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Long-Term Monitoring of Pavement Maintenance Materials Test Sites

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LTPP

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FOREWORD

Pothole repair in asphalt concrete pavements is one of the most commonly performed highway maintenance operations. The Strategic Highway Research Program's (SHRP) H-106 pothole repair experiment was part of the most extensive pavement maintenance experiment ever conducted. The information derived from the study will contribute greatly towards advancing the state of the practice of response-type pothole-patching operations.

This report provides information to pavement engineers and maintenance personnel on the results of the H-106 pothole repair experiment. It presents the performance and cost-effectiveness of various cold-mix materials and procedures for repairing asphalt concrete-surfaced pavements.

The Federal Highway Administration (FHWA) has distributed this document primarily in electronic form. Copies are being sent to FHWA regional and division offices, SHRP Coordinators, and all data users. A copy can be found through the Long-Term Pavement Performance (LTPP) web page at http://www.tfhrc.gov/pavement/ltpp/ltpphome.htm by selecting the LTPP Data Base button.

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Director
Office of Engineering
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16. Abstract

The Strategic Highway Research Program's (SHRP) H-106 pothole repair experiment was part of the most extensive pavement maintenance experiment ever conducted. Started under SHRP and continued under the Long-Term Pavement Performance program's Long-Term Monitoring project, it provides valuable data on the performance and cost-effectiveness of various cold-mix materials and procedures for repairing asphalt concrete-surfaced pavements. The information derived from this study will contribute greatly toward advancing the state of the practice of response-type pothole-patching operations.

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: Volumes greater than 1000 l shall be shown in m^3.				
		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/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	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		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.71	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		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/m^2	candela/m^2	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/in^2

* 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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1. INTRODUCTION

The Strategic Highway Research Program's (SHRP) H-106 pothole repair experiment, part of the most extensive field experiment of its kind ever undertaken, provides valuable data on the performance and cost-effectiveness of various cold-mix materials and procedures for repairing potholes in asphalt concrete-surfaced pavements. The results of the experiment can potentially be used to reduce the cost of pavement maintenance.

Objectives

The primary objective of this project was to determine which combinations of material and patching procedures provided the most cost-effective repair of potholes in asphalt concrete-surfaced pavements. Cost-effectiveness was a function of many factors, including material cost, labor cost, equipment cost, productivity, and performance of the repairs.

A secondary objective was to identify correlations between performance observed in the field and material properties determined in the laboratory. Such correlations would help establish material specifications based on desirable material characteristics that are indicative of good field performance.

Project Overview

Beginning in March 1991 and ending in February 1992, 1,250 pothole patches were placed at eight test sites located throughout the United States and Canada. The potholes were repaired using materials supplied by SHRP and were placed (under supervision of the SHRP contractor) by local maintenance forces representing six different State departments of transportation (DOTs), one Canadian province, and one city department of public works. Figure 1 shows the locations of the eight test sites within the four different climatic regions as defined for SHRP Long-Term Pavement Performance (LTPP) projects.

The materials and procedures used at the test sites and listed in table 1 represented the best of those identified in a previous SHRP study — the H-105[1] project. The H-105 project surveyed and interviewed highway agency personnel and material suppliers to determine the most promising materials and procedures for pothole repair. It was originally intended that each test site would have patches made of similar materials and use procedures A to J in table 1. In addition the K, L, M, and N patch types were included at the Ontario and Oregon sites, where it was decided that the edge seal and semipermanent procedures should be placed using more than one material. Inclement weather and premature failure of the unsealed patches in Ontario made placing the edge seal around the designated patches impractical, so no type B, K, or M patches ended up being placed at that site. Also, the PennDOT 486 material was unavailable at the time of the Ontario installation, so no type E repairs were placed there. In Oregon, a spray-injection device under evaluation by the Oregon DOT was to be used to place the spray-injection patches; however, mechanical problems with the device resulted in only one patch being placed during a 2-h period, and no other devices were available to complete the repairs planned at the test site.

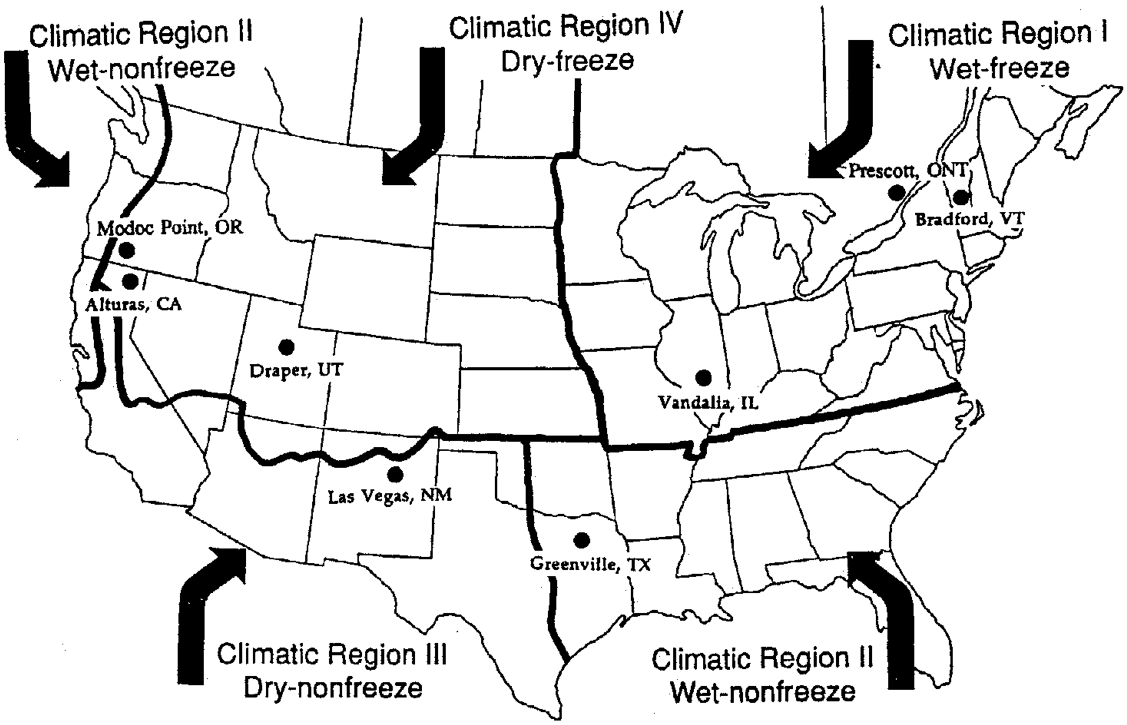

Figure 1. Pothole repair test site locations and climatic regions.

Table 1. Summary of material/procedure combinations.

Patch Type	Material	Procedure	Test Site							
			CA	IL	NM	ON	OR	TX	UT	VT
A[a]	UPM High-Performance Cold Mix	Throw-and-roll (TAR)	✓	✓	✓	✓	✓	✓	✓	✓
B		Edge seal (ES)	✓	✓	✓		✓	✓	✓	✓
C		Semipermanent (SP)	✓	✓	✓	✓	✓	✓	✓	✓
D	PennDOT 485	Throw-and-roll (TAR)	✓	✓	✓	✓	✓	✓	✓	✓
E	PennDOT 486	Throw-and-roll (TAR)	✓	✓	✓		✓	✓	✓	✓
F	Local material	Throw-and-roll (TAR)	✓	✓	✓	✓	✓	✓	✓	✓
G	HFMS-2 w/Styrelf®	Throw-and-roll (TAR)	✓	✓	✓	✓	✓	✓	✓	✓
H	Perma-Patch	Throw-and-roll (TAR)	✓	✓	✓	✓	✓	✓	✓	✓
I	QPR 2000	Throw-and-roll (TAR)	✓	✓	✓	✓	✓	✓	✓	✓
J	Spray injection	Spray injection (SI)	✓	✓	✓	✓		✓	✓	✓
K	QPR 2000	Edge seal (ES)					✓			
L		Semipermanent (SP)				✓	✓			
M	PennDOT 485	Edge seal (ES)					✓			
N		Semipermanent (SP)				✓	✓			
X	Local material	Surface seal (SS)		✓						
X	Local material	Heat and tack (HT)					✓			

[a] = control patch type for all sites.

Test Site Characteristics

Table 2 shows some of the pertinent characteristics of each test site location.

Table 2. Test site characteristics for pothole repair project.

Test Site	Route	No. of Lanes	2-dir. ADT (vpd)	Annual Precipitation[a]	Annual Days < 0 °C [a]
Alturas, CA	US 395	2	1,000	0.36 m	190
Vandalia, IL	I-70	4	15,000	0.96 m	100
Las Vegas, NM	Rte 518	2	1,700	0.36 m	120
Modoc Point, OR	US 97	2	5,400	0.41 m	180
Greenville, TX	FM 1570	2	7,500	1.02 m	50
Draper, UT	I-15 Frontage Rd (Minuteman Drive)	2	1,500	0.41 m	180
Bradford, VT	Rte 25	2	2,100	0.94 m	160
Prescott, ON	Rte 2	2	4,500	0.81 m	140

ADT = Average Daily Traffic
vpd = volume per day
[a] = Historical averages from the *Climatic Atlas of the United States*, 1968.
°C = (°F - 32) ÷ 1.8.

Test Site Descriptions

US 395 – Alturas, California

The test site in California was split into three different areas, as shown in figure 2. The first group of patches was located in both the northbound and southbound lanes of US 395, just south of the Modoc/Lassen county line, at milepost (M.P.) 138.5 in Lassen County. The second group of patches was located in the northbound lane of US 395, just north of Likely, at M.P. 5.5 in Modoc County. The third group was located north of Alturas, in both the northbound and southbound lanes of US 395, between M.P. 31 and M.P. 32 in Modoc County.

The relative infrequency with which potholes occurred along this route forced the lengthening of the original site. Drought conditions for the few years prior to the test site installation reduced the amount of breakup along this route, and the lack of precipitation caused less moisture-induced distress among the repair patches. An increase in precipitation during the winter of 1993 resulted in very wet conditions, and necessitated the overlay of the test site in the spring of 1993. A total of 106 weeks of performance data were collected at this site.

The cross section of this pavement was 102 mm of asphalt concrete over 254 mm of granular material. The shoulders consisted of a strip of asphalt concrete approximately 305 mm wide beyond the edge stripe, and a section of gravel approximately 1.83 m wide.

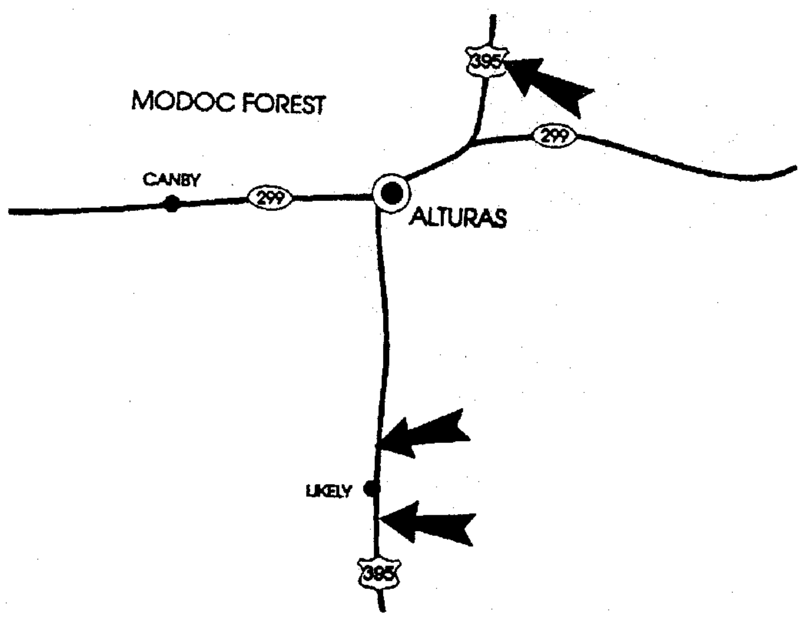

Figure 2. Alturas, California, pothole repair test site.

I-70 – Vandalia, Illinois

The test site in Illinois was located west of Vandalia, in the westbound lane of I-70 in Fayette County, as shown in figure 3. All patches were located in the outside (travel) lane, with the majority adjacent to the asphalt concrete shoulder. The patches were located between M.P. 57 and M.P. 63.

This site carried the greatest volume of traffic of any site in the experiment, with approximately 6,000 of the 15,000 two-way average daily traffic (ADT) classified as trucks. The climate during the test period was generally warmer and wetter than average. The excessive moisture caused the formation of many new potholes along the site. A total of 133 weeks of performance data were collected at this site.

The cross section of this pavement was 102 mm of asphalt concrete over 254 mm of continuously reinforced concrete pavement (CRCP). The shoulders were asphalt concrete on both the inside and outside lanes; the inside shoulder was 1.22 m wide, and the outside was 3.05 m wide.

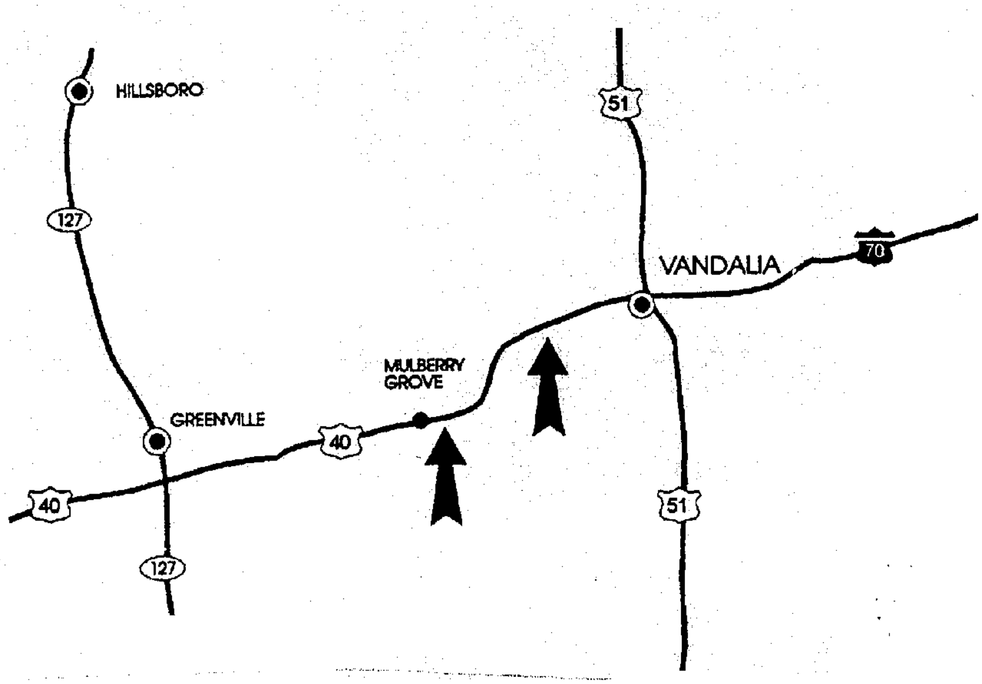

Figure 3. Vandalia, Illinois, pothole repair test site.

Route 518 – Las Vegas, New Mexico

The test site in New Mexico was located north of Las Vegas, in the southbound lane of Route 518 in Mora County, between M.P. 22 and M.P. 16, ending just north of the Mora-San Miguel county line, as shown in figure 4.

The weather was drier than average during the test period, and relatively few new potholes developed along this test site after the repair installation. A total of 110 weeks of performance data were collected at this test site.

The cross section of this pavement was 102 mm of asphalt concrete surface over 381 mm of crushed stone. The shoulders throughout the site consisted of a strip of asphalt concrete 305 mm wide and gravel 1.52 m wide.

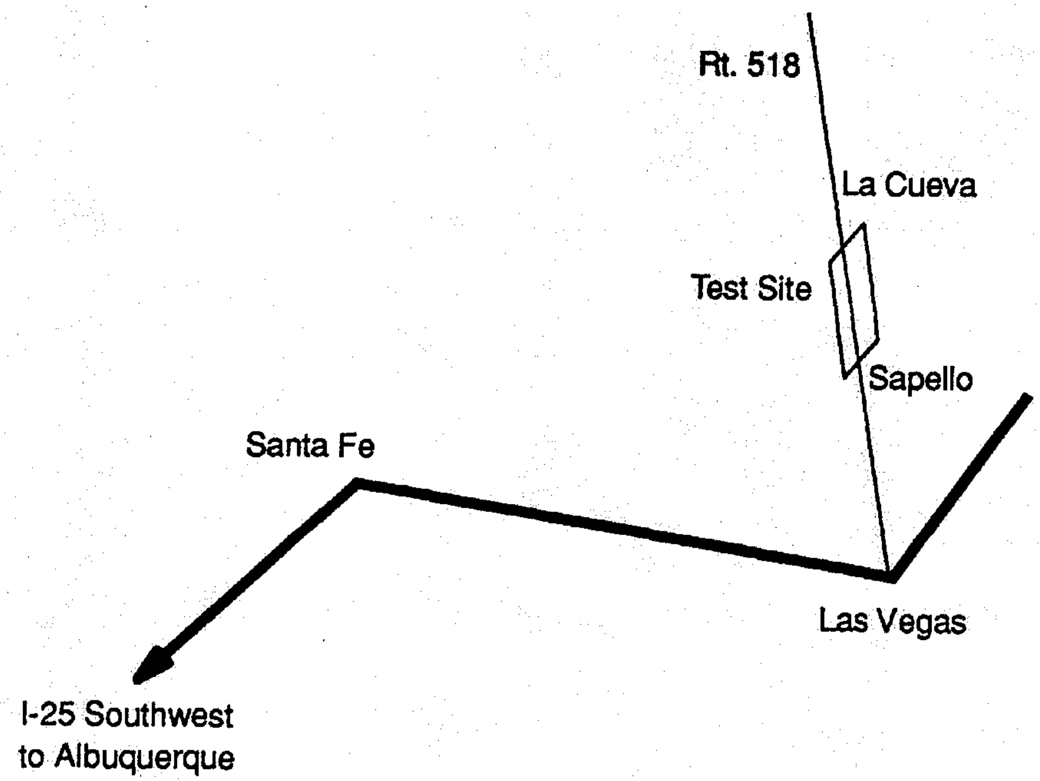

Figure 4. Las Vegas, New Mexico, pothole repair test site.

US 97 – Modoc Point, Oregon

The test site in Oregon was located along two stretches of the northbound lane of US 97, north of Klamath Falls in Klamath County. The first section was at M.P. 270, and the second section was just south of M.P. 265, as shown in figure 5.

The weather at this site was significantly drier than average during the experiment, though the winter of 1993 brought above-average precipitation and hastened the need for an overlay along this section. This stretch of US 97 has an estimated 1,900 of its 5,400 two-way ADT classified as trucks. It is an alternate route for vehicles traveling along I-5, which is west of the site, because U.S. 97 is slightly shorter and has fewer grades than the interstate route. A total of 67 weeks of performance data were collected at this test site.

The cross section of this pavement was 102 mm of asphalt concrete surface over 254 mm of granular material. The shoulders were approximately 305 mm of asphalt concrete and 1.52 m of gravel.

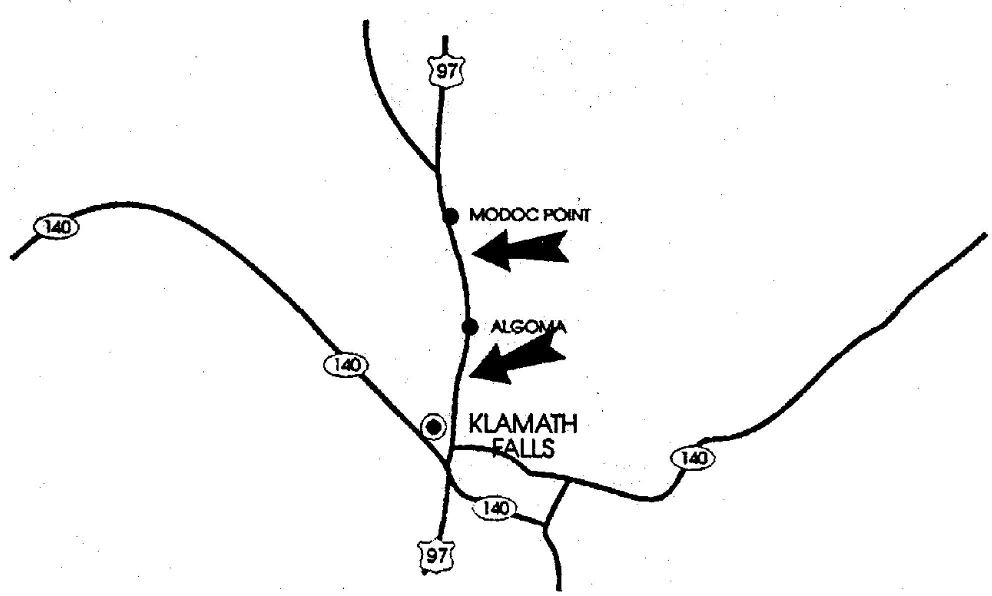

Figure 5. Modoc Point, Oregon, pothole repair test site.

FM 1570 – Greenville, Texas

The test site in Texas was southwest of the intersection of I-30 and US 69, south of Greenville, as shown in figure 6. The patches were located west of the intersection of FM 1570 and US 69 in both the east- and westbound lanes.

The weather at this site was wetter than average, especially during the spring of 1992, when heavy rainfall and a large number of trucks carrying equipment and materials to a factory at the west end of the test section caused major damage to the entire pavement system. Several sections of the test site had to be reconstructed, resulting in the loss of 29 percent of the 150 patches placed. Because the trucks were loaded on their way into the plant, but unloaded on their way out, only the westbound lane experienced this damage. A total of 242 weeks of performance data were collected at this test site.

The cross section of this pavement was 102 mm of asphalt concrete over 205 mm of gravel. The shoulders consisted of a strip of asphalt concrete approximately 610 mm wide and a 1.83 m width of turf.

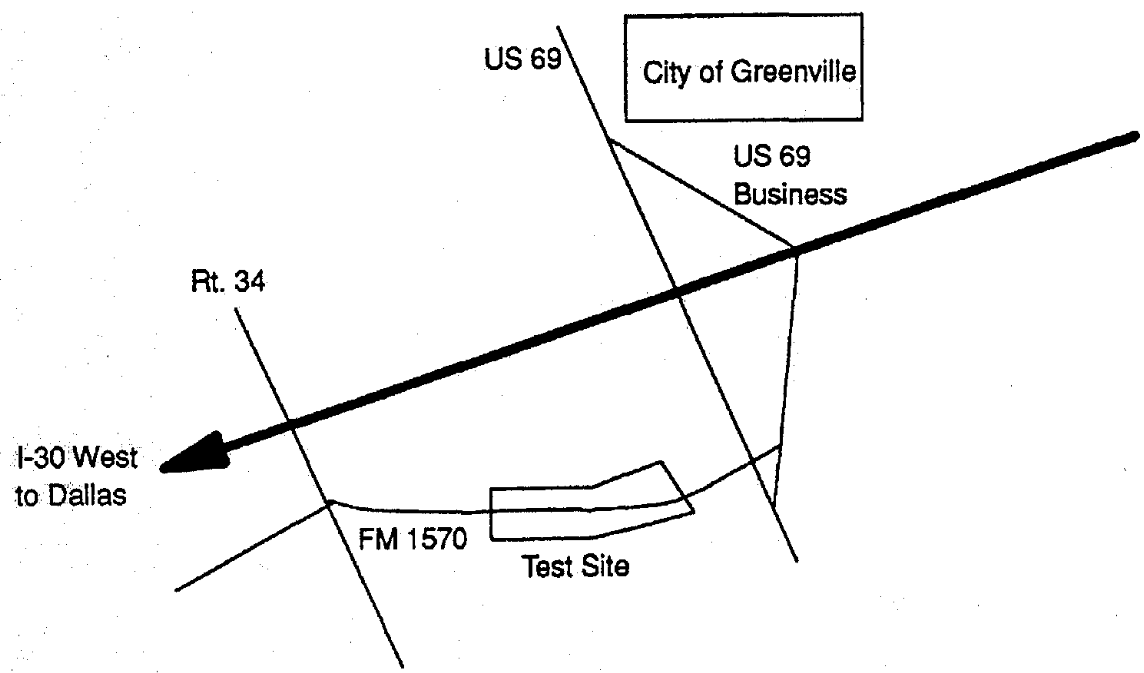

Figure 6. Greenville, Texas, pothole repair test site.

I-15 Frontage Road (Minuteman Drive) – Draper, Utah

The test site in Utah was directly east of I-15, south of exit 294, along a frontage road (Minuteman Drive) in Draper, as shown in figure 7. The patches were located in the northbound lane of the frontage road, approximately 0.40 km south of the intersection of 12300 South Street and Minuteman Drive.

The weather at this site was slightly wetter than average, especially during the spring of 1992, when thunderstorms were more frequent than usual. This additional moisture accelerated the breakup of the pavement directly north of the test section, to the point where major reconstruction was needed. A total of 132 weeks of performance data were collected at this test site.

The cross section of this pavement consisted of 89 mm of asphalt concrete over 203 mm of crushed stone. A portland cement concrete (PCC) pavement approximately 203 mm thick may underlay the crushed stone. The shoulders along the test site consisted of a strip of asphalt concrete that is approximately 305 mm wide and a width of gravel that is 610 mm.

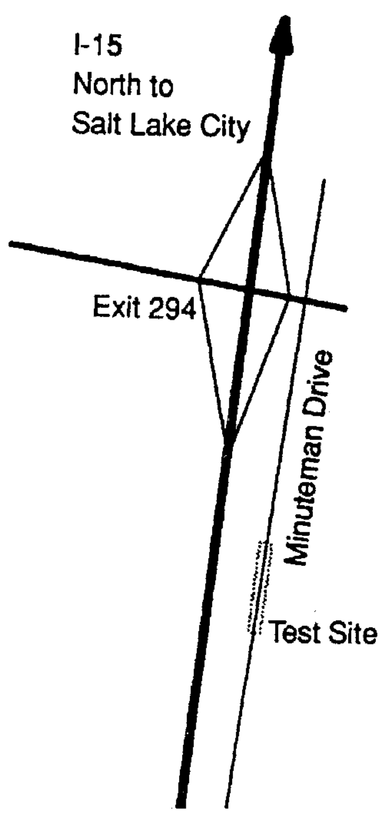

Figure 7. Draper, Utah, pothole repair test site.

Route 25 – Bradford, Vermont

The Vermont test site was located northwest of the intersection of I-91 and Route 25 near Bradford in Orange County, as shown in figure 8. The patches were all in the southbound lane of Route 25 between M.P. 6.5 and M.P. 5.5.

The weather was wetter than average, which caused the pavement at the test site to deteriorate throughout the monitoring period. This deterioration necessitated the placement of an overlay in the spring of 1993. A total of 105 weeks of performance data were collected at this test site.

The cross section of this pavement consisted of approximately 114 mm of asphalt concrete over 457 mm of crushed gravel. The shoulders along the site consisted of asphalt concrete 305 mm wide and gravel 914 mm wide.

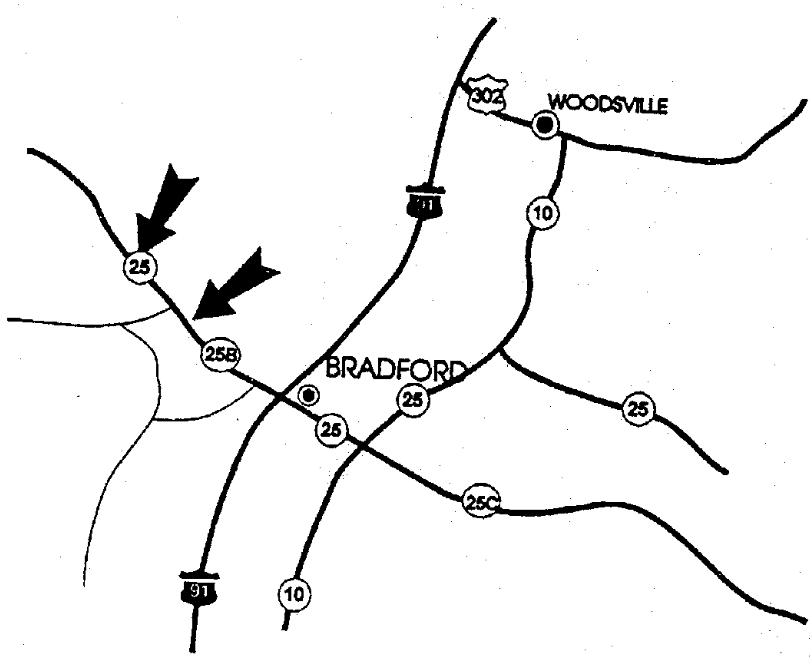

Figure 8. Bradford, Vermont, pothole repair test site.

Route 2 – Prescott, Ontario

The test site in Ontario was located just west of the Prescott city limits, running parallel to Highway 401 along the St. Lawrence River in Grenville County, as shown in figure 9. The patches were located in both the east- and westbound lanes, for approximately 4.2 km starting at the west edge of the city limits.

The weather at this site was wetter and slightly colder than average. Right after the test site installation was completed, a severe winter storm occurred, which required plowing and the placement of several tons of salt. This weather was the most severe of any experienced by the test sites so soon after installation and caused a significant amount of patch failure in a very short time. A total of 198 weeks of performance data were collected at this test site.

The cross section of this pavement consisted of approximately 102 mm of asphalt concrete over 205 mm of gravel. The shoulders along the site consisted of asphalt concrete 305 mm wide and gravel 1.52 m wide.

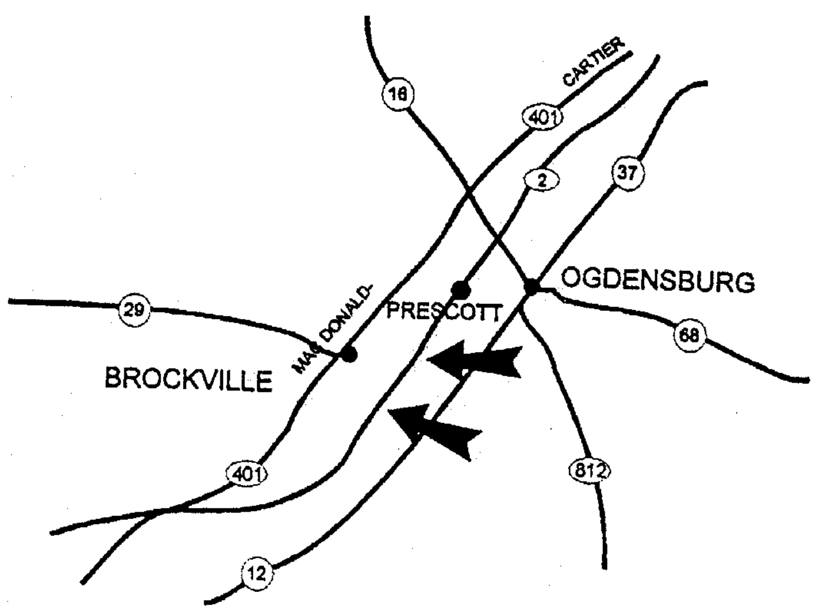

Figure 9. Prescott, Ontario, pothole repair test site.

2. TEST SITE INSTALLATION

This experiment was designed to evaluate the performance of many different materials, procedures, and equipment used in the repair of potholes in asphalt concrete-surfaced pavements. Although there is no shortage of potholes along the millions of miles of asphalt concrete roadways in the United States and Canada, finding locations suitable for this experiment was much more difficult than originally anticipated. More than 30 proposed test sites were visited to find the eight final locations.

Test Site Arrangements

Before the installation of a test site could begin, several arrangements had to be made, such as obtaining repair materials, shipping materials to the test site, scheduling the crew to perform the installation, and notifying manufacturers of the planned installation of their materials. Participating manufacturers were notified of the placement schedule so that a representative could be on hand, if desired. The manufacturers' representatives were present to ensure that placement procedures were consistent from material to material. The successful handling of these details allowed for a smooth installation phase.

Installation Process

The original experimental plan called for between 150 and 200 open potholes per test site.[2] These potholes were to be left open until patches could be placed using the experimental materials and procedures. It became apparent early in the site selection process that no highway agency would allow that many potholes to remain unrepaired for that length of time because of the danger potholes pose to the traveling public and the potential damage they can cause to vehicles.

A compromise was reached to address the problem by having patches in place at the test sites, as long as those patches could be removed and the original potholes used in the project. Although some resistance to this plan was expected, none of the participating agencies objected to removing in-place repairs to allow placement of the experimental repairs. In fact, all of the agencies seemed to have confidence that the experimental patches would work as well as or better than the patches they were currently placing.

Layout

Before any of the experimental patches could be placed at a given site, the site had to be readied for the installation procedure. The layout of the pothole locations was marked the morning the patches were to be installed. Marking locations earlier would have been impractical because of the nature of pothole development and the speed with which a set of patches can be laid out.

The original test plan called for placing a series of 20 patches, alternating control patch types with experimental patch types, until 10 of each had been placed. To conserve materials and reduce the amount of time needed to install patches at a test site, the placement order was modified to a series of 30 patches, alternating between control patches and two types of experimental patches. Figures 10 and 11 show the layouts for a typical section for both the 20- and 30-patch scenarios. The 30-patch placement order reduced the total number of patches needed from 200 to 150, but still maintained a one-to-one comparison between control and experimental patches. In cases where there was only one type of experimental patch, the 20-patch placement order was used.

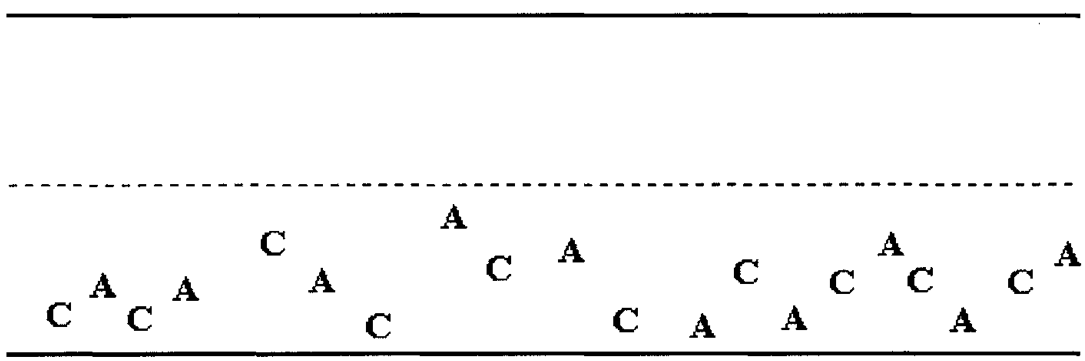

Figure 10. Example of 20-patch placement order.

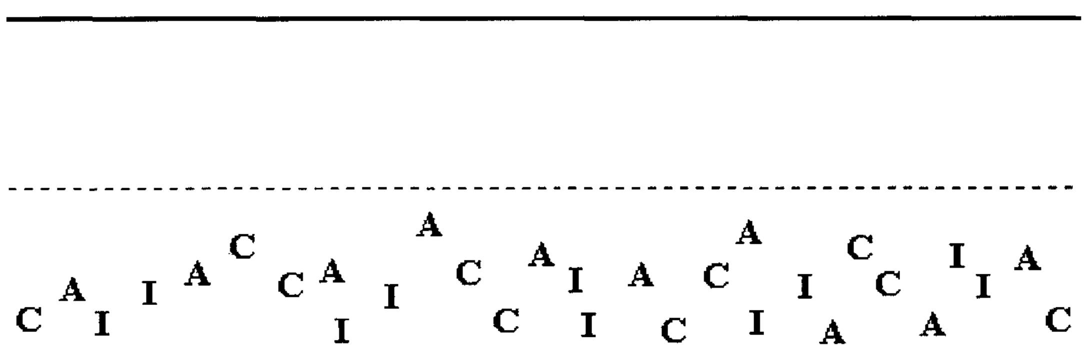

Figure 11. Example of 30-patch placement order.

Laying out the test site consisted of identifying areas for creating potholes and designating a patch type for each location. The locations and accompanying designations for a set of patches were marked with paint on the day the patches were to be placed.

Preparation

The next step in the installation of the test sites was to create potholes by removing existing patches. Patches were removed using a backhoe at six of the sites. At New Mexico and Ontario, where no backhoe was available, a jackhammer and hand tools were used, respectively.

Once the potholes were opened, the adverse moisture condition was created by filling the holes with water that had been transported to the site. Water could not be added at the Ontario site because of extremely low temperatures. However, some snowfall did provide an adverse moisture condition to go along with the adverse temperature conditions, which were defined as less than 7 °C. During installation at the other seven sites, adverse moisture conditions occurred naturally only 1 day each in Illinois, New Mexico, and Utah. To evaluate the effects of adverse temperature conditions, sites in Ontario and Oregon were installed in January and February 1992. Adverse temperature conditions were present each day of installation at the sites, although temperatures in Ontario were colder on average than in Oregon.

Materials

The cold-mix materials used for the experimental patches were those identified during the SHRP H-105 project as having the potential to perform very well.[1] In most instances, participating agencies were not using these materials, which meant that the materials had to be shipped to the test site from wherever they were produced. When possible, the experimental materials were shipped from a single producer to each test site to reduce material variability between sites.

Table 1 lists all the materials used during the test site installations. For the Pennsylvania DOT (PennDOT) 485 and 486, the high-float medium-set emulsion (HFMS-2), and the QPR 2000, the cold mixes were taken from stockpiles, placed into 208 l drums at the source, and shipped to the test sites. The Perma-Patch material was shipped to each test site via pallets of 27-kg bags.

The UPM High-Performance Cold Mix was obtained from asphalt plants in the vicinity of each test site. Approximately 11 metric tons of UPM cold mix were shipped to each site. With the exception of the sites in Utah and New Mexico, which used UPM obtained from the same plant in Colorado, a different producer supplied each of the test sites.

<u>UPM High-Performance Cold Mix</u>

The UPM High-Performance Cold Mix is a proprietary cold-mix material produced using a specially formulated binder and aggregate available in the vicinity of the plant producing the mix. Samples of local aggregate are tested by UPM to determine local production specifications. In most cases, the initial run of the material through a plant was supervised by a UPM representative to ensure that the cold mix was of sufficient quality. The UPM High-Performance Cold Mix purchased for this project cost approximately $80 per metric ton, not including the cost of shipping from the plants to the test sites.

Perma-Patch

The Perma-Patch cold mix also is a proprietary material made with a specially formulated binder. This material may be produced at any asphalt plant using the local aggregate in much the same way that the UPM mix is produced. For this project, only one plant was used. The Perma-Patch cold mix used for this project cost approximately $80 per metric ton, excluding the cost of shipping from the plant to the test sites.

QPR 2000

The QPR 2000 cold mix also is a proprietary material made with a specially formulated binder. The material used for this project was produced at a central plant and shipped to the test sites. This material may be produced at any asphalt plant using local aggregate in much the same way that the UPM mix is produced.

Two grades of QPR 2000 were used. The first was a "southern" mix formulated for warmer climates, which was used in Texas and New Mexico. The second was a "northern" mix, which was used at the remaining six test sites. The QPR 2000 used for this project cost approximately $80 per metric ton, excluding the cost of shipping from the plant to the test sites.

PennDOT 485

The PennDOT 485 material was produced by an asphalt plant in Pennsylvania according to Specification 485, which lists acceptable bituminous binders and additives, as well as fine and coarse aggregate. Gradations for the combined fine and coarse aggregate also are given, along with guidelines for the percent of residue of asphalt cement based on the absorption of the aggregate used. Additional requirements for the actual mixing of the materials and acceptance testing are specified. The PennDOT 485 material used for this project cost approximately $40 per metric ton, excluding the cost of shipping from the plant to the test sites.

PennDOT 486

The PennDOT 486 material was produced according to Specification 486 in the same manner as PennDOT 485. The major difference between the 485 and 486 specifications is the addition of polypropylene or polyester fibers in the 486 material. For this project, polyester fibers were used. The PennDOT 486 material cost approximately $45 per metric ton, excluding the cost of shipping from the plant to the test sites.

HFMS-2 (modified)

The modified HFMS-2 material was produced using a high-float, medium-setting emulsion that contains styrene butadiene (trade name Styrelf) as an additive. Two sources for the HFMS-2 cold mix were used, one for the sites in Ontario and Oregon and one for the remaining sites. Elf Asphalt formulated the modified binder used in both instances. The HFMS-2 material cost approximately $65 per metric ton, excluding the cost of shipping from the plant to the test sites.

Spray Injection

The spray-injection materials consisted of a crushed aggregate and an emulsified asphalt. Both materials were transported to the test site, where they were combined by the spray-injection device as the patch was being formed. A single-size aggregate was generally used, with a top size of 9.5 mm. The emulsion was heated in a tank on the spray-injection device, generally to about 60 °C.

The cost of spray injection can be calculated over the life of a device or by using the rate charged by companies performing pothole-patching services. The average purchase price for a trailer unit without a truck was approximately $35,000, while a single-chassis unit cost was approximately $100,000. Daily rates for spray-injection operations range from $700 to $1,000. Costs for spray-injection services also can be quoted on a per-square-meter cost, by tank of emulsion (approximately 950 l), or by the quantity of material placed.

Local Materials

The local materials placed at each site are typical of those used by agencies that perform pothole-patching operations on a daily basis. These materials were usually inexpensive cold mixes made with rounded aggregate and very little binder, resulting in a dry-looking material. However, in some instances, local crews used high-quality, proprietary cold mixes rather than the inexpensive ones. The cost of the local materials used for this project ranged from $18 per metric ton for local cold mixes to over $110 per metric ton for proprietary cold mixes.

Equipment

For the most part, the equipment used to place the experimental patches was that typically used by maintenance crews everywhere: dump trucks, pickup trucks, shovels, brooms, rakes, jackhammers, compressors, pavement saws, vibratory plate compactors, single-drum vibratory rollers, dual steel-wheeled rollers, and rubber-tired rollers. The only piece of equipment not normally used by maintenance crews was the spray-injection device.

Three brands of spray-injection devices were used in this project. The first was a Rosco RA-200, which was used in Illinois and Oregon. The second was a Durapatcher, which was used in Texas, New Mexico, Utah, and California. The third was a Wildcat Roadpatcher, which was used in Vermont and Ontario. Aggregate and binder from local sources near the test sites was used in the Rosco and Durapatcher. Aggregate and binder supplied by the contractor who provided the patching service was used in the Roadpatcher.

The spray-injection devices used in this study represent the two main types of devices used today. The first type consists of a trailer unit that carries a heated tank (generally between 950 and 1,900 l capacity) for the binder material and a delivery system that can deliver aggregate, binder, or both, or just air to a nozzle that can be directed at the pothole. The vehicle towing the trailer is generally a single-axle dump truck that carries dry, virgin aggregate, which is fed into the delivery system on the trailer. The nozzle for this type of device is usually supported by a swinging boom and generally is handled by a worker walking behind the trailer unit. The Durapatcher (figure 12) and the Rosco RA-200 are examples of this type of equipment.

The second type of device combines storage for binder and aggregate with delivery systems on a single chassis. The nozzle for this device generally is controlled by the driver of the vehicle, so that no workers are actually on the roadway. The Wildcat Roadpatcher, which was used in Ontario and Vermont, is an example of this type of equipment and is shown in figure 13.

Procedures

Four major repair procedures were used in the pothole repair experiment: throw-and-roll, edge seal, semipermanent, and spray injection. Each of the procedures was to be used at all sites. However, because of various problems, edge seal patches were not placed at Ontario and spray-injection patches were not placed at Oregon.

Figure 12. Durapatcher spray-injection device.

Figure 13. Wildcat Roadpatcher spray-injection device.

Throw-and-roll

The most prevalent method of patching potholes is the "throw-and-go" or "dump-and-run" method. For this project, the method was altered to a "throw-and-roll" technique by compacting patches with the tires of the material truck. This was the predominant technique used for placing patches during the H-106 experiment. The steps for the throw-and-roll procedure are as follows:

1. Place material into pothole (without any preparation or removal of water and debris prior to material placement).
2. Compact patch using truck tires (with between four and eight passes).
3. Check compacted patch for slight crown. (If depression is present after rolling, additional material is added and rolled to bring patch surface above surrounding pavement level.)
4. Move on to next distress location.

The optimum crew size for this operation was found to be two laborers, with appropriate traffic control provided.

Edge Seal

The edge seal patches were merely throw-and-roll patches that had the interface between the patch and pavement covered by a bituminous tack material and sand. This procedure is intended to limit the amount of water that penetrates through the edges of the patch. The steps for the edge seal procedure, as it was carried out during this experiment, are as follows:

1. Place material into pothole (without any preparation or removal of water and debris prior to material placement).
2. Compact patch using truck tires (with between four and eight passes).
3. Check compacted patch for slight crown. (If depression is present after rolling, additional material is added and rolled to bring patch surface above surrounding pavement level.)
4. Allow pavement and patch surfaces to dry, generally for 1 day after the installation. Place a band of bituminous tack material between 102 mm and 152 mm wide along the perimeter of the patch. Figure 14 shows a patch made using the edge seal procedure.
5. Place a layer of cover aggregate over the tack material to prevent tracking (coarse sand was used at all sites).
6. Move on to next distress location.

The optimum crew size for this operation is two laborers patching, with appropriate traffic control provided. This procedure requires two passes through the distress locations: one to place the patches and one to place the edge seal materials.

Figure 14. Asphaltic material placed as edge seal around patch.

Semipermanent

The procedure recommended by most agencies and research groups for repairing potholes is the semipermanent, or "do-it-right," method. It is basically a partial-depth repair. The time and effort to perform this procedure is thought to improve the success rates for these patches.[3] The steps for the semipermanent procedure used in this project are as follows:

1. Remove all water and debris from pothole by using compressed air, brooms, shovels, or other available equipment.
2. Square up the sides of the pothole so they are vertical and have sound pavement on all sides (it is not necessary to create a square or rectangular area as long as the sides are vertical). The squaring up can be achieved by using either a jackhammer equipped with a spade bit or a pavement saw, as seen in figure 15.
3. Place the patching material into the cleaned, squared hole. The material should mound in the center and taper down to the edges so that it meets the surrounding pavement edge.
4. Compact the material starting in the center and working out toward the edges, which will cause the material to pinch into the corners. A one-man compaction device, such as a single-drum vibratory roller or vibratory plate compactor, as shown in figure 16, should be used.
5. Move on to the next distress location.

The optimum crew size for this operation is four laborers patching, with appropriate traffic control provided. Generally two laborers prepare the repair areas (steps 1 and 2) and two laborers place the repairs (steps 3 and 4).

Figure 15. Straightening sides using pavement saw.

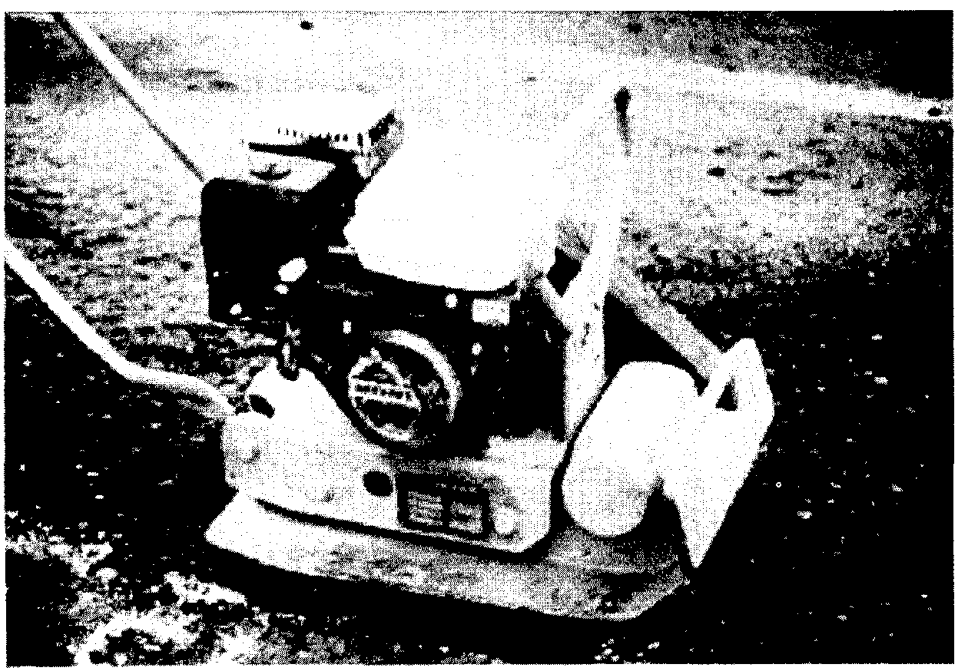

Figure 16. Compaction using vibratory plate compactor.

Spray-Injection

Although three different devices were used for placing spray-injection patches, the same basic procedure was followed in all cases. As with the other procedures, the spray-injection procedure began with potholes filled with water. Spray-injection devices carry clean, dry aggregate and virgin binder and perform the mixing operation as the materials are shot into the pothole. The steps used for the spray-injection procedure are as follows:

1. Blow water and debris from pothole using air flow from aggregate delivery system.
2. Spray bottom and sides of pothole with binder material to act as tack coat.
3. Spray aggregate and binder into the pothole simultaneously so that the aggregate is coated as it impacts the repair.
4. Continue spraying aggregate and binder into the pothole until it is filled just above the level of the surrounding pavement.
5. Cover the top of the patch with a layer of aggregate sufficient to prevent tracking by passing vehicles.
6. Move on to next distress location.

The optimum crew size for this is two operators patching with a device similar to the Durapatcher or Rosco, or one operator using a device similar to the Roadpatcher. Appropriate traffic control must be provided in all instances.

Other Procedures

Participating agencies were permitted to request one additional material or procedure beyond those already described above. Agencies in Illinois and Oregon took advantage of this opportunity. The additional repair procedure used in Illinois was termed surface seal, and it consists of the following steps:

1. Place material into pothole (without any preparation or removal of water and debris prior to material placement).
2. Compact patch using truck tires (with between four and eight passes).
3. Check compacted patch for slight crown. (If depression is present after rolling, additional material is added and rolled to bring patch surface up above surrounding pavement level.)
4. Move on to next distress location.
5. The day after the patches are placed, cover the entire surface of the patch using a bituminous material and cover that material with aggregate to prevent tracking.

The optimum crew size for this operation is two laborers patching, with appropriate traffic control provided. This procedure requires two passes through distress locations: one to place the repair material and one to place the surface seal.

The additional repair procedure used in Oregon was termed tack-and-heat, and it consists of the follow steps:

1. Remove debris and water from pothole using brooms.
2. Place asphalt emulsion into pothole as tack coat.
3. Heat tack coat using propane torch to get the emulsion to break faster.
4. Heat the cold mix with the propane torch, as shown in figure 17, to make it easier to place and to improve the mixture's compaction.
5. Compact patch using material truck (with between four and eight passes).
6. Check compacted patch for slight crown. (If depression is present after rolling, additional material is added and rolled to bring patch surface up above surrounding pavement level.)
7. Move on to next distress location.

The optimum crew size for this operation is two laborers patching, with appropriate traffic control provided.

Figure 17. Heating cold mix with propane torch.

Documentation

During the installation process, data were collected on the patches placed and the operations performed. The data collected included:

- Installation date.
- Patch location (milepost, lane direction, and offset).

- Lane width.
- Climatic conditions (temperature and relative humidity).
- Patch dimensions (length, width, and depth).
- Time for preparation of pothole (for semipermanent only).
- Time for material placement (all procedures).
- Time for compaction (all procedures except spray injection).
- Number of compaction passes (all procedures except spray injection).
- Number of patches compacted together (all procedures except spray injection).

Productivity and Cost Data

A major goal of the project was to measure the productivity of different patching operations. During the eight test site installations, data were collected on the productivity of each highway maintenance crew making the repairs. The crews were observed using four primary repair procedures: throw-and-roll, edge seal, semi-permanent, and spray injection. Productivity rates for the different site, procedure, and material combinations were calculated using the size of the potholes and the time taken to install each pothole using each procedure.

Cost data for the equipment and labor rates given throughout this report are average rates and are intended to be illustrative. Rates that are more accurate for an agency's particular situation can be substituted to easily determine more meaningful cost figures.

Comments

Overall, the installation of the pothole repairs went very smoothly. Thanks to the cooperation of all participating agencies, the repairs were placed with a great deal of consistency within, as well as among, test sites. Other than equipment-specific details, such as types of rollers and trucks available, there was very little deviation among the patches placed from one site to another, despite variations in crews.

3. MATERIAL TESTING

A series of laboratory tests were also performed on the pothole repair materials. The laboratory tests were intended to define characteristics that could be related to performance of the patches. These characteristics could then be used to develop specifications regarding the mixing and placement of the materials that provide good performance.

Laboratory Tests Performed

The tests performed on the pothole repair materials were intended to characterize properties of the mixture, as well as properties of the aggregate and binder separately. The majority of the tests performed were similar to those designed for hot-mix asphalt concrete materials. However, to compensate for the different properties of cold mixes, samples of the repair materials were aged in an oven to stabilize the samples for testing. This step was especially necessary for the resilient modulus and Marshall stability and flow tests. The following tests were performed on the samples:

- Resilient Modulus.
- Marshall Stability and Flow.
- Maximum and Bulk Specific Gravity.
- Anti-Stripping.
- Workability.
- Extraction and Binder Content.
- Viscosity (recovered binder only).
- Penetration (recovered binder only).
- Ductility (recovered binder only).
- Softening Point (recovered binder only).
- Sieve Analysis.

A description of each test and the modifications made to accommodate the differences between hot- and cold-mix materials are given in the following section.

Resilient Modulus

The resilient modulus test was performed according to American Society of Testing of Materials (ASTM) D 4123 at a temperature of 25 °C. Testing was performed at three different frequencies (0.33, 0.50, and 1.00 Hz). To get testworthy samples, the cold-mix materials were aged by heating them overnight at 135 °C, compacting them hot using 75 blows per side, and allowing the compacted samples to cool in the molds prior to extrusion. The aging and compaction of these samples made the materials more representative of those that have been in place for several months under traffic.

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Marshall Stability and Flow

The Marshall stability and flow test was performed according to ASTM D 1559. As with the resilient modulus samples, the Marshall samples were aged prior to compaction and testing to get results that are more representative of in-situ stability after several months of traffic.

Maximum and Bulk Specific Gravity

The maximum and bulk specific gravity tests were performed according to ASTM D 2041 and ASTM D 2726, respectively. The values from these two tests were used to calculate the percent air voids of the mixes. The compaction used to prepare the bulk specific gravity test samples was the same as that used to prepare samples for the resilient modulus and Marshall tests.

Anti-Stripping

The anti-stripping test was performed according to ASTM D 1664. This test is one of the few for which no aging or special preparation of the cold-mix samples was necessary.

Workability

Penetrometers, two of the devices developed in previous research on asphalt cold-mix materials, were used in this project to test workability[3,4] in the laboratory. One was a probe developed by the Pennsylvania Transportation Institute (PTI). The other, developed as part of a Federal Highway Administration (FHWA) study on the mix design of cold mixes, was a modification of the PTI penetrometer, where the bullet-shaped attachment was substituted with a specially made blade.

The workability test was performed according to procedures documented by PTI and using a probe developed by PTI that was 9.5 mm in diameter.[3] When this probe was compared directly with the blade attachment, the blade attachment was approximately five times larger than the probe. The circular probe seems to work for stiffer mixes because the smaller cross section presents less resistance. The blade attachment seems to work for softer mixes because the length of the blade in contact with the mix provides more resistance.

Extraction and Binder Content

The extraction testing and binder recovery tests were performed according to ASTM D 2172 and ASTM D 136, respectively.

Viscosity

The viscosity test was performed according to ASTM D 2171 on the binder recovered from the extraction process. Samples of binder were aged in a manner similar to that used for the other mixtures: the recovered binder was heated at 60 °C until there was no further reduction in weight, which indicated that the lighter volatiles had been driven off and the material remaining was primarily residual binder.

Penetration

The penetration test was performed according to ASTM D 5, with the recovered binder samples prepared in the same way as the samples for the viscosity test.

Ductility

The ductility test was performed according to ASTM D 113, with the recovered binder samples prepared in the same way as the samples for the viscosity test. Several samples were too soft to remain above the bottom of the tank, where they were stretched in solution. Attempts to raise the specific gravity of the solution did not help.

Softening Point

The softening point test was performed according to ASTM D 36, with the recovered binder samples prepared in the same way as the samples for the viscosity test. Several residual binders proved too soft for this test to be performed successfully.

Sieve Analysis

The sieve analysis was performed according to ASTM D 136. Because of the variety of sieves used on the samples, direct comparison of the gradations of the different materials was difficult.

Laboratory Testing Results

Table 3 shows the results from the laboratory testing process. This table contains the mean values for each test performed for each material.

Field Testing

In addition to laboratory testing, workability and rolling-sieve tests were performed in the field during each installation.

Table 3. Summary of laboratory testing results.

Test Procedure	Standard	Conditions (units)	Mean values for given materials (sites given below)									
			485	486	HFMS	Perma	QPR	QPR	UPM	Local	UPM	Local
			All		CA, IL, NM, TX, UT, VT		TX, NM	CA, IL, UT,VT	TX	TX	IL	IL
Resilient Modulus	ASTM D 4123	77 °F, 0.33 Hz (ksi)	457	34	353	182	160	N/P	290	732	N/P	N/P
		77 °F, 0.50 Hz (ksi)	455	33	343	183	160	N/P	281	742	N/P	N/P
		77 °F, 1.00 Hz (ksi)	468	34	352	186	160	N/P	292	755	N/P	N/P
Marshall Stability and Flow	ASTM D 1559	Stability (lb)	4550	2570	3680	4620	4400	3190	5080	6640	2400	822
		Flow (0.01 in)	12.3	14.7	12.8	8.7	12.8	11.8	9.7	10.3	11.0	9.1
Bulk Spec. Grav.	ASTM D 2726		2.30	2.26	2.11	2.30	2.24	2.21	2.26	2.12	2.21	2.33
Max. Spec. Grav.	ASTM D 2041		2.50	2.54	2.45	2.66	2.61	2.58	2.54	2.42	2.55	2.51
Air Voids		(percent)	8.3	11.0	13.6	13.4	13.8	14.3	10.9	12.2	12.8	7.4
Anti-stripping	ASTM D 1664	Modified (percent)	+95	+95	+95	+95	+95	N/P	+95	+95	N/P	N/P
Workability	PTI Method	Ambient Temp.	0.47	0.25	0.40	0.43	0.25	N/P	0.5	0.5	N/P	N/P
AC Content	ASTM D 136	(residual percent)	4.1	4.4	3.8	3.5	5.2	4.2	3.5	4.1	4.2	4.0
Viscosity	ASTM D 2171	140 °F (poise)	311	41	30700	4070	354	693	640	3230	251	17
Penetration	ASTM D 5	77 °F (dmm)	201	+400	34	70	268	165	196	49	229	[a]
Ductility	ASTM D 113	77 °F (cm)	+150	[a]	12	+150	+150	N/P	+150	+100	N/P	N/P
Softening Point	ASTM D 36	(°F)	104	< 86	150	132	102	112	109	128	103	[a]

Notes: [a] = Recovered binder too soft to test. "N/P" indicates test not performed. Conversion of Units: °C = (°F - 32)/1.8; kPa = 0.1449 psi; kg = 2.2046 lb; mm = 25.4 × in.

Table 3. Summary of laboratory testing results (continued).

Test Procedure	Standard	Conditions (units)	Mean values for given materials (sites given below)								
			UPM	Local	QPR	Perma	HFMS	Local	UPM	Local	UPM
			NM, UT	UT	ON, OR			OR	OR	ON	ON
Resilient Modulus	ASTM D 4123	77 °F, 0.33 Hz (ksi)	N/P	N/P	N/P	N/P	N/P	N/P	N/P	N/P	N/P
		77 °F, 0.50 Hz (ksi)	N/P	N/P	N/P	N/P	N/P	N/P	N/P	N/P	N/P
		77 °F, 1.00 Hz (ksi)	N/P	N/P	N/P	N/P	N/P	N/P	N/P	N/P	N/P
Marshall Stability and Flow	ASTM D 1559	Stability (lb)	4010	3800	2380	4120	5630	2300	4760	1760	2310
		Flow (0.01 in)	11.8	9.8	10.7	14.0	15.7	11.3	14.3	12.0	13.3
Bulk Spec. Grav.	ASTM D 2726		2.16	2.26	2.25	2.28	2.24	2.22	2.19	2.13	2.21
Max. Spec. Grav.	ASTM D 2041		2.30	2.44	2.60	2.57	2.46	2.52	2.49	2.47	2.59
Air Voids		(percent)	6.1	7.4	13.4	11.4	8.9	12.0	12.2	13.9	14.8
Anti-stripping	ASTM D 1664	Modified(percent)	N/P	N/P	N/P	N/P	N/P	N/P	N/P	N/P	N/P
Workability	PTI Method	Ambient Temp.	N/P	N/P	N/P	N/P	N/P	N/P	N/P	N/P	N/P
AC Content	ASTM D 136	(residual percent)	4.0	4.3	5.1	3.5	5.0	2.7	4.4	4.7	4.1
Viscosity	ASTM D 2171	140 °F (poise)	290	2170	74	2932	1288	1126	517	42	69
Penetration	ASTM D 5	77 °F (dmm)	350	69	>400	82	159	121	211	>350	>350
Ductility	ASTM D 113	77 °F (cm)	N/P	N/P	N/P	N/P	N/P	N/P	N/P	<86	<86
Softening Point	ASTM D 36	(°F)	97	123	>86	126	115	108	108		

Notes: [a] = Recovered binder too soft to test. "N/P" indicates test not performed. Conversion of Units: °C = (°F - 32)/1.8; kPa = 0.1449 psi; kg = 2.2046 lb; mm = 25.4 × in.

Workability

The workability testing consisted of simply inserting a penetrometer into the cold mix and recording the maximum resistance encountered. The scale on the penetrometers ranged from 0 to 4.5 (tons/ft^2), so test results ranged from 0 to 4.5 as well.

Head-to-head testing was carried out at one point between the PTI and FHWA penetrometers. For the same material at the same temperature, the PTI device provided useful results for stiffer mixes, while the FHWA device was effective on looser materials. Since workability only becomes a problem when mixes get stiff, as happens at lower temperatures, the PTI device provided more meaningful results.

Rolling Sieve

The rolling sieve procedure was developed by the Ministry of Transportation of Ontario (MTO) to evaluate stockpiled patching materials for durability under the abrasive action of traffic.[5] For this project, the procedure was carried out in both the laboratory and the field to see if any correlations could be drawn between the test results and the observed performance. The development of such correlations would facilitate the development of specifications to test the suitability of stockpiled material by simply performing the test procedure.

The procedure carried out for this project consisted of the following steps:

1. Fill a standard Marshall mold and collar with approximately 1,000 to 1,200 g of stockpiled cold mix.
2. Compact the material in the mold with only three blows of the standard Marshall hammer.
3. Extrude and record the weight of the compacted sample.
4. Place the compacted sample into a standard 305-mm-diameter sieve with a mesh opening of 25.4 mm so that both the sieve and the sample are standing upright. Place a lid on the sieve so that the sample is contained with the lid on one side and the mesh on the other.
5. Roll the sieve back and forth with the sample inside. The sieve should roll approximately 305 mm in each direction. The rolling continues for 20 passes, at approximately 1 s per pass.
6. After rolling, place the sieve horizontally with the mesh down. There should be enough space to allow loose material to fall through the mesh. After 10 s in this position, the sieve and lid should be turned over so that the material left in the sieve falls onto the lid.
7. Weigh material retained in the sieve. Calculate the percentage of material lost as:
$$[(W_{orig} - W_{after}) / (W_{orig})] \times 100 = \text{Percentage Lost}$$

The MTO report stated that a loss of more than 35 percent was unacceptable. Because this procedure was performed in the field, the temperature could not be controlled as in the laboratory. The original laboratory procedure was carried out at -10 °C. For this project, the ambient temperatures ranged from 0 to 23 °C, with distinct trends for increasing percentage of loss as temperatures rose. Although this test allowed distinctions to be made between the materials, the field performance did not provide any data to correlate higher percentage losses to poor failure.

4. FIELD PERFORMANCE

A series of field evaluations were conducted to determine the performance trends and life-cycle costs of the various repair types. Evaluations were made at 1, 3, and 6 mo after the installations were completed, and semiannual inspections were performed for the remainder of the study. Data were collected on the failed repairs and information was gathered regarding the types and severities of distress that developed in the surviving patches.

To reduce variability during the performance monitoring trips, all field performance data were collected by the same individual. Arrangements were made with participating agencies to provide traffic control while the performance data were collected. Depending on the weather and the schedule of the traffic control crew, data collection at a given site was generally completed in 1 day.

Performance Data Collection

Two main types of data were collected during the field performance evaluations. The first type was survival data. Survival data consisted of the number of patches still in-service along the test site for every set of experimental and control patches placed at each site. The number of patches lost to overlays also was noted during the collection of field data and was used in the calculation of the percentage of repairs surviving. For example, if 7 of 10 repairs were noted as surviving during a particular inspection, then the survival rate was calculated as 70 percent. If one of the surviving repairs was lost to an overlay, the survival rate was then calculated as 67 percent (6 of 9).

The second type of data collected gauged the distresses present in the surviving patches. These distresses included bleeding, cracking, dishing, edge disintegration, missing patch, raveling, and shoving. Numerical ratings from 0 to 10 were assigned to each repair in each distress category, with 10 corresponding to "no distress observed" and 0 corresponding to the worst case of the particular distress type.

Summary of Performance Data

Survival Data

The most important indicator of repair performance is the percentage of patches surviving over time. Survival data collected during each monitoring trip and the percentage surviving for each repair type were calculated over time. Tables 4 through 11 show the percentage of patches surviving for each repair type at each site at various time intervals following installation. It should be noted that the timing of the rehabilitation projects performed by the participating agencies at the test sites resulted in different total performance times for each site. In addition, in some cases, repairs were noted as failed when new material had been placed at the H-106 repair location

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(even when the new material wore away and revealed that the H-106 repair was still intact). The repairs noted as failed could have been changed to surviving, but were not.

Table 4. Summary of patch survival–US 395, Alturas, California.

Patch material (procedure)	Percentage of patches surviving at each evaluation (time since installation given in wk for each evaluation)					
	Eval. 1 (5)	Eval. 2 (12)	Eval. 3 (39)	Eval. 4 (55)	Eval. 5 (75)	Eval. 6 (106)
Local Material (TAR)	100	100	100	90	80	70
UPM (TAR)	100	90	90	90	90	90
PennDOT 486 (TAR)	100	100	100	90	90	90
Spray Injection	90	90	90	90	80	70
UPM (TAR)	100	100	100	100	100	100
PennDOT 485 (TAR)	100	100	100	100	100	100
Perma-Patch (TAR)	100	100	100	100	100	100
UPM (TAR)	100	100	100	100	100	100
HFMS-2 (TAR)	100	100	100	100	100	100
UPM (SP)	100	100	90	70	70	70
UPM (TAR)	100	100	70	50	40	40
UPM (ES)	100	90	90	80	80	50
QPR 2000 (TAR)	100	100	90	80	80	60
UPM (TAR)	100	100	100	70	60	40

Procedures: TAR =Throw-and-roll; ES = Edge seal; SP = Semipermanent.

Table 5. Summary of patch survival-I-70, Vandalia, Illinois.

Patch material (procedure)	Percentage of patches surviving at each evaluation (time since installation given in wk for each evaluation)						
	Eval. 1 (4)	Eval. 2 (13)	Eval. 3 (31)	Eval. 4 (62)	Eval. 5 (83)	Eval. 6 (102)	Eval. 7 (133)
Local Material (TAR)	10	10	0	0	0	0	0
UPM (TAR)	100	100	100	78	33	33	14
QPR 2000 (TAR)	80	80	70	60	10	10	0
Local Material (Local)	80	80	60	50	0	0	0
UPM (TAR)	100	100	100	100	10	10	0
HFMS-2 (TAR)	100	100	100	90	10	10	0
PennDOT 486 (TAR)	100	100	70	70	10	0	0
UPM (TAR)	90	90	90	90	30	20	0
UPM (ES)	100	100	100	100	30	30	0
PennDOT 485 (TAR)	100	100	100	100	80	20	0
UPM (TAR)	100	100	100	100	90	50	0
Perma-Patch (TAR)	100	100	100	100	80	20	0
UPM (SP)	100	100	100	100	100	70	0
UPM (TAR)	100	100	100	100	100	50	0
Spray Injection	100	100	100	100	100	60	0

Procedures: TAR = Throw-and-roll; ES = Edge seal; SP = Semipermanent.

Table 6. Summary of patch survival–Rte 518, Las Vegas, New Mexico.

Patch material (procedure)	Percentage of patches surviving at each evaluation (time since installation given in wk for each evaluation)					
	Eval. 1 (6)	Eval. 2 (13)	Eval. 3 (34)	Eval. 4 (61)	Eval. 5 (84)	Eval. 6 (110)
PennDOT 486 (TAR)	100	100	70	60	50	50
UPM (TAR)	100	100	90	70	60	60
Local Material (TAR)	100	100	80	50	40	30
PennDOT 485 (TAR)	100	100	100	90	90	90
UPM (TAR)	100	100	90	80	70	70
HFMS-2 (TAR)	100	100	70	40	30	30
UPM (SP)	100	100	90	90	90	90
UPM (TAR)	100	100	90	80	70	70
UPM (ES)	100	100	100	100	100	100
Perma-Patch	100	100	100	100	100	100
UPM (TAR)	100	100	90	90	90	90
QPR 2000 (TAR)	100	100	100	100	100	100
		Eval. 2 (7)	Eval. 3 (28)	Eval. 4 (55)	Eval. 5 (78)	Eval. 6 (104)
Spray injection		100	100	100	100	100
UPM (TAR)		100	100	90	90	90

Procedures: TAR = Throw-and-roll; ES = Edge seal; SP = Semipermanent.

Table 7. Summary of patch survival–US 97, Modoc Point, Oregon.

Patch material (procedure)	Percentage of patches surviving at each evaluation (time since installation given in wk for each evaluation)				
	Eval. 1 (5)	Eval. 2 (16)	Eval. 3 (25)	Eval. 4 (36)	Eval. 5 (67)
PennDOT 485 (TAR)	100	100	100	100	100
UPM (TAR)	100	100	100	100	100
QPR 2000 (TAR)	100	100	100	100	100
QPR 2000 (SP)	100	100	100	100	N/A
UPM (TAR)	100	100	100	100	N/A
PennDOT 485 (SP)	100	100	100	100	N/A
UPM (SP)	100	100	100	100	100
UPM (TAR)	100	100	100	100	100
Perma-Patch (TAR)	100	100	100	100	100
UPM (TAR)	100	100	100	100	100
HFMS-2 (TAR)	100	100	100	100	100
Local Material (TAR)	60	60	60	60	30
UPM (TAR)	100	100	100	100	100
PennDOT 486 (TAR)	100	100	100	100	90
UPM(ES)	100	100	100	100	89
UPM (TAR)	100	100	100	100	70
Local Material (Local)	100	100	100	100	40
QPR 2000 (ES)	100	100	100	100	80
UPM (TAR)	100	100	100	100	78
PennDOT 485 (ES)	100	100	100	100	100

Procedures: TAR = Throw-and-roll; ES = Edge seal; SP = Semipermanent.
N/A = All repairs lost to overlay between Eval. 4 and Eval. 5.

Table 8. Summary of patch survival–FM 1570, Greenville, Texas.

Patch material (procedure)	Percentage of patches surviving at each evaluation (time since installation given in wk for each evaluation)									
	Eval. 1 (5)	Eval. 2 (13)	Eval. 3 (26)	Eval. 4 (62)	Eval. 5 (84)	Eval. 6 (143)	Eval. 7 (160)	Eval. 8 (184)	Eval. 9 (215)	Eval. 10 (242)
Local Material (TAR)	20	20	20	0	0	0	0	0	0	0
UPM (TAR)	100	90	90	67	67	50	50	50	50	50
UPM (ES)	100	100	100	100	100	80	80	80	40	0
UPM (TAR)	100	100	100	80	80	80	80	80	40	40
HFMS-2 (TAR)	100	100	100	100	100	80	80	80	80	60
Perma-Patch (TAR)	100	90	90	50	50	50	50	50	50	50
UPM (TAR)	100	100	100	100	67	67	33	33	33	33
QPR 2000 (TAR)	100	100	100	100	100	67	67	67	67	67
PennDOT 485 (TAR)	100	100	100	90	90	90	90	90	90	90
UPM (TAR)	100	100	100	90	90	50	50	50	50	50
UPM (SP)	100	100	100	90	90	70	70	70	50	40
PennDOT 486 (TAR)	100	100	100	20	20	20	20	20	20	20
UPM (TAR)	100	100	100	60	60	30	30	30	20	10
		Eval. 2 (8)	Eval. 3 (21)	Eval. 4 (57)	Eval. 5 (79)	Eval. 6 (138)	Eval. 7 (155)	Eval. 8 (179)	Eval. 9 (210)	Eval. 10 (237)
Spray Injection		100	100	100	100	89	89	89	89	78
UPM (TAR)		100	100	100	100	89	89	89	89	89

Procedures: TAR = Throw-and-roll; ES = Edge seal; SP = Semipermanent.

Table 9. Summary of patch survival-I-15, Frontage Road, Draper, Utah.

Patch material (procedure)	Percentage of patches surviving at each evaluation (time since installation given in wk for each evaluation)					
	Eval. 1 (6)	Eval. 2 (13)	Eval. 3 (32)	Eval. 4 (63)	Eval. 5 (79)	Eval. 6 (132)
PennDOT 486 (TAR)	100	100	100	100	100	100
UPM (TAR)	100	100	100	100	100	100
PennDOT 485 (TAR)	100	100	100	100	100	80
HFMS-2 (TAR)	100	100	100	100	100	100
UPM (TAR)	100	100	100	100	100	86
Spray Injection	100	100	100	100	100	88
Local Material (TAR)	100	100	100	100	100	100
UPM (TAR)	100	100	100	90	90	88
Perma-Patch (TAR)	100	100	100	100	100	100
UPM (ES)	100	100	100	100	100	89
UPM (TAR)	100	100	100	100	90	67
UPM (SP)	100	100	100	100	100	78
QPR 2000 (TAR)	100	100	100	100	100	100
UPM (TAR)	100	100	100	90	90	78

Procedures: TAR = Throw-and-roll; ES = Edge seal; SP = Semipermanent.

Table 10. Summary of patch survival-Rte 25, Bradford, Vermont.

Patch material (procedure)	Percentage of patches surviving at each evaluation (time since installation given in wk for each evaluation)					
	Eval. 1 (5)	Eval. 2 (12)	Eval. 3 (33)	Eval. 4 (58)	Eval. 5 (74)	Eval. 6 (105)
Local Material (TAR)	100	100	100	40	20	20
UPM (TAR)	100	100	100	30	20	10
UPM (ES)	100	100	90	90	70	70
UPM (TAR)	100	100	90	70	50	40
HFMS-2 (TAR)	100	100	100	60	50	20
Perma-Patch (TAR)	100	100	100	90	80	80
UPM (TAR)	100	100	100	70	40	40
QPR 2000 (TAR)	100	100	100	80	70	70
PennDOT 485 (TAR)	100	100	100	100	100	100
UPM (TAR)	100	100	100	90	80	80
PennDOT 486 (TAR)	100	100	100	80	80	80
Spray Injection	100	100	100	100	90	90
UPM (TAR)	100	100	100	100	90	90
UPM (SP)	100	100	100	100	100	100

Procedures: TAR = Throw-and-roll; ES = Edge seal; SP = Semipermanent.

Table 11. Summary of patch survival–Rte 2, Prescott, Ontario.

Patch material (procedure)	Percentage of patches surviving at each evaluation (time since installation given in wk for each evaluation)								
	Eval. 1 (7)	Eval. 2 (14)	Eval. 3 (24)	Eval. 4 (44)	Eval. 5 (94)	Eval. 6 (119)	Eval. 7 (146)	Eval. 8 (175)	Eval. 9 (198)
PennDOT 485	60	50	50	44	44	44	44	44	44
UPM (TAR)	70	30	30	30	30	30	30	30	30
UPM (TAR)	70	50	40	40	40	40	40	40	40
Local Material (TAR)	100	100	80	80	80	80	80	80	80
UPM (TAR)	90	90	90	90	90	90	70	60	60
PennDOT 485 (TAR)	80	80	80	80	80	80	80	80	80
QPR 2000 (TAR)	90	90	70	70	70	70	60	60	60
UPM (TAR)	100	100	60	60	60	60	60	60	60
QPR 2000 (TAR)	90	70	30	30	30	30	20	20	20
Perma-Patch (TAR)	90	80	80	80	80	80	80	80	80
UPM (TAR)	80	80	80	80	80	80	80	80	80
UPM (SP)	80	80	80	80	80	80	80	80	80
QPR 2000 (SP)	90	90	90	90	90	90	90	90	90
UPM (TAR)	80	70	60	60	60	60	60	60	60
PennDOT 485 (SP)	70	60	50	50	50	50	50	50	50
Spray Injection	80	80	80	78	78	78	78	78	78
UPM (TAR)	100	40	40	40	40	40	40	40	40
		Eval. 2 (7)	Eval. 3 (17)	Eval. 4 (37)	Eval. 5 (87)	Eval. 6 (112)	Eval. 7 (139)	Eval. 8 (168)	Eval. 9 (191)
HFMS-2 (TAR)		100	70	70	70	70	70	70	70
UPM (TAR)		70	70	70	70	70	70	70	70

Procedures: TAR = Throw-and-roll; ES = Edge seal; SP = Semipermanent.

Figures 18 through 21 show the different failure rates of repairs pooled over different categories. The plots represent raw values and do not take into account variability resulting from specific factors such as traffic, pavement structure, and climate. The statistical analysis and accompanying results are provided in section 5.

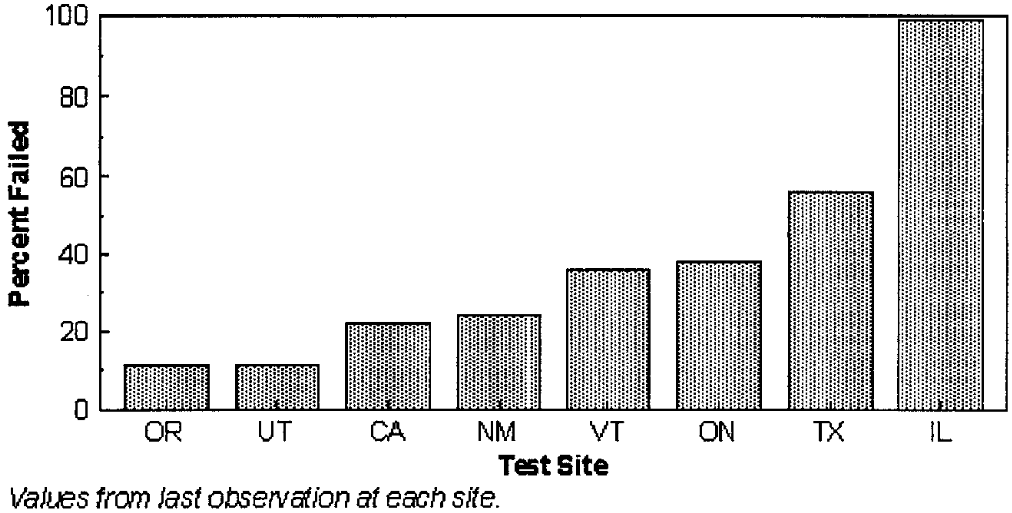

Figure 18. Pothole repair patch survival by site.

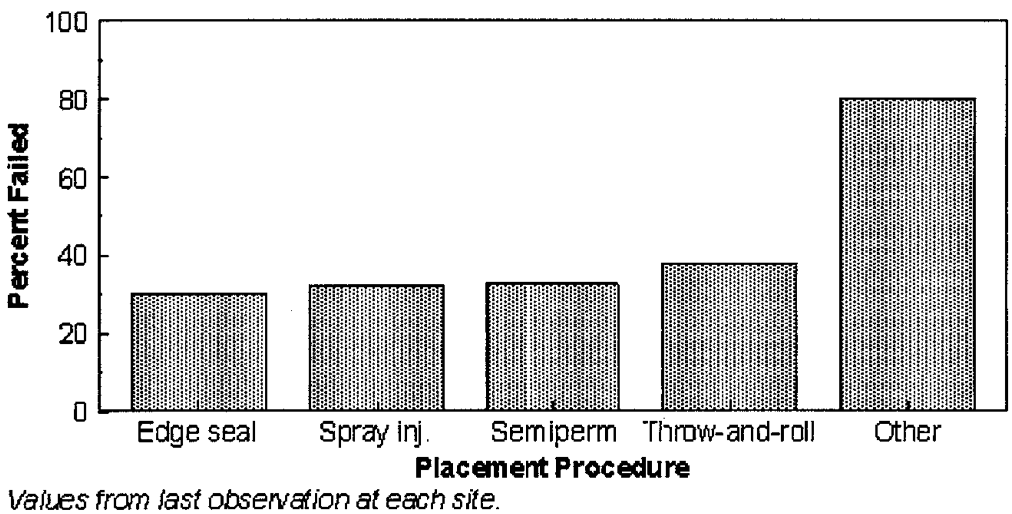

Figure 19. Pothole repair patch survival by procedure.

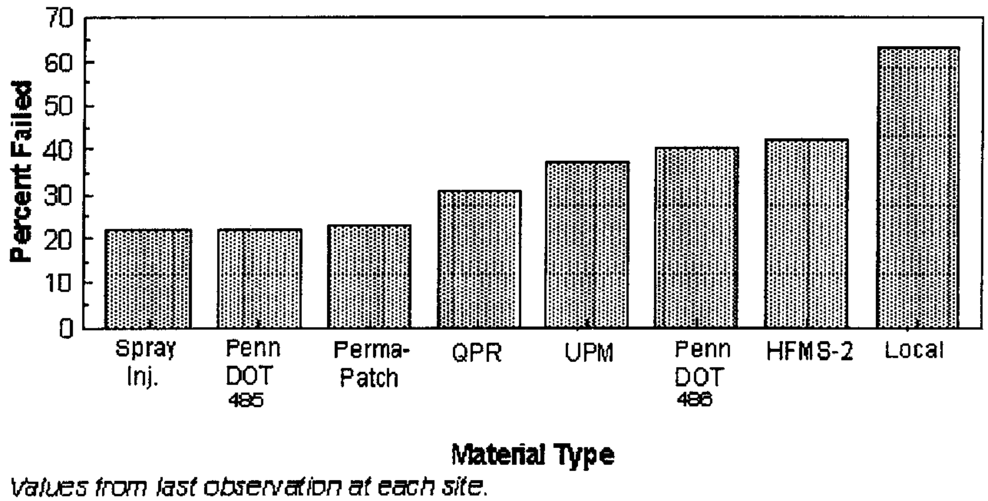

Figure 20. Pothole repair patch survival by material.

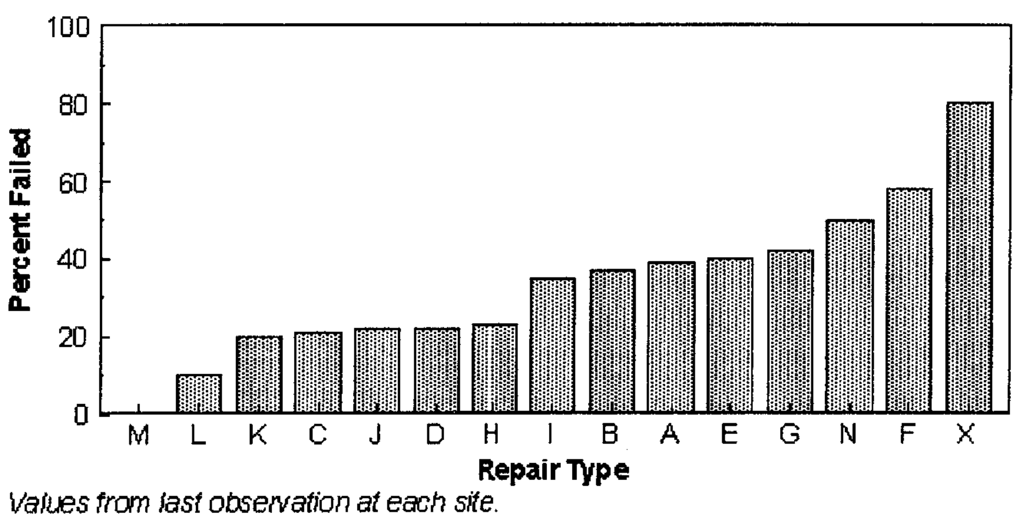

Figure 21. Pothole repair patch survival by repair type.

Figures 22 through 28 illustrate the survival plots for the patch sets at the Ontario test site, based on the data presented in table 11. As can be seen, the repair types are grouped in sets according to how they were installed. The groupings emphasize the comparison of patches within each set, as such comparisons yield the least variability in traffic, cross section, subgrade support, drainage, and other factors.

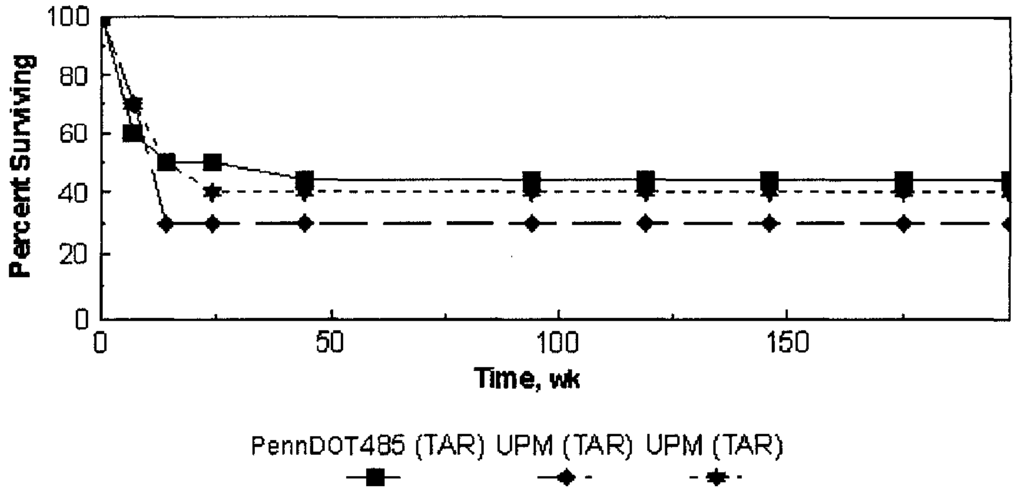

Figure 22. Survival of pothole repairs for Ontario test site-set 1.

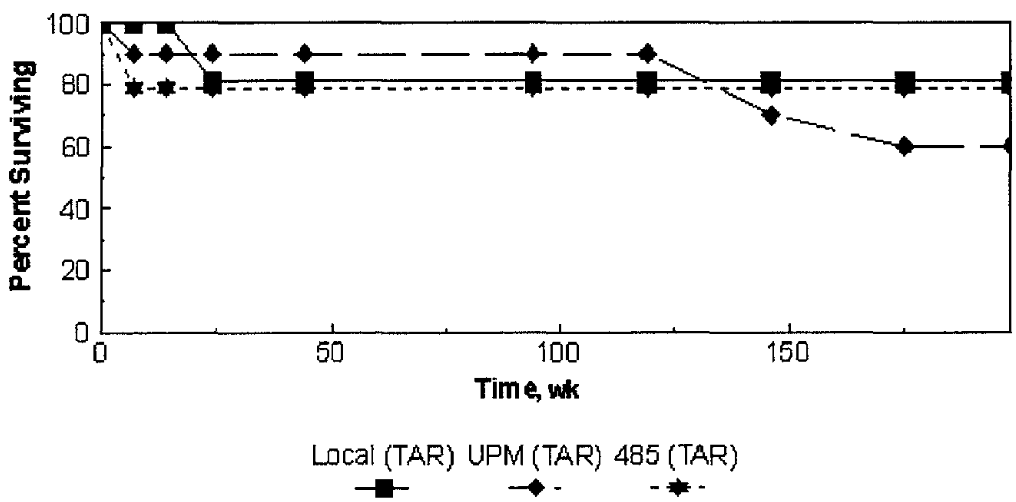

Figure 23. Survival of pothole repairs for Ontario test site-set 2.

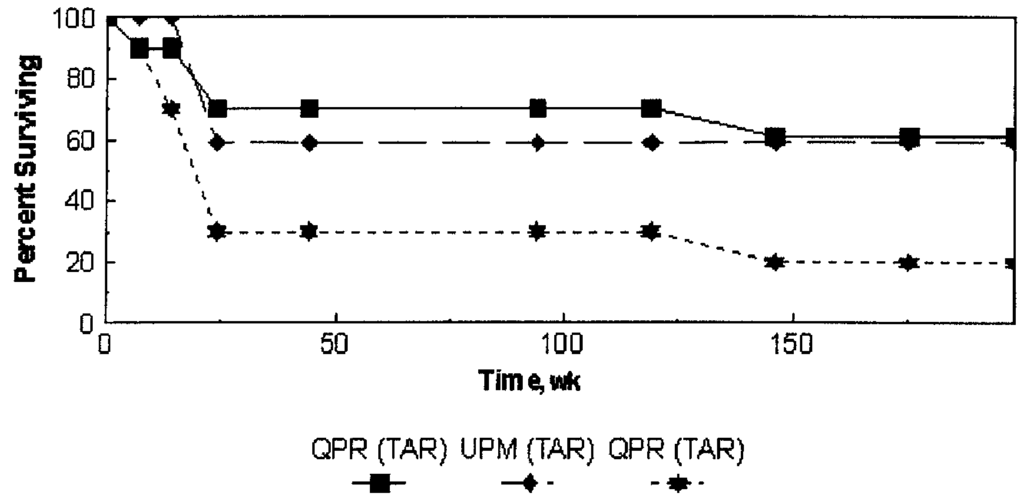

Figure 24. Survival of pothole repairs for Ontario test site-set 3.

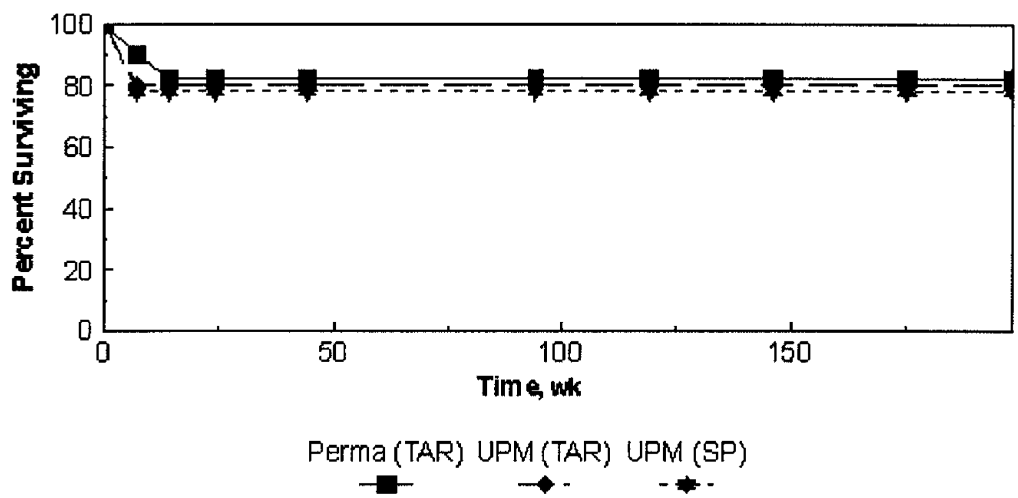

Figure 25. Survival of pothole repairs for Ontario test site-set 4.

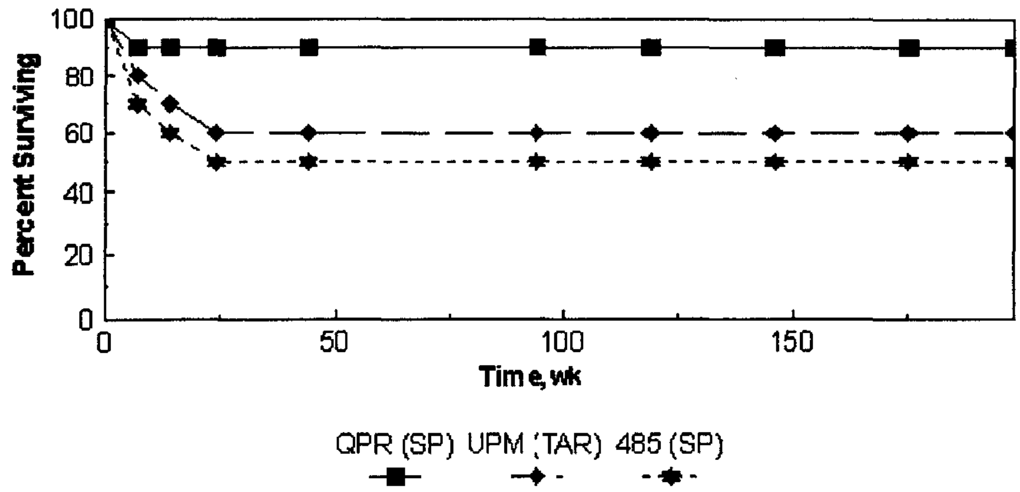

Figure 26. Survival of pothole repairs for Ontario test site-set 5.

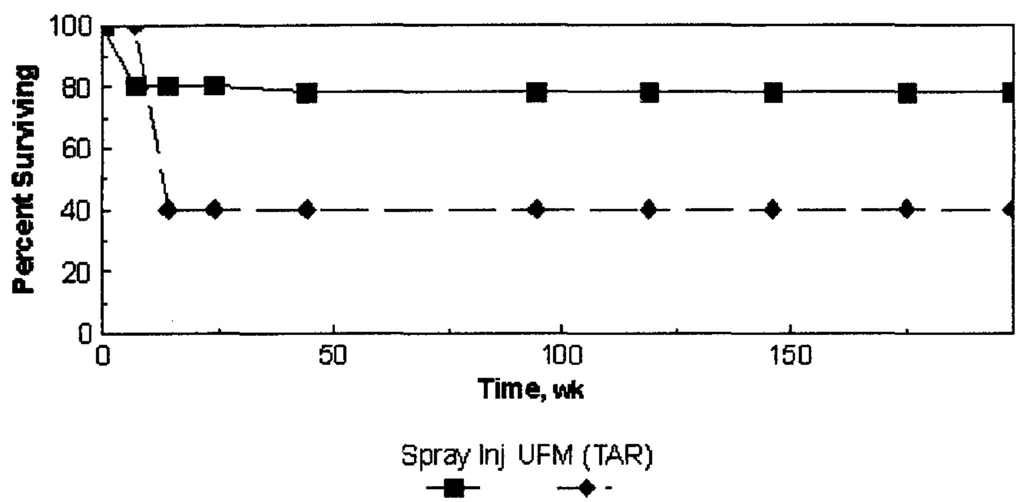

Figure 27. Survival of pothole repairs for Ontario test site-set 6.

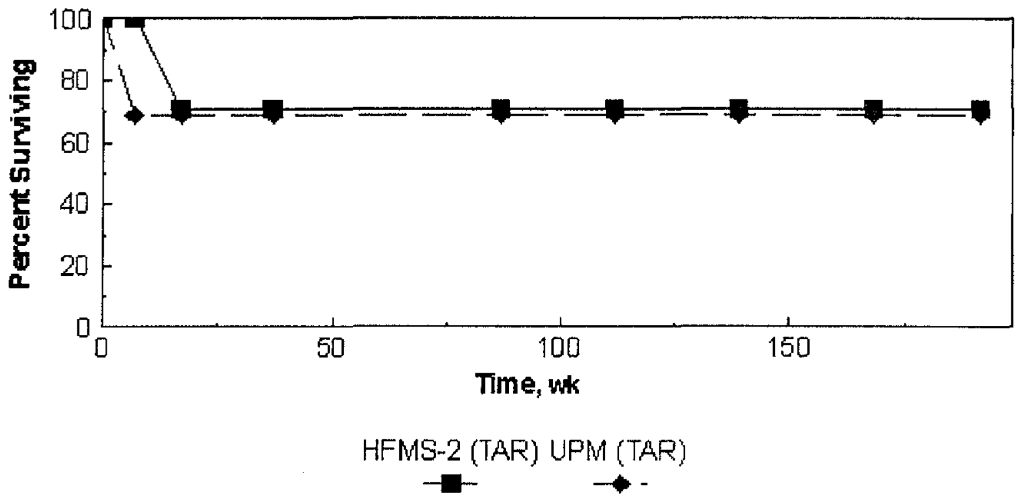

Figure 28. Survival of pothole repairs for Ontario test site–set 7.

One of the reasons that the analysis has concentrated on the differences within the groups is the variability of the performance observed from one set of control patches to the other. Figure 29 illustrates the survival plots for each of the seven sets of control patches placed at the Ontario test site. The percentage surviving after 198 wk varies from 30 to 80 percent, although the materials, placement procedure, and compaction were the same. The most likely source of the variability is differences in the pavement support, drainage, and other in-situ factors, which would have been similar for the rest of the repair types. Comparisons between different patch types at different locations throughout the test site would be irrelevant due to the differences in performance caused by site-specific factors.

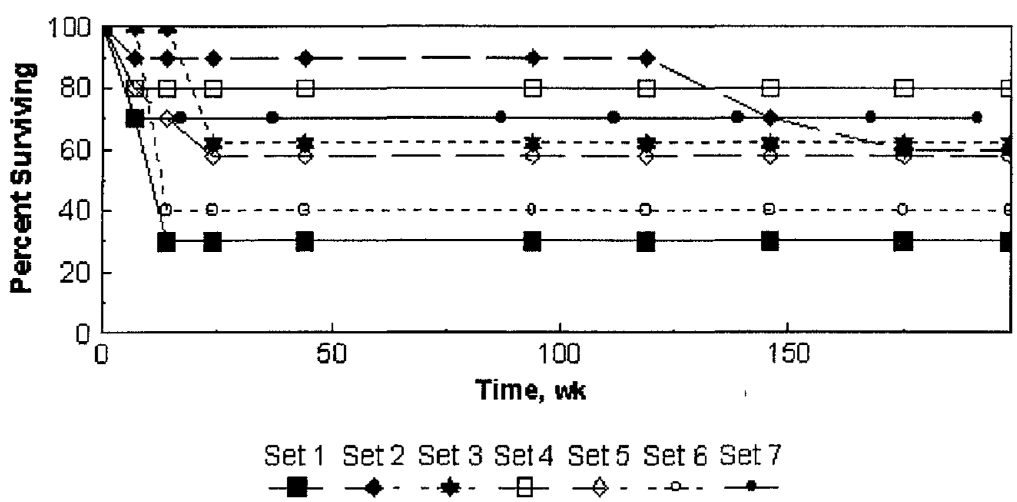

Figure 29. Survival of pothole repairs for control patches–Ontario test site.

Distress Data

During the course of the field evaluations, it became apparent that not all of the distress types noted were meaningful. An example of this was the "missing patch" distress, characterized by significant amounts of patching material missing for no apparent reason. Very few patches were recorded with this distress because patches that developed holes were quickly repaired by the participating agency, leading them to be considered failed.

Some of the more significant distresses noted at the test sites were dishing, raveling, and edge disintegration. However, bleeding was prevalent among the PennDOT 486 patches but was not widespread among the other patches placed. Figures 30 through 34 show examples of bleeding, shoving, cracking, raveling, and edge disintegration as they were noted in the field.

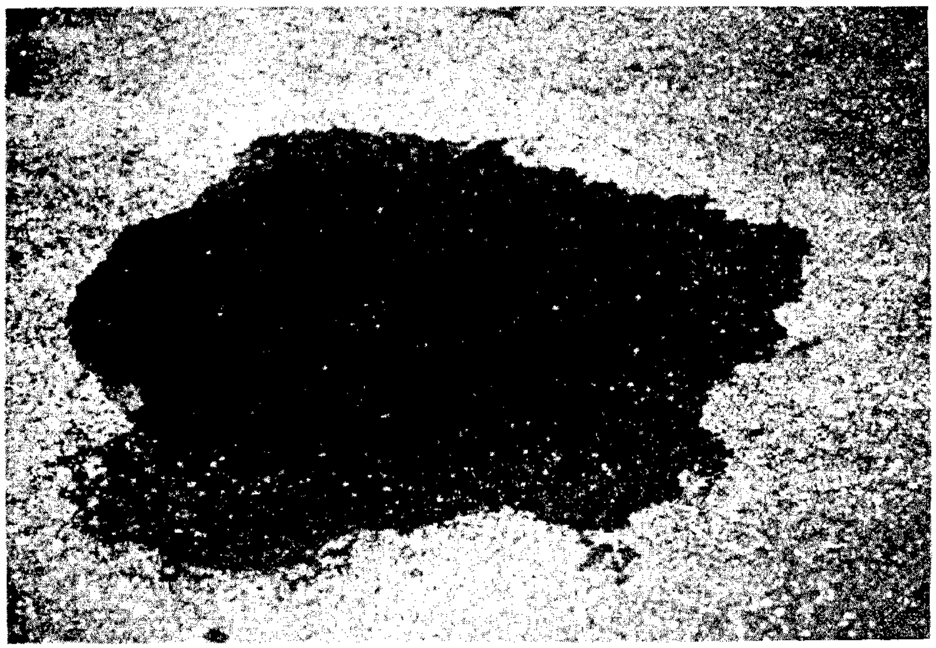

Figure 30. Example of bleeding distress.

Figure 31. Example of shoving distress.

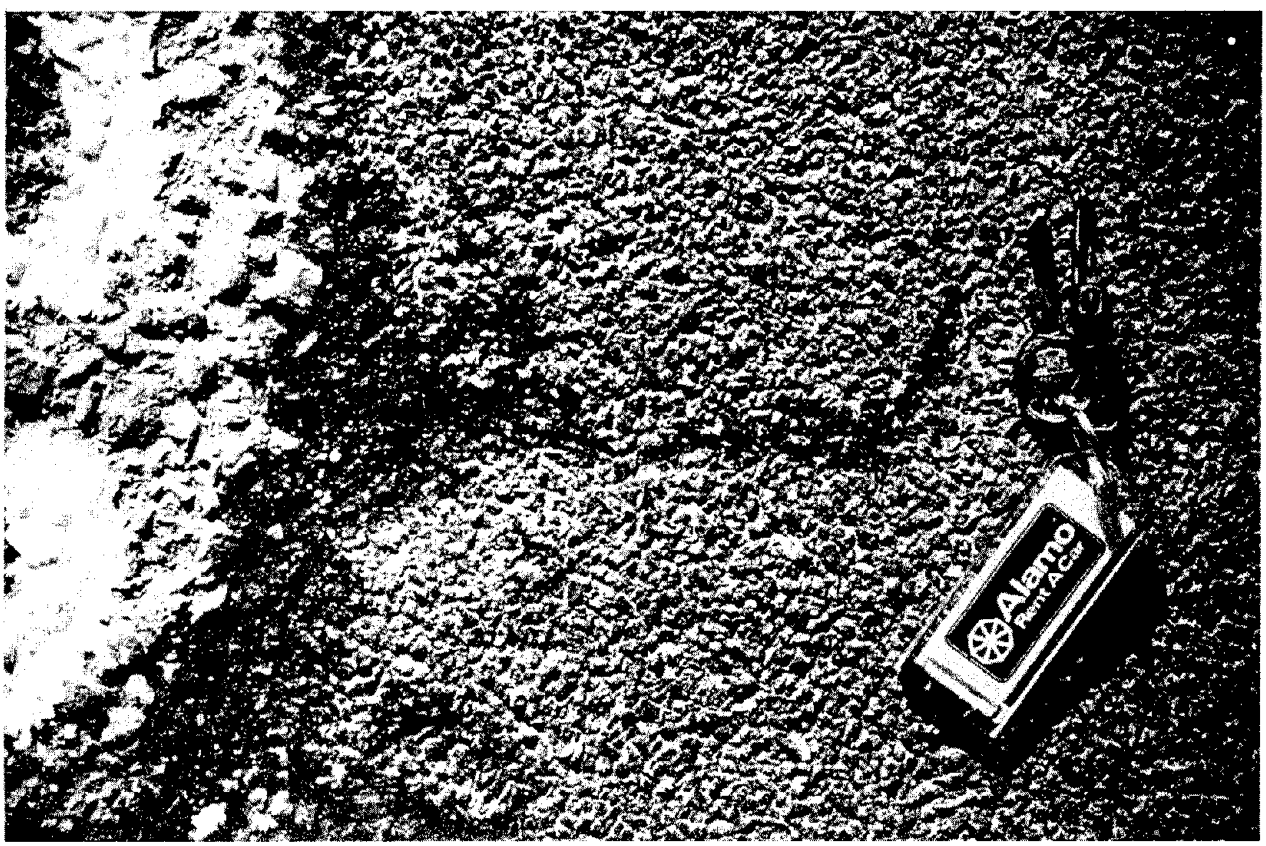

Figure 32. Example of cracking distress.

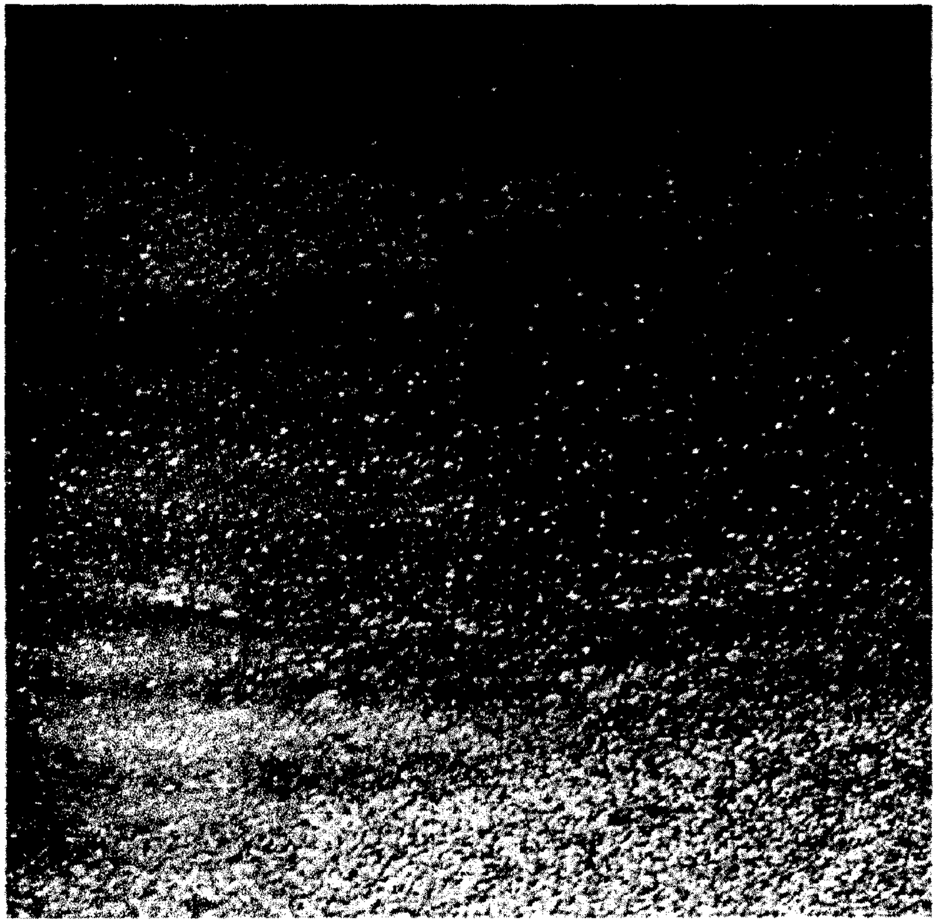

Figure 33. Example of raveling distress.

Figure 34. Example of edge disintegration distress.

5. ANALYSIS

The prime objective of this project was to determine which combinations of material and patching procedures provided the most cost-effective repair of potholes in asphalt concrete-surfaced pavements. Cost-effectiveness was a function of many factors, including material cost, labor cost, equipment cost, productivity, and performance of the repairs.

A secondary objective was to identify correlations between performance observed in the field and material properties determined in the laboratory. Such correlations would help establish material specifications based on desirable material characteristics that are indicative of good field performance. Statistical analysis provided the basis to determine if correlations existed.

Statistical Methodology

The SAS® statistical package was used for most of the analyses performed on the data from this experiment. Raw data were prepared in ASCII format and then analyzed using ASCII command files, which consisted of SAS statements to read in the raw data, perform the analysis, and produce the final output. This standard approach allowed the analyses to be performed repeatedly over the course of the experiment, allowing for interim assessment of repair performance.

The primary analysis consisted of comparing two groups of repairs to determine if there were statistically significant differences in survival over time. To determine correlations between the laboratory characteristics and the field performance, average values of the material property were compared with mean survival ratings and mean distress ratings for each repair type.

Field Performance

As discussed earlier, survival and distress development were the two main aspects of field performance that were monitored for the pothole repair experiment. The survival data were used to calculate the estimated service life of the different patch types. Survival data also were used as a criterion for determining statistically significant differences between the performance of different repair types over time. The distress data were used to identify failure mechanisms and to correlate them with the material characteristics data collected during the laboratory testing.

Patch Survival Ratings

Table 12 shows the survival rating values of each repair type placed at each test site. These ratings were derived by dividing the calculated area under the survival plots by the area that a repair type with no failures would have for the same time span.

Table 12. Summary of pothole repair survival ratings.

Set No.	Test Site Locations															
	CA		IL		NM		OR		TX		UT		VT		ON	
	Type	Rating	Type	Rating	Type	Rating	Type	Rating	Type	Rating	Type	Rating	Type	Rating	Type	Rating
1	F	89.1	F	3.0	E	67.3	D	100.0	F	4.5	E	100.0	F	58.6	D	46.3
	A	90.8	A	57.5	A	77.4	A	100.0	A	62.5	A	100.0	A	55.1	A	32.7
	E	94.4	I	40.4	F	62.6	I	100.0			D	96.0			A[a]	42.6
2	J	84.9	X	34.4	D	94.3	L	100.0	B	80.1	G	100.0	B	84.7	F	81.9
	A	100.0	A	56.7	A	83.0	A	100.0	A	76.6	A	97.2	A	71.9	A	80.5
	D	100.0	G	54.8	G	56.0	N	100.0	G	88.3	J	97.6	G	69.2	D[a]	80.4
3	H	100.0	E	44.6	C	92.1	C	100.0	H	57.6	F	100.0	H	90.6	I	68.8
	A	100.0	A	55.2	A	83.0	A	100.0	A	64.2	A	93.2	A	71.9	A	63.8
	G	100.0	B	61.2	B	100.0			I	82.5	H	100.0	I	85.0	I[a]	31.8
4	C	81.3	D	68.0	H	100.0	H	100.0	D	91.8	B	97.8	D	100.0	H	80.7
	A	62.2	A	71.6	A	92.1	A	100.0	A	70.6	A	90.8	A	90.6	A	80.4
	B	80.8	H	68.0	I	100.0	G	100.0	C	77.1	C	95.6	E	88.7	C	80.4
5	I	83.9	C	74.5	J	100.0	F	54.6	E	34.5	I	100.0	J	96.3	L	90.2
	A	76.5	A	73.1	A	94.0	A	100.0	A	49.0	A	91.2	A	96.3	A	61.8
			J	73.8			E	97.7					C	100.0	N	52.0
6							B	97.5	J	93.4					J	78.7
							A	93.1	A	94.0					A	43.2
							X	86.1								
7							K	95.4							G	71.9
							A	94.9							A	70.5
							M	100.0								

[a] = Originally supposed to be edge sealed, but no edge seal was placed.
Note: Letters designating repair types correspond to those used in Table 1.

Tables 13 and 14 illustrate how the survival ratings for the experimental repairs were computed. The sample survival data in table 13 are entered into the worksheet shown in table 14, where each average percent surviving (P_{avg}) is calculated by averaging the two values for percent surviving (P_{surv}) that straddle the line being calculated, as shown in the two shaded areas. Each time interval (T_T) is calculated by subtracting the smaller time ($T_{(I)}$) from the larger time ($T_{(I+1)}$) for the two straddling lines.

Table 13. Sample patch survival data.

Time, wk (T_T)	Repairs in place (R_{IP})	Repairs failed (R_F)	Repairs lost to overlay (R_L)	Percent surviving (P_{SURV})
0 (Inst.)	30	0	0	100
4	28	2	0	93
10	26	2	2	93
16	24	3	3	89
30	20	7	3	74
40	19	8	3	70
52	15	10	5	60

$P_{SURV} = \{R_{IP} / (R_F + R_{IP})\} \times 100$

Each partial area (A_{PART}) is calculated by multiplying the P_{AVG} and T_T values for that line. Each total area (A_{TOT}) represents the time interval (T_T) multiplied by 100. The A_{TOT} values represent the best possible performance that can be expected for any repair type (i.e., 100 percent survival) for the time period observed. By dividing the sum of the A_{PART} values by the sum of the A_{TOT} values, the survival rating is calculated.

Significant Differences

The survival ratings provided one means of quantifying performance for the different repair types. Another procedure, the SAS® LIFETEST, was used to identify statistically significant differences between two repair sets on the basis of the changes in repair survival over time. A confidence level (α) of 0.10 was used as the threshold of significance for the LIFETEST, as well as for other SAS procedures.

Table 14. Worksheet for calculating patch survival rate.

Observation number (I)	Time, wk (T)	Percent surviving (P_{SURV})	Average percent surviving (P_{AVG})	Time interval (T_T)	Partial area (A_{PART})	Total possible area (A_{TOT})
0	0	100				
			96.5	4	386	400
1	4	93				
			93.0	6	558	600
2	10	93				
			91.0	6	546	600
3	16	89				
			81.5	14	1141	1400
4	30	74				
			72.0	10	720	1000
5	40	70				
			65.0	12	780	1200
6	52	60				
7						
8						
9				Total	4131	5200

<u>Performance Rating</u>

$(A_{PART}/A_{TOT}) \times 100$

$(4131/5200) \times 100 = 79$ percent

$P_{AVG} = (P_{SURV(I)} + P_{SURV(I+1)})/2$

$T_T = T_{(I+1)} - T_{(I)}$

$A_{PART} = P_{AVG} \times T_T$

$A_{TOT} = T_T \times 100$

SAS analysis of the survival over time for each set of experimental patches indicated relatively few differences when compared with the appropriate sets of control patches. Out of a possible 80 experimental-control comparisons, only 11 proved significantly different at $\alpha = 0.10$. Table 15 shows the statistically significant comparisons identified by the SAS analyses.

As table 15 shows, three of the eight sites had local materials with significantly worse survival performance than the control material. These results indicate that the majority of experimental repair types did not perform significantly differently from the control patches (86 percent). This is most likely due to the fact that the H-105 project had identified those repair types with a good chance of survival and eliminated the poorer performing materials.

Table 15. Summary of significant differences in performance comparisons ($\alpha = 0.10$).

Test site	Better performing repair	Poorer performing repair
CA	Control	Spray injection
IL	Control	Local/throw-and-roll
	Control	Local/surface seal
	Control	PennDOT 486/throw-and-roll
NM	Control	HFMS-2/throw-and-roll
	UPM/edge seal	Control
OR	Control	Local/throw-and-roll
TX	Control	Local/throw-and-roll
	PennDOT 485/throw-and-roll	Control
VT	QPR 2000/throw-and-roll	Control
ON	Control	QPR 2000/throw-and-roll

Comparison among different sets of control patches within test sites did show differences in survival throughout the same site. An example of these differences can be seen in figure 29 for the control patches at the Ontario test site. These differences indicate that the performance of the control patches was affected by site-specific factors, such as underlying support and drainage, since the material, placement procedure, and compaction effort were the same for each set.

Expected Repair Life

To calculate the cost-effectiveness of the patches, it was necessary to know the expected life of the patches. Table 16 shows the mean expected life of each repair type for all of the sites. Also included in table 16 are the maximum ages of the repairs for each test site. These site-specific maximum ages must be taken into account so that the repairs in Oregon with a mean age of 67 wk are not assumed to be significantly worse than those in Texas, where the mean life of the repairs was as high as 242 wk.

Table 16. Mean repair life for all repair types at all test sites, in wk.

Set	Test site (maximum possible life in wk)															
	CA (106)		IL (133)		NM (110)		OR (67)		TX (242)		UT (132)		VT (105)		ON (198)	
	Type	Life	Type	Life	Type	Life	Type	Life	Type	Life	Type	Life	Type	Life	Type	Life
1	F	91	F	1	E	68	D	67	F	5	E	132	F	50	D	82
	A	96	A	66	A	80	A	67	A	124	A	132	A	47	A	68
	E	99	I	48	F	58	I	67			D	127			A[a]	82
2	J	86	X	36	D	102	L	67	B	176	G	132	B	86	F	161
	A	106	A	69	A	88	A	67	A	176	A	127	A	66	A	166
	D	106	G	66	G	53	N	67	G	205	J	127	G	62	D[a]	158
3	H	106	E	47	C	100	C	67	H	129	F	132	H	93	I	134
	A	106	A	72	A	88	A	67	A	129	A	122	A	69	A	124
	G	106	B	83	B	110			I	189	H	132	I	86	I[a]	59
4	C	83	D	87	H	110	H	67	D	220	B	127	D	105	H	159
	A	59	A	104	A	100	A	67	A	146	A	115	A	93	A	158
	B	79	H	89	I	110	G	67	C	175	C	121	E	91	C	158
5	I	84	C	118	J	104	F	3	E	69	I	132	J	100	L	178
	A	75	A	108	A	94	A	67	A	100	A	117	A	100	A	121
			J	133			E	64					C	105	N	101
6							B	64	J	216					J	154
							A	58	A	220					A	83
							X	48								
7							K	61							G	143
							A	61							A	132
							M	67								

[a] = Originally supposed to be edge sealed, but no edge seal was placed.

Laboratory/Field Performance Correlations

To identify correlations between material properties and field performance, comparisons were made between mean laboratory test values and mean field performance values, such as survival rating and average distress ratings. SAS analysis using a MANOVA regression model yielded no significant correlations. The most critical factor in identifying significant correlations between laboratory properties and field performance was the aging that was performed on the laboratory samples prior to testing. The heating of the specimens to harden the cold-mix materials was necessary to allow testing using hot-mix asphalt procedures such as Marshall stability and resilient modulus, but precluded determination of material properties during the pre-set condition, where most of the differences in field performance were noted.

Productivity

A major emphasis of the pothole repair experiment was to document the productivity of different pothole-patching operations. During the eight test site installations, data were collected on the installation productivity of the different agency crews. The crews' productivity levels were observed for the different repair procedures: throw-and-roll, edge seal, semipermanent, spray injection, surface seal, and tack-and-heat. During the experiment the times required to perform each of these procedures were noted along with information collected on the size of the potholes. Those data were used to calculate the productivity rates for the different operations.

Patching Times

Each repair procedure consisted of several steps: pothole preparation, material placement, and compaction. In the case of the edge seal procedure or the surface seal procedure used in Illinois, additional steps were performed after the patches had been placed and compacted. Beginning and ending times were recorded for given activities during each installation, and the elapsed time from beginning to end was calculated. The mean values of individual activities, as well as the entire procedure, are listed in table 17.

Pothole Volumes

Other data collected during the installation procedures included the dimensions of the potholes that were created. Width, length, and depth of the potholes were measured after the previous repairs had been removed and before the experimental patches had been placed. Table 18 shows a summary of the patch volume information.

Table 17. Summary of patching times, in min/patch.

Procedure	Activity	Test site								Average
		CA	IL	NM	OR	TX	UT	VT	ON	
Throw-and-Roll	Placement	2.0	3.1	2.4	1.2	2.2	1.5	1.5	1.3	
	Compaction	1.0	1.9	0.8	0.3	0.7	0.5	0.3	0.4	
	Total	**3.0**	**5.0**	**3.2**	**1.5**	**2.9**	**2.0**	**1.8**	**1.7**	**2.6**
Edge Seal	Placement	1.4	2.9	2.1	1.2	2.0	1.1	1.2		
	Compaction	1.0	1.5	0.7	0.4	0.5	0.4	0.4		
	Placing seal	1.0	1.0	1.0	1.0	1.0	1.0	1.0		
	Total	**3.4**	**5.4**	**3.8**	**2.6**	**3.5**	**2.5**	**2.6**		**3.2**
Semipermanent	Preparation	2.8	15.2	0.9	24.3	12.1	5.4	4.1	2.0	
	Placement	1.6	3.9	2.5	1.4	4.8	2.7	1.2	1.1	
	Compaction	2.6	2.5	1.0	1.3	1.1	1.0	1.0	1.1	
	Total	**7.0**	**21.6**	**4.4**	**27.0**	**18.0**	**9.1**	**6.3**	**4.2**	**13.3**
Spray Injection	Placement	1.9	2.4	2.7		2.0	3.9	2.3	4.6	
	Total	**1.9**	**2.4**	**2.7**		**2.0**	**3.9**	**2.3**	**4.6**	**2.8**

Table 18. Summary of average pothole volumes.

Procedure	Mean volume by test site, 0.01 m³								Weighted mean
	CA	IL	NM	OR	TX	UT	VT	ON	
Throw-and-roll	4.8	4.0	3.1	1.4	5.7	3.7	2.8	0.8	**3.1**
Edge seal	5.4	6.5	2.3	1.1	4.2	3.4	4.5		**3.4**
Semi-permanent	5.1	6.2	2.5	2.3	10.5	4.2	4.2	1.4	**3.4**
Spray injection	4.0	3.1	3.4		5.4	4.5	3.7	1.1	**3.7**

Information on the time required to patch potholes and the size of the potholes repaired was used to calculate the productivity of the patching operation with the use of the following equation:

$$P = (V_{avg}/T_{avg}) \times (2{,}000 \text{ kg/m}^3) \times (1 \text{ metric ton}/2{,}000 \text{ kg}) \times (60 \text{ min/h}) \quad (1)$$

where

P	= Productivity of the patching crew, metric tons/h.
V_{avg}	= Average volume of the potholes being patched, m^3.
T_{avg}	= Average time required to patch the potholes, min.

This equation gives the productivity of the crew while it is patching. Table 19 shows the average productivity values for the four procedures included in this experiment.

Table 19. Average productivity values for various operations.

Procedure	Average Productivity (metric tons/h)	Laborers Recommended	Average Productivity (metric tons/person-day)
Throw-and-roll	1.5	2	3.0
Edge seal	1.3	2	2.6
Semi-permanent	0.3	4	0.3
Spray injection	1.5	2	3.1

The values for productivity in metric tons/person-day shown in table 19 assume that patching is performed for half of an 8-h day. The actual percentage of a day spent patching versus setting up, taking breaks and lunches, or traveling between pothole locations could not be taken into account in this project. The presence of persons to monitor the installation for the nationwide experiment did not allow an opportunity to view the crews working as they would on a normal day.

In addition, the potholes created for this project did not develop naturally, so data were lacking as to how far apart naturally occurring potholes would be spaced. The distance between pothole locations affects how much time is spent traveling between patch locations and results in different total productivity values for different projects.

Cost-Effectiveness

Major elements that influence the cost-effectiveness of a pothole-patching operation are:

- Labor rates.
- Material purchase and shipping costs.
- Productivity of the patching crew.
- Total quantity of potholes to be repaired.
- Equipment costs.
- Performance of the repairs (either expected life or survival rating).

The following section describes each of these elements in greater detail.

Labor Rates

The cost of labor for a pothole-patching operation is usually determined by the experience and seniority of the crew members and the number of crew members actually involved. To calculate cost-effectiveness, information on labor rates on a per day basis is needed. The value of labor rates should be given for the entire patching crew, including supervisors. The labor rate can then be multiplied by the number of days needed for patching to get a total cost for the patching operation over 1 yr.

Material Purchase and Shipping Costs

For each type of cold mix available to an agency, there will be an associated purchase cost that can be expressed in dollars/metric ton. There will also be some cost associated with shipping the material from the plant where it is produced to an agency's yard. The total per ton cost associated with buying the cold mix and stockpiling it in the yard should be used to determine material costs.

Productivity of the Patching Crew

The average productivity achieved is crew dependent (i.e., it varies by crew make-up, experience, etc.). One way of estimating average productivity is to divide the total amount of cold mix placed during a season by the total days spent patching. The value should be expressed in terms of metric tons/day of material placed.

Total Quantity of Potholes To Be Repaired

This value is one of the most difficult to calculate. It is intended to represent only the new potholes that develop during a given year and should not include "repeat" potholes—those that reappear as previously placed material loosens or degrades. For calculating total patching costs, this value should be in metric tons of material. If volume of potholes is easier to estimate, a density of 2,000 kg/m^3 can be used to convert volume to mass.

Equipment Costs

Depending on the type of patching operation performed, different pieces of equipment are needed (trucks, compressors, jackhammers, compaction devices, and spray-injection devices), each of which has associated costs. To calculate patching costs, the dollars/day rate for all necessary equipment should be used.

Performance of the Repairs

Obviously, how the patches perform is a major factor in determining the cost-effectiveness of any pothole-patching operation. Patches that last a long time and require very little repatching greatly reduce the labor and equipment costs for the overall repair operation.

The total patching cost for any patching operation can be calculated using the following equation:

$$C_T = [(L_{TOT}/L_{MEAN})] \times [(N/P_o) \times (C_L + C_E + C_{TC}) + (N \times C_M)] \quad (2)$$

where

C_T = Total cost of patching operation, dollars.
L_{TOT} = Total time until rehabilitation of pavement surface, mo.
L_{MEAN} = Mean life for repair type, mo.
N = Material needed for initial patching operation, metric tons.
P_O = Productivity of the operation, metric tons/day.
C_L = Cost of labor needed for patching operation, dollars/day.
C_E = Cost of equipment needed for patching operation, dollars/day.
C_{TC} = Cost of traffic control for patching operation, dollars/day.
C_M = Cost of material delivered to yard, dollars/metric ton.

The annual cost for patching operations is then calculated by simply dividing the total cost (C_T) by total time in years until rehabilitation.

Consider, for example, a project requiring 200 metric tons of material (N) initially, a crew that can place 5.0 metric tons/day (P_o), with labor costs of $400/day ($C_L$), equipment costs of $50/day ($C_E$), and traffic control costs of $500/day ($C_{TC}$). The crew decides to use a material costing $80/metric ton with a mean survival life of 30 mo (L_{MEAN}). The total cost for a 3-yr analysis period—the length of time until the pavement is overlaid—will be $64,800, or $21,600/yr. If the same crew decides to use a less expensive material with a lesser mean survival rate (say, $25/metric ton with a mean survival life of 6 mo), the total cost for the patching operation will be $258,000, or $86,000/yr.

Table 20 shows the ratios of annual cost-effective values of each repair type placed at each test site. The lower ratios represent the lowest costs for each site, with the repairs with 1.0 values being the most cost-effective for each particular site.

Table 20. Summary of annual cost-effectiveness ratios (best cost-effectiveness signified by ratio of 1.0).

Set	Test site															
	CA		IL		NM		OR		TX		UT		VT		ON	
	Type	Ratio	Type	Life	Type	Life	Type	Life	Type	Life	Type	Life	Type	Life	Type	Life
1	F	1.1	F	77.6	E	1.5	D	1.0	F	42.2	E	1.1	F	2.0	D	1.9
	A	1.3	A	1.6	A	1.5	A	1.2	A	2.1	A	1.2	A	2.6	A	2.7
	E	1.1	I	2.1	F	1.7	I	1.2			D	1.1			A[a]	2.3
2	J	1.8	X	2.8	D	1.0	L	14.3	B	2.2	G	1.2	B	2.1	F	1.2
	A	1.2	A	1.4	A	1.4	A	1.2	A	1.5	A	1.3	A	1.9	A	1.1
	D	1.0	G	1.4	G	2.1	N	14.3	G	1.2	J	1.6	G	1.9	D[a]	1.0
3	H	1.3	E	1.8	C	14.6	C	14.3	H	2.0	F	1.0	H	1.3	I	1.4
	A	1.3	A	1.4	A	1.4	A	1.2	A	2.0	A	1.3	A	1.8	A	1.5
	G	1.1	B	1.9	B	1.6			I	1.4	H	1.2	I	1.4	I[a]	3.2
4	C	18.3	D	1.0	H	1.1	H	1.2	D	1.0	B	1.9	D	1.0	H	1.2
	A	2.1	A	1.1	A	1.2	A	1.2	A	1.8	A	1.4	A	1.3	A	1.2
	B	2.3	H	1.1	I	1.1	G	1.1	C	18.1	C	16.4	E	1.2	C	14.3
5	I	1.5	C	12.1	J	1.4	F	2.1	E	3.3	I	1.2	J	1.6	L	12.7
	A	1.7	A	1.0	A	1.2	A	1.2	A	2.6	A	1.4	A	1.2	A	1.5
			J	1.3			E	1.1					C	14.3	N	22.1
6							B	1.8	J	1.5					J	1.5
							A	1.3	A	1.2					A	2.2
							X	1.8								
7							K	1.9							G	1.2
							A	1.3							A	1.4
							M	1.7								

[a] = Originally supposed to be edge sealed, but no edge seal was placed.

6. SUMMARY OF FINDINGS AND RECOMMENDATIONS

The H-106 pothole-repair project 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 response-type pothole-patching operations. A summary of the key findings and recommendations of this study are provided in the section below.

Findings

Based on the information available to date, the following observations have been made:

- The overall survival rates for dry-freeze sites are significantly higher than for wet-freeze sites—85 percent versus 48 percent, respectively. This difference seems to indicate that precipitation at the wet-freeze sites causes quicker failure. However, the presence of other variables, such as traffic, pavement age, and subgrade support, do not permit a definitive analysis of the effects of precipitation.

- Of the 80 sets of experimental patches placed, only eight performed significantly poorer than the comparable control patches at $\alpha = 0.10$. The majority of these materials failed by raveling out until the pothole reappeared. This type of failure was generally observed in less than 1 month.

- The throw-and-roll technique proved just as effective as the semipermanent procedure for those materials for which the two procedures were compared directly. The semipermanent procedure has higher labor and equipment costs and lower productivity; thus, the throw-and-roll procedure would be more cost-effective in most situations, if quality materials are used.

- Pothole patches are intended to be temporary repairs, but the success rate observed in this project indicates that materials are available that can remain in service for several years. Overall, 56 percent of all patches survived until the last round of performance monitoring, with 31 percent failed and 13 percent lost to overlay.

- The spray-injection repairs performed as well as the comparable control patches at all sites. This procedure, however, depends on the expertise of the operator. For example, at the California test site an operator from Mississippi, using volcanic aggregate with higher absorptive characteristics than the operator was accustomed to, failed to use enough binder. The low residual binder content led to raveling of the aggregate and some premature failures. At most sites, the spray-injection patches had not set when opened to traffic and appeared soft. In spite of this, the spray-injection patches performed well.

- Of the eight agencies that participated in this experiment, three have switched from the inexpensive cold mixes they had used previously to one of the materials provided through the project. One agency also has purchased a spray-injection device to replace its conventional cold-mix patching material for pothole patching.

- Correlations between laboratory characteristics and field performance have been difficult to identify as the samples used in the laboratories had to be aged. Differences in performance were most apparent during the early stages of the repair life, before the repairs had set—a condition that was not reproducible in the laboratory.

Recommendations

The H-106 project represents a first step toward improving the state of the practice of everyday maintenance operations. Although some progress was made, additional work remains to be done. Some recommendations for improving the pothole repair process, based on the findings of this research effort, include the following:

- **Use high-productivity operations in adverse weather.** When weather conditions include cold temperatures and precipitation, the prime objective of the patching operation should be to repair potholes as quickly as possible. The throw-and-roll and spray-injection procedures produced high-quality repairs very quickly in all cases. Quality materials should be used with the throw-and-roll procedure, and the spray-injection device should be well maintained and operated by an experienced technician.

- **Use the best materials available to reduce repatching.** The cost of patching the same potholes over and over because of poor-quality material quickly offsets the savings from purchasing a less expensive cