective nature, the creation of a relational data base was a logical decision. The ORACLE® Relational Data Base Manager was selected for use on this project because of its sophisticated sorting and querying capabilities and its ability to handle such a large amount of data. ORACLE is also being used by the SHRP P-016, the Information Management System for LTPP data. The data base resides on a Compaq® personal computer and occupies approximately 20 Mb of hard disk space. It requires approximately 3 Mb of RAM to operate. The data base also has the ability to perform error-checking and report generation.

This data base is a major output of the project, and contains product information and performance histories of patching and sealing materials, as well as performance information on various equipment types for patching and sealing activities. The contents are based entirely on the information received in the returned questionnaires. There is also a good deal of information concerning manufacturers of the various materials, and agencies and individuals who responded to the questionnaire.

Within each category (materials or equipment), further divisions were made regarding the pavement type and application of the material or equipment type. For example, separate categories exist for crack sealing in AC pavements, crack sealing in PCC pavements, joint sealing in PCC pavements, pothole patching in AC pavements, and spall repair in PCC pavements.

A user's manual describing the use and manipulation of the project data base is provided in volume III of this series of reports. This volume also contains supplemental information on the development of the data base.

Presentation and Interpretation of Data

The results from the questionnaires have been summarized and presented in each of the chapters for the appropriate materials. A caution to the reader is required, however, concerning the interpretation of the data. Several statistics are reported on the performance data, including high and low values, the mean, the standard deviation, and the number of responses, *n*. When the number of responses is small, the significance of a statistic such as the mean is essentially null. This is true because the responses of a small number of respondents can not be considered to be representative of the group as a whole. As *n* gets larger, it is hoped that the range of experiences is better represented in the responses received.

An indication of the scatter in the responses can be seen in the standard deviation. If the value of the standard deviation is high, a large scatter in the data is indicated. Conversely, when the standard deviation is very small in relation to the mean, the data is more tightly packed around the mean. This should be kept in mind when reviewing the data tables and the discussion of the data.

3

PCC Joint Resealing

The resealing of transverse joints in concrete pavements is an activity performed only by some State and local highway agencies. The purpose of joint resealing is to reduce the amount of water that can enter the pavement structure through the joint and to prevent the intrusion of incompressible material into the joint. Water that enters the pavement structure through the joint can cause various moisture-related distresses such as pumping, faulting, base and subbase erosion, and loss of support. However, joint resealing is not done by all agencies because of concern about its cost-effectiveness.

To date, the performance and success of joint resealing projects has been less than satisfactory. In fact, several studies have indicated that only a small portion of existing concrete pavements are effectively sealed.[1,2,3,4] Thus, there is a critical need to improve the performance and effectiveness of concrete pavement joint sealing.

The continual intrusion of incompressible material into a transverse joint over time produces large compressive stresses as the concrete slabs expand during the warm months. If the compressive stresses exceed the compressive strength of the concrete, blowups, buckled or shattered slabs, and joint spalling can occur. In some instances there has been damage to bridges adjacent to such concrete slabs caused by a pressure buildup resulting from incompressible material in successive joints.

Sealants are usually placed in the three joint types found in PCC pavements: transverse joints, longitudinal lane-shoulder joints, and longitudinal lane-lane joints. The most commonly sealed joint is the transverse joint. The effects of both water and incompressibles entering this joint make it a critical joint.

Studies have shown that the longitudinal lane-shoulder joint is a major source of water infiltration, and should also be sealed.[5] This joint is very difficult to seal if the shoulder is asphalt concrete, because the sealant must be able to adhere to two different substrates and also be able to sustain large vertical strains, as asphalt concrete deflects much more than portland cement concrete.

Another type of joint sealed in concrete pavements is the longitudinal concrete-concrete joint between adjacent traffic lanes. Lane separation and minor faulting at such joints can appreciably increase the amount of water infiltrating into the underlying layers of a pavement. Sealing each of these joints will prevent water and incompressibles from entering the pavement system, thus enhancing pavement performance.

The sealing of all three of these joints was considered at the outset of the PCC joint sealing investigation. However, time and budgetary limitations made it necessary to focus on the joint considered to be most critical; in this case, the transverse joint. Therefore, the following discussion of PCC joint resealing pertains to the sealing of transverse joints only.

Material Performance Synthesis

Several factors influence the performance of a joint sealant. These factors include:[6]

- Depth of sealant
- Width of joint
- Joint spacing
- Properties of sealant (e.g., extensibility, strength, and durability)
- Properties and condition of the sealant-joint interface
- Characteristics and properties of the joint (e.g., maximum change in joint width, environmental factors, load transfer, and base support)
- Types of stress to which sealant will be subjected (e.g., tensile or compressive loads and temperature range)
- Proper joint cleaning
- Quality of workmanship
- Mechanical ties across joints

All of these factors must be considered in selecting a joint-sealant system so that the sealant material will prove compatible with the existing pavement design, joint characteristics, and environment.

Through the literature search and the questionnaire survey discussed in chapter 2, joint sealant material types used in current practice, the problems associated with their use, and their performance in the field were investigated. This section discusses the results of this investigation and its implications on the SHRP H-106 experimental project.

Types of Sealants

The results from the questionnaires and available literature indicate that there are many different types of joint sealants on the market today, each with their own inherent characteristics. Consequently, the performance characteristics of these sealant materials vary widely. In the past, joint sealant materials for PCC pavements have been classified in several different ways. They have been broken down into such categories as hot- and cold-poured, self-leveling and nonself-leveling, and petroleum-based and nonpetroleum-based. However, with the introduction of new sealant materials and variations in existing materials, the following general categories utilized by the American Concrete Institute (ACI) are adopted for use.[7]

- Thermoplastic Materials
  - cold-applied
  - hot-applied
- Thermosetting Materials
  - chemically-curing
  - solvent release
- Preformed Compression Seals

Hot-Applied Thermoplastic Materials

Thermoplastic sealants can be grouped into hot-applied and cold-applied materials. The hot-applied thermoplastics are those which become soft upon heating and harden on cooling, usually without a change in chemical composition.

Asphalt Cement

Asphalt cement is a product of the fractional distillation of crude oil. The consistency of asphalt cement is generally classified according to its viscosity, with softer materials having lower viscosity values (higher penetration values) than stiffer materials.

The cost of asphalt cement is significantly lower than other sealants. The material possesses temperature susceptibility and poor elastic properties and, thus, does not function well as a sealant in joints that undergo considerable movement.

Asphalt cement also has a narrow working range of temperatures. Although different grades can be selected for use in different climates, each grade is limited by either tracking in hot temperatures or brittleness in low temperatures.

Asphalt Rubber

Rubber is the simplest modifier that can be added to asphalt cement. Asphalt rubber, or rubberized asphalt, is produced by mixing vulcanized or ground tire rubber (typically 20 to 25 percent by weight) with hot asphalt cement, which causes the rubber to swell up with asphalt. The desirable properties of rubber, high elasticity and high melting point, are imparted to the asphalt, resulting in an increase in elasticity, cohesiveness, and softening point. The addition of too much rubber can create problems, however, by making the mixture so viscous that it cannot be pumped.

Because no polymer cross-linking occurs with the addition of rubber to asphalt, the asphalt-rubber mixture is capable of "melting" back together in the summer if it has cracked in the winter.

Asphalt rubbers, together with polymerized asphalt rubbers (discussed in the following section) are the most commonly used sealants for PCC pavements. The elastic properties lent to the asphalt by the rubber compounds have made them far more effective than conventional asphalt cement, cutback asphalt, or emulsified asphalt sealants.

Polymerized Asphalt Rubber

Although these materials have been produced for nearly 40 years, only in the last 15 to 20 years have they been used extensively. These sealants are also produced by mixing ground tire rubber (approximately 30 percent by weight) with asphalt. However, before the rubber is added, it is heated for about 15 hours until it forms a melted liquid. It is then added, along with a polymer, to the asphalt cement.

Greater elasticity and a larger working range are characteristics of the resultant mixture. Furthermore, greater resilience is gained by mixing a polymer with the asphalt rubber. The use of a softer asphalt cement base provides an even greater working range. While elastic and resilient properties are vastly improved with the addition of rubber and polymer, adhesive properties are reduced since less asphalt cement is available for bonding. This is a drawback in the context of bonding with substrates; however, by the same token, tracking is also reduced.

Polymerized asphalt rubber materials are generally formulated to conform to one of two standard specifications. These specifications are American Society for Testing and Materials (ASTM) D 1190 and ASTM D 3405. The ASTM D 1190 specification has been in existence for a longer period (since 1952) and is less restrictive in terms of property requirements. The ASTM D 3405 specification came into existence in 1978.

Several highway agencies and sealant manufacturers have improved upon these two standard specifications. For instance, the use of a softer base asphalt provides a more extensible material, capable of undergoing greater elongations. States have adopted modified D 3405 specifications in order to make these materials better comply with their expectations for sealants.

Fiberized Asphalt

Hot asphalt cement is often modified with the addition of fibers to form a fiberized asphalt. The high tensile-strength fibers reinforce the asphalt cement, thus increasing its strength capabilities. Although the elasticity of such a mixture is slightly improved, fiberized asphalt is not capable of undergoing large movements. And, as with the rubberized and polymerized asphalts, the addition of the modifiers takes away from the adhesive properties of the asphalt cement.

There are three types of fibers that can be added to asphalt cement: polyester, polypropylene, and polyethylene. The first two types are the most commonly used. Polypropylene and polyethylene have much lower melting points (310 °F and 280 °F, respectively) than polyester (485 °F).[8] Thus, more control must be exercised in the field with polypropylene and polyethylene in order to keep from melting the fibers. This may hamper the sealing operation, but since the asphalt cement is heated to lower temperatures, less oxidation occurs.

Polyvinyl Chloride (PVC)/Coal Tar

Coal tars and pitches are products formed from the destructive distillation of coal. In their basic form, these materials have seen limited application as sealants. However, in 1964, PVC/coal tar, consisting of about 10 percent PVC plastic and 90 percent coal tar and fillers, was introduced to the pavement industry.

A field-molded material, PVC/coal tar shows excellent resistance to fuel spillage. In addition, it has a much higher softening points than asphalt-based sealants, resulting in considerably less tracking. For these reasons, PVC/coal tar is used considerably in pavements subject to jetblast and fuel spillage. These sealants are commonly used on airport aprons, refueling areas, and at the ends of runways.

PVC/coal tar materials also have excellent bonding capabilities to concrete. However, due to variable performance in the field and the health problems posed by this sealant (PVC/coal tars have been labeled carcinogens), the use of these materials remains questionable.

Cold-Applied Thermoplastic Materials

Cold-applied thermoplastics set either by the release of solvents or by the breaking of emulsions upon exposure to the atmosphere.[7] Generally, these materials are applied at ambient temperatures or are heated to only 120 °F to 140 °F prior to placement.

Cutback Asphalt

Cutback asphalt is obtained by fluxing or "cutting back" residual asphalt with a distillate. If a light solvent such as gasoline is used to soften the residual asphalt, the cutback produced is classified as rapid-curing. Similarly, if a medium solvent such as kerosene is used, the cutback is referred to as medium-curing, and if a less volatile distillate such as diesel fuel is used, the cutback is labelled slow-curing.

The primary advantage of cutbacks is cold application. Once the petroleum distillates used to liquify the asphalt cement have evaporated, the material reverts to asphalt cement. The properties of cured cutbacks are similar to asphalt cement. In some cases, rubber has been added to cutbacks to provide greater elasticity and higher softening points.

There is indication that highway agencies are getting away from using cutback asphalts as a joint sealant material. This is likely a result of their poor performance and also because of the environmental restrictions placed on their use.

Asphalt Emulsion

Emulsified asphalt is a dispersion of asphalt particles in water with the presence of an emulsifying agent, such as soap. The purpose of the water is to serve as a transporting medium for the asphalt. Emulsions are classified as rapid-setting, medium-setting, or slow-setting, depending upon the speed at which the emulsion breaks.

Like cutbacks, the primary advantage of emulsions is that they do not require heating. In addition, they can be applied in damp conditions without seriously affecting their performance.

Emulsions, on the other hand, lack desirable elastic properties, have a tendency to flow more readily through joints, and are more easily tracked. The substandard properties of emulsions can be substantially improved by the addition of modifying agents, such as rubber or a polymer (rubberized emulsions), or by incorporating special manufacturing processes (high float emulsions).

Thermosetting Materials

Thermosetting materials are one- or two-component materials. They set by the release of solvents, by the breaking of emulsions on exposure to the air, or by curing through a chemical reaction in which they are transformed from a liquid state to a solid state.[7] Those that cure chemically are more common and have properties that make them suitable as sealants over a wide range of temperatures and applications. Examples of sealant materials in this category include silicones, polysulfides, and polyurethanes. While having the potential for increased performance, materials in this category generally have high costs.

Silicone

Silicone sealants were first introduced into the transportation field as a concrete pavement joint sealant in the early 1970s. They are one-part polymer materials which, upon curing, form a continuous silicone-oxygen-silicone network. The low modulus value of silicone sealants allow them to withstand cyclic movement of concrete pavements.

Silicones are highly resistant to environmental effects, in that they are insensitive to temperature changes and ultraviolet light. They do harden somewhat with time; however, the rate of hardening is <u>much</u> lower than thermoplastic materials.

The major drawback of silicones is their price. At about $2 to $3 per pound, they are over two times costlier than polymerized asphalt rubber. However, due to the typical thin layer application, smaller quantities of material are placed per lineal foot. In addition, the equipment costs for installing silicone are less than the equipment costs for installing hot-applied materials.

Preformed Compression Seals

Preformed compression seals are premolded strips of styrene, urethane, neoprene, or other synthetic materials that are inserted into transverse joints in a state of compression. The seals are intended to maintain contact pressure with the joint faces and therefore are not subject to adhesion failures, one of the primary failure modes of field-molded sealants.

Excellent performance can be obtained from compression seals placed in newly constructed pavements. Failure of these materials is usually by compression set, whereby the sealant loses its outward thrust capabilities after being compressed for long periods of time. This results in the sealant moving downward or out of the joint. The effectiveness of these seals is reduced when they are placed in older pavements, particularly those with joint spalls and cracked slabs.

Material Use and Performance

The performance of a joint sealant is difficult to define, and in many instances depends largely on the performance expectations of the user. As was expected, with the diverse backgrounds of the respondents from the many states asked to judge the performance of sealant materials, and the extensive published material reviewed, various definitions of good sealant performance were encountered. There are, however, more or less universal factors on which sealants were evaluated. These include:

- Adhesion, or bonding capabilities
- Cohesion, or internal resistance to cracking
- Resistance to the infiltration of incompressibles
- Resiliency
- Weathering, or change in properties over time
- Compression set (preformed compression seals only)

It must be pointed out, however, that the failure of sealants in any of these modes may or may not be directly related to the properties of the sealant. The joint and pavement design, the prevailing environmental conditions, the condition of the joint prior to sealing, the integrity of the concrete adjacent to the joint, installation procedures (e.g. overheating), and the quality of the workmanship can all influence the performance of the sealant material.

Table 3-1 provides a general overview of the information obtained from the questionnaires. Each generic category of sealant is listed along with information on the number of responses for given applications and ranges in performance and years of experience.

Table 3-1. General summary of questionnaire responses for PCC joint sealing.

Sealant Type	Total Number of Responses	Experience (years of use)		Range of Life Expectancy (Years)
		Average	Range	
Asphalt Cement	8	23.4	2 - 50	1 - 10
Asphalt Emulsion	16	18.5	10 - 35	1 - 10
Modified Emulsion	3	6.7	5 - 10	1 - 5
Asphalt Cutback	9	25.3	7 - 50	0.5 - 10
Asphalt Rubber	34	11.5	3 - 40	0.1 - 13
Polymerized/Rubberized Asphalt	32	7.8	0.5 - 15	1 - 10
Fiberized Asphalt	6	7.1	4 - 12	2 - 4
Silicone	30	5.8	1 - 12	1 - 10
PVC Coal Tar	1	10.0	10	2.5 - 4
Polysulfide	1	15.0	15	10
Compression Seal	17	16.3	2 - 25	2 - 18

It should be noted that the results presented here are broad interpretations. Performance trends have been averaged across different climates and across different pavement and joint designs. There is no doubt that installation procedures and conditions (wet or contaminated joints) can have an impact on performance. In fact, they were often cited as reasons for failures in sealant performance in this investigation. Furthermore, some sealants may have more application to certain concrete pavement joints than others with, for instance, sealants placed in longitudinal PCC/PCC joints undergoing much less movement than sealants placed in transverse joints or in longitudinal PCC/AC shoulder joints. However, the review of sealants materials presented does provide some insight into the relative performance of the various sealing materials in use today.

Although there is some concern as to the correct categorization of the various sealants by some of the respondents to the survey, the results are summarized as was reported in the questionnaires. In the following sections, overall performance trends are presented for the specific sealant classifications. Additional information is also provided on the different types of sealants within each category.

Hot-Applied Thermoplastic Materials

Asphalt Cement

The summary of the performance of asphalt sealant materials from the questionnaires is given in table 3-2. Although asphalt cement has had a long history of use as a joint sealant, having been used for an average of 19.4 years, it generally has not performed well. For the optimum case in this investigation (dry joint, temperature above 40 °F), asphalt cement averaged about 2.7 years of life expectancy for transverse joints. For those cases when installation temperatures were less than 40 °F and the joint was wet, service life was reduced.

Little information was available from the literature concerning the performance of asphalt cement joint sealants. In a research study conducted by New York State Department of Transportation, all 10 test sections sealed with asphalt cement failed within 3 years (7 in the first 2 years). The failure was generally attributed to the material becoming brittle and to loss of bond (adhesion failure).[9] Peterson reports that asphalt cement has been used by 11 agencies as a joint/crack sealer with performance ranging from poor to good, and an average performance rating of fair.[3]

Table 3-2. Summary of questionnaire responses for the performance of asphalt cement in PCC joint sealing.

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	1	4	1	3
Low	1	1	1	0.5
Average	1	2.17	1	2.69
Standard Deviation	0	1.33	0	1.75
Number of Responses	3	6	3	8

Fiberized Asphalt

Fiberized asphalt sealants are a relatively new product and the questionnaire confirmed that with only six agencies reporting they had used the material as a joint sealant. Their combined experience averaged 7.1 years. The only information obtained on performance was for the optimum condition with dry joints and temperature in excess of 40 °F. Two respondents reported life expectancies ranging from 2 to 4 years for this condition.

Little published information on performance could be found. However, one study compares the performance of an overlaid pavement where the cracks and joints of the underlying slabs had been sealed with fiberized asphalt and with rubberized asphalt.[10] This study indicates that the fiberized asphalt sealant not only delays the onset of reflective cracking, but also reduces the amount and severity of reflective cracks.

Asphalt Rubber

Thirty-four respondents reported they had used asphalt rubber sealants for between 3 to 40 years, with an average of 11.5 years of use. Table 3-3 is a summary of the results from the survey of experience for rubberized asphalt sealants. The average life expectancy for asphalt rubber ranged from 3.5 to 6.1 years, and was higher in each of the four conditions of application in comparison to the results obtained for all the other thermoplastic sealant types investigated. Better performance was reported for dry joint conditions, but temperature at time of application was again not a major factor in the performance of the sealants. It must be noted that, generally, there was a large variation in the performance reported by the respondents as evidenced by the relatively high standard deviations in table 3-3.

A search of the available literature revealed a good deal of information on asphalt rubber joint sealants. Generally, the reported performance of these materials is not exceptional, although New York reports that asphalt rubber sealants worked fairly well, providing at least 3 years of service.[9] They further indicate that asphalt rubber sealants perform much better than asphalt cement sealants and that they are less temperature-sensitive and quite resistant to embedment of incompressibles.

Pennsylvania reports poor and fair performance for two rubberized asphalt sealant types after 9 years of service.[11] The sealant exhibiting fair performance is an improved asphalt rubber sealant with a higher latex content. It actually provided satisfactory performance for 6 years.

Georgia reports the failure of two asphalt rubber sealants after 4 years of service.[12] They note that these sealants are not very pliable at cold temperatures and suffer a great many

Table 3-3. Summary of questionnaire responses for the performance of asphalt rubber in PCC joint sealing.

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	10	13	10	12
Low	1	1.5	0.1	3
Average	4.67	6.10	3.53	5.33
Standard Deviation	4.73	4.34	4.48	3.57
Number of Responses	3	11	4	24

adhesion failures, particularly after the first winter. Delaware indicates numerous adhesion failures associated with rubberized asphalt sealants.[13] A study in Great Britain also shows that adhesion failures are common with rubberized asphalts.[6]

An Arizona study of three rubberized asphalt sealants indicates that they deteriorated rapidly, becoming hard and brittle in the winter and soft and ductile in the summer.[14] As such, the materials were not capable of keeping incompressible materials from infiltrating. A Minnesota study indicates that after 3 years, 35 percent of the linear footage of joints sealed with asphalt rubber sealants had failed.[6] In his joint sealing synthesis, Peterson reports that hot-poured rubberized asphalt joint/crack sealants are used by 36 agencies.[3] He further indicates that the performance of the rubberized asphalt joint sealants ranges from very poor to very good, with an average rating of good.

Polymerized Asphalt Rubber

The results on the performance of polymerized asphalt rubber sealants are presented in table 3-4. The results were obtained from 32 respondents whose experience with the material ranged from 0.5 to 15 years, with an average of 7.8 years. For the optimum condition, application with dry joints and temperatures in excess of 40 °F, the average life expectancy was 5.3 years. Life expectancy decreased for wet joint conditions on the average, but the effect of temperature was negligible.

Although the references cited above on the performance of asphalt rubber do not specifically mention polymerized asphalt rubber, it is believed that in most cases they were categorized together with asphalt rubber sealants. Utah reports poor performance for three low-modulus, polymerized asphalt rubber sealants conforming to ASTM D 3405.[15] These sealants are noted as failing either in adhesion or cohesion after 2 years of service.

PVC/Coal Tar

One respondent reported the use of PVC/coal tar sealants over a period of 10 years. Average life expectancies for dry joint conditions of 2.5 and 4 years were noted for application temperatures below 40 °F and above 40 °F, respectively. In addition, the literature search revealed a fair amount of information on PVC/coal tar sealants. For instance, a Minnesota study reveals that joints sealed with a PVC/coal tar displayed less than 2 percent failure after 3 years.[6] A study in New York State concludes that PVC/coal tar performed better than asphalt rubber sealants and a tar-modified polyurethane after 3 years of service.[9]

Table 3-4. Summary of questionnaire responses for the performance of polymerized asphalt rubber in PCC joint sealing.

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	1	7	1	10
Low	1	3	1	1
Average	1	4	1	5.3
Standard Deviation	0	1.51	0	2.55
Number of Responses	1	8	2	23

PVC/coal tar sealants in Utah displayed fair performance after 2 years.[15] Delaware has had good performance with such a material after 1 year of service.[13] Georgia reports fair performance with a PVC/coal tar after 4 years of service, but notes that the material is very brittle and weathered in the winter, returning to a somewhat soft and pliable condition in the summer.[12]

In an Arizona study, a PVC/coal tar sealant initially performed well, but eventually hardened and allowed the embedment of incompressible material after 7 years of service.[14] On a separate roadway, Arizona reports poor performance for PVC/coal tars (brittle and cracked, some adhesion failures) after 5 years.[14]

Peterson reports six responses for a grouping of miscellaneous materials including PVC/coal tars and polyurethanes. The performance of these materials ranges from very poor to good, with an average rating just above fair.[3]

Cold-Applied Thermoplastic Materials

Cutback Asphalt

Like the asphalt cements, cutback asphalts have had a long history of use as a joint sealant. From the questionnaires, the average experience with cutbacks was about 25 years. However, as indicated in table 3-5, the performance of cutbacks has not been very good. Even for the optimum conditions (temperature above 40 °F and a dry joint), the average life was about 3 years in transverse joints. From the results, the effect of installation temperature on life expectancy was negligible. Life expectancy was appreciably reduced when the sealant was applied under wet joint conditions.

Little performance information on cutback asphalts was available from the literature. Peterson reports that cutbacks have been used by 17 agencies, with an average rating of poor to fair.[3] Barksdale and Hicks report that cutbacks have performed poorly as a longitudinal PCC mainline/AC shoulder joint sealant.[5]

Asphalt Emulsion

Table 3-6 provides a summary of the performance of emulsions from the questionnaires. Sixteen agencies reported using emulsified asphalt as a joint sealant, with an average of nearly 19 years of experience. It is observed in table 3-6 that for the optimum conditions, the average life expectancy for emulsions was about 4.3 years for transverse joints. In this case,

Table 3-5. Summary of questionnaire responses for the performance of cutback asphalt in PCC joint sealing.

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	2	2	2	4
Low	1	1	1	0.5
Average	1.67	1.40	1.67	1.92
Standard Deviation	0.58	0.55	0.58	1.36
Number of Responses	3	5	3	6

Table 3-6. Summary of questionnaire responses for the performance of asphalt emulsion in PCC joint sealing.

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	2	10	2	10
Low	1	1	1	1
Average	1.5	4.25	1.67	4.33
Standard Deviation	0.58	4.4	0.52	4.13
Number of Responses	4	10	6	15

life expectancies for wet conditions were also lower, but installation temperature did not seem to have an appreciable effect on performance.

Peterson reports that emulsions were used by ten highway agencies.[3] The performance ranged from very poor to good, with an average rating of fair. It was further noted that joints sealed with emulsions had to be resealed often.

Modified emulsions, whose properties are enhanced by the addition of modifying agents such as rubber or polymers, or by the use of some special manufacturing process, have also been used as joint sealants in PCC pavements. The results for modified emulsion sealants obtained from the survey indicate an average life expectancy of 3 to 5 years. The data obtained was limited though, with only three respondents reporting the use of modified emulsion sealant. It is not possible, as a result, to make any conclusions about the comparative performance of the two types of emulsion sealants.

Thermosetting Materials

Silicone

Silicone sealants have been gaining widespread use in the last few years. The questionnaire revealed that 30 agencies have used or are currently using silicone sealants. This ranks third behind the number of respondents who reported the use of asphalt rubber and polymerized asphalt rubber. The range of experience with silicone sealants ranged from 1 to 12 years and averaged 5.8 years. The summary of the life expectancy of silicone sealants is given in table 3-7. Long performance periods were reported, with average life expectancies of 7.0 and 8.8 years, respectively, for the sealant applied to a joint in dry condition, at temperatures below and above 40 °F.

The literature on silicone sealants has generally indicated good performance. A report by Georgia, which was the first state to use silicone sealants in a highway application, indicated that silicone sealants had performed well. After 10 years of service, the sealants were still soft and resilient.[16] However, proper installation procedures were noted to be critical to their performance.

Zimmer, et. al.,[17] evaluated the field performance of silicone joint sealant installations throughout the country. Fifteen sites, representing the four main climatic zones, were inspected. The results indicated that silicone sealant performance was generally good, with some performing excellently after 6 years of service. Again, proper installation procedures were identified as a critical element in the performance of silicone joint sealants.

Table 3-7. Summary of questionnaire responses for the performance of silicone in PCC joint sealing.

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	-	10	1	10
Low	-	2	1	2.5
Average	-	7.0	1	8.79
Standard Deviation	-	3.83	0	2.04
Number of Responses	-	4	4	21

Utah installed two silicone sealants on a test site in 1984 and reported good performance for both after 2 years of service.[15] However, there were some spall-related and saw/tine-related failures occurring in association with the material. It is believed that silicone's rather stiff modulus and strong adhesion capabilities cause small fractures in the surrounding concrete to further open. This same spall-related problem has been found to occur with asphalt-based sealants, but to a much lesser degree.

Delaware reports good performance with silicone sealants after nearly 2 years of service.[13] Arizona reports good performance from a silicone sealant after 7 years of service.[14] Adhesion failures were the only problems noted, believed to have occurred as a result of the sealant being placed too high in the joint. On a separate project, Arizona reports problems with a silicone sealant, believed to be associated with the improper tooling of the material against the joint wall. In his 1982 synthesis, Peterson indicates that seven agencies were using silicone sealants. Performance data was limited, but generally its performance ranged from good to very good.[3]

An additional work item for the silicone has been the required final tooling step in which the material is tooled against the joint walls. However, a new silicone joint sealant material has been introduced that is self-leveling and eliminates the cost and potential problems associated with the tooling operation. No performance data were available on this new, self-leveling silicone sealant.

Other Thermosetting Materials

Other thermosetting materials, including polysulfides, polyurethanes, and polyurethane coal tars, have been used for joint sealing purposes by several agencies. However, only one response to the questionnaires indicated the use of one of these materials (polysulfide). The material had been used for 15 years and had provide an average performance of 10 years.

A review of the literature indicated that these materials have had more widespread use. A study in Great Britain indicates that polyurethanes were very elastic materials and provided good performance; however, poor performance was exhibited by polysulfides, which were noted as being less elastic than polyurethanes and consistently failed in adhesion.[6] In Minnesota, joints sealed with polysulfide and polyurethane materials averaged 23 percent failure after 3 years.[6]

A study in New York State notes that a tar-modified polyurethane exhibited satisfactory performance after 3 years.[9] Delaware has had fair performance with a polyurethane sealant.[13] Pennsylvania reports very poor performance with urethane and polysulfide materials after 9 years of service.[11] Georgia reports fair to poor performance with two polysulfide materials, a polyurethane material, and a urethane coal tar material, all substances failing extensively in adhesion, but still being very resilient after four years.[12] The failure of the materials is attributed to poor shape factors. In a study in Arizona, poor performance is reported for two polyurethane sealant materials (adhesion failures) after 5 years.[14] It is noted that the methods used to install these materials are very time consuming and do not produce a satisfactory product.

As mentioned before, Peterson reports six responses for a grouping of miscellaneous materials including PVC coal tars and polyurethanes. The performance of these materials ranged from very poor to good, with an average rating just above fair.[3]

Preformed Compression Seals

Seventeen respondents indicated that they had up to 25 years of experience with preformed compression sealants. The average number of years of experience was 16.3. The summary of the life expectancies for preformed compression seals is shown in table 3-8. For optimum conditions, average life expectancies of about 10 years were reported for transverse joints. Similar to field-molded sealants, the life expectancy of preformed compression seals was again affected by moisture conditions in the joint at the time of installation.

An early performance review of preformed seals in Minnesota, North Dakota, Michigan, Ohio, and California indicated that they were effective in keeping incompressible materials from infiltrating the joints and were in generally good condition after up to 8 years of service.[18] New York evaluates three neoprene compression sealants and concluded that they had performed well, except in spalled areas, after 3 years of service.[9] It was further mentioned that they were easy to install.

After 9 years of service, Pennsylvania reports good performance with preformed compression seals.[11] Georgia has experienced good success with preformed compression seals, although there are some problems with the lubricant adhesive and sand trapped between the seal and joint face.[12] Georgia also notes better performance with closed-cell seals than with open-cell seals.

A Michigan study shows neoprene seals performed well and reduced the occurrence of blowups.[6] A study in Minnesota shows a wide range in the performance of preformed joint sealants, from 2 percent failures to 50 percent failures.[6] In Great Britain, preformed compression seals have performed well, but require a joint with a well-shaped sealing groove with vertical faces, very little spalling, and a constant width.[6]

Table 3-8. Summary of questionnaire responses for the performance of compression seals in PCC joint sealing.

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	7	10	7	18
Low	2	2	2	2
Average	5.75	6.6	5	9.76
Standard Deviation	2.50	2.88	2.47	4.91
Number of Responses	4	5	5	15

Peterson reports that five agencies are using preformed joint sealants, with performance ranging from poor to very good.[3] High costs are cited as one problem with preformed joint seals, although this is not a performance indicator. An FHWA study which evaluated the performance of concrete pavements throughout the country notes excellent performance for preformed compression seals, with some exceeding 12 years of service.[19]

Related Findings

The dimensions of prepared joints depend on the properties of the sealant. The shape factor, defined as the ratio of sealant width to sealant depth (and not as the width and depth of the sealant reservoir), typically ranges from 0.5 to 1.0 for thermoplastic sealants and 1.0 to 2.0 for thermosetting sealants. Typically, recessed sealants are placed 0.13 to 0.25 in below the pavement surface.

All of the sealants (polymerized asphalt rubbers, PVC/coal tar, and silicones) evaluated in the Utah study were placed in 0.38- x 0.38-in prepared joints (shape factor = 1.0), recessed 0.25 in below the pavement surface.[15] It is not mentioned whether the shape factor had any effect on the failures of the polymerized asphalt rubber sealants. The silicone sealants evaluated and found to provide good performance by Zimmer, et. al., were placed with shape factors ranging from 0.6 to 1.0.[17] On average, these sealants were recessed 0.19 in.

Little experimentation has been done with regard to placing sealant materials in an overband over joints. It is believed by many that such a design creates a rhythmic sensation of noise that can be a distraction to drivers. However, with the improved wear characteristics of the fiberized and polymerized asphalt rubber sealants and their apparently good performance as overbands in AC cracks, this may be a feasible alternative. The thickness of the sealant overband must be limited to less than 0.13 in so that the sealant is not damaged by snowplows and the smoothness of the road is not significantly altered. Thermosetting materials such as silicone cannot be placed in this fashion as they do not possess good wear characteristics.

Summary of Findings

From the questionnaire responses and from the review of the available literature, several trends regarding the performance of concrete joint sealants are apparent. It is clear that straight asphalt cements, cutback asphalts, and emulsified asphalts, without an additive, are not adequate for concrete joint sealing applications, particularly in a joint where much movement is expected. These materials do not resist the infiltration of incompressibles and cannot withstand the stresses that are created by large joint movements.

A wide range of performance data was noted for the asphalt rubber sealant materials. The major failure mode for these materials was loss of adhesion. PVC coal tars had the promise of providing a long-lasting seal and, in fact, came with a 10-year warranty from one manufacturer. However, their widely variable performance and potential health hazards have cast a cloud of uncertainty over their use.

Fiberized asphalt sealants, while used only by a few agencies, appear to offer reasonable performance. The fibers in the sealant impart tensile strength to the material, thereby hindering the onset of cohesion failures, but potentially increasing the probability of adhesion failures.

Thermosetting materials displayed a range of performance. Silicone sealants generally performed well, but other thermosetting materials used by different agencies often yielded opposite results. Polysulfides generally exhibited poor performance. Adhesion failures were cited as the primary failure mode. Polyurethanes exhibited slightly better performance than polysulfides materials. Again, the primary mode of failure was loss of adhesion.

From the available information, the sealants providing the best overall performance are the silicones and polymerized asphalt rubber sealants. Indications for silicone sealant are that it can last 10 years or more, although there apparently might be problems with the sealant adhering so well to the joint face that it opens up small fractures in the surrounding concrete, resulting in joint failures.

Polymerized asphalt rubbers have been noted to provide 5 or more years of service. These materials possess excellent elastic and tracking characteristics; however, their adhesion properties are not nearly as good as asphalt cement's adhesion properties.

It is recognized that preformed compression seals provide excellent sealant performance in newly constructed PCC pavements. Although, they are occassionally used in PCC resealing operations, their performance in joints that have been previously sealed is considerably lower than their performance in newly constructed pavement joints. Furthermore, resealing PCC joints with preformed compression seals is a somewhat costly and intricate operation, which does not mesh with the typical maintenance routine. For these reasons, preformed compression seals are not considered for further investigation in this study.

One of the difficulties in evaluating the performance of the various sealant materials is that the materials themselves are continually being changed or modified. New formulations or other refinements are always being made to a product in order to improve its performance. This makes interpreting the performance data of a specific product an even more difficult task. As previously indicated, the results presented here are broad representations, but are still believed to provide a general indication of the relative performance of the various materials.

Based on the research conducted in the SHRP H-105 project, the following materials are considered worthy of continued investigation for the resealing of transverse PCC joints:

- Silicone
- Polymerized Asphalt Rubber (ASTM D 3405)
- Low-Modulus Polymerized Asphalt Rubber (Modified ASTM D 3405)

Further discussion of materials and operations will revolve around these sealants.

Pertinent Material Properties and Tests

The performance of a joint sealant depends to a large extent on the material properties of the sealant. In this section, the pertinent material properties that influence the performance of the joint sealants identified as being promising are discussed. In addition, several laboratory tests are presented which can be used to measure the desirable properties. Factors attributable to adjoining concrete slabs, such as excessive joint openings or weak concrete at the joint, are not discussed in this section.

Key Distress Manifestations and Their Causes

The following five distresses have been identified as the most common failure modes for the sealants in question:

- Adhesion Failure
- Cohesion Failure
- Extrusion/Tracking
- Elasticity/Resilience
- Aging/Weathering

Adhesion

Adhesion failure, or debonding of the sealant from the joint face, is primarily caused in one of three ways: poor installation procedures (i.e., inadequate cleaning), poor sealant properties (elasticity and adhesion), or use of an incorrect shape factor. Generally, sealant failure can be attributed to deficient material properties, although joints are often poorly prepared by sealing crews, leaving moisture or dirt to inhibit bonding.

With continuous temperature and moisture changes in pavements and the resulting expansion and contraction of the pavement slab, stress concentrations at the sealant-joint interface eventually lead to a weakening of the bond and a peeling of the sealant from the joint face. Very low temperatures also cause sealants to become very brittle, occassionally resulting in adhesion failure.

Cohesion

Cohesion can be defined as a material's internal resistance to splitting. Sealants possessing poor cohesion are unable to withstand the internal stresses induced when the sealant is extended; this is usually the case for sealants placed in cold climates or placed with small shape factors (width to depth ratio < 0.5). The result is cracking of the sealant. In addition, sealants possessing poor elastic properties generally develop high internal stresses, resulting in either adhesion or cohesion failure.

Extrusion/Tracking

The softening of sealant material as a result of high temperatures, and the closing of joints due to slab expansion, can lead to the extrusion of sealant from joints. An increase in stickiness usually accompanies sealant softening and, when sealant is displaced by the expanded slabs, tires tend to track and pull the sealant out of the joint.

Aging/Weathering

Aging and the effects of weathering can cause sealants to lose their resilience, strength, and durability. Some sealants lose their volatiles to the atmosphere and are damaged with the passage of time. Others may react with substances such as oils, gas, and ozone, resulting in a loss of quality. The use of relatively inert sealants with the proper material characteristics will reduce such losses.

Intrusion of Incompressibles

This phenomenon occurs as a result of sealants not being resilient enough to reject the penetration of pebbles, rocks, or other foreign objects. A material with poor resilience will not sufficiently reject the forced intrusion of incompressibles by traffic. This is particularly true in high temperatures, when sealants soften.

If incompressibles successfully penetrate the sealant and the sealant is unable to reject them, then they are likely to become permanently embedded. Eventually, the concrete slabs will expand to a point where the embedded incompressibles will cause the concrete to blow up, buckle, or spall.

Desirable Material Properties

For satisfactory performance, joint sealants must have certain properties which will contribute to their effectiveness. Desirable properties may be classified as performance-related, application-related, and maintenance-related. These properties are listed below (adapted from reference 7).

Performance-Related Properties

To ensure good performance, a sealant material in a joint must:

- Be impermeable
- Be able to deform to accommodate expected joint movements
- Be able to sufficiently recover its original properties after cyclical deformations
- Remain in contact with joint walls
- Resist internal rupture (i.e., failure in cohesion)
- Resist unacceptable softening at higher service temperatures
- Not harden or become unacceptably brittle at lower service temperatures
- Not be adversely affected by aging, weathering, or other service factors for a reasonable performance period
- Resist intrusion of incompressible materials

Application-Related Properties

To allow for an effective installation, a sealant material must:

- Be relatively easy to install
- Not require special equipment
- Not contain expensive or complicated substances harmful to the installer, concrete, or environment
- Resist excessive flow due to gravity
- Resist tracking or adhesion to tires and pick-up
- Cure or set-up relatively quickly

Maintenance-Related Properties

To allow for ease of maintenance, a sealant material must:

- Be repairable and easily replaceable

It is obvious that no single material has all of these characteristics. Therefore, selection of a sealant is often a matter of choosing the material that possesses the specific characteristics most desired or needed for the given application.

Laboratory Tests Used to Measure Desirable Material Properties

A multitude of tests are available for evaluating the properties of joint sealants. Unfortunately, many do not relate very well to actual field conditions, making their relevance questionable. Furthermore, some tests are conceptually sound, yet provide data from which only general assertions can be made.

Despite the myriad of such tests, several were investigated and found to be good indicators of field performance. Tables 3-9 and 3-10 list these tests for hot-applied elastomeric sealants and silicone sealants, respectively. As can be seen, some are ASTM standardized tests while others are state or privately developed tests. However, each of these tests were determined to be applicable for measuring the desirable material properties listed in the previous section.

Implementation of Research Findings into Experimental Plan

This section provides an overview of the experimental plan developed for the field evaluation of the relative effectiveness of PCC pavement joint sealants and joint configurations to meet the needs described above. Under project H-106, SHRP will conduct a field performance evaluation of various joint sealant materials, designs, and installation procedures subjected to a variety of external influences.

The evaluation will be conducted on in-service pavements in their first or second resealing stage. The specific objectives of the H-106 study as they relate to the joint resealing experiment can be summarized as follows:

- To evaluate the relative performance of selected sealant materials in joint resealing projects based on carefully designed and controlled field installations

Table 3-9. Laboratory tests for measuring desirable polymerized asphalt rubber material properties.

Desired Property	Laboratory Test(s)	Source
Resistance to Tracking	(1) Flow (2) Softening Point	ASTM D 3407-78 ASTM C 36-86
Adhesion	(1) Bond	ASTM C 3407-78
Extensibility	(1) Elongation (2) Ductility @ 39.2 °F	ASTM D 412-87 ASTM D 113-86 Modified
Internal Stress	(1) Tensile Stress @ 150% elongation (2) Force Ductility	ASTM D 412-87 Utah Test
Elongation at adhesive or cohesive failure	(1) Tensile Strength Adhesion	ASTM D 3583-85
Weathering	(1) Artificial Weathering	ASTM G 53-88/ ASTM D 3583-85
Ease of Placement	(1) Brookfield Viscosity	ASTM D 3236
Elasticity	(1) Resilience	ASTM D 3407-78
Wear	(1) Abrasion	ASTM D 3910-84
Flexibility	(1) Cold Bend	Utah Test

Table 3-10. Laboratory tests for measuring desirable silicone material properties.

Desired Property	Laboratory Test(s)	Source
Resistance to Tracking	(1) Flow (2) Tack-Free Time	ASTM D 2202-88 ASTM C 679-87
Adhesion/Cohesion	(1) Adhesion and Cohesion Under Cyclic Movement	ASTM C 719-86
Extensibility	(1) Elongation	ASTM D 412-87
Internal Stress	(1) Tensile Stress @ 150% elongation	ASTM D 412-87
Elongation at adhesive or cohesive failure	(1) Tensile Strength Adhesion	ASTM D 3583-85
Weathering	(1) Artificial Weathering	ASTM G 53-88/ ASTM D 3583-85

- To determine the effect of selected sealant configurations on sealant performance based on the results from the field installations
- To perform laboratory testing of the various sealant materials before and after their installation in order to identify material properties and tests which strongly correlate to the actual field performance of the sealant materials

Experimental Plan Overview

In order to fulfill the above objectives, a carefully designed and carefully controlled field experiment and evaluation of sealant installations will be conducted. The experiment has been designed using statistical concepts to accurately evaluate the factors that influence joint sealant performance and to allow for the drawing of valid conclusions. The preliminary experimental designs were developed for average climatic conditions within each of SHRP's four climatic zones (see figure 3-1). After actual site selection, these designs may have to be revised slightly to address specific climatic influences of each site.

Although there are many factors that could be considered in the conduct of this experiment, only those which are believed to significantly affect sealant performance will be studied. These variables include:

- Climate
- Joint Spacing
- Sealant Material
- Sealant Configuration

Five test sites are planned for an evaluation of the various sealant materials and configurations. The factorial designs for the joint resealing experiments are shown in tables 3-11 through 3-14.

Joint resealing test sites will consist of two identical sets, or replicates, of test sections placed adjacent to one another. Multiple replicates provide added reliability in determining the significance of a particular treatment and also serve as "backups" should one section receive inadvertent maintenance or be otherwise rendered invalid. Test sections within replicates will consist of one combination of a specified material and configuration. Each joint resealing test section will consist of 10 full-width transverse working joints to be resealed.

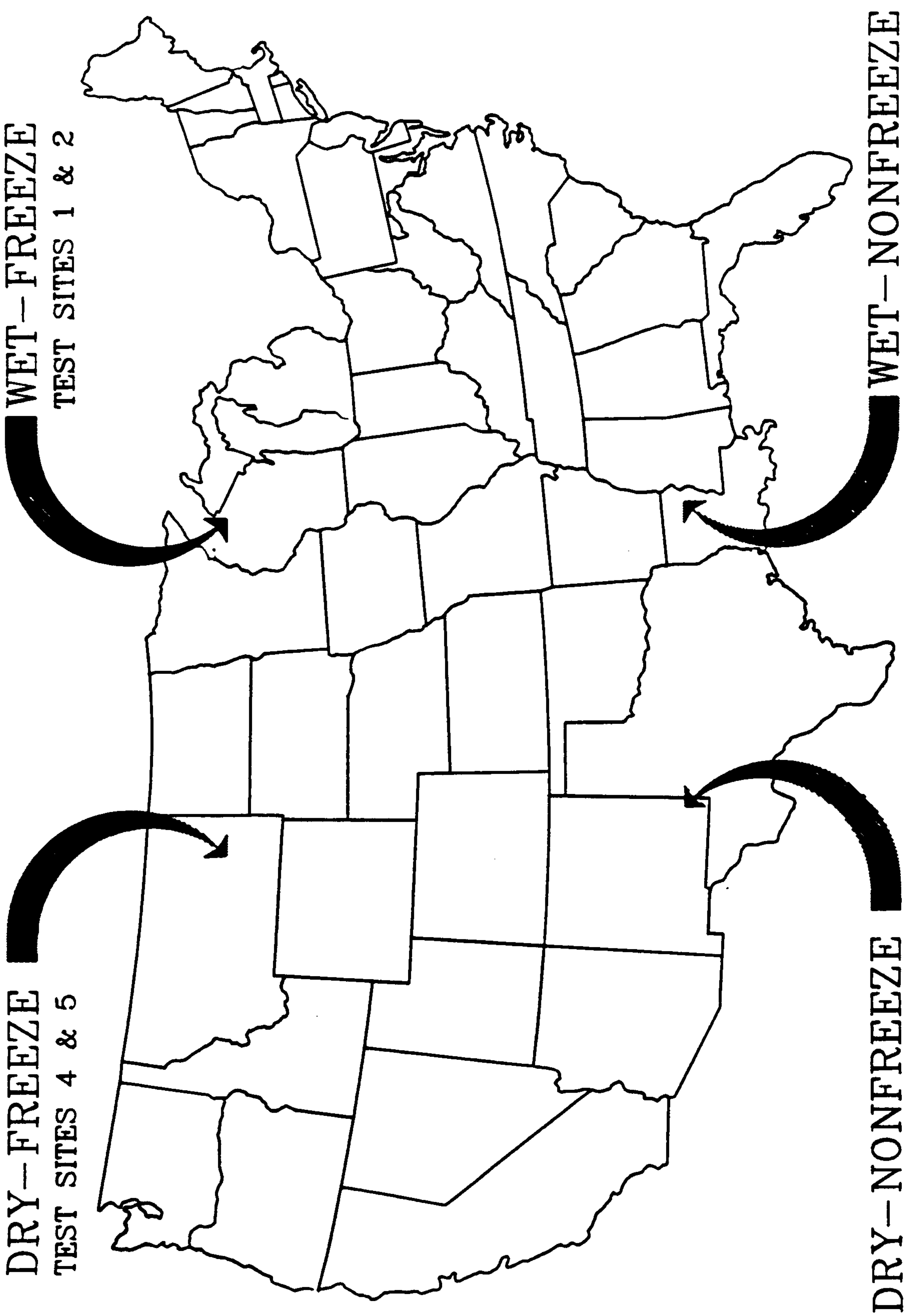

Figure 3-1. Strategic Highway Research Program (SHRP) four climatic zones.

Figure 3-1
SHRP Climatic Zones

Table 3-11. Factorial design matrix for the wet-freeze climatic region.

	Short-Jointed Pavements (≤ 30 ft)			Long-Jointed Pavements (35 - 60 ft)		
	Config. 1	Config. 2	Config. 3	Config. 1	Config. 2	Config. 3
Selected D 3405 Control Material	3 * Reps	2 Reps	2 Reps	2 Reps	2 Reps	2 Reps
Crafco RoadSaver 231	2 Reps	2 Reps	2 Reps	2 Reps	2 Reps	2 Reps
Koch 9030	2 Reps	2 Reps	2 Reps	2 Reps	2 Reps	2 Reps
Meadows Sof-Seal	2 Reps	2 Reps	2 Reps	2 Reps	2 Reps	2 Reps
Dow Corning 888	2 Reps			2 Reps		
Dow Corning 888-SL	2 Reps			2 Reps		
Mobay Baysilone (SL)	2 Reps			2 Reps		

* 3 reps included for an evaluation of the effectiveness of primer

Table 3-12. Factorial design matrix for the dry-freeze climatic region.

	Short-Jointed Pavements (≤ 30 ft)			Long-Jointed Pavements (35 - 60 ft)		
	Config. 1	Config. 2	Config. 3	Config. 1	Config. 2	Config. 3
Selected D 3405 Control Material	2 Reps	2 Reps	2 Reps			
Crafco RoadSaver 231	2 Reps	2 Reps	2 Reps			
Koch 9030	2 Reps	2 Reps	2 Reps			
Meadows Sof-Seal	2 Reps	2 Reps	2 Reps			
Dow Corning 888	2 Reps					
Dow Corning 888-SL	2 Reps					
Mobay Baysilone (SL)	2 Reps					

Table 3-13. Factorial design matrix for the wet-nonfreeze climatic region.

	Short-Jointed Pavements (≤ 30 ft)			Long-Jointed Pavements (35 - 60 ft)		
	Config. 1	Config. 2	Config. 3	Config. 1	Config. 2	Config. 3
Selected D 3405 Control Material	2 Reps	2 Reps	2 Reps			
Crafco RoadSaver 231	2 Reps	2 Reps	2 Reps			
Koch 9030	2 Reps	2 Reps	2 Reps			
Meadows Sof-Seal	2 Reps	2 Reps	2 Reps			
Dow Corning 888	2 Reps					
Dow Corning 888-SL	2 Reps					
Mobay Baysilone (SL)	2 Reps					

Table 3-14. Factorial design matrix for the dry-nonfreeze climatic region.

	Short-Jointed Pavements (≤ 30 ft)			Long-Jointed Pavements (35 - 60 ft)		
	Config. 1	Config. 2	Config. 3	Config. 1	Config. 2	Config. 3
Selected D 3405 Control Material	2 Reps	2 Reps	2 Reps			
D 3405 Material	2 Reps	2 Reps	2 Reps			
D 3405 Material	2 Reps	2 Reps	2 Reps			
Selected LM D 3405 Material	2 Reps	2 Reps	2 Reps			
Dow Corning 888	2 Reps					
Dow Corning 888-SL	2 Reps					
Mobay Baysilone (SL)	2 Reps					

Climate

Figure 3-1 shows the four primary U.S. climatic regions as defined by SHRP. One test site will be placed in each of the wet-nonfreeze, dry-nonfreeze, and dry-freeze climatic regions, while two test sites will be placed in the wet-freeze region. The multiple test sites within the wet-freeze region will enable investigation into the effect of joint spacing on sealant performance.

Joint Spacing

Due to the prevalence of short-jointed concrete pavement construction, the primary portion of the experiment will be conducted on those designs. However, recognizing that there are many long-jointed concrete pavements which are in need of effective joint resealing, the wet-freeze region will include a site for long-jointed concrete pavements. For this experiment, short-jointed designs are defined as those pavements with joint spacing 30 ft or less; long-jointed designs are defined as those pavements with joint spacing between 35 and 60 ft.

Sealant Materials

Within each test site, a total of seven different materials (four hot-poured materials and three silicone materials) and three different configurations will be evaluated. One hot-poured material conforming to ASTM D 3405-78 will be used throughout the experiment to serve as a control. The other materials to be installed at every site include low modulus hot-poured sealant materials and silicone sealant materials. The low modulus hot-poured materials are more ductile than their ASTM D 3405-78 counterparts. The silicone sealant material will include one standard material and two self-leveling materials. However, participating highway agencies are encouraged to expand upon the experiment by including specific materials in which they are interested.

The use of a primer prior to sealant installation may be used as recommended by the manufacturer. However, at one site (short-jointed pavements in the wet-freeze climatic region), the use of primer will be evaluated by comparing the performance of the D 3405-78 control material when installed with and without a primer. It will be conducted for the standard recessed configuration only (sealant configuration 1).

Sealant Configurations

The following three sealant configurations will be used in the experiment:

- Sealant Configuration 1—Conventional recessed sealant configuration with backer rod (placed to manufacturer's recommended shape factor). Joint preparation includes diamond saw refacing and sandblast cleaning (figure 3-2)

- Sealant Configuration 2—Overband sealant configuration with backer rod. Joint preparation includes diamond saw refacing and sandblast cleaning (figure 3-3)

- Sealant Configuration 3—Overband sealant configuration without backer rod. The joint will be routed only to remove existing sealant; no refacing or cleaning will be done (figure 3-4)

Field Evaluations

Field inspections will be conducted at each test site in order to fully evaluate the performance of each sealant material. These inspections will be made at the following times subsequent to installation.

- 1 month
- 4 months
- 7 months
- 13 months
- 19 months

The evaluations will be conducted in the outer lane only of multi-lane facilities. Failure modes of the joint-sealant systems will be classified according to the following categories:

- Sealant material failures
  - adhesion
  - cohesion
- Concrete system failures
  - saw/tine related
  - spalling related
- Intrusion of incompressible materials

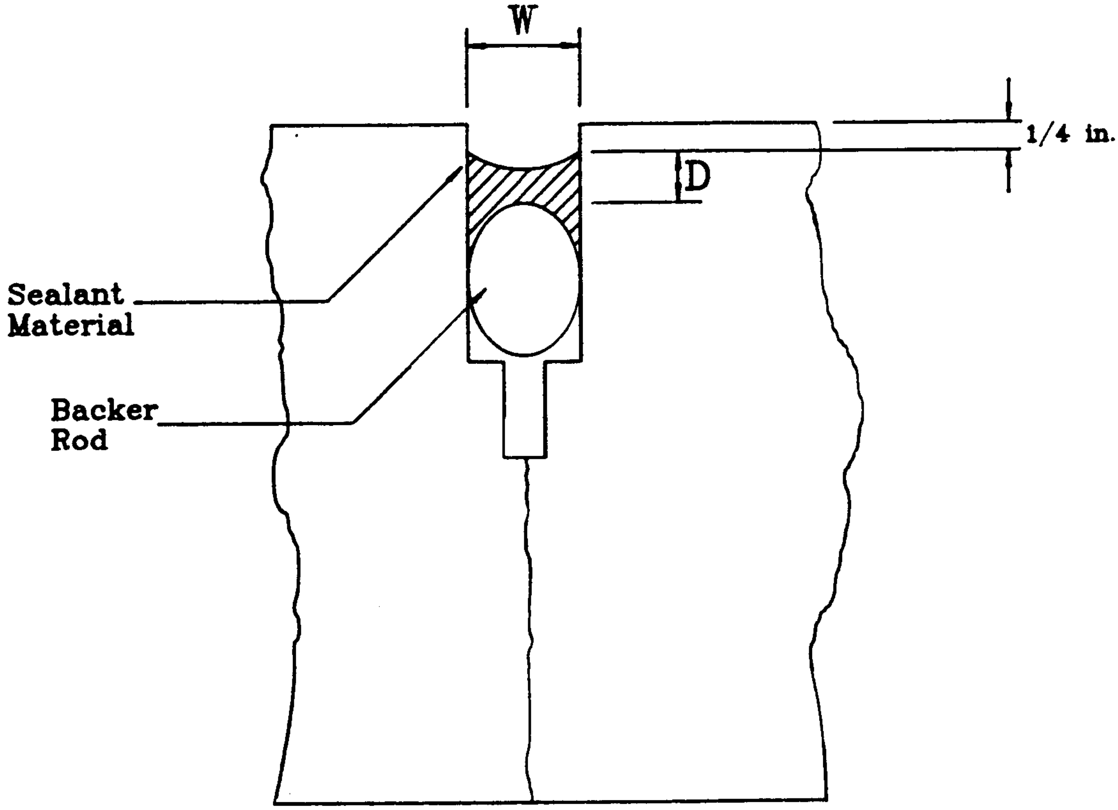

Figure 3-2. Standard recessed sealant configuration.

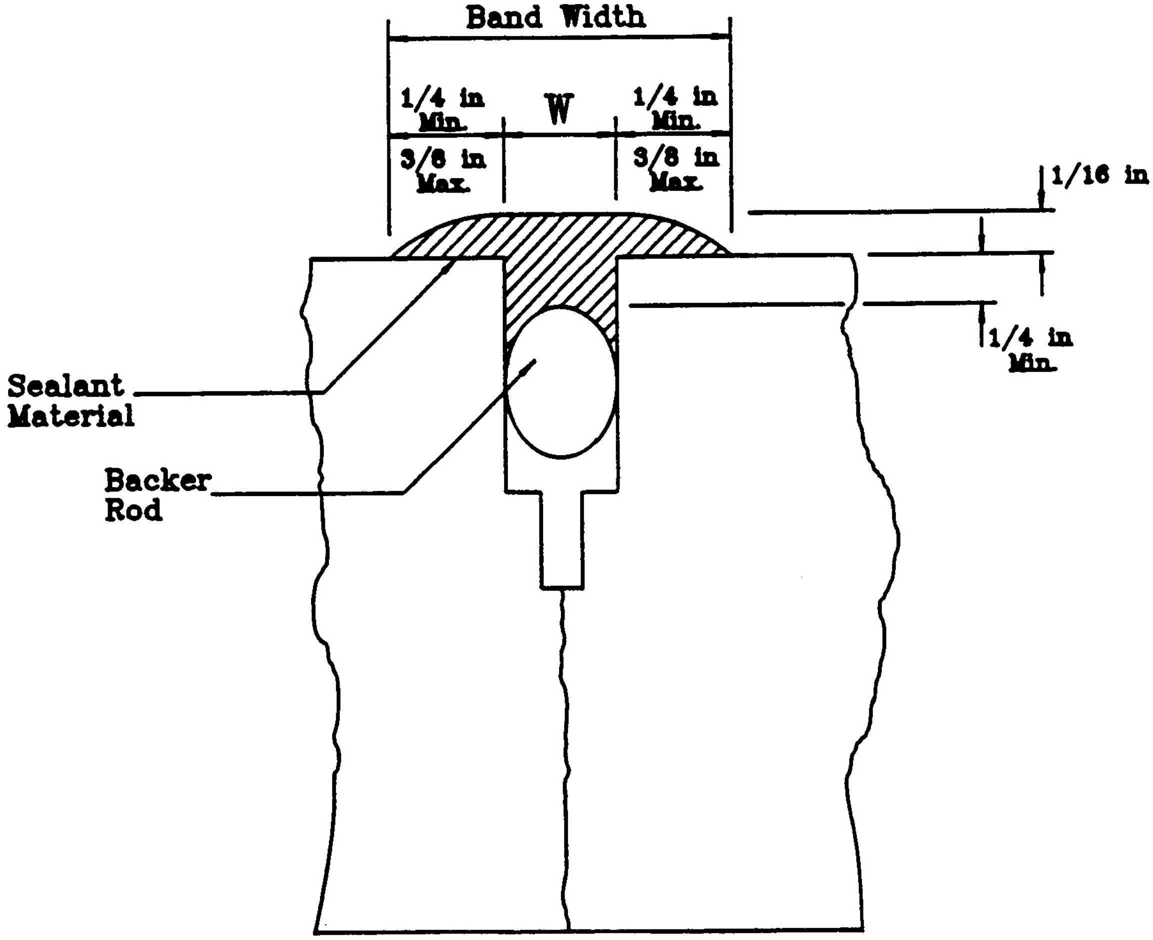

Figure 3-3. Overband sealant configuration.

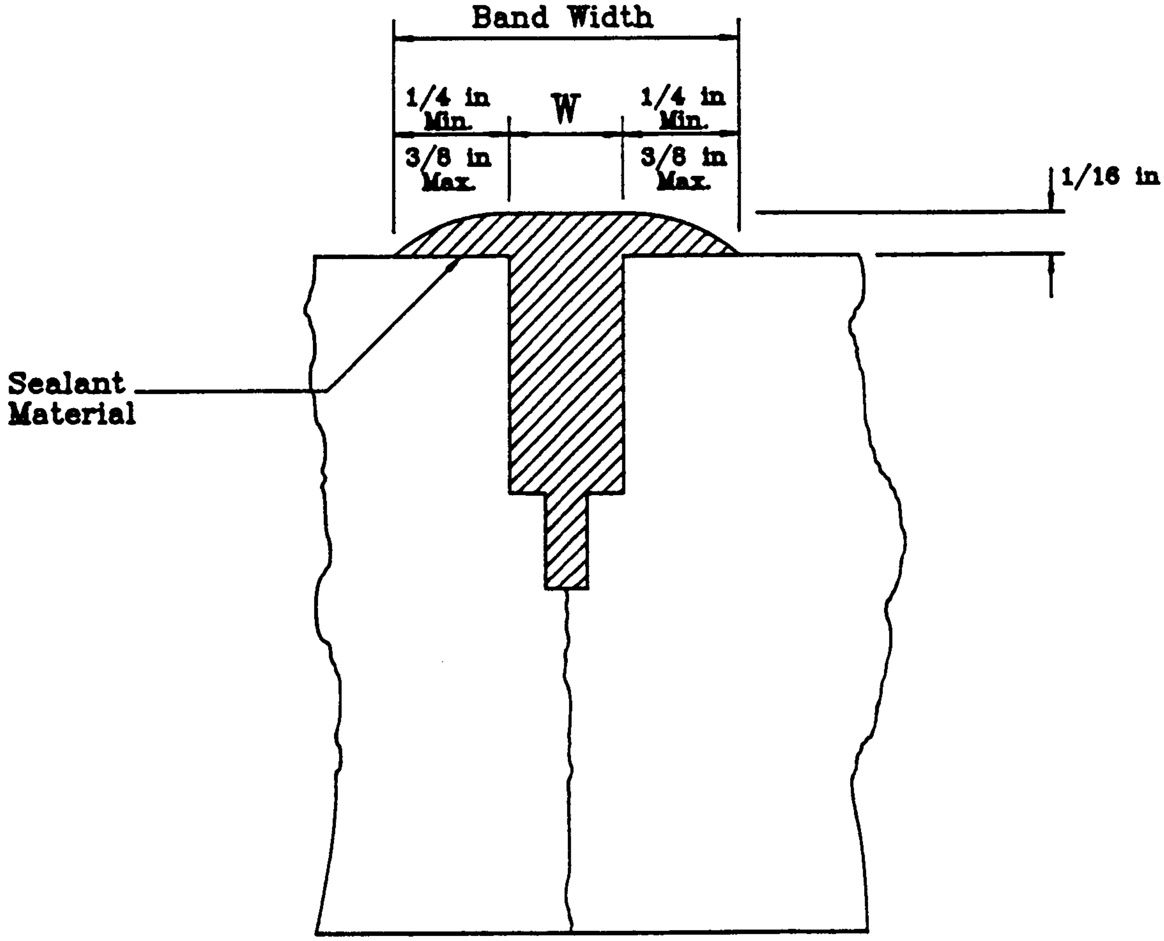

Figure 3-4. Overband sealant configuration with minimal cleaning.

- Other failures
  - bubbling
  - weathering
  - aging
  - tracking

In addition to the above evaluations, two quick field tests will be conducted on joint sealants. The coin test will be done to analyze resilience and the pull-out test will be performed to analyze adhesion and elongation properties.

Joint faulting and joint movements will be measured at each joint. These measurements will be useful in the evaluation to compare with the initial readings taken prior to installation to obtain an indication of the progression of these performance indicators over time.

Finally, extensive photographic documentation will be taken of the various installations, particularly showing the failures occurring in the various sealant types and their progression over the length of the study. Videotaping of certain aspects of the sealant evaluations may also be desired to more clearly indicate failure modes.

Data Analysis

Analysis of the data will begin as soon as the first set of performance data is obtained. The data will be analyzed individually for each site initially and then combined with the other sites to provide for a national analysis.

At each site, regional evaluations can be performed by comparing the relative performance of each individual sealant material and sealant configuration. This will provide information on the best performing sealants by climatic region. The evaluation of the laboratory testing data will attempt to correlate lab testing results with actual field performance.

The national analysis will compare the results obtained across climatic regions to ascertain any regional or national trends. Through the use of the ASTM D 3405 "control" section, relative comparisons can be made across climatic regions. The results from the laboratory analysis again will be considered, this time on a national basis, to try to identify any tests which correlate to actual field performance. Additional analyses will consider costs in order to perform a life-cycle cost analysis of each material.

Future Evaluations

Given the relatively short time frame available for the study, it should be pointed out that the length of the proposed experiment (approximately 19 months) is not long enough to fully evaluate the various sealant materials and configurations. Although several localized failures may occur, it is quite likely that most, if not all, of the sealant materials will still be performing satisfactorily after 19 months. It is believed that additional monitoring (say, for another 3 or more years after the initial 19-month evaluation) will be necessary for a more complete and accurate evaluation of the performance of the sealant materials. It is hoped that the additional monitoring will be assumed either by the participating states or by the Federal Highway Administration (FHWA).

Bibliography

Blaise, E. J. *Value Engineering Study of Crack and Joint Sealing*. Report FHWA-TS-84-221. FHWA, U.S. Department of Transportation, Washington, D.C., December 1984.

Brown, D. D. *Effects of Various Sealing Systems on Portland Cement Concrete Joints*. Highway Research Record No. 389. Highway Research Board, Washington, D.C., 1972, pp. 28-39.

Bryden, J. E., W. M. McCarty, and L. J. Cocozzo. *Maintenance Resealing of Rigid Pavement Joints*. Report NYSDOT-ERD-77-RR49. New York State Department of Transportation, Albany, May 1977.

Bugler, J. W. *Rigid Pavement Joint Resealing: Field Application, State of the Art*. Transportation Research Record No. 990. TRB, National Research Council, Washington, D.C., 1984, pp. 16-20.

Ellwanger, D. Sealing With Silicone. *APWA Reporter*, April 1989, pp. 10-11.

Guide to Joint Sealants for Concrete Structures. *American Concrete Institute Journal and Proceedings*, July 1970, pp. 489-536.

Huff, B. J. and B. A. Vallerga. Characteristics and Performance of Asphalt-Rubber Material Containing a Blend of Reclaim and Crumb Rubber. Transportation Research Record No. 821 TRB, National Research Council, Washington, D.C., 1981, pp. 29-37.

Joint Sealants Prolong Pavement Life. But Preparation and Installation Techniques are Critical. *Better Roads*, January 1985, pp. 20-22.

McBride, J. C. and M. S. Decker. Performance Evaluation of Utah's Concrete Pavement Joint Seals. *Transportation Research Record No. 535*. TRB, National Research Council, Washington, D.C., 1975, pp. 35-50.

McCullough, B. F. Selection of Pavement Joint Sealant Material. *ASCE Journal of Transportation Engineering*. March 1982, pp. 137-155.

McCurrich, L. H. and M. R. Cook. Airfield and Road Pavement Use in the U.K. of High Performance Coal Tar Pitch PVC Joint Sealants, and a Comparison of U.K. and ASTM Standards. Paper prepared for the Joint Congress on Joint and Bearings, Construction Chemicals Ltd., 1981, pp. 669-689.

McKerall, C. B. Jr. Evaluation of Joint Seal Conditions and Resealing Operations-Airfield Pavements. TRB, National Research Council, Washington, D.C., January 1980.

Mellott, D. and G. Hoffman. Concrete Pavement Joints and Sealing Methods. *Adhesives Age*, November 1982, pp. 29-34.

Peterson, D.E. Resealing Joints and Cracks in Rigid and Flexible Pavements. *NCHRP Synthesis of Highway Practice No. 98*, TRB, National Research Council, Washingtonk, D.C., December 1982.

Shober, S. F. Portland Cement Concrete Pavement Performance as Influenced by Sealed and Unsealed Construction Joints. *Transportation Research Record No. 1088*, TRB, National Research Council, Washington, D.C., 1986, pp. 7-12.

Spells, S. and J. M. Klosowski. The Importance of Sealant Modulus to the Long-Term Performance of Concrete Highway Joints Sealants. *Transportation Research Record No. 1041*, TRB, National Research Council, Washington, D.C., 1985, pp. 82-86.

Spells, S. and J. M. Klosowski. Silicone Sealants for Use in Concrete Construction. Paper prepared for the Joint Congress on Joints and Bearing, Dow Corning Corp., 1981, pp. 217-235.

Watson, S. C. Sealing of Airfield and Highway Pavements Using Performed Extruded Compression Joint Seals. Paper prepared for the Joint Congress on Joints and Bearing, Watson Bowman Associates Inc., 1987, pp. 691-717.

Zimmer, T. R., S. H. Carpenter, and M. I. Darter. Field Performance of a Low-Modulus Silicone Highway Joint Sealant. *Transportation Research Record No. 990*, TRB, National Research Council, Washington, D.C., 1984, pp.31-37.

Value Engineering Study on Crack and Joint Sealing. Delaware Department of Transportation, Dover, May 1983.

4

AC Crack Sealing/Filling

Cracking is one of the primary forms of distress in asphalt pavements and often is the basis for deciding both when a pavement needs rehabilitation and what is the appropriate type of rehabilitation. The development of cracks reduces the integrity and serviceability of a pavement. Furthermore, the failure to repair cracks in a timely fashion can contribute to accelerated deterioration in the form of crack growth, spalls, secondary cracks, and potholes.

Many asphalt pavements in service today are plagued by cracking, either induced by thermal movements or by pavement fatigue from loads. Those pavements which are not cracked now will ultimately develop cracks. With approximately 2 million miles of asphalt-surfaced roadways in the United States, there is ample justification to investigate ways of treating cracks to minimize their effect and extend pavement life.

Although technology has not advanced to the point where asphalt pavements can be designed and built not to crack, there are actions which can temporarily correct cracking problems and/or prevent further crack deterioration. Two of these are crack sealing and crack filling. Crack sealing is a comprehensive operation, involving thorough crack preparation and placement of high quality materials in unique configurations into or over working cracks. Such treatment is required in order for a material to perform its intended function of <u>preventing</u> the intrusion of water into cracks.

Crack filling, on the other hand, requires less pretreatment since its intended function is different—to reduce the amount of water infiltrating into the crack and to reinforce cracks in the adjacent pavement. Filling involves limited crack preparation and placement of less expensive materials into nonworking cracks.

Timing is a vital factor in determining appropriate treatments. For instance, pavements that have just begun to develop transverse working cracks are prime candidates for crack sealing.

Assuming that an appropriate material is properly installed, several years of life may be added to a pavement at a relatively low cost by increasing the time it takes for cracks to deteriorate. For example, the Province of Ontario has data that shows that crack sealing adds about 4 years of life to asphalt concrete pavements.[20] Obviously, when done right, this maintenance operation is very cost-effective.

At the other end of the spectrum, aged pavements experiencing a multitude of distresses are more likely candidates for some type of rehabilitation, such as an overlay or reconstruction. Somewhere in between these two examples are pavements which can benefit from the application or successive applications of a crack filler to retard the development of potholes. At a lower operational cost than crack sealing, crack filling can slightly extend life by temporarily "gluing" a pavement together.

This chapter discusses the performance of AC crack sealing and filling materials and the selection of crack sealants and fillers to be evaluated in the SHRP H-106 experiment. Although there is some overlap among sealant and filler materials, an effort will be made to address each separately with limited repetition.

Material Performance Synthesis

As discussed in chapter 2, an extensive literature search and review was performed to identify materials used in the various maintenance operations being studied. Many sealant/filler materials were examined, most with highway applications but some with alternative applications. A checklist of desirable sealant properties and characteristics was developed which, through a process of elimination, helped in the identification. The checklist consisted of the following material properties and characteristics:

- Ability to be easily and properly placed in or over a crack
- Adequate adhesion to remain bonded to asphalt concrete crack faces
- Sufficient cohesive strength to withstand internal rupture
- Adequate resistance to softening and flow at high in-service pavement temperatures to prevent tracking
- Adequate flexibility and extensibility to prevent rupture when extended at low in-service temperatures
- Low internal forces when extended
- Sufficient elasticity to resist intrusion of incompressibles
- Sufficient pot life at application temperatures for application of practical amount of prepared material

- Resistance to degradation from weathering and aging
- Resistance to degradation from abrasion/wear
- Compatibility with asphalt concrete
- Short cure time to allow for prompt opening to traffic

As mentioned in chapter 3, no single material has the ability to exhibit all of these characteristics. Therefore, it is a matter of selecting from a large range of materials those which provide a favorable combination of each of the listed properties.

An approach to determine which materials possess desirable properties is to examine documented performance records. The research reports and questionnaire responses served this purpose well. Several different materials and their associated deficiencies were identified in this way. The following three sections briefly discuss the findings of research conducted with respect to sealant/filler materials.

Types of Sealants/Fillers

AC crack sealant/filler materials are categorized in much the same manner as PCC joint sealant materials, except that preformed compression seals and thermosetting solvent release materials are not used to seal AC cracks.

- Thermoplastic Materials
  - hot-applied
  - cold-applied
- Thermosetting Chemically-Cured Materials

Most of the discussion on joint sealant material types in chapter 3 is applicable in this chapter as well, as many of the thermoplastic and thermosetting materials used in PCC joint sealing are also used in AC crack sealing. The primary difference is that the sealants must be compatible with asphalt concrete. Thus, most thermosetting materials are not recommended for use in AC crack sealing.

Hot-Applied Thermoplastic Materials

Hot-applied thermoplastics are materials which soften when heated and harden when cooled, usually without chemical change. Materials in this category that are used to seal/fill AC cracks include modified and unmodified asphalts and coal tars. Typically, these materials possess properties that are temperature dependent and they experience hardening with age.

The bulk of materials used in sealing today are hot-applied thermoplastics, and most of those contain modifiers. Modifiers such as polymer, rubber, or fiber add substantial performance capabilities to the base material (i.e., asphalt, coal tar). Hot-applied thermoplastic crack fillers typically consist of a base material, with or without the addition of modifying agents.

Cold-Applied Thermoplastic Materials

Cold-applied thermoplastics are materials that set either by the release of solvents or the breaking of emulsions on exposure to air. Emulsified and cutback asphalts are typical cold-applied thermoplastics. These materials harden with age as well, and lack some of the desirable properties found in hot-applied thermoplastics.

Modifiers, such as rubber and polymer, have also occasionally been added to these materials to improve performance capabilities. However, cold-applied thermoplastics are generally used as crack fillers since associated costs are low and limited material preparation is required (i.e., little or no heating).

Thermosetting Chemically-Cured Materials (Silicones)

Chemically-cured thermosetting materials are one- or two-component systems which cure to a solid state from the liquid form in which they are applied by chemical reaction. Typical characteristics of these materials include resistance to weathering, and flexibility and resilience at both high and low temperatures. Included in this category are polysulfides, polyurethanes, and silicones.

Thermosetting materials have seen very little use in asphalt pavements due mainly to their incompatibility with asphalt concrete, as mentioned earlier. However, other factors such as very high costs have also prevented the acceptance of thermosetting materials in AC crack sealing operations. Recently, a specially formulated silicone was developed by a manufacturer for use in asphalt concrete pavements. This product may open the gates to the use of these materials as AC crack sealants.

Material Use and Performance

Based on questionnaire responses and meetings with highway agencies, a good percentage of states are sealing cracks in asphalt pavements. In fact, of 37 states that returned AC crack sealing questionnaires, 29 indicated that the operation is conducted by their own maintenance forces. The remaining 8 states either did not seal AC cracks at all or contracted out crack sealing jobs.

A separate questionnaire form for AC crack filling was not prepared. And, since several agencies do not distinguish between filling and sealing operations, it is likely that the crack sealing questionnaire responses are a mixture of sealing and filling. However, it is still worthwhile to see which materials and procedures are being used to treat cracks in asphalt pavements.

Table 4-1 summarizes the experience of respondent agencies with various sealant materials. As can be seen, emulsified asphalt was used by the most respondents (62), followed by asphalt rubber (40), polymerized asphalt rubber (29), cutback asphalt (24), asphalt cement (21), and fiberized asphalt (13). The remaining material types were reported as used by five or less respondents.

Four materials have been used by respondents for more than 10 years, on average. These include asphalt cement, emulsified asphalt, cutback asphalt, and PVC/coal tar.

Hot-Applied Thermoplastic Materials

Asphalt Cement

Table 4-2 summarizes the life expectancy statistics of asphalt cement as reported by questionnaire respondents. As can be seen, this material was used mostly in dry conditions (approximately 75 percent of the responses). Average life expectancy was highest for warm (>40 °F), dry conditions at just slightly over 2 years. Less than 1 year of average life expectancy was calculated for both wet conditions.

In a similar study conducted by Peterson, 10 of 43 highway agencies responding to questionnaires reported using asphalt cement to seal AC cracks.[3] On a performance rating scale of very poor to very good, an average effectiveness rating of fair to good was determined from the responses for this material.

Only one reference was found from the literature concerning the performance of asphalt cement. Pennsylvania included in their study the placement and evaluation of a mineral-filled asphalt cement.[21] Although used extensively in the past by the Pennsylvania Department of Transportation (PennDOT) in an overband configuration, this material, placed flush in a routed crack, performed poorly in the experiment. It experienced considerable flow during application, became brittle and cracked in cold weather, and showed poor resistance to extrusion and to the intrusion of particles.

Table 4-1. General summary of questionnaire responses for AC crack sealing.

Sealant Type	Total Number of Responses	Experience (years of use)		Range of Life Expectancy (Years)
		Average	Range	
Asphalt Cement	21	16.6	1 - 25	0.1 - 5
Asphalt Emulsion	62	14.8	1 - 35	0.1 - 5
Modified Emulsion	4	3.8	2 - 5	1 - 5
Cutback Asphalt	24	19.4	1 - 12	0.1 - 4
Asphalt Rubber	40	6.9	1 - 15	0.1 - 12
Polymerized Asphalt Rubber	29	6.9	1 - 15	0.1 - 10
Fiberized Asphalt	13	4.4	0 - 12	1 - 5
Silicone	2	6.5	1 - 12	10
PVC/Coal Tar	1	15	15	7

Table 4-2. Summary of questionnaire responses for the performance of asphalt cement in AC crack sealing (probably filling).

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	1.5	4	1	5
Low	0.1	0.2	0.1	0.1
Average	0.93	1.66	0.78	2.08
Standard Deviation	0.45	1.13	0.45	1.58
Number of Responses	6	14	4	19

PVC/Coal Tar

One respondent noted the use of PVC/coal tar in sealing AC cracks. Although it is not recommended for use in asphalt concrete pavements, the respondent reported a life expectancy of 7 years when placed in warm, dry conditions.

Three agencies reported using a tar-based product in the report by Peterson.[3] An average effectiveness rating of very poor to poor was determined for this product. Comments regarding tar included "too rigid" and "short life." Again, further documented performance data was not obtained for this type of material.

Asphalt Rubber

Nearly 70 percent of the respondents indicated placing this material type in dry conditions. As can be seen in table 4-3, expected life averaged 4.3 years for application in warm, dry conditions and 2.2 years in cold, dry conditions. When placed in wet conditions, however, an average life expectancy of less than 1 year was obtained. It should be noted that a few of the questionnaire responses provided little insight as to whether a particular material consisted of mixed-in rubber (asphalt rubber) or melted-in rubber (polymerized asphalt rubber).

Thirty-one agencies noted the use of hot-applied asphalt rubber in the study conducted by Peterson.[3] An average effectiveness rating of good to very good was reported for this sealant class. Asphalt rubber and polymerized asphalt rubber are believed to have composed this sealant class; however, further breakdown was not made.

Three different asphalt rubber products, placed in routed cracks, were evaluated in the Pennsylvania project.[21] Two of the three products were deemed unacceptable, showing signs of excessive flow during installation and inadequate bonding. The acceptable product, an AC-20 with 25 percent rubber, exhibited good elastic and bonding characteristics and did not flow or track.

A study conducted in Iowa included the placement and evaluation of two asphalt rubber products placed in refaced cracks.[22] After two years, all sections employing these products had failed in bond. In some cases it was noted that the sealant had slumped into the cracks, creating depressions at the top.

Table 4-3. Summary of questionnaire responses for the performance of asphalt rubber in AC crack sealing.

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	1	5	1	12
Low	0.1	0.3	0.2	0.5
Average	0.87	2.18	0.84	4.26
Standard Deviation	0.34	1.82	0.36	2.78
Number of Responses	7	10	5	19

Polymerized Asphalt Rubber

Table 4-4 presents the performance results for polymerized asphalt rubber. As noted earlier, a few responses were indistinguishable with regard to material type (i.e., asphalt rubber or polymerized asphalt rubber). Further breakdown by specification within the polymerized asphalt rubber family was not attempted.

Based on the questionnaire performance statistics, 84 percent of respondents noted placement of this material in dry conditions. Average life expectancies of this material were similar to the average life expectancies of asphalt rubber. An average of about 4 years of service life was obtained for this material applied in warm, dry conditions. And, for placement in cold, dry conditions, slightly over 2 years of average service life was reported. Although only five respondents provided life expectancy data for placement in wet conditions, roughly 1.5 years of average service life was determined.

An experiment conducted by Utah in the early 1980s involved the placement and performance evaluation of several polymerized asphalt rubber products placed in various configurations and climates.[23] Among eight sealants placed at a moderate temperature site, five were found to be performing satisfactorily (less than 40 percent failure) after 1 year of service. Three of these products conformed to ASTM D 3405 while the remaining two met ASTM D 1190 specifications. Three years after installation, however, none of the eight sealants was performing satisfactorily.

In a supplemental Utah experiment conducted at cold temperature sites, thirteen polymerized asphalt rubber materials were placed and evaluated. Inspection after 2 years revealed that only five sealants were performing satisfactorily. Three of these materials satisfied the requirements of ASTM D 3405. A fourth sealant, with a very low modulus, exceeded the requirements of ASTM D 3405. The fifth sealant, which conformed to ASTM D 1190, was the only material to have less than 50 percent failure after 3 years.

Utah also found that performance of high ductility, low modulus sealants was enhanced by applying them in a band-aid configuration. In addition, it found that the practice of routing to create reservoirs was not as beneficial.

In addition to the two asphalt rubber products, Iowa placed two ASTM D 1190 sealants, one ASTM D 3405 sealant, and one low-modulus ASTM D 3405 sealant in their experiment.[22] After 2 years, the ASTM D 3405 sealant and two ASTM D 1190 sealants were found to be performing adequately (less than 50 percent failure) in asphalt overlays of PCC. No materials

Table 4-4. Summary of questionnaire responses for the performance of polymerized asphalt rubber in AC crack sealing.

Life Expectancy (years)				
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	3	5	3	0.5
Low	0.1	0.3	0.3	10
Average	1.55	2.8	1.43	4.02
Standard Deviation	2.05	1.75	1.4	2.57
Number of Responses	2	6	3	21

were performing adequately in full-depth asphalt pavements after 2 years. The low modulus D 3405 material failed after 2 years in both pavement types.

Ontario conducted a four-trial sealing experiment in the early 1980's as well.[24] Since the first trial provided little in the way of relative performance, a second trial was organized. After nearly 1 year, eight sealants exhibited less than 50 percent splitting. Four of these sealants, all conforming to D 3405, showed less than 20 percent splitting. The other four materials met the requirements of D 1190. Each sealant in this trial was placed overbanded in 19-mm x 19-mm routed cracks.

The top three sealant performers observed in the second trial were then placed and evaluated in the third and fourth trials. Various reservoir dimensions were examined in the third trial and it was found that the sealants performed best by overbanding them in 19-mm x 19-mm routed cracks. After the fourth trial, involving the same three sealants, recommendations were made for countersinking sealants into routed reservoirs 40 mm wide x 5 mm deep.

Fiberized Asphalt

A total of 13 respondents noted the use of fiberized asphalt in AC crack sealing. It is likely that this material's limited use is due to its short time on the market. Those respondents that indicated using it averaged roughly 4 years experience.

As can be seen in table 4-5, 12 of the 14 performance responses given were for application under dry conditions. For temperatures above 40 °F, life expectancy averaged 3.1 years, and for temperatures below 40 °F, life expectancy averaged 2.7 years.

No highway agencies reported the specific use of fiberized asphalt in the study conducted by Peterson; however, several materials were not identified from the questionnaire responses.

Pennsylvania ranked a fiberized asphalt (AC-20 with 7 percent polypropylene fibers) second out of 10 sealants installed in their experiment.[21] They noted that after one winter of exposure (during a March evaluation), the sealant could be pulled loose by hand and considerable moisture had accumulated under the sealant. Yet, during a July inspection, the material had a smooth surface and was tightly bonded to the pavement. It was further indicated that the material had good resistance to extrusion.

Table 4-5. Summary of questionnaire responses for the performance of fiberized asphalt in AC crack sealing.

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	1	4	1	5
Low	1	1	1	1
Average	1	2.75	1	3.13
Standard Deviation	0	1.5	0	1.73
Number of Responses	1	4	1	8

Cold-Applied Thermoplastic Materials

Emulsified Asphalt

Sixty-two responses were given for the use of emulsions in sealing AC cracks. A summary of the performance data is displayed in table 4-6. Mean life expectancy was highest for placement in dry conditions; 2.3 years when placed above 40 °F and 2.1 years when placed below 40 °F. Slightly over 1 year of average life expectancy was determined for placement of emulsions in wet conditions.

Only four responses were given in the questionnaires for modified emulsions. From the three performance responses given for application in warm, dry conditions, an average service life of 4.7 years was determined, with the range from 4 to 5 years.

Twenty highway agencies indicated the use of emulsions in the study by Peterson.[3] An average effectiveness rating of fair was determined. Additionally, five respondents noted the use of rubberized emulsion; an average effectiveness rating of fair to good was determined.

A proprietary emulsion and a CRS-2 emulsion were placed and evaluated in the Pennsylvania study.[21] The proprietary emulsion ranked fourth and the standard emulsion eighth among a total of 10 sealants placed. Both materials were placed flush in routed cracks. A sand cover was applied to both materials to prevent tracking; however, the proprietary emulsion was extruded in trafficked areas. Both sealants were partially eroded by water and the standard emulsion showed significant performance variation, probably from varying ratios of emulsion and sand.

Ontario placed three rubberized asphalt emulsions in their first trial.[24] Each was placed flush in routed cracks. One of the materials was washed out by rain. Nearly 1 year after placement, the other two emulsions had completely failed, either in adhesion or cohesion.

A standard CRS-2 emulsion was placed and evaluated in the Iowa study.[22] In each of six sections in which it was placed, at least 75 percent bond failure was recorded after 4 months, and, after 2 years, there was little or no evidence that an emulsion had been installed.

Asphalt Cutback

Twenty-four respondents noted the use of asphalt cutbacks to seal AC cracks. Performance results from the returned questionnaires are displayed in table 4-7. As usual,

Table 4-6. Summary of questionnaire responses for the performance of emulsified asphalt in AC crack sealing (probably filling).

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	4.5	5	4.5	5
Low	0.1	0.2	0.2	0.42
Average	1.07	2.15	1.3	2.28
Standard Deviation	1.21	1.79	1.15	1.63
Number of Responses	11	21	12	33

placement in dry conditions resulted in best performance, although the performance gap between placement in dry and wet conditions was not very considerable. An average of 1 to 1.2 years of service life was calculated for dry conditions, while 0.7 to 0.9 years of service life was averaged for wet conditions.

In the study by Peterson, 20 respondents indicated the use of asphalt cutbacks and two respondents indicated the use of rubberized asphalt cutbacks.[3] Average effectiveness ratings for these two sealants were fair and good to very good, respectively. Although data for the rubberized emulsions and rubberized cutbacks were limited, it appeared in this report that the addition of rubber to asphalt cement, emulsions, and cutbacks, significantly increased the effectiveness ratings.

A rubberized cutback asphalt was placed and evaluated in the Ontario study.[24] The material, placed flush in a routed crack, showed complete failure after 1 year. The mode of failure was not specifically indicated, although it was either adhesive or cohesive in nature.

Thermosetting Chemically-Cured Materials

Two respondents noted the use of silicone in AC crack sealing. Both of these products were identified as PCC joint sealants; their use in asphalt concrete pavements was discouraged by the manufacturer. Each respondent listed 10 years of life expectancy when placed in dry conditions. However, only one respondent indicated considerable experience with silicone in this application.

Peterson revealed no specific responses to the use of thermosetting materials.

A two-part, asphalt-extended urethane was investigated in the Ontario experiment.[24] Placed flat in routed cracks, this material experienced considerable tracking shortly after placement and had still not set up the following day. After nearly 1 year, the urethane was performing unacceptably (more than 50 percent splitting).

Minnesota reported the recent installation of a self-leveling cold-applied silicone, specially made for use in asphalt concrete pavements.[25] Although too early to derive accurate performance information, Minnesota claims the material shows promise as an AC crack sealant.

Table 4-7. Summary of questionnaire responses for the performance of asphalt cutback in AC crack sealing (probably filling).

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	1.5	0.1	1	4
Low	0.1	4	0.1	0.4
Average	0.87	0.99	0.7	1.17
Standard Deviation	0.44	0.98	0.47	0.94
Number of Responses	10	15	6	16

Related Findings

It is apparent from tables 4-2 through 4-7 that the performance of sealants placed in dry conditions is substantially better than the performance of the same sealants placed in wet conditions. In most cases, average expected service lives were 2 to 4 times greater when sealants were placed in dry conditions. Furthermore, the average reported life expectancy of sealants placed in temperatures above 40 °F was usually greater than the average reported life expectancy of sealants placed in temperatures below 40 °F.

Crack refacing was utilized in each of the four state/province reports (see references 21-24). Studies in Utah and Ontario found that performance of materials in refaced cracks was marginally better than performance in unsawn or unrouted cracks.[23,24] However, the cost-effectiveness was not documented in either report. In fact, Ontario subsequently recommended using a 40-mm x 5-mm rout.

The use of a hot, compressed-air (HCA) lance to clean and dry cracks prior to sealing was recommended for further evaluation in three of the four reports. Researchers found the HCA lance to be beneficial to sealant performance; however, its cost-effectiveness was not clear, thereby warranting further study.

Although the primary sealant configurations in these four experiments were recessed or flush, overbanded seals (with or without cut reservoirs) showed good performance. This was especially true with the high ductility, low modulus materials such as the polymerized asphalt rubbers.

Questions regarding configurations and procedures were not included in the questionnaires sent to highway agencies. However, responses to equipment questionnaire forms provided a fair indication of crack sealing procedures followed by states. In addition, visits made to various state agencies helped to reveal information about material configurations being used.

In general, it was found that crack refacing (i.e., routing, sawing) is done mostly by northern states, because horizontal crack movement is much greater with the higher temperature ranges. Many southern and seaboard States use only compressed air in preparing cracks for sealing. These states believe that AC crack movement is not significant enough to warrant reservoir creation and contend, along with a few northern states, that the refacing operation is not cost-effective. The conventional configuration for sealant material placed in unrouted cracks is the overband.

Those respondent agencies claiming to reface cracks generally noted using routers rather than saws. The primary reason cited was that cracks were harder to follow with a saw than with a router. The shape factor (the ratio of crack width to sealant reservoir depth) created by maintenance forces that reface was generally reported to be 1.0 with widths and depths ranging from 0.5 to 0.75 in. The most common material configurations were the overband, flush, and recess configurations.

Summary of Findings

Of the available materials that have been performance tested in the field, hot-applied polymerized asphalt rubbers conforming to high-performance specifications (i.e., ASTM D 3405 and modified ASTM D 3405) generally provide the best performance as AC crack sealants. These low-modulus, high-ductility materials are much more flexible and extensible, and are more capable of retaining these characteristics for significant periods of time. Based on the performance information collected, these materials typically perform for about 3 to 6 years, depending on the conditions in which they are placed.

In general, fiberized asphalts and asphalt rubbers were found to provide fair to good performance as AC crack sealants and good to excellent performance as crack fillers. Because of their excellent strength and resistance to abrasion, fiberized asphalts are placed in a band over cracks. Like asphalt rubbers, they are relatively inexpensive and do not require a refaced channel, which reduces the costs associated with their installation.

Although performance information on the asphalt-compatible silicone was limited, this sealant material has been noted as promising. Provided it maintains a good bond and does not pull tremendously on the asphalt when extended, it should perform adequately for 5 to 10 years.

In summary, the following material types have been identified as promising sealants/fillers and will be placed and evaluated in the AC crack sealing/filling experiment.

Crack Sealants	Crack Fillers
Polymerized Asphalt Rubber	Asphalt Rubber
Low-Modulus Polymerized Asphalt Rubber	Fiberized Asphalt
Fiberized Asphalt	Asphalt Cement
Asphalt-Compatible Silicone	Proprietary Emulsion

Pertinent Material Properties and Tests

Key Distress Manifestations and Their Causes

The documented performance information presented in the previous section provides a good indication of the better performing materials. However, it is important to further examine in detail why each material performs as it does. To accomplish this, the primary distresses found to plague the performance of AC crack sealants must be identified. These distresses include:

- Adhesion Failure
- Cohesion Failure
- Weathering/Aging
- Abrasion
- Extrusion/Tracking/Pull-Outs
- Intrusion of incompressibles

Adhesion

Adhesion failure is the most frequent cause of sealant failure. It is caused by one or more of the following factors:

- Sealant material
- Improper configuration
- Inadequate crack preparation
- Incorrect installation procedures

Some sealant materials typically lack compatibility with asphalt. For instance, asphalt-based sealants adhere well to asphalt concrete because they are of the same base. However, the addition of modifiers to asphalt, such as polymers, tends to decrease the amount of asphalt in contact with the substrate, thereby reducing the bond. Furthermore, some sealants may exhibit excellent bond strength under moderate extension, but do not possess the necessary adhesiveness to undergo large extension, as is experienced by pavements in northern climates. This deficiency may be attributed to a lack of stickiness, a high modulus of elasticity, or a combination of both.

The presence of dirt or moisture in cracks is very detrimental to bonding. These substances tend to inhibit the interface between sealant and substrate such that a true bond is never achieved and early failure is probable. Although it is not a material problem, the degree of cleanliness and dryness does affect some materials more than others, particularly the modified asphalts.

Cohesion

As discussed in chapter 3, cohesion is a material's internal resistance to splitting. A sealant must contain sufficient internal cohesion to resist the forces incurred when it is extended.

Weathering/Aging

The effects of weathering and aging cause sealants to lose or alter some of their key components, such as volatiles. Asphalt-based sealants are particularly vulnerable to weathering while silicone is very resistant to the effects of environment.

Abrasion

Sealant wear has not been proven to be a significant cause of failure in most studies. However, with the increased use of materials placed exposed to high levels of traffic, durability becomes a more critical issue. Materials placed in an overband must be able to resist the abrasive action of tires.

Extrusion/Tracking/Pull-Outs

Extrusion refers to the displacing of sealant from the crack by expansion of the asphalt concrete. Tracking and pull-outs refer to the softening of sealant under high temperatures and the subsequent adhering of the sealant to tires. The result is either a trail of sealant left down the road or actual uprooting of the sealant from the crack. Obviously, a sealant cannot perform its function if it has been pulled out of the crack.

Intrusion of Incompressibles

Although not as important in AC cracks as PCC joints, the infiltration of incompressibles into a crack can cause problems when the crack closes.

Desirable Material Properties

The twelve properties listed at the beginning of this section are all integral to the success of AC crack sealants. However, attaining all, let alone most, of the desirable properties is a very difficult task due to the interdependence of each property. For instance, modifiers may be added to a material to make it more flexible, but often this reduces the material's adhesiveness.

Some desirable properties are regularly achieved in the production of today's sealants. However, most properties are only partially achieved. For this reason, the following properties were selected for further study:

- Ability to be easily and properly placed in a crack
- Adequate adhesion to remain bonded to asphalt concrete crack faces
- Sufficient cohesive strength to withstand internal rupture
- Adequate resistance to softening and flow at high in-service pavement temperatures
- Adequate flexibility and extensibility to prevent rupture when extended at low in-service temperatures
- Low internal stresses when extended
- Sufficient resiliency to resist intrusion of incompressibles
- Resistance to degradation from weathering
- Resistance to degradation from abrasion/wear
- Compatibility with asphalt concrete

Laboratory Tests to Measure Desirable Material Properties

Most highway agencies have adopted or developed standard testing procedures and specifications for the sealant materials they install. Although such tests and specifications do help in weeding out poorly performing sealants, they do not prevent the acceptance of some substandard products. Only a few of the laboratory tests pertain to measuring the desirable material properties listed in the previous section. As a supplement to these laboratory tests, other tests were sought to further characterize important material properties. Table 4-8 lists the tests, both standard and nonstandard, which were identified to be applicable for measuring the above desired material properties.

Implementation of Research Findings into Experimental Plan

A portion of the SHRP H-106 project will involve the placement and evaluation of specific materials in experimental test sites using various configurations and installation procedures. This section is a condensed summary of the experimental plan developed for evaluating the performance of AC crack sealants/fillers.

Table 4-8. Laboratory tests for measuring desirable material properties.

Desired Property	Laboratory Test(s)	Source
Tracking	(1) Flow (2) Softening Point	ASTM D 3407-78 ASTM D 36-86
Ease of Placement	(1) Brookfield Viscosity	ASTM D 3236
Adhesion	(1) Bond (2) Asphalt Compatibility	ASTM D 3407-78 ASTM D 3407-78
Elasticity	(1) Resilience	ASTM D 3407-78
Flexibility	(1) Cold Bend	Utah Test
Extensibility	(1) Elongation (2) Ductility @ 39.2 °F	ASTM D 412-87 ASTM D 113-86 Modified
Internal Stress	(1) Force Ductility (2) Tensile Stress @ 150% elongation	Utah Test ASTM D 412-87
Elongation at adhesive or cohesive failure	(1) Tensile Strength Adhesion	ASTM D 3583-85
Weathering	(1) Artificial Weathering	ASTM G 53-88
Wear	(1) Abrasion	ASTM D 3910-84

Experimental Plan Overview

Several experimental factors were identified in this project as having considerable influence on the performance of AC crack sealant/filler materials.

- Climate
- Traffic
- Weather conditions during sealing
- Material type (and manufacturer)
- Material configuration
- Crack preparation
- Pavement design
- Pavement age
- Material preparation
- Crack movement
- Crack deterioration
- Drainage profile

Due to limited funding, however, detailed investigation into the effects of only the major factors could be obtained. The first six factors in the list above are considered to be of prime importance in this experiment; however, the remaining factors will also be examined to a certain degree. For instance, the effects of crack movement and crack deterioration will be revealed through the performance of a material used as a longitudinal crack filler and as a transverse crack sealer. Typically, much less movement occurs at longitudinal cracks, but pavement deterioration may be greater.

Climate

The use of four transverse crack sealing test sites and one longitudinal crack filling test site was decided for the study. Because of the greater need for longer lasting sealant systems, multiple crack sealing experiments were devised for the benefit of highway agencies nationwide. At least one test site was assigned to each SHRP climatic zone, as shown in figure 3-1.

Within each climatic region, one transverse crack sealing test site was proposed. And, although of less importance, a longitudinal crack filling test site was proposed. Key factors in this test site are material type, material configuration, and crack preparation procedures.

Traffic

Because traffic was found to influence the performance of partially- or fully-exposed sealant materials (i.e., band-aid, flush), it was included for evaluation at one of the test sites. At this particular site, consisting of a two-lane, one-way road with paved shoulders, sealants in the two traffic lanes and the shoulder will be examined. Each lane constitutes different traffic levels as shown below.

- Outside Lane (Medium Traffic)
- Passing Lane (Low Traffic)
- Shoulder (No Traffic)

Weather Conditions During Sealing

One of the test sites was designed to examine the performance of materials and specialized equipment used in sealing in two weather conditions: ideal (warm, dry) and adverse (cold, wet). Highway agencies often are compelled to seal cracks in foul weather. The effects of various materials placed in these conditions and the use of a hot air lance to assist in drying the cracks will be examined at this test site.

Materials, Configurations, and Procedures

For each experimental test site, an array of materials, configurations, and preparation procedures was formulated. Each item (material, configuration, procedure) was identified in the H-105 project as being either promising or innovative.

Six materials, five configurations, and three preparation procedures were identified for crack sealing operations and were thereby incorporated into each crack sealing test site. Although the same items were utilized at each test site, different combinations were selected for the various sites. For example, more emphasis was placed on routing in northern test sites than in southern test sites because this operation is more often performed by northern states. For crack filling operations, a total of four materials, two configurations, and two preparation procedures were identified and incorporated into the longitudinal crack filling test site. Table 4-9 illustrates the national layout of AC crack sealing tests while table 4-10 lists the material products that will actually be placed.

Table 4-9. Test site summary.

Test Site	Climatic Region	Operation	Weather Condition	Pavement Type	Traffic
1	Wet-freeze	Sealing	Ideal	Flexible or Composite*	Medium
2	Wet-nonfreeze	Sealing	Ideal	Flexible	Medium/Low/None
3	Dry-nonfreeze	Sealing	Ideal	Flexible or Composite*	Medium
4A	Dry-freeze	Sealing	Ideal	Flexible or Composite*	Medium
4B	Dry-freeze	Sealing	Adverse	Flexible or Composite*	Medium
4C	Dry-freeze	Filling	Ideal	Flexible or Composite*	Medium

* AC overlay of jointed concrete pavement

Table 4-10. Crack sealing/filling experiment materials.

Sealing Materials	**Filling Materials**
Polymeric Materials (1 product)*	Fiberized Materials (1 product)**
Crafco Roadsaver 221	Hercules FiberPave 5010 + AC
Koch 9005	Kapejo BoniFibers + AC
W.R. Meadows Hi-Spec	
Low-Modulus Polymeric Materials	Asphalt Cement
Koch 9030	AC-20
Crafco Roadsaver 34515	Emulsion
W.R. Meadows Sof-Seal XLM	Witco CRF
Silicone Materials	Asphalt-Rubber (1 product)*
Dow Corning 890 SL	Crafco AR2
	W.R. Meadows Sealtight CR-90
Fiberized Materials (1 product)*	Koch 9000
Kapejo Bonifibers + AC	
Hercules FiberPave 5010 + AC	

* One sealant product will be randomly selected from the options listed.

** The fiber product not selected for placement in the crack sealing experiment shall be placed in the longitudinal crack filling experiment.

The following configurations and preparation procedures also will be utilized and evaluated for effectiveness in the experiment:

Configurations for Sealants

- Rout & Flush: 0.75-in x 0.75-in reservoir (for polymerized sealants)
- Rout & Band-Aid: 0.75-in x 0.75-in reservoir (for polymerized sealants)
- Rout & Band-Aid: 1.5-in wide x 0.2-in deep reservoir (for polymerized and fiberized sealants)
- Band-Aid, No Rout: (for polymerized and fiberized sealants)
- Rout/Saw & Recess: Shape Factor = 1.0, either 0.5-in x 0.5-in or 0.75-in x 0.75-in reservoir (for silicone sealant)

Configurations for Fillers

- Band-Aid, No Rout: (for fiberized and rubberized fillers)
- Flush, No Rout: (for asphalt cement, emulsion, and fiberized filler)

Preparation Procedures for Sealants

- Hot, compressed-air lance
- Wire brush and compressed air
- Compressed air and backer rod

Preparation Procedures for Fillers

- Compressed air
- No preparation

Figure 4-1 illustrates the proposed sealant/filler configurations to be utilized.

The materials, configurations, and preparation procedures listed were developed to provide experiments from which valid conclusions could be derived. Tables 4-11 through 4-14 show the factorial designs for each AC crack sealing/filling test site.

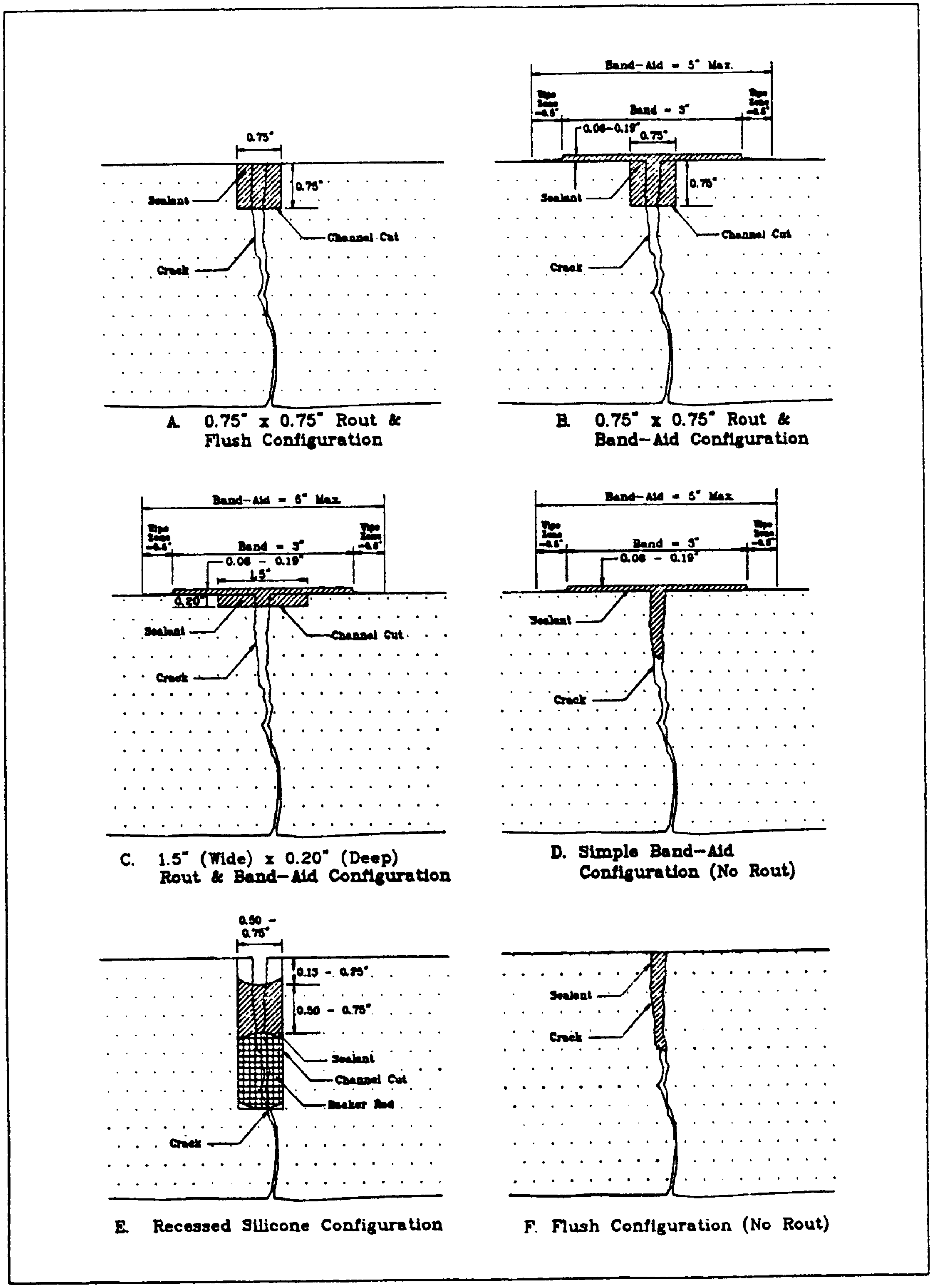

Figure 4-1. Sealant/filler configurations.

Table 4-11. Factorial design matrix for wet-freeze climatic region.

TEST SITE 1

		Sealant Material					
Configuration	Prep.	Selected D 3405 Control Material	Crafco 34515	Koch 9030	Meadows Sof Seal XLM	Dow 890 SL	Fibers + AC
A	1	2 Reps					
	2						
B	1	2 Reps	2 Reps	2 Reps	2 Reps		
	2						
C	1	2 Reps					
	2						
D	1	2 Reps	2 Reps	2 Reps	2 Reps		2 Reps
	2	2 Reps					
E	1						
	2						
	3					2 Reps	

Configuration
A. Rout and Flush (0.75-in x 0.75-in)
B. Rout and Band-Aid (0.75-in x 0.75-in)
C. Rout and Band-Aid (1.5-in x 0.2-in)
D. Band-Aid, No Rout
E. Rout/Saw & Recess (0.5-in x 0.5-in or 0.75-in x 0.75-in)

Preparation
1. Hot, Compressed-Air Lance
2. Wire Brush and Compressed Air
3. Compressed Air and Backer Rod

	Inappropriate Material & Configuration Combination
	Possible Combination
2 Reps	Selected Combination for Project

Table 4-12. Factorial design matrix for wet-nonfreeze climatic region.

TEST SITE 2		Sealant Material					
Configuration	Prep.	Selected D 3405 Control Material	Crafco 34515	Koch 9030	Meadows Sof Seal XLM	Dow 890 SL	Fibers + AC
A	1	2 Reps					
	2						
B	1	2 Reps	2 Reps	2 Reps	2 Reps		
	2						
C	1						
	2						
D	1	2 Reps	2 Reps	2 Reps	2 Reps		2 Reps
	2	2 Reps					
E	1						
	2						
	3					2 Reps	

Configuration
A. Rout and Flush (0.75-in x 0.75-in)
B. Rout and Band-Aid (0.75-in x 0.75-in)
C. Rout and Band-Aid (1.5-in x 0.2-in)
D. Band-Aid, No Rout
E. Rout/Saw and Recess (0.5-in x 0.5-in or 0.75-in x 0.75-in)

Preparation
1. Hot, Compressed-Air Lance
2. Wire Brush and Compressed Air
3. Compressed Air and Backer Rod

	Inappropriate Material & Configuration Combination
	Possible Combination
2 Reps	Selected Combination for Project

Table 4-13. Factorial design matrix for dry-nonfreeze climatic region.

TEST SITE 3		Sealant Material					
Configuration	Prep.	Selected D 3405 Control Material	Crafco 34515	Koch 9030	Meadows Sof Seal XLM	Dow 890 SL	Fibers + AC
A	1	2 Reps					
	2						
B	1	2 Reps	2 Reps	2 Reps	2 Reps		
	2						
C	1						
	2						
D	1	2 Reps	2 Reps	2 Reps	2 Reps		2 Reps
	2	2 Reps					
E	1						
	2						
	3					2 Reps	

Configuration
A. Rout and Flush (0.75-in x 0.75-in)
B. Rout and Band-Aid (0.75-in x 0.75-in)
C. Rout and Band-Aid (1.5-in x 0.2-in)
D. Band-Aid, No Rout
E. Rout/Saw and Recess (0.5-in x 0.5-in or 0.75-in x 0.75-in)
F. Flush, No Rout

Preparation
1. Hot, Compressed-Air Lance
2. Wire Brush and Compressed Air
3. Compressed Air and Backer Rod
4. Compressed Air
5. None

	Inappropriate Material & Configuration Combination
	Possible Combination
2 Reps	Selected Combination for Project

Table 4-14. Factorial design matrix for dry-freeze climatic region.

TEST SITE 4A - Crack Sealing, Ideal Conditions

		Sealant Material					
Configuration	Prep.	Selected D 3405 Control Material	Crafco 34515	Koch 9030	Meadows Sof Seal XLM	Dow 890 SL	Fibers + AC
A	1	2 Reps					
	2						
B	1	2 Reps					
	2						
C	1	2 Reps	2 Reps	2 Reps	2 Reps		
	2						
D	1	2 Reps	2 Reps	2 Reps	2 Reps		2 Reps
	2	2 Reps					
E	1						
	2						
	3					2 Reps	

Configuration
A. Rout and Flush (0.75-in x 0.75-in)
B. Rout and Band-Aid (0.75-in x 0.75-in)
C. Rout and Band-Aid (1.5-in x 0.2-in)
D. Band-Aid, No Rout
E. Rout/Saw and Recess (0.5-in x 0.5-in or 0.75-in x 0.75-in)

Preparation
1. Hot, Compressed-Air Lance
2. Wire Brush and Compressed Air
3. Compressed Air and Backer Rod

	Inappropriate Material & Configuration Combination
	Possible Combination
2 Reps	Selected Combination for Project

Table 4-14. Factorial design matrices for dry-freeze climatic region (continued).

TEST SITE 4B - Crack Sealing, Adverse Conditions		Sealant Material					
Configuration	Prep.	Selected D 3405 Control Material	Crafco 34515	Koch 9030	Meadows Sof Seal XLM	Dow 890 SL	Fibers + AC
A	1	2 Reps					
	2						
B	1	2 Reps					
	2						
C	1	2 Reps	2 Reps	2 Reps	2 Reps		
	2						
D	1	2 Reps	2 Reps	2 Reps	2 Reps		2 Reps
	2	2 Reps					
E	1						
	2						
	3					2 Reps	

<u>Configuration</u>
A. Rout and Flush (0.75-in x 0.75-in)
B. Rout and Band-Aid (0.75-in x 0.75-in)
C. Rout and Band-Aid (1.5-in x 0.2-in)
D. Band-Aid, No Rout
E. Rout/Saw and Recess (0.5-in x 0.5-in or 0.75-in x 0.75-in)

<u>Preparation</u>
1. Hot, Compressed-Air Lance
2. Wire Brush and Compressed Air
3. Compressed Air and Backer Rod

(shaded)	Inappropriate Material & Configuration Combination
	Possible Combination
2 Reps	Selected Combination for Project

Table 4-14. Factorial design matrices for dry-freeze climatic region (continued).

TEST SITE 4C - Crack Filling, Ideal Conditions		Filler Material			
Configuration	Prep.	Asphalt Cement	Witco CRF	Asphalt Rubber	Fiberized Asphalt
D	4			2 Reps	2 Reps
	5				
F	4	2 Reps	2 Reps	2 Reps	
	5	2 Reps			

Configuration
D. Band-Aid, No Rout
F. Flush, No Rout

Preparation
4. Compressed Air
5. None

(shaded)	Inappropriate Material & Configuration Combination
	Possible Combination
2 Reps	Selected Combination for Project

Field Evaluations

Field evaluations of the sealant materials were proposed for each test site. As with the PCC joint sealing experiment, evaluations will be conducted in the outer lane only of multilane facilities. The exception to this is test site 2, which requires evaluation of sealants in both traffic lanes and the shoulder. Inspections are planned for the following times subsequent to installation:

- 1 month
- 3 months
- 8 months
- 12 months
- 20 months

Installations will be examined for the following types of failures:

- Sealant material failures
  - adhesion
  - cohesion
- Pavement failures
  - cracking
  - spalling
  - burns
- Stone intrusion
- Other failures
  - tracking
  - bubbling
  - aging

The coin test will be conducted on these sealants in addition to measurements of crack movement. Photographs of sealant failures will be taken as well.

Data Analysis

Material performance in this experiment will be complemented by a rigorous laboratory testing scheme. The tests identified earlier will be run on samples taken from each lot of material used in the experiment. It is hoped that a strong correlation can be developed between the results of these laboratory tests and field performance. As agencies become informed of the correlations developed, they will likely revise their existing specifications to include some of the more useful laboratory tests.

Bibliography

Chehovits, J. and M. Manning. Materials and Methods for Sealing Cracks in Asphalt Concrete Pavements. Transportation Research Record No. 990, TRB, National Research Council, Washington, D.C., 1984, pp. 21-30.

Belangie, M.C. and D.I. Anderson. *Crack Sealing Methods and Materials for Flexible Pavements*. Report FHWA/UT-85/1. Utah Department of Transportation, Salt Lake City, May 1985.

Knight, N.E. Sealing Cracks in Bituminous Overlays of Rigid Bases. Transportation Research Record No. 1041, TRB, National Research Council, Washington, D.C., 1985, pp. 75-81.

Peterson, D.E. Resealing Joints and Cracks in Rigid and Flexible Pavements. NCHRP Synthesis of Highway Practice No. 98, TRB, National Research Council, Washington, D.C., December 1982.

Turgeon, C. M. *Evaluation of Materials and Methods for Bituminous Pavement Crack Sealing and Filling*. Final Report Draft, Minnesota Department of Transportation, St. Paul, Minnesota, June 1989.

Evers, R.C. and D.F. Lynch. Sealing Cracks in Asphaltic Concrete Pavements, Paper prepared for Paving in Cold Areas Mini-Workshop, Tsukuba Science City, Japan, October 1984.

Dunshee, B.D., R.R. Samuelson, and D. Rorholm. *Improved Asphalt Surfaces and Asphalt Resurfacing Performance Through Crack Maintenance*. Final Report, Iowa Department of Transportation, Ames, April 1987.

Bertelson, T. Asphalt Rubber Used as a Crack Sealer. Paper prepared for the National Seminar on Asphalt-Rubber, Nevada Department of Transportation, October 1981, pp. 131-134.

Blaise, E.J. *Value Engineering Study of Crack and Joint Sealing*. Report FHWA-TS-84-221, FHWA, U.S. Department of Transportation, Washington, D.C., December 1984.

Chong, G.J., and W.A. Phang. *Improved Preventative Maintenance: Sealing Cracks In Flexible Pavements In Cold Regions*. Ontario Ministry of Transportation, Downsview, Canada, December 1987.

Sampson, J. M. *Transverse Crack Maintenance Strategies for AC Pavements*. Minnesota Department of Transportation Task Force Report, St. Paul, December 1988.

Value Engineering Study on Crack and Joint Sealing. Delaware Department of Transportation, Dover, May 1983.

5

PCC Spall Repair

Spalls in concrete pavements are defined as a localized deterioration of the pavement, usually manifested on the pavement surface as shallow cracking that leads to the eventual dislodging of concrete material. Spalls most commonly occur along joints, cracks, or the free edge of a slab. Development of concrete spalls may be attributed to problems of construction, design, materials, performance, or any combination of these factors.

Construction problems which can lead to concrete spalling include poor concrete finishing techniques, inadequate consolidation, dowel misalignment, and insufficient concrete cover over reinforcing steel. Design problems include poor mix design, inadequate joint design, and inappropriate joint placement. Materials problems include the use of D-cracking susceptible aggregate or reactive aggregate. Failure to keep incompressible materials out of joints can cause the build up of large compressive stresses in the pavement, eventually spalling the concrete.

Working cracks are subject to mechanical conflict on both sides of the crack and can also be infiltrated by incompressible materials. Either of these actions will cause working cracks to spall. The use of chlorides as deicing agents on pavements with steel reinforcement initiates and accelerates the corrosion of the steel, resulting in spalling.

As spalling increases in severity, a corresponding increase in surface roughness is experienced which greatly reduces pavement serviceability. Spall repair is usually accomplished by either full-depth or partial-depth repair procedures. Partial-depth repairs are generally limited to distresses that do not penetrate beyond the top third of the slab and are not larger than half the lane width. This study is limited to the examination of partial-depth spall repair materials.

Material Performance Synthesis

The primary objective in any pavement repair is to place a material that will perform in a satisfactory manner over a reasonable life span. There are many secondary objectives, however, that may become paramount for a specific application. The following list of desirable material characteristics is by no means exhaustive:

- Short cure time (high early strength) to allow for rapid opening to traffic
- Long-term strength and durability to hold up under traffic loadings
- Ability to be placed in a variety of conditions (i.e., cold and hot temperatures, wet and dry conditions)
- Ability to be easily and properly placed
- Minimum surface preparation required for placement
- Pose no environmental or health hazards to maintenance personnel applying it
- Resistance to degradation from freeze-thaw action
- Noncorrosive to reinforcing steel
- Excellent bonding capabilities
- High reliability of good patch performance

It would be highly desirable to identify a patching material and set of procedures that could produce a repair that met all of these criteria. However, it is rather unlikely that such a formulation currently exists. Experience has shown that many materials are extremely sensitive to temperature and moisture conditions, and thus only can be used under limited patching applications. Because of this, there are many different types of materials being used to form partial-depth repairs in concrete pavements under of a variety of conditions.

Types of Repair Materials

A variety of materials have been used for spall repair. Several classification schemes have been developed, whereby repair materials are divided into inorganic and organic products.[1,2] Two additional categories, consisting of bituminous patching materials, can be included.

- Inorganic Materials (Cementitious)
- Organic Materials (Polymeric)
- Conventional Bituminous Materials
    - hot mix
    - cold mix

• Modified/Proprietary Bituminous Materials

Inorganic materials are cementitious materials that include portland cement-based products, gypsum-based products (calcium sulphate), magnesium phosphates, and high alumina cements (HAC). The organic materials can be classified by family, depending on the primary component of the polymer. Some of the most widely used organic materials include epoxy, polyester, acrylic, and urethane. Bituminous materials may be conventional hot or cold mixes or bituminous mixtures with modifying agents.

Within each material classification, a diverse number of materials exist. Many products of similar chemical composition have very different performance characteristics. Therefore, the following generic description of the different material types is a generalization, and should be understood as such.

Inorganic or Cementitious Patching Materials

Portland Cement Concrete (PCC)

Portland cement concrete is one of the most common materials used to patch concrete spalls. Its use is very common when the proper ambient conditions exist and when there is sufficient time available before the repaired pavement must be opened to traffic. The curing time can be shortened by using Type III cement instead of Type I or II, and by using an epoxy bonding agent. The use of calcium chloride as an accelerator or nonchloride accelerators can speed up the initial strength gain of regular portland cement concrete so that it can be opened to traffic in a very short time. However, the use of chloride accelerators is a questionable practice in any pavement which includes steel. The use of portland cement concrete as a patch material generally is not recommended under adverse climatic conditions (e.g., cold and wet).

Portland cement concrete has a distinct advantage over many other patching materials in that it is relatively inexpensive, readily available, a reliable product, has the same coefficient of expansion as the pavement, and has well-documented and understood properties and abilities. Contractors are familiar with the mixing and placing of portland cement concrete, and know how to work with it to provide acceptable results. Therefore, portland cement concrete patching materials are considered the standard for partial-depth patching to which all other materials should be compared.

Modified Portland Cement Concrete

Portland cement concrete can be modified with a latex emulsion to create a polymer-modified concrete. Styrene-butadiene, acrylics, and polyvinyl acetate are among the polymers which have been used. Polymerization is accelerated with an appropriate water-soluble admixture. The resultant material is more impermeable than regular concrete, has a higher tensile strength, and a lower modulus of elasticity. These properties come about through a combination of the polymerization of the latex and the hydration of the cement. Other modifications include the addition of poly fibers, steel fibers, fumed silica, and other additives.

Gypsum-Based Concrete

A gypsum-based (calcium sulphate) patching mixture has seen limited use for spall repair on concrete pavements. It has been shown to develop high early strength and bonds fairly well to the existing concrete. However, it does not appear to perform well when exposed to moisture, and has shown some durability problems. Additionally, the excess of free sulfates in the typical gypsum mixture have been found to promote the corrosion of steel in reinforced pavements, and its use is therefore limited to non-reinforced pavements.

Magnesium Phosphate Concrete

A concrete patching product with magnesium phosphate as the active ingredient has been widely used. This type of material is favored because of its rapid set time and high early strength. It bonds well to dry portland cement concrete, but not as well to damp concrete. It appears to shrink very little as it sets and does not contribute very much to corrosion of reinforcing or load transfer steel present in the pavement.

Magnesium phosphate concretes can be water-activated or nonwater, liquid-activated; the water-activated type is more common. This type of material is extremely sensitive to substrate preparation, substrate surface moisture, quantity of water added to the mixture, and aggregate type (limestones are not acceptable). In addition, it must not come into contact with fresh portland cement before setting. These limitations make it difficult to use, and have led to variable field performance.

High Alumina Cements

As with the other cementitious products, high alumina cements (calcium aluminates) have several characteristics that make them useful as a concrete patching material. Among these are rapid strength gain, good bonding properties (on a dry surface), and very low shrinkage. It has also been reported, however, that high alumina cements experience a strength loss at curing temperatures above 135 °F and will cause corrosion of reinforcing or load transfer steel. As with most of the cementitious materials, large variations in performance based on different proprietary formulations exist. Good bond strength and no environmental hazards are among the advantages of high alumina cements.

Organic or Polymer-Based Materials

A second group of patching materials can be classified under the polymer heading. Polymers are materials that are formed by combining molecules of a single family or several similar families into molecular chains. Polymer resins generally consist of resin molecules and an initiator used to start the free radical producing process, whereby the resin molecules are linked together into long chains. The selection of initiators depends on the ambient conditions during which the patch is to be placed. Another additive can be used to promote crosslinking between the polymer chains; crosslinking between chains helps to ensure the strength of the polymer.

Polymers can be further subdivided according to classification of the monomer resin that is used to form the molecular structure of the material. Common groups include epoxies, methacrylates, polyester-styrene, and urethane.

Depending on the application, polymer patching materials are typically blended with an aggregate, ranging in size from sand to 3/8-in stone. The aggregate provides a wearing surface, makes the patch more economical, and helps make the polymer patching mixture more thermally compatible with the PCC substrate.

Some polymers pose toxic, flammable, and explosive hazards during storage, shipping, mixing, or application. The proportioning and sequence of mixing is critical in some cases, and failure to follow the directions can lead to severe injury. The use of polymers may necessitate specially trained crews, depending on the specific material and formulation.

Epoxy Concrete

Epoxies have been used as a spall repair material at least as early as the 1950s. Epoxies can have variable properties, including setting time, strength, and abrasion resistance. In general, epoxy resins are impermeable and excellent adhesives, but tend to be very expensive.
Epoxies can be applied under a variety of temperature and moisture conditions, although some sacrifice in performance generally results in formulations designed for wet or cold conditions.

One of the biggest problems with epoxies is that they are generally not thermally compatible with portland cement concrete. This problem of thermal incompatibility is partially addressed by extending the epoxy with aggregate, yet the thickness of epoxy patches must be limited to avoid debonding due to thermal stress. Additionally, the epoxy itself does not wear well, and the aggregate must provide good skid resistance and wear characteristics.

Methyl Methacrylate Concrete

Methyl methacrylates have been used in the polymer concrete industry for many years; their use for pavement repair dates back at least as far as 1975, when a patch was placed on the Major Deegan Expressway in New York City.[26] In that application, the patch remained in good condition for at least 5 years.

The properties of methyl methacrylate concrete include between 30 minutes and 60 minutes of working time, very high compressive strengths, and good adhesion properties to a clean, dry PCC substrate. They also have good oil and water resistance and high tensile and flexural strength.

Drawbacks include high initial cost and potential environmental and health hazards from prolonged exposure to the fumes and the material. The fumes are also flammable, and can cause an explosion if exposed to a spark or flame. Methyl methacrylate polymers reportedly can be placed over a range of temperatures from 35 °F to 95 °F. Some research suggests a range of temperatures from 20 °F to 130 °F.[27] The desired working time, curing time, and viable temperature range are functions of the initiator and promoter concentrations.

A new type of methacrylate, known as a high molecular weight methacrylate (HMWM), is currently replacing methyl methacrylates for use as a pavement patching material. This material has many of the same properties as the methyl methacrylates, yet is neither volatile nor poses a health or environmental hazard.[28]

Polyester-Styrene Concrete

Polyester-styrene polymers have many of the same properties as methyl methacrylates except for having a much slower rate of strength gain, which limits their usefulness as a rapid patching material. An additional difference is that the polyester-styrene polymer generally costs much less than methyl methacrylate. With the widespread use and availability of polyester resins, nonproprietary polyester-styrene mixtures can be developed for use as a patching material.

Acrylic Concrete

Acrylic patching materials are not common, but have seen limited use in the past. They are characterized by high bond strengths, but are expensive, pose an environmental hazard, and require dry aggregate and a dry substrate.

Polyurethane Concrete

Polyurethane patching materials generally consist of a two-part polyurethane resin mixed with aggregate. These type of materials have been used for a number of years with variable results. Currently, there are two types of polyurethanes available. The older type is moisture intolerant, with its major drawback being that it foams when it comes in contact with moisture. A newer, more moisture-tolerant polyurethane is now available, which apparently can be placed on a wet substrate with no adverse effects.

Standard patching procedures consist of filling the patch area with aggregate, and then adding the two-part polyurethane. The polyurethane cures in approximately 90 seconds, making for an extremely quick repair. Also, polyurethane is a more flexible patching material, which may be able to resist impact and localized stress concentrations better than more rigid patching materials.

Furfuryl Alcohol Polymer Concrete

The use of this material, which consists of a furfuryl alcohol monomer, other additives, and aggregate, to patch concrete and asphalt pavements is reported by researchers at Brookhaven National Laboratory.[29] Under development as a product for the rapid repair of bomb-damaged runways, the purpose was to produce a material that could develop high early strength when placed in wet conditions and in temperatures ranging from 0 °F to 126 °F. Two formulations of the polymer were developed to optimize performance over the entire range of temperatures.

The furfuryl alcohol polymer was developed for use as a rapid runway repair material under adverse (both climate and need) conditions. As such, the goals were not entirely identical to a formulation developed for roadway repair. It is not clear how modifications made to this formulation might enhance or detract from its performance on a roadway.

Conventional Bituminous Patching Materials

Bituminous materials have long been used to patch concrete pavements. While it is often perceived that the use of a bituminous patching product in a portland cement concrete pavement is, at best, temporary, there are several offsetting considerations. Either hot mix or cold mix is available at most times throughout the year for patching AC potholes. This material is comparatively inexpensive, has no special handling requirements, and can be placed, in most cases, with a minimum of equipment and manpower. Additionally, bituminous patches can be opened to traffic very soon after being placed, and can be placed under a wide variety of climatic conditions.

Unlike the cementitious patching products, which are considered for permanent repairs only, bituminous patching materials can be considered either for permanent or temporary repairs. This distinction, however, is often made not as much by the selection of materials, but by the conditions under which the material is used or by the amount of surface preparation that takes place before the patch is placed. Furthermore, it is debatable whether a bituminous patching material can truly provide for a permanent repair on a PCC pavement, due to the inherent incompatibility of the materials. Many bituminous patches become fairly rough due to consolidation. Yet, many highway agencies use bituminous patching materials for both permanent and temporary repairs, so both applications will be examined.

Bituminous Hot Mix (Asphalt Concrete)

The bituminous mixture that is commonly used for asphalt concrete wearing surfaces can also be used as a patching material for concrete spalls. Asphalt concrete is a dense-graded material consisting of hot mineral aggregates plant-mixed with hot asphalt cement. This material usually is available only during the normal construction season.

Hot mix can be used as a "permanent" spall repair material when extensive preparation of the patch area is conducted and efforts are made to adequately compact the material. Because of its high quality, hot mix is primarily used in temperatures above freezing and when the pavement surface is dry for the permanent repair.

In temporary patching with hot mix, the material is the same as for permanent patching, but spall preparation and compaction are different. Usually, the material is applied to an unprepared spall and a truck is driven over it to compact it. Although the time required to place this type of patch is significantly reduced, the life of temporary patches is substantially shorter than the life of permanent patches. Temporary patching is usually conducted during more adverse conditions when a quick fix is needed to temporarily increase the pavement serviceability. A more permanent repair can then be constructed when conditions improve.

Bituminous Cold Mixes

Bituminous cold mixes are mixtures that consist of a liquid bituminous binder (such as an asphalt emulsion or asphalt cutback) and aggregate. A common characteristic of these mixes is that they can be stockpiled and used as needed over a period of time, in contrast with the use of bituminous hot mix, which needs to be batched just prior to placement.

There is little, if any, difference between the formulation of the cold mix used as a permanent patch material and that used as a temporary patch material. The primary difference lies in the application conditions, such as preparation and weather. When the patch area is carefully prepared and the mixture sufficiently compacted, a more permanent patch results. When the material is placed in an unprepared spall, and compaction is conducted by traffic, the resulting patch is considered temporary. Heating of the material prior to placement can be done in cold weather, resulting in improved performance.

Modified/Proprietary Bituminous Patching Materials

A wide variety of additives have been added to both hot and cold bituminous mixes. Additives such as rubber, fiber, sulphur, and anti-stripping agents impart desirable properties to an asphalt material. Most of these materials are proprietary, yet some state agencies have developed such mixtures.

A sulfur/asphalt composite mixture has been used on a limited basis in some states and in Canada. Widespread use has been made of these mixtures for the patching of bituminous pavements, and has migrated in some cases to PCC pavements.[30] Although information on this patching material is limited, it can be used both for permanent and temporary patching in hot and cold temperatures.

In recent years, fibers have been added to asphalt-aggregate mixtures. The most common fibers utilized are polypropylene and polyester fibers. The high tensile strengths possessed by fibers add considerable strength to the mixture. Various modified/proprietary bituminous mixes are discussed in chapter 6, "AC Pothole Repair."

Material Use and Performance

From the literature searches and questionnaires returned, a considerable amount of information was obtained on users' experience with many of the material types considered. Table 5-1 provides an overall summary of the PCC spall repair questionnaire responses. The table gives a general indication of highway agency usage and experience with the various generic material types, as well as estimated performance ranges.

As can be seen in table 5-1, respondents indicated using bituminous cold mix as a temporary fix most often (51 responses). This was followed by portland cement concrete (47), permanent bituminous hot mix (37), temporary bituminous hot mix (36), and proprietary bituminous cold mix (27). Less than five responses each were received for materials such as high alumina cement, methyl methylcrylate, polyester styrene, and asphalt cement. Due to the small number of responses for these materials, reliable performance statistics could not be derived.

Responses also indicated that most experience is with bituminous hot and cold mixes. An average use of 15 years or more was calculated for these materials from the questionnaire responses; some respondents reported up to 60 years of use. Other longstanding repair materials include epoxy (14.9 years average use) and portland cement concrete (13.2 years average use).

The following sections report in more detail the use and performance of the various generic materials types discussed previously.

Inorganic (Cementitious) Patching Materials

Performance information was collected on a wide range of cementitious products. In contrast to the bituminous products, which were categorized according to their use as both temporary and permanent patching materials, it was assumed that cementitious products would only be used as a permanent patching material. The results from the questionnaires largely supported this reasoning, as there were very few uses cited in either wet conditions or when the ambient temperature was below freezing.

Portland Cement Concrete (PCC)

Performance results from the questionnaires are summarized in table 5-2. The majority of the respondents cited its use when the ambient temperature is above freezing and the pavement is

Table 5-1. General summary of questionnaire responses for PCC spall repair.

Repair Material Type	Total Number of Responses	Experience (Years of Use)		Range of Life Expectancy (Years)
		Average	Range	
Portland Cement Concrete	47	13.2	1 - 50	0.5 - 14
Magnesium Phosphate Concrete	12	8.3	3 - 15	0.5 - 5
Epoxy	21	14.9	1 - 35	1 - 8
Polymer	6	6.0	2 - 10	0.5 - 8
Bituminous Hot Mix (Temporary)	36	18.2	1 - 40	0.01 - 5
Bituminous Hot Mix (Permanent)	37	20.6	3 - 60	0.02 - 6.5
Bituminous Cold Mix (Temporary)	51	20.8	1 - 60	0.01 - 4
Bituminous Cold Mix (Permanent)	23	15.3	1 - 50	0.02 - 4
Fiberized Asphalt Mix	7	6.2	5 - 12	0.26 - 1.5
Proprietary Cold Mix	27	5.6	0.4 - 10	0.02 - 4

Table 5-2. Summary of questionnaire responses for the performance of portland cement concrete in PCC spall repair.

	Life Expectancy (years)			
Temperature	<32 °F		>32 °F	
Cavity Condition	Wet	Dry	Wet	Dry
High	10	10	10	14
Low	0.5	2	0.5	1
Average	4.63	6.40	6.59	6.76
Standard Deviation	4.03	3.51	3.75	4.30
Number of Responses	4	5	11	34

dry. In these conditions, it had an average service life of 6.8 years. Portland cement concrete was used much less by the respondents under other less favorable climatic conditions.

Many different researchers have considered the use of various PCC patching products in both comparative laboratory and field studies. A report by the California Department of Transportation (Caltrans) discusses the use of both accelerated Type I cement and Type III cement for spall repair.(28) It is noted that physical properties and bonding of PCC are not improved in rapidly setting concrete; it is only the rate of strength gain that is augmented.

Because of its well-documented properties and abilities, comparatively low price, and widespread availability, most studies compare more exotic patching materials to PCC. This is the case with an extensive lab study performed by the Federal Highway Administration.(31) In the battery of tests to which the different products were subjected, the Type III cement included in this study as a control, performed as well, or better in most cases. Research by the Oregon Department of Transportation suggested that where suitable curing time was available, the performance of low slump, high early strength PCC was quite satisfactory.(32) It was also 14 times cheaper than the only higher-rated material.

A comparative study was also performed by researchers in Arizona, involving 6 different materials including Type III PCC.(33) After a year of service they found that the general appearance of the patches was good, but that there was also a high level of crazing and longitudinal cracking. Patches that were cored showed delamination at the bond interface.

Finally, an evaluation of many different repairs constructed with both different mixtures of PCC and proprietary patching materials was performed in Virginia.(34) There it was concluded that "portland cement concrete containing carefully chosen admixtures will provide satisfactory results at a lower cost than will proprietary products." It was also noted, however, that more patch failures resulted from improper construction techniques than from the specific patching material. In any case, for the use of more expensive and proprietary materials to be justifiable, they certainly must outperform standard materials.

Modified Portland Cement Concrete

No respondents reported using or having experience with latex-modified concrete. However, in a study done for the Pennsylvania Department of Transportation, two districts reported the successful use of this type of patching material.(35) The only negative comment was that the patches developed hairline cracking. It was also stated that the use of this material requires tight quality control and that it should not be placed when the ambient temperature is expected to go below 45 °F. This material must be applied to a wet surface and requires a curing period of several days. Research has shown that wet curing will cause a significant loss of compressive strength of the modified concrete.[36]

A study prepared by the New York State Department of Transportation reported the use of several cement/polymer mixtures.[37] These mixes were only used in warm weather patching and showed variable performance. One proprietary product, a mixture of cement, silica sands, resins, and other additives, deteriorated after 2 months. Another, a fast-setting hydraulic cement with a powdered-resin additive, was in very good condition after 30 months, when placed in a properly prepared spall.

More information is needed on modified PCC. There has been experience with poly fibers, steel fibers, fumed silica, and other modifying additives. The experience of users with different modified concretes needs to be further explored.

Gypsum-based Concrete

The use of gypsum as a patching material was reported on six of the returned questionnaires, and performance data was given in four of those questionnaires. In general, experience with gypsum was found to be limited. An average of 6.7 years of experience was determined for gypsum. Performance of gypsum placed in the best conditions (dry, >32 °F) was somewhat poor, with a mean service life of 2.7 years.

Perhaps because of the reported poor performance of this type of patching product, extensive performance information was not available from the literature. A lab study performed 15 years ago noted that although its compressive strength was very good, the material did not inhibit penetration of chlorides and its rate of wear was quite rapid.[31] It also exhibited durability deficiencies when subjected to repeated rapid freezing and thawing.

A study in New York reported on the summer placement of six patches of a proprietary gypsum patching material. Traffic wore down the patches and six patches, which were feathered, failed within 0.5 years.[37] In Virginia, the gypsum-based patches that were examined did not perform satisfactorily; patches that were evaluated did not last one year.[38] Its future use was advised against. However, a non-proprietary blend of cement, gypsum, sand, and a water reducer, showed promise when applied in both cold and warm weather. There were four patches placed that were in very good condition after 2.3 years of service.

Research by Caltrans has shown that this is a suitable material for the patching of <u>plain</u> concrete pavements.[28] The excess of free sulfates in the typical gypsum mixture have been found to promote the corrosion of steel in reinforced pavements.

Magnesium Phosphate Concrete

A total of 12 respondents reported using magnesium phosphate patching materials. Table 5-3 summarizes performance responses with this material. Most of the respondents reported using it as a patching material in dry, above-freezing conditions. There it showed an average service life of 2.5 years. A higher average service life (3.5 years) was calculated for its use in warm, wet conditions, but the small sample size did not provide for a valid statistical conclusion.

Unlike the results from the questionnaires, the use of magnesium phosphate patching products is widely reported in the literature and in conversations with a number of different agencies. Several laboratory studies have reported on the properties of magnesium phosphate materials.[28,31,37,38] Ramey et. al. reported that it did not appear to be an attractive early cure material, due to its low strength and poor energy absorption capacity at a young age.[39] It did, however, have good thermal durability.

A study by Kudlapur et. al. was conducted to identify cold-weather concrete patching materials.[40] Both a water-activated and a nonwater, liquid-activated magnesium phosphate cement were compared to a methyl methacrylate and a polyurethane-based polymer concrete. Overall, the water-based magnesium phosphate performed the best, followed by the liquid-based magnesium phosphate. The water-based product was recommended only for short-term patching or when the patch would be protected from water. It was noted that use of the liquid-activated magnesium phosphate provided a good compromise between performance and environmental concerns (especially in comparison with the methyl methacrylates).

There have been several field studies that reported on the use of magnesium phosphate cement. In the study reported by Hartvigas, two different proprietary mixes were used for winter patching.[37] The patches received different preparation, but the same general principle was followed; all loose material was removed, followed by cleaning out, drying, and placement of the material. One product performed well for about 1 year and the other lasted about 1.5 years. One proprietary product was tried under summer patching conditions. The two patches placed were both in good condition after 2.3 years of service.

The Oregon Department of Transportation study had similar results.[32] While the proprietary material used had high early strength and could be placed in a wet area, the five patches placed experienced shrinkage cracking and, after 1 year in service, two of them had failed. Similar experiences were reported in Arizona.[33] Although the general appearance of the patches was good, about half showed slight crazing. In addition, there was some longitudinal

Table 5-3. Summary of questionnaire responses for the performance of magnesium phosphate concrete in PCC spall repair.

	Life Expectancy (years)			
Temperature	<32 °F		>32 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	5	5	5	5
Low	5	5	0.5	1
Average	5	5	3.5	2.5
Standard Deviation	0	0	2.6	1.58
Number of Responses	1	2	3	9

cracking and one of the cores showed delamination within the patch material. Overall, Arizona reported poor performance of magnesium phosphate patches. The Virginia study also reported dissatisfaction with the use of a magnesium phosphate patching material, although the stated reason was that it did not last 10 years.[34]

Caltrans, which has many years of practical experience with magnesium phosphates, reports that it does not work well with any moisture whatsoever (in contradiction to the results reported by Kudlapur et. al.).[41] Its use should only be considered under hot and dry conditions, which have no adverse effects on its performance. This suggests its use as a patching material in desert climates. The substrate should not be dampened, and even the trowels used to finish the patch should be dried prior to being used for finishing.

High Alumina Cements

There were only two respondents who indicated use of high alumina cements as a concrete patching material. Some performance information was provided, but the small sample size did not provide for a valid statistical conclusion.

The early comparative laboratory study by the FHWA that included over 10 different products examined the properties of two high alumina cements.[31] These proprietary mixes were found to have very different early strength properties; one compared quite favorably to high early strength concrete and the other did not fare well at all. Both had bond strengths below that of the Type III concrete. It was noted that the temperature of the patch must be kept below 68 °F for 24 hours to avoid deterioration of the patch.

Arizona also evaluated two proprietary high alumina cement mixtures, one with fibers and the other with superplasticizers.[33] Both patch materials exhibited a high level of crazing and longitudinal cracks, but after one year had not failed. The Virginia field evaluation included three proprietary high alumina cement mixtures, none of which were performing satisfactorily. They exhibited thermal cracking and loss of strength; however, smaller patches did appear to perform better than the larger ones.

High alumina cements have been used by Caltrans for many years with varying results.[28] Overall, they found that these perform well, but that there is a wide variation in performance based on different proprietary formulations. Good bond strength, no environmental hazard, and the ability to be placed in deep patches are some of the advantages of this product.

Organic or Polymer-Based Patching Materials

While polymers have been used by transportation agencies in various stages from experimentation to active use for over 30 years, the performance information on polymers is rather scarce. There were 27 references given in the questionnaires indicating use of polymers for concrete patching. Of these, four references to polymers in general were listed, without additional information about the specific type of polymer. The rest of the responses were divided between epoxies, methyl methacrylates (MMA) and polyester styrene. Because it is not clear how familiar the respondents are with the different types of polymers, it can not be unequivocally stated that all of the references to epoxy do not actually include other polymers.

Epoxy Concrete

A total of 21 responses were noted indicating the use of epoxy as a patching material. It bears repeating that this information is of questionable reliability as, in the absence of specific brand information, it is not clear that the products identified as epoxy are actually epoxies. With that in mind, the data on epoxies is summarized in table 5-4. There was an average experience of almost 15 years with this material, and it was used primarily in warm, dry conditions. Under those conditions, it had an average life of 6.6 years, but there was a wide range in the reported results.

Epoxies have been used as a spall repair material at least as early as the 1950s. A report by the Virginia Highway Research Council in 1971 discussed the use of epoxy as a patching product prior to placing an epoxy overlay.[38] After reviewing both lab and field tests and many field placements of epoxy overlays, it was concluded that abrasion or wear was the definitive factor affecting the service life of the application. Other limiting factors included poor skid resistance and the need for precise mixing.

Excellent basic research has been reported by Caltrans on a number of polymers, including epoxies.[28] Epoxies can have rather variable properties, including setting time, strength, and abrasion resistance. In general, epoxy resins are impermeable and excellent adhesives, but tend to be very expensive.

A fairly recent National Cooperative Highway Research Program (NCHRP) study, *Highway Uses of Epoxy with Concrete*, also discusses the use of epoxy as a patching material.[42] In this synthesis, of the 38 states responding to a questionnaire, 33 state agencies reported having used epoxy mortar as a spall repair material, and 25 were still using it. The use of an

Table 5-4. Summary of questionnaire responses for the performance of epoxy in PCC spall repair.

	Life Expectancy (years)			
Temperature	<32 °F		>32 °F	
Cavity Condition	Wet	Dry	Wet	Dry
High	1.5	3	5	20
Low	1	1.5	1.5	1
Average	1.25	2.25	3.25	6.64
Standard Deviation	0.35	1.06	2.47	6.81
Number of Responses	2	2	2	14

aggregate with the epoxy was found to reduce cost, provide additional wear resistance, and improve the thermal characteristics of the material.

The Oregon DOT field study of patching materials included one epoxy formulation.[32] It was found to cure rapidly with no shrinkage, and 6 patches were exhibiting excellent durability after a year of service. Its disadvantages were noted as being difficult to use, expensive, and requiring dry materials and a dry substrate.

Methyl Methacrylate Concrete

Although a couple of responses were noted for use of MMA, no performance data was provided. Therefore, the following discussion is primarily a summary of the literature.

In a laboratory comparison of four different cold-weather patching materials, the MMA had the best overall performance.[39] However, if environmental factors were included in the evaluation, that ranking could change since MMA formulations have been noted for their extreme volatility and noxious odor. It was also noted in this report that the MMA concrete could be placed in the presence of moderate surface moisture and appeared to offer excellent durability properties.

A study conducted by researchers at Oklahoma University examined MMA polymers in both laboratory and field settings.[27] A review of other current research showed that this material performed better over a wider range of conditions than other polymers, with polyester-styrene resins serving as an acceptable alternative because of their low cost.

After lab testing, the MMA was used exclusively in field testing. Testing was also performed with two proprietary mixtures; they performed well but were twice as expensive as the mix used by the researchers. Field testing was performed over a variety of climatic and pavement conditions and a patching procedure for this material was developed. Long-term performance data were not reported.

Polyester-Styrene Concrete

The performance of patches placed with polyester-styrene have generally been quite good, based on a review of the literature. However, no performance data was provided by respondents to the questionnaire. One study reported that the material, placed as an overlay, has performed satisfactorily with no significant wear for 38 months to date.[28] A combination lab and field study examined both polyester-styrene and methyl methacrylate polymers.[27] However, because the MMA performed better in lab tests, only it was used in the field studies.

A comparative field study in Oregon noted that after one year of service on five patches placed, one polyester-styrene patch had failed completely and the other four were debonded.[32]

Acrylic Concrete

While no performance data were provided on acrylic polymer concretes in the questionnaires, three proprietary mixtures were evaluated in Oregon's 1980 study.[32] They all had very similar properties, with the only patching failures occurring in the substrate. Disadvantages noted included the high cost of the material, the environmental hazards, and the need for dry aggregate and a dry substrate.

Polyurethane Concrete

California reports the use of a polyurethane concrete as an emergency repair material.[43] Patches placed with minimum preparation appeared to perform well and could be opened to traffic in 10 to 20 minutes. Some formulations, however, have foamed upon contact with wet aggregate used as an extender or a wet substrate.

Arizona also placed several patches with a proprietary polyurethane mixture.[33] Its advantages were noted as having a rapid set time and being provided in a dispenser which performed the component mixing. It did not seem to perform well, however, despite the fact that after a year the patches were still in place.

In a comparative laboratory study, it was concluded that "polyurethane emerges as inferior by all criteria and is not recommended for use unless special circumstances dictate otherwise."[40] In any case, its use was not recommended on wet surfaces.

Furfuryl Alcohol Polymer Concrete

This particular material, when developed, was subject to both laboratory and field testing under simulated hot and cold and wet and dry weather conditions. It was found that the material performed better in wet conditions at both temperature extremes. Problems that were encountered included segregation, foaming, and rough surface texture, but these were not deemed insurmountable. Good bonding was not achievable without the use of a primer.

Conventional Bituminous Patching Materials

Unlike the cementitious patching products, information was solicited in the questionnaire on both temporary and permanent uses of bituminous patching materials. This distinction, however, is often not made as much by the selection of materials, but by the conditions under which the material is used or by the amount of surface preparation that takes place before the patch is placed.

The distinction also becomes clearer in the number of responses on the use of materials under different conditions, as that reflects a sort of self-selection; some materials are simply not used under certain climatic and pavement surface conditions. The responses also point out that there is a range of interpretation as to what is meant by "temporary" and "permanent." Many of the performance periods provided for temporary and permanent materials suggest either very low expectations or that the materials are not performing adequately.

Bituminous Hot Mix (Asphalt Concrete)

A total of 36 responses and 37 responses were noted for the use of hot mix as a temporary and permanent patching material, respectively. In both applications, respondents had an average of over 18 years of experience in working with asphalt concrete as a patching material. Tables 5-5 and 5-6 summarize the performance of this material as recorded by respondents.

The distribution of the responses for both applications shows that bituminous hot mix is generally used in temperatures above freezing and when the pavement surface is dry. Under those conditions, average service lives of 1.8 years (temporary) and 3.1 years (permanent) were calculated.

For hot mix used in cold, dry conditions, average performance was between 1 and 1.5 years. And, when used in wet conditions at any temperature, average performance was well below 1 year. One respondent noted the use of bituminous hot mix in a cold laid application. Its performance in this application was significantly worse when compared with its performance applied hot.

Bituminous Cold Mix

The results from the questionnaires are summarized in tables 5-7 and 5-8. A total of 51 respondents indicated use of bituminous cold mix as a temporary repair while 23 respondents reported using it as a permanent repair. An average of 20.8 years and 15.3 years of

Table 5-5. Summary of questionnaire responses for the performance of bituminous hot mix as a temporary PCC spall repair.

	Life Expectancy (years)			
Temperature	<32 °F		>32 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	1	3	2.5	5
Low	0.01	0.08	0.02	0.03
Average	0.41	1.08	0.81	1.80
Standard Deviation	0.42	1.00	0.94	1.43
Number of Responses	14	19	20	31

Table 5-6. Summary of questionnaire responses for the performance of bituminous hot mix as a permanent PCC spall repair.

	Life Expectancy (years)			
Temperature	<32 °F		>32 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	1	3	1	6.5
Low	0.02	0.1	0.08	0.75
Average	0.44	1.46	0.52	3.06
Standard Deviation	0.43	1.07	0.47	1.86
Number of Responses	12	17	14	32

experience, respectively, was noted for this material. Cold mixes were used most often as a concrete patch material in warm, dry conditions. Under those conditions, it had an average service life of 1.1 years (temporary application) and 1.7 years (permanent application). Under all other conditions, this product had mean service lives less than 1 year.

Again, there appeared to be little, if any, difference between the formulation of the cold mix used as a permanent patch material and that used as a temporary patch material. The primary differences are in the application conditions, including surface preparation and climate.

Modified/Proprietary Bituminous Patching Materials

Twenty-seven respondents noted the use of proprietary bituminous cold mixes for spall repair. Performance results are summarized in table 5-9. In general, performance of these mixtures placed in good conditions was similar to performance of permanent bituminous cold mix and temporary bituminous hot mix placed in good conditions. Placed in warm, dry conditions, an average service life of 1.7 years was determined. Performance of these materials placed in adverse conditions was much better than the corresponding performance of its generic hot and cold mix counterparts. Average performance was greater than 1 year when applied in all conditions.

Proprietary cold mix has been used as a patching material for a short time; the questionnaire respondent's average experience with this application was approximately 5.6 years.

An extensive field study was performed by local government agencies on the use of a proprietary bituminous cold mix for patching both PCC and AC pavements.[44] This study, which compared a proprietary cold mix to a standard bituminous cold mix, showed that the proprietary mix lasted approximately three times longer than the standard mix under all conditions in a year-long evaluation. These results, gathered from a total of 219 proprietary patch placements and 99 cold mix patches placed in 26 cities across the United States, reflect a trend similar to that of the respondents to this study's questionnaire.

Seven respondents reported the use of bituminous hot or cold mixes with the addition of fibers. Performance data was limited, but all indications show that little or no improvement to performance was made with the inclusion of fibers.

The literature on PCC spall repair contains several references to a sulfur/asphalt composite mixture, although no performance information was reported on it. Widespread use has been made of these mixtures for the patching of bituminous pavements, and its use has migrated in some cases to PCC pavements.[45] In a comparison to cold mix patches in Canada, a large

Table 5-7. Summary of questionnaire responses for the performance of bituminous cold mix as a temporary PCC spall repair.

Life Expectancy (years)				
Temperature	<32 °F		>32 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	1	4	1	5
Low	0.01	0.02	0.01	0.02
Average	0.31	0.53	0.33	1.12
Standard Deviation	0.4	0.73	0.39	1.13
Number of Responses	32	39	32	48

Table 5-8. Summary of questionnaire responses for the performance of bituminous cold mix as a permanent PCC spall repair.

Life Expectancy (years)				
Temperature	<32 °F		>32 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	3	5	3	5
Low	0.02	0.02	0.02	0.08
Average	0.63	0.99	0.62	1.75
Standard Deviation	0.87	1.30	0.87	2.26
Number of Responses	12	18	15	22

Table 5-9. Summary of questionnaire responses for the performance of proprietary bituminous cold mix for PCC spall repair.

	Life Expectancy (years)			
Temperature	<32 °F		>32 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	3	3	4	4
Low	0.02	0.08	0.02	0.08
Average	1.03	1.30	1.13	1.74
Standard Deviation	1.01	1.02	1.04	1.34
Number of Responses	22	21	21	21

number of repairs were placed in both cold and warm weather.[30] Researchers concluded that after 33 months of service, "many of the repairs were still serviceable," in contrast with the cold mix patches, which required frequent replacement.

Summary of Findings

A wide variety of products have been used in the past 20 to 30 years, both routinely and experimentally, for the repair of spalls in portland cement concrete pavements. The major thrust of <u>improvements</u> in this area has been toward the development of materials that rapidly develop load-bearing strength, can be applied under a number of adverse climatic conditions, and will provide suitable performance over a long-term period. It is also a goal to develop repair materials that are suitable for placement on pavements that can not be properly prepared for repair.

There are several cementitious products that appear to approach some, but not all, of the desirable criteria. Many alternate materials have not been proven more effective than ordinary Type I, II, or III portland cement concrete, which has the additional advantages of thermal and material compatibility with the existing substrate.

Developments in polymers appear to be very promising. Researchers are working on products that develop very high early strength and can be placed in both damp and freezing conditions. Work is also underway on flexible patching materials and patching materials that are made from rubberized aggregate. These show promise in their ability not only to carry loads, but also to be placed at joints where excessive movement must be accommodated.

While polymers have been used in the transportation industry for many years, patch performance information is scarce. It appears that while some of the desirable performance characteristics can be obtained, others, such as abrasion resistance and long-term durability, remain unsolved.

There is also a wide variety of bituminous products that have been used for both temporary and permanent patching of PCC pavements. Furthermore, some of the products discussed in chapter 6 on pothole repair may have application for PCC repair. More information is needed on the performance of these materials.

It should be mentioned that considerable emphasis has been given over the years to the development and use of materials with high strength, either over the short or long term. However, the strength of the substrate is often much lower than the strength of the patching material. In some instances, this disparity has even caused failures in the surrounding pavement. This raises the question of whether less emphasis should be placed on the development of high strength materials in order to obtain other, more desirable properties, such as durability.

While some discussion of material costs was made in this chapter, costs were not considered in the performance of the materials. However, expense is one of the primary factors affecting users' decisions to purchase a particular material; the costs of some of the more exotic materials can run as much as 20 times higher than the costs of conventional PCC, for example. Modified bituminous materials are typically at least twice as expensive as the conventional standard hot or cold mixes.

The costs of a material must be examined on the basis of cost-effectiveness or life cycle costs. This is accomplished by taking into account material, labor, and equipment costs, and weighing them against performance.

Many patching materials were investigated in the H-105 project with respect to chemical and physical composition and field performance. However, only a few of these materials were identified as having promising performance capabilities and were, therefore, selected for further investigation. The following materials were among those selected for further study:

- Portland cement concrete
- Gypsum-based concrete
- Epoxy
- Urethane concrete
- Magnesium phosphate concrete
- High alumina cement
- Hydraulic cement concrete
- Modified/proprietary bituminous cold mix

Pertinent Material Properties and Tests

Key Distress Manifestations and Their Causes

A number of different distress types can affect the performance of a partial-depth patch, ultimately leading to failure of the repair. Distresses which manifest themselves on the patch surface include:

- Spalling
- Surface cracking
- Wearing/ravelling
- Patch surround deterioration
- Debonding

Patch Spalling

Spalling of a patch is caused by the inability of the patching material to resist internal stress. Spalling can be caused by any of the following mechanisms:

- A thinly placed patching material cracks and debonds along the patch/substrate boundary under the impact of traffic
- Mechanical conflict between the patch and the adjacent slab causes spalling in the patch at the joint/crack interface
- Compressive stresses generated deep at the joint/crack interface cause a surface spall in the interior of the patch

Spalling in patches can be minimized through the use of proper patch design and construction. By using a joint forming material between the new patch and the adjacent slab, mechanical conflict at the joint/crack interface can be avoided. Also, most patching materials should not be "feather-edged", but instead should be placed with a minimum thickness of approximately 2 in. Patching material properties that will help to reduce spalling include material flexibility, high bond strength, and high tensile strength.

A brittle material has a greater tendency to spall if mechanical conflict at the joint/crack interface is high enough to produce compressive stresses in excess of the compressive strength of the material. A patch made with a flexible, nonbrittle material will absorb the stress created through mechanical conflict, not allowing it to become high enough to cause spalling. Furthermore, a flexible material will deform slightly to accommodate movement in the substrate as it deflects under traffic or expands due to temperature changes.

Bond strength is another important property that helps to prevent spalling. If the material is placed thinly and the bond is insufficient, pieces of the patch will spall off as cracking and debonding occur. A material which forms a strong bond can remain functional and in place even if cracking occurs. For this reason, the bond strength formed between the patching material and the substrate is critical in preventing spalling.

The tensile strength of the patching material will indicate how well the patching material will resist tensile stress. As a patch is subjected to traffic, vertical deflections will occur which will introduce tensile stresses into the patch. If a patching material has a significantly different coefficient of thermal expansion than the PCC substrate, tensile stress may develop during temperature changes. Additionally, the mechanical conflict that can occur between the patch and the adjacent slab at the joint/crack interface may cause very high tensile stresses to develop in the patch. A patching material which is unable to adequately resist these stresses will spall.

Patch Cracking

Surface cracking of the patch surface is most commonly caused by shrinkage of the patching material during hydration. Cracking can also occur if tensile stress in the patch becomes too great. Cracks provide a path for water and deicing salts to penetrate into the patch, possibly contributing to debonding, patch deterioration, or corrosion of the reinforcing bars or steel dowels in the substrate. Material properties which have an impact on patch cracking include the amount of shrinkage during hydration, tensile strength, and thermal compatibility of the patching material.

Wearing/Ravelling of the Patch Surface

A partial depth patch will wear if the material can not adequately resist the abrasive forces of traffic. When the patching material deteriorates under the influence of freeze-thaw cycling or exposure to deicing chemicals, ravelling of the surface results. Wearing and ravelling reduces the serviceability of the pavement and can result in further deterioration of the patch. The ability of the patching material to resist wearing and ravelling can be related to the durability of the aggregate, or the stability of the binder when subjected to load, climate, and application of chemicals (e.g., deicing salts, oil). Construction can also contribute to wearing/ ravelling if too much water is added or if water is used to allow easier finishing of the patch.

Patch Surround Deterioration

Occasionally, the pavement surrounding a patch will deteriorate, even if the patch is functioning well. This distress may be in the form of spalling at the slab/patch joint, a corner break in the adjacent slab, or the need for a second patch placed adjacent to the original patch. This type of distress is usually not directly related to the patching material properties, but is more indicative of the weakened condition of the substrate. The patch can provide a stress concentration point in the pavement, and since the patching material is commonly stronger than the substrate, distress formation may occur in the existing PCC pavement.

Bond Failure in Patch

One of the most critical factors that influences the serviceability of a partial depth patch is the strength of the bond between the patch and the substrate. This bond is enhanced through proper preparation of the substrate, including the correct substrate moisture conditions (some patching material require a dry substrate while others require saturated surface dry conditions), adequate cleaning of the patch area, and in certain situations, the application of a bonding agent.

A patching material's ability to form a strong bond is related to the chemical and mechanical interactions created with the existing PCC. The strength of the bond can decrease over time due to traffic and climatic factors. The thermal compatibility of the patching material with PCC can contribute to debonding, as can the presence of cracks in the patch which allow water and deicing chemicals access to the bond interface. Corrosion of reinforcing or load transfer devices can also lead to patch debonding.

Desirable Material Properties

A patching material must possess several characteristics in order for it to be effective. The material must be sufficiently durable to resist the effects of traffic and climatic cycles to which it will be subjected. It must possess good adhesion to the substrate, since debonding will ultimately lead to failure of the patch. The patching material must cure rapidly, being able to support traffic within the desired time frames.

Patching materials must also be chemically and thermally compatible with the portland cement concrete substrate. Incompatibility translates into a disintegrated system for which failure, bond or otherwise, is imminent. Finally, the patching material must be easily and safely handled and placed.

Laboratory Tests Used to Measure Desirable Material Properties

A number of laboratory tests can be used to measure material properties which may be correlated to the performance of the patch under field conditions. Some of the tests attempt to measure intrinsic properties of the patching materials (e.g., modulus of elasticity, tensile strength), whereas other tests attempt to simulate field conditions to estimate how the material will perform (e.g., resistance to freezing and thawing, susceptibility to scaling). Table 5-10 lists the laboratory tests determined to be applicable for measuring desirable material properties.

Initial Setting Time

The initial setting time of the material generally will not contribute to distress formation, but is critical to proper patch placement, and thus must be considered as an influential patching material performance property. The setting time is the time that is available from mixing until the material can no longer be easily worked or finished. A short setting time will not allow adequate placement and finishing of the patching material, possibly leading to poor serviceability of the patch.

A manual method is recommended for the determination of the initial setting time. This method will require the material to be worked with a trowel until it begins to stiffen and can not be easily molded. Additionally, the mixture temperatures will be taken at different times to evaluate the rate of reaction of the mixture.

Compressive Strength

The compressive strength of the material is an important indicator of how well the material will resist stress induced by traffic loading or mechanical conflict which may occur at the joint/crack interface. The compressive strength should be evaluated for specimens that have cured for less than 24 hours using ASTM C 109, "Compressive Strength of Hydraulic Cement Mortars." For specimens that are to be cured for 24 hours or more, it is recommended that ASTM C 39, "Compressive Strength of Cylindrical Concrete Specimens" be used.

Modulus of Elasticity

The modulus of elasticity of the material should be determined in accordance with ASTM C 469, "Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression." The modulus of elasticity is important when considering how a material deforms or strains under an applied load. A material with a very high modulus of elasticity will be stiffer and will not yield as well to movement in the substrate or to mechanical conflict that may occur at the joint/crack interface.

Flexural Strength

The flexural strength of the material will be tested in accordance with ASTM C 78, "Flexural Strength of Concrete (Using Simple Beam with Third Point Loading)." This flexural test will be used to evaluate the tensile strength of each material. Materials with high tensile strength

Table 5-10. Laboratory tests for measuring desirable patching material properties.

Property	Laboratory Test	Source
Initial Setting Time	(1) Workability	
Strength	(1) Compressive Strength (2) Flexural Strength	ASTM C 109 or ASTM C 39 ASTM C 78
Stiffness	(1) Modulus of Elasticity	ASTM C 469
Adhesion	(1) Bond Strength (2) Bond Strength	ASTM C 882 California Method
Freeze/Thaw	(1) Resistance to Rapid Freezing and Thawing	ASTM C 666A
Scaling	(1) Scaling Resistance to Deicing Chemicals	ASTM C 672
Abrasion/Wear	(1) Resistance to Surface Abrasion	California Test 550
Shrinkage	(1) Length Change	ASTM C 157
Compatibility	(1) Thermal Expansion Coefficient.	ASTM C 884

will be more able to resist tensile stress, which is the most common cause of cracking in a cured cementitious material.

Bond Strength

The strength of the bond between the patching material and the substrate is absolutely critical to the long-term performance of the patch. A well-bonded patch is more able to resist spalling and cracking then an unbonded patch, and a strong bond will prevent the ejection of a patch from the spall. Because of this, two different methods are to be used when evaluating the strength of the bond.

The first method is in accordance with ASTM C 882, "Bond Strength of Epoxy-Resin Systems used with Concrete." In this method, cylindrical substrate specimens will be produced and cut at an incline, and the patching material will be bound to the substrate. The composite cylinder will then be tested in compression, and the magnitude of the stress and mode of failure noted.

The second method is one which is commonly used by Caltrans and is called the California Method, "Method of Test of Bonding Strength of Concrete Overlay and Patching Materials to PCC." This testing procedure is based on the centerpoint loading at the bond interface. The magnitude of the stress at failure and mode of failure will be recorded.

Resistance to Freezing and Thawing

Each patching material's resistance to freezing and thawing will be evaluated in accordance with ASTM C 666A, "Resistance of Concrete to Rapid Freezing and Thawing." This test examines the stability of the aggregate and binder when subjected to rapid changes in temperature and freeze-thaw action. Information obtained should be useful in predicting a material's propensity to disintegrate under climatic influences.

Susceptibility to Scaling Caused by Deicing Chemicals

ASTM C 672, "Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals" is to be used to examine each material's ability to resist ravelling when subjected to deicing chemicals. Materials that deteriorate significantly during testing will likely have a problem in the field if applied where deicing chemicals are normally used.

Resistance to Wear

The ability of each patching material to resist wear will be evaluated in accordance with California Test 550, "Method for Determining the Surface Abrasion Resistance of Concrete Specimens."

Length Change

The length change or shrinkage that a material experiences as it cures can lead to the formation of cracks in the patch. Each material will be tested in accordance with ASTM C 157, "Length Change of Hardened Cement Mortar and Concrete" to assess the potential for shrinkage problems.

Thermal Compatibility of Patching Materials

Thermal compatibility of patching materials with the PCC substrate is a leading cause of patch debonding. If the materials are thermally incompatible, high stress will develop at the bond interface, ultimately resulting in bond failure and the ejection of the patch from the spall. This property will be evaluated in accordance with ASTM C 884, "Thermal Compatibility Between Concrete and an Epoxy-Resin Overlay."

Implementation of Research Findings into Experimental Plan

This section provides an overview of the experimental plan developed to determine the most effective PCC spall repair materials and procedures. These materials and procedures will most likely contribute to some, if not all, of the following performance features:

- Increased cost-effectiveness
- Increased life of the repair
- Faster curing time to facilitate early opening of repair to traffic
- Faster repair procedures, decreasing the lane occupancy time of maintenance crews

Experimental Plan Overview

The overall success of spall repair is governed by many factors. The following list of factors were identified in this project as having considerable influence on the performance of PCC spall repairs.

- Climate
- Traffic
- Pavement design
- Cavity preparation
- Patch type (partial- or full-depth)
- Patching material type & brand
- Patching procedures
- Weather conditions during repair
- Severity/size of spall
- Location of spall
- Drainage
- Timing
  - pavement age/condition.
  - time of application.

Incorporating each one of these factors in detail into the experimental plan would be difficult, from both a monetary and technical standpoint. For this reason, some of the more important factors were selected to provide a foundation on which to design the experiment.

Climate

The PCC spall repair experiment will consist of four test sites, one located in each of SHRP's four climatic zones, as shown in figure 3-1. This way, any general performance trends which would appear to be independent of climate can be identified.

Traffic

Traffic is believed to have an effect on spall performance. However, to minimize the number of variables, traffic will be constrained to a range of 3,000 to 50,000 vehicles/day (bi-directional). This traffic range will permit lane closures for installation and evaluation, yet will provide excellent testing grounds.

Patch Type

As mentioned earlier, only partial-depth patching procedures will be utilized in the experiment. Such repairs are surficial in nature, requiring less time and effort than full-depth repairs.

Preparation Procedures

Four different preparation procedures will be employed in the experiment:

1. Rigorous partial-depth patching
2. Concrete removal by hand, sandblast clean
3. Concrete removal by milling, sandblast clean
4. Cavity sweeping only

The rigorous preparation method basically involves saw-cutting the boundaries of the hole, removing the deteriorated concrete by pneumatic hammer, installing a joint block, sandblasting the hole, and applying a bonding agent.

The second and third methods are not as comprehensive, as only the deteriorated concrete is removed (manually or by milling), a joint block is installed, the hole is sandblasted, and a bonding agent is applied.

Finally, the fourth method requires only sweeping of loose material and water from the hole. This method will be used for emergency repairs.

Patching Materials

Each test site will use a total of seven patching materials, with the exception of the wet-freeze climatic test site, which will include nine materials. The specific patching materials to be placed and evaluated and their generic type include:

• Type III PCC	Portland Cement Concrete
• MC-64	Epoxy
• Duracal	Gypsum-Based Concrete
• Percol	Urethane Concrete
• Set-45	Magnesium Phosphate Concrete
• Five-Star Highway Patch	High Alumina Cement
• SikaPronto 12	High Molecular Weight Methacrylate

- Sylvax UPM — Modified/Proprietary Bituminous Cold Mix
- Pyrament 505 — Hydraulic Cement Concrete

Weather Conditions During Repair

Most repairs will be performed under favorable weather conditions. However, there is a need to identify effective emergency repair materials, capable of performing well in cold, wet conditions. For this reason, three specially formulated materials will be placed in adverse weather conditions at the wet-freeze test site.

Overall National Layout of Tests

Each test site will be composed of two replicates to provide greater statistical validity. Within each replicate will be a number of test sections which incorporate a specified combination of patching materials and patching procedures. Ten spall repairs will be made in a test section using a prescribed material and procedure. Each repair will be marked in the field using permanent marking paint and identification tags. The experimental matrices for each test site are shown in tables 5-11 through 5-13.

Field Evaluations

Field inspections will be conducted at each test site in order to fully evaluate the performance of each repair material. The proposed inspections will take place at the following times subsequent to installation:

- 3 months
- 6 months
- 12 months
- 18 months
- 24 months

The patches will be inspected for all of the primary patch distresses identified earlier, and those that are found will be recorded during each evaluation. In addition, other patch distresses and associated pavement distresses will be examined. As in the other experiments, photographs will be taken of patches in order to show failure mechanisms and the progression of patch deterioration over time.

Table 5-11. Factorial design matrix for the wet-freeze climatic region.

WET-FREEZE CLIMATIC ZONE				
Material Type	Rigorous Patching Procedure	Clean and Patch Procedure	Mill and Patch Procedure	Adverse Conditions Procedure
Type III PCC	2 Reps	2 Reps	2 Reps	
Duracal	2 Reps	2 Reps		
Set-45	2 Reps	2 Reps	2 Reps	
Five Star H.P.	2 Reps	2 Reps	2 Reps	
MC-64	2 Reps	2 Reps		
SikaPronto 12	2 Reps	2 Reps		
Percol	2 Reps	2 Reps	2 Reps	2 Reps
Pyrament				2 Reps
Sylvax				2 Reps

Table 5-12. Factorial design matrix for the dry-freeze climatic region.

DRY-FREEZE CLIMATIC ZONE			
Material Type	Rigorous Patching Procedure	Clean and Patch Procedure	Mill and Patch Procedure
Type III PCC	2 Reps	2 Reps	2 Reps
Duracal	2 Reps	2 Reps	
Set-45	2 Reps	2 Reps	
Five Star H.P.	2 Reps	2 Reps	
MC-64	2 Reps	2 Reps	
SikaPronto 12	2 Reps	2 Reps	
Percol	2 Reps	2 Reps	

Table 5-13. Factorial design matrix for the nonfreeze climatic regions.

WET AND DRY-NONFREEZE CLIMATIC ZONES		
Material Type	Rigorous Patching Procedure	Clean and Patch Procedure
Type III PCC	2 Reps	2 Reps
Duracal	2 Reps	2 Reps
Set-45	2 Reps	2 Reps
Five Star H.P.	2 Reps	2 Reps
MC-64	2 Reps	2 Reps
SikaPronto 12	2 Reps	2 Reps
Percol	2 Reps	2 Reps

Material Performance Characterization

As in the other experiments, the performance of the patching materials will be complemented by a rigorous laboratory testing scheme. The tests identified earlier in table 5-10 will be run on samples taken from each lot of material used in the experiment. A strong correlation is expected between the results of the laboratory tests and field performance.

Bibliography

Anderson, D.A. and H.R. Thomas. Pothole Repair in Pennsylvania. Paper prepared for the proceedings of Purdue University's 70th Annual Road School, West Lafayette, 1984, pp. 28-46.

Anderson, D.A., H.R. Thomas, Z. Siddiqui, and D.D. Krivohlavek. *More Effective Cold, Wet-Weather Patching Materials for Asphalt Pavements*. Report FHWA/RD-88/001. Pennsylvania State University, University Park, September 1987.

Beaudoin, J.J. and P.J. Serada. Field Studies of a Sulphur/Asphalt Composite Pothole Repair System. *Durability of Building Materials*, National Research Council Canada, November 1983, pp. 1-6.

Culley, R. W. *Field Trials With Sand-Sulphur-Asphalt Maintenance Mixes*. Technical Report 29, Saskatchewan Highways and Transportation, September 1979.

Epoxies for Concrete Repair and Restoration. *Concrete Construction*, March 1979, pp. 169-174.

Knab, L.I. *Factors Related to the Performance of Concrete Repair Materials*. USAE Technical Report REMR-CS-12, National Bureau of Standards, March 1988.

Krauss, P.D. *New Materials and Techniques for the Rehabilitation of Portland Cement Concrete*. Report FHWA/CA/TL-85/16. California Department of Transportation, Sacramento, October 1985.

Kudlapur, S., A. Hanaor, P.N. Balaguru, and E.G. Nawy. Evaluation of Cold Weather Concrete Patching Materials. Title No. 86-M5, *ACI Materials Journal*, January-February 1989.

Kumar, V.R. and K. Majidzadeh. *A Field and Laboratory Evaluation of Pavement Patching Material.* Report FHWA/OH-87/003. Resource International Inc., May 1987.

Mildenhall, H.S. and G.D. Northcott. *A Manual for the Maintenance and Repair of Concrete Roads.* Department of Transport, Cement and Concrete Association.

Parker Jr., F., G.E. Ramey, R.K. Moore, and J.W. Jordan Jr.. A Field Evaluation of Factors Affecting Concrete Pavement Surface Patches. Transportation Research Record No. 1041 TRB, National Research Council, Washington, D.C., 1985, pp. 53-59.

Parker Jr., F., W.L. Shoemaker, and R.L. Reckart. *A Field Study of PCC Pavement Patching Materials and Procedures.* Highway Research Center, Auburn University.

Quinn, W.J. and G. Beecroft. *The Evaluation of Pavement Patching Materials in Oregon.* Final Report, Oregon Department of Transportation, Salem, November 1980.

Ramey, G.E., R.K. Moore, F. Parker, Jr., and A.M. Stickland. Laboratory Evaluation of Four Rapid-Setting Concrete Patching Materials. Transportation Research Record No. 1041, TRB, National Research Council, Washington, D.C., 1985, pp. 47-52.

Research Pays Off. Illinois Improves Patching Procedures for Continuously Reinforced Concrete Pavements. *TRNews*, TRB, National Research Council, Washington, D.C., May-June 1986, pp. 8-9.

Rissel, M.C. *Improved Methods for Patching on High-Volume Roads.* Report FHWA/RD-80/076. Byrd, Tallamy, MacDonald and Lewis, January 1986.

Sprinkel, M.M. *Evaluation of Concrete Pavement Patching Techniques. Final Report.* Report FHWA/VA-89-22. Virginia Department of Transportation, May 1989.

Stark, B. Oregon Finds Inlay Patching Effective. Roads and Bridges, August, 1988, p. 59.

Struble, L. and N. Waters. *Tensile Test to Measure Adhesion Between Old and New Cement Paste.* National Bureau of Standards, January 1988.

Sundquist, C.R. and B.T. Squires. *Patching and Grouting Materials. Final Report.* Research Report CA-HWY-MR635148(7)-72-06. State of California, Division of Highways, Sacramento, January 1972.

Thornton, J.B. and W. Golden. Pavement Restoration Measures to Precede Joint Resealing. Transportation Research Record No. 752, TRB, National Research Council, Washington, D.C., 1980, pp. 6-15.

Wyant, D.C., *Evaluation of Concrete Patching Materials*. Report VHWA/VA-84/35. Virginia Department of Highways and Transportation, Richmond, May 1984.

6

AC Pothole Repair

There is probably nothing that aggravates highway users more and reduces their respect for a highway agency than hitting a pothole. Not only do potholes cause vehicle damage, but they present safety hazards for the highway user.

A large number of agencies use the "throw-and-go" pothole repair procedure, or the equivalent "dump-and-run", using conventional cold mix materials. This is due to the intense pressures placed on maintenance crews to fill as many potholes as possible during the spring thaw period. The life of these repairs typically ranges from a few hours to a few weeks. When highway users notice this rapid failure rate, they become even more aggravated. This repeated process of filling and refilling potholes ultimately results in the expenditure of large amounts of scarce maintenance funds, without providing any long-lasting benefit to the highway system. It also exposes maintenance crews to hazardous conditions in the traffic lane more often than is necessary.

The effective repair of potholes is a major problem for most highway agencies. Asphalt concrete surfaced pavements represent a large majority of existing pavements, and nearly all of these pavements develop potholes as they deteriorate and are exposed to cold wet weather.

A few agencies have invested significant effort toward the improvement of pothole repair procedures and materials and, as a result, have significantly increased the life of these repairs and the cost-effectiveness of such work. This has also reduced the number of times that maintenance crews need to occupy traffic lanes for pothole repairs. There are a number of new non-proprietary and proprietary materials that have shown promising results for use in adverse conditions. These developments give hope that there exists improved materials and procedures for pothole repair, that, if exploited throughout the U.S., would result in both considerable savings in maintenance costs and increased safety to both maintenance workers and the traveling public.

The greatest need and potential benefit for improved pothole repair of asphalt-surfaced pavements is for rapid repairs applied under adverse wet and cold conditions.

Material Performance Synthesis

Bituminous patching mixtures must develop certain properties in order to perform well. These properties include:

- Stability or resistance to shoving and rutting
- Stickiness or adhesion for bonding to the sides and bottom of a pothole
- Binder resistance to stripping in the presence of water
- Durability or resistance to deterioration caused by traffic and climate
- Workability or ease of handling, shoveling, and compacting
- Storageability with no reduced workability

The questionnaire responses and research reports were thoroughly examined, with three goals in mind:

- To identify available pothole patching materials
- To identify the performance of the various material types, making special note of the better performing patch mixes
- To ascertain the presence or lack of the above properties in each material type identified

Types of Repair Materials

Pothole patching materials can be broken down into the following categories:

- Conventional bituminous materials
  - hot mix
  - cold mix
- Modified/proprietary bituminous materials
- Proprietary concrete mixes

Bituminous Hot and Cold Mixes

Bituminous hot mixes are hot-mixed and hot-laid asphalt concrete materials. They are produced using specified percentages of asphalt cement and strictly-graded, quality aggregate.

Bituminous cold mixes are cold-mixed and cold-laid asphalt-aggregate mixtures. Such materials utilize liquid asphalt, in the form of an emulsion or cutback, as the binder.

Typically, the aggregate and aggregate gradation used in cold mixes are of lower quality than those used in hot mixes. Although some special agents and processes may be used in producing conventional bituminous mixes, they usually are not of great significance.

Just as bituminous mixes are used in temporary or permanent PCC spall repairs, they are also used in temporary or permanent AC pothole repairs. The primary difference between these two repair types lies in application conditions (i.e., hole preparation and weather).

Modified/Proprietary Bituminous Patching Materials

Modified/proprietary bituminous materials, as noted in chapter 5, can be broken down into generic categories according to the type of modifier added and the processes employed in producing the mix. For instance, additives such as rubber, fiber, sulfur, and anti-stripping agents are commonly blended in with asphalt binder to enhance the performance of pothole patching mixes. Some brief descriptions of the more commonly used proprietary patching materials are given below.

Sylvax UPM

Sylvax UPM is a bituminous patching material composed of a specially treated proprietary liquid-asphalt blend, which is plant-mixed with a locally available aggregate. It can be placed at sub-freezing temperatures as well as at warmer temperatures. The aggregate is crushed with a maximum top size of 3/8 in and 2 percent maximum passing the #200 sieve.[46] Both open-graded and densely-graded mixes are available.

Perma-Patch

Perma-Patch is a uniform mixture of compatible mineral aggregate and bituminous material. The aggregate is crushed, and has a maximum size of 3/8 in and a maximum of 3 percent passing the #200 sieve. The bituminous material is "Perma-Patch Liquid" provided by the manufacturer.[47]

Fiberized Asphalt Mix

Fibers can be added to either hot or cold bituminous mixes as reinforcement. The fibers, typically polypropylene or polyester, purportedly improve the bond with the asphalt and aggregate and function to redistribute the loads more uniformly. Proprietary fiber mixes available include FiberPave and BoniFibers.

Quality Pavement Repair (QPR) 2000

QPR 2000 is a ready-to-use, pre-mixed asphalt patch material made from selected aggregate, asphalt with chemical solvents, and additives. It can be applied to either wet or dry surfaces and either hot or subfreezing temperatures. In addition, it can be opened to traffic immediately after placement and can be stored in a stockpile for up to a year.[48]

Proprietary Cementitious Materials

Cementitious materials have seen some use in the repair of AC potholes. However, such applications are not recommended due to thermal and chemical incompatibilities between the asphalt concrete and patching material. Cementitious materials that have been used in pothole repair include Duracal and Set-45.

Material Use and Performance

A large number of responses were received from highway agencies regarding the use of AC pothole repair materials. Table 6-1, which summarizes these responses, shows usage and experience with the various material types, as well as estimated performance ranges.

As can be seen, the majority of responses (70) were for the use of bituminous hot mix in a permanent application. This was followed closely by temporary bituminous cold mix (65), permanent cold mix (45), temporary hot mix (40), and the proprietary bituminous cold mix, Sylvax UPM (27). Fiberized asphalt mix was the only other material type to receive more than ten responses.

Five responses were received for the proprietary bituminous mix, Perma-Patch. In addition, the use of several other proprietary bituminous materials was noted. Each of these mixtures were noted fewer than three times and thus were grouped together. A few of the products within this category will be discussed later in this chapter.

The questionnaire responses also indicated that agencies have most experience with hot and cold bituminous mixes. Experience averaged more than 15 years for these materials, regardless of placement procedures.

Table 6-1. General summary of questionnaire responses for AC pothole repair.

Repair Materal Type	Total Number of Responses	Experience (Years of Use)		Range of Life Expectancy (Years)
		Average	Range	
Bituminous Hot Mix (temporary)	40	21	2.5 - 45	0.01 - 10
Bituminous Hot Mix (permanent)	70	20.3	3 - 45	0.01 - 20
Bituminous Cold Mix (temporary)	65	19.4	1 - 50	0.003 - 5
Bituminous Cold Mix (permanent)	45	13.4	1 - 45	0.003 - 4.5
Sylvax UPM (proprietary)	27	6.4	1 - 12	0.01 - 5
Perma-Patch (Proprietary)	5	3.3	1 - 5	0.25 - 1.5
Fiberized Mix	11	6.9	4 - 12	0.25 - 2
Other Proprietary Bituminous Mixes	20	7.7	1 - 15	0.08 - 7
Proprietary PCC	3	6.3	3 - 8	5 - 8

An in-depth evaluation was performed on the pothole questionnaire responses, in which comparisons were made with regard to material performance and use. The results of these analyses are presented for each material category.

Bituminous Hot Mix (Asphalt Concrete)

Statistical performance summaries for hot mix patch materials placed temporarily and permanently are given in tables 6-2 and 6-3, respectively. By definition, a temporary patch indicates that the patch material was placed and compacted in the hole with none or very little preparation. A permanent patch indicates that some type of preparation was performed, such as cutting boundaries, cleaning out the hole (either drying or not drying it), placing a tack material, and then placing and compacting the patch material. The following observations are based upon this data.

1. The longest lasting AC patch is placed using permanent procedures at >32 °F in a dry hole (4.4 years average). The shortest lasting AC patch is placed using permanent procedures at <32 °F in a wet hole (3.2 months average).

2. The effect on patch life of placing hot mix material into a dry hole versus a wet hole is very large.

    - A temporary AC patch placed at <32 °F lasts 4.7 times longer (dry life/wet life)
    - A temporary AC patch placed at >32 °F lasts 3.2 times longer
    - A permanent AC patch placed at <32 °F lasts 6.0 times longer
    - A permanent AC patch placed at >32 °F lasts 4.9 times longer

3. The effect on patch life of placing a permanent cold mix patch versus a temporary cold mix patch is significant.

    - A dry hole at >32 °F lasts 1.9 times longer (permanent life/temporary life)
    - A dry hole at <32 °F lasts 1.3 times longer
    - A wet hole at >32 °F lasts 1.2 times longer
    - A wet hole at <32 °F lasts about the same as a dry hole

4. The effect on patch life of placement of an AC patch at a warmer temperature is very significant for both permanent and temporary patches (warmer temperatures would include use of a hotbox to keep the mix warm).

Table 6-2. Summary of questionnaire responses for the performance of bituminous hot mix in temporary AC pothole repair.

	Life Expectancy (years)			
Temperature	<32 °F		>32 °F	
Pothole Condition	Wet	Dry	Wet	Dry
High	1	5	4.5	10
Low	0.01	0.12	0.01	0.33
Average	0.3	1.42	0.73	2.33
Standard Deviation	0.32	1.3	1.07	2.3
Number of Responses	17	18	17	20

Table 6-3. Summary of questionnaire responses for the performance of bituminous hot mix in permanent AC pothole repair.

	Life Expectancy (years)			
Temperature	<32 °F		>32 °F	
Pothole Condition	Wet	Dry	Wet	Dry
High	1	5	5	20
Low	0.01	0.15	0.01	0.75
Average	0.27	1.78	0.89	4.41
Standard Deviation	0.3	1.4	1.29	3.45
Number of Responses	10	14	16	37

- A temporary AC patch placed at >32 °F in a wet hole lasts 2.4 times longer (warmer temperature life/colder temperature life)
- A permanent AC patch placed at >32 °F in a wet hole lasts 3.3 times longer
- A temporary AC patch placed at >32 °F in a dry hole lasts 1.6 times longer
- A permanent AC patch placed at >32 °F in a dry hole lasts 2.4 times longer

Bituminous Cold Mix

Statistical performance summaries for bituminous cold mixes placed both temporarily and permanently are given in tables 6-4 and 6-5, respectively. The following observations are based upon this data.

1. The longest lasting cold mix patch is placed using permanent procedures at >32 °F in a dry hole (1.5 years average). The shortest lasting cold mix patch is placed using temporary procedures at <32 °F in a wet hole (0.31 years or 3.7 months average).

2. The effect on patch life of a dry hole versus a wet hole is very large.

   - A temporary cold mix patch placed at <32 °F lasts 2.4 times longer (dry life/wet life)
   - A temporary cold mix patch placed at >32 °F lasts 3.0 times longer
   - A permanent cold mix patch placed at <32 °F lasts 1.6 times longer
   - A permanent cold mix patch placed at >32 °F lasts 2.4 times longer

3. The effect on patch life of placing a permanent AC patch versus a temporary AC patch is significant under most conditions.

   - A dry hole at >32 °F lasts 1.3 times longer (permanent life/temporary life)
   - A dry hole at <32 °F lasts 1.3 times longer
   - A wet hole at >32 °F lasts 1.6 times longer
   - A wet hole at <32 °F lasts 1.9 times longer

4. The effect on patch life of temperature at placement of a cold mix patch is significant for dry holes. It is not significant for wet holes.

   - A temporary cold mix patch placed at >32 °F in a wet hole lasts about the same (warm placement life/cold placement life)

Table 6-4. Summary of questionnaire responses for the performance of bituminous cold mix in temporary AC pothole repair.

	Life Expectancy (years)			
Temperature	<32 °F		>32 °F	
Pothole Condition	Wet	Dry	Wet	Dry
High	2	4	2	5
Low	0.003	0.02	0.01	0.08
Average	0.31	0.76	0.38	1.15
Standard Deviation	0.49	1.01	0.50	1.3
Number of Responses	27	7	2	29

Table 6-5. Summary of questionnaire responses for the performance of bituminous cold mix in permanent AC pothole repair.

	Life Expectancy (years)			
Temperature	<32 °F		>32 °F	
Pothole Condition	Wet	Dry	Wet	Dry
High	3	3.5	3	4.5
Low	0.003	0.02	0.02	0.08
Average	0.58	0.97	0.62	1.48
Standard Deviation	0.97	1.09	0.95	1.14
Number of Responses	8	12	8	17

- A permanent cold mix patch placed at >32 °F in a wet hole lasts about the same
- A temporary cold mix patch placed at >32 °F in a dry hole lasts 1.5 times longer
- A permanent mix patch placed at >32 °F lasts 1.5 times longer

Modified/Proprietary Bituminous Patching Materials

The statistical performance summary for all proprietary patching materials, as determined from the questionnaire responses, is displayed in table 6-6. In addition, table 6-7 shows the individual average service lives of several proprietary bituminous materials. The following observations were made based upon this data.

1. The effect on average patch life of proprietary materials in a dry hole versus a wet hole is significant, but not as large as conventional cold mix materials.

    - A patch placed at <32 °F lasts 1.6 times longer (dry life/wet life)
    - A patch placed at >32 °F lasts 1.6 times longer as well

2. The effect on patch life of temperature at placement of a proprietary patch is significant, but again less than conventional cold mix.

    - A patch placed at >32 °F in a wet hole lasts about 1.1 longer (warm placement/cold placement life)
    - A patch placed at >32 °F in a dry hole also lasts about 1.1 times longer

3. The various proprietary patches showed different estimates of life, although data was limited for most materials. However, some look very promising in terms of increased life.

Proprietary Cementitious Materials

Only two proprietary cementitious materials were noted for use in patching potholes. One respondent indicated five to seven years of performance using Duracal in a composite AC/PCC pavement. No performance estimates were given for Set-45, the other concrete patching material.

Table 6-6. Summary of questionnaire responses for the performance of all proprietary cold mixes in AC pothole repair.

	Life Expectancy (years)			
Temperature	<32 °F		>32 °F	
Pothole Condition	Wet	Dry	Wet	Dry
High	6	6	6	6
Low	0.01	0.01	0.02	0.08
Average	1.08	1.77	1.21	1.88
Standard Deviation	1.15	1.99	1.38	1.32
Number of Responses	47	47	49	50

Table 6-7. Mean expected lives for proprietary patch materials.

	Mean Life Expectancy (years)			
Temperature	<32 °F		>32 °F	
Pothole Condition	Wet	Dry	Wet	Dry
All Proprietary Matlerials (50)	1.08	1.77	1.21	1.88
Sylvax UPM (23)	1.17	1.4	1.4	1.99
Perma-Patch (3)	0.75	1.17	0.75	2.13
Fiberized Mix (9)	0.72	0.89	0.86	1.14
Kotal (2)	0.09	0.18	0.29	0.6
Winter-Patch (1)	1.5	2.5	2	4
Bitucrete (1)	-	-	-	1
Eccitex (1)	-	3	-	3
QPR 2000 (1)	3	3	-	-
Thermopatch (1)	-	-	-	0.3
Western HyGrade (1)	0.17	0.17	0.17	1
Instant Road Repair (1)	0.7	0.41	0.5	1
Hydropatch (1)	0.5	1	1.5	2.5
Wespro (1)	2	2	4.5	4.5
Allapatch (1)	1.5	2	2.5	4
QuickFill (1)	1	-	1	-
Insta-Patch (1)	1	2	1	2

( )—Number of Responses

Comparison of Hot Mixes,
Cold Mixes, and Proprietary Mixes

Table 6-8 summarizes some of the results for placement in cold (< 32 °F) conditions.

1. The average proprietary material greatly out-performed conventional cold mix for cold temperatures and wet holes (a ratio of 3.5 times longer life for both temporary and permanent patches). Proprietary materials are designed to improve performance life under these conditions.

2. The average proprietary patch material also out-performed conventional cold mix materials for cold temperatures and dry hole conditions, but not by as much (a ratio of 2.2 for temporary and 1.8 for permanent material).

3. The proprietary mixture performs somewhat better in a dry hole (ratio of 1.6), but a dry hole has a much greater effect on conventional materials (ratio of 2.4 for temporary cold mix and 4.7 for temporary hot mix). Thus, the proprietary materials do have a significant effect on extending patch life for wet and cold hole applications.

4. For warm application conditions (> 32 °F), the proprietary materials, on average, do not have as significant an advantage over conventional materials. Table 6-9 shows a summary of the data for warm temperature applications. There is little advantage, if any, for dry hole conditions, but somewhat more for wet hole conditions. It must be remembered that the above estimates are given for the mean proprietary material; therefore, some of these materials exhibited performance much better than the mean and some less than the mean.

5. The ratio of life between the proprietary material and cold mix temporary materials are shown in table 6-10 for the most highly recommended materials when placed under cold and wet conditions.

If any of these estimates are even close to actual performance, there appears to be some products that will provide significantly improved life over conventional cold mixtures.

Review of Literature on Patching Materials

There have been several studies conducted during the last 10 years on pothole patching materials. Some are part of formal research contracts, while others are more informal studies

Table 6-8. Comparison of the expected life of different patching materials when placed during cold temperatures (<32 °F).

	Life Expectancy (years)	
Temperature	<32 °F	
Pothole Condition	Wet	Dry
Hot Mix—Temporary	0.3	1.42
Cold Mix—Temporary	0.31	0.76
Proprietary*	1.15	1.61
Hot Mix—Permanent	0.27	1.78
Cold Mix—Permanent	0.58	0.97
Proprietary*	1.15	1.61

Table 6-9. Comparison of the expected life of different patching materials when placed during warm temperatures (>32 °F).

	Life Expectancy (years)	
Temperature	>32 °F	
Pothole Condition	Wet	Dry
Hot Mix—Temporary	0.73	2.33
Cold Mix—Temporary	0.38	1.15
Proprietary*	1.21	1.88
Hot Mix—Permanent	0.89	4.41
Cold Mix—Permanent	0.62	1.48
Proprietary*	1.21	1.88

* Mostly temporary procedures

Table 6-10. Ratio of life between proprietary materials and cold mix temporary materials when placed under cold and wet conditions.

Material	**Ratio (Material life/Cold mix life)**
Duracal* (n=1)	16.1
QPR 2000 (n=1)	9.7
Allapatch (n=1)	4.9
Winterpatch (n=1)	4.9
Sylvax UPM (n=21)	3.8
QuickFill (n=1)	3.2
Insta-Patch (n=1)	3.2
Perma-Patch (n=3)	2.4
Cold mix with fibers(n=4)	2.3

*Used only on one AC/PCC overlay project.

conducted by state agencies. The results from these studies complement the results received from the questionnaires and are summarized below.

Pennsylvania Department Of Transportation

Pennsylvania utilizes standard wearing course AC hot mix (1/2-in maximum size) for pothole repair when it is available. Otherwise cold stockpile material is used.[49]

An extensive study by Kandhal and Mellott of the Pennsylvania DOT resulted in the development of a new cold mix patch material (PennDOT designation 485).[50] The mix design has the following characteristics:

- Aggregate gradation: Open-graded with 100 percent passing 3/8-in sieve, 85 to 100 percent passing the No. 4 sieve, 10 to 40 percent passing the No. 8 sieve, 0 to 10 percent passing the No. 16 sieve, and a maximum of 2 percent passing the No. 200 sieve. This results in a mix that is finer and more workable than their conventional mix.

- Aggregate shape: Crushed aggregate is required.

- Binder: A minimum residual bituminous binder content of 4.5 percent is recommended. The use of a cutback asphalt, emulsified-cutback asphalt, or road tar is permitted with the grade depending upon the time of year. A high-float emulsion is approved for year-round use.

- Antistrip agent: This is selected after testing with the aggregate that will be used. Bituminous suppliers are required to conduct the wet coating test, static immersion test, and stripping test using the job aggregate. The contractor is required to perform a water resistance test and the workability test on the mixture.

- Preparation: The mix is produced in hot mix plants using heated, dried aggregate.

Pennsylvania Transportation Institute (1987)

This is the most substantial study ever conducted on pothole repair materials.[51] Both laboratory and field studies were conducted to develop and test improved cold mix, stockpiled patching mixtures. The study focused on binder improvements, while recommending an aggregate having the following characteristics based on other research:

- Crushed angular particles
- Maximum of 1 to 2 percent passing the No. 200 sieve
- Maximum aggregate size of less than 0.5 in

A wide variety of modifiers that could be used with cutback and emulsions were reviewed, and SBR latex (which imparts improved low temperature ductility and workability), butyl rubber (an adhesion promoter which also improves the low-temperature ductility), and an SBS block copolymer were identified as the most promising modifiers. The block copolymer was later dropped, although due to recent new developments it is recommended for study. Fibers were also utilized along with the butyl rubber.

The following six materials were utilized in field trials:

- MC-800, a conventional cutback used in control mixes
- MC-800L, a latex-modified MC-800
- HFMS-2, a conventional high-float, medium-setting emulsion
- HFMS-2L, a high-float, medium-setting emulsion with SBR latex
- HFMS-2B, a high-float, medium-setting emulsion modified with butyl rubber
- HFMS-2BF, a high-float, medium-setting emulsion modified with butyl rubber and fibers

A total of 410 repairs were made in Pennsylvania in the spring of 1986. Both the control mix (MC-800) and an experimental mix were used on any given day. The PennDOT standard (permanent) procedure was used for approximately two-thirds of the repairs; the remaining repairs were made according to a nonstandard (throw and go) procedure.

Results from the field trials indicated that all of the experimental mixtures and the control mix performed very well during stockpiling, transport, and placement. No stripping problems were experienced in the stockpile or during placement. Some loss in low-temperature workability was noted with the butyl modifier, but this was offset by the addition of the fibers. All of the experimental mixtures were preferred by the crews over the control PennDOT mix. The mixes were easy to compact at mix temperatures as low as 20 °F to 30 °F, and hole depths as deep as 6 in were compacted.

After 1 year, performance evaluations showed significant differences in the behavior of the different mixes, as shown in figure 6-1. The latex-modified binders, MC-800L and HFMS-2L, had an excessive amount of drainage which was attributed to the latex separating from the asphalt. The MC-800L did not perform as well as the standard control mixture, and was not recommended for further study.

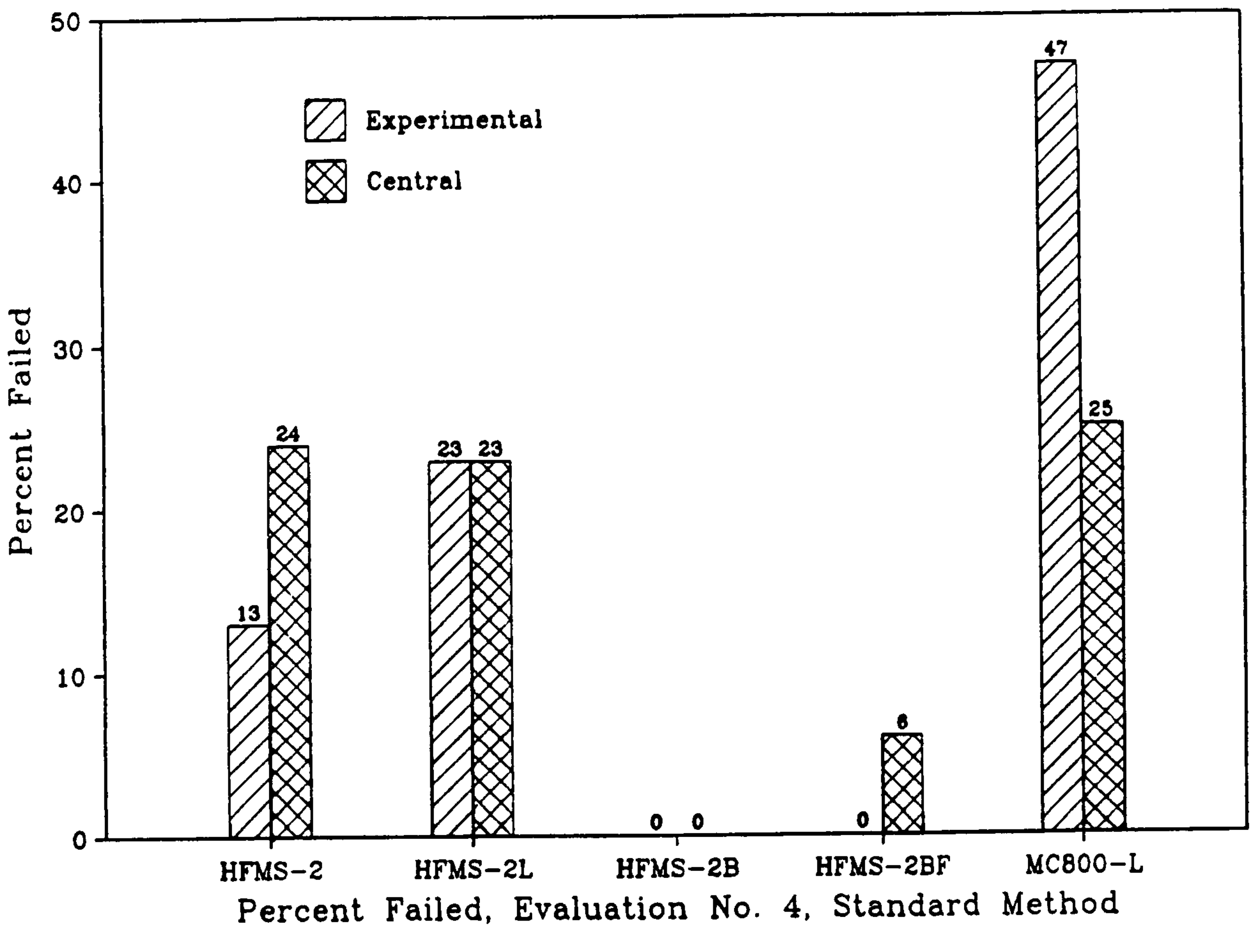

Figure 6-1. Performance of mixes, standard procedure, evaluation number 4.[51]

The most successful binders were those based on the HFMS-2 emulsion. The butyl-modified high-float emulsion, especially with the addition of fibers, has the characteristics necessary to produce a mix with significantly improved performance and to be a cost-effective replacement for conventional cutbacks or emulsions.

Ohio Department of Transportation (1986)

In this study laboratory and field testing was performed for nine experimental patching materials used in cold, wet weather conditions. A summary of the results is shown in table 6-11.[52]

The overall results showed that the HPM (Sylvax UPM) proprietary material and the PennDOT 485 cold mix performed very well. The performance of ODOT 921 cold mix is categorized as good or fair. Overall conclusions from the study are as follows:

1. The field tests indicate that only two materials have shown satisfactory performance, HPM cold mix and PennDOT 485 cold mix. Both materials appear to be well suited to high traffic volume highways. Both of these materials were subjected to a wide variety of patching situations. The HPM and PennDOT cold mix material had fewer or no failures, compared to the standard cold mix material when placed in poorly conditioned potholes.

2. The HPM material and the PennDOT 485 cold mix performed well under all installation conditions. The HPM performed just as well or better in the "as found" holes with no preparation versus the prepared holes, under wet conditions versus dry, or with minimum compaction versus compacted.

3. The study shows that cold mix material designed on a rational basis will perform satisfactorily over a long period of time.

4. The performance of reheated hot mix was not satisfactory in cold, wet weather installation.

5. Hot mix patching material is not suitable for cold, wet weather patching. The preferred alternative, therefore, is to use cold mix materials. This study established that HPM and PennDOT 485 cold mix are two materials that can perform satisfactorily in cold, wet weather patching.[52]

Table 6-11. Summary of results obtained from Ohio Department of Transportation experimental study of patch life.[52]

	Performance (%)		
Material & Description	Good	Fair	Failure
Tar & Stone	0	0	100
Sulfur asphalt hot mix (Sulf-a-Bond, premanufactured hot mix with sulfur blended into binder)	0	0	100
Heated 404 mix (hot mix stored during summer is used by heating in a portable heater)	0	23	77
Perma Pave cold mix (Instant Road Repair)	0	38	62
Latex rubber asphalt cold mix	33	0	67
Heated ODOT 921 cold mix (with MC-250 or MC-800)	36	18	46
Standard ODOT 921 cold mix (with MWS 300 binder)	55	10	35
Penn DOT 485 cold mix (open-graded mix with less than 2 percent passing #200, MC-250, crushed aggregate, plus antistrip agent)	81	10	9
HPM cold mix (Sylvax UPM, proprietary)	91	8	1

Saskatchewan Highways and Transportation

Full-scale, province-wide field trials were conducted with sand-sulfur-asphalt maintenance mixes for leveling and filling of transverse cracks that have depressed. The material is produced by Shell Canada, Ltd. and is called Thermopatch.[45]

Thermopatch is a blend of sulfur, asphalt, and aggregate with various formulations with different performance characteristics. The aggregate must fit within the geometry of the site where the mix is to be placed, and there must be sufficient voids in the mix to accommodate the added sulfur. For a given aggregate, the two most important properties of stability and flexibility are dependent on the ratio of sulfur/asphalt by weight.

Strict control of mix temperature is mandatory for safety reasons and to ensure a mix of suitable workability. There are safety precautions that must be followed during preparation and application. Most of these conditions will not exist when the material is used in pellet form.

The material was placed in transverse cracks that had settled or depressed (at least 0.4 in). The patch material pours into the crack depression, sets up very quickly, and no compaction is required. The patch has a tendency to wear off from traffic; therefore, on high traffic volume highways a wearing surface treatment should be placed over the patch. The performance was satisfactory after 12 months in service as reported in reference 49. The questionnaire life expectancy reported by Saskatchewan was 3 to 4 years. They have had 10 years of experience with this material and conclude that it is an effective and economical method for filling shallow depressions.

Safety precautions should take into account emissions of sulfur particulate and hydrogen sulfide gas, explosions of sulfur dust, flammability of liquid sulfur, and traffic control in the work area.[53]

It should be noted that in field tests a similar asphalt sulfur blend material did not work well for the Ohio DOT or Arizona DOT.[52,53]

Arizona Department of Transportation

Sulfur, asphalt, and sand (SAS) patching materials were developed in the laboratory using marginal aggregate sources and sulfur. The development of a pourable, self-compacting, and durable patching material was the primary objective of this study. In addition, Arizona desired to utilize aggregate sources not presently being used.[53]

SAS mixtures must be placed at temperatures above 265 °F, so a means of heating and keeping the material warm in the field was needed. Field trials using small recycling equipment were not satisfactory because of high SO_2 emissions. The concept of SAS patching materials has potential but was not recommended until new equipment is developed.[53]

Minnesota Department of Transportation

Research has been conducted on several cold mix patching materials over the years. Minnesota DOT recommends Spec 2381 materials for cold mix patching operations, which is similar to the PennDOT 485 material.[54]

- Aggregate gradation: An open graded mix, with 100 percent passing the 1/2-in sieve, 95 to 100 percent passing the 3/8-in sieve, 75 to 100 percent (or 50 to 85 percent) passing the #4 sieve, 10 to 35 percent (or 25-50 percent) passing the #10 sieve, 0 to 8 percent (or 5 to 25 percent) passing the #40 sieve, and 0 to 3 percent passing the #200 sieve. Hydrated lime is sometimes added.

- Aggregate shape: Must be composed of 100 percent crushed material.

- Binder: MC-250 or MC-800.

- Anti-stripping additives: Tests are conducted to determine the appropriate type.

This mixture has performed very well, similarly to Sylvax UPM, and costs much less ($30/ton versus $65/ton).

1986 FHWA Study

A study on improved methods for patching on high-volume roads was completed in 1986.[55] Recommended patching materials based upon limited field trips and recommendations from state agencies included Sylvax, Perma-Patch, and fibers for reinforcing.

City of Toronto, Ontario

The Department of Public Works utilizes a fleet of self-contained, radio-equipped, mobile units (hot-boxes) to provide heated AC hot mix for all seasons of the year.[56] Potholes are dried out using a torch. Performance of repairs performed in such a manner is reported as very good. A cost analysis comparing conventional cold mix patching with infrared AC hot mix patching showed that the cold mix patching procedure was 70 percent more costly per square yard.

New York State Department of Transportation

Use of preheated asphalt mix and an infrared pavement heater have produced long-lasting patches.[57] Patches have lasted 7 to 10 times longer than those made with conventional cold mix.

Value Engineering Study By Four States

This study recommended several improvements for patching procedures, and stated that hot AC mixtures should be used in all cases where available. Hot mix material makes a better, longer lasting patch than any other material. Economically, it seems the most feasible material to use within a 25-mile radius of a plant. For cold weather patching, heating of the stockpile mix is recommended.[58]

MC-250 seems to provide the best stockpile mix, in terms of workability, but is not recommended for patching potholes in warm weather.

Department of Transport, United Kingdom

The use of hot mix asphalt concrete, similar to that used in original construction for permanent patch work, is recommended.[59]

National Science Foundation

A field test was conducted in 26 cities in 1977 to compare the performance and cost of Sylvax UPM with conventional cold mix patches, each placed using temporary procedures.[45] A total of 219 UPM patches and 99 conventional cold mix patches were placed and monitored over a period of 12 months in these cities.

The conventional cold mixes demonstrated a 46 percent failure rate compared to a Sylvax UPM failure rate of 17 percent. This represents an improvement of almost 3 to 1 for the overall performance of UPM versus the standard cold mix.[45] Note that the questionnaires from this study showed the increased life expectancy of UPM to be 3.6 times that of conventional cold mixes under wet and cold conditions.

The study also indicated that the conventional cold mixes failed at a constant rate over the 12 month period, while the UPM patches primarily failed within the first 3 months and then practically no further patches failed for the remaining 9 months.

A cost study showed that even though the initial cost for UPM was higher ($35/ton versus $15/ton), when the failure rates are considered, the effective cost per ton was lower for UPM ($106 for cold mix versus $94 for UPM).[45]

Related Findings

Permanent versus Temporary Patching Procedures

Permanent patching procedures (assuming dry hole conditions) improve the life of AC hot mix patches under cold conditions by a factor of 1.78/0.3 = 5.9, or 590 percent. For conventional cold mixes, the improvement for a wet hole condition is 0.97/0.31 = 3.1, or 310 percent. Figure 6-2 illustrates these results.

Cold versus Warm Temperatures

Warm temperatures contribute to increased service life of conventional mixtures in wet holes (by a factor of 2.4 for AC hot mix and 1.2 for cold mix), and also for proprietary mixtures (by a factor of 1.1). These results are shown in figure 6-3. Heating the mixtures may be one way of achieving this life increase, even during cold weather.

Wet Hole versus Dry Hole

One of the most effective ways to improve on the service life of patches is to dry the hole prior to placement of the material. Conventional patching materials (using temporary procedures in cold temperatures) showed an improvement in life of 2.5 (cold mix) to 4.7 (hot mix) times. All proprietary materials, usually designed for wet conditions, showed a smaller improvement of 1.4 times. Figure 6-4 illustrates these results.

Summary of Findings

Bituminous hot mix has shown the longest service life of all materials when it is placed using permanent procedures in a dry hole (1.8 to 4.4 years on average, depending on the temperature). The experiences of many agencies and research studies support this conclusion.[55,56,57,58,59.]

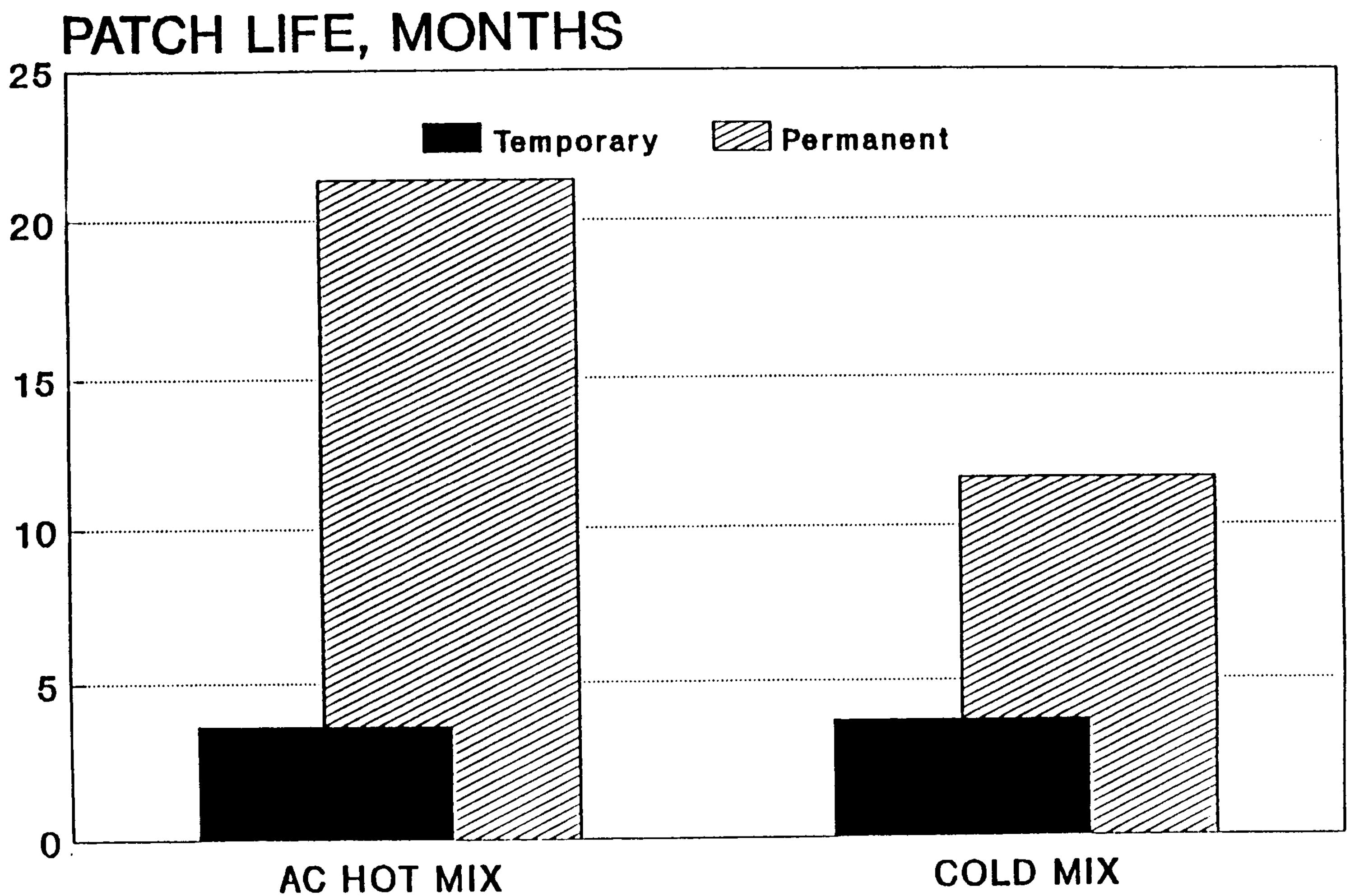

Figure 6-2. Life expectancy of permanent and temporary patch materials placed in permanent and temporary conditions.

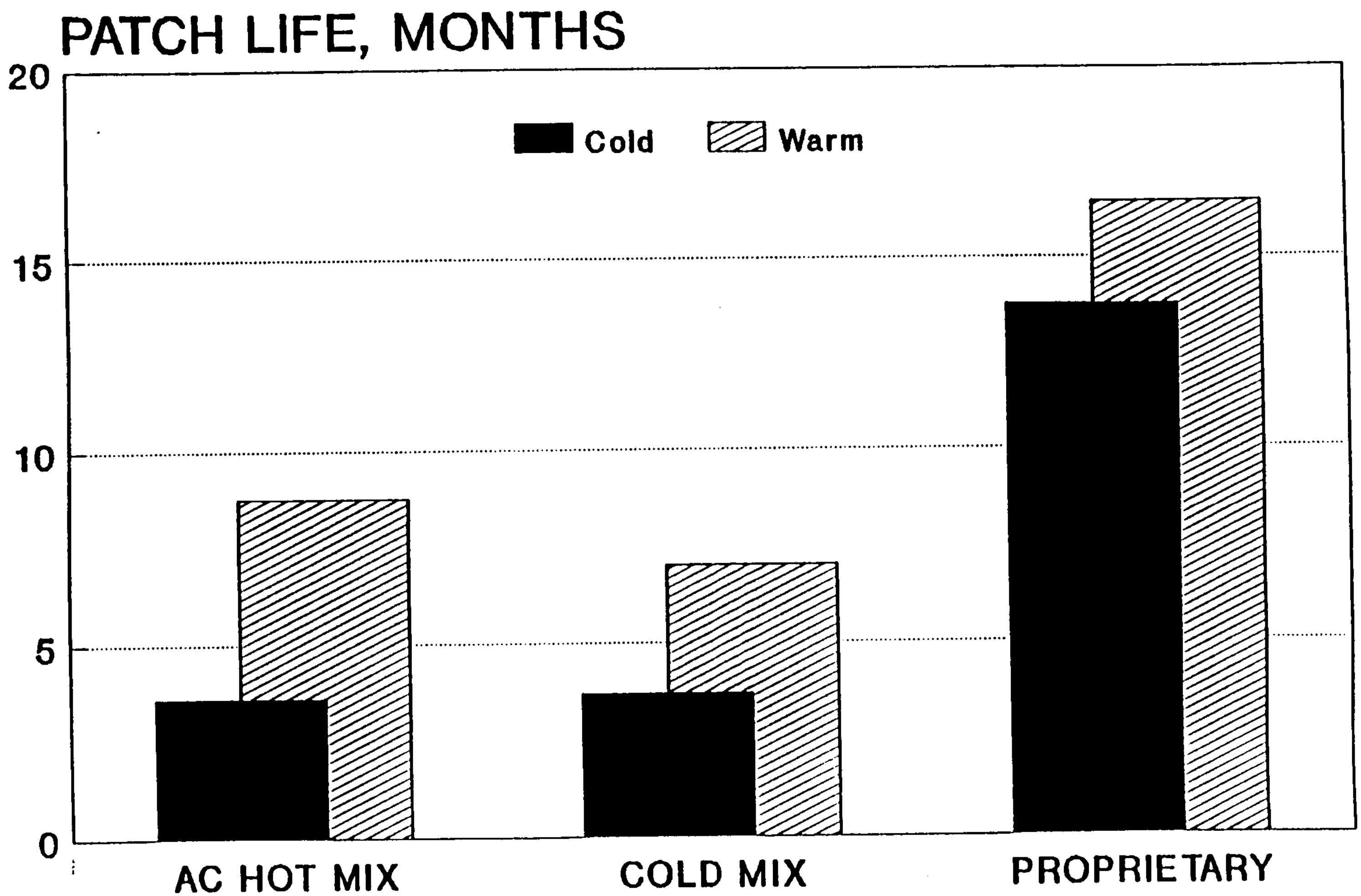

Figure 6-3. Life expectancy of patch materials placed in wet potholes in cold and warm temperatures.

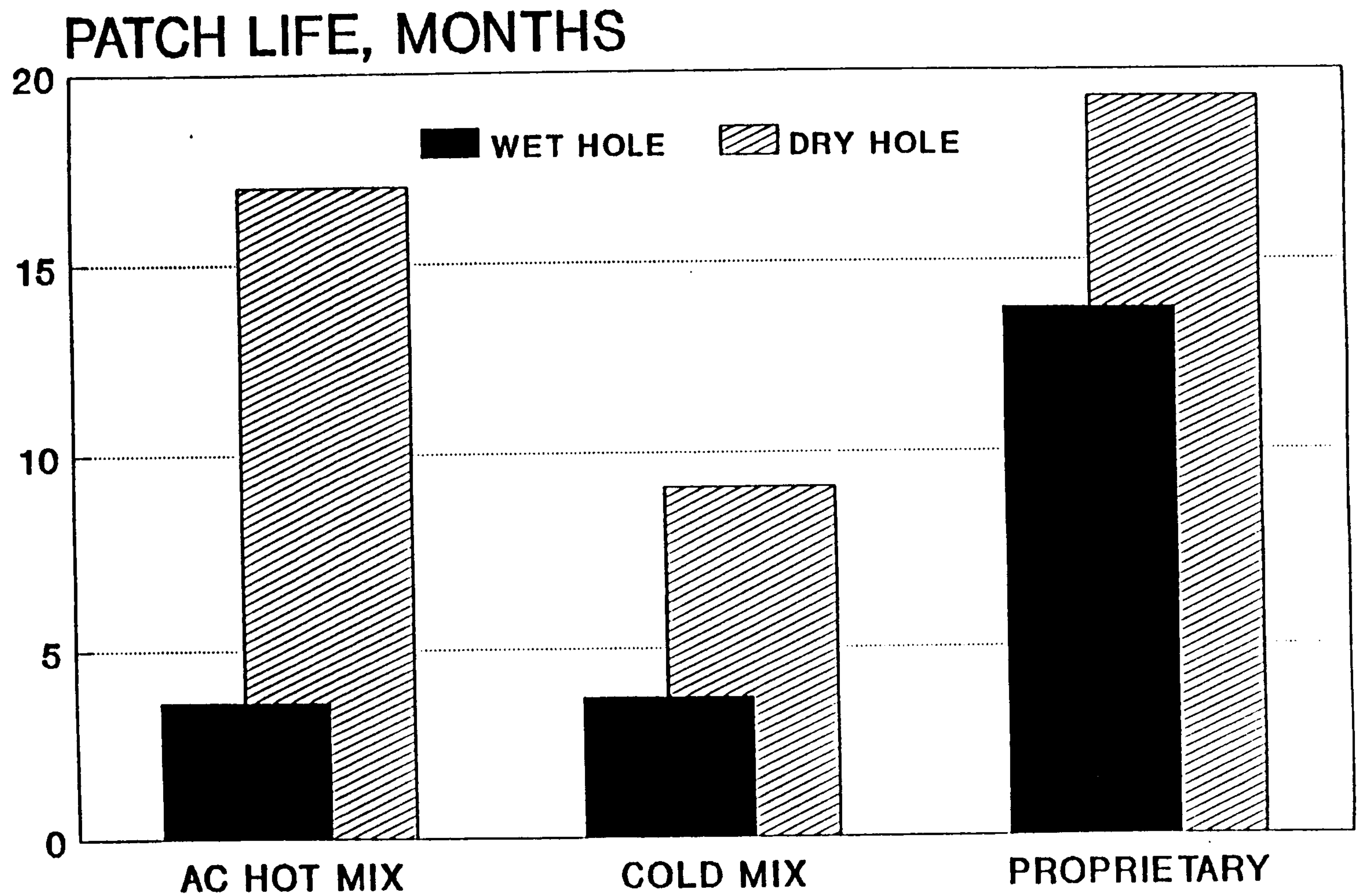

Figure 6-4. Life expectancy of patches placed in wet and dry potholes, in cold temperatures.

However, if hot mix is placed in a wet hole using either temporary or permanent procedures, its life is reduced by a factor of more than 10. The Oregon study showed that the performance of reheated hot mix was not satisfactory in cold, wet weather installation and that hot mix patching material is not suitable for cold, wet weather patching.[32] This problem may be overcome when automated patching equipment can prepare a dry hole and deliver hot mix to the hole and adequately compact it, even in cold, wet conditions.

When bituminous hot mix material is not available, these results clearly support the Pennsylvania findings for cold mix: a large improvement in durability can be achieved if the mix is heated and placed using permanent patching procedures.

Large improvements in the service life of conventional cold mix patch materials can be attained if such patches are placed using permanent patching procedures (as opposed to temporary procedures), and the hole is dry (as opposed to wet). Increased life on the order of 3 to 4 times were reported by using agencies with long-term experience.

Although data were not directly available, it follows that cold mix that is heated and placed hot into the prepared hole would provide even better performance.

The questionnaires also indicated that when conventional cold mix is placed into a wet hole in either cold or warm temperature conditions, its life will be from a few days to at most a few months.

The questionnaires and several experimental field studies showed that several patch materials (which vary from conventional state specifications in both binder and aggregate), would provide greatly increased service life, particularly when used under cold and wet conditions. However, their performance under warm and dry hole conditions was not much greater than that of conventional materials. Some of the most promising proprietary/modified patching materials are described below, in no particular order. Figure 6-5 illustrates these results.

Sylvax UPM is a widely used proprietary material for patching AC pavements.[45,46] On average, its service life under cold and wet conditions was 3.8 times greater than that of conventional cold mix patches placed with temporary procedures. This material showed far superior performance compared to cold mix in field trials conducted in 1977 in 26 cities.[45] This material was tested along with several other mixtures in the Ohio field study.[52] UPM and the PennDOT 485 material performed about the same, and both were highly rated.[45,49]

The use of Perma-Patch showed increased service life of patches under cold and wet conditions by a factor of 2.4, based upon results from five agencies.

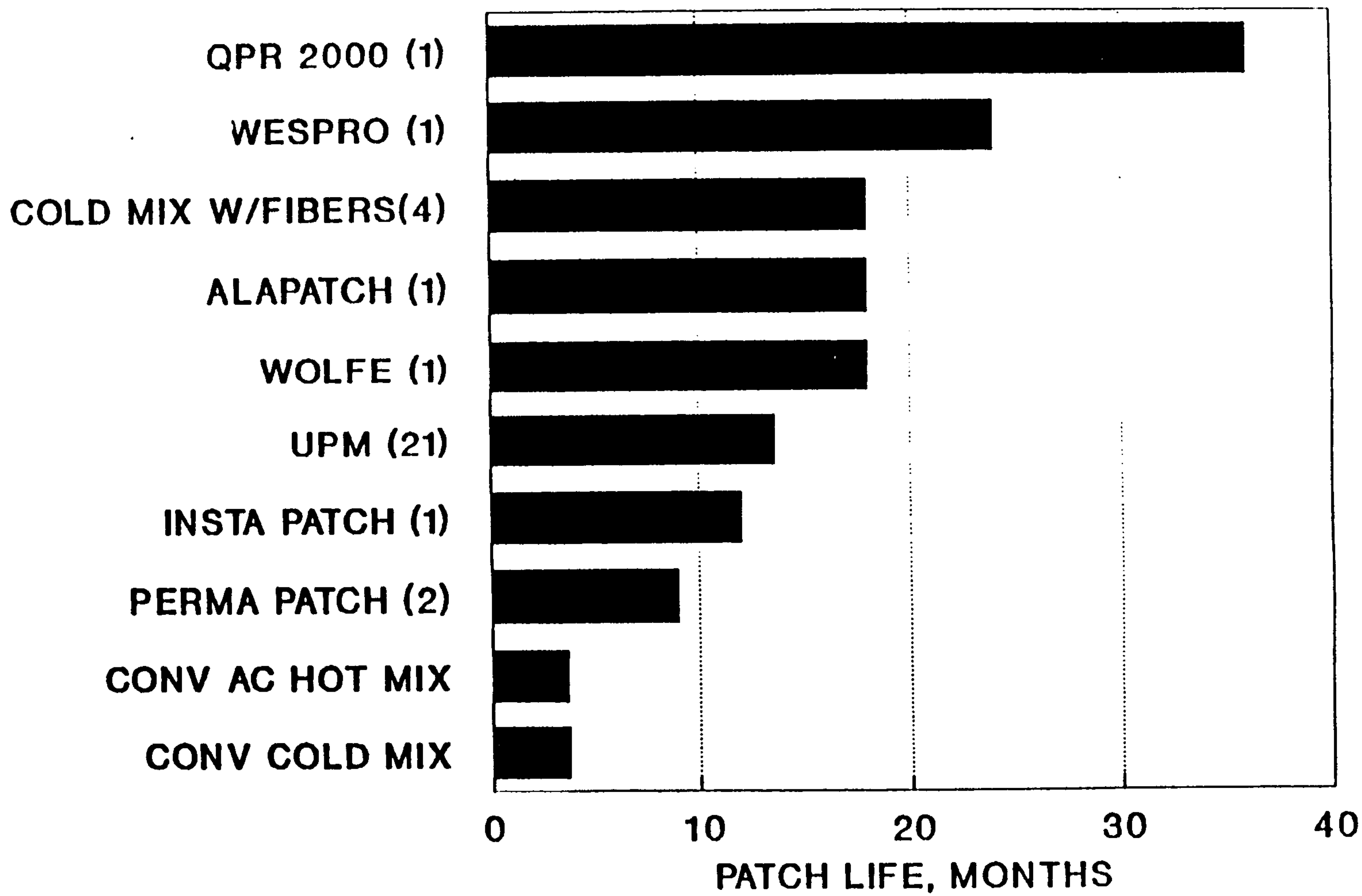

Figure 6-5. Life expectancy of various proprietary patch materials in temporary (wet hole, cold temperature) conditions.

Cold mix patches containing fibers performed better than conventional cold mix patches by a factor of 2.4, based upon results from four agencies.

QPR 2000 received very good ratings in one Canadian province, showing an improvement of 3.0 years/0.08 years = 3.7 in service life in that province.[48] This product was also given good recommendations by one state agency that is currently testing it.

The Thermopatch concept (sulfur, asphalt, and sand) of material that could be poured into a depressed transverse crack to level it out received good recommendations from one Canadian province, but environmental and construction problems precluded its use in one southwestern state.[53]

A material called Wespro was highly recommended by one western State highway department, providing 2 years of service under wet and cold installation conditions.

Two materials, Allapatch and Wolfe, were noted by one midwestern state as giving 1.5 years of service under cold and wet installation conditions.

The product Duracal, a gypsum-based (calcium sulphate) patching mixture, was successfully used to patch an AC overlay over a PCC pavement under wet and cold conditions in one state. An estimated life of 5 to 7 years was given. Utilizing a rigid patching material for flexible pavements may create roughness problems, however.

A material called Insta-Patch was given a much higher estimate of life over conventional cold mix (1 year versus 0 years) by a southwestern state highway agency.

An extensive study by the Pennsylvania DOT resulted in the development of a new cold mix patch material (PennDOT designation 485).[49] The mix design includes an open-graded aggregate gradation, crushed particles, 2 percent maximum passing the #200 sieve, a minimum residual bituminous binder content of 4.5 percent (cutback asphalt, emulsified-cutback asphalt, or road tar is permitted), and an antistripping agent. This mixture was given very high ratings in the field studies conducted by the Ohio DOT.[52]

Minnesota DOT Spec 2381 material was developed over the past several years for cold mix patching. It is very similar to the PennDOT 485 material. This mixture has performed very well in the field, similarly to Sylvax UPM as reported by Minnesota, and costs much less ($30/ton versus 65/ton).[54]

A major study was conducted by the Pennsylvania Transportation Institute on the development of new improved binders for cold mix patches.[51] They identified some improved binders that showed improved performance in the laboratory and in the field.

- MC-800, conventional cutback used in control mixes
- MC-800L, latex-modified MC-800
- HFMS-2, conventional high-float, medium-setting emulsion
- HFMS-2L, high-float, medium-setting emulsion with SBR latex
- HFMS-2B, high-float, medium-setting emulsion modified with butyl rubber
- HFMS-2BF, high-float, medium-setting emulsion modified with butyl rubber and fibers

Results from field trials indicated that all of the experimental mixtures, as well as the control mix, performed very well during stockpiling, transport, and placement. After one year, performance evaluations showed significant differences in the behavior of the different mixes. The most successful binders were those based on the HFMS-2 emulsion. The butyl-modified high-float emulsion, especially with the addition of fibers, has the characteristics necessary to produce a mix with significantly improved performance and to be a cost-effective replacement for conventional cutbacks or emulsions.[49]

Based on the user questionnaires and published literature, many different materials were noted as providing good to excellent performance in the repair of potholes. However, only a small percentage of these materials were deemed worthy of further investigation, due in large part to their sound performance statistics. These materials are listed below.

- Sylvax UPM
- PennDOT 485 or MnDOT 2381
- Fiberized cold mix
- HFMS emulsion with butyl rubber
- Perma-Patch
- QPR 2000
- Bituminous cold mix

Due to the lack of success in temporary repairs and the urgent need for long-lasting, quick repairs, considerable attention must be given to these types of repairs. For this reason, the promising materials listed above have been identified from a performance standpoint as exemplary pothole repair materials.

Pertinent Material Properties and Tests

Key Distress Manifestations and Their Causes

In order to further identify the most promising patching materials, a thorough understanding of the failure mechanism is needed. The most common distresses encountered during the service life of a patch are:

- Shoving
- Raveling
- Dishing
- Debonding

Shoving

Shoving occurs when traffic pushes against the patch, leaving a permanent upward vertical displacement in the repair. Shoving can be caused by several factors, including binder and aggregate type and proportions.

A soft binder can contribute to mixture instability. The binder should not be too soft nor should it soften excessively in hot weather. In addition, too much binder will soften the mix, and insufficient binder will not coat all of the aggregate, leaving loose aggregate in the mix. Finally, aggregate should be crushed, open-graded, and contain no more than 2 percent passing the No. 200 mesh.

Raveling

Raveling is the loss of aggregate from the surface of the repair due to inadequate cohesion within the mix. Raveling is usually caused by loss of adhesion between the binder and aggregate, excess fines in the binder, stripping of the binder from the aggregate, inadequate aggregate interlock, and poor compaction.

Dishing

Dishing occurs as a result of a mix compacting under traffic, thereby leaving a depression in the repair. It is most often caused by inadequate compaction or instability of the mix.

Debonding

If a patch material possesses insufficient adhesion or if the pothole in which the material was to be placed was not properly cleaned, then the patch material will become debonded from the hole. Once this occurs, the patch will progressively deteriorate under the effects of moisture and traffic.

Desirable Material Properties

Bituminous patching mixtures must develop certain properties in order to perform well. These properties are:

- Stability: Materials must resist shoving and rutting
- Adhesiveness/Cohesiveness: Depending upon the construction procedure and the size of the patch, the materials must be sticky enough to adhere well to the sides and bottoms of holes as well as to each other
- Resistance to Water Action: The binder must adhere to the aggregate and not strip off in the presence of water
- Durability: The materials must resist deterioration and disintegration due to traffic
- Workability: The materials must be easily handled, shoveled, and compacted. Thus the material must be loose, with no large lumps
- Storageability: The materials must be able to be stored for a long period of time and still retain their workability

Laboratory Tests to Measure Desirable Material Properties

The purpose of the material testing program is to characterize the properties of a mixture that affect performance. For cold mix pothole patching materials, there are two areas of performance that must be cataloged if field performance differences are to be analyzed. These areas are the structural adequacy of the mix placed in the hole and the workability/storageability of the stockpile mix.

The tests shown in table 6-12 were determined to be the most applicable tests for measuring desirable mixture properties. In addition, the binder and aggregate components of each material will be separated by means of an extraction test (ASTM D 2172). In this manner, the individual components can be tested to further measure desirable properties. Table 6-13 lists the tests to be conducted on extracted material samples.

Table 6-12. Laboratory (and field) tests for measuring desirable mix properties.

Desired Property	Laboratory/Field Test(s)	Source
Stability	(1) Resilient Modulus (2) Marshall Stability (3) Density	ASTM D 4123 ASTM D 1559 ASTM D 2950
Resistance to Water Action	(1) Anti-Stripping	ASTM D 1664
Workability	(1) Workability	Pennsylvania Trans. Inst. Test (Report No. FHWA-RD-88-001

Table 6-13. Laboratory tests for measuring desirable mix component properties.

Desired Property	Laboratory Test(s)	Source
Workability	(1) Viscosity (2) Penetration	ASTM D 2171 ASTM D 5
Durability	(1) Softening Point	ASTM D 36
Adhesiveness/ Cohesiveness	(1) Ductility	ASTM D 113
Stability, Durability	(1) Sieve Analysis	ASTM C 136

Implementation of Research Findings into Experimental Plans

Objective

The specific objective of the H-106 experiment for pothole repair of asphalt-surfaced pavements is to field test improved materials and procedures for rapid pothole repair under adverse wet and cold conditions that will provide one or more of the following benefits to highway agencies:

- Increased overall cost-effectiveness of the operation
- Increased life of the repair
- Reduced lane occupancy time of maintenance crews (for both initial and repeat repairs)
- Provide a base line for comparison of future materials and procedures

There are also benefits to highway users due to fewer lane closures for pothole repairs, which translate into fewer traffic delays and lane closure accidents.

Key products of this research under the H-106 contract will be documented results on the cost-effectiveness, constructability, productivity, and performance of specific pothole repair materials and procedures used under adverse wet and cold conditions in several States.

It is expected that several materials and procedures will show significant performance and productivity improvements over conventional materials and procedures. This information will then be available to highway agencies for use and/or further testing in their own maintenance repair programs in terms of procedures, materials, and specifications.

Experimental Plan Overview

The experimental design describes the types of repairs and field layout to fulfill the objectives of the study. The experimental design provides for nationwide testing of the most promising materials and procedures for pothole repair of AC surfaced pavements under adverse wet and cold conditions.

The experimental factors selected are those variables that are believed to have a strong impact on the results. The exact effect of each factor may not be known, however, and that is one reason why they are included in the experiment. The following major factors have been identified for this experiment:

- Climate
- Pavement Design
- Traffic
- Repair Materials/Procedures

Due to the limited amount of money budgeted for the H-106 project, several items such as replications and proposed number of permanent repair installations were reduced. However, it was determined that little in the way of experimental validity and content would be sacrificed.

Climate

Experimental test sites will be located in each of SHRP's four major climatic/geographic zones of the U.S., as shown in figure 3-1:

- Wet-freeze
- Wet-nonfreeze
- Dry-freeze
- Dry-nonfreeze

Ideally, one or two states will be selected in each climatic zone to place experimental pothole repair sections.

Pavement Design

It is believed that pothole repairs perform differently when placed in either AC flexible pavements, or AC surface over PCC slab pavements. In order to verify this belief, both pavement types will be used in the freeze climatic zones. The following sites are defined:

Site 1: Wet-Freeze—AC flexible
Site 2: Wet-Freeze—AC/PCC
Site 3: Wet-Nonfreeze—AC flexible or AC/PCC
Site 4: Dry-freeze—AC flexible
Site 5: Dry-freeze—AC/PCC
Site 6: Dry-Nonfreeze—AC flexible or AC/PCC

Ideally, sites 1 and 2 will be in one state and sites 4 and 5 will be in one state to reduce travel, but this is not absolute essential.

Traffic Level

Highways having a medium or higher level of traffic volume are required. Highways having low volumes (e.g., < 300 Average Daily Traffic (ADT) or < 30 trucks/day, in two directions) are not to be considered.

Repair Materials/Procedures

Type A.	Sylvax UPM, rapid placement procedure. This "control" material will be placed at all sites for comparative purposes across all other material types and climatic zones
Type B.	Sylvax UPM, rapid placement procedure with edge sealing
Type C.	Sylvax UPM, semi-permanent placement procedure
Type D.	H-106 Specification Material, rapid placement procedure
Type E.	H-106 Specification Material with either polypropylene or polyester fibers, rapid placement procedure
Type F.	Conventional local area cold mix, rapid placement procedure (Note: this material is the cold mix currently in use in the local test site area)
Type G.	High-Float Medium Setting Emulsion with Butyl Rubber (Kalene 800) polymer, rapid placement procedure
Type H.	Perma-Patch, rapid placement procedure
Type I.	QPR 2000, rapid placement procedure
Type J.	Injection spray patch material, to be placed by automated equipment that uses this procedure

Rapid emergency repairs shall consist of the following steps:

1. Remove loose material in hole
2. Place material, overfill hole

3. Compact with truck tires

Semi-permanent repairs shall consist of the following steps:

1. Remove loose pieces surrounding edge
2. Clean/dry hole with heat lance
3. Place material
4. Compact with Single-Drum Vibratory Roller
5. Edge sealing (use asphalt emulsion material and a cover aggregate placed around the perimeter of the patch)

Applying a tack coat to the pothole prior to repair will not be required for either procedure.

Field Layout Of Pothole Repairs Required For a Given State

If a state is primarily interested in repairing potholes in, say, the composite AC/PCC type of pavement, ideally one (but more if necessary) pavement section will be selected, probably several miles in length, that has a sufficient traffic level and number of potholes (or that would be expected to develop a sufficient number over the spring thaw or wet season). All experimental pothole repairs would be placed on this highway section to keep the problem of relocating these potholes to a reasonable level. If enough potholes cannot be found on a single highway section, additional sections having the same characteristics in the same area may be utilized.

In general, it is desirable to fill a minimum of 10 holes for each repair type under consideration in a given type of pavement (AC or AC/PCC), as this would give a reasonable sample from which to estimate the percent of failures/successes for each type of repair (e.g., 1 out of 10 gives a 10 percent failure), although more would certainly be desirable.

To provide some uniformity in hole size, it is desirable to only include potholes having a size of not less than 1 ft^2 and not greater than 10 ft^2.

It is desirable, but not required (due to problems with obtaining some materials), that all of the above repair types (A through J) be placed at all sites. For an experiment in a given state on a given section of highway that does include all types A through J (for a pavement type such as AC/PCC), this would require the following total number of repairs. During a single day's work, Type A control repairs will be placed every other hole as further discussed below and shown in figure 6-6.

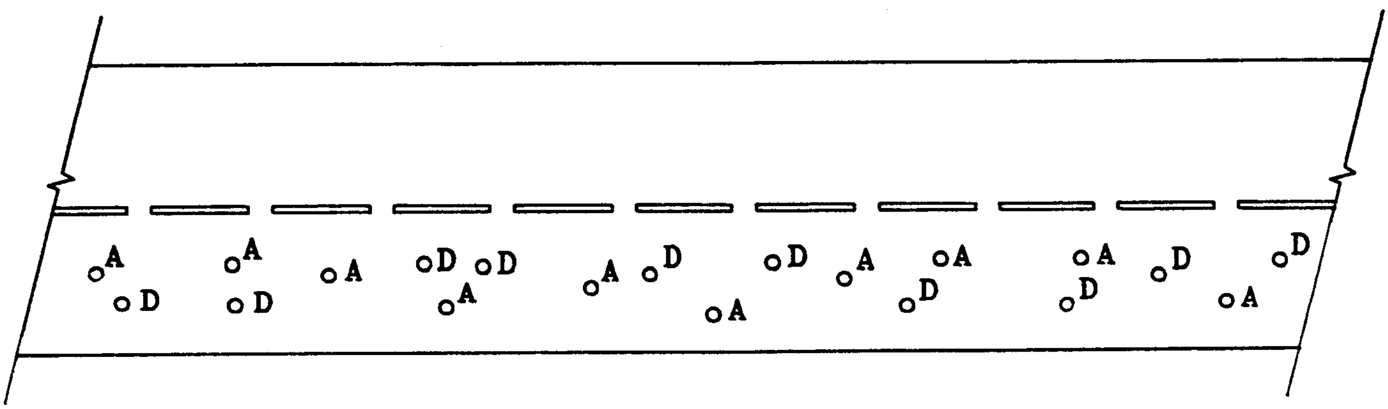

Figure 6-6. Example layout of 1 to 2 days work to place Type A and Type D repairs (10 each). Other repair types are placed similarly.

Work Day 1	Type A: 10	Type B: 10 (alternating holes)	
Work Day 2	Type A: 10	Type C: 10	
Work Day 3	Type A: 10	Type D: 10	
Work Day 4	Type A: 10	Type E: 10	
Work Day 5	Type A: 10	Type F: 10	
Work Day 6	Type A: 10	Type G: 10	
Work Day 7	Type A: 10	Type H: 10	
Work Day 8	Type A: 10	Type I: 10	
Work Day 9	Type A: 10	Type J: 10	
No. of Repairs:	90	90	= 180 total

Note: It is assumed that a minimum of 20 potholes can be repaired during a single workday, on average. Thus, a total of about 9 workdays would be required to place all 180 repairs. Due to contingencies, it is assumed that it will take about 3 weeks of time to place the 180 minimum potholes. Daily placement order must be randomized at each site (e.g., A and D, A and J, A and B).

Test Site Monitoring

Each pothole patch constructed will be marked such that it can be readily identified for inspection over a period of 24 months. This will be accomplished through the use of permanent paint marks and identification tags located adjacent to the patch.

Key data will be obtained from each pothole repair location prior to repair, during the repair operation, and at the following times subsequent to construction:

- 1 month
- 3 months
- 6 months
- 12 months
- 24 months

The post-installation evaluations will inspect for all of the patch distresses noted earlier will be inspected for. In addition, photographs will be taken which show the progression of the distresses over time.

Bibliography

Anderson, D.A. and H.R. Thomas. Pothole Repair in Pennsylvania. Paper prepared for the Proceedings of Purdue University's 70th Annual Road School, West Lafayette, 1984, pp. 28-46.

Anderson, D.A., H.R. Thomas, Z. Siddiqui, and D.D. Krivohlavek. *More Effective Cold, Wet-Weather Patching Materials for Asphalt Pavements*. Report FHWA/RD-88/001. Pennsylvania State University, University Park, September 1987.

Beaudoin, J.J. and P.J. Serada. Field Studies of a Sulphur/Asphalt Composite Pothole Repair System. *Durability of Building Materials*, National Research Council Canada, November 1983, pp. 1-6.

Brewer, W.B. *A New Technological Tool for Patching Asphalt Pavement*. Oklahoma Department of Transportation, May 1988.

Briggs, G.M. Infrared Heating Makes Patches Stick. *Rural and Urban Roads*, August 1971.

Bullock, D. and R. Olson. *Investigation 354: Method and Materials for Patching Potholes*. Minnesota Department of Transportation, St. Paul, September 1982.

Compaction Keys City's Pothole Patching Problem. *Roads and Bridges*, May 1987, p. 41.

Culley, R.W. *Field Trials With Sand-Sulphur-Asphalt Maintenance Mixes*. Technical Report 29. Saskatchewan Highways and Transportation, September 1979.

Decker, D.S., Griffin, D.F., and J.P. Nielsen. *An Evaluation of Asphalt-Rubber Mixtures for Use in Pavement Systems*. Report CEEDO-TR-79-02. Air Force Systems Command, April 1979.

Delp, L. Asphaltic Pavement Patching in Kansas. Highway Research Record No. 298, Highway Research Board, Washington, D.C., 1969, pp. 13-16.

Guenther, D.A. *Mechanization of Patching (Bituminous).* Report FHWA-TS-79-224. Ohio State University, Columbus, Ohio, February 1979.

Hot Asphalt Patching Done Year-Around in "Smooth Street" Program. *Rural and Urban Roads,* August 1970, pp. 32-34.

Kandahl, P.S. and D.B. Mellot. A Rational Approach to the Design of Bituminous Stockpile Patching Mixtures. *Transportation Research Record No. 821,* TRB, National Research Council, Washington, D.C., 1981.

Kumar, V.R. and K. Majidzadeh. *A Field and Laboratory Evaluation of Pavement Patching Material.* Report FHWA/OH-87/003. Ohio Department of Transportation, Columbus, 1986.

Little, R.J. *Field Evaluation of Microwave Patching System.* Report FHWA/IL/PR-092. Illinois Department of Transportation, Springfield, June 1981.

McCullagh, F. R. *Field and Laboratory Evaluation of Sulfur Asphalt Patching Materials.* Report FHWA/AZ-82/175. FHWA, U.S. Department of Transportation, Washington, D.C., 1982.

Marker, V. Repairing Potholes in Asphalt Pavements. *Plant Engineering,* November 1975, pp. 81-82.

Microwaves Offer Maximum Potential. *Better Roads,* September 1982, pp. 16-17.

Niessner, C. W. *Optimizing Maintenance Activities, Fifth Report, Bituminous Patching (Valaue Engineering Study of Bituminous Patching).* Report FHWA-TS-78-220. FHWA, U.S. Department of Tranpsortation, Washington, D.C., 1978.

O'Connor, J. Make Spring Street Patching a Permanent Repair. *American City and County,* March 1982, pp. 28-33.

Osborne, B.K. Solving a Weak Link in Pavement Patches. *Public Works,* July 1988.

Preferred Method 1—Patching. Standing Committee on Highway Maintenance, Department of Transport, United Kingdom, 1988.

Preventive Maintenance Beats Pothole Patching. *American City and County,* September 1979, pp. 111-114.

Quinn, W.J. and G. Beecroft. *The Evaluation of Pavement Patching Materials in Oregon, Final Report.* Oregon State Highway Division, Salem, 1980.

Rissel, M. C. *Improved Methods for Patching High-Volume Roads.* Report FHWA/RD-86/076. FHWA, U.S. Department of Transportation, Washington, D.C., 1986.

Thomas, H.R. and D.A. Anderson. Pothole Repair: You Can't Afford Not To Do It Right. *Transportation Research Record No. 1102,* TRB, National Research Council, Washington, D.C., 1986, pp. 32-40.

Thomas, H.R., S. Zahuruddin, and D.A. Anderson. Cost-Effective Use of Manpower for Manual Pothole Repair. *Transportation Research Record No. 985,* TRB, National Research Council, Washington, D.C., 1984, pp. 1-8.

7

PCC Crack Sealing

Cracks in portland cement concrete pavements are largely the result of thermal curling stresses and load-bearing forces.[60] Their type, prevalence, and severity are primary factors in determining the appropriate repair procedures to take. For instance, if the cracks are significantly spalled, then partial- or full-depth patching may be recommended. If considerable faulting exists, then grinding or slab-stabilization may be appropriate. Crack sealing is considered effective for extending pavement life and reducing pavement deterioration.[3] Pavement deterioration is accelerated by water entering the pavement and incompressibles filling unsealed cracks.

Special consideration must be made in identifying which cracks should be sealed. When cracks are deteriorated to the extent that damaging elements may easily infiltrate, then they should be sealed. At this severity level, they are referred to as "working" cracks. Many transportation agencies define working cracks by specifying a particular crack opening. This width varies among agencies, from 0.13 in to 0.25 in. Sealing cracks smaller than these provides very few benefits and generally does not prove to be cost-effective.

Timing is important in the effectiveness of sealing PCC cracks. If working cracks are deteriorated to the point where they are accompanied by spalls, secondary cracks, or other distresses, then alternate, and more expensive, repair methods will most likely need to be sought, such as those mentioned previously. Here again, policies on this matter vary among transportation agencies.

The condition in which a sealant is placed plays a significant role in the sealant performing to its potential. The erratic surfaces and paths associated with cracks in PCC pavements makes sealing cracks more difficult than sealing joints. Without the creation of a reservoir, formed by routing or sawing, the factors affecting the performance of a sealant are ignored. These factors include the shape factor, horizontal movement (thermal expansion and contraction of cracks), the condition of the sealant-crack interface, and the properties of the sealant.

Material Performance Synthesis

The key factors in the selection of PCC crack sealants are similar to the factors for the selection of PCC joint sealants, as presented by the American Concrete Institute.[7] Selection should be based on a sealant's ability to:

- Act as an impermeable material
- Deform to accommodate the movement and rate of movement occurring at the joint
- Sufficiently recover its original properties and shape after cyclical deformations
- Remain in contact with the joint faces
- Withstand internal rupture
- Resist flow due to gravity or unacceptable softening at higher service temperatures
- Not harden or become unacceptably brittle at lower service temperatures
- Not be adversely affected by aging, weathering, or other service factors for a reasonable service life
- Resist wear, pick-up, and intrusion of foreign material

The greater a sealant's ability to fulfill each one of these functions, the more likely it is to perform its desired role: keeping water and incompressibles out of the pavement system. Some sealants are superior to others in certain categories. As a result, performance and failure modes vary.

Types of Sealants

There is currently a wide variety of materials available for sealing PCC cracks. Each sealant has its own unique properties and characteristics which affect its performance and ease of placement. Sealant categories for PCC cracks are similar to categories for PCC joints, with, perhaps the exception of preformed compression seals. Due to the twisted path associated with PCC cracks, the installation of preformed compression seals is tedious and the performance of these seals is not good. Thus, the general categories utilized by the American Concrete Institute are reduced to the following:[7]

- Thermoplastic Materials
  - cold-applied
  - hot-applied
- Thermosetting Materials
  - chemically-curing
  - solvent-release

Descriptions of sealants within each category can be found in chapter 3.

Material Use and Performance

Performance data on the following materials used in PCC crack sealing were obtained from questionnaire responses received from transportation agencies and from literature pertaining to this operation. Unfortunately, documented performance reports of actual PCC crack sealing tests were not obtained. The only source of performance information utilized, other than the questionnaires, was the report by Peterson, entitled "*Resealing Joints and Cracks in Rigid and Flexible Pavements*."[3] The questionnaire responses collected in this report for PCC crack sealing were combined with the responses collected for PCC joint sealing.

Questionnaire responses provided information on the service life of various sealant types and brands. Of the 37 states that responded to the questionnaires, 31 stated that they seal cracks in PCC pavements. The other four states either did not possess PCC pavements or had policies opposing the operation. Table 7-1 is a general breakdown of respondent states' experience with the use of various materials as PCC crack sealants. The total number of responses, experience, and reported life expectancy ranges are listed for each material.

As can be seen, polymerized asphalt rubber was used by the most respondents (30), followed by asphalt rubber (28), asphalt cement (12), and silicone (11). The remaining generic material types were reported for use by fewer than 10 respondents.

As with PCC joint sealing, responding agencies had the most experience with asphalt cutbacks, asphalt cements, asphalt emulsions, and asphalt rubbers; an average of more than years of experience was noted for each of these materials.

Table 7-1. General summary of questionnaire responses for PCC crack sealing.

Sealant Material Type	Total Number of Responses	Experience (Years of Use)		Range of Life Expectancy (Years)
		Average	Range	
Asphalt Cement	12	21.6	4.5 - 35	0.5 - 6
Asphalt Emulsion	7	13.0	10 - 35	1 - 7.5
Modified Emulsion	3	4.3	3 - 5	3 - 5
Asphalt Cutback	7	27.0	7 - 35	1 - 4
Asphalt Rubber	28	11.0	3 - 40	1 - 9
Polymerized Asphalt Rubber	30	8.6	1 - 15	0.1 - 10
Fiberized Asphalt	7	6.1	1 - 12	2 - 4
PVC/Coal Tar	1	10	10	3 - 5
Silicone	11	5.5	1 - 12	1 - 12
Preformed Compression Seal	1	-	-	-

Hot-Applied Thermoplastic Materials

As discussed in chapter 3, hot-applied thermoplastic materials are asphalt- or tar-based materials which become soft upon heating and harden on cooling. Included in this category of PCC crack sealants are PVC/coal tar, asphalt cement, asphalt rubber, polymerized asphalt rubber, and fiberized asphalt. Of the 37 states that responded to the questionnaire, 27 indicated using some type of hot-applied thermoplastic sealant.

PVC/Coal Tar

Only one respondent indicated the use of PVC/coal tar in PCC crack sealing. The respondent noted 5 years life expectancy in warm (>40 °F), dry conditions and 10 years of experience with this material.

Asphalt Cement

Nine different states accounted for the 12 responses received for this material. Table 7-2 summarizes in detail the life expectancy statistics of asphalt cement as reported by these respondents. This material was mostly noted for application in dry conditions (approximately 83 percent of the responses). Average life expectancy for warm (>40 °F), dry conditions at 2.3 years, although application in cold (<40 °F), dry conditions was nearly the same (2.2 years). On average, responding agencies had nearly 22 years experience with this material as a PCC crack sealant.

Eleven agencies indicated the use of asphalt cement in PCC joint/crack sealing, as reported by Peterson.[3] An average effectiveness rating of fair to good was determined for this material.

Asphalt Rubber

Asphalt rubber was found to be the second most widely used PCC crack sealant, as indicated by questionnaire respondents. Twenty-four of the 28 performance responses (86 percent) were for placement in dry conditions. Table 7-3 shows that its highest average life expectancy was 4.0 years when placed in warm (>40 °F), dry conditions. Average respondent experience was 11 years.

In the study by Peterson, 36 agencies reported the use of rubberized asphalt.[3] Its average effectiveness rating was good to very good.

Table 7-2. Summary of questionnaire responses for the performance of asphalt cement in PCC crack sealing.

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	1	3	1	6
Low	1	1	1	0.5
Average	1	2.21	1	2.25
Standard Deviation	0	1.15	0	1.62
Number of Responses	2	7	2	12

Table 7-3. Summary of questionnaire responses for the performance of asphalt rubber in PCC crack sealing.

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	5	5	5	9
Low	1	2	1	0.5
Average	3.00	4.00	3.00	4.03
Standard Deviation	2.83	1.26	2.83	2.03
Number of Responses	2	6	2	18

Table 7-4. Summary of questionnaire responses for the performance of polymerized asphalt rubber in PCC crack sealing.

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	1	7	1	10
Low	1	2	0.1	1
Average	1.00	4.19	0.78	4.48
Standard Deviation	0	1.73	0.45	2.21
Number of Responses	2	8	4	30

Polymerized Asphalt Rubber

Polymerized asphalt rubber, used by 36 respondents, was determined to have an average life expectancy of approximately 4.5 years when placed in dry conditions with temperatures above 40 °F. Table 7-4 summarizes the life expectancy statistics for this material. Less than 15 percent of the questionnaire responses for this material were for placement in wet conditions. And, for this particular application, less than 1 year of average life expectancy was determined. Respondents' experience with polymerized asphalt rubber averaged roughly 8.6 years.

The effectiveness and use of polymerized asphalt rubber was not specifically listed in the study by Peterson. It is believed that any references to these materials were categorized with the asphalt rubber sealants.

Fiberized Asphalt

The use of fiberized asphalt was noted by seven questionnaire respondents. However, only three life expectancy responses were noted; each for placement in warm, dry conditions. These responses averaged 3.3 years. Based on the numbers given by the seven respondents, experience with fiberized asphalt averaged approximately 6 years.

Cold-Applied Thermoplastic Materials

These asphalt- or polymer-based materials set either by the release of solvents or the breaking of emulsions. Included in this class of sealants are emulsions and cutbacks. Of the 37 states that responded to the questionnaires, 12 indicated using cold-applied thermoplastic materials.

Asphalt Emulsion

Ten respondents indicated the use of emulsions, usually rapid- or medium-set types, as PCC crack sealants. Average life expectancy for the emulsions was highest for the warm, dry and cold, dry placement conditions (2.5 years and 2.3 years, respectively), as seen in table 7-5. A greater percentage (27 percent) reported placing emulsions in wet conditions, perhaps indicating that this material is regarded more as a filler. Nearly 18 years of average experience was determined for PCC crack sealing with emulsions.

Three respondents noted the use of emulsions with modifiers such as polymer and rubber. Five years of average life expectancy was determined for these materials when placed in warm, dry conditions.

Table 7-5. Summary of questionnaire responses for the performance of asphalt emulsion in PCC crack sealing.

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	1.5	5	2	7.5
Low	1	1	1	1
Average	1.17	2.35	1.75	2.54
Standard Deviation	0.29	1.55	0.96	2.13
Number of Responses	3	7	4	12

Table 7-6. Summary of questionnaire responses for the performance of asphalt cutback in PCC crack sealing.

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	1.5	4	1	4
Low	1	1	1	1
Average	0.75	1.75	1.00	3.00
Standard Deviation	0.29	0.96	0	1.55
Number of Responses	4	4	2	6

A total of 10 respondents noted the use of emulsions in the study by Peterson.[3] An average effectiveness rating of fair to good was reported. In addition, one respondent indicated the use of a rubberized emulsion, giving it a rating of good to very good.

Cutback Asphalt

Seven questionnaire respondents indicated the use of asphalt cutbacks as PCC crack sealants. Again, these materials may be regarded more as crack fillers, since nearly 40 percent of the responses were for application in wet conditions. Table 7-6 shows that the average life expectancy was highest for cutbacks when placed in warm, dry conditions (3.0 years). Based on the data provided by the seven respondents, experience for this material averaged 27 years.

In the report by Peterson, 17 of 43 responding agencies listed using cutbacks.[3] An average effectiveness rating of poor to fair was determined for this material. Additionally, two agencies listed the use of rubberized asphalt cutbacks. The average effectiveness rating was good to very good.

Thermosetting Materials

These polymeric sealing materials are either one- or two-component systems that solidify by chemical reaction or by the release of solvents. Polyurethanes, polysulfides, and silicones are some of the more common sealants in this class. Questionnaire responses indicated that only 8 of the 37 states are employing this class of sealer. Of these 8 agencies, 7 reported using silicones (for a total of 11 responses) and 1 reported using epoxy.

Respondent experience with the silicones was limited, averaging less than 6 years, but average life expectancy was quite high at 8.2 years when placed in warm, dry conditions. One respondent noted the use of epoxy estimated 20 years of service life, while claiming 12 years of experience with the material.

In the study by Peterson, seven agencies indicated the use of silicone.[3] An average effectiveness rating of good to very good was determined for this material. Specific information with regard to other thermosetting materials was not given in the report.

Related Findings

Based on the questionnaire responses, life expectancy for the sealants was 1.3 to 5 times longer when installed in dry cracks as compared to placement in wet cracks. Furthermore,

Table 7-7. Summary of questionnaire responses for the performance of silicone in PCC crack sealing.

	Life Expectancy (years)			
Temperature	<40 °F		>40 °F	
Crack Condition	Wet	Dry	Wet	Dry
High	-	-	1	12
Low	-	-	1	1
Average	-	-	1.00	8.17
Standard Deviation	-	-	0	3.79
Number of Responses	-	-	1	9

with the exception of asphalt cutbacks, little difference in life expectancy was found between placement in warm conditions and cold conditions.

No real indications were given in the questionnaires as to the configurations in which sealants were placed in PCC cracks. However, it was found that most of the respondents using silicones, refaced cracks with concrete saws and employed backer rods to help provide the desired shape factor.

Some respondents noted refacing cracks for the placement of thermoplastic sealants. Of these responses, saws were mostly used. In addition, several respondents indicated using band-aid squeegees to form the sealant into an overband application.

Summary of Findings

Many studies have been done on PCC joint sealing operations while very few, if any, have been done on PCC crack sealing. Because of the different physical characteristics and mechanical actions associated with joints and cracks, the joint sealant reports were deemed inappropriate for use as a basis for crack sealant performance. The performance of a sealant in a crack may not be as good as its performance in a joint. This is because channel geometries are poorer and more vertical movement is likely to occur in cracks.

Despite moderate input from transportation agencies and the lack of applicable literature, a foundation was laid concerning the performance of PCC crack sealing materials. Although these materials will not be tested as PCC crack sealants in the field, the findings in this chapter should prove valuable for future investigation into the PCC crack sealing operation. With this in mind, a recap of material performance is given below.

The most potentially effective crack sealant reported was silicone. It has been quite successful as a joint sealer in new concrete pavements and the few agencies who are testing it as a PCC crack sealer anticipate a service life of 5 to 10 years. Its main drawback is its cost. At $2 to $3 per pound, it is at least twice as expensive as the next best performing material, polymerized asphalt rubber.

Polymerized asphalt rubber sealants have been noted to serve adequately for 3 to 7 years. Their considerably lower costs and only slightly lower performance statistics make them just as attractive, if not more so, than the silicones.

Asphalt rubbers were found to provide 3 to 4 years of adequate service. The inclusion of rubber in the asphalt cement adds significantly to the elasticity, weathering resistance, and tracking resistance of the asphalt cement.

Hot-applied asphalt cements were frequently used by transportation agencies. The exclusion of modifiers significantly reduces extensibility and resistance to accelerated weathering. In addition, depending on the asphalt base and the climate in which they are placed, asphalt cements can experience problems of softening to the extent that sealant extrusion can occur. Typically, 2 to 3 years of service can be expected from this type of sealant placed in cracks with small movements.

The poorest performing materials were the cold-applied thermoplastics. These sealants can be effective for 3 to 4 years if used in cracks with small movements. Performance is reduced to less than 2 years if these sealants are used in cracks with significant movement.

Bibliography

Guide to Joint Sealants for Concrete Structures. _ACI Journal_, American Concrete Institute, July 1970.

Peterson, D.E. Resealing Joints and Cracks in Rigid and Flexible Pavements. _NCHRP Synthesis of Highway Practice No. 98_. TRB, National Research Council, Washington, D.C., December 1982.

8

Summary of Recommended Experimental Plans

An evaluation of the performance of materials and procedures for joint/crack sealing and spall/pothole patching in both flexible and rigid pavements has been presented in this report. In addition, condensed overviews of the four experimental plans developed for the SHRP H-106 project are provided. The H-106 experiments represent the most comprehensive set of pavement maintenance experiments ever conducted. They will provide a vast amount of new information to the state of the art.

Extensive performance data were examined from questionnaires, literature, and knowledgeable individuals. The performance trends established and reported in this study were general in nature, due to inherent weaknesses in the performance data sources. For instance, much of the data collected was found to be subjective. Questionnaire and personal interview responses essentially consisted of the educated guesses of experienced individuals. Furthermore, many of the research studies utilized were found to be incomplete, as the evaluation of the maintenance materials was often performed on a limited basis, or without considering a number of variables known to affect performance.

Despite these shortcomings, the information collected on material performance, properties, and testing was quite comprehensive and representative of the current status of materials used in pavement surface repairs.

The major objective of the experimental plans is to test and evaluate the performance of the repair materials and procedures recognized as promising or innovative. By conducting carefully designed and field-controlled experiments, a large amount of detailed and general information will be collected and scientifically analyzed. The result will be well-documented guidance on the performance of many maintenance materials and the procedures and conditions in which they were placed. Such information will greatly benefit the pavement surface maintenance programs of many highway agencies, not only with regard to the effectiveness of materials and procedures, but with respect to:

- Cost-effectiveness of the operation
- Facilitated operations (i.e., reduced lane occupancy times and, in turn, reduced work zone hazards for maintenance crews)
- State-of-the-art base line for comparison of future materials and procedures
- Identification of laboratory tests that are more indicative of field performance

For participating states, more specific benefits will be realized, such as:

- First-hand observation of the performance of materials and procedures tested in their climate on their pavements
- The opportunity to test their own innovative and promising materials and technologies through supplemental test sections
- Special training of maintenance crews to perform operations

Several desirable material properties, found to play key roles in the successful performance of repairs, were discussed in the previous chapters. These properties are often measured in the laboratory by highway agencies as a prerequisite to being considered for placement. Depending on the agency, certain requirements are placed on materials before they are used. Often, agencies adopt standard specifications from ASTM or AASHTO. However, some states have been more active in this area and have developed and incorporated their own specifications.

Laboratory testing, in the general sense, provides a user with only a limited indication of how a material will perform in the field. Some tests are better performance indicators than others, as they pertain more to the measurement of desirable properties. Comprehensive sets of these tests were identified and presented in the preceding chapters. Applicable tests will be conducted on samples of each of the materials prior to their placement in the field.

In devising each experimental plan, a number of factors believed to be influential in controlling the size of the experiments were identified. However, because of budgetary and feasibility constraints, only the factors perceived to be most significant and relevant to the stated objectives were incorporated. Items such as materials, procedures, and climate were deemed necessary for evaluation in each experiment, whereas factors such as traffic and pavement design could only be justified in a few of the experiments.

Construction of the experimental test sections will likely commence in the spring of 1991. In the interim, an intense effort will take place to locate potential test sites, given the constraints listed in each experimental plan. At the same time, extensive coordination with highway agencies and material and equipment manufacturers will be required to further establish their participatory roles in the experimental projects. For instance, as mentioned previously, participating states will be given the option of incorporating additional test sections to test local materials and procedures which show promise. The number of additional experimental test sections will most likely depend on the lengths of candidate pavement construction sections.

Once the test sites have been selected, final designs will be assembled, taking into account any justified changes and additions. Furthermore, just prior to construction, test site pavements will be inspected for existing deterioration and laid out in a manner such that significant distresses that would cause problems will be avoided.

All aspects of each maintenance activity will be closely monitored during the construction of the test sites. Whereas most other experimental projects have failed to consider the effects of factors such as existing distress, surface preparation, and material preparation, complete installation records will be kept in the H-106 experiments. Thus, any construction-related or pavement-related failures of the installed materials will not mistakenly be identified as materials-related.

Performance evaluations will be conducted at various time intervals following construction of the experimental test sections. These evaluations will be meticulous, as material, system, and pavement failures will be observed and recorded. The evaluations will then be correlated with the results of the intensive laboratory testing schemes. For example, debonding exhibited in the field will be compared with the results of tests designed to measure bond strength, taking into consideration items such as traffic and freeze-thaw cycles. In this manner, specific trends can be established which indicate more precisely how a material will perform in the field, given certain laboratory testing results.

Performance data will be analyzed using the material and procedural controls outlined in the plans. Analyses will be conducted on both a test site level and a national level. At the local test site level, head-to-head performance between materials and procedures will be examined. The national analyses will compare the results obtained across pavement types and climatic zones to ascertain any regional or national trends. Sound statistical principals and techniques will be used in conducting the analyses.

In addition to material performance data and physical tests, productivity data with respect to materials and procedures will be analyzed. This analysis will indicate relative installation costs and time requirements which are vital to cost-effectiveness and worker safety.

The sequence of the H-105 and H-106 research projects provides a means by which the state-of-the-technology of pavement surface maintenance activities will be advanced. In the H-105 project, the status quo of sealing and patching operations was determined, providing a base from which explicit experimental plans could be developed. Once implemented and conducted, the H-106 experiments will provide vital information on the many aspects associated with pavement surface repair operations. Such information will consequently boost the technology and provide a base line to which similar future projects can be compared.

References

1. R.H. Brink. *NCHRP Synthesis of Highway Practice No. 56: Joint-Related Distress in PCC Pavement.* TRB, National Research Council, Washington, D.C., 1979 36 pp.

2. M.I. Darter and E.J. Barenberg. *Zero-Maintenance Pavement: Results of Field Studies on the Performance Requirements and Capabilities of Conventional Pavement Systems.* Report FHWA-RD-76-105. FHWA, U.S. Department of Transportation, Washington, D.C., 1976, 377 pp.

3. D.E. Peterson. *NCHRP Synthesis of Highway Practice No. 98: Resealing Joints and Cracks in Rigid and Flexible Pavements.* TRB, National Research Council, Washington, D.C., December 1982, 62 pp.

4. M.I. Darter, E.J. Barenberg, and W.A. Yrjanson. *NCHRP Report No. 281: Joint Repair Methods for Portland Cement Concrete Pavements.* TRB, National Research Council, Washington, D.C., December 1985, 83 pp.

5. R.D. Barksdale, and R.G. Hicks. *NCHRP Report No. 202: Improved Pavement-Shoulder Joint Design.* TRB, National Research Council, Washington, D.C., June 1979, 103 pp.

6. B.F. McCullough. Selection of Pavement Joint Sealant Material. *Journal of Transportation Engineering Proceedings*, American Society of Civil Engineers, Vol. 108, No. TE2, March 1982, pp. 137-155.

7. ACI Committee 504. Guide to Joint Sealants for Concrete Structures. *ACI Journal,* July 1970, pp. 489-536.

8. Crafco, Inc., Interview with J. Chehovits, Chandler, Arizona, Oct. 18, 1989.

9. J.E. Bryden, W.M. McCarty, and L.J. Cocozzo. *Research Report 49: Maintenance Resealing of Rigid Pavement Joints*. New York State Department of Transportation, Albany, May 1977, 39 pp.

10. D.R. Mills and T.J. Keller. *Evaluation of W.R. Meadows and Hercules Crack and Joint Sealing Membrane Materials*. Delaware Department of Transportation, Dover, March 1987, 3 pp.

11. D. Mellott and G. Hoffman. Concrete Pavement Joint and Sealing Methods. *Adhesives Age*, November 1982, pp. 29-34.

12. J.B. Thornton. *Project No. 6903: Rigid Pavement Joints and Sealants Study*. Georgia Department of Transportation, Forest Park, Georgia, September 1975, 144 pp.

13. *Value Engineering Study on Crack and Joint Sealing*. Delaware Department of Transportation, Dover, May 1983, 16 pp.

14. F.R. McCullagh, T.M. Wolfe, and M. D'Souza. *Performance of Concrete Joint Sealants in Hot Climates*. Report FHWA-AZ-7904. Arizona Department of Transportation, Phoenix, November 1987, 38 pp.

15. G.A. Loza and D.I. Anderson. *Evaluation of Concrete Joint Sealants—Clear Creek Summit to Belknap Interchange*. Report UDOT-MR-88-3. Utah Department of Transportation, Salt Lake City, June 1988, 20 pp.

16. W. Gulden and J.B. Thornton. *Project No. 7504: Restoration Methods for Jointed Concrete Pavements*. Georgia Department of Transportation, Forest Park, May 1985, 220 pp.

17. T.R. Zimmer, S.H. Carpenter, and M.I. Darter. Field Performance of a Low-Modulus Silicone Highway Joint Sealant. In *Transportation Research Record No. 990*, TRB, National Research Council, Washington, D.C., 1984, pp. 31-37.

18. D.D. Brown. Effects of Various Sealing Systems on Portland Cement Concrete Joints. In *Highway Research Record 389*, Highway Research Board, National Research Council, Washington, D.C., 1972, pp. 28-39.

19. K.D. Smith, D.G. Peshkin, M.I. Darter, A.L. Mueller, and S.H. Carpenter, *Performance of Jointed Concrete Pavements, Volume I—Evaluation of Concrete Pavement Performance and Design Features*. Report FHWA-RD-89-136. FHWA, U.S. Department of Transportation, Washington, D.C., June 1989, 200 pp.

20. G.J. Chong and W. A. Phang. *Improved Preventive Maintenance: Sealing Cracks In Flexible Pavements In Cold Regions*. Report PAV-87-01. Ontario Ministry of Transportation, Downsview, Ontario, December 1987, 31 pp.

21. N.E. Knight. *Sealing Cracks in Bituminous Overlays of Rigid Bases*. Report 80-24. Pennsylvania Department of Transportation, Harrisburg, July 1984, 58 pp.

22. B.D. Dunshee, R.R. Samuelson, and D. Rorholm. *Improved Asphalt Surfaces and Asphalt Resurfacing Performance Through Crack Maintenance*. Project HR-213. Iowa Department of Transportation, Ames, April 1987, 29 pp.

23. M.C. Belangie and D.I. Anderson. *Crack Sealing Methods and Materials for Flexible Pavements*. Report FHWA/UT-85/1. Utah Department of Transportation, Salt Lake City, May 1985, 74 pp.

24. R.C. Evers and D.F. Lynch. Sealing Cracks in Asphaltic Concrete Pavements. Paper presented at Paving in Cold Areas Mini-Workshop, Tsukuba Science City, Japan, October 1984, 43 pp.

25. C.M. Turgeon. *Evaluation of Materials and Methods for Bituminous Pavement Crack Sealing and Filling*. Investigation 9LRR660. Minnesota Department of Transportation, St. Paul, June 1989, 18 pp.

26. R.P. Webster, J.J. Fontana, and L.E. Kukacka. Rapid Patching of Concrete Using Polymer Concrete. Paper presented at the Continuously Reinforced Concrete Pavement Workshop, February 15-16, 1978, New Orleans, LA. (Brookhaven National Laboratory, Upton).

27. C.R. Root, D.A. Ismailia, and C.E. Locke. *Polymer Concrete Patching, Volume II*. Report FHWA-OK-80-002, University of Oklahoma, Norman, April 1980, 23 pp.

28. P.D. Krauss. *New Materials and Techniques for the Rehabilitation of Portland Cement Concrete*. Report FHWA/CA/TL-85/16. California Department of Transportation, Sacramento, October 1985, 83 pp.

29. L.E. Kukacka and T. Sugama. Furfuryl Alcohol Polymer Concretes for Use in All-Weather Repairs of Concrete and Asphalt Surfaces. In *Polymer Modified Concrete*, (D.W. Fowler, ed.). American Concrete Institute, Detroit, Michigan, 1987, pp. 91-111.

30. J.J. Beaudoin and P.J. Sereda. Field Studies of a Sulphur/Asphalt Composite Pothole Repair System. In *Durability of Building Materials*, 2, (P.J. Sereda, ed.). Elsevier Science Publishers, Amsterdam, 1983, pp 1-16.

31. R.G. Pike and W.M. Baker. *Concrete Patching Materials*. Report FHWA-RD-74-55, FHWA, U.S. Department of Transportation, Washington, D.C., April 1974, 41 pp.

32. W.J. Quinn and G. Beecroft. *The Evaluation of Pavement Patching Materials in Oregon*, Oregon Department of Transportation, Salem, November 1980, 16 pp.

33. P. Mueller, J. Zaniewski, and S.L. Tritsch. Concrete Pavement Spall Repair. Paper prepared for presentation at the Transportation Research Board. Arizona Department of Transportation, Phoenix, January 1988, 35 pp.

34. D.C. Wyant. *Evaluation of Concrete Patching Materials*. Report FHWA/VA-84/35, Virginia Highway and Transportation Research Council, Charlottesville, May 1984, 18 pp.

35. P. Smith, A. Meyer, L. Barlow, and J. Patroni. *Cost Effective Spall Repair of Concrete Pavements*. Report FHWA-PA-85-046-84-04. Pennsylvania Department of Transportation, Harrisburg, August 1986, 82 pp.

36. S. Popovics. Strength Losses of Polymer-Modified Concretes Under Wet Conditions. In *Polymer Modified Concrete*, (D.W. Fowler, ed.). American Concrete Institute, Detroit, Michigan, 1987, pp. 165-189.

37. L. Hartvigas. *Research Report 74: Patching Flexible and Rigid Pavements*. Report FHWA/NY/RR-79/74. New York State Department of Transportation, Albany, October 1979, 45 pp.

38. W.T. McKeel, Jr. *Evaluation of Epoxy Compounds as a Material for Patching and Protecting Concrete*. Report VHRC 70-R33. Virginia Highway Research Council, Charlottesville, March 1971, 37 pp.

39. G.E. Ramey, R.K. Moore, F. Parker, Jr., and A.M. Strickland. Laboratory Evaluation of Four Rapid-Setting Concrete Patching Materials. In *Transportation Research Record 1041*, TRB, National Research Council, Washington, D.C., 1985, pp. 47-52.

40. S. Kudlapur, A. Hanaor, P.N. Balaguru, and E.G. Nawy. Evaluation of Cold-Weather Concrete Patching Materials. Technical Paper 86-M5. *ACI Materials Journal*, January-February 1989, pp.36-44.

41. Telephone conversation with Leo Ferroni, California Department of Transportation, Sacramento, October 6, 1989.

42. H.L. Furr. *NCHRP Synthesis of Highway Practice 109: Highway Uses of Epoxy with Cement.* TRB, National Research Council, Washington, D.C., October 1984, 67 pp.

43. E. Maggenti. *Rapid Pavement Repair Using Polyurethane.* Report CA/TL-86/04, California Department of Transportation, Sacramento, February 1986, 25 pp.

44. *Street Patching Operations, Field Test Evaluation Program, Sylvax UPM Improved Street Patch Material.* Report No. NSF/RA-770582. Public Technology, Inc., Washington, D.C., 1977, 26 pp.

45. R.W. Culley. *Field Trials with Sand-Sulphur-Asphalt Maintenance Mixes.* Technical Report 29. Saskatchewan Highways and Transportation, Regina, September 1979, 45 pp.

46. U.P.M., The High Performance Cold Patch. Brochure. Sylvax Chemical Corporation, 342 Madison Avenue, New York, N.Y. 1981.

47. *Specifications for Modified Bituminous Cold-Mix Material (Perma-Patch).* Delaware Department of Transportation, Dover, 1988, 4 pp.

48. Quality Pavement Repair 2000, The Permanent Cold Patch. Brochure. Canadian Protective Products, Inc., Pickering, Ontario, Canada, 1989, 4 pp.

49. D.A. Anderson and H.R. Thomas. Pothole Repair in Pennsylvania. In the proceedings of the 70th Annual Road School, Purdue University, West Lafayette, Indiana, 1984, pp. 28-46.

50. P.S. Kandahl and D.B. Mellot. Rational Approach to the Design of Bituminous Stockpile Patching Mixtures. In *Transportation Research Record 821*, TRB, National Research Council, Washington, D.C., 1981, pp. 16-22.

51. D.A. Anderson, H.R. Thomas, Z. Siddiqui and D.D. Krivohlavek. *More Effective Cold, Wet-Weather Patching Materials for Asphalt Pavements*. Report FHWA-RD-88-001, FHWA, U.S. Department of Transportation, Washington, D.C., 1987, 149 pp.

52. V.R. Kumar and K. Majidzadeh. *A Field and Laboratory Evaluation of Pavement Patching Material*. Report FHWA/OH-87/003. Ohio Department of Transportation, Columbus, 1986, 130 pp.

53. F.R. McCullagh. *Field and Laboratory Evaluation of Sulfur Asphalt Patching Materials*. Report FHWA/AZ-82/175, Arizona Department of Transportation, Phoenix, August 1982, 12 pp.

54. *Specification 2381—Bituminous Stockpile Patching Mixture*. Minnesota Department of Transportation, St. Paul, Minnesota, May 1, 1985, 4 pp.

55. M.C. Rissel. *Improved Methods for Patching on High-Volume Roads*. Report FHWA/RD-86/076. FHWA, U.S. Department of Transportation, Washington, D.C., 1986, 175 pp.

56. B.K. Osborne. Solving a Weak Link in Pavement Patches. In *Public Works*, July, 1988, pp. 70-71.

57. G.M. Briggs. Infrared Heating Makes Patches Stick. In *Rural & Urban Roads*, August 1971, pp. 24-25.

58. C.W. Niessner. *Optimizing Maintenance Activities: Fifth Report, Bituminous Patching (Value Engineering Study of Bituminous Patching)*. Report FHWA-TS-78-220. FHWA, U.S. Department of Transportation, Washington, D.C., 1978, 28 pp.

59. *Preferred Method 1—Patching*. County Surveyors Department, County Hall Truro, United Kingdom Department of Transport, Standing Committee on HIG, United Kingdom, 1988, 16 pp.

60. M.B. Snyder, M.J. Reiter, K.T. Hall, and M.I. Darter. *Rehabilitation of Concrete Pavements, Vol. I-Repair Rehabilitation Techniques*. Report FHWA-RD-88-071. FHWA, U.S. Department of Transportation, Washington, D.C., April 1989, 249 pp.