LTPP Pavement Maintenance Materials: PCC Partial-Depth Spall Repair Experiment, Final Report

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LTPP

FOREWORD

Partial-depth spall repair on portland cement concrete pavements is a commonly performed highway maintenance operation. The Strategic Highway Research Program's (SHRP) H-106 partial-depth spall repair study was part of the most extensive pavement maintenance experiment ever conducted. The information derived from this study will contribute greatly toward advancing the state of the practice of spall repair on portland cement concrete pavements.

This report provides information to pavement engineers and maintenance personnel on the results of the H-106 partial-depth spall repair experiment. It presents the performance and cost-effectiveness of various spall repair materials and procedures for repairing spalls on portland cement concrete pavements.

This report will be of interest to anyone concerned with the maintenance and rehabilitation of portland cement concrete pavements.

T. Paul Teng, P.E.
Director
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16. Abstract

The Strategic Highway Research Program (SHRP) H-106 maintenance experiment and the Federal Highway Administration (FHWA) Long-Term Monitoring (LTM) of Pavement Maintenance Materials Test Sites project studied the repair of partial-depth spalls in concrete pavements. The purpose of partial-depth spall repair is to restore a pavement's structural integrity, improve its ride quality, and extend its serviceable life.

Highway agencies spend a large amount of time and money annually performing partial-depth spall repairs, both as temporary and permanent fixes. Frequently, the repairs are not made as efficiently as desired or do not perform as long as intended. The primary consequences are added disruption to traffic, more exposure of patching crews to traffic, and additional maintenance expenditures. The purpose of this study, then, was to address the merits and deficiencies of current spall repair materials, designs, and practices. The study evaluated the relative performance of selected patching materials, as well as the effect of selected repair methods. The study also examined repair material properties and tests that correlate well with field performance.

This report documents the entire portland cement concrete (PCC) partial-depth spall repair study, including the installation of 30 unique repair types (i.e., combinations of patching material and patching method) at 4 different test sites, the laboratory testing of experimental repair materials, and the 7-year performance monitoring of the various partial-depth repairs. It also discusses the results of comprehensive statistical analyses conducted on material performance and laboratory testing data. The results of a detailed cost-effectiveness analysis are also presented.

17. Key Words

Concrete pavement, pavement maintenance, partial-depth spalls, spall repair, patching materials, bituminous patch, cementitious patch, performance, service life, cost-effectiveness

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		AREA		
in²	square inches	645.2	square millimeters	mm²
ft²	square feet	0.093	square meters	m²
yd²	square yards	0.836	square meters	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	square kilometers	km²
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft³	cubic feet	0.028	cubic meters	m³
yd³	cubic yards	0.765	cubic meters	m³
NOTE: Volumes greater than 1000 l shall be shown in m³.				
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celcius temperature	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m²	cd/m²
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in²	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm²	square millimeters	0.0016	square inches	in²
m²	square meters	10.764	square feet	ft²
m²	square meters	1.195	square yards	yd²
ha	hectares	2.47	acres	ac
km²	square kilometers	0.386	square miles	mi²
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m³	cubic meters	35.71	cubic feet	ft³
m³	cubic meters	1.307	cubic yards	yd³
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m²	candela/m²	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in²

* SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

(Revised September 1993)

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CHAPTER 1. INTRODUCTION

Objectives

Spalling is a common distress in jointed concrete pavements that decreases pavement serviceability and, if left unrepaired, can become hazardous to highway users. It is defined as the cracking, breaking, chipping, or fraying of concrete slab edges at joints and cracks, and is the result of high compressive stresses that develop in the concrete when joints or cracks cannot properly close due to the presence of incompressible materials.

The depth of spalling in a concrete slab can vary from a few millimeters (i.e., sliver spalls) to the full depth of the slab. Once initiated, spalls tend to grow or propagate under repeated thermal stresses and traffic loadings. For safety purposes, most spalls are treated before they extend below the top third of the slab. Repairs of this nature are commonly referred to as partial-depth spall repairs.

Highway maintenance crews spend a large amount of time and money annually performing partial-depth spall repairs, both as temporary and as permanent fixes. The ability to place patches quickly and to the level of permanence required for a given project can reduce the amount of time that crews are exposed to traffic (by decreasing the amount of time spent repatching the same areas) and can increase the serviceability of the highway.

To examine the merits and deficiencies of current spall repair materials and practices, the Strategic Highway Research Program (SHRP) and the Federal Highway Administration (FHWA) consecutively sponsored one of the most extensive partial-depth patching investigations ever undertaken. In the spring and summer of 1991, four partial-depth spall repair test sites were installed throughout the United States under the SHRP H-106 project (Innovative Materials Development and Testing) using various materials and installation methods under a range of climatic conditions. Periodic performance evaluations of the many experimental patches placed were conducted until the completion of the project in March 1993. Believing that additional information could be obtained from the four test sites, the FHWA authorized a follow-up project (Long-Term Monitoring [LTM] of Pavement Maintenance Materials Test Sites) starting in October 1993, which provided for continued annual test site evaluations through 1997.

The primary aim of the combined H-106/LTM study was to determine the most effective and economical materials and procedures for placing quality, long-lasting partial-depth patches in jointed concrete pavements. A secondary objective of the study was to identify any performance-related material tests that would enhance the material selection process and provide a better guarantee of patch performance.

Scope

This report presents a summary of all aspects of the partial-depth spall repair experiment of the H-106/LTM study, including test site installation, materials testing, field performance, and data analysis. Chapter 2 details the installation process, including test site arrangements, test site layout and preparation, patching materials and procedures, documentation of the installation process, and the collection of productivity and cost. Chapter 3 describes the materials tests performed and the corresponding results. In chapter 4, the field performance data collection is described and a summary of performance data is presented. Chapter 5 details the statistical methodology used to analyze the data and presents the results of the analysis of field performance, laboratory test-field performance correlations, productivity, and cost-effectiveness. In chapter 6, the overall findings and recommendations of the experiment are discussed.

Project Overview

Beginning in March 1991, more than 1,600 partial-depth patches were placed at 4 test sites located throughout the United States. The repairs were made using materials supplied by SHRP and were placed under SHRP contractor supervision by local maintenance forces from two different State departments of transportation (DOT's) and two contractors working for the State DOT's. The test sites were located on moderate- to high-volume four-lane highways in four climatic regions. The locations of the test sites and the four climatic regions (originally defined for the SHRP Long-Term Pavement Performance [LTPP] projects and subsequently adopted for this project) are listed below and are illustrated in figure 1.

• PA 28—Kittanning, Pennsylvania	Wet-freeze region
• I-15—Ogden, Utah	Dry-freeze region
• I-20—Columbia, South Carolina	Wet-nonfreeze region
• I-17—Phoenix, Arizona	Dry-nonfreeze region

The original testing plan for the partial-depth spall repair project was developed in the SHRP H-105 project (Smith et al., 1991). The materials and procedures included in the actual test site installations were somewhat different from those originally proposed, as various State agencies requested that additional materials and procedures be included in accordance with the provisions of the SHRP H-106 contract.

Repair Materials

Originally, nine materials and four testing procedures were selected for study. However, the States in which the test sites were constructed were allowed to add an additional material or procedure of their choice to the experiment. As a result, two additional materials and one repair procedure were incorporated into the experiment. The following 11 materials were evaluated in the study:

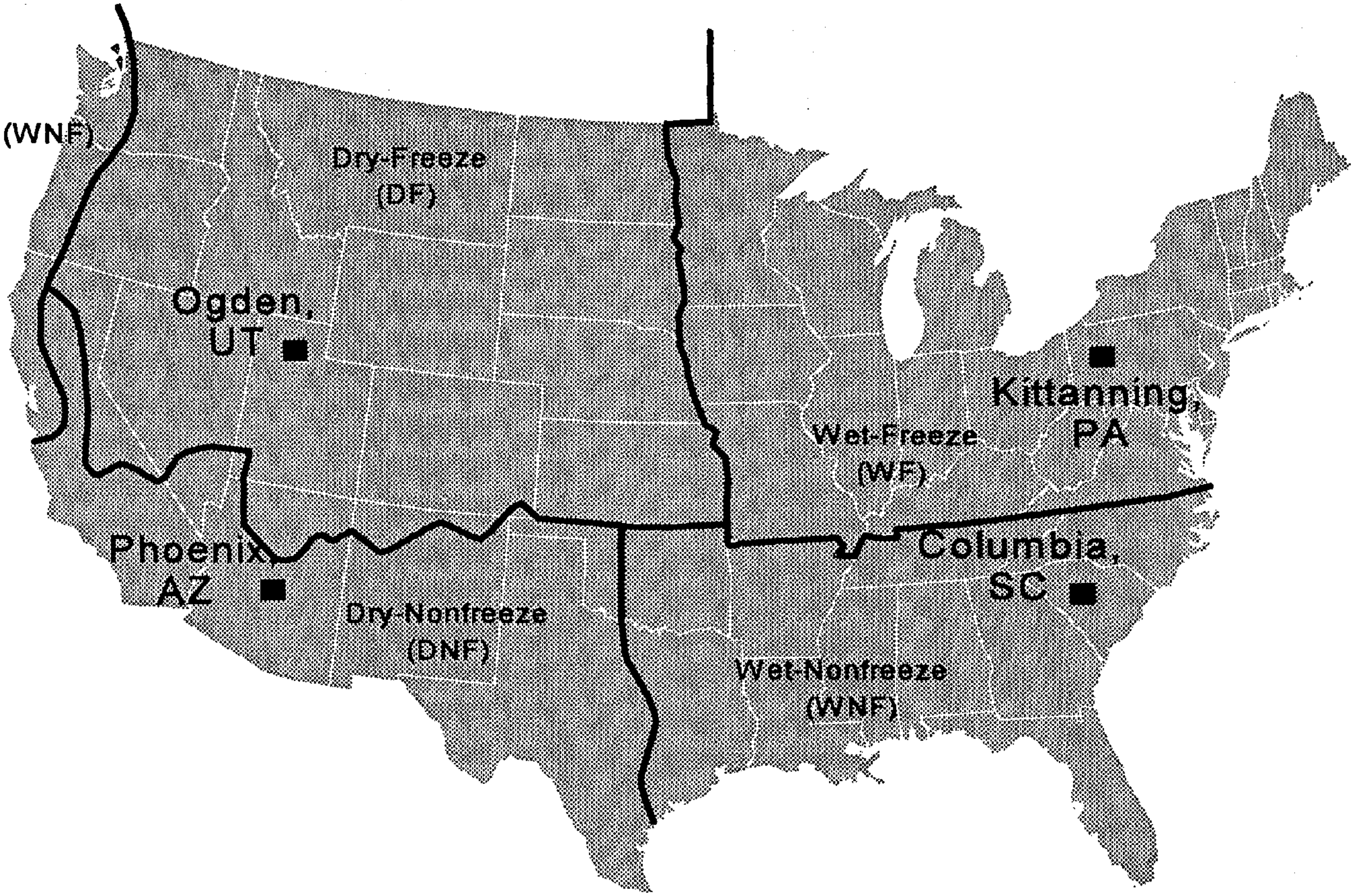

Figure 1. Spall repair test site locations and climate regions.

- Type III portland cement concrete (PCC).
- Duracal®, a gypsum-based concrete.
- Set-45®, a magnesium phosphate concrete (powder-based).
- Five Star® Highway Patch, a modified, high-alumina concrete.
- MC-64, an epoxy concrete.
- SikaPronto® 11, a high-molecular-weight methacrylate concrete.
- Percol FL, a flexible polyurethane concrete.
- UPM High Performance Cold Mix, a bituminous cold mix.
- Pyrament® 505, a blended hydraulic cement concrete.
- Penatron® R/M-3003, a flexible epoxy-urethane concrete.
- Spray-injected bituminous mix (AMZ and Rosco).

Repair Procedures

Five different repair procedures were evaluated, varying mainly in the method used to remove the deteriorated concrete. The five procedures were as follows:

- Saw-and-patch.
- Chip-and-patch.
- Mill-and-patch.
- Waterblast-and-patch.
- Clean-and-patch under adverse conditions.

Most of the procedures were evaluated under normal conditions, which were defined as conditions corresponding to an ambient air temperature above 10°C at the time of patching and a substrate that is dry prior to preparation. However, spall distresses must sometimes be patched under adverse conditions. To determine whether a cost-effective material could be found for this situation, three materials were tested under adverse conditions using the clean-and-patch procedure. Adverse conditions were defined as an ambient air temperature below 4°C at the time of patching and a substrate that is surface-saturated.

Table 1 summarizes the material–procedure combinations used at each test site. Not all of the material–procedure combinations were placed at all of the test sites. Some materials (e.g., spray-injected Rosco and AMZ, Penatron R/M-3003) were placed at the request of a participating highway agency. South Carolina and Pennsylvania requested the spray-injected materials, and Arizona requested the addition of Penatron R/M-3003. Arizona also requested the addition of the waterblast-and-patch procedure. Because equipment was not available, the mill-and-patch procedure was not installed in Utah. Equipment operation difficulties prevented installation of the waterblast-and-patch procedure in Arizona.

Test Site Characteristics

This section briefly describes the characteristics of the four spall repair test sites. Table 2 presents a summary of the location, route, number of lanes, annual daily traffic (ADT), annual precipitation, and annual number of days less than 0°C for each test site.

Table 1. Summary of number and types of repairs placed for H-106 spall repair experiment.

Procedure	Pennsylvania (wet-freeze)				Utah (dry-freeze)			South Carolina (wet-nonfreeze)		Arizona (dry-nonfreeze)			TOTAL
	Saw-and-Patch	Chip-and-Patch	Mill-and-Patch	Adverse Clean-and-Patch	Saw-and-Patch	Chip-and-Patch	Waterblast-and-Patch	Saw-and-Patch	Chip-and-Patch	Saw-and-Patch	Chip-and-Patch	Mill-and-Patch	
Type III PCC	22	24	20		25	35	37	20	20	20	20		243
Duracal					22	25		20	20	20	20		127
Set-45	20	20	20		25	23		20	20	20	20		188
Five Star HP	20	20	20		19	34		20	20	20	20		193
MC-64	20	20			25	28		19	20	20	20	20	192
SikaPronto 11	21	20			26	28		20	20	20	20		175
Percol FL	20	20	20	20	29	29		21	20	20	20	20	239
Pyrament 505	20	20		19								20	79
UPM High Performance Cold Mix		20		20		31			20		20		111
Penatron R/M-3003										20			20
Spray injection (AMZ)									20				20
Spray injection (Rosco)		21											21
TOTAL	143	185	80	59	171	233	37	140	180	160	160	60	1,608
	467				441			320		380			

Table 2. Test site characteristics.

Test Site	Route	No. of Lanes, two directions	Two-way ADT, vpd	Annual Precipitation, mm[a]	Annual Days < 0°C[a]
Kittanning, PA	PA 28	4	3,400	1067	120
Ogden, UT	I-15	4	20,000	406	180
Columbia, SC	I-20	4	24,000	1168	31
Phoenix, AZ	I-17	6	125,000	178	17

[a] Historical averages from the *Climatic Atlas of the United States* (U.S. Dept. of Commerce, 1983).
ADT = Average daily traffic.
vpd = vehicles per day.

PA 28, Kittanning, Pennsylvania

As shown in figure 2, the test site in the wet-freeze region was located in Pennsylvania on PA 28, northeast of Pittsburgh between Freeport and Kittanning. The adverse-condition test sections were located in both the northbound and southbound driving lanes, with the experiment replicated once in each direction. The normal-condition test sections were placed in all four lanes of the route, with a majority of the test sections located in the driving lanes. The topography of this site was hilly with two interchanges and several bridges. The pavement was constructed in 1971 as a 229-mm jointed reinforced concrete (JRC) pavement on a 356-mm cement-stabilized subbase. At the time of installation, the transverse joints, spaced at 14.2 m, were sealed with a bituminous sealant and the sealant was in fair condition. The shoulders were asphalt concrete (AC).

There was extensive spalling in parts of the test section, often with more than one spall per joint. When the test site was first inspected, the spalls were judged to be limited to the upper one-third of the pavement (coring was not performed). This was confirmed during the installation of the adverse-condition test sections. However, when the remainder of this test site was installed and more rigorous concrete removal techniques were employed, the spalls appeared to extend deeper into the pavement, and dowels often were exposed. Due to limited resources and other constraints, there were no departures from the procedures outlined for the experiment. This site was in the SHRP region that experiences the most severe climatic conditions—both significant precipitation and freezing temperatures. The climate and the fair amount of salt deposited on this route each year may have contributed to the depth of the spalling found there.

I-15, Ogden, Utah

The test site in the dry-freeze region was located in Utah on I-15 in the passing lane, north of Ogden between exits 357 and 360, as shown in figure 3. The pavement was built in 1971 and consisted of a 164-mm jointed plain concrete (JPC) pavement on a concrete subbase. The joints were randomly spaced between 3.6 m and 5.5 m and were sealed with silicone sealant at the time of the installation of the test site. The shoulders were concrete. There were spalls on a majority of the joints, but they were fairly small in size. The topography was very flat, and no structures

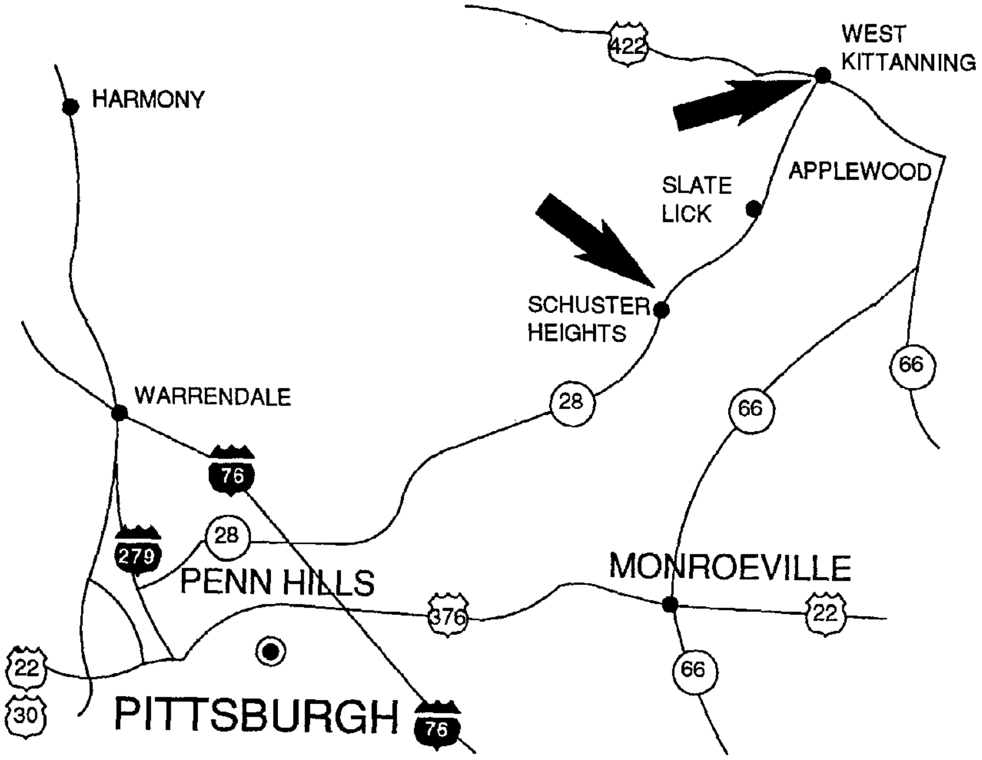

Figure 2. Pennsylvania test site location.

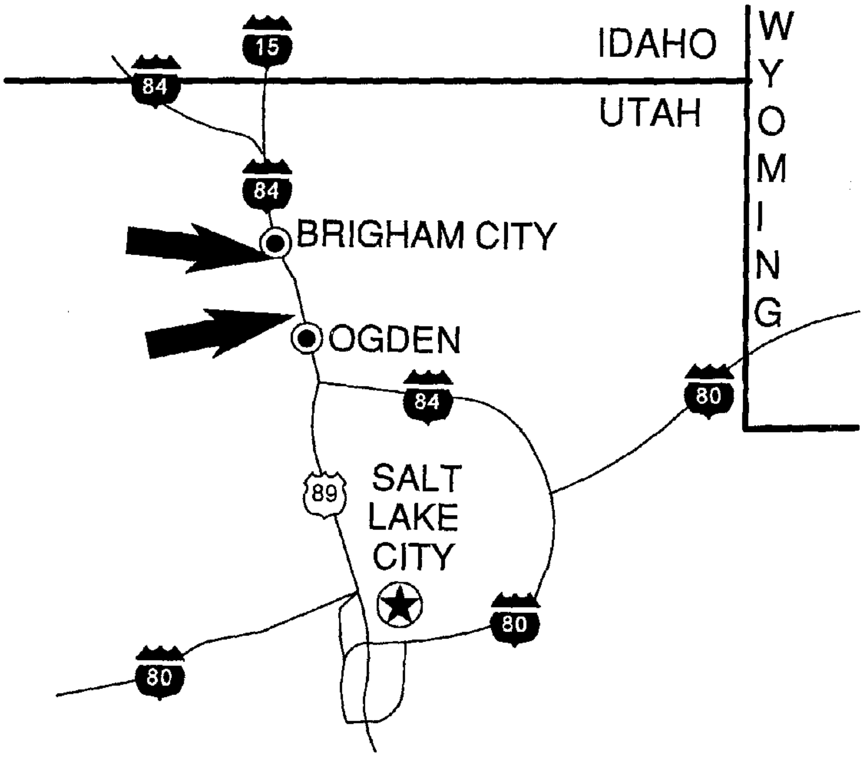

Figure 3. Utah test site location.

were located within the test site boundaries. The test site was surrounded by a lake on the west side and mountains on the east. This test site was installed in April, and the temperature range during installation was 6 to 21°C. This area is subject to rapid fluctuations in temperature and large amounts of snowfall. The use of studded tires on this route caused some wearing of the pavement. This route receives a fair amount of salt each year.

I-20, Columbia, South Carolina

The test site for the wet-nonfreeze region was located in Columbia, South Carolina, on the westbound driving lane of I-20, as shown in figure 4, between mile markers 58 and 61. The pavement was constructed in 1966 and consisted of a 229-mm jointed concrete pavement on a 152-mm stabilized aggregate subbase. The joints were spaced at 9.15 m and were sealed with an asphalt sealant at the time of installation of the test site. The shoulders were AC. There were spalls or existing patches of AMZ spray-injected mix at almost every joint, and the terrain for the majority of the site was flat. There was one structure over a railroad crossing.

I-17, Phoenix, Arizona

The test site in the dry-nonfreeze region was located in the northbound and southbound passing lanes of I-17 in Phoenix, Arizona, between the Camelback and Thomas Roads exits (mileposts 202 to 204), as shown in figure 5. The pavement was constructed in 1961 and consisted of a 229-mm JPC surface over a 76-mm granular base and a 152-mm granular subbase. The joints were spaced 4.6 m apart and were constructed using metal joint inserts. At the time of the test site installation, the joints were not sealed and there was a great deal of joint debris infiltration. The pavement was grooved to remove faulting and restore friction. The section contained many existing patches and many of the spalls were full-lane width. The shoulders were JPC also.

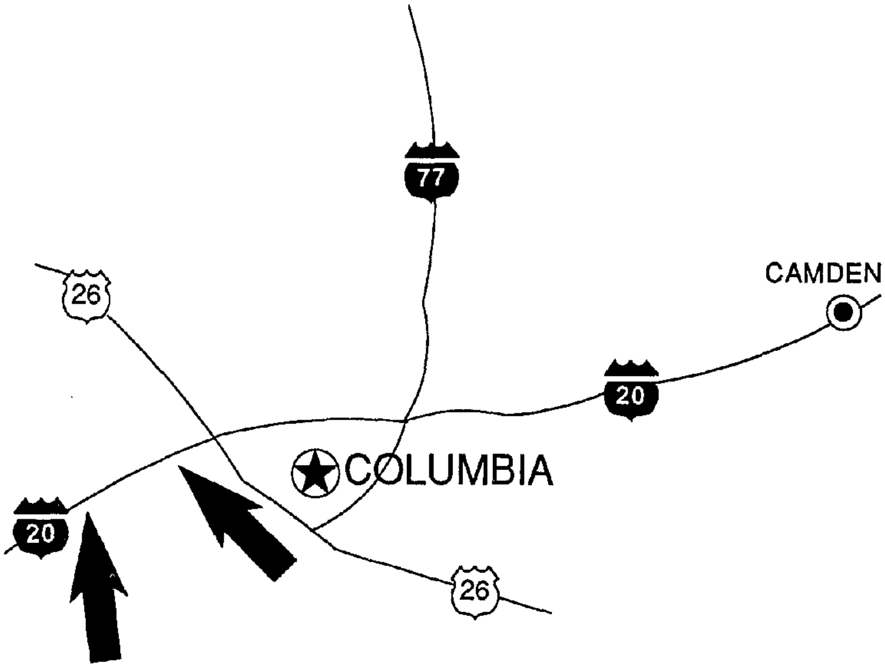

Figure 4. South Carolina test site location.

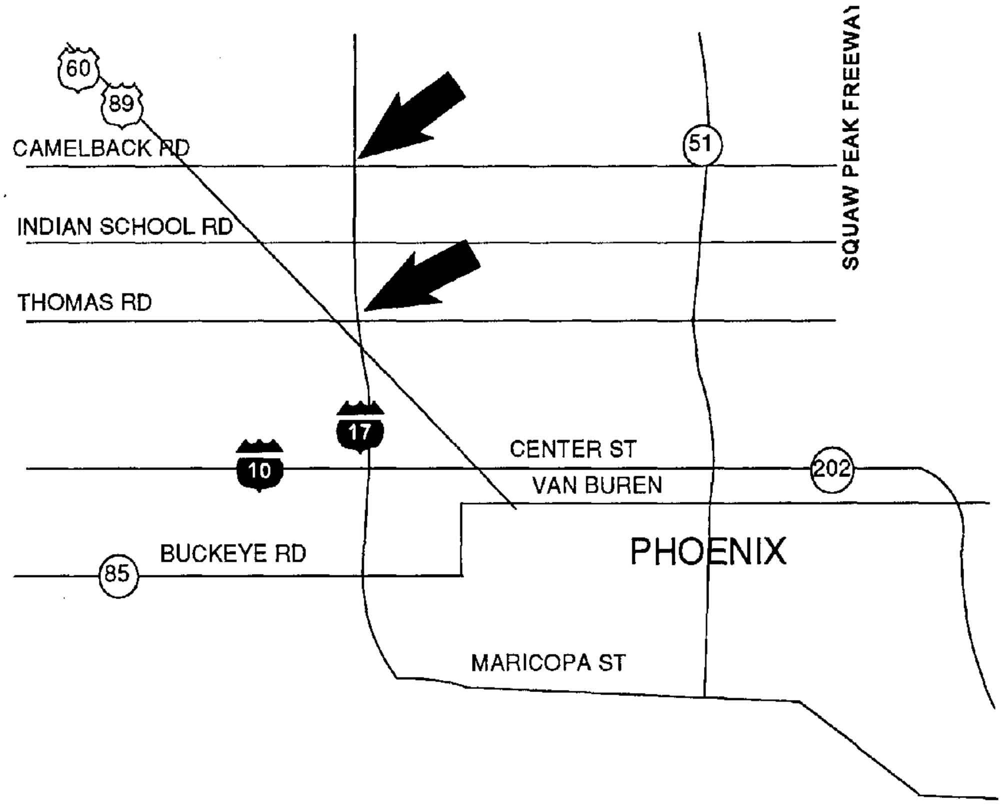

Figure 5. Arizona test site location.

CHAPTER 2. TEST SITE INSTALLATION

The test site selection process began in November 1990. A total of 33 potential sites were examined, of which the 4 sites described in chapter 1 were selected for use. Installation of the test sites began in March 1991 and continued through August 1991. Installation of the test sites was regulated and monitored by engineers with the SHRP H-106 contractor, together with representatives from the participating State DOT's and manufacturers of repair materials. This chapter presents an overview of the installation process, material costs, productivity rates, equipment requirements, problems encountered during installation, and comments on the materials and procedures used.

Test Site Arrangements

The installation dates for each test site are shown in table 3. Specific construction schedules were given in SHRP H-106 *Experimental Design and Research Plan (EDRP)* (Evans et al., 1991). It was originally planned that all the installations would be performed by State maintenance crews; however, private contractors were used for the installations at two of the test sites.

The first step in the site installation process was to find test sites that met the requirements outlined in the SHRP H-106 *EDRP* (Evans et al., 1991). Once the test sites were selected, close coordination among the H-106 project team, the State DOT's and contractors, and the material manufacturers was critical for smooth and efficient installation of the test sites.

Based on estimations of patch size, product yield, and material waste factors, the repair materials were ordered and shipped to the test site. Each repair material was obtained from a single production batch when possible, to minimize variability, and was shipped to the four test sites. A separate shipment from each batch was sent to the laboratory for independent testing.

Because it was considered critical that the materials be placed correctly and in accordance with manufacturers' recommendations, representatives of repair material manufacturers were requested to observe and participate in the installation of their material. In addition, a recognized expert in the field of patching attended the first installation in Utah to provide advice on quality control and material performance evaluation. Overall, the interest among the material manufacturers was high; almost all sent representatives to at least one test site. The presence of a representative for the Type III PCC was not requested because it was felt that most agencies would be familiar with the use of Type III PCC as a patching material. Because South Carolina and Pennsylvania regularly use AMZ and Rosco spray-injection machines for patching, representatives of these companies also were not requested to attend. Table 4 indicates which material manufacturers were represented at the test sites.

Table 3. Summary of spall repair installation schedule.

Spall Repair Project Site	Participating Agency	Installation Start Date	Installation Completion Date	Number of Construction Days
PA 28, Kittanning, PA	Commonwealth of Pennsylvania DOT– Armstrong County	Adverse: 3/11/91	Adverse: 3/27/91	4
		Normal: 6/4/91	Normal: 7/22/91	22
I-20, Columbia, SC	South Carolina Dept. of Highways and Public Transportation–Lexington County	5/6/91	5/29/91	13
I-15, Ogden, UT	Utah DOT–Research and Development/Wadsworth Construction Co.	4/22/91	5/1/91	5
I-17, Phoenix, AZ	Arizona DOT– Research/Bentson Contractors	5/29/91	6/9/91	8

Table 4. Manufacturers' representatives present at test site.

Material	Test site			
	Pennsylvania	Utah	South Carolina	Arizona
Type III PCC	no	no	no	no
Duracal	—	yes	yes	yes
Set-45	yes	yes	yes	yes
Five Star HP	no	yes	yes	yes
MC-64	yes	yes	yes	yes
SikaPronto 11	no	yes	yes	yes
Percol FL	yes	yes	yes	yes
Pyrament 505	yes	—	—	yes
UPM	no	yes	no	no
Penatron	—	—	—	yes
AMZ	—	—	no	—
Rosco	no	—	—	—

— Material not installed at this location.

Installation Process

The installation process encompassed selection and marking of the repair areas; removal of the deteriorated concrete; and mixing, placement, and finishing of the repair materials. This section presents the details of the installation process.

Layout

The original experimental plan called for 10 patches to be placed for every material–procedure treatment in each test section. These test sections were placed in random order, consecutively along the test site pavement. After the placement of the first block of treatments, the sequence was repeated randomly for the second replicate. A typical test section layout is shown in figure 6. At the Pennsylvania and Utah sites, more than 10 patches were included in some of the test sections. All patches placed were evaluated and considered in the analyses described in later chapters.

A few days before installation was begun, the spalls to be repaired were selected. The perimeter of each repair location was determined by sounding the pavement with a hammer or steel rod. Only deteriorated areas at joints were selected. The removal area was marked 50 to 75 mm beyond the sound area on all nonjoint sides. Deteriorated or unsound areas smaller than 150 mm long and 75 mm wide were not repaired.

Spalls within the test section that previously had been patched with an asphalt patching mix were included for repair in all sections. These spalls were repaired using the chip-and-patch, saw-and-patch, waterblast-and-patch, and mill-and-patch procedures. Repair areas closer than 0.3 m to each other were marked as one repair area. Each repair area was marked with a painted code that indicated the patching procedure and material to be used.

Preparation

After the repair areas were marked, the existing transverse and longitudinal joints bordering repair areas to be patched with a rigid material (i.e., Type III PCC, Duracal, Five Star HP, Set-45, SikaPronto 11, and Pyrament 505) were sawed using a double-bladed concrete saw. The depth of

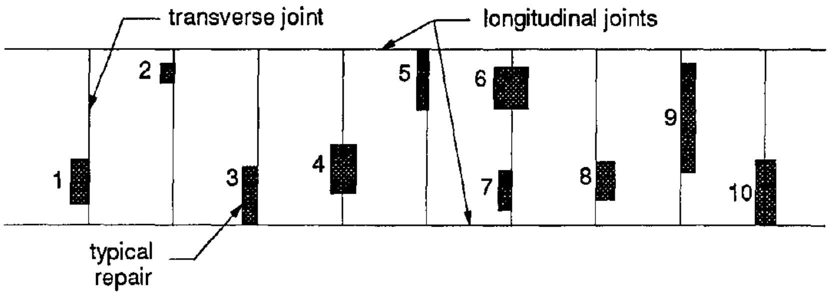

Figure 6. Layout of a typical test section.

the saw cut was generally deeper than the depth of the repair. In most cases, a depth of 100 to 125 mm proved to be sufficient. The saw cut extended 50 to 75 mm beyond the repair area in each direction. The saw cut to re-establish the joint was eliminated for the repair areas that were to be patched with flexible materials (i.e., Percol FL, MC-64, Penatron R/M-3003, UPM High Performance Cold Mix, and spray-injected mix), as well as for the patches to be installed under adverse conditions. The joints were sawed a minimum of 1 day in advance of the removal and replacement operations, so that the spall would be sufficiently dry for those patching materials requiring a dry substrate.

Procedures

The deteriorated concrete was removed using one of five procedures: saw-and-patch, chip-and-patch, mill-and-patch, waterblast-and-patch, and adverse-condition clean-and-patch. This section describes the concrete removal procedures included in the experiment.

After the removal of the deteriorated concrete was complete, the remaining concrete was again tested for soundness. If further unsound concrete was observed, the unsound material was removed to a sufficient depth using the same procedure used for the initial removal.

If the depth of removal of unsound material using the saw-and-patch, chip-and-patch, mill-and-patch, or waterblast-and-patch procedure exceeded one-half the nominal pavement thickness, or if dowel bars were encountered, a full-depth repair was recommended. However, because of the constraints of traffic, labor, and equipment, the construction of full-depth repairs was not feasible, and partial-depth repairs were installed. This was particularly true during construction of the Pennsylvania test site, where dowel bars were often encountered.

Saw-and-Patch Procedure

Using a diamond-bladed concrete saw, the rectangular marked areas were sawed with neat vertical faces 38 to 50 mm deep. The saw cut extended 50 to 75 mm beyond the limits of the repair area in each direction. A pneumatic hammer with a maximum weight of 13.6 kg was used for the initial removal. The operation started in the center of the patch area and worked toward, but not all the way to, the patch boundaries. A light pneumatic hammer with a maximum weight of 6.8 kg and handtools were used near the patch boundaries.

Chip-and-Patch Procedure

All loose and unsound concrete within the repair area was removed using a pneumatic hammer of up to 6.8 kg and handtools, and was swept away using a stiff broom. Fresh concrete faces at least 25 mm deep were exposed on all sides.

Mill-and-Patch Procedure

All unsound concrete within the marked area was removed to a minimum depth of 38 mm using an approved carbide-tipped milling machine. The milling machine had a drum diameter of 0.9 m or less and was capable of making a cut 305 mm wide or narrower. A carbide-tipped, cold-milling machine is shown in figure 7. Milling proceeded in such a manner as to produce vertical edges at the patch boundaries. A small amount of sound material at patch corners could not be removed by milling from any direction. This material was removed by light chipping hammers, as shown in figure 8. Care was exercised to minimize spalling the sound concrete at the patch boundaries.

Waterblast-and-Patch Procedure

All unsound concrete within the marked area was removed to a minimum depth of 38 mm, with neat vertical faces, using an approved waterblasting machine. The waterblasting equipment produced a water jet under a minimum pressure of 207,000 kPa and was controlled by a mobile robot, as shown in figure 9. The maximum depth of concrete removal was determined by the waterblasting pressure and speed of the water jet. Care was exercised to remove only the unsound concrete.

Figure 7. Carbide-tipped, cold-milling machine.

Figure 8. Corners of patch being removed after milling.

Figure 9. Waterblasting equipment with mobile robot.

Clean-and-Patch Procedure

This procedure was used only with the bituminous spray-injected materials. In accordance with the manufacturer's recommendations, only the deteriorated concrete that could be removed using shovels or handpicks was removed.

Clean-and-Patch Procedure—Adverse Conditions

Deteriorated and loose concrete within the repair area was removed primarily using handtools. Occasionally, a light pneumatic hammer was allowed if the spalled area was large or if the cracked concrete was held tightly in place.

Cleaning and Preparing the Repair Area

The remaining steps of the patching procedures are similar for all but the clean-and-patch procedure. When cleaning and patching, sandblasting was eliminated, as was joint preparation and the installation of the bond-breaker for the bituminous materials. When a spray-injection machine was used with the clean-and-patch procedure under good conditions, the repair area was not sandblasted. Instead, it was airblown with the spray-injection machine. For the adverse-condition clean-and-patch procedure, if moisture was not present in the repair hole at the time of material placement, water was lightly sprayed into the open hole. Furthermore, immediate sealing of the joint adjacent to the patch was not required.

For the other procedures, after removal of the deteriorated concrete was completed, the surfaces within the repair area were cleaned thoroughly by sandblasting. Oil-free airblasting was then used to remove any dust that remained. The air compressor was checked for moisture and oil by placing a piece of clean cloth over the air jet nozzle and checking for residue. The cleanliness of the surfaces was checked by using a black glove or cloth.

Following the cleaning operation, a joint bond-breaker was placed full-depth in the joints adjacent to repair areas that were to be patched with nonflexible repair materials (i.e., Type III PCC, Duracal, Set-45, Five Star HP, MC-64, SikaPronto 11, and Pyrament 505), as shown in figure 10. The joint bond-breaker consisted of a 102-mm-high, 13-mm-wide, closed-cell polystyrene foam board that was slightly wider than the saw cut. In back-to-back repair areas at a joint, difficulty was encountered in maintaining a true, straight joint line. In locations deeper than 102 mm, it was also difficult to stack the joint bond-breaker to the desired height. Latex caulking was used occasionally to seal any irregularities or gaps between the joint bond-breaker and joint opening in order to prevent repair material from flowing into the joint or crack opening below the bottom of the patch. A joint bond-breaker was not installed in repair areas that would be patched with Percol FL, Penatron R/M-3003, UPM High Performance Cold Mix, AMZ, or Rosco.

After the surface of the existing concrete was cleaned and the joint bond-breaker was installed as needed, the repair surfaces were prepared as required by the manufacturers of the individual repair materials. This preparation, which included such activities as application of a bonding agent or a light spray of water, is detailed in the following sections.

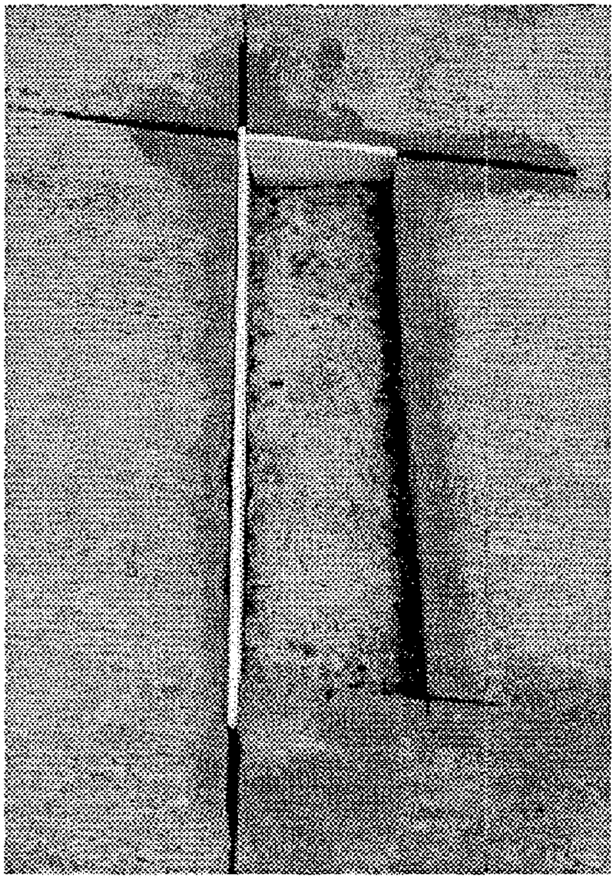

Figure 10. Joint bond-breaker installed at patch edges.

Materials

Instructions on the proper mixing, placing, finishing, curing, and handling of the individual patching materials were obtained from the manufacturer of each product. Furthermore, most manufacturers were asked to send a representative to each of the test sites for at least the first day that the product was being installed. The purpose was to provide a brief training session and general guidance to ensure that their product was properly installed.

The cementitious products were prepackaged in easy-to-handle 16- to 23-kg bags; the aggregate was provided in 45-kg bags. The aggregate was proportioned in the field using precalibrated buckets.

Type III PCC

The Type III PCC mix was prepared in a mobile 2.3-m^3 drum mixer, as shown in figure 11. First, the water (11.4 L) was added to the mixer, followed by the coarse aggregate (100 kg), the air-entraining agent (30 mL), and the fine aggregate (50 kg). This combination was allowed to

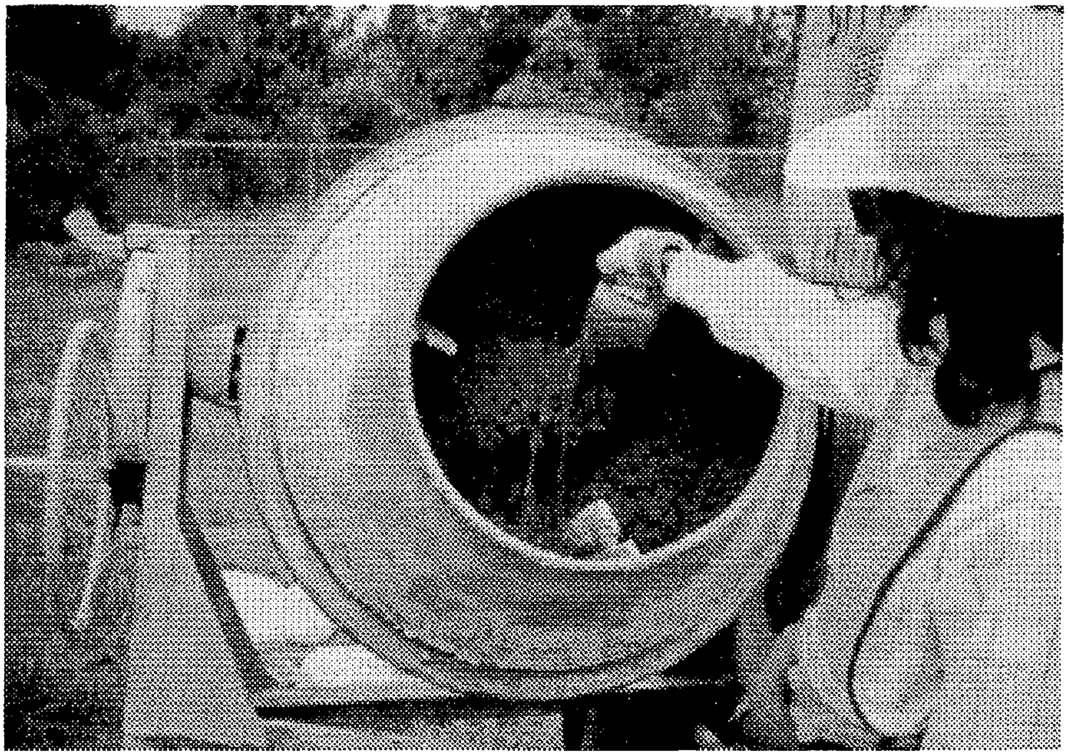

Figure 11. Type III PCC mobile drum mixer.

mix for 3 minutes. The Type III portland cement (43 kg) was added next and allowed to mix for another 3 minutes. The accelerating agent (1.9 L) was added and mixed for 1 minute, followed by the superplasticizer (355 mL). The combination was mixed for 2 minutes. If the mix looked stiff at this time, up to 0.5 L of water was added as needed. The water–cement ratio for the mix varied from 0.30 to 0.33.

The Type III PCC repair material required that the bottom and sides of the repair area be primed with a medium-viscosity epoxy bonding agent. The bonding agent was prepared by mixing part B with part A for 3 minutes, using an electric drill with a Jiffy mixer. A paintbrush was used to apply the epoxy evenly to the repair surfaces, as shown in figure 12. While the epoxy was still tacky, the prepared Type III PCC mix was shoveled into the repair area and vibrated using a pencil vibrator.

After vibration, the surface of the patch was troweled level with the surface of the pavement and finished with a float, as shown in figure 13. The mix was sometimes stiff to work with and vibration was essential to make the work finishable. A curing compound was applied after 1 to 2 minutes and, if necessary, the patch was covered with an insulating blanket.

The working time for the Type III PCC mix was 20 minutes, and the opening time was 4 hours at 27°C. Insulating blankets were used during cooler temperatures to achieve the same opening time.

Figure 12. Application of epoxy bonding agent.

Figure 13. Troweling/finishing of Type III PCC patch.

Duracal

Duracal was mixed using a drum mixer. The water was added first (6.62 L per bag of Duracal), followed by the pea gravel (23 kg per bag of Duracal), the Duracal (23 kg per bag), and the sand (23 kg per bag of Duracal). The cement and aggregate were mixed for a minimum of 2 to 3 minutes. If the mix looked stiff or dry, up to an additional 0.47 L of water was added, as needed. Generally, only one bag of Duracal per batch was used. The area to be patched was sprayed with water, and then the concrete was shoveled into the repair area. The mix was vibrated by moving a trowel up and down throughout the patch. A curing compound was used only if the air temperature was above 32°C and it was windy. The working time for the Duracal concrete was approximately 10 minutes, and the opening time was 1 hour at 27°C and 1.5 hours at 10°C.

Five Star HP

The mixing of Five Star HP was accomplished using a mortar mixer. Generally, two to three bags of Five Star HP per batch were mixed at one time. With the mixer running, the water was added to the mixer (2.8 L per bag of Five Star HP). The cement was then added to the mixer (23 kg per bag), followed by the pea gravel (14 kg per bag of Five Star HP). This combination was mixed for 5 to 6 minutes. As is common with this material, the mix looked very dry until it had been mixed for almost 4 minutes. However, additional water was not added, as the mix is very sensitive to water content.

Before the mix was shoveled into the repair hole, the hole was sprayed with water. The mix was vibrated by moving a trowel up and down throughout the patch. The manufacturer recommends that the surface of the patch be kept moist for at least 30 minutes after the mix has stiffened. This was accomplished by spraying water onto the patch every 5 to 10 minutes, for a total of 30 minutes. The working time for the Five Star HP concrete was approximately 10 minutes, and the opening time was 1 hour at 27°C and 2 hours at 10°C.

Set-45

The mixing of Set-45 was accomplished using a mortar mixer. With the mixer running, the water was added to the mixer (1.9 L per bag of Set-45). Then the cement was added (23 kg per bag), followed by the pea gravel (14 kg per bag of Set-45). This combination was mixed for 2 to 3 minutes. The mix was shoveled into a dry hole, worked with a trowel, and air cured. The working time was approximately 10 minutes, and the opening time was 1 hour at 27°C and 3 hours at 10°C.

Pyrament 505

A mortar mixer was used for mixing Pyrament 505. With the mixer running, the water was added to the mixer (2.2 L per bag of Pyrament 505). The pea gravel was then added to the mixer (14 kg per bag of Pyrament 505), followed by the cement (23 kg per bag). This combination was mixed for 6 to 7 minutes. Before the mix was shoveled into the hole, the hole was sprayed with water. Then the mix was worked and leveled with a trowel and finished with a float.

Approximately 5 minutes after finishing, a curing compound was sprayed on the surface. The working time was approximately 10 minutes, and the opening time was 1.5 hours at 27°C and 2 hours at 10°C.

SikaPronto 11

Preparation of SikaPronto 11 involves mixing component A, a liquid set initiator, with the cement and then adding the aggregate. Two different methods of mixing SikaPronto 11 were used. The first method involved using electric drills with Jiffy mixers to mix the three components. The second method used the standard mortar mixer. It was believed that the first method would provide more uniform mixing; however, because of the size of the batches mixed, this method proved to be inefficient. The mortar mixer seemed to provide satisfactory results and was more convenient to use.

Before the SikaPronto 11 mix was poured into the dry hole, the hole was primed with the methylmethacrylate primer, SikaPronto 19, as specified by the manufacturer. The SikaPronto 19 primer was prepared by combining component B with component A and mixing for 3 minutes, using a low-speed electric drill and a "Sika" paddle provided by the manufacturer. The primer was brushed onto the surfaces of the repair area.

The mix was placed in the prepared hole while the primer was still tacky and was vibrated with a mechanical vibrator. The manufacturer recommends that the SikaPronto 11 be placed in lifts with sufficient cure time between lifts if the thickness of the repair is greater than 38 mm. However, because of the nature of this project, it was not practical to place the material in lifts and the material was placed in one lift only. Following placement, the patches were air cured. The SikaPronto 19 primer has a pot life of 20 minutes and will remain tacky for 20 minutes at 21°C. The SikaPronto 11 mix has a working time of 20 minutes and an opening time of 2 hours at 27°C.

Percol FL

After the spall area was cleaned, the repair area was filled to grade with 19-mm washed and oven-dried crushed stone. Percol FL, a flexible two-component polyurethane resin, was pumped directly over the preplaced aggregate and allowed to percolate through the voids around the aggregate until it was flush with the pavement surface. Immediately following the flooding of the repair area with the resin, 6.4-mm aggregate was broadcast over the top of the repair as a friction layer, as shown in figure 14. An air-powered Percat 500 pump drove equal amounts of each resin thorough an impingement mixer to the discharge nozzle. The resin was pumped from two 208-L tanks. The initial set time for the Percol FL was 60 seconds, and the opening time was 2 to 3 minutes at 27°C, as well as at 4.5°C.

Figure 14. Placement of Percol FL.

MC-64

MC-64, a two-component epoxy, comes prepackaged with long-grain rubber aggregate in two 19-L buckets. One bucket contains a premeasured amount of resin A, and the other contains a premeasured amount of resin B. These two components were first mixed individually for 3 minutes, then part B was added to part A and the combination was mixed for 5 more minutes. Timers were used to keep track of mixing times. Stainless steel 530-mm Jiffy mixers, powered with 19-mm drill motors, were used for mixing the components, as shown in figure 15.

After mixing the two components, the material was poured into the prepared spall. Although the manufacturer states that the material may be placed in one lift, under the supervision of the manufacturer's representative, the material was placed in 50-mm lifts with as little as 4 to 5 minutes between lifts. A stiff asphalt-impregnated styrofoam board was used to work the material to the patch corners and level with the pavement. The working time was 10 minutes, and the opening time was 2 hours at 27°C, as well as at 4.5°C.

Penatron R/M-3003

Before Penatron R/M-3003 was mixed, the repair hole was filled to grade with 19- to 25-mm washed and dried, crushed granite rock. The Penatron R/M-3003 15-L kit comes with two parts of component A and two parts of component B.

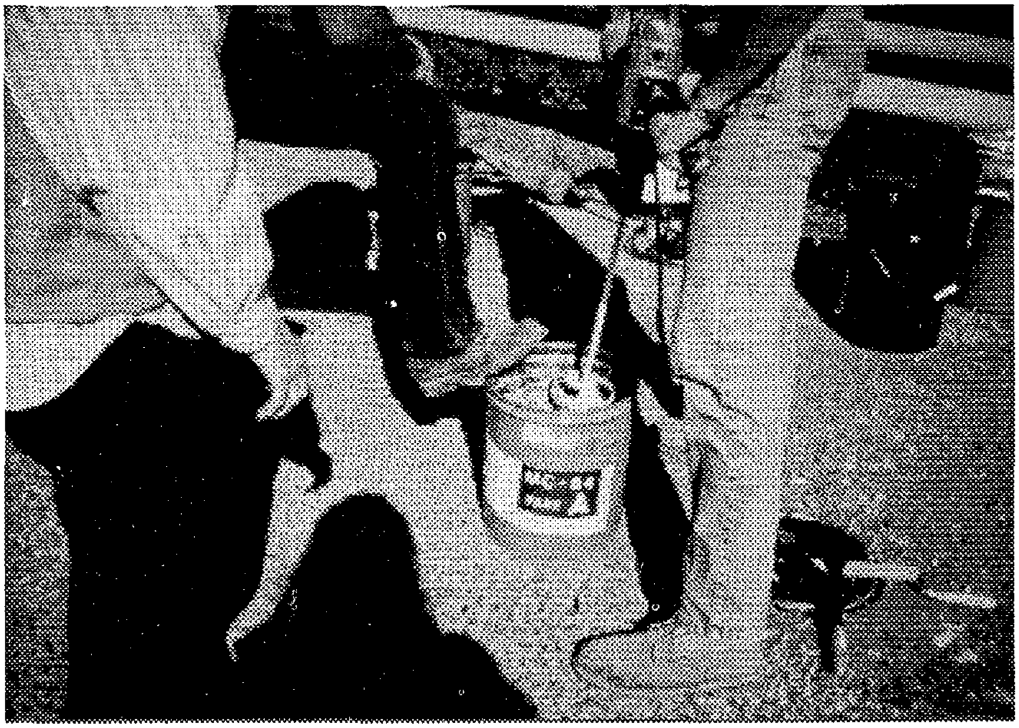

Figure 15. Mixing of MC-64.

First, part A was poured into a clean, 19-L mixing bucket. Jiffy mixers were used for mixing. While mixing part A, part B was slowly and carefully poured into the same bucket. The mixture must be continuously agitated during the addition of part B. After the two components were added to the mixing bucket, mixing was continued for another minute. Immediately following mixing, the product was poured into the repair hole and allowed to encapsulate the pre-placed rock until the patch was level with the surrounding surface. A cardboard trowel was used to finish the surface. The working time for Penatron R/M-3003 was approximately 5 minutes, and the opening time was 45 minutes.

UPM High Performance Cold Mix

UPM High Performance Cold Mix is a premixed bituminous material. It was shoveled directly from 208-L drums into the repair areas with no additional preparation. The repair areas were overfilled and then compacted using a vibratory roller or plate until the patches were level with the pavement, as shown in figure 16.

Spray-Injected Mix

This bituminous mix was placed using a Rosco or AMZ spray-injection machine. As soon as the hole was cleaned with the machine's blower, the operator sprayed a tack coat into the hole and along the edges of the pavement surface surrounding the repair area. Then, a mixture of liquid asphalt and aggregate was sprayed directly into the prepared hole. When the repair was filled level with the pavement surface, a coating of chip stone was applied to prevent tracking.

Figure 16. Compaction of UPM repair.

Joint Sealing

After a cure time of at least 1 week, the transverse joints bordering the partial-depth patches were sealed using each State's joint or crack sealing specification and materials at the time of installation. There were considerable differences in these specifications and standards. In South Carolina, a soft, bituminous joint sealant was applied heavily at the joint location. In Pennsylvania, a soft, bituminous sealant was applied around the entire perimeter of the patch. In Utah, a silicone joint sealant was applied. The test site in Arizona was not sealed because of the high traffic volume at the site and the need to minimize the disruption of traffic.

Equipment

The mixing, placing, and patch preparation procedures used in this experiment required some equipment commonly used by maintenance crews everywhere, such as jackhammers, concrete saws, and mechanical vibrators, as well as some less commonly used equipment, including spray-injection machines and waterblasting equipment. Table 5 shows the equipment typically used to prepare patches using each of the five procedures included in the project. Table 6 shows the mixing and placement equipment and supplies typically used with the rapid-setting spall repair materials included in the project. In all cases, the manufacturers' materials specifications were consulted for mixing and placing equipment requirements.

Table 5. Typical equipment used for the five patch preparation procedures.

Equipment	Preparation Procedure				
	Saw-and-Patch	Chip-and-Patch	Mill-and-Patch	Waterblast-and-Patch	Adverse Clean-and-Patch
Sounding equipment: rod, chain, or ball-peen hammer	✓	✓	✓	✓	✓[a]
Double-bladed concrete saw for joint sawing	✓	✓	✓	✓	
Single-bladed concrete saw for sawing patch boundaries	✓				
6.8-kg jackhammer with air compressor	✓	✓	✓[b]		✓[a]
13.7-kg jackhammer with air compressor	✓[c]	✓[c]			
Stiff brooms for debris removal	✓	✓	✓	✓	✓
Handtools (e.g., pick axe)	✓	✓			✓
Truck for hauling removed material	✓	✓	✓		✓
Waterblasting machine				✓	
Carbide-tipped, cold-milling machine			✓		
Sandblasting equipment with directional nozzle, sand, air compressor	✓	✓	✓	✓	✓[a]
Airblasting equipment with oil and water filtering capability, air compressor	✓	✓	✓	✓	✓[a]

[a] Jackhammers were used for large areas, or when the deteriorated concrete could not be removed using handtools. Sandblasting, airblasting, and sounding were not used under adverse conditions.

[b] To remove rounded edges.

[c] 13.7-kg jackhammers were preferred. 13.7-kg hammers were **never** used at patch boundaries.

Table 6. Typical mixing and placement equipment and supplies.

Typical equipment and supplies	Type III	Duracal	Set 45	Five Star	MC 64	SikaPronto	Penatron	Pyrament	Percol FL	UPM	Spray Inj
Potable water/hose/pump	✓	✓	✓	✓		✓		✓			
Drum mixer (1.9-2.5 m^3)[a]	✓	✓						✓			
Mortar mixer (0.9-1.2 m^3)			✓	✓		✓					
19-mm electric drills and 533-mm stainless steel Jiffy mixers	✓[b]				✓[b]	✓[b]	✓				
Bonding agent brush/roller	✓					✓					
Vibrators and/or screeds	✓	✓	✓			✓		✓			
Trowels	✓	✓	✓	✓	✓	✓		✓			
Shovels	✓	✓	✓	✓		✓		✓		✓	
Curing compound, applicator, burlap, or plastic sheeting[c]	✓	✓	✓					✓			
Insulating blankets[d]	✓							✓			
Vibratory roller or plate										✓	
Electric generator[e]	✓	✓	✓	✓	✓	✓	✓	✓	✓		
Grayco Percat 500[f]									✓		
Spray-injection machine[g]											✓
Nonwater cleaning solvent					✓	✓	✓		✓	✓	
Compression cylinders/rod	✓	✓	✓	✓				✓			
Slump cone	✓	✓	✓	✓				✓			
Air meter, rod, water bulb	✓										

[a] Mixers used had at least twice the volume of the amount of material to be mixed.
[b] Capable of 400 to 600 rpm.
[c] Used in hot (> 29°C), windy (>41 km) weather.
[d] Used in weather below 7°C.
[e] Used as needed; sufficient for demand.
[f] Air-driven, automatic, ration-metering pump.
[g] Capable of delivering chip-size aggregate and asphalt emulsion (e.g., AMZ, Rosco).

Documentation

To evaluate the performance and cost-effectiveness of the repair procedures and materials, detailed information regarding the installation of the test sites was collected. The information collected includes:

- Patch length, width, and depth.
- Degree of faulting at the joint.
- Whether reinforcing steel or dowels were visible during patch preparation.
- Date of patch placement.
- Patch area preparation procedure used.
- Patching material used.
- Bonding material used.
- Climatic conditions at time of construction.
- Time before opening to traffic.
- Time required for construction.
- Workability of the material.

Productivity and Cost Data

Productivity and cost data were necessary to determine the overall cost-effectiveness of the materials and procedures being evaluated. Productivity data were collected at each of the test sites during installation of the test site. Material cost data were obtained from the manufacturers of the repair materials.

Productivity

Three factors seemed to affect the efficiency of the patching operations: personnel, equipment, and traffic control. As mentioned earlier, two of the spall repair test sites, Utah and Arizona, were constructed by private contractors. The contractors at both of these sites had more personnel and more and better equipment available than the participating State agencies. A major problem encountered at both the South Carolina and Pennsylvania sites was equipment breakdown. The majority of the equipment used by the States was old, poorly maintained, or of insufficient capacity.

Traffic control requirements varied from site to site. In Utah, overnight traffic control was set up for the duration of the construction. In Arizona and South Carolina, temporary traffic control was set up and removed every workday. In Pennsylvania, temporary traffic control was used during the first 3.5 weeks and overnight traffic control was used for the remaining 2 weeks. Use of temporary traffic control reduced the productive time available in each workday by 1 to 2 hours and resulted in downtime for the personnel not involved with traffic control. There also was a significant amount of downtime near the end of the day after placement of the last patch for the day.

At the Arizona test site, all construction work was performed at night or on weekends because of the high traffic volume of the roadway. Though not quantifiable in this situation, night work appeared to reduce productivity somewhat. Table 7 shows the number of patches installed at each test site and the approximate time required for the installations. "Productive hours" were determined by subtracting the time necessary for setting up and removing traffic control, scheduled breaks, and the hour needed for cure time at the end of the day from the scheduled work hours.

Maintenance repairs of this nature usually are performed with the adjacent lane open to traffic. Many of the patching operations, such as sawing or removal of the deteriorated concrete by milling, waterblasting, or chiseling, often require encroachment into the adjacent lane. This, of course, also affects productivity. More important, it affects the safety of the repair crew. Patching procedures and materials that minimize the time required for repairing the pavement are highly desirable.

Crew Size

The various procedures and materials that were evaluated required different labor for the removal and replacement of the deteriorated concrete. Summaries of the labor requirements for the procedures and materials evaluated in the project are shown in tables 8 and 9, respectively. For the majority of the installations, the patching operations were done sequentially, with different crews responsible for different activities.

Table 7. Time required for placement of spall repairs.

Participating Agency	Productive Hours per Day	Number of Patches Installed	Number of Days	Average Number of Patches per Hour
Commonwealth of Pennsylvania DOT - Armstrong County Maintenance Crew	Temporary Traffic Control: 4 to 6	205[a]	13.5	3
	Overnight Traffic Control: 6	175	8.0	4
South Carolina DOH&PT - Lexington County Maintenance Crew	7	320	12.5	4
Utah DOT - Wadsworth Construction Co.	9.5[b]	440[c]	5	9
Arizona DOT - Bentson Contractors	Weeknight: 6.5	245	5.5	7
	Weekend: 12.5	140	1.5	7

[a] Does not include the patches installed under adverse conditions or the Rosco patches that were installed 1 month after the majority were installed.

[b] Traffic control was left in place during the weekdays and removed during the weekend.

[c] At this test site, a test section consisted of 10 joints rather than 10 patches. All spalls on the joint were repaired.

Table 8. Labor requirements for the various spall repair procedures.

Spall Repair Procedure	Required Labor
Re-establishing joint sawing	1 person operating saw 1 person directing saw
Saw-and-patch	1 person directing saw 1 person operating saw 2 persons operating pneumatic hammers 2 persons cleaning repair hole 1 person removing debris
Chip-and-patch	2 persons operating pneumatic hammers 2 persons cleaning repair hole 1 person removing debris
Mill-and-patch	1 person operating milling machine 1 person directing milling machine 2 persons operating pneumatic hammers 2 persons cleaning repair hole 1 person removing debris
Waterblast-and-patch	1 person operating waterblaster 1 person operating water truck 1 person cleaning repair hole
Clean-and-patch	1 person operating pneumatic hammer 1 person cleaning repair hole
Inserting joint bond-breaker	1 person installing joint board (available for other activities)

Table 9. Labor requirements for the various spall repair materials.

Repair Material	Required Labor
Type III PCC	2 persons mixing and applying epoxy 2 persons proportioning and mixing Type III PCC mix 3 persons placing, compacting, and finishing
Duracal	1 person proportioning and mixing Duracal 2 persons placing, compacting, and finishing
Five Star HP	1 person proportioning and mixing Five Star HP 2 persons placing, compacting, and finishing 1 person spraying curing water
Set-45	1 person proportioning and mixing Set-45 2 persons placing, compacting, and finishing
Pyrament 505	1 person proportioning and mixing Pyrament 505 2 persons placing, compacting, and finishing
SikaPronto 11	2 persons mixing and applying SikaPronto 19 2 persons proportioning and mixing SikaPronto 11 2 persons placing, compacting, and finishing
MC-64	4 persons mixing MC-64 2 persons placing and finishing
Percol FL	1 person placing rock into prepared hole 1 person driving truck with pumps and tanks 1 person applying Percol FL 1 person applying broadcast aggregate
Penatron R/M- 3003	1 person placing rock into prepared hole 2 persons mixing Penatron R/M-3003 3 persons placing and finishing
UPM	2 persons shoveling and placing mix 1 person operating vibratory roller or plate
AMZ/Rosco	1 person driving truck 1 person operating binder/aggregate sprayer

Every operation except sawing was performed within a reasonable time following the preceding operation. For example, a crew would saw the patch boundaries, followed by a crew using jackhammers to remove the concrete, followed by another crew sandblasting and airblasting the patches clean. The sawing was performed at least 1 day before the other operations. Generally, four or five repair areas were prepared for receiving the repair material before the mixing of the repair material was started. This decreased the amount of waste and allowed more efficient use of the repair material. At no time was the patching material placed more than 30 minutes after airblasting.

Tables 8 and 9 list the minimum number of personnel used by the participating agencies. In certain cases, such as with the placement of the aggregate with the Percol FL or Penatron R/M-3003 and the insertion of the joint bond-breaker, persons could be used for two activities that did not occur simultaneously. A supervisor generally was responsible for overseeing the crews and their operations. Inspection was performed by the SHRP H-106 project staff.

Material Cost

The cost of the materials evaluated in this experiment varied greatly, as shown in table 10. The costs shown in the table do not include shipping or any discounts that may be realized by buying large quantities. Cementitious materials are readily available through local distributors. However, the newer polymer materials had an additional cost (not shown in the table) because they required shipping from the source of production.

Table 10. Spall repair material cost.

Material	Unit	Weight of Aggregate per Unit of Material, kg	Cost per unit, $	Cost per m^3, $
Type III PCC	42.7 kg	154.4	5.00	172.50[a]
Duracal	22.7 kg	45.4	7.50	279.70
Five Star HP	22.7 kg	13.6	18.00	1098.00
Set-45	22.7 kg	13.6	21.50	1293.93
SikaPronto 11	30.9 kg	17.0	113.00	5672.38[a]
MC-64	15.1 L	N/A	129.00	8560.85
Percol FL	3.8 L	22.2	29.00	3502.76
Pyrament 505	22.7 kg	13.6	9.00	575.08
Penatron R/M-3003	15.1 L	40	188.00	6221.32
UPM High Performance Cold Mix	1.1 Mton	853.5	65.00 to 80.00	182.98 to 235.26
AMZ/Rosco	1.1 Mton	varies	35.00 to 60.00[b]	91.49 to 143.77

[a] The cost does not include the cost of the bonding agent. Due to the small number of spalls being repaired at one time using this material, a significant amount of waste was encountered. The cost of the epoxy bonding agent used was $13/L, and the cost of the methacrylate bonding agent was $29/L.

[b] The cost of the spray-injected bituminous patching material represents averages provided by the manufacturers. These costs include the cost of purchasing the equipment (amortized over the life expectancy of the equipment), maintenance, binder, aggregate, and other variable costs.

Comments

During the installation process, observations were made regarding the ease and workability of the materials and procedures. The following sections describe these observations.

Saw-and-Patch Procedure

The saw-and-patch procedure is generally the most accepted way of patching partial-depth spalls. The advantages of this procedure are that the saw leaves vertical edge faces, the forces experienced by the pavement during removal of the concrete within the sawed boundaries are isolated to within the patch area, and very little spalling of the remaining pavement occurs. However, if water is used during the sawing operation, the repair area may be saturated for some time afterward. Some patching materials are very susceptible to the moisture condition of the substrate and will not bond to a wet surface. If such a material is being used, concrete replacement operations may have to be delayed. It was found that no spalling of the edges resulted from allowing traffic onto the repair areas that had been cut 1 to 2 days prior to being replaced. Furthermore, if additional unsound concrete is found beyond the original boundaries after the initial removal, the saw must be brought back to saw new boundaries, which may create a delay. To obtain the depth of cut required for the patch boundaries, the boundaries must be overcut 50 to 75 mm in each direction. These overcuts may create a weak area that may deteriorate in the future unless cleaned and sealed. If the area to be patched is adjacent to the open lane of traffic, the saw must encroach into that lane, creating a somewhat dangerous condition. Generally, the removal of the deteriorated concrete within the sawed boundaries was much easier and quicker than when the boundaries had not been sawed.

Chip-and-Patch Procedure

The chip-and-patch procedure (without sandblasting) is frequently used by highway agencies when it is perceived that there is not enough time to patch using the more rigorous saw-and-patch procedure. This method has other merits as well. Once the joint sawing has been completed, the concrete saw is not needed again. It is much easier with this method to remove any additional unsound concrete found after the initial removal. The chisel also leaves a rough vertical edge, thus providing more bonding area for the replacement material. If a light jackhammer is used around the periphery of the patch, the spalling can be controlled.

The chip-and-patch procedure also does not leave saw overcuts, which may be a plane of weakness or require sealing. Therefore, including the time required to saw and dry the patching area, resaw, and seal the overcuts, this method may take less time than the more rigorous saw-and-patch method. Unfortunately, because of confounding factors, the analysis of productivity could not determine which of these two procedures is actually faster.

The main objections to the chip-and-patch method are the fact that damage to the remaining concrete can occur when heavy pneumatic hammers are used and that the patch edges may be feather-edged. The transmission of destructive forces may be reduced by allowing a heavy pneumatic hammer only at the center of the area to be removed. A light pneumatic hammer should be used around the edges. Also, the work should progress from the inside of the patch toward the edges and the chisel point should be directed toward the inside of the patch. Feather-edging of the patch edges can be minimized by requiring a minimum 25-mm vertical face on all sides. It was also felt that sandblasting is required to achieve proper bond.

Mill-and-Patch Procedure

The milling machine is very efficient in removing large areas of spalled concrete. With a milling head of 0.3 m, the smallest currently available for this use, the repair area will be a minimum of 0.09 m^2. Therefore, if the area to be repaired is small, the patch may be larger than necessary. The exposed bottom surface of the concrete created by milling is very rough and very level, as shown in figure 17. The hole created by the operation will tend to be concave, rather than vertical, at the boundaries that are perpendicular to the direction of the milling. The milling operation also caused spalling on the edges of the adjacent pavement. The removed concrete becomes a fine slurry that is easy to wash away. The size of the machine and the location of the milling head in relation to the rest of the equipment affects the efficiency of the removal operation.

The orientation of the concave edges was parallel to the direction of traffic where possible. However, because of traffic constraints, the equipment was not always able to maneuver into such an orientation. It may be desirable in such cases to chisel the edges to form a vertical face. This was done on all but one test section in Arizona. Cementitious materials, in particular, may not perform well when feather-edged.

Figure 17. Patch area for milling operation.

Milling machines are generally readily available in most regions of the United States. However, a suitable machine, at a reasonable cost, could not be located in Utah. The cost of renting a milling machine, including an operator, may vary from $250/day to $200/hour. A Caterpillar PR-105 pavement profiler was used in Arizona, and a Barcomill 100 milling machine was used in Pennsylvania.

Between 6 and 10 teeth were replaced daily in Pennsylvania. In Arizona, 31 teeth were replaced the first day, 13 the second day, and 6 the third day. An average rate of 2.3 m^2/hr was achieved at both test sites. This rate includes the time to travel to each spall repair location and orientation of the machine. The rate was significantly greater when the repair areas were larger and located away from the adjacent lane of traffic. The rate does not include the time to straighten the concave edges left by milling. The machine used at both test sites seemed more suited for milling asphalt. More powerful equipment may be more efficient for milling concrete. Less spalling of the adjacent pavement may also result from using a more powerful machine.

Waterblast-and-Patch Procedure

The use of a high-pressure water jet (207,000 kPa) to remove the deteriorated concrete was attempted at the test sites in Arizona and Utah. The main advantage of using a high-pressure water jet is that once the jet nozzle speed and pressure are adjusted, only the weak concrete is removed. The operation also can be done with as few as two people. Another advantage may be the finished condition of the exposed faces of the repair hole. The bottom and sides of the finished area are extremely rough and angular, providing more surface area to which the new replacement material may bond. A disadvantage may be that the finished surfaces are saturated, which may limit possible replacement materials to those that require a wet bonding surface. Otherwise, time is required to allow the area to become dry. Another concern is that the fine slurry laitance left by the removal process requires careful attention in the sandblasting phase of the patching operation.

The waterblasters were originally expected to remove the concrete at a rate of 5.4 m^2/hr; however, problems with equipment at both locations brought this rate down significantly. In Utah, it took 3 days of in-the-field diagnostic work before the operator could get the jet to work properly. Once the equipment was operational, a production rate of 0.9 m^2 to 1.4 m^2/hr was achieved. A significant amount of time was needed to orient the nozzle at each patch location. The waterblaster broke the concrete down to fine and coarse aggregate, and this aggregate was ejected out of the hole. A protective shield was constructed around the area under repair to avoid damage to traversing traffic. The cost of renting the equipment was $10,000/month.

In Arizona, the first working day was spent trying to get the waterblasting equipment operational (without success). The subcontractor spent the next day "fixing" the waterblaster. The following working day, another 1.5 hours were spent in the field adjusting the water jet nozzle speed and pressure. When the equipment was working, it was difficult to control the depth of removal. After removing the deteriorated concrete at five spall locations, the equipment again broke down. At the time, a production rate of 0.6 m^2 to 0.7 m^2/hr was being achieved. It was speculated that the aggregate in the original pavement was a very tough granite and was therefore requiring extra demolition time. The cost of subcontracting this work was $4,352 per day, not including mobilization and transportation costs.

Adverse-Condition Patching

When patching under adverse conditions and using a cementitious material, it is very unlikely that a wet saw can be used to re-establish the joint. It will therefore be very difficult to install the joint bond-breaker to the proper depth, slightly below the depth of removal. In cold weather, hot water and insulating blankets are also required. At the adverse-condition test site, a heated water tank was not available. Although the water tank was insulated, it was very difficult to maintain the warm temperature of the water. Insulating blankets also were difficult to keep in place because of wind gusts created by passing trucks in the adjacent lane.

It should also be noted that in one test section involving the installation of UPM, the repair hole was not wetted prior to placement of the material because no water was available at the job site that morning. Only handtools were to be used to remove the loose concrete, but only the very loose material was removable with handtools. Therefore, a small jackhammer was used to remove all of the deteriorated material.

Joint Preparation

Re-establishing the joint with a partial-depth saw cut and removing any point of mechanical conflict is considered critical to the performance of the new patch. If this saw cut is not deep enough or wide enough, inserting the joint bond-breaker is difficult. Figure 10, shown earlier, illustrates the proper placement of the foam bond-breaker prior to the placement of the repair material. It was suggested that latex sealant be used to caulk any irregularities or openings between the backer board and the joint. This proved to be extremely difficult and time-consuming. Often, the sawed joint was not located directly over the working crack. The performance of patches installed in that situation is highly questionable. On back-to-back repairs at a joint, maintaining the alignment of the backer board is difficult. Stiffer boards may be required for such repairs.

Type III PCC

Type III PCC is the most commonly used rapid-setting cementitious patching material; therefore, the maintenance and construction crews are familiar with the placing, consolidation, finishing, and curing techniques necessary to install this product. To achieve the high, early strength desired for this project, many admixtures were incorporated into the mix design. The addition of these admixtures in the proper quantities, in proper sequence, and at the proper time required much attention. The mix was workable at the two test sites where air temperatures at the time of placement were below 27 °C. However, it was stiff and difficult to work with at higher temperatures.

Duracal

Of the products being evaluated, Duracal is most like "regular" concrete to handle. The proportioning, mixing, placing, and finishing of this product were very easy to accomplish. The product is self-leveling and does not require mechanical vibration or a curing compound under normal conditions. Although a bonding agent was not applied before placement of Duracal, the manufacturer suggests that a bonding agent be used on shallow patches. Feather-edging is not recommended. This product is more tolerant of higher ambient air temperatures than the other cementitious products that were evaluated.

Five Star HP

The Five Star HP concrete looks very dry during most of the mixing cycle and appears wet only during the last few minutes of mixing. The temptation to add water must be resisted, as the strength is adversely affected by the addition of water. The concrete is fairly self-leveling and only requires compaction by trowel. The product is temperature-sensitive and will set quickly at temperatures above 27 °C. A chemical retarding additive is available to lengthen the working time if patching is done in hot weather. One tube of Summerset per bag of material is added during mixing to gain an additional 5 minutes of working time. Summerset was used in South Carolina and Pennsylvania. One major drawback to this product is the requirement for wet curing the material for 30 minutes after placement. This is difficult to ensure and oversee in a moving operation. It is also difficult to determine exactly when the material has set sufficiently to start wetting the surface.

Set-45

Set-45 is very sensitive to ambient air temperatures. When the air temperature is below 27 °C, the working time for the product is approximately 10 minutes and the product is easily placed and finished. However, when the air temperature is above 27 °C, the working time for the product is much less. At the Arizona, Pennsylvania, and South Carolina test sites, the product set in the wheelbarrow or in the patch before it could be compacted. Though the use of ice water to slow the initial set was recommended (and used in South Carolina), it was often impractical to do so. For this reason, Set-45 is available in a "hot weather" formula. It should be noted that the substrate must be dry and that the product should not be used to repair pavement constructed with limestone aggregate. The presence of limestone aggregate can be checked by wetting the freshly exposed concrete face with vinegar. If bubbles appear, the pavement contains limestone aggregate. Set-45 also emits a peculiar, although not harmful, odor.

Pyrament 505

Pyrament 505 was easy to mix, place, and finish when placed under normal conditions during the project (an ambient air temperature above 4 °C). It behaved very much like regular concrete. This product takes more time for mixing than the other cementitious products being evaluated (except the Type III PCC mix) and appears dry until the last few minutes of the mix cycle. It was less workable under adverse conditions, which are defined in this project as an ambient air temperature below 4 °C and a repair area saturated with surface moisture. Without hot water and insulating blankets, the material will not set in the time stated. For small maintenance operations, such as the project at the Pennsylvania test site, it may be difficult to keep the water sufficiently hot for the time required for patch preparation. The product's workability under high air temperatures was not evaluated, as it was not installed under this condition.

SikaPronto 11

When properly mixed and under normal conditions during the experiment (4 to 32°C), SikaPronto 11 was easy to work with and finished very easily. Even under higher air temperatures (> 32°C), the SikaPronto 11 concrete retained its workability. However, the primer required for its placement, SikaPronto 19, gelled very rapidly at these high temperatures and became difficult to apply to the patch substrate. The manufacturer recommended that the product be installed in lifts because of the heat of hydration of this product. However, time and construction constraints made it impractical to do this. No adverse effects have been noted to date from this method of placement.

A major concern with this product may be its toxicity. In particular, masks are recommended to avoid breathing the fumes. However, during mixing and placement, the material looked and finished very much like regular concrete; because of this similarity to a nontoxic repair material, workers may tend to disregard the face mask recommendation.

At three of the four test sites, product representation for SikaPronto 11 was very poor. The local manufacturer's representatives were either not available or not very knowledgeable about the product and its installation. Because its mixing and use are different from normal concretes, it may be difficult to get this product to perform properly.

Percol FL

Use of polyurethanes for pavement patching is fairly new to most maintenance and construction workers. With the proper equipment, the procedure to install the material is simple. The required equipment, the PERCAT 500, may be purchased for $10,000 or rented for $750/month. A qualified technician is required to adjust the pumps for proper mixing of the two component resins prior to dispensing Percol FL. Once the pumps have been adjusted, the machine is easy to operate. A Percol Polymerics Inc. representative was available at the four test sites to operate and adjust the equipment (which took considerable time at some locations). It is also critical that clean, oven-dried aggregate be used with this product; even a small amount of dust or moisture may cause poor bonding or bubbling.

Properly filling the repair hole to grade with the 19-mm aggregate is critical to achieving a smooth-riding patch. If the hole is overfilled, the resultant patch is very rough. If the hole is underfilled, additional resin will be required, and the cost of the repair will be increased. The product sets very rapidly. If a friction aggregate is to be broadcast over the repair area, it must be done within the critical time period. This critical time period is very short at high ambient air temperatures. At the Arizona and Pennsylvania test sites, to achieve a smoother finish, the repair area was not filled flush with the resin, but was underfilled approximately 6 mm. When the resin started to react, the repair area was sprayed with a very fine mist of the resin and the friction aggregate was broadcast. The repairs in Utah and South Carolina are rough and have an uneven finish.

It should be noted that Percol FL has a very low viscosity and is therefore difficult to place on pavements with slopes and grades. A qualified, experienced technician may be able to produce a smooth patch by adjusting the dispensing rate. However, even though they were placed by the manufacturer's representative, many of the patches installed on a grade in this experiment were not level.

A major advantage of this product is its rapid setting time. If Percol FL can be applied to shallow, rapidly cleaned (non-sandblasted) patches, repairs may be performed using a moving traffic control operation. One potential disadvantage with Percol FL is that the disposal of the unused portion of this product may be of concern in certain States.

MC-64

The use of epoxies for pavement patching is unfamiliar to most maintenance and construction workers. As with most epoxies, proportioning and mixing is critical to the performance of MC-64. The manufacturer's representative ensured that the materials were mixed properly. Using two or three Jiffy mixers at a time is essential for an efficient operation. Each mixer requires one operator, as well as an additional operator to pour part B into part A and clock the mixing time. Part B must always be added to part A, and if using only one mixer, part B must be mixed first. The mixing paddles must not be interchanged, as this may cause the product to set prematurely. The finishing technique for this material is also very different from commonly used techniques and must be carefully observed. An asphalt-impregnated board is used in a repeated up-and-down stroke to work the resin to the surface, as well as to move the material. Both the mixing and finishing required many persons and much time. An advantage of this product is that very little equipment is required; therefore, mobilization time and cost are minimized. Another advantage is that because the component parts are premeasured, material properties are less variable.

Users should note that this product has a very low viscosity at high temperatures and may require special care in placing it on pavements with slopes and grades when patching in hot weather. The product must be worked against the grade repeatedly until it has set. The disposal of the unused portion of this product may be of concern in certain States.

Penatron R/M-3003

The mixing and placing of Penatron R/M-3003 was relatively easy. However, care was required during mixing because of the requirement that agitation of component A must be ongoing during the addition of component B. Placement of the correct gradation and amount of aggregate in the repair hole results in a smooth patch and optimal use of materials, thereby reducing cost. As with the epoxy and polyurethane materials, this product has a very low viscosity and is difficult to place on pavements with slopes and grades. The disposal of the unused portion of this product may be of concern in certain States.

UPM High Performance Cold Mix

The placement of the bituminous cold mix is very simple. The only advice on the installation procedure is to leave the patch slightly high (3 to 6 mm) to allow for additional compaction from traffic.

AMZ/Rosco

The placement of this spray-injection bituminous material is very simple; however, an experienced operator is needed to control the flow of the aggregate and asphalt to the nozzle because these variables are not preset. There is also a significant amount of overspraying, making the patch appear larger than it is and resulting in a rough patch.

Test Site Conditions

Although the test sites were carefully screened for their suitability to the demands of the SHRP H-106 project, unexpected pavement conditions were encountered at the Pennsylvania site. Ideally, only spalls that measure less than one-third the pavement thickness in depth are suitable for partial-depth repairs. However, the depth of the deterioration below the spalled area is difficult to determine prior to actually repairing the spall. At the Pennsylvania test site, joint deterioration often was more severe than the surface visual inspection indicated. Many of the spalled areas were deteriorated to the depth of the dowel bars and below. Because of time constraints and the unavailability of proper equipment to perform full-depth repairs, partial-depth repairs were installed and will be evaluated as part of this project.

At the Arizona test site, a majority of the work was performed at night. Although floodlights were used, the relative darkness made it difficult to determine if the area of deterioration at each repair location had been completely removed and if the repair area was sufficiently clean. Noise from the high traffic volume muted the effectiveness of sounding the pavement.

CHAPTER 3. MATERIAL TESTING

In addition to the identification of appropriate test locations and the installation of many different patch types, the SHRP H-106 project included a series of laboratory tests on the materials used in the experiment. The laboratory testing was an attempt to define pertinent material characteristics that could be related to the performance of the materials in the field. Once these characteristics were identified, the next step would be to formulate sample specifications regarding the materials, mixing, and placement of rapid-setting, partial-depth spall repair materials that would take advantage of characteristics indicative of good performance while avoiding characteristics indicative of poor performance.

Laboratory Tests Performed

The tests performed on the rapid-setting, partial-depth spall repair materials were intended to characterize the physical properties of the materials. Appropriate tests were run on the various materials according to their classification as cementitious, polymer, or bituminous. However, since the life of the individual spall repairs often is longer than the duration of this project, the ability of this experiment to determine performance-related specifications and to predict spall repair life is limited. Continued monitoring of patches will provide the additional field performance data needed to establish correlations between laboratory data and field performance.

All materials were prepared and cured in the laboratory according to the manufacturers' recommendations. If a product could be extended with aggregate, the maximum percentage recommended by the manufacturer was used to extend the material. All materials for the laboratory evaluation were sampled from the materials being used at one of the test sites. Manufacturers were requested to ship materials to all of the test sites from one manufacturing lot or one day's production to reduce overall material variability. Aggregate for each of the materials also came from a single source, and this aggregate was used in making the laboratory specimens.

The tests and test procedures used for the cementitious or polymeric patching materials included the following:

- Compressive Strength of Hydraulic Cement Mortars, ASTM C 109 and Compressive Strength of Cylindrical Concrete Specimens, ASTM C 39.
- Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression, ASTM C 469.
- Flexural Strength of Concrete (Using Simple Beam With Third-Point Loading), ASTM C 78.
- Bond Strength of Epoxy-Resin Systems Used with Concrete, ASTM C 882 and Caltrans Method of Test of Bonding Strength of Concrete Overlay and Patching Materials to PCC.
- Resistance of Concrete to Rapid Freezing and Thawing, ASTM C 666A.
- Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals, ASTM C 672.

- Method for Determining the Surface Abrasion Resistance of Concrete Specimens, Caltrans California Test 550.
- Length Change of Hardened Cement Mortar and Concrete, ASTM C 157.
- Thermal Compatibility Between Concrete and an Epoxy-Resin Overlay, ASTM C 884.

Laboratory evaluation for the bituminous patching materials included the following:

- Resilient Modulus: ASTM D 4123.
- Marshall Stability: ASTM D 1559.
- Antistripping: ASTM D 1664.
- Workability: Pennsylvania Transportation Institute method.
- Extraction: ASTM D 2172.
- Sieve Analysis: ASTM C 136.

Laboratory Test Results

Compressive strength is often used for specifying and evaluating cementitious spall repair materials. For rapid repairs, early strength gain is of interest. Figure 18 shows the strength-gain curves for the spall repair materials that were tested. It is interesting to see that materials with the highest early strengths were not necessarily those with the highest ultimate strength. The unusual strength-gain curve for Set-45 could not be explained. Based on the Least-Squares Difference T-test and a confidence level of 95 percent, at 2 hours, Set-45 was significantly stronger than the other materials, and Percol FL and Type III PCC were significantly weaker than the others. However, at 28 days, Type III PCC was significantly stronger than all other materials, with Pyrament 505 having the next highest compressive strength. MC-64 and Percol FL were significantly lower in compressive strength than all other materials at 28 days. Set-45, Five Star HP, and Duracal were not significantly different in terms of compressive strength at 28 days.

Bond strength is thought to be an important factor in determining field performance. The bond strengths of the spall repair materials are shown in figures 19 and 20. It is interesting to note that, in general, the bond strengths of the materials that were specified to be installed wet decreased when tested using a dry substrate, and materials that were specified to be installed dry lost bond strength when tested using a wet substrate.

Several exceptions to that statement should be noted. Percol FL, whose manufacturer claims that the material is moisture-tolerant, lost strength significantly when applied to a wet substrate. Also, Five Star HP and Pyrament 505 manufacturers recommended that their materials be applied to a saturated, dry (SSD) surface. The slant-shear and center-point bond strength tests indicated that the bond strength was weaker when applied to a wet substrate. It can also be seen that some materials were more tolerant of changed conditions than others. A partial listing of the results of the tests for the cementitious and polymeric materials is given in table 11. Table 12 gives the results of the tests on the bituminous materials when tested using a wet substrate.

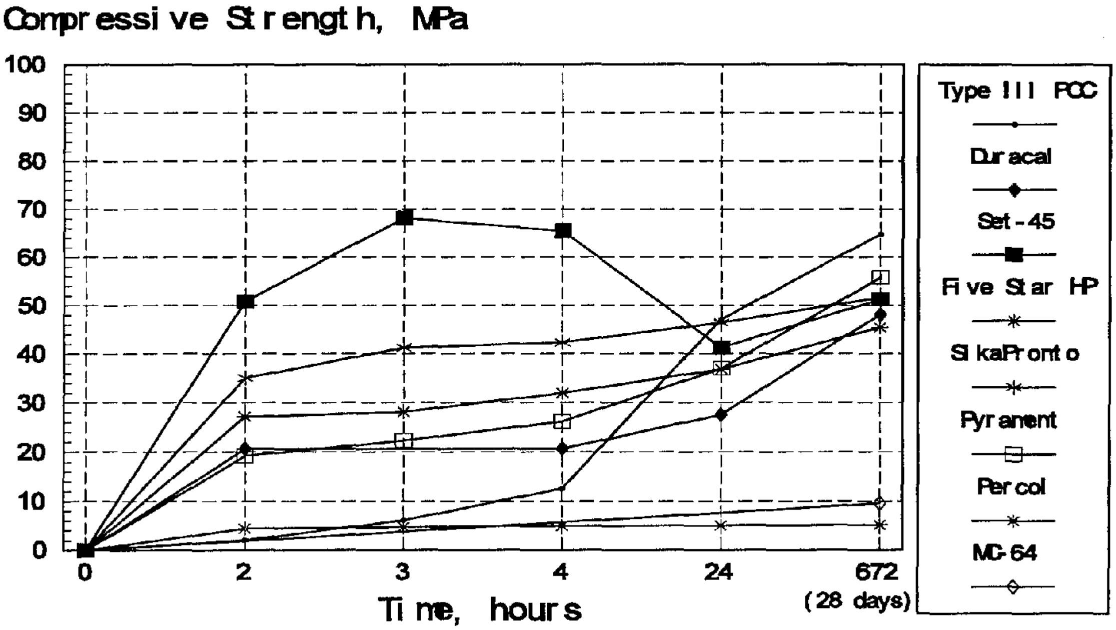

Figure 18. Compressive strengths of spall repair materials.

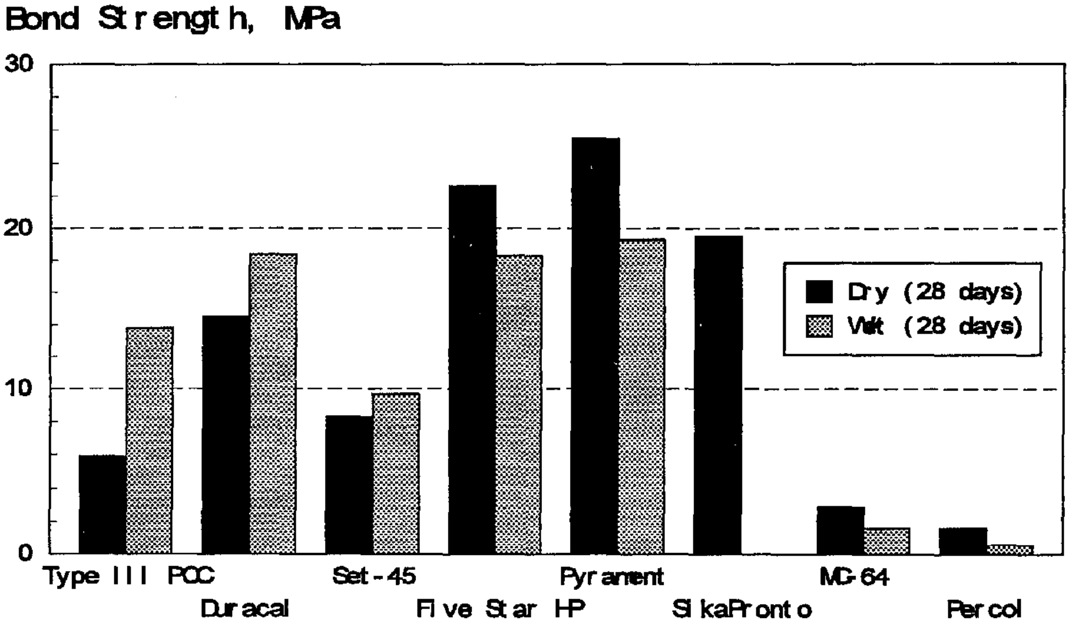

Figure 19. 28-day slant-shear bond strengths of spall repair materials.

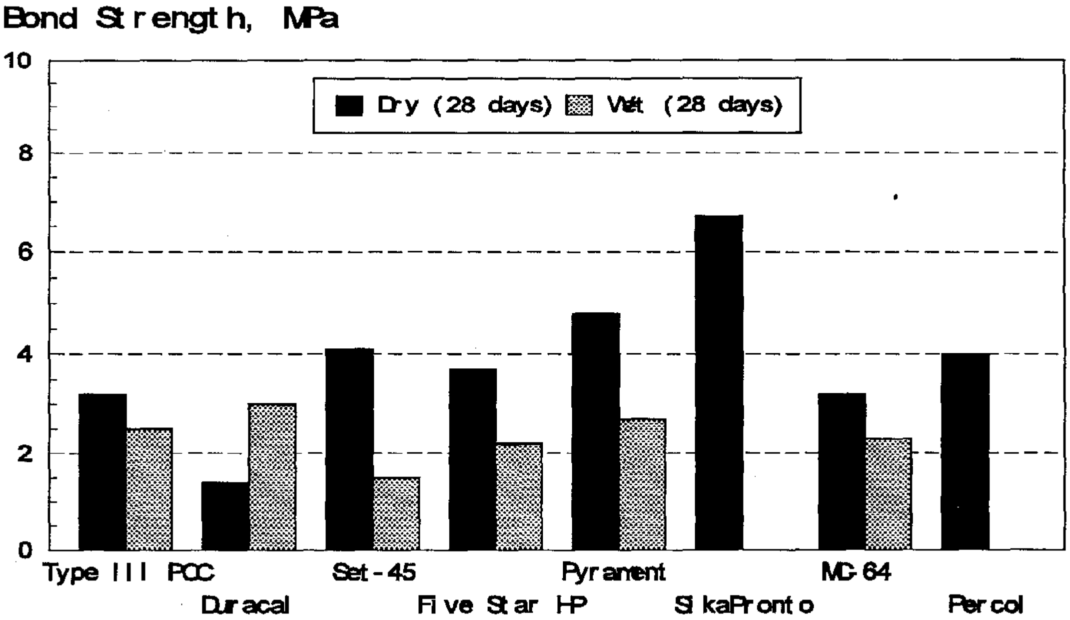

Figure 20. 28-day center-point bond strengths of spall repair materials.

Table 11. Summary of laboratory test results of cementitious and polymer materials.

Material	Modulus of Elasticity, 10^6 kPa	Poisson's Ratio	28-day Modulus of Rupture, kPa	Freeze-Thaw Weight Change, g	Durability Factor	Abrasion Loss, g	Scaling, 100 cycles
Type III	48.0	0.17	8004	-12.3	101.3	18.7	4
Duracal	38.6	0.25	4520	-39.4	43	19.8	4
Set-45	46.2	0.2	3416	-36	24.9	23.7	5
Five Star	38.6	0.17	4658	NA	10.1	19.5	3
Pyrament	49.7	0.16	8487	-5.6	124.9	25.5	4
SikaPronto	23.8	0.3	15180	3.5	76.3	12.7	0
MC-64	—	—	—	61.7	96.2	-0.8	0
Percol FL	—	—	—	56.9	57.1	0	0

NA:	Sample was too badly deteriorated to make measurement.
—	Test was not appropriate.

Table 12. Summary of laboratory test results of bituminous materials.

Test	Standard		UPM	AMZ
Resilient Modulus	ASTM D 4123	25°C and 0.33 Hz, MPa	2001	
		25°C and 0.50 Hz, MPa	1939	
		25°C and 1.00 Hz, MPa	2015	
Marshall Stability	ASTM D 1559	Stability, kg	2306	2187
		Flow, mm	2.464	4.343
Bulk Spec. Grav.	ASTM D 2726		2.26	2.15
Max. Spec. Grav.	ASTM D 2041		2.54	2.45
Air Voids		percent	10.9	12.17
Anti-Stripping	ASTM D 1664	Modified, percent	+95	
Workability	PTI Method	Ambient Temp.	0.5	
Extraction	ASTM D 2172 ASTM D 136	D_{50}		
		Asphalt content, percent	3.5	4.0
Viscosity	ASTM D 2171	60°C, poise	640	4904
Penetration	ASTM D 5	25°C, 100 g, 5 sec., dmm	196	68
Ductility	ASTM D 113	25°C, 5 cm/min, cm	+150	
Softening Point	ASTM D 36	°C	43	53

CHAPTER 4. FIELD PERFORMANCE

A large amount of data were collected during the field evaluations of the four test sites to monitor the development of distresses and the occurrence of patch failures. Distresses characteristic of cementitious and polymer patches and of bituminous patches were observed and recorded. These distresses were rated according to the portion of the patch experiencing the distress and the severity of the distress. This chapter presents summary performance data for both survival and distress development.

Performance Data Collection

Once the experimental patches were placed, they were monitored for performance via on-site visual evaluations. At each site, an immediate (within 3 days after patch placement) inspection was performed to record the development of drying shrinkage cracks and any construction-related failures. Additional evaluations were then conducted under the SHRP H-106 project at approximately 1, 3, 6, 12, and 18 months following the date of installation.

Under the FHWA *LTM* project, annual evaluations were performed between Fall 1993 and Spring 1998. A "deep-winter" evaluation was also made of the repairs in January and February 1995 to assess pavement joint openings and patch bonding characteristics in cold weather. The dates of the field performance evaluations and the corresponding ages of the repairs for each test site are shown in table 13. The evaluations mainly entailed a visual evaluation of the patches to determine if failure had occurred and, if not, to record the type, severity, and density of various patch distresses. Specifically, the cementitious and polymer patch distresses and observations included:

- Spalling.
- Cracking.
- Wearing.
- Oxidizing.
- Edge fraying.
- Patch-adjacent deterioration.
- Pavement corner cracking.
- Joint sealant condition.
- Faulting.
- Patch debonding.

The bituminous patch distresses and observations included:

- Dishing.
- Raveling.
- Shoving.

Table 13. Spall repair test site evaluation schedule.

Evaluation Number	Planned Nominal Age, months	Test Site									
		Pennsylvania (Adverse)		Pennsylvania (Normal)		South Carolina		Arizona		Utah	
		Month of Evaluation	Age, months	Month of Evaluation	Age, months	Month of Evaluation	Age, months	Month of Evaluation	Age, months	Month of Evaluation	Age, months
Installation		3/11/91-3/27/91		6/4/91-7/22/91		5/6/91-5/29/91		5/29/91-6/9/91		4/22/91-5/1/91	
Post-Installation	0	3/91	0	6/91	0	5/91	0	6/91	0	4/91	0
1	1	4/91	1	8/91	2	7/91	2	7/91	1	5/91	1
2	3	7/91	4	10/91	4	9/91	4	9/91	3	8/91	4
3	9	10/91	7	3/92	9	1/92	8	1/92	7	3/92	11
4	12	3/92	12	6/92	12	5/92	12	6/92	12	7/92	15
5	18	6/92 10/92	15 19	10/92	16	9/92	16	10/92	16	9/92	17
6	30	10/93	31	10/93	28	11/93	30	11/93	29	10/93	30
7	42	7/94	40	7/94	37	7/94	38	8/94	38	7/94	39
8	48[a]	2/95	47	2/95	44	1/95	44	2/95	44	1/95	45
9	54	12/95	57	12/95	54	1/96	56	9/95	51	11/95	55
10	66	3/97	72	3/97	69	1/97	68			11/96	67
11	78	6/98	87	6/98	84					6/98	86

[a] Deep-winter performance evaluation.

- Cracking.
- Bleeding.
- Edge disintegration.
- Missing patch.

Each cementitious and polymer patch was sounded using a 0.68-kg to 0.91-kg steel hammer to determine whether debonding had occurred. The percentage of area debonded was recorded to the nearest 5 percent.

The data presented in this report represent distresses that were recorded during the initial inspection or any one of the evaluations that followed. At the time of the evaluations, the distress types and their severity and density were observed and recorded in terms of the percentage of the patch area or perimeter affected.

Summary of Overall Performance Data

The percentages of surviving patches at the final inspection for each site are shown in figures 21 through 23, grouped by site, procedure, and materials, respectively. It is important to note that these charts do not provide rankings of patch performance, but are simply a means of showing the overall performance percentages. Chapter 5 presents the statistically

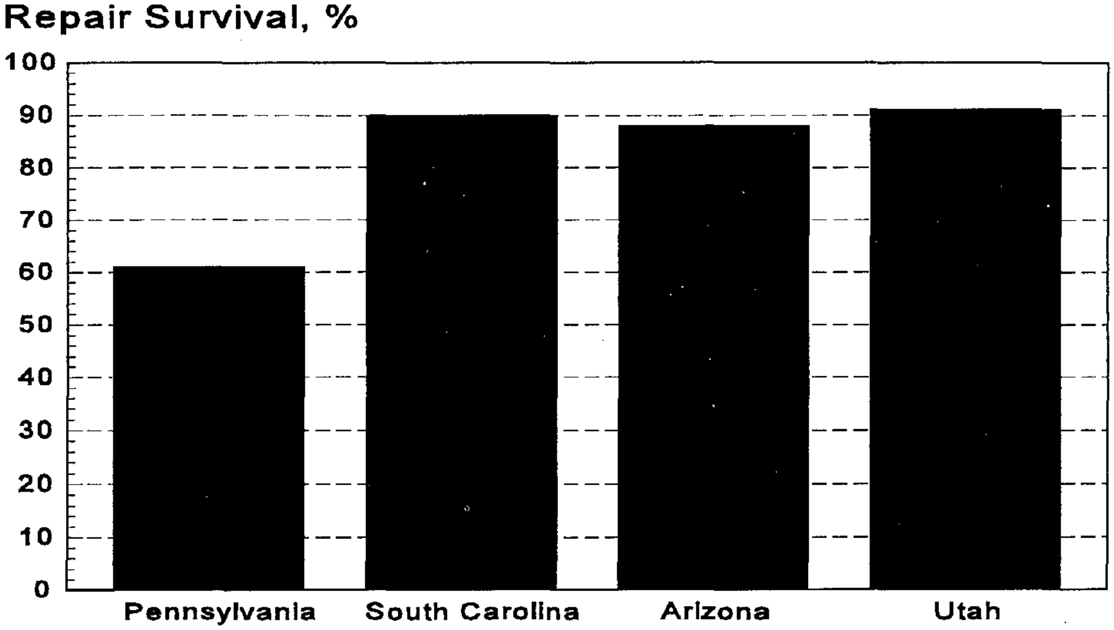

Figure 21. Percentage of surviving patches by test site.

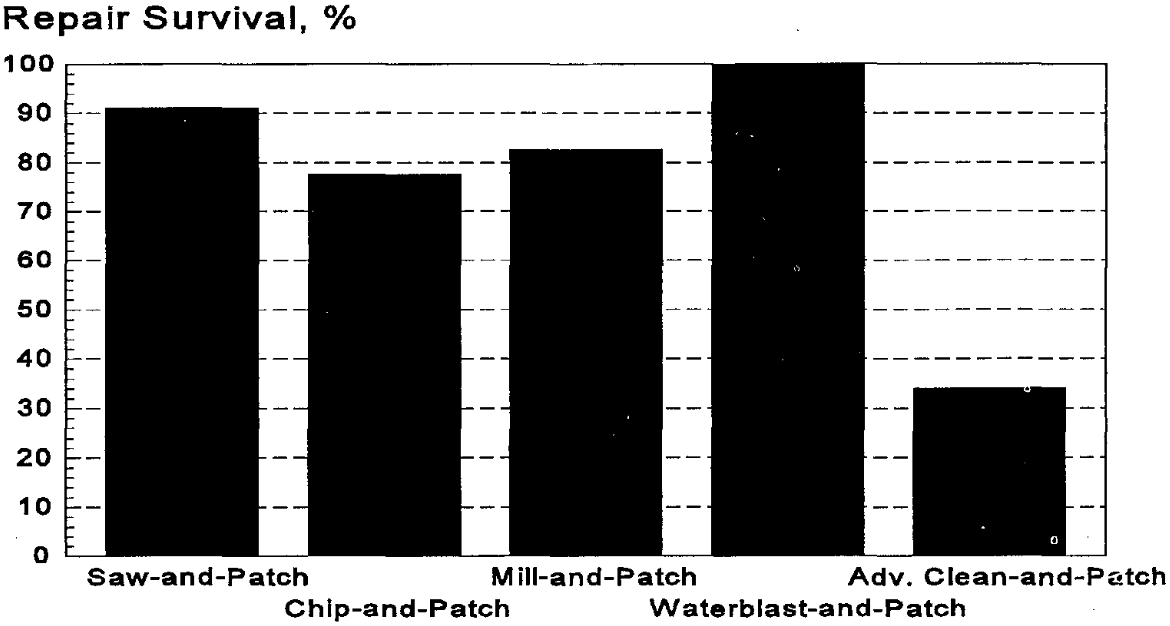

Figure 22. Percentage of surviving patches by concrete-removal procedure.

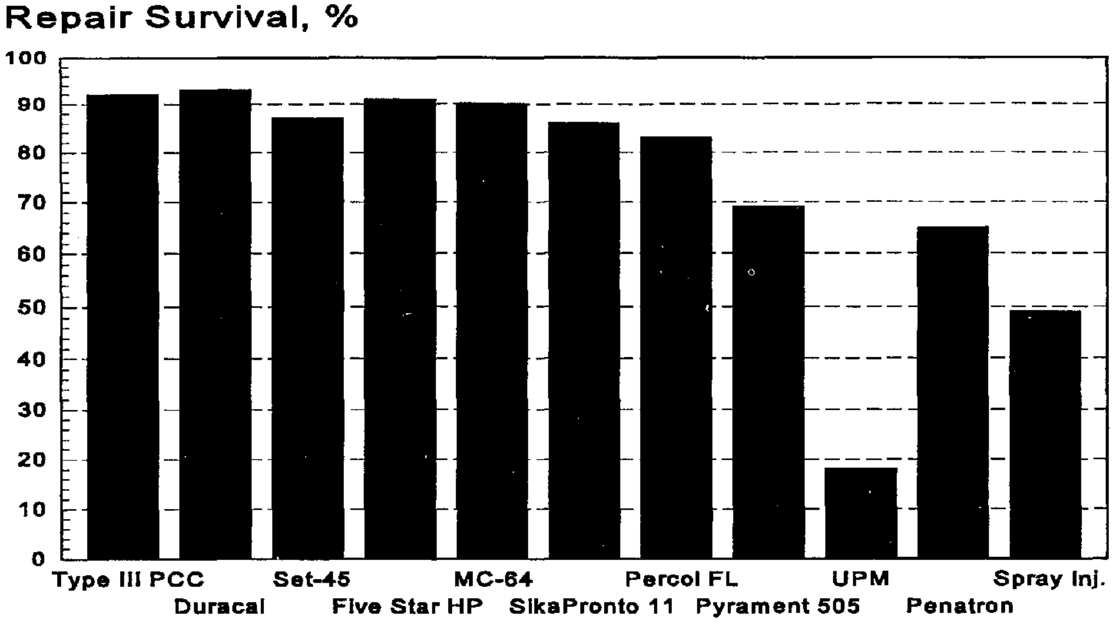

Figure 23. Percentage of surviving patches by material.

significant differences that were found to exist among the materials and procedures, and provides meaningful rankings of the performance of different repairs.

Conceptually, a patch is considered failed if it can no longer service traffic safely. As seen in figure 21, as of the final evaluations, 39 percent of the patches were failed at the Pennsylvania test site, 12 percent were failed at the Arizona test site, 10 percent were failed at the South Carolina test site, and 9 percent were failed at the Utah test site.

Of the concrete-removal procedures, the adverse-condition clean-and-patch procedure, not surprisingly, showed the highest percentage of patch failure at 66 percent (figure 22). The procedures conducted under normal conditions experienced patch failure rates as follows: chip-and-patch at 23 percent, mill-and-patch at 17 percent, and saw-and-patch at 9 percent. The waterblast-and-patch had no failures. It should be noted that the waterblast-and-patch result was based on 26 patches placed at the Utah test site, the saw-and-patch result was based on 613 patches, the chip-and-patch on 742 patches, the mill-and-patch on 140 patches, and the adverse-condition clean-and-patch on 56 patches.

With respect to the performance characteristics of materials, the UPM High Performance Cold Mix experienced the most failures with 82 percent, followed by the spray-injected mix with 51 percent. Penatron RM-3003 and Pyrament 505 experienced 35 and 31 percent failure over the life of the experiment, respectively. The Percol FL, SikaPronto 11, and Set-45 experienced 17, 14, and 13 percent failure, respectively. The lowest percentages of failure were experienced by the MC-64, Five Star HP, Type III PCC, and Duracal at 10, 9, 8, and 7 percent, respectively.

The low survival rates of the UPM and spray-injection repairs were not unexpected, especially for those sites where the evaluation period was approximately 7 years. The high survival rates for the Type III PCC were somewhat of a surprise, given that the cost is generally much lower than the other rigid repair materials. The low survival rates at the Pennsylvania site generally reflect the overall condition of the pavement, which was the poorest of the four sites. The high survival rates at the other three sites appear to be a function of the overall condition of the sites and the fact that Utah and Arizona had repairs placed in the passing lane, reducing the amount of truck traffic encountered by those repairs.

Summary of Site-Specific Field Performance Data

During the field inspection visits to the partial-depth spall repair test sites, data were collected regarding repair survival and distress types and severities present. Survival of the repairs was determined by whether the local agency had to repatch spalls that were originally patched with the experiment materials. In several instances at the Arizona test site, surface patches were placed over some of the H-106 repairs, resulting in their being reported as having failed. During subsequent inspections, the surface patches had worn off, showing that the original H-106 repairs were still in place. When the original H-106 repairs reappeared, their status was changed to show survival.

The performance of the partial-depth spall repairs was evaluated on two criteria: survival of the repairs over time relative to the other repair types and the current distress conditions of the surviving repairs. Early analyses under the SHRP portion of the project concentrated on the distress information because of the low number of failures that occurred. An increased number of failures during recent evaluations has produced some statistically significant differences in survival of the various repair types. As a result of these differences in patch survival, less emphasis was placed on the identification of distress differences among the repair types. Table 14 shows the various repair types and the survival numbers for each site.

Survival Data

Each partial-depth spall repair placed as part of the H-106 project was categorized as surviving, failed, or lost to overlay. The percentage of repairs surviving for a given repair type was then calculated as follows:

$$P_{SURV} = [(N_{SURV})/(N_{SURV} + N_{FAIL})] \times 100 \qquad \text{(Eq. 1)}$$

where:
P_{SURV} = Percentage of a repair type surviving at the time of the inspection.
N_{SURV} = Number of patches surviving for a repair type at the time of the inspection.
N_{FAIL} = Number of patches failed for a repair type at the time of inspection.

Table 14. Summary of repair survival at time of last test site inspection (number surviving/total repairs placed).

Repair material	Pennsylvania				Utah			South Carolina[a]		Arizona[a]			Total
	Saw-and-Patch	Chip-and-Patch	Mill-and-Patch	Adverse Clean-and-Patch	Saw-and-Patch	Chip-and-Patch	Waterblast-and-Patch	Saw-and-Patch	Chip-and-Patch	Saw-and-Patch	Chip-and-Patch	Mill-and-Patch	
Type III PCC	15/22	16/24	17/20		25/25	21/21[b]	26/26[b]	20/20	20/20	20/20	20/20		200/218
Duracal					21/22	21/25		20/20	18/20	19/20	19/20		118/127
Set-45	16/20	13/20	17/20		25/25	23/23		17/20	18/20	16/20	19/20		164/188
Five Star HP	14/20	16/20	14/20		19/19	34/34		20/20	20/20	19/20	20/20		176/193
MC-64	16/20	7/20			25/25	26/26[a]		19/19	18/20	20/20	20/20	20/20	171/190
SikaPronto 11	17/21	7/20			26/26	28/28		17/20	16/20	20/20	20/20		151/175
Percol FL	19/20	19/20	12/20	12/20	29/29	29/29		21/21	14/20	10/20	18/20	16/20	199/239
Pyrament 505	17/19[a]	10/20		6/18[a]								20/20	53/77
UPM Cold Mix		0/20		1/18[a]		0/31			13/20		6/20		20/109
Penatron RM-3003										13/20			13/20
Spray-injection		2/21							18/20				20/41
Total (by method)	$\frac{114}{142}$	$\frac{90}{185}$	$\frac{60}{80}$	$\frac{19}{56}$	$\frac{170}{171}$	$\frac{182}{217}$	$\frac{26}{26}$	$\frac{134}{140}$	$\frac{155}{180}$	$\frac{137}{160}$	$\frac{142}{160}$	$\frac{56}{60}$	$\frac{1285}{1577}$
Total (by site)	283/463				378/414			289/320		335/380			

[a] Some repairs were lost from the experiment due to other operations (i.e., slab replacement, full-depth patching) and those repairs were not included in the survival calculations.

[b] Several repairs were excluded from the performance calculations due to inconsistencies noted during installation.

Figures 24 through 27 show the survival trends of the various repair types placed at each of the four test sites. These figures indicate that the percentage of repairs surviving after 4 to 7 years is quite variable for the Pennsylvania and Arizona test sites, whereas all but three repair types experienced no failure over 7 years of observation at the Utah test site. The fact that the repairs were all in the passing lane and not subjected to the majority of the truck traffic was one of the factors contributing to the good performance observed at the Utah site. The overall good condition of the pavement, which was better than any of the other spall repair test sites, also provided the repairs with a better opportunity for good performance.

Distress Data

The distresses most often observed during the field inspections of the spall repair test sites consisted of cracking of the patches and delamination of the rigid and two-part epoxy repairs from the underlying PCC material. Deterioration of repair edges, aging and raveling of material, cracking, and loss of material pieces were the predominant distresses observed for the bituminous repairs. In many instances, the distresses developed during the initial year after placement and continued to worsen over time as climate and traffic continued to wear on the repairs.

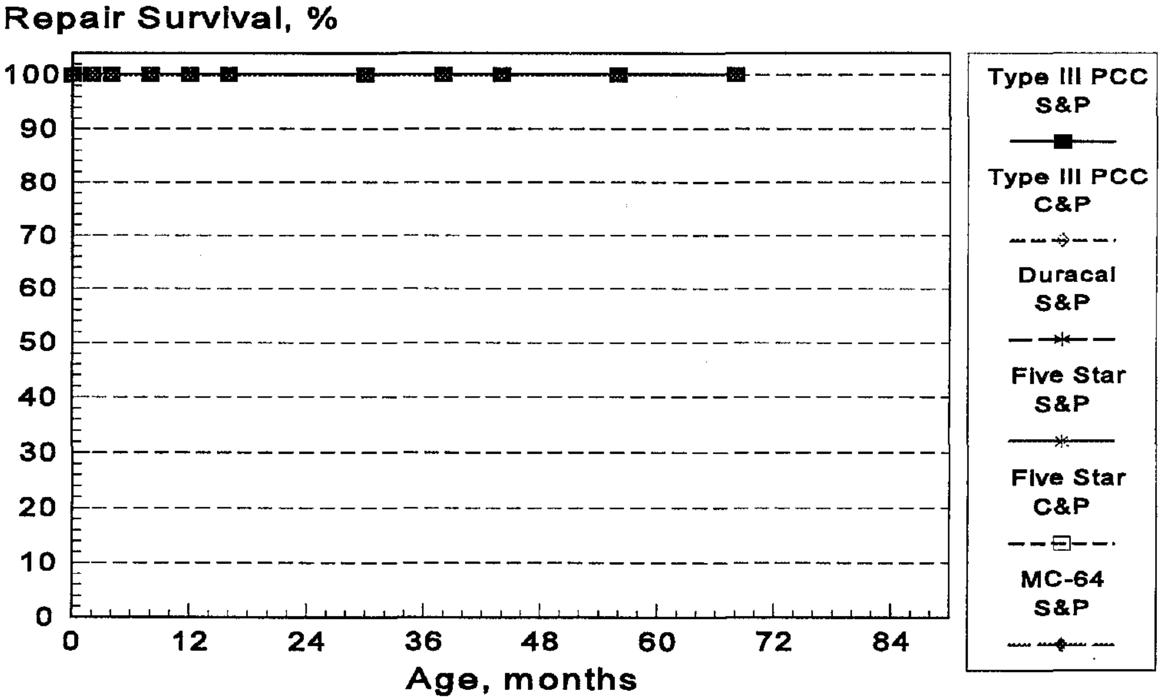

Figure 24. Spall repair survival at South Carolina test site.

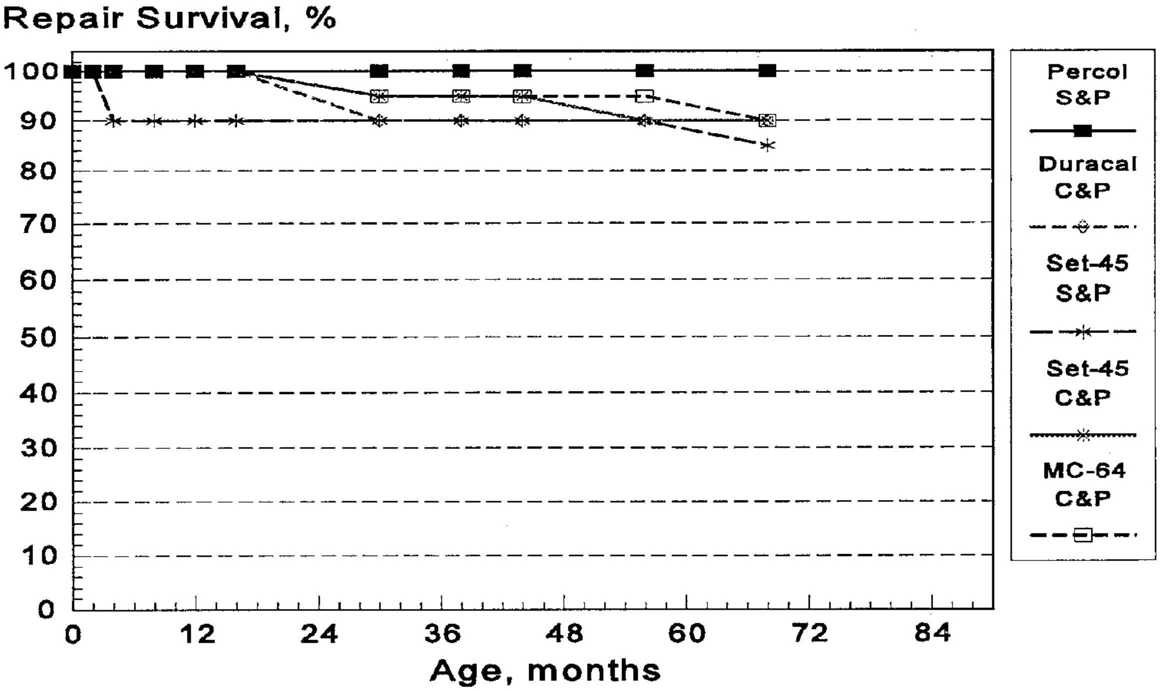

Figure 24. Spall repair survival at South Carolina test site (continued).

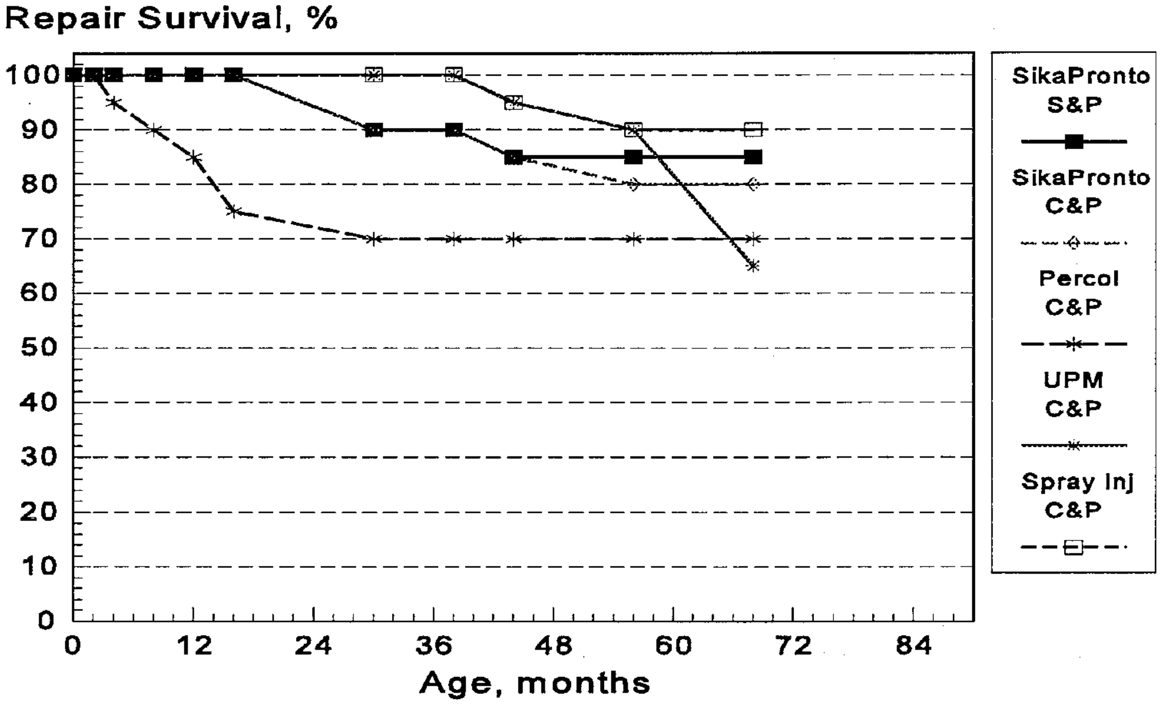

Figure 24. Spall repair survival at South Carolina test site (continued).

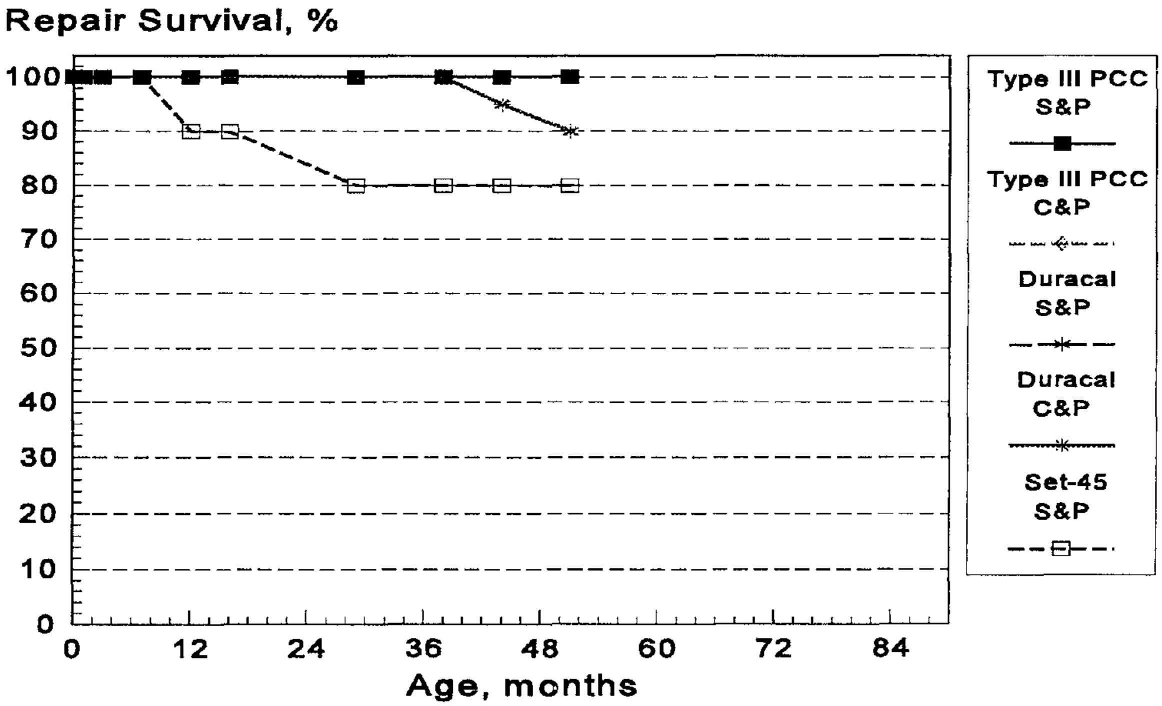

Figure 25. Spall repair survival at Arizona test site.

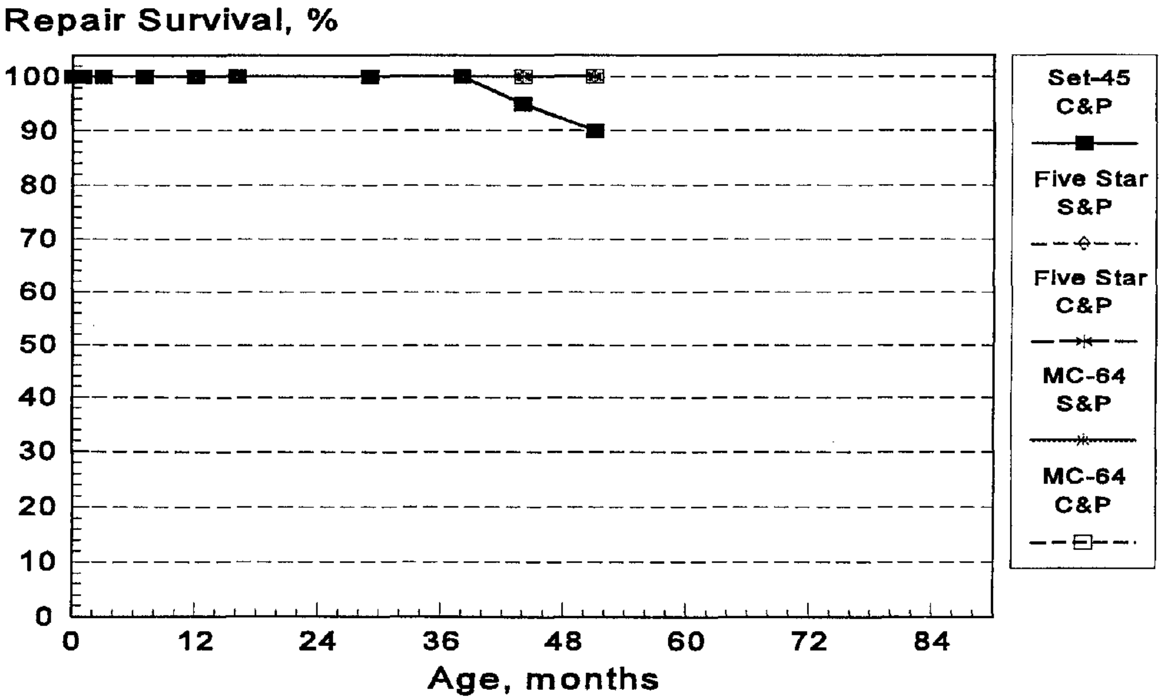

Figure 25. Spall repair survival at Arizona test site (continued).

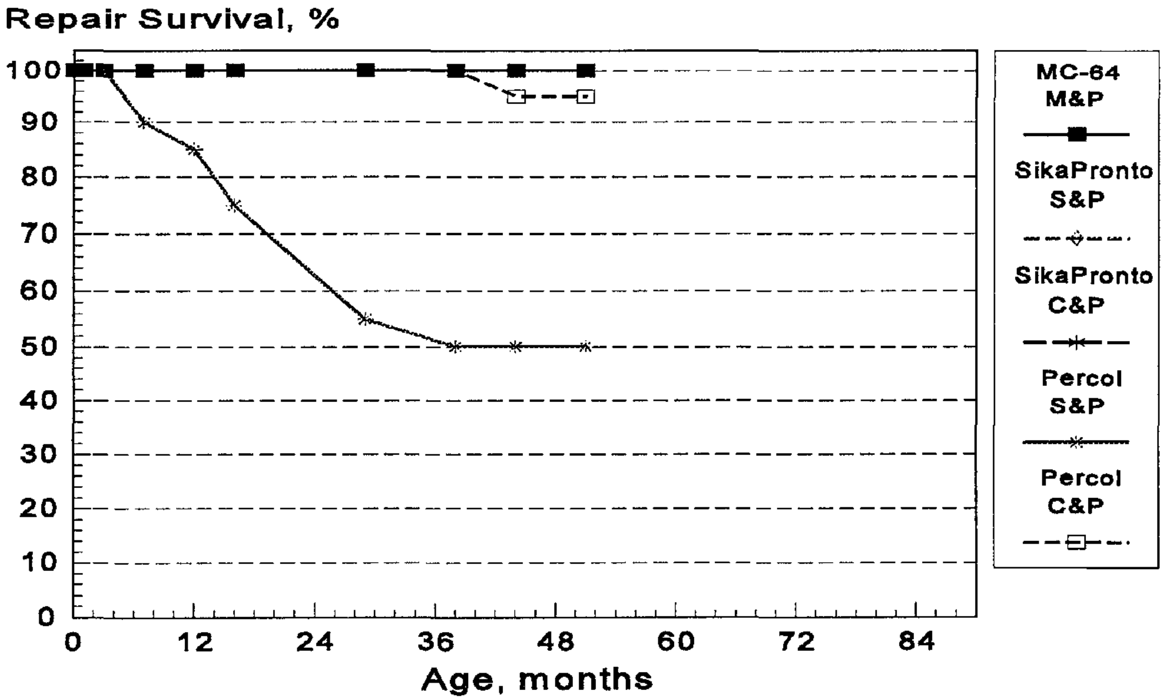

Figure 25. Spall repair survival at Arizona test site (continued).

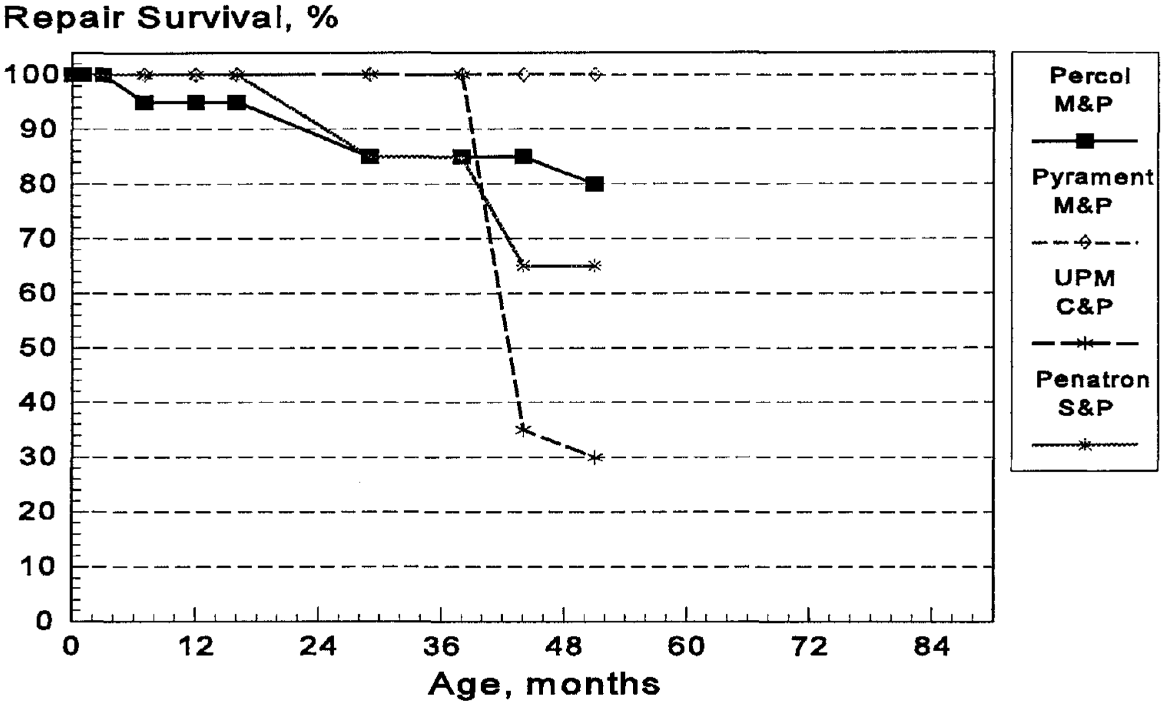

Figure 25. Spall repair survival at Arizona test site (continued).

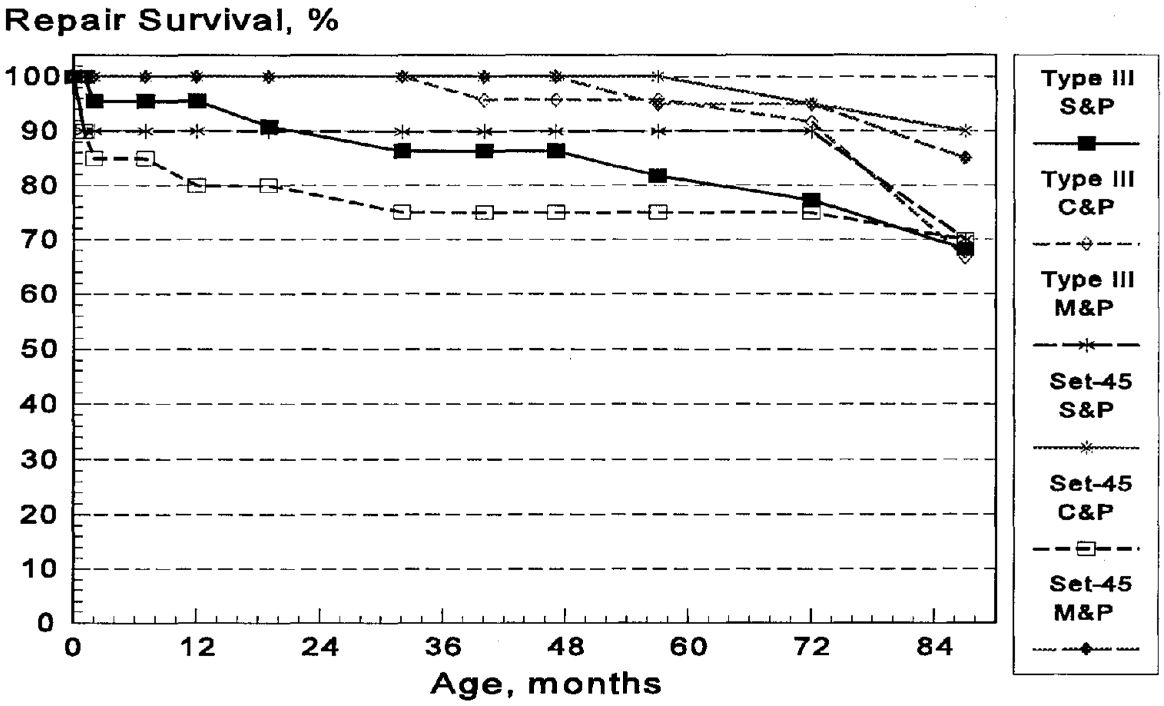

Figure 26. Spall repair survival at Pennsylvania test site.

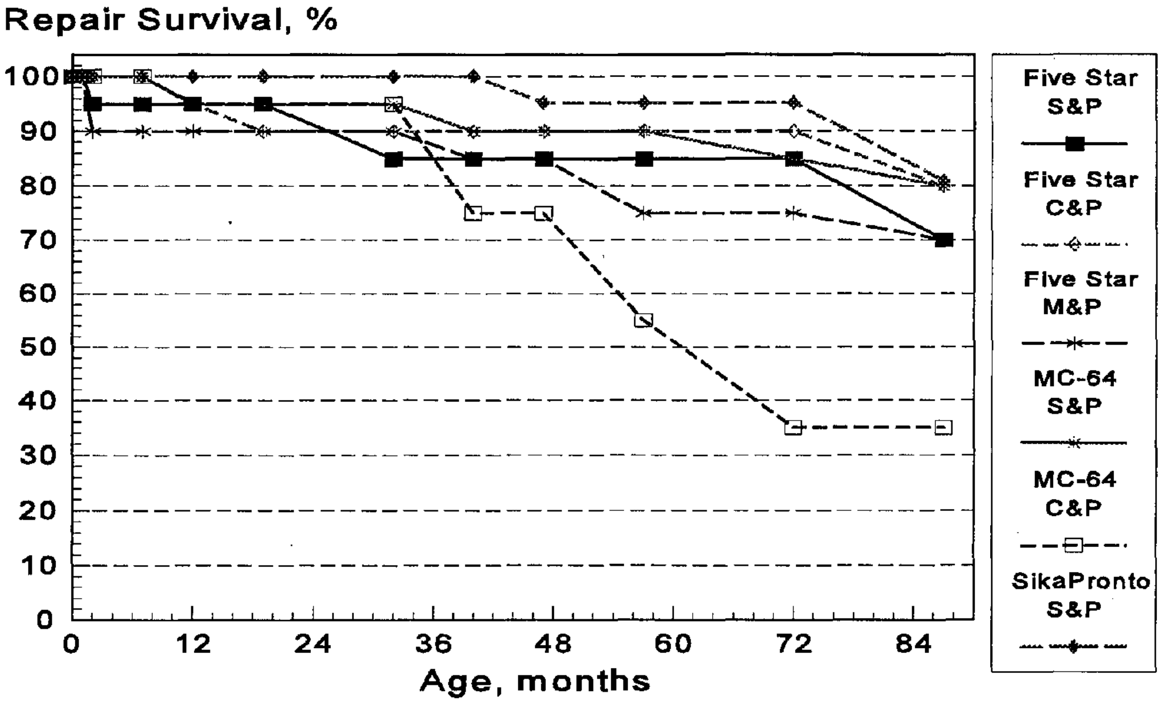

Figure 26. Spall repair survival at Pennsylvania test site (continued).

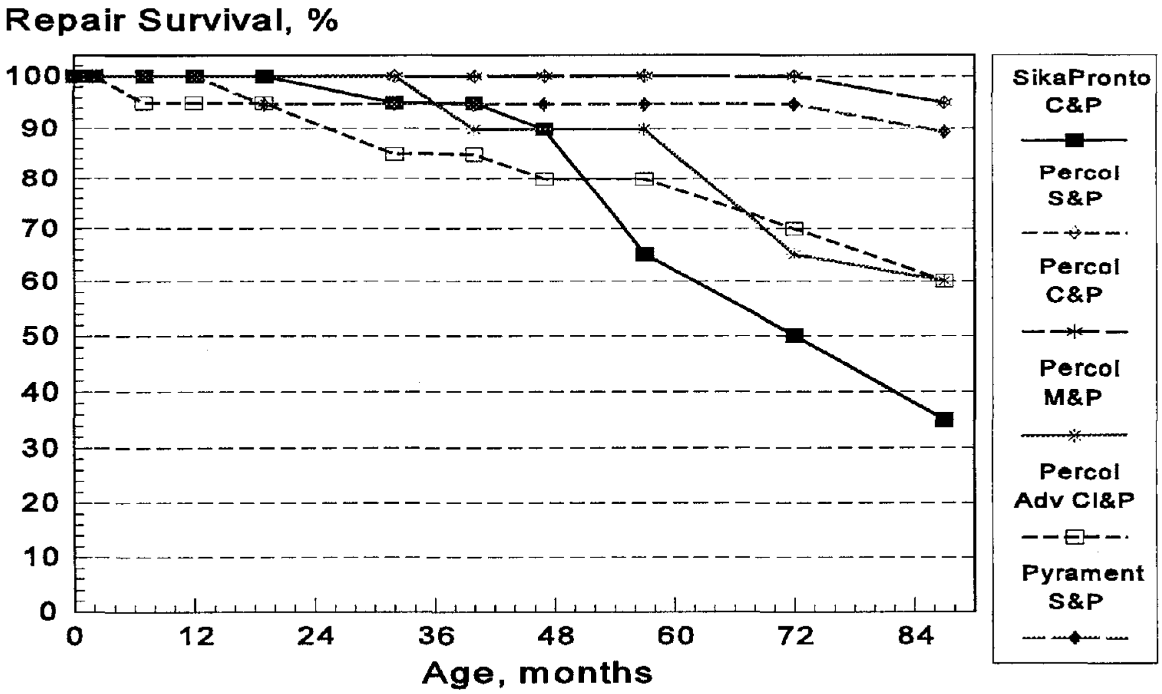

Figure 26. Spall repair survival at Pennsylvania test site (continued).

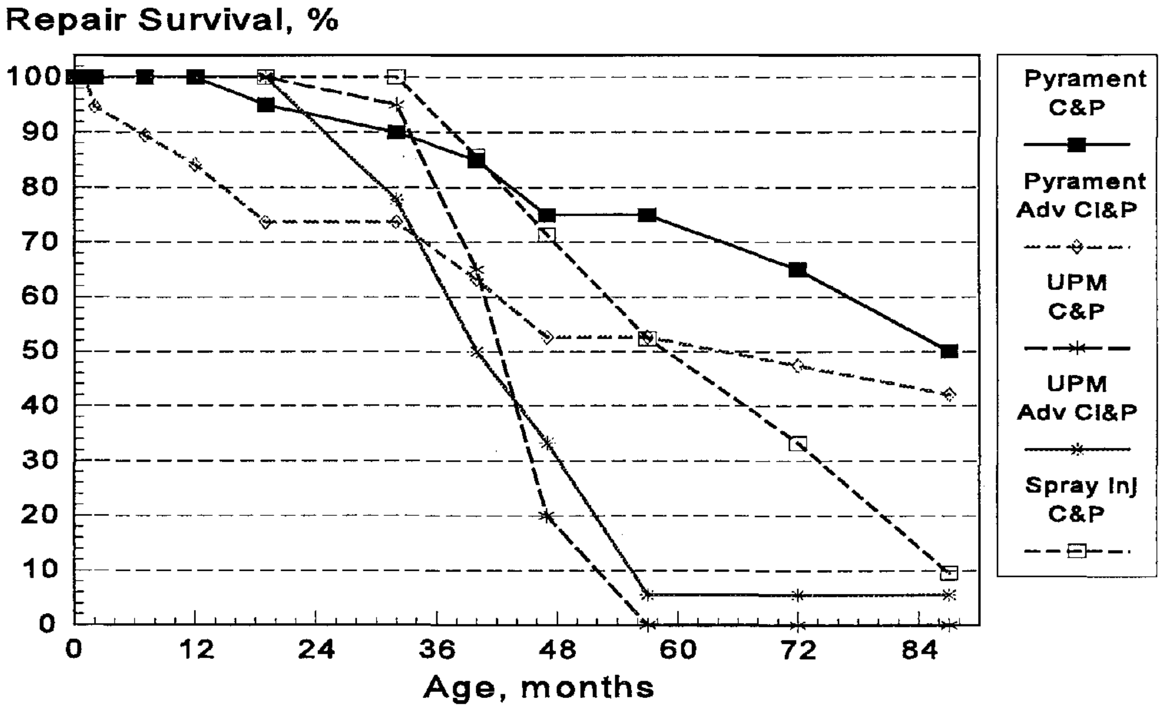

Figure 26. Spall repair survival at Pennsylvania test site (continued).

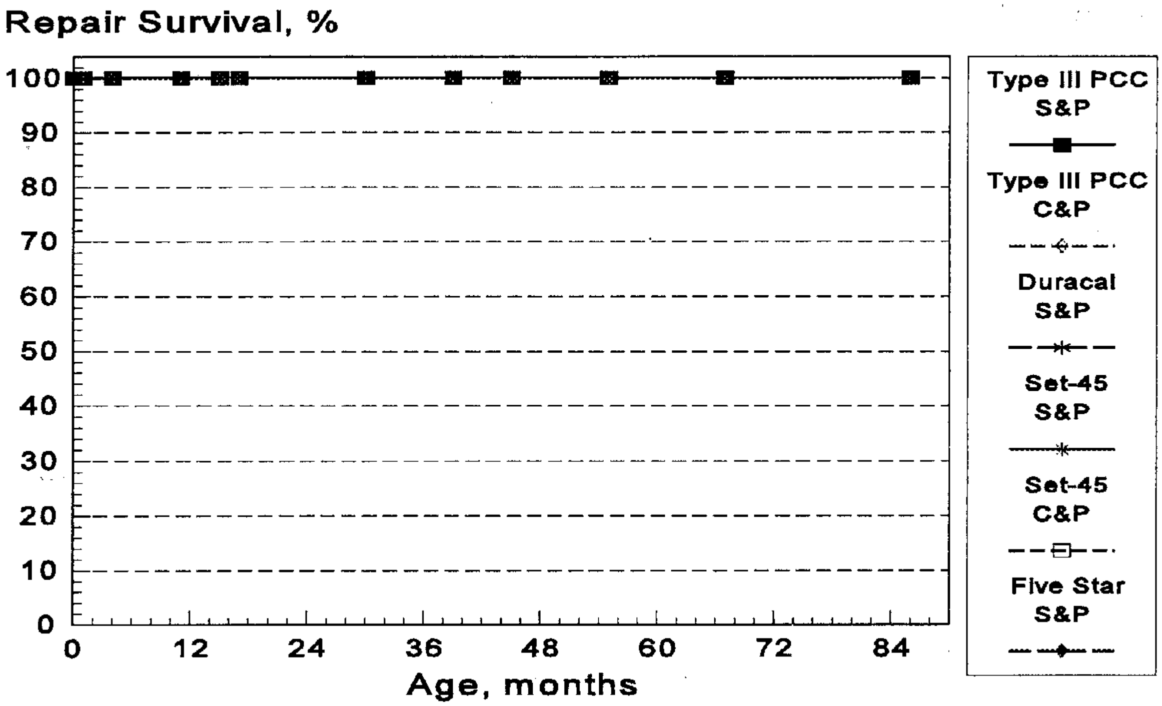

Figure 27. Spall repair survival at Utah test site.

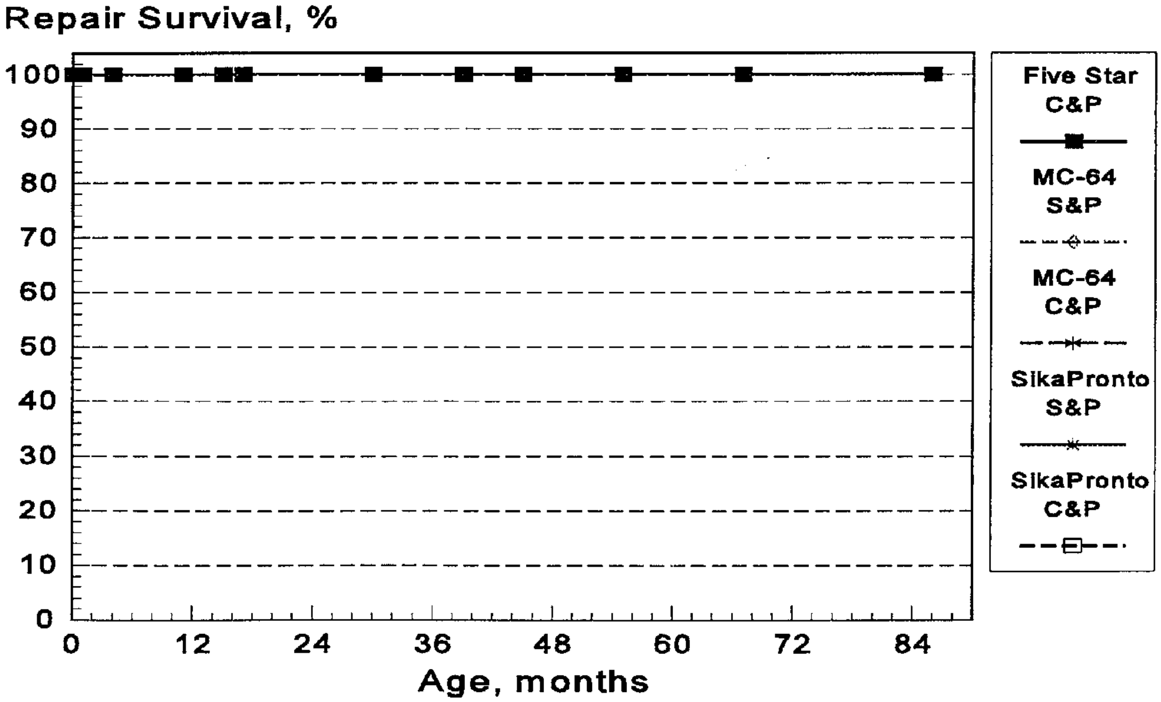

Figure 27. Spall repair survival at Utah test site (continued).

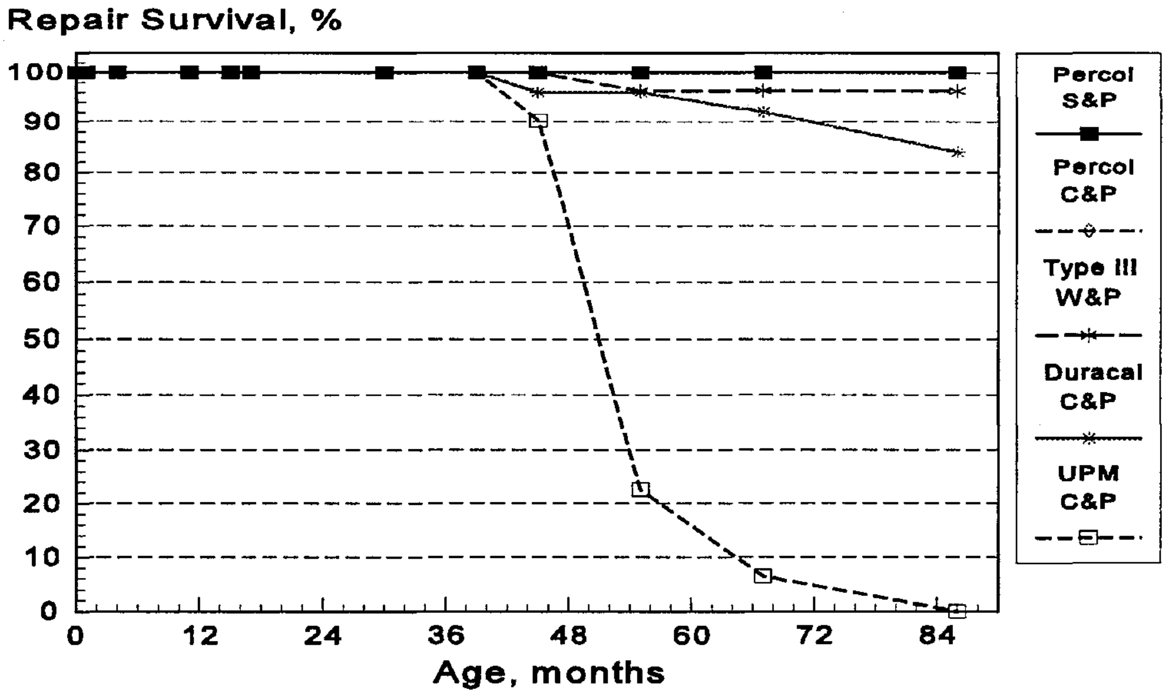

Figure 27. Spall repair survival at Utah test site (continued).

CHAPTER 5. DATA ANALYSIS

The primary factor by which spall repairs are judged by highway agencies is their ability to remain functional (i.e., in place and sustaining traffic) over the desired length of time. The desired length of time can range anywhere from a few months to many years, depending on the overall condition of the PCC pavement and the agency's short- and long-term strategies for keeping the pavement serviceable. For instance, in the case where an overlay is scheduled to occur within a few years, the repairs must perform well for this amount of time. If, on the other hand, no rehabilitation is planned for many years, then long-term repairs must be placed. In both cases, the overall costs (including material, labor, and equipment costs) of making the patches must be weighed against the expected life of the patches.

As stated in chapter 1, the primary objective of this experimental project was to determine the most effective and economical materials and procedures for placing partial-depth patches in concrete pavement. To accomplish this objective, a statistical analyses was conducted on the field performance data to identify differences in performance among the various repair types. This was followed by a detailed cost-effectiveness analysis, whereby the total cost of placing a given repair type was weighed against how long the repair would perform.

A secondary objective included seeking out correlations between field performance and laboratory testing data. It was envisioned that new information in this area would lead to improved performance-based material specifications.

This chapter describes the statistical methods used to analyze the various types of installation, field performance, and laboratory testing data, and presents the results of the analyses performed. Listed below are the various types of analyses that were conducted in order to interpret the data.

- Survival analysis—Statistical analysis to identify significant differences in long-term performance between repair types.
- Cost-effectiveness analysis—Life-cycle cost analysis and comparison using long-term performance trends.
- Laboratory testing–field performance correlation analysis—Statistical analysis of laboratory testing and field performance data to identify performance-indicative laboratory tests.

Statistical Methodology

With the number of repair failures observed over the course of the field inspections, analyses of the repair survival data were performed using a method that compares two repair types in terms of the percentage of repairs surviving over time. By comparing all repair types to each other, and looking for the presence of statistically significant differences between various repair types, the repair types can be ordered from best to worst in terms of time-series survival characteristics. This type of analysis was needed to determine which of the differences observed in figures 24 through 27 were statistically significant given the number of repairs actually placed and the level of reliability chosen.

In addition to the survival analyses, attempts were made to identify correlations between the field performance data and the material property data collected through laboratory testing during the initial SHRP phase of the project. Also, based on the overall costs of placing the various experimental patches and the documented performance characteristics of the patches, a cost-effectiveness analysis was conducted to determine which repair types had the lowest total life-cycle costs.

Survival Analysis

At all test sites, the survival data collected for each repair type consisted of the number of repairs surviving, failed, or lost to overlay at the time of inspection. These data were compared on a one-on-one basis for each combination of repair types within a test site. Since there was no "control" repair type, comparisons were made between all repair types. By combining repair types that had no statistically significant differences based on a confidence level of 90 percent ($\alpha = 0.10$), performance groupings were established that indicated distinct levels and rankings of repair performance. Tables 15 through 18 show, for each test site, the repair types that were statistically similar and those that were statistically different, based on the observed survival characteristics. The grouping numbers represent levels of performance, with 1 indicating best performance, 2 indicating next best performance, and so on.

Table 15. Spall repair survival groupings for Utah test site.

Repair Material	Repair Procedure	Survival Groupings, indicated by numbers			
Type III PCC	Saw-and-patch	1[a]	2		
	Chip-and-patch	1[a]	2		
Set-45	Saw-and-patch	1[a]	2		
	Chip-and-patch	1[a]	2		
Five Star HP	Saw-and-patch	1[a]	2		
	Chip-and-patch	1[a]	2		
MC-64	Saw-and-patch	1[a]	2		
	Chip-and-patch	1[a]	2		
SikaPronto 11	Saw-and-patch	1[a]	2		
	Chip-and-patch	1[a]	2		
Percol FL	Saw-and-patch	1[a]	2		
	Chip-and-patch	1[a]	2		
Type III PCC	Waterblast-and-patch		2	3	
Duracal	Saw-and-patch		2	3	
	Chip-and-patch			3	
UPM	Chip-and-patch				4

Group 1 repair types showed no failure after 86 months.

Table 16. Spall repair survival groupings for Pennsylvania test site.

Repair Material	Repair Procedure	Survival Groupings, indicated by numbers							
Percol FL	Saw-and-patch	1							
	Chip-and-patch	1							
Set-45	Saw-and-patch	1	2						
	Mill-and-patch	1	2						
SikaPronto 11	Saw-and-patch	1	2						
Pyrament 505	Saw-and-patch	1	2						
MC-64	Saw-and-patch	1	2	3					
Five Star HP	Chip-and-patch	1	2	3					
Type III PCC	Mill-and-patch	1	2	3					
	Chip-and-patch		2	3	4				
Five Star HP	Saw-and-patch		2	3	4				
Type III PCC	Saw-and-patch		2	3	4				
Five Star HP	Mill-and-patch		2	3	4	5			
Set-45	Chip-and-patch		2	3	4	5	6		
Percol FL	Mill-and-patch			3	4	5	6		
	Adverse clean-and-patch			3	4	5	6		
Pyrament 505	Chip-and-patch				4	5	6	7	
SikaPronto 11	Chip-and-patch					5	6	7	
MC-64	Chip-and-patch						6	7	
Spray-injection	Chip-and-patch							7	
MC-64	Chip-and-patch							7	8
UPM	Chip-and-patch								8
	Adverse clean-and-patch								8

Table 17. Spall repair survival groupings for South Carolina test site.

Repair Material	Repair Procedure	Survival Groupings, indicated by numbers			
Type III PCC	Saw-and-patch	1[*]	2		
	Chip-and-patch	1[*]	2		
Duracal	Saw-and-patch	1[*]	2		
Five Star HP	Saw-and-patch	1[*]	2		
	Chip-and-patch	1[*]	2		
MC-64	Saw-and-patch	1[*]	2		
Percol FL	Saw-and-patch	1[*]	2		
UPM	Chip-and-patch		2	3	
Spray-injection	Chip-and-patch		2	3	
Set-45	Chip-and-patch		2	3	
Duracal	Chip-and-patch		2	3	
MC-64	Chip-and-patch		2	3	4
Set-45	Saw-and-patch		2	3	4
SikaPronto 11	Saw-and-patch			3	4
	Chip-and-patch			3	4
Percol FL	Chip-and-patch				4

[*] Group 1 repair types showed no failure after 67 months.

Table 18. Spall repair survival groupings for Arizona test site.

Repair Material	Repair Procedure	Survival Groupings, indicated by numbers					
Type III PCC	Saw-and-patch	1[a]	2				
	Chip-and-patch	1[a]	2				
Five Star HP	Saw-and-patch	1[a]	2				
	Chip-and-patch	1[a]	2				
MC-64	Saw-and-patch	1[a]	2				
	Chip-and-patch	1[a]	2				
	Mill-and-patch	1[a]	2				
SikaPronto 11	Saw-and-patch	1[a]	2				
	Chip-and-patch	1[a]	2				
Pyrament 505	Mill-and-patch	1[a]	2				
Duracal	Saw-and-patch		2	3			
	Chip-and-patch		2	3			
Set-45	Chip-and-patch		2	3			
Percol FL	Chip-and-patch		2	3			
	Mill-and-patch			3	4		
Set-45	Saw-and-patch			3	4		
Penatron R/M-5005	Saw-and-patch				4	5	
UPM	Chip-and-patch					5	6
Percol FL	Saw-and-patch						6

[a] Group 1 repair types showed no failure after 51 months.

The survival groupings shown in tables 15 through 18 indicate some differences in the survival characteristics of the different repair types. In general, there was a group of repair types that experienced very little failure, a group of repairs that did not perform very well, and a group of repairs that performed somewhere in between. Overall, the order of the repairs in terms of good survival performance remained fairly constant over the various field inspections. In South Carolina, five of the top seven performers were placed using the saw-and-patch procedure, as were five of the top nine performers in Pennsylvania. By contrast, only two of the top seven in South Carolina and two of the top nine in Pennsylvania were placed using the chip-and-patch procedure, indicating that the saw-and-patch procedure may provide longer lasting repairs.

Type III PCC repairs experienced no failures at the Utah, Arizona, and South Carolina sites. The Type III PCC repairs at the Pennsylvania site were somewhere in the middle with respect to the survival performance ranking. Since Type III PCC was one of the less expensive materials in the study, its good performance was expected to result in high cost-effectiveness ratings.

The bituminous repairs (UPM High Performance Cold Mix and spray-injection repairs) were some of the poorer performers in Arizona, Pennsylvania, and Utah. At the South Carolina site, the UPM repairs were somewhere in the middle of the performance ranking. However, the relatively low material costs and high productivity rates make these repairs desirable in short-term situations where overlays or rehabilitation projects only require 2 to 3 years of survival from partial-depth spall repairs.

Laboratory Test–Field Performance Correlation Analysis

Although differences in field performance became more obvious during the final field inspection efforts, and differences were noted in the laboratory testing results conducted at the beginning of the project, no significant correlations were identified between field performance indicators and laboratory-determined material characteristics. The two primary field performance indicators used were based on repair survival and were as follows:

- The percentage of repairs surviving at a given inspection.
- A survival rating based on the area under the performance over time graph.

No significant correlations were identified between either of these field performance indicators and the material properties.

Cost-Effectiveness Analysis

Perhaps the most important comparison of the various partial-depth spall repair types was cost-effectiveness. To determine the cost-effectiveness of a repair type, it is necessary to have information on the initial material purchase and installation costs, as well as the expected life of the repairs. Another piece of information that was added to the cost-effectiveness calculations for this project was the expected life of the pavement section, as shown in the following equation:

$$C_T = (L_{TOT}/L_{MEAN}) \times [(N/P_O) \times (C_L + C_E + C_{TC} + C_{UD}) + (N \times C_M)] \qquad \text{(Eq. 2)}$$

where: C_T = Total cost of patching operation, \$.
L_{TOT} = Total time until rehabilitation of pavement surface, months.
L_{MEAN} = Mean life for repair type, months.
N = Material needed for initial patching operation, Mtons.
P_O = Productivity of the patching operation, Mtons/day.
C_L = Cost of labor needed for patching operation, \$/day.
C_E = Cost of equipment needed for patching operation, \$/day.
C_{TC} = Cost of traffic control needed for patching operation, \$/day.
C_{UD} = Cost of user delay due to repair operation, \$/day.
C_M = Cost of material delivered to yard, \$/Mton.

The annual cost for a patching operation was then calculated by simply dividing the total cost (C_T) by the total time until rehabilitation (L_{TOT}), with L_{TOT} in months.

Because the amount of time needed for various repairs was dependent on factors such as the time until rehabilitation, different projects had different performance needs from the repair types. A section that was to be rehabilitated in 2 years did not need repairs lasting as long as a section that was to be rehabilitated in 10 years.

Table 19 shows the values used for equipment, labor, and productivity in the cost-effectiveness calculations. The mean survival for a repair type and maximum expected life values

Table 19. Assumed costs for partial-depth spall repair operations.

Removal equipment	Double-blade concrete saw	$225/day
	Single-blade concrete saw	$150/day
	7-kg jackhammer	$60/day
	14-kg jackhammer	$80/day
	Handtools	$15/day
	Haul truck	$25/day
	Milling machine	$500/day
	Sandblaster	$200/day
	Airblaster	$150/day
	Waterblaster	$1,000/day
Mixing and placing equipment	Water, hose, and pump	$5/day
	Drum mixer	$35/day
	Mortar mixer	$20/day
	Jiffy mixer	$15/day
	Bonding agent brush	$1/day
	Vibrators and screeds	$20/day
	Hand trowels and shovels	$1/day
	Curing compound applicator	$2/day
	Vibratory roller/plate compactor	$25/day
	Generator	$40/day
	Grayco Percat 500	$40/day
	Non-water cleaning solvent	$25/day
	Air meter	$5/day
	Cylinders and slump cone	$5/day
Other costs	Removal and placement labor	$120/day/person
	Traffic control	$150/day
	User delay cost	$0/day

were determined for each test site. Tables 20 through 23 show the cost-effectiveness values for each repair type at the spall repair test sites as calculated using equation 2. The values in tables 20 through 23 represent the final cost-effectiveness values for the H-106 repairs, since no additional data will be collected.

The data in these tables show that similar performance of the bituminous repairs provides the lowest overall cost-effectiveness values, with the UPM chip-and-patch repairs having the lowest annual costs per m^3 in Arizona, South Carolina, and Utah. The relatively good survival performance, along with relatively low material costs and high productivity, indicates that these are the most desirable repairs for these particular sites. The information in tables 20 through 23 also shows that for the repair materials placed, the chip-and-patch procedure had lower annual costs in all 28 comparisons at all 4 sites. The difference between the procedures was consistent for both the $0/day user delay and the $1,000/day user delay scenarios.

The investigation of the effect of user delay costs was to determine whether the increased cost of making repairs during lane closure, with the costs to the traveling public, would change the overall cost-effectiveness findings. In general, no differences were observed in the overall lowest five annual cost repair types for any site, though the order from number 1 to number 5 did change in Arizona, Pennsylvania, and Utah.

Table 20. Summary of final cost-effectiveness values for South Carolina test site (lowest five annual costs highlighted).

Repair Material	Repair Procedure	Maximum Possible Repair Life, months	Mean Repair Life, months	Annual Adjusted Cost, $/m^3 ($0 user delay)	Annual Adjusted Cost, $/m^3 ($1,000 user delay)
Type III PCC	Saw-and-patch	68	68.0	3,176	4,279
	Chip-and-patch	68	68.0	1,448	2,000
Duracal	Saw-and-patch	68	68.0	1,854	2,533
	Chip-and-patch	68	62.8	952	1,319
Set-45	Saw-and-patch	68	60.8	2,129	2,888
	Chip-and-patch	68	64.2	989	1,348
Five Star HP	Saw-and-patch	68	68.0	1,854	2,533
	Chip-and-patch	68	68.0	892	1,231
MC-64	Saw-and-patch	68	68.0	3,054	3,790
	Chip-and-patch	68	64.8	2,246	2,632
SikaPronto 11	Saw-and-patch	68	61.3	3,380	4,133
	Chip-and-patch	68	60.1	2,291	2,675
Percol FL	Saw-and-patch	68	68.0	1,880	2,450
	Chip-and-patch	68	50.3	1,540	1,924
UPM	Chip-and-patch	68	62.3	527	829
Spray-injection	Chip-and-patch	68	65.3	697	985

Table 21. Summary of final cost-effectiveness values for Pennsylvania test site (lowest six annual costs highlighted)

Repair Material	Repair Procedure	Maximum Possible Repair Life, months	Mean Repair Life, months	Annual Adjusted Cost, $/m^3 ($0 user delay)	Annual Adjusted Cost, $/m^3 ($1,000 user delay)
Type III PCC	Saw-and-patch	87	71.2	3,032	4,085
	Chip-and-patch	87	78.9	1,248	1,724
	Mill-and-patch	87	77.6	1,026	1,348
Set-45	Saw-and-patch	87	83.0	1,560	2,116
	Chip-and-patch	87	63.7	997	1,360
	Mill-and-patch	87	83.5	646	831
Five Star HP	Saw-and-patch	87	73.7	1,712	2,339
	Chip-and-patch	87	77.8	780	1,077
	Mill-and-patch	87	70.9	723	940
MC-64	Saw-and-patch	87	78.0	2,662	3,304
	Chip-and-patch	87	58.0	2,509	2,941
SikaPronto 11	Saw-and-patch	87	82.8	2,502	3,059
	Chip-and-patch	87	64.5	2,134	2,492
Percol FL	Saw-and-patch	87	86.3	1,482	1,931
	Chip-and-patch	87	86.3	898	1,122
	Mill-and-patch	87	73.3	970	1,147
	Adverse clean-and-patch	91	70.1	778	916
Pyrament 505	Saw-and-patch	87	78.2	1,831	2,530
	Chip-and-patch	87	67.2	1,056	1,463
	Adverse clean-and-patch	91	52.2	540	801
UPM	Chip-and-patch	87	38.0	866	1,360
	Adverse clean-and-patch	91	42.4	289	510
Spray-injection	Chip-and-patch	87	55.2	859	1,200

Table 22. Summary of final cost-effectiveness values for Arizona test site (lowest five annual costs highlighted).

Repair Material	Repair Procedure	Maximum Possible Repair Life, months	Mean Repair Life, months	Annual Adjusted Cost, $ per m^3 ($0 user delay)	Annual Adjusted Cost, $ per m^3 ($1,000 user delay)
Type III PCC	Saw-and-patch	51	51.0	4,235	5,706
	Chip-and-patch	51	51.0	1,931	2,666
Duracal	Saw-and-patch	51	50.4	2,501	3,417
	Chip-and-patch	51	50.4	1,186	1,644
Set-45	Saw-and-patch	51	43.1	3,003	4,074
	Chip-and-patch	51	50.4	1,260	1,718
Five Star HP	Saw-and-patch	51	51.0	2,472	3,377
	Chip-and-patch	51	51.0	1,189	1,642
MC-64	Saw-and-patch	51	51.0	4,073	5,053
	Chip-and-patch	51	51.0	2,854	3,344
	Mill-and-patch	51	51.0	2,712	3,039
SikaPronto 11	Saw-and-patch	51	51.0	4,062	4,967
	Chip-and-patch	51	51.0	2,699	3,151
Percol FL	Saw-and-patch	51	32.0	3,996	5,205
	Chip-and-patch	51	49.7	1,558	1,948
	Mill-and-patch	51	44.8	1,586	1,874
Pyrament	Mill-and-patch	51	51.0	1,037	1,393
UPM	Chip-and-patch	51	42.2	779	1,223
Penatron	Saw-and-patch	51	43.2	3,990	4,916

Table 23. Summary of final cost-effectiveness values for Utah test site (lowest five annual costs highlighted).

Repair Material	Repair Procedure	Maximum Possible Repair Life, months	Mean Repair Life, months	Annual Adjusted Cost, \$/m^3 (\$0 user delay)	Annual Adjusted Cost, \$/m^3 (\$1,000 user delay)
Type III PCC	Saw-and-patch	86	86.0	2,512	3,384
	Chip-and-patch	86	86.0	1,145	1,581
	Waterblast-and-patch	86	84.1	3,380	4,272
Duracal	Saw-and-patch	86	85.2	1,480	2,021
	Chip-and-patch	86	81.8	731	1,013
Set-45	Saw-and-patch	86	86.0	1,505	2,042
	Chip-and-patch	86	86.0	738	1,007
Five Star HP	Saw-and-patch	86	86.0	1,466	2,003
	Chip-and-patch	86	86.0	705	974
MC-64	Saw-and-patch	86	86.0	2,415	2,997
	Chip-and-patch	86	86.0	1,692	1,983
SikaPronto 11	Saw-and-patch	86	86.0	2,409	2,946
	Chip-and-patch	86	86.0	1,601	1,869
Percol FL	Saw-and-patch	86	86.0	1,487	1,937
	Chip-and-patch	86	86.0	901	1,126
UPM	Chip-and-patch	86	47.0	699	1,098

CHAPTER 6. SUMMARY OF FINDINGS AND RECOMMENDATIONS

The SHRP H-106 experiment and subsequent FHWA LTM project represent the most comprehensive pavement surface maintenance study ever conducted. In the partial-depth spall repair portion of the study alone, more than 1,600 individual spalls were patched using 30 distinct repair types (i.e., combinations of material and patching method). The patches were placed at four U.S. test sites, with each site representing one of four distinct climatic zones.

Extensive laboratory testing of the experimental repair materials was conducted at the outset of the study and each patch placed in the study was routinely evaluated for field performance over a period of time ranging from 4.25 to 7.25 years, depending on the test site.

The details of the test sites constructed as part of the H-106 partial-depth spall repair study were provided in chapters 1 and 2 of this report. An in-depth discussion of the results of several laboratory tests performed on the experimental materials was provided in chapter 3. Complete documentation of the field performance collected in the study was given in chapter 4, and the results of various data analyses designed to distinguish repair performance and cost-effectiveness were presented in chapter 5.

This chapter summarizes the major findings and observations of the partial-depth spall repair study. The findings are divided into general findings and specific findings about materials and methods. Also contained in this chapter are various recommendations concerning spall repair operations that could be useful to the maintenance community, including highway administrators and practitioners, industry personnel, and researchers.

Findings

General

- In general, three of the four sites experienced very good performance for all repair types, with 88 percent survival at the Arizona test site, 90 percent survival at the South Carolina test site, and 91 percent survival at the Utah test site. The 61-percent survival at the Pennsylvania test site appeared to be related to the condition of the overall pavement, which was poorer than the conditions of the other three sites.

- Based on the survival analysis, three different groupings of repair types were identified: those that performed well, those that performed poorly, and those somewhere in between.

- The cost-effectiveness calculations for each site provided some consistent results in that the differences in annual cost figures were primarily a factor of the initial material and installation costs.

- The needed duration of repair survival must be factored into the decision of which material and methods should be used. For situations where only 2 to 3 years of performance are needed (due to impending overlay or rehabilitation plans), different repair types will be dictated when compared to situations where repairs are expected to last 10 to 12 years.

- Although it has not been considered directly in the analyses performed in this report, decisions on what type of repair will be placed should be made with the safety of the maintenance crews and the traveling public in mind. Longer lasting, more durable repairs mean less repeat patching and less overall time on the road for crews, and should be a goal of those making decisions on the process. Simpler repair types that require less equipment and fewer workers on the road should also be considered.

Materials

- The cost-effectiveness analysis showed that repairs made with Duracal, Set-45, Five Star, and the UPM High Performance Cold Mix had the lowest five or six annual costs at each site where they were installed.

- The bituminous repairs (UPM High Performance Cold Mix and spray-injection) performed very well for a period of 3 to 4 years, but generally experienced rapid failure after a point where the AC materials had oxidized and become more brittle. Once the repairs began to experience significant cracking, it did not take long for the repairs to be broken into pieces that were pulled from the spalls.

- The performance of the Percol FL was somewhat inconsistent in that different repetitions experienced different results, even though they were placed under similar conditions with the same crews. This behavior was most pronounced at the Pennsylvania and South Carolina test sites.

- The flexible repairs placed in areas where they spanned the existing PCC joint experienced a great deal of reflective cracking from the underlying joint. The formation of a joint in the flexible materials, as was done in the rigid repairs, could have prevented some of this deterioration.

Methods

- In all 28 of the situations where a repair material was placed using both the saw-and-patch and the chip-and-patch procedures, the annual costs of the chip-and-patch repairs were lower than the costs of the saw-and-patch repairs. This was the result of similar performance characteristics observed for all of the repairs placed and the lower installation costs associated with the chip-and-patch procedure.

- Although the waterblast-and-patch repairs experienced no failures at the Utah site, the difficulties encountered in the use of the device in both Arizona and Utah indicate that the technology was not easily applied, thereby requiring the use of experienced maintenance workers to make for an efficient operation.

Recommendations

Partial-Depth Spall Repair Operations

- In situations where large-scale partial-depth spall repair operations are to be performed, it is imperative that the maintenance forces have an understanding of the future plans for the pavement sections to be maintained. Pavement sections scheduled for rehabilitation within 3 years will require different spall repair options than those sections that would be rehabilitated in 3 to 7 years or longer.

- Spall repair operations being considered for shorter timeframes (less than 3 years) can use less permanent repair options, such as using asphalt cold mix, as the most cost-effective option. Spall repair operations being considered for longer timeframes (more than 7 years), should use more permanent repair materials, such as Set-45, Duracal, or even Type III PCC.

- Partial-depth spall repairs placed on both sides of existing pavement joints should have joints formed in the repair to match the underlying pavement. This is true even for flexible pavement repairs.

- Based on the cost-effectiveness of the different operations, the chip-and-patch procedure is recommended over the saw-and-patch procedure for the majority of the materials evaluated. The higher productivity and reduced equipment needs make the chip-and-patch procedure more desirable.

- The waterblast-and-patch procedure provided good results when the equipment was operating properly and with personnel familiar in its use. The same level of good performance could not be expected for a maintenance crew first using the device.

Education and Research

- The information gathered and findings developed under the H-106/LTM study should be disseminated to all individuals involved in the repair of partial-depth spalls, including highway maintenance policy-makers, supervisors, crewpersons, pavement researchers, and persons responsible for the evaluation of new repair products and equipment.

- The importance of placing the longest lasting repairs possible should be emphasized among the pavement maintenance community. There are repair materials and methods that can provide nearly permanent repairs, which eliminates the need for repairing the same areas over and over. This can reduce the amount of time that crews need to be working under traffic situations, improving the level of safety for both the maintenance crew and the traveling public.

- Highway maintenance agencies need to develop a system for objectively evaluating new materials and equipment as they become available. The H-106/LTM project evaluated many materials and devices available in the late 1980s and early 1990s, but did not evaluate any new alternatives developed in the past few years.

- There is a need for development of laboratory test procedures that can be used as indicators of field performance level for different materials. At a minimum, procedures for the acceptance or rejection of material supplies should be developed to help identify potentially serious failures before repairs are placed on the road.

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APPENDIX A. TEST SITE LAYOUTS

The order of placement of the test sections within each spall repair test site was randomly determined. In Arizona, 40 test sections were installed and evaluated. The test sections consisted of combinations of 10 materials and 4 patching procedures. Tables A-1 and A-2 show the test section layouts for Arizona replicates 1 and 2, respectively. In Pennsylvania, 46 test sections of 10 different materials in combination with 4 different patching procedures were installed and evaluated. The test section layouts for Pennsylvania are shown in tables A-3 and A-4. In South Carolina, the 32 test sections consisted of combinations of 8 materials and 2 patching procedures, as shown in tables A-5 and A-6. In Utah, 34 test sections of 9 materials in combination with 4 patching procedures were installed and evaluated, as shown in tables A-7 and A-8.

Table A-1. Test section layout for Arizona replicate 1 (dry-nonfreeze).

Test Section Number	Procedure	Material
1	Chip-and-patch	Duracal
2	Chip-and-patch	UPM High Performance Cold Mix
3	Saw-and-patch	Set-45
4	Chip-and-patch	Set-45
5	Mill-and-patch	Percol FL
6	Saw-and-patch	Duracal
7	Chip-and-patch	SikaPronto 11
8	Saw-and-patch	SikaPronto 11
9	Mill-and-patch	Pyrament 505
10	Mill-and-patch	MC-64
11	Saw-and-patch	Percol FL
12	Chip-and-patch	Percol FL
13	Waterblast-and-patch	Pyrament 505
14	Chip-and-patch	Five Star HP
15	Chip-and-patch	MC-64
16	Saw-and-patch	MC-64
17	Saw-and-patch	Type III PCC
18	Chip-and-patch	Type III PCC
19	Saw-and-patch	Five Star HP
20	Chip-and-patch	Penatron R/M-3003

Table A-2. Test section layout for Arizona replicate 2 (dry-nonfreeze).

Test Section Number	Procedure	Material
1	Mill-and-patch	Percol FL
2	Saw-and-patch	Set-45
3	Mill-and-patch	Pyrament 505
4	Chip-and-patch	Percol FL
5	Saw-and-patch	Duracal
6	Chip-and-patch	UPM High Performance Cold Mix
7	Saw-and-patch	SikaPronto 11
8	Chip-and-patch	Duracal
9	Chip-and-patch	Set-45
10	Saw-and-patch	MC-64
11	Mill-and-patch	MC-64
12	Chip-and-patch	MC-64
13	Chip-and-patch	Type III PCC
14	Chip-and-patch	Five Star HP
15	Saw-and-patch	Five Star HP
16	Waterblast-and-patch	Pyrament 505
17	Saw-and-patch	Percol FL
18	Saw-and-patch	Type III PCC
19	Chip-and-patch	SikaPronto 11
20	Chip-and-patch	Penatron R/M-3003

Table A-3. Test section layout for Pennsylvania replicate 1 (wet-freeze).

Test Section Number	Procedure	Material
1	Chip-and-patch	UPM High Performance Cold Mix
2	Saw-and-patch	Pyrament 505
3	Chip-and-patch	SikaPronto 11
4	Chip-and-patch	Set-45
5	Chip-and-patch	MC-64
6	Chip-and-patch	Percol FL
7	Saw-and-patch	Percol FL
8	Saw-and-patch	Five Star HP
9	Saw-and-patch	Set-45
10	Saw-and-patch	Type III PCC
11	Chip-and-patch	Five Star HP
12	Adverse clean-and-patch	Percol FL
13	Saw-and-patch	SikaPronto 11
14	Mill-and-patch	Percol FL
15	Saw-and-patch	MC-64
16	Mill-and-patch	Type III PCC
17	Chip-and-patch	Type III PCC
18	Mill-and-patch	Set-45
19	Adverse clean-and-patch	Pyrament 505
20	Mill-and-patch	Five Star HP
21	Chip-and-patch	Pyrament 505
22	Adverse clean-and-patch	UPM High Performance Cold Mix
23	Chip-and-patch	Penatron R/M-3003

Table A-4. Test section layout for Pennsylvania replicate 2 (wet-freeze).

Test Section Number	Procedure	Material
1	Adverse clean-and-patch	Pyrament 505
2	Chip-and-patch	Pyrament 505
3	Chip-and-patch	UPM High Performance Cold Mix
4	Saw-and-patch	Pyrament 505
5	Saw-and-patch	Five Star HP
6	Chip-and-patch	Five Star HP
7	Chip-and-patch	Type III PCC
8	Chip-and-patch	MC-64
9	Saw-and-patch	Type III PCC
10	Chip-and-patch	SikaPronto 11
11	Adverse clean-and-patch	Percol FL
12	Saw-and-patch	Set-45
13	Mill-and-patch	Type III PCC
14	Mill-and-patch	Five Star HP
15	Chip-and-patch	Percol FL
16	Mill-and-patch	Percol FL
17	Saw-and-patch	Percol FL
18	Saw-and-patch	MC-64
19	Saw-and-patch	SikaPronto 11
20	Chip-and-patch	Set-45
21	Adverse clean-and-patch	UPM High Performance Cold Mix
22	Mill-and-patch	Set-45
23	Chip-and-patch	Spray-Injected Mix

Table A-5. Test section layout for South Carolina replicate 1 (wet-nonfreeze).

Test Section Number	Procedure	Material
1	Saw-and-patch	SikaPronto 11
2	Chip-and-patch	SikaPronto 11
3	Saw-and-patch	Percol FL
4	Saw-and-patch	MC-64
5	Saw-and-patch	Duracal
6	Chip-and-patch	Duracal
7	Chip-and-patch	Type III PCC
8	Saw-and-patch	Type III PCC
9	Chip-and-patch	Set-45
10	Saw-and-patch	Set-45
11	Chip-and-patch	MC-64
12	Chip-and-patch	Percol FL
13	Chip-and-patch	Five Star HP
14	Chip-and-patch	UPM High Performance Cold Mix
15	Saw-and-patch	Five Star HP
16	Chip-and-patch	Spray-Injected Mix

Table A-6. Test section layout for South Carolina replicate 2 (wet-nonfreeze).

Test Section Number	Procedure	Material
1	Saw-and-patch	MC-64
2	Chip-and-patch	Five Star HP
3	Saw-and-patch	Five Star HP
4	Chip-and-patch	SikaPronto 11
5	Chip-and-patch	Set-45
6	Saw-and-patch	SikaPronto 11
7	Chip-and-patch	Type III PCC
8	Saw-and-patch	Percol FL
9	Chip-and-patch	Percol FL
10	Chip-and-patch	Duracal
11	Saw-and-patch	Duracal
12	Saw-and-patch	Type III PCC
13	Chip-and-patch	UPM High Performance Cold Mix
14	Chip-and-patch	MC-64
15	Saw-and-patch	Set-45
16	Chip-and-patch	Spray-Injected Mix

Table A-7. Test section layout for Utah replicate 1 (dry-freeze).

Test Section Number	Procedure	Material
1	Chip-and-patch	UPM High Performance Cold Mix
2	Chip-and-patch	Duracal
3	Chip-and-patch	Set-45
4	Chip-and-patch	MC-64
5	Mill-and-patch	Type III PCC
6	Chip-and-patch	Five Star HP
7	Saw-and-patch	Set-45
8	Saw-and-patch	Percol FL
9	Saw-and-patch	Five Star HP
10	Saw-and-patch	Duracal
11	Chip-and-patch	SikaPronto 11
12	Saw-and-patch	Type III PCC
13	Saw-and-patch	MC-64
14	Waterblast-and-patch	Type III PCC
15	Chip-and-patch	Percol FL
16	Saw-and-patch	SikaPronto 11
17	Chip-and-patch	Type III PCC

Table A-8. Test section layout for Utah replicate 2 (dry-freeze).

Test Section Number	Procedure	Material
1	Saw-and-patch	Set-45
2	Chip-and-patch	MC-64
3	Chip-and-patch	Duracal
4	Saw-and-patch	Percol FL
5	Chip-and-patch	Percol FL
6	Chip-and-patch	Set-45
7	Chip-and-patch	Type III PCC
8	Saw-and-patch	Duracal
9	Waterblast-and-patch	Type III PCC
10	Chip-and-patch	Five Star HP
11	Mill-and-patch	Type III PCC
12	Saw-and-patch	SikaPronto 11
13	Saw-and-patch	Five Star HP
14	Saw-and-patch	MC-64
15	Chip-and-patch	UPM High Performance Cold Mix
16	Saw-and-patch	Type III PCC
17	Chip-and-patch	SikaPronto 11

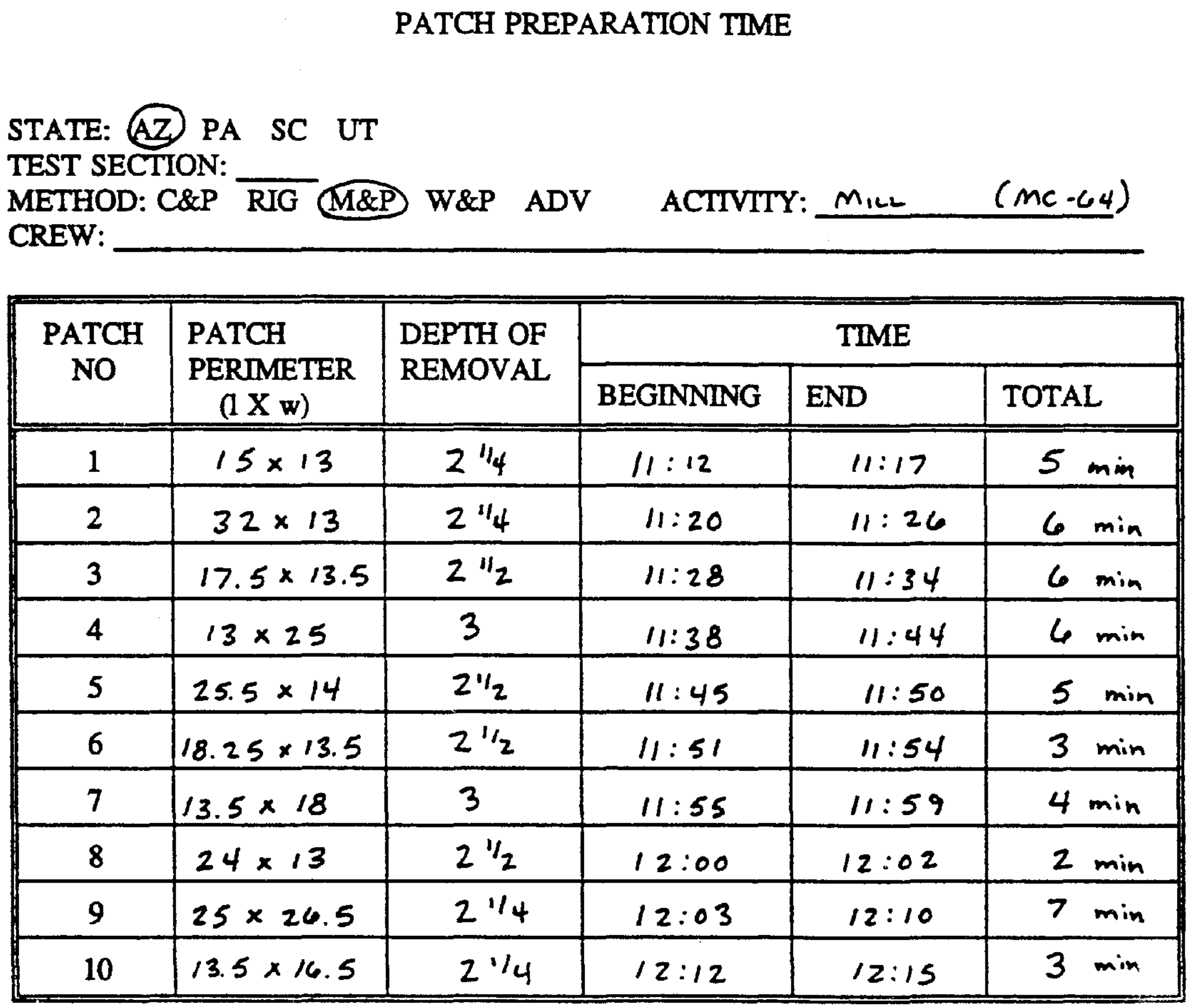
APPENDIX B. INSTALLATION DATA

Forms

The forms used to record installation data are shown in figures B-1 and B-2. Figure B-1 shows the form used to monitor productivity of the patching operation. Figure B-2 shows the form used to record information regarding each specific partial-depth spall repair. Both forms show data collected in the field.

Summary Data

Selected summary installation data are shown in tables B-1 through B-4. The data shown for each section identification number (SECTION ID) represent averages or typical values for the approximately 10 partial-depth patches that were installed in that section. The first two digits of the section identification number indicate the site (04 = Arizona, 42 = Pennsylvania, 45 = South Carolina, 49 = Utah). The third character represents the spall repair experiment (S). The fourth character represents the climatic region (1 = wet-freeze, 2 = dry-freeze, 3 = wet-nonfreeze, 4 = dry-nonfreeze). The fifth character is the material code and the seventh character is the procedure code, as shown in table B-5. The sixth character of the section identification number is the dummy variable, "0".

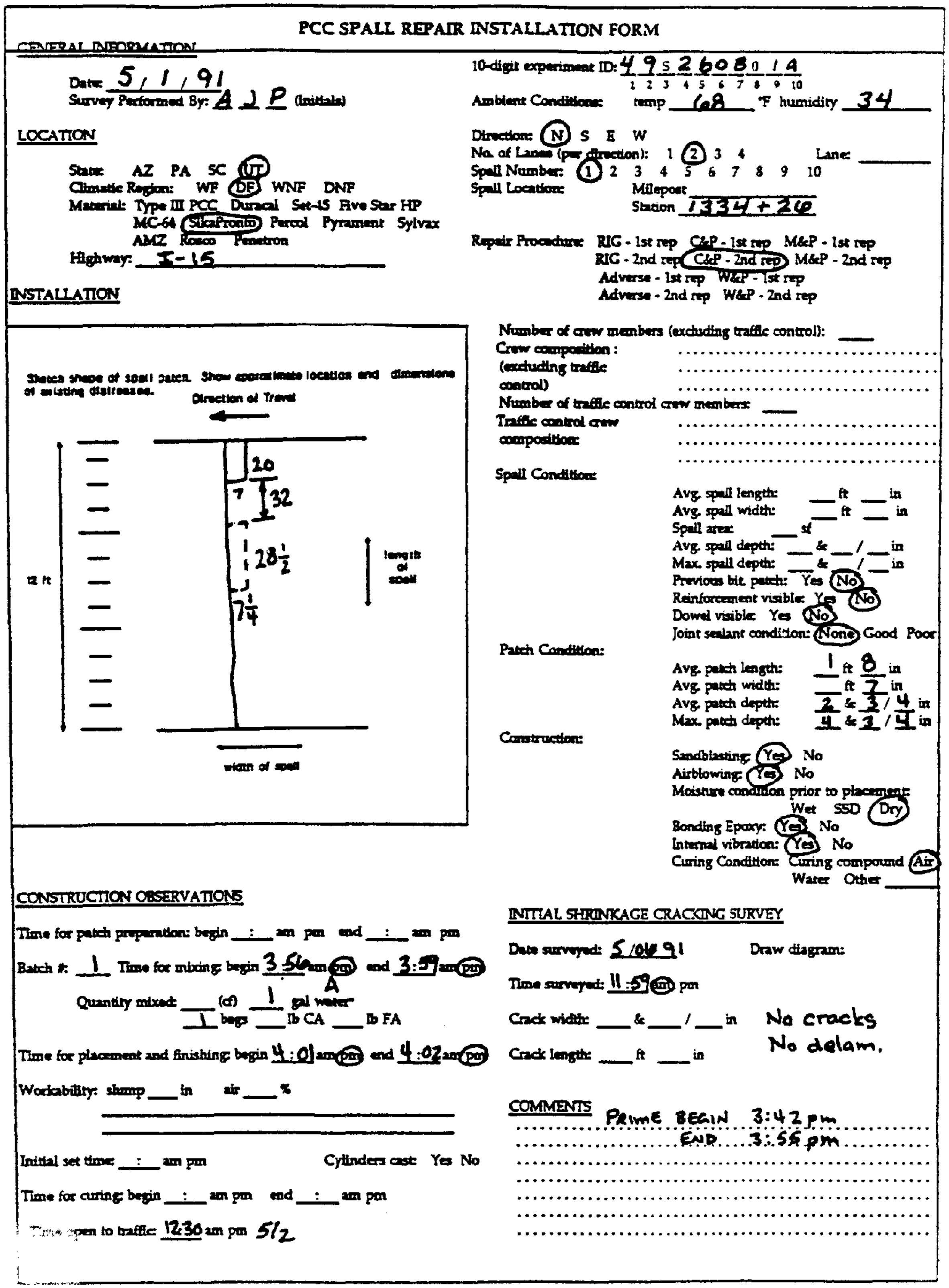


PATCH PREPARATION TIME

STATE: [✓ AZ] PA SC UT
TEST SECTION: ____
METHOD: C&P RIG [✓ M&P] W&P ADV ACTIVITY: Mill (MC-64)
CREW: ____

PATCH NO	PATCH PERIMETER (1 X w)	DEPTH OF REMOVAL	TIME		
			BEGINNING	END	TOTAL
1	15 x 13	2 1/4	11:12	11:17	5 min
2	32 x 13	2 1/4	11:20	11:26	6 min
3	17.5 x 13.5	2 1/2	11:28	11:34	6 min
4	13 x 25	3	11:38	11:44	6 min
5	25.5 x 14	2 1/2	11:45	11:50	5 min
6	18.25 x 13.5	2 1/2	11:51	11:54	3 min
7	13.5 x 18	3	11:55	11:59	4 min
8	24 x 13	2 1/2	12:00	12:02	2 min
9	25 x 26.5	2 1/4	12:03	12:10	7 min
10	13.5 x 16.5	2 1/4	12:12	12:15	3 min

Figure B-1. Patch preparation time form.



PCC SPALL REPAIR INSTALLATION FORM

GENERAL INFORMATION

Date: 5 / 1 / 91
Survey Performed By: A J P (initials)

10-digit experiment ID: 4 9 5 2 6 0 8 0 1 A
1 2 3 4 5 6 7 8 9 10
Ambient Conditions: temp 68 °F humidity 34

LOCATION

State: AZ PA SC [✓ UT]
Climatic Region: WF [✓ DF] WNF DNF
Material: Type III PCC Duracal Set-45 Five Star HP MC-64 [✓ SikaPronto] Percol Pyrament Sylvax AMZ Rosco Penetron
Highway: I-15

Direction: [✓ N] S E W
No. of Lanes (per direction): 1 [✓ 2] 3 4
Lane: ____
Spall Number: [✓ 1] 2 3 4 5 6 7 8 9 10
Spall Location: Milepost ____
Station 1334 + 26

Repair Procedure: RIG - 1st rep C&P - 1st rep M&P - 1st rep RIG - 2nd rep [✓ C&P - 2nd rep] M&P - 2nd rep Adverse - 1st rep W&P - 1st rep Adverse - 2nd rep W&P - 2nd rep

INSTALLATION

Sketch shape of spall patch. Show approximate location and dimensions of existing distresses.

Direction of Travel

12 ft

20

7

32

28½

7¼

length of spall

width of spall

Number of crew members (excluding traffic control): ____
Crew composition: (excluding traffic control) ....
Number of traffic control crew members: ____
Traffic control crew composition: ....

Spall Condition:

Avg. spall length: ___ ft ___ in
Avg. spall width: ___ ft ___ in
Spall area: ___ sf
Avg. spall depth: ___ & ___ / ___ in
Max. spall depth: ___ & ___ / ___ in
Previous bit. patch: Yes [✓ No]
Reinforcement visible: Yes [✓ No]
Dowel visible: Yes [✓ No]
Joint sealant condition: [✓ None] Good Poor

Patch Condition:

Avg. patch length: 1 ft 8 in
Avg. patch width: ___ ft 7 in
Avg. patch depth: 2 & 3 / 4 in
Max. patch depth: 4 & 3 / 4 in

Construction:

Sandblasting: [✓ Yes] No
Airblowing: [✓ Yes] No
Moisture condition prior to placement: Wet SSD [✓ Dry]
Bonding Epoxy: [✓ Yes] No
Internal vibration: [✓ Yes] No
Curing Condition: Curing compound [✓ Air] Water Other ____

CONSTRUCTION OBSERVATIONS

Time for patch preparation: begin ___:___ am pm end ___:___ am pm
Batch #: 1 Time for mixing: begin 3 56 am [✓ pm] end 3:59 am [✓ pm]
Quantity mixed: ___ (cf) 1 gal water
1 bags ___ lb CA ___ lb FA
Time for placement and finishing: begin 4:01 am [✓ pm] end 4:02 am [✓ pm]
Workability: slump ___ in air ___ %

Initial set time: ___:___ am pm
Cylinders cast: Yes No
Time for curing: begin ___:___ am pm end ___:___ am pm
Time open to traffic: 12:30 am pm 5/2

INITIAL SHRINKAGE CRACKING SURVEY

Date surveyed: 5/02 91
Draw diagram:
Time surveyed: 11:59 [✓ am] pm
Crack width: ___ & ___ / ___ in
Crack length: ___ ft ___ in

No cracks
No delam.

COMMENTS

PRIME BEGIN 3:42 pm
END 3:56 pm

Figure B-2. Spall repair installation form.

Table B-1. Selected summary installation data for Arizona (dry-nonfreeze).

Section ID	Date	Temp, °C	Humidity, %	Lane	Direction	Average Patch Depth, mm	Average Patch Width, mm	Average Patch Length, mm	Average Patch Area, m²
04S4101	6/1/91	25	10	3	N	76	254	3658	0.93
04S4102	6/3/91	21	53	3	N	64	343	305	0.10
04S410A	6/6/91	24	32	3	S	76	495	686	0.34
04S410B	6/5/91	28	10	3	S	64	216	357	0.08
04S4201	5/30/91	25	7	3	N	51	724	381	0.28
04S4202	5/30/91	25	7	3	N	64	381	356	0.13
04S420A	6/7/91	19	44	3	N	64	394	394	0.15
04S420B	6/7/91	18	44	3	N		254	381	0.10
04S4301	5/31/91	26	20	3	N	70	267	965	0.26
04S4302	5/31/91	21	10	3	N	64	508	305	0.15
04S430A	6/4/91	27	10	3	N	64	368	254	0.09
04S430B	6/5/91	23	27	3	N		305	610	0.19
04S4401	6/5/91	24	32	3	N	64	114	241	0.03
04S4402	6/2/91	18	51	3	N	57	216	851	0.18
04S440A	6/9/91	26	20	3	S	70	203	1956	0.40
04S440B	6/9/91	24	11	3	S	64	305	762	0.23
04S4501	6/2/91	29	25	3	N	83	356	584	0.21
04S4502	6/2/91	17	50	3	N	51	406	1016	0.41
04S4503	6/4/91	21	51	3	N	57	381	330	0.13
04S450A	6/8/91	31	20	3	S	83	483	813	0.39
04S450B	6/9/91	23	20	3	S	51	357	191	0.07
04S450C	6/5/91	19	49	3	N	51	330	1219	0.40
04S4601	5/30/91	26	10	3	N	70	203	3658	0.74
04S4602	5/31/91	23	10	3	N	64	305	838	0.26
04S460A	6/6/91	21	40	3	N	76	140	229	0.03
04S460B	6/7/91	20	41	3	N	64	635	343	0.22
04S4701	6/1/91	22	35	3	N	64	241	3658	0.88
04S4702	6/5/91	21	45	3	N	76	419	3658	1.53
04S4703	6/2/91	25	34	3	N	83	305	559	0.17
04S470A	6/6/91	24	20	3	S	70	267	330	0.09
04S470B	6/6/91	24	20	3	S	76	419	445	0.19
04S470C	6/2/91	27	20	3	N	70	305	711	0.22
04S4803	6/2/91	20	47	3	N	89	330	1270	0.42
04S4807	6/4/91	19	49	3	N	64	394	813	0.32
04S4902	5/30/91	31	7	3	N	51	279	660	0.18
04S490B	5/30/91	23	20	3	N	51	432	279	0.12
04S4B01	6/9/91	26	20	3	S	64	267	1168	0.31
04S4B0A	6/9/91	26	11	3	S	76	279	813	0.23

Table B-2. Selected summary installation data for Pennsylvania (wet-freeze).

Section ID	Date	Temp, °C	Humidity, %	Lane	Direction	Average Patch Depth, mm	Average Patch Width, mm	Average Patch Length, mm	Average Patch Area, m²
42S1101	7/10/91	22	70	1	N	89	305	1372	0.42
42S1102	7/16/91	33	34	1	N	76	165	1245	0.21
42S1103	7/16/91	30	46	1	N	66	406	787	0.32
42S110A	7/15/91	22	61	1	N	89	114	838	0.10
42S110B	7/18/91	31	52	1	S	102	127	1549	0.20
42S110C	6/17/91	23	30	1	S	51	432	1003	0.43
42S1301	7/11/91	29	36	1	N	64	610	381	0.23
42S1302	7/9/91	26	51	1	N	76	610	305	0.19
42S1303	6/20/91	27	50	1	N	51	445	1219	0.54
42S130A	7/17/91	28	53	1	N	76	102	787	0.08
42S130B	7/2/91	27	90	1	S	89	1346	305	0.41
42S130C	6/18/91	24	40	1	S	57	470	584	0.27
42S1401	7/1/91	31	40	1	S	76	159	1372	0.22
42S1402	7/17/91	30	49	1	N	51	114	762	0.09
42S1403	6/20/91	34	25	1	N	64	432	787	0.34
42S140A	6/13/91	19	40	1	S	51	546	813	0.44
42S140B	7/10/91	31	38	1	N	102	152	1422	0.22
42S140C	6/17/91	32	34	1	S	64	406	1321	0.54
42S1501	6/24/91	27	50	1	S	57	159	432	0.07
42S1502	6/24/91	18	30	1	S	38	610	813	0.50
42S150A	6/25/91	31	40	1	S	64	445	610	0.27
42S150B	6/25/91	29	50	1	S	51	165	357	0.06
42S1601	7/15/91	32	30	1	N	102	152	864	0.13
42S1602	7/11/91	22	64	1	N	76	152	737	0.11
42S160A	7/18/91	35	35	1	S	64	229	864	0.20
42S160B	7/11/91	26	49	1	N	102	241	914	0.22
42S1701	6/26/91	33	34	1	S	51	508	597	0.30
42S1702	6/26/91	32	32	1	S	64	203	686	0.14
42S1703	6/19/91	32	40	1	N	44	406	1676	0.68
42S1704	3/12/91	-4	20	1	N	51	305	508	0.15
42S170A	6/27/91	23	20	1	S	64	254	356	0.09
42S170B	6/27/91	27	50	1	S	64	1041	279	0.29
42S170C	6/19/91	29	50	1	S	64	432	1422	0.61
42S170D	3/11/91	2	20	1	S	102	127	533	0.07
42S1801	7/9/91	21	68	1	N	64	178	686	0.12
42S1802	7/17/91	33	33	1	N	51	660	279	0.18
42S1804	3/27/91	20	56	1	N	25	152	483	0.07
42S180A	7/1/91	27	60	1	S	51	140	1295	0.18
42S180B	6/12/91	27	50	1	S	178	711	330	0.23
42S180D	3/12/91	4	53	1	S	64	610	508	0.31
42S1902	7/8/91	27	70	1	N	102	483	1753	0.85
42S1904	3/26/91	16	40	1	N	51	76	305	0.02
42S190B	7/9/91	28	36	1	N	51	152	787	0.12
42S190D	3/26/91	19	34	1	S		254	914	0.23
42S1A02	8/7/91	24	60	1	N	51	406	406	0.16
42S1A0H	8/7/91	21	60	1	N	114	406	457	0.19

Table B-3. Selected summary installation data for South Carolina (wet-nonfreeze).

Section ID	Date	Temp, °C	Humidity, %	Lane	Direction	Average Patch Depth, mm	Average Patch Width, mm	Average Patch Length, mm	Average Patch Area, m^2
45S3101	5/23/91	29	30	1	W	44	254	813	0.21
45S3102	5/21/91	24	60	1	W	83	356	838	0.30
45S310A	5/28/91	31	90	1	W	70	305	1194	0.36
45S310B	5/22/91	21	40	1	W	57	254	559	0.14
45S3201	5/21/91	24	60	1	W	70	279	610	0.17
45S3202	5/21/91	24	60	1	W	44	254	737	0.19
45S320A	5/22/91	27	90	1	W	64	279	1143	0.32
45S320B	5/22/91	27	80	1	W	64	279	1194	0.33
45S3301	5/22/91			1	W		584	762	0.45
45S3302	5/23/91	32		1	W	64	279	889	0.25
45S330A	5/28/91	34	90	1	W	89	330	1029	0.34
45S330B	5/23/91	31	70	1	W	64	254	1067	0.27
45S3401	5/29/91	32	90	1	W	57	254	1270	0.32
45S3402	5/29/91	34	90	1	W	70	292	1524	0.45
45S340A	5/30/91	32	70	1	W	83	254	914	0.23
45S340B	5/30/91	31	70	1	W	76	241	483	0.12
45S3501	5/14/91	36	42	1	W	38	343	1067	0.37
45S3502	5/15/91	32	56	1	W	57	191	597	0.11
45S350A	5/17/91	32	44	1	W	76	305	1956	0.60
45S350B	5/16/91	25	78	1	W	57	318	699	0.22
45S3601	5/14/91	37	37	1	W	51	279	2337	0.65
45S3602	5/13/91	34	51	1	W	102	254	737	0.19
45S360A	5/29/91	32	90	1	W	76	267	2438	0.65
45S360B	5/30/91	30	90	1	W	57	152	673	0.10
45S3701	5/15/91	30	71	1	W	64	305	787	0.24
45S3702	5/15/91	30	71	1	W	64	241	851	0.21
45S370A	5/17/91	31	80	1	W	64	305	813	0.25
45S370B	5/17/91	31	57	1	W	83	305	1295	0.40
45S2902	5/20/91	22	79	1	W	70	267	914	0.24
45S390B	5/20/91	32	70	1	W	51	279	813	0.23
45S3A02	5/24/91	23	70	1	W	64	241	686	0.17
45S3A0B	5/24/91	23	70	1	W	38	254	965	0.24

Table B-4. Selected summary installation data for Utah (dry-freeze).

Section ID	Date	Temp. °C	Humidity, %	Lane	Direction	Average Patch Depth, mm	Average Patch Width, mm	Average Patch Length, mm	Average Patch Area, m²
49S2101	4/24/91	17	38	1	N	51	203	1118	0.23
49S2102	4/26/91	13	34	2	N	64	178	178	0.03
49S2105	5/1/91	19	32	2	N	64	305	1854	0.57
49S2106	4/24/91	18	37	2	N	38	203	838	0.17
49S210A	5/1/91	20	34	2	N	57	178	279	0.05
49S210B	4/30/91	17	37	2	N	64	178	267	0.05
49S210E	5/1/91	19	30	2	N	83	203	1607	0.33
49S210Y	5/1/91	6	61	2	N	89	254	229	0.06
49S2201	4/24/91	18	34	2	N	64	229	406	0.09
49S2202	4/23/91	20	34	2	N	51	152	445	0.07
49S220A	4/30/91	13	42	2	N	64	191	292	0.05
49S220B	4/30/91	8	59	2	N	64	152	457	0.07
49S2301	4/22/91	16	30	2	N	83	191	559	0.11
49S2302	4/22/91	21	30	2	N	70	229	1067	0.24
49S230A	4/26/91	12	34	2	N	51	203	254	0.05
49S230B	4/30/91	17	38	2	N	64	229	1080	0.25
49S2401	4/24/91	17	33	1	N	57	203	610	0.12
49S2402	4/22/91	16	30	2	N	70	152	762	0.12
49S240A	5/1/91	11	40	2	N	64	152	279	0.04
49S240B	4/30/91	17	38	2	N	76	178	508	0.09
49S240Y	5/1/91	11	40	2	N	64	178	1016	0.18
49S2501	4/24/91	16	48	2	N	51	203	2134	0.43
49S2502	4/23/91	21	34	2	N	64	152	279	0.04
49S250A	5/1/91	13	39	2	N	51	178	1067	0.19
49S250B	4/26/91	14	34	2	N	44	203	292	0.06
49S250Y	5/1/91	14	34	2	N	57	203	330	0.07
49S2601	4/26/91	14	34	2	N	51	203	203	0.04
49S2602	4/24/91	19	38	2	N	64	203	1067	0.22
49S260A	5/1/91	8	63	2	N		229	229	0.05
49S260B	5/1/91	20	34	2	N	70	178	508	0.09
49S2701	4/30/91	17	38	2	N	44	521	445	0.23
49S2702	4/30/91	17	36	2	N	89	203	610	0.12
49S270A	4/30/91	13	48	2	N	51	203	483	0.10
49S270B	4/30/91	13	48	2	N	64	178	254	0.04
49S2902	4/23/91	21	34	2	N	51	197	521	0.10
49S290B	5/1/91	18	34	2	N	51	229	305	0.07

Table B-5. Material and procedure codes.

Material Code	Material Name	Procedure Code	Procedure Name
1	Type III PCC	1, A, X	Saw-and-patch
2	Duracal	2, B, Y	Chip-and-patch
3	Set-45	3, 7, C, G	Mill-and-patch
4	Five Star HP	4, D	Adverse-condition clean-and-patch
5	MC-64	5, 6, E, F	Waterblast-and-patch
6	SikaPronto 11	8, H	Good-condition clean-and-patch
7	Percol FL		
8	Pyrament 505		
9	UPM High Performance Cold Mix		
A	Spray-Injected Mix		
B	Penatron R/M-3003		

APPENDIX C. MATERIAL TESTING DATA

The cementitious and polymer materials were tested by an independent laboratory (LAW Engineering) in Atlanta, Georgia. The samples were prepared and cured according to the material manufacturer's instructions to the extent possible. The following testing standards were used:

- Initial Set, ERES Test Method as given in the SHRP H-106 *EDRP*.
- Test Method for Compressive Strength of Hydraulic Cement Mortars, ASTM C 109, using 51-mm × 51-mm cube specimens for the 2-, 3-, and 4-hour tests.
- Test Method for Compressive Strength of Cylindrical Concrete Specimens, ASTM C 39, using 76-mm × 152-mm cylindrical specimens for the 24-hour tests and 102-mm × 203-mm for the 28-day tests.
- Test Method for Static Modulus of Elasticity and Poisson's Ratio of Concrete in Compression, ASTM C 469, using 102-mm × 203-mm cylindrical specimens for the 28-day compressive strength test. A combined compressometer–extensionmeter was used in this test.
- Test Method for Flexural Strength of Concrete, ASTM C 78, using 76-mm × 102-mm × 406-mm specimens.
- Test Method for Bond Strength of Epoxy-Resin Systems Used With Concrete, ASTM C 882.
- Method of Test of Bonding Strength of Concrete Overlay and Patching Materials to PCC, Caltrans, using 76-mm × 102-mm × 406-mm specimens. For the above two bond tests, BurkEpoxy MV and SikaPronto 19 were used as the bonding agent for the Type III PCC and SikaPronto 11 concrete, respectively, in the dry substrate condition.
- Test Method for Resistance of Concrete to Rapid Freezing and Thawing, ASTM C 666A, Procedure A, using 76-mm × 102-mm × 406-mm specimens, 4 hours per cycle.
- Test Method for Scaling Resistance of Concrete Surfaces Exposed to Deicing Chemicals, ASTM C 672, using 229-mm × 229-mm × 76-mm specimens.
- Test Method for Determining the Surface Abrasion Resistance of Concrete Specimens, Caltrans California Test 550.
- Test Method for Length Change of Hardened Cement Mortar and Concrete, ASTM C 157, using 76-mm × 76-mm × 286-mm specimens. All specimens were stored in air at a temperature of 23 ± 1.7°C and a relative humidity of 50 ± 4 percent.
- Test Method for Thermal Compatibility Between Concrete and an Epoxy-Resin Overlay, ASTM C 884, using 306-mm × 306-mm × 76-mm concrete blocks and a 13-mm overlay. All specimens were at a 7-day age when the test cycle commenced.

All of the test specimens were air cured until the age of test at a temperature of 23 ± 1.7°C and a relative humidity of 50 ± 4 percent, except for Type III PCC, Five Star HP, and Pyrament 505, which were moist cured at a temperature of 23 ± 1.7°C.

The bituminous materials were tested by a second independent laboratory (Southwestern Laboratories) in Houston, Texas, using the following testing standards:

- Test Method for Indirect Tension Test for Resilient Modulus of Bituminous Mixtures, ASTM D 4123. Samples were aged by heating them overnight in an oven at 135°C, compacting them hot using 75 blows per side, and allowing the compacted samples to cool in the molds prior to extrusion. Testing was performed at 25°C at three different frequencies: 0.33, 0.50, and 1.00 Hz.
- Test Method for Resistance to Plastic Flow of Bituminous Mixtures, ASTM D 1559. Samples were aged and compacted in the manner described for the resilient modulus test method.
- Test Method for Bulk Specific Gravity and Density of Compacted Bituminous Mixtures Using Saturated Surface-Dry Specimens, ASTM D 2726. The compaction effort used to prepare the samples was the same as for the resilient modulus and Marshall sample preparation.
- Test Method for Theoretical Maximum Specific Gravity of Bituminous Paving Mixtures, ASTM D 2041. The samples were prepared in the same manner as the bulk specific-gravity samples.
- Test Method for Coating and Stripping of Bitumen-Aggregate Mixtures, ASTM D 1664.
- PTI Workability Test, developed by the Pennsylvania Transportation Institute (PTI) (Anderson et al., 1988). The laboratory procedure used the 9.5-mm diameter probe developed by PTI. When this attachment was compared directly to the blade attachment, the reading of the blade attachment was approximately five times larger. The circular probe seems to work for stiffer mixes, where the smaller cross-section presents less resistance. The blade attachment seems to work for softer mixes, where the length of the blade in contact with the mix provides more resistance.
- Test Methods for Quantitative Extraction of Bitumen From Bituminous Paving Mixtures, ASTM D 2172.
- Test Method for Viscosity of Asphalts by Vacuum Capillary Viscometer, ASTM D 2171. The viscosity tests were performed on the binder recovered from the extraction process. Samples of binder were aged in a manner similar to the mixtures, in that the recovered binder was heated at 60°C until the reduction in weight stopped. This was used as an indication that the lighter volatiles had been driven off and the material remaining was primarily the residual binder.
- Test Method for Penetration of Bituminous Materials, ASTM D 5. Preparation of the recovered binder samples was the same for this test as for the viscosity test.
- Test Method for Ductility of Bituminous Materials, ASTM D 113. Preparation of the recovered binder samples was the same as for the viscosity test.
- Test Method for Softening Point of Bitumen (Ring-and-Ball Apparatus), ASTM D 36. Preparation of the recovered binder samples was the same as for the viscosity test.
- Method for Sieve Analysis of Fine and Coarse Aggregates, ASTM C 136.
- Test Method for Recovery of Asphalt From Solution by Abson Method, ASTM D 1856.

Tables C-1 through C-18 show the detailed results of the laboratory tests conducted on cementitious and polymer materials. Tables C-19 through C-21 and figure C-1 show the results of the laboratory tests conducted on bituminous materials.

Table C-1. Mix proportions (Smith et al., 1991).

Mix	Component	Quantity
Duracal	Duracal	11 kg
	Lone Star Coarse Aggregate	11 kg
	Lone Star Sand	11 kg
	Water	3.06 kg
Type III PCC	Dundee Type III Portland Cement	43 kg
	10-mm Pea Gravel	100 kg
	Sand	54 kg
	Water	11 kg
	Daravair	22 mL
	DCI	1.9 L
	Melment	0.4 L
Set-45	Set-45	22.7 kg
	10-mm Pea Gravel	13.6 kg
	Water	1.9 L
Five Star HP	Highway Patch	22.7 kg
	10-mm Pea Gravel	13.6 kg
	Water	33.1 kg
Pyrament 505	Pyrament 505	22.7 kg
	10-mm Pea Gravel	13.6 kg
	Water	2.2 kg
SikaPronto 11 (plant-proportioned)	SikaPronto 11 Part A	3.6 L
	Part B	30.9 kg
	10-mm Pea Gravel	17 kg
MC-64 (plant-proportioned)	Part A	3.8 L
	Part B	3.8 L
	Part B	30.9 kg
	10-mm Pea Gravel	17 kg
MC-64 (plant-proportioned)	Part A	3.8 L
	Part B	3.8 L
Percol FL (plant-proportioned)	Component A (by volume)	1 L
	Component B (by volume)	1 L

Table C-2. Initial set test results.

	Product							
	Duracal	Type III PCC	Set-45	Five Star HP	Pyrament 505	SikaPronto 11	MC-64	Percol FL
Initial Temperature, °C								
Ambient	21	5	23	23	23	24	23	23
Materials	22	23	22	22	22	23	23	23
Mixture	23	27	23	22	26	23	27	25
Mixing Time, min								
1	73	79	76	72	79	74	—	—
2	73	79	79	72	79	74	—	—
3	73	79	80	72	80	73	—	—
4	73	79	81	72	80	73	—	—
5	73	78	82	72	79	74	—	—
7	73	78	84	72	78	74	—	—
10	73	77	90	72	76	74	—	—
15	73	76		72	75	75	—	—
20	73	75		72	74	76	—	—
25	73	74		72	74	76	—	—
30	73	74		72	74	78	—	—
35	73	73		72	74	80	—	
40	73	73		73		83	—	
45	73	73		75				
50		73						
55		73						
60		74						

— MC-64 and Percol FL were not finishable.

Table C-3. Compressive strength test results, ASTM C 109, ASTM C 39.

Product	Specimen	Compressive Strength, MPa									
		2 hours		3 hours		4 hours		24 hours		28 days	
		Ind.	Average	Ind.	Average	Ind.	Average	Ind.	Average	Ind.	Average
Duracal	1	20.8	20.9	21.7	21.4	22.6	21.8	27.6	27.8	50.6	49.0
	2	20.9		20.4		22.3		27.6		47.8	
	3	21.1		22.0		20.4		28.1		48.5	
Type III PCC	1	1.9	2.0	6.1	6.5	12.1	13.0	48.9	47.4	63.9	64.6
	2	2.1		5.7		12.7		46.2		68.6	
	3	2.2		6.8		14.3		47.2		61.3	
Set-45	1	35.3	20.9	69.5	68.9	66.7	65.9	41.7	40.9	51.6	52.0
	2	57.9		69.2		68.3		37.8		47.6	
	3	59.5		68.3		62.8		43.00		56.9	
Five Star HP	1	26.2	27.6	30.3	29.9	31.7	32.1	34.2	36.8	46.2	45.4
	2	27.3		30.2		32.9		37.00		45.5	
	3	29.4		29.1		31.7		39.1		44.5	
Pyrament 505	1	18.7	18.3	22.0	22.7	26.3	26.5	37.2	36.9	57.9	56.6
	2	18.6		22.6		27.1		36.5		54.2	
	3	17.6		23.6		25.9		36.9		57.7	
Sika Pronto 11	1	31.6	35.1	36.7	42.0	38.4	42.4	46.2	46.0	51.7	10.3
	2	36.0		43.6		44.4		46.1		51.9	
	3	37.9		45.7		44.4		46.0		51.5	
MC-64	1	—	—	—	—	—	—	—	—	9.6	9.9
	2	—		—		—		—		9.6	
	3	—		—		—		—		10.2	
Percol FL	1	4.9	4.5	4.6	4.6	4.54	4.8	5.7	5.4	4.9	5.4
	2	4.9		4.5		5.2		5.3		5.2	
	3	3.6		4.8		4.7		5.4		6.3	

Ind. = Individual test result.

— Specimens continued to deform under load without well-defined fracture occurring.

Table C-4. Static modulus of elasticity and Poisson's ratio test results, ASTM C 469.

Product	Test Age, days	Specimen	Static Modulus of Elasticity, 10^3 MPa		Poisson's Ratio	
			Ind.	Average	Ind.	Average
Duracal	28	1	38.58	38.58	0.27	0.25
		2	38.58		0.25	
		3	38.24		0.22	
Type III PCC	28	1	45.82	47.89	0.16	0.17
		2	49.26		0.17	
		3	48.57		0.17	
Set-45	28	1	47.20	46.16	0.20	0.20
		2	45.47		0.20	
		3	46.16		0.20	
Five Star HP	28	1	39.62	38.58	0.16	0.17
		2	37.21		0.17	
		3	38.93		0.18	
Pyrament 505	28	1	49.95	49.61	0.15	0.16
		2	49.95		0.15	
		3	49.61		0.17	
SikaPronto 11	28	1	23.77	23.77	0.31	0.30
		2	23.08		0.28	
		3	24.12		0.32	
MC-64	28	1	—	—	—	—
		2	—		—	
		3	—		—	
Percol FL	28	1	—	—	—	—
		2	—		—	
		3	—		—	

Ind. = Individual test result.

— Strain range exceeded 20% beyond capacity of compressometer or strain gauge.

Table C-5. Flexural strength test results, ASTM C 78 (24 hours).

Product	Age, hours	Specimen	Average Width, mm	Average Depth, mm	Span Length, mm	Maximum Load, N	Modulus of Rupture, MPa	Average Modulus of Rupture, MPa
Duracal	24	1	76	103	305	11,422	4.3	4.4
		2	76	102	305	11,320	4.5	
		3	76	102	305	11,578	4.5	
Type III PCC	24	1	76	102	305	12,232	4.7	4.2
		2	76	104	305	11,120	4.1	
		3	76	104	305	10,319	3.8	
Set-45	24	1	79	102	305	9,416	3.5	3.2
		2	79	102	305	7,579	2.8	
		3	76	102	305	8,207	3.2	
Five Star HP	24	1	76	102	305	9,132	3.6	3.8
		2	76	102	305	10,720	4.1	
		3	76	102	305	9,652	3.7	
Pyrament 505	24	1	76	102	305	8,807	3.4	3.4
		2	79	102	305	8,949	3.4	
		3	76	102	305	8,994	3.5	
SikaPronto 11	24	1	79	107	305	36,985	12.6	13.3
		2	79	104	305	40,040	14.2	
		3	79	104	305	36,718	13.1	
MC-64	24	1	76	102	305	9,203	—	—
		2	76	102	305	8,576	—	
		3	76	102	305	9,158	—	
Percol FL	24	1	74	102	305	9,795	—	—
		2	74	102	305	7,539	—	
		3	74	102	305	8,562	—	

— No fracture occurred. Maximum load obtained at 35-mm maximum deflection allowed by testing jig.

Table C-6. Flexural strength test results, ASTM C 78 (28 days).

Product	Age, days	Specimen	Average Width, mm	Average Depth, mm	Span Length, mm	Maximum Load, N	Modulus of Rupture, MPa	Average Modulus of Rupture, MPa
Duracal	28	1	76	102	305	11872	5	5
		2	76	102	305	10764	4	
		3	76	102	305	12468	5	
Type III PCC	28	1	76	102	305	22004	9	8
		2	77	103	305	18308	7	
		3	77	102	305	22774	9	
Set-45	28	1	76	102	305	9372	4	3
		2	77	102	305	8113	3	
		3	77	102	305	9225	4	
Five Star HP	28	1	76	102	305	11787	5	5
		2	76	102	305	13153	5	
		3	76	102	305	11098	4	
Pyrament 505	28	1	76	102	305	22596	9	8
		2	76	102	305	22071	9	
		3	76	102	305	21057	8	
SikaPronto 11	28	1	76	102	305	39979	16	15
		2	79	102	305	40588	15	
		3	77	102	305	39374	15	
MC-64	28	1	79	104	305	18401	—	—
		2	76	104	305	17828	7	
		3	79	104	305	18401	—	
Percol FL	28	1	74	104	305	9145	—	—
		2	74	104	305	11164	—	
		3	74	104	305	11640	—	

— No fracture occurred. Maximum load obtained at 35-mm maximum deflection allowed by testing jig.

Table C-7. Slant-shear bond test results, ASTM C 882 (dry condition, 24 hours).

Product	Age, hours	Specimen	Bond Area, mm²	Type of Fracture[a]	Position of Fracture[b]	Bond Strength, MPa	
						Ind.	Average
Duracal	24	1	9117	A	I	12	10
		2	9117	A	I	7	
		3	9117	A	I	10[c]	
Type III PCC	24	1	9117	A	I	3	3
		2	9117	A	I	3	
		3	9117	A	I	3	
Set-45	24	1	9117	A	I	4	4
		2	9117	A	I/P	4	
		3	9117	A	I	10	
Five Star HP	24	1	9117	A	I	18	18
		2	9117	A	I	17	
		3	9117	A	I	18	
Pyrament 505	24	1	9117	A	I	19	19
		2	9117	A	I	20	
		3	9117	A	I	17	
SikaPronto 11	24	1	9117	A	I	16	17
		2	9117	A	I	17	
		3	9117	A	I	17	
MC-64	24	1	9117	A/C	I/B	2	2
		2	9117	A/C	I/B	2	
		3	9117	A/C	I/B	3	
Percol FL	24	1	9117	A	I/B	2	2
		2	9117	A	I	2	
		3	9117	A	I/B	2	

Ind. = Individual test result.

[a] A = adhesive failure, C = cohesive failure.

[b] I = interface, B = base concrete, P = patching material.

[c] Discarded, bad specimen.

Table C-8. Slant-shear bond test results, ASTM C 882 (dry condition, 28 days).

Product	Age, days	Specimen	Bond Area, mm^2	Type of Fracture[a]	Position of Fracture[b]	Bond Strength, MPa	
						Ind.	Average
Duracal	28	1	9117	A	I	17	15
		2	9117	A	I	11	
		3	9117	A	I	16	
Type III PCC	28	1	9117	A	I	7	6
		2	9117	A	I	7	
		3	9117	A	I	5	
Set-45	28	1	9117	A	I	9	8
		2	9117	A	I	8	
		3	9117	A	I	8	
Five Star HP	28	1	9117	A/C	B/P/I	22	22
		2	9117	C	B/P	21	
		3	9117	A/C	B/P/I	24	
Pyrament 505	28	1	9117	C	B/P	25	25
		2	9117	C	B/P	26	
		3	9117	A/C	B/P/I	25	
SikaPronto 11	28	1	9117	A	I	20	20
		2	9117	A	I	20	
		3	9117	A	I	19	
MC-64	28	1	9117	A/C	I/B	3	3
		2	9117	A/C	I/B	3	
		3	9117	A/C	I/B	3	
Percol FL	28	1	9117	A	I	2	2
		2	9117	A	I	1	
		3	9117	A	I	2	

[a] A = adhesive failure, C = cohesive failure.

[b] I = interface, B = base concrete, P = patching material.

Ind. = Individual test result.

Table C-9. Slant-shear bond test results, ASTM C 882 (wet condition, 24 hours).

Product	Age, hours	Specimen	Bond Area, mm^2	Type of Fracture[a]	Position of Fracture[b]	Bond Strength, MPa	
						Ind.	Average
Duracal	24	1	9117	A	I	11	11
		2	9117	A	I	14	
		3	9117	A	I	9	
Type III PCC	24	1	9117	A	I	8	9
		2	9117	A	I	10	
		3	9117	A	I	10	
Set-45	24	1	9117	A	I	4	5
		2	9117	A/C	I/P	6	
		3	9117	A	I	4	
Five Star HP	24	1	9117	A	I	15	15
		2	9117	A	I	14	
		3	9117	A	I	17	
Pyrament 505	24	1	9117	A	I	12	9
		2	9117	A/C	I/P	7	
		3	9117	A	I	8	
SikaPronto 11	24	1	9117	A	I	0	0[c]
		2	9117	A	I	0	
		3	9117	A	I	0	
MC-64	24	1	9013	A	I	1	1
		2	9013	A	I	1	
		3	9013	A	I	1	
Percol FL	24	1	9117	A	I	0	0
		2	9117	A	I	0	
		3	9117	A	I	0	

Ind. = Individual test result.

[a] A = adhesive failure, C = cohesive failure.

[b] I = interface, P = patching material.

[c] Specimens debonded after demolding.

Table C-10. Slant-shear bond test results, ASTM C 882 (wet condition, 28 days).

Product	Age, days	Specimen	Bond Area, mm^2	Type of Fracture[a]	Position of Fracture[b]	Bond Strength, MPa	
						Ind.	Average
Duracal	28	1	9117	A	I	19	18
		2	9117	A	I	17	
		3	9117	A	I	17	
Type III PCC	28	1	9117	A	I/P	13	14
		2	9117	A	I	15	
		3	9117	A	I	13	
Set-45	28	1	9117	A	I	11	10
	30	2	9117	A	I	5[c]	
	30	3	9117	A	I	8	
Five Star HP	28	1	9117	A	I	20	18
		2	9117	A	I	18	
		3	9117	A	I	17	
Pyrament 505	28	1	9117	A	I	20	20
		2	9117	A	I	18	
		3	9117	A	I	21	
SikaPronto 11	28	1	9117	A	I	0	0[d]
		2	9117	A	I	0	
		3	9117	A	I	0	
MC-64	28	1	9117	A	I	1	2
		2	9117	A	I/P	2	
		3	9117	A	I	2	
Percol FL	28	1	9117	A	I	0	1
		2	9117	A	I	1	
		3	9117	A	I	0	

Ind. = Individual test result.

[a] A = adhesive failure.

[b] I = interface, P = patching material.

[c] Discarded, bad specimen.

[d] Specimens debonded after demolding.

Table C-11. Center-point bond strength test results, Caltrans (dry condition, 24 hours).

Product	Age, hours	Specimen	Width, mm	Depth, mm	Span, mm	Position of Fracture[a]	Area of Break, %	Maximum Load, N	Modulus of Rupture, MPa	
									Ind.	Average
Duracal	24	1	78.7	104.1	304.8	I	N/A	2980	1.6	1.6
		2	76.2	101.6	304.8	I	N/A	3154	1.8	
		3	76.2	101.6	304.8	I	N/A	2504	1.4	
Type III PCC	24	1	76.2	101.6	304.8	I	N/A	5338	3.1	2.9
		2	76.2	101.6	304.8	I	N/A	5782	3.4	
		3	76.2	101.6	304.8	I	N/A	3558	2.1	
Set-45	24	1	78.7	101.6	304.8	I	N/A	5129	2.9	2.4
		2	78.7	101.6	304.8	I	N/A	3078	1.8	
		3	78.7	101.6	304.8	I	N/A	4199	2.4	
Five Star HP	24	1	76.2	101.6	304.8	I	N/A	6156	3.6	3.6
		2	76.2	104.1	304.8	I	N/A	7139	4.0	
		3	76.2	101.6	304.8	I	N/A	5725	3.3	
Pyrament 505	24	1	78.7	101.6	304.8	I	N/A	3781	2.1	2.3
		2	77.5	102.9	304.8	I	N/A	4283	2.4	
		3	76.2	102.9	304.8	I	N/A	3999	2.3	
SikaPronto 11	24	1	76.2	101.6	304.8	I	N/A	10435	6.1	6.1
		2	78.7	104.1	304.8	I	N/A	9915	5.3	
		3	76.2	101.6	304.8	I	N/A	11712	6.8	
MC-64	24	1	78.7	104.1	304.8	I	N/A	4951	2.8	2.5
		2	78.7	104.1	304.8	I	N/A	4359	2.4	
		3	78.7	104.1	304.8	I	N/A	4194	2.3	
Percol FL	24	1	78.7	101.6	304.8	I	N/A	5974	3.3	3.4
		2	73.7	101.6	304.8	I	N/A	5551	3.3	
		3	73.7	101.6	304.8	I	N/A	5840	3.5	

Ind. = Individual test result. N/A = Not applicable.

[a] I = interface.

Table C-12. Center-point bond strength test results, Caltrans (dry condition, 28 days).

Product	Age, days	Specimen	Width, mm	Depth, mm	Span, mm	Position of Fracture[a]	Area of Break, %	Maximum Load, N	Modulus of Rupture, MPa	
									Ind.	Average
Duracal	28	1	76.2	101.6	304.8	I/B	5	3229	1.5	1.6
		2	76.2	104.1	304.8	I/P	5	25251	1.7	
		3	76.2	104.1	304.8	I	N/A	1134	---[b]	
Type III PCC	28	1	78.7	104.1	304.8	I	N/A	5427	2.9	3.3
		2	78.7	104.1	304.8	I	N/A	6227	3.6	
		3	78.7	104.1	304.8	I	N/A	5871	3.4	
Set-45	28	1	78.7	101.6	304.8	I	N/A	7143	4	4.0
		2	78.7	101.6	304.8	I/B	10	6899	3.9	
		3	78.7	101.6	304.8	I/B	10	7410	4.2	
Five Star HP	28	1	76.2	104.1	304.8	I/P	80	7442	4.1	3.7
		2	76.2	104.1	304.8	I/P	60	6690	3.7	
		3	76.2	104.1	304.8	I/P	70	5951	3.3	
Pyrament 505	28	1	78.7	104.1	304.8	I/B	5	9563	5.1	4.8
		2	76.2	104.1	304.8	B	100	8407	4.7	
		3	76.2	104.1	304.8	I/B	10	8029	4.4	
SikaPronto 11	28	1	76.2	101.6	304.8	I/B	95	11787	6.9	6.6
		2	76.2	101.6	304.8	I/B	95	11565	6.7	
		3	78.7	101.6	304.8	I/B	70	11387	6.4	
MC-64	28	1	76.2	104.1	304.8	I/P	5	6112	3.4	3.3
		2	73.7	104.1	304.8	I	N/A	5533	3.2	
		3	73.7	104.1	304.8	I	N/A	5667	3.2	
Percol FL	28	1	76.2	101.6	304.8	I/B	40	6894	4.0	4.0
		2	76.2	101.6	304.8	I/B	5	7090	4.1	
		3	76.2	101.6	304.8	I	N/A	6423	3.9	

Ind. = Individual test result. N/A = Not applicable.

[a] I = interface, B = base concrete, P = patching material.

[b] Discarded, bad specimen.

Table C-13. Center-point bond strength test results, Caltrans (wet condition, 24 hours).

Product	Age, hours	Specimen	Width, mm	Depth, mm	Span, mm	Position of Fracture[a]	Area of Break, %	Maximum Load, N	Modulus of Rupture, MPa	
									Ind.	Average
Duracal	24	1	76.2	104.1	304.8	I	N/A	4101	2.3	1.7
		2	78.7	104.1	304.8	I	N/A	2500	1.3	
		3	76.2	104.1	304.8	I	N/A	2393	1.3	
Type III PCC	24	1	76.2	104.1	304.8	I	N/A	1268	0.7	0.6
		2	76.2	101.6	304.8	I	N/A	983	0.6	
		3	76.2	101.6	304.8	I	N/A	916	0.5	
Set-45	24	1	78.7	104.1	304.8	I	N/A	2784	1.5	1.5
		2	78.7	104.1	304.8	I	N/A	2736	1.4	
		3	76.2	106.7	304.8	I	N/A	3047	1.6	
Five Star HP	24	1	78.7	101.6	304.8	I/P	30	2736	1.6	1.6
		2	78.7	101.6	304.8	I	N/A	2607	1.5	
		3	76.2	101.6	304.8	I/P	30	3216	1.9	
Pyrament 505	24	1	78.7	106.7	304.8	I	N/A	3211	1.7	2.0
		2	78.7	104.1	304.8	I	N/A	4444	2.4	
		3	78.7	106.7	304.8	I	N/A	4074	2.1	
SikaPronto 11	24	1	78.7	104.1	304.8	I	N/A	0	0	0[b]
		2	78.7	104.1	304.8	I	N/A	0	0	
		3	78.7	104.1	304.8	I	N/A	0	0	
MC-64	24	1	76.2	101.6	304.8	I	N/A	3332	1.9	2.0
		2	76.2	104.1	304.8	I	N/A	3736	2.1	
		3	78.7	104.1	304.8	I	N/A	3781	2.0	
Percol FL	24	1	73.7	101.6	304.8	I	N/A	0	0	0[b]
		2	73.7	101.6	304.8	I	N/A	0	0	
		3	73.7	101.6	304.8	I	N/A	0	0	

Ind. = Individual test result. N/A = Not applicable.

[a] I = interface, P = patching material.

[b] Specimens debonded after demolding.

Table C-14. Center-point bond strength test results, Caltrans, (wet condition, 28 days).

Product	Age, days	Specimen	Width, mm	Depth, mm	Span, mm	Position of Fracture[a]	Area of Break, %	Maximum Load, N	Modulus of Rupture, MPa	
									Ind.	Average
Duracal	28	1	78.7	101.6	304.8	I	N/A	5827	3.3	3.0
		2	78.7	101.6	304.8	I	N/A	4888	2.8	
		3	78.7	101.6	304.8	I	N/A	5338	3.0	
Type III PCC	28	1	78.7	101.6	304.8	I	N/A	4519	2.5	2.5
		2	78.7	101.6	304.8	I	N/A	4252	2.4	
		3	78.7	101.6	304.8	I/B	5	4608	2.6	
Set-45	28	1	78.7	101.6	304.8	I/P	5	2691	1.5	1.6
		2	78.7	104.1	304.8	I	N/A	2736	1.4	
		3	78.7	101.6	304.8	I/P	40	3007	1.7	
Five Star HP	28	1	78.7	104.1	304.8	I	N/A	3914	2.1	2.3
		2	78.7	104.1	304.8	I/P	70	4577	2.4	
		3	78.7	104.1	304.8	I	N/A	4226	2.3	
Pyrament 505	28	1	76.2	101.6	304.8	I	N/A	4848	2.8	2.7
		2	76.2	104.1	304.8	I	N/A	4782	2.7	
		3	73.7	101.6	304.8	I	N/A	4092	2.4	
SikaPronto 11	28	1	78.7	104.1	304.8	I	N/A	0	0	0[b]
		2	78.7	104.1	304.8	I	N/A	0	0	
		3	78.7	104.1	304.8	I	N/A	0	0	
MC-64	28	1	73.7	101.6	304.8	I	N/A	4226	2.5	2.3
		2	71.1	101.6	304.8	I	N/A	3465	2.2	
		3	73.7	101.6	304.8	I	N/A	3412	2.1	
Percol FL	28	1	73.7	101.6	304.8	I	N/A	0	0	0[b]
		2	73.7	101.6	304.8	I	N/A	0	0	
		3	73.7	101.6	304.8	I	N/A	0	0	

Ind. = Individual test result. N/A = Not applicable.

[a] I = interface, B = base concrete, P = patching material. [b] Specimens debonded after demolding.

Table C-15. Freeze-thaw test results, ASTM C 666.

Product	Sample	No. of Cycles	Initial Weight, g	Final Weight, g	Weight Change, g		Initial Resonant Frequency, kHz	Final Resonant Frequency, kHz	Relative Dynamic Modulus	Durability Factor	
					Ind.	Average				Ind.	Average
Duracal	1	152	7,690.4	7,678.7	-11.7	-39.4	2,223	1,699	58.4	29.6	43.0
	2	190[a]	7,569.9	7,555.5	-14.4		2,227	2,163	94.3	59.7	
	3	260	7,662.3	7,570.2	-92.1		2,223	1,504	45.8	39.7	
Type III PCC	1	308	7,780.8	7,778.0	-2.8	-12.3	2,470	2,424	96.3	98.9	101.3
	2	308	7,845.6	7,845.0	-0.6		2,510	2,468	96.7	99.3	
	3	308	7,801.5	7,768.1	-33.4		2,417	2,454	103.1	105.8	
Set-45	1	72	7,469.5	7,452.2	-17.3	-36.0	1,605	1,299	58.6	14.1	24.9
	2	72[a]	7,473.6	7,462.3	-11.3		1,615	1,499	86.2	20.7	
	3	227	7,463.9	7,384.4	-79.5		2,470	1,792	52.6	39.8	
Five Star HP	1	72	7,515.8	NA	NA	NA	2,241	1.392	38.6	9.3	10.1
	2	72	7,370.1	NA	NA		2,215	NA	NA	NA	
	3	72	7,501.2	NA	NA		2,227	1,493	44.9	10.8	
Pyrament 505	1	308	7,688.9	7,687.7	-1.9	-5.6	2,400	2,481	106.9	109.7	124.9
	2	308	7,671.7	7,667.0	-1.7		2,410	2,473	105.3	108.1	
	3	308	7,682.1	7,671.8	-10.3		1,998	2,470	152.8	156.9	
SikaPronto 11	1	306	7,296.3	7,295.2	-1.1	3.5	1,983	1,747	77.6	79.2	76.3
	2	306	7,403.1	7,408.0	4.9		1,970	1,783	81.9	83.6	
	3	306	7,313.4	7,320.1	6.7		1,992	1,602	64.7	66.0	
MC-64	1	306	2,691.1	2,807.4	116.3	61.7	1,805	1,690	87.7	89.4	96.2
	2	306	2,638.7	2,693.7	55.0		1,834	1,813	97.7	99.7	
	3	306	2,690.8	2,704.6	13.8		1,857	1,835	97.6	99.6	
Percol FL	1	306	6,149.3	6,172.0	22.7	56.9	3.081	2,156	49.0	49.9	57.1
	2	306	6,163.0	6,206.3	43.3		2.854	2,218	60.4	61.6	
	3	306	5,894.3	5,998.9	104.6		1.542	1,181	58.7	59.8	

Ind. = Individual test result.

[a] Specimens fractured near midsection; test terminated.

NA = Not available. Samples were too badly deteriorated to make a reading or weight measurement.

Table C-16. Wear-resistance test results, Caltrans T 550.

Product	Specimen	Abrasion Loss, g		Percent loss		Test Age, days
		Ind.	Average	Ind.	Average	
Duracal	1	21.5	19.8	2.27	2.04	7
	2	18.6		1.83		7
	3	19.3		2.01		7
Type III PCC	1	19.6	18.7	1.86	1.77	7
	2	17.5		1.67		7
	3	18.9		1.77		7
Set-45	1	23.9	23.7	2.46	2.45	7
	2	23.5		2.45		7
	3	23.7		2.44		7
Five Star HP	1	20.0	19.5	2.19	2.11	7
	2	19.6		2.14		7
	3	18.8		1.99		7
Pyrament 505	1	25.9	25.5	2.70	2.65	7
	2	23.7		2.35		7
	3	26.8		2.91		7
SikaPronto 11	1	12.3	12.7	1.27	1.31	7
	2	13.0		1.35		7
	3	10.8[a]		1.06[a]		7
MC-64	1	-0.8	-0.8	-0.22	-0.21	8
	2	-0.6		-0.16		8
	3	-0.9		-0.25		8
Percol FL	1	0.0	0.0	0.0	0.01	8
	2	0.0		0.0		8
	3	0.2		0.03		8

Ind. = Individual test result.

[a] Discarded, sample size too high.

Table C-17. Thermal compatibility test results, ASTM C 884.

Product	Specimen	Number of Cycles	Observation		Result
			Delamination	Horizontal Crack	
Duracal	1	5	Yes	None	Fail
	2	5	No	None	Pass
	3	5	No	None	Pass
Type III PCC	1	5	No	None	Pass
	2	5	No	None	Pass
	3	5	No	None	Pass
Set-45	1	5	No	None	Pass
	2	5	No	None	Pass
	3	5	No	None	Pass
Five Star HP	1	5	No	None	Pass
	2	5	No	None	Pass
	3	5	No	None	Pass
Pyrament 505	1	5	No	None	Pass
	2	5	No	None	Pass
	3	5	No	None	Pass
SikaPronto 11	1	5	No	None	Pass
	2	5	No	None	Pass
	3	5	No	None	Pass
MC-64	1	5	Yes	None	Fail
	2	5	No	None	Pass
	3	5	Yes	None	Fail
Percol FL	1	5	No	None	Pass
	2	5	No	None	Pass
	3	5	No	None	Pass

Table C-18. Length-change test results, ASTM C 157.

Product	Specimen	Length Change, %					
		4 hours	8 hours	24 hours	3 days	28 days	60 days
Duracal	1	-0.017	0.002	-0.003	-0.004	-0.017	-0.025
	2	-0.016	-0.012	-0.014	-0.014	-0.023	-0.032
	3	-0.020	-0.015	-0.009	-0.014	-0.027	-0.037
	Average	-0.018	-0.008	-0.009	-0.011	-0.022	-0.031
Type III PCC	1	-0.002	-0.005	-0.013	-0.021	-0.039	-0.059
	2	-0.006	-0.019	-0.025	-0.031	-0.043	-0.062
	3	-0.007	-0.007	-0.014	-0.028	-0.039	-0.059
	Average	-0.005	-0.010	-0.017	-0.027	-0.040	-0.060
Set-45	1	-0.005	-0.005	-0.007	-0.009	-0.009	-0.013
	2	-0.014	-0.016	-0.018	-0.020	-0.024	-0.027
	3	-0.011	-0.017	-0.019	-0.021	-0.022	-0.025
	Average	-0.010	-0.013	-0.015	-0.017	-0.018	-0.022
Five Star HP	1	-0.005	-0.008	-0.012	-0.018	-0.032	-0.039
	2	-0.009	-0.013	-0.020	-0.025	-0.039	-0.047
	3	-0.006	-0.008	-0.017	-0.021	-0.035	-0.040
	Average	-0.007	-0.010	-0.016	-0.021	-0.035	-0.042
Pyrament 505	1	0.000	-0.020	-0.042	-0.042	-0.052	-0.055
	2	-0.002	-0.016	-0.038	-0.037	-0.048	-0.053
	3	-0.007	-0.022	-0.039	-0.041	-0.054	-0.056
	Average	-0.003	-0.019	-0.040	-0.040	-0.051	-0.055
SikaPronto 11	1	-0.017	-0.022	-0.027	-0.032	-0.042	-0.047
	2	-0.010	-0.013	-0.025	-0.025	-0.035	-0.036
	3	-0.019	-0.027	-0.033	-0.035	-0.043	-0.051
	Average	-0.015	0.0210	-0.028	-0.031	-0.040	-0.045
MC-64	1	—	—	—	—	—	—
	2	—	—	—	—	—	—
	3	—	—	—	—	—	—
	Average	—	—	—	—	—	—
Percol FL	1	—	—	—	—	—	—
	2	—	—	—	—	—	—
	3	—	—	—	—	—	—
	Average	—	—	—	—	—	—

— Unable to obtain well-defined readings. Specimens exhibited elastic behavior at all ages. Bottom gauge stud was pushed inside specimen by specimen's own weight.

Table C-19. Summary of laboratory testing for UPM (South Carolina and Arizona).

Test Name, ASTM Designation	Replicate Number			Average Values
	1	2	3	
Resilient Modulus, D 4123				
25°C, 0.33 Hz, MPa	2201	2390	1405	2000
25°C, 0.50 Hz, MPa	2123	2321	1378	1941
25°C, 1.00 Hz, MPa	2197	2427	1421	2015
Marshall Stability, D 1559, kg	2257	2408	2259	2308
Marshall Flow, mm	2.3	2.5	2.5	2.5
Bulk Specific Gravity, D 2726	2.260	2.254	2.264	2.259
Maximum Specific Gravity, D 2041	2.535	2.536	2.539	2.537
Air Voids, %	10.8	11.1	10.8	10.9
Anti-Stripping, Modified D 1664	+95%	+95%	NA	+95%
Workability, PTI Method	0.5	0.5	0.5	0.5
AC Content, D 2172, %	3.5	3.3	3.6	3.5
Viscosity, D 2171, 60°C, Poise	621	657	NA	639
Penetration, D 5, 25°C, 100 g, 5 sec, dmm	200	192	NA	196
Ductility, D 113, 25°C, 50 mm/min, mm	1500+	1500+	NA	1500+
Softening Point, D 36, °C	42.2	43.3	NA	42.8

NA = Not available.

Table C-20. Summary of laboratory testing for UPM (Utah).

Test Name, ASTM Designation	Replicate Number			Average Values
	1	2	3	
Resilient Modulus, D 4123				
25°C, 0.33 Hz, MPa				
25°C, 0.50 Hz, MPa				
25°C, 1.00 Hz, MPa				
Marshall Stability, D 1559, kg	1861	1897	1699	1819
Marshall Flow, mm	3.05	2.9	3.05	3.0
Bulk Specific Gravity, D 2726	2.162	2.173	2.154	2.163
Maximum Specific Gravity, D 2041	2.298	2.315	2.301	2.305
Air Voids, %	5.9	6.1	6.4	6.1
Anti-Stripping, Modified D 1664				
Workability, PTI Method				
AC Content, D 2172, %	4.0	4.0	4.1	4.0
Viscosity, D 2171, 60°C, Poise	351	229	NA	193
Penetration, D 5, 25°C, 100 g, 5 sec, dmm	336	363	NA	350
Ductility, D 113, 25°C, 50 mm/min, mm				
Softening Point, D 36, °C	38	34	NA	36

NA = Not available.

Table C-21. Summary of laboratory testing for spray-injected mix (South Carolina).

Test Name, ASTM Designation		Replicate Number			Average Values
		1	2	3	
Marshall Stability, D 1559, kg		2086	2205	2270	2187
Marshall Flow, mm		4.8	3.7	4.8	4.3
Bulk Specific Gravity, D 2726		2.139	2.154	2.157	2.150
Maximum Specific Gravity, D 2041		2.451	2.447	2.445	2.448
Air Voids, %		12.7	12.0	11.8	12.2
Extraction-Gradation, % Passing, D 2172, C 136 Sieve Size	12.7 mm	99.3	99.3	99.2	99.3
	9.5 mm	85.0	83.1	84.7	84.3
	No. 4	31.6	33.7	45.6	37.0
	No. 8	7.4	8.6	21.1	12.4
	No. 16	3.2	3.5	11.7	6.1
	No. 30	2.0	2.0	7.3	3.8
	No. 50	1.4	1.3	4.7	2.5
	No. 100	1.0	0.9	2.9	1.6
	No. 200	0.7	0.6	1.8	1.0
	% A.C.	3.9	3.9	4.2	4.0
Viscosity, D 2171, 60°C, Poise		4831	4976	NA	4904
Penetration, D 5, 25°C, 100 g, 5 sec, dmm		68	67	NA	68
Softening Point, D 36, °C		53.1	53.6	NA	53.3

NA = Not available.

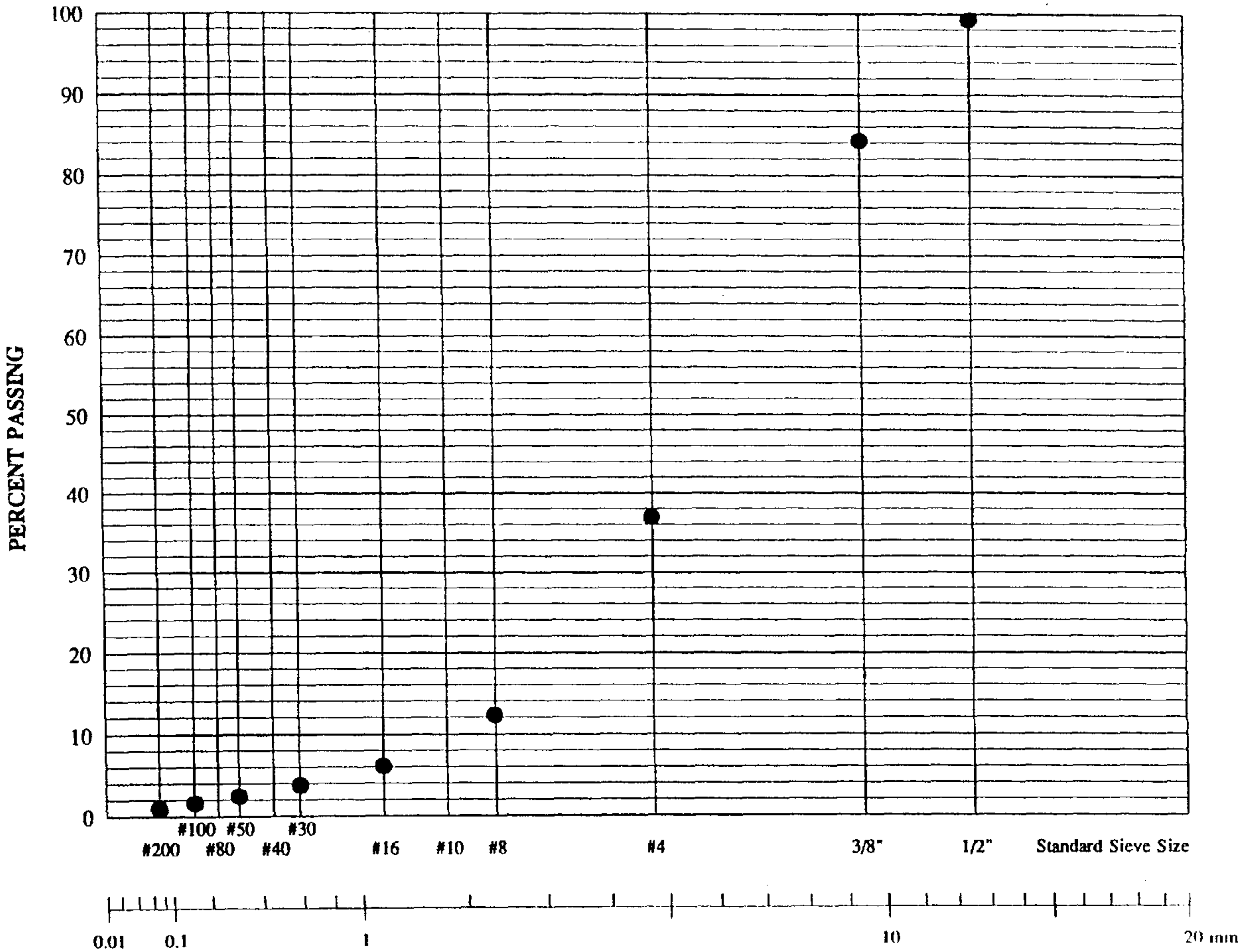


Figure C-1. Gradation for spray-injected mix (South Carolina).

1 in = 25.4 mm

APPENDIX D. FIELD PERFORMANCE DATA

Field evaluation of the experimental partial-depth patches entailed mainly visual observations of the distresses. At the time of the evaluations, only the length, width, depth (if appropriate), and severity of the distresses were recorded. Later, these dimensions were converted into percentages and ratings. Non-numeric observations, such as adjacent patch type and joint sealant condition also were recorded. In addition, photographs were taken during the evaluations to visually document the condition of the patches.

Distress Identification Guide and Performance Rating Procedure

This section presents the guidelines that were used during field surveys to record the performance of the partial-depth patches. It is subdivided according to the performance measures used for cementitious and polymeric patches and those used for bituminous patches.

Concrete and Polymer Patches

The following distresses were measured during the field performance evaluations of cementitious and polymeric patches:

- Transverse cracking—Cracking in the interior of the patch transverse to the longest dimension of the patch. It excluded cracking at the perimeter of the patch. Length was measured in English units to the nearest 1 in (25.4 mm) and width in English units to the nearest 0.01 in (0.254 mm), up to a maximum of 0.06 in (1.5 mm). If the crack was frayed, it was indicated.

- Longitudinal cracking—Cracking parallel to the longest dimension of the patch. It excluded cracking at the perimeter of the patch. Length was measured in English units to the nearest 1 in (25.4 mm) and width in English units to the nearest 0.01 in (0.254 mm), up to a maximum of 0.06 in (1.5 mm).

- Perimeter cracking/debonding—Cracking or debonding of the patch/pavement interface as a result of shrinkage of the patch away from the sides of the original pavement. The sides of the patch where the perimeter cracking was observed were recorded. Length was measured in English units to the nearest 1 in (25.4 mm) and width in English units to the nearest 0.01 in (0.254 mm), up to a maximum of 0.06 in (1.5 mm).

- Spalling—Full- or partial-depth cracking and debonding of the repair material, either within the patch itself or in the surrounding pavement. The severity, as defined below, and dimension of the spalled area were recorded.
  - Low severity: The spall extended less than 76 mm from the edge of the patch, was not full depth, and, if fragmented, the loose pieces were retained within the patch.

  - Medium severity: The spall extended more than 76 mm from the perimeter of the patch and was not fragmented, or the spall was less than 76 mm and the fragmented pieces were missing from the patch.
  - High severity: The patch was severely spalled with missing pieces greater than 76 mm in length or width. Temporary patching may have been placed because of the spalling.

- Wearing—The wearing away of the surface of the patch. The severity level, defined below, and the dimensions of the affected area in each severity category were recorded.
  - Low severity: Cement had started to wear away, such that the aggregate was exposed no more than 3 mm.
  - Medium severity: Cement had started to wear away, such that the aggregate was exposed 3 to 6 mm or the whole patch surface was worn down 3 to 6 mm.
  - High severity: Cement had started to wear away, such that the aggregate was exposed more than 6 mm or the whole patch surface was worn down 6 mm or more.

- Oxidizing—Hardening or surface cracking of the patching material. This distress applied only to the epoxy and polymer concretes. The severity levels for oxidizing were as follows:
  - Low severity: The patch had started to darken and harden, but with little or no appreciable cracking.
  - Medium severity: The patch had darkened and hardened and was starting to crack.
  - High severity: The patch had darkened and hardened, and cracking was present in significant quantities.

- Edge fraying—Minor raveling or wear of the repair material around the patch perimeter due to overfinishing, high placement, or wear over the joint bond-breaker. The severity, as defined below, and length in each severity category were recorded.
  - Low severity: The fraying was less than 13 mm wide and 13 mm deep.
  - Medium severity: The fraying was 13 to 25 mm wide and less than 13 mm deep.
  - High severity: The fraying was 25 to 50 mm wide and less than 13 mm deep. If the fraying was wider than 50 mm, the distress was classified as wear or spalling, whichever was more appropriate.

- Debonding—Loss of bond between the original pavement substrate and the repair material, particularly at the bottom interface. The location and dimension of the debonded area were recorded.

- Adjacent pavement deterioration—Spalling or cracking of the pavement immediately adjacent to the patch. The severity and dimension of the deterioration were recorded.

- Adjacent pavement corner break—Full-depth cracking of the adjacent pavement running from the patch to the corner of the slab or shoulder. The width of the crack and the severity of any crack spalling were recorded.

- Joint sealant condition—The condition of the poured joint sealant at the location of the original transverse joint, as defined below, was recorded.
  - Good: Sealant was bonded to the edges and was preventing the intrusion of incompressibles into the joint.
  - Poor: Sealant was worn, not bonded, or low, and did not prevent the intrusion of incompressibles into the joint.
  - None: The joint was either not sealed or the sealant had completely worn away.

Bituminous Patches

The distresses measured during the field performance evaluation of bituminous patches were as follows:

- Dishing—Depression or subsidence of the patching material below the surface of the adjacent pavement material. The difference in elevation between the highest and lowest point of the patch was measured and recorded in English units to the nearest 0.25 in (6.35 mm).

- Raveling—Wearing away of the patch surface caused by the dislodging of aggregate particles and loss of asphalt binder. Wearing was classified into the categories defined below, and the area affected in each category was recorded.
  - Low severity: Loss of small rocks.
  - Medium severity: Loss of large rocks.
  - High severity: Top 0.5 in (12.7 mm) gone.
  - Very high severity: Top 1 in (25.4 mm) gone.

- Shoving—Upheaval of the patching material above the surface of the adjacent pavement surface. The difference in elevation between the highest and lowest point of the patch was measured and recorded in English units to the nearest 0.25 in (6.35 mm).

- Cracking—Cracking in the interior portions of the patch. Cracking near the edge of the patch was excluded. The length and average width of the individual cracks were measured and recorded. Alligator cracking was recorded as high severity and the area of cracking was recorded.

- Bleeding—The presence of free asphalt binder on the patch surface. The approximate area of the patch affected was recorded.

- Edge disintegration—Cracking or spalling along the edge of the patch, adjacent to the original pavement. The approximate area of the patch that was affected was recorded.

- Missing patch—The occurrence of patching material missing from the patch. The approximate area of the patch affected was recorded.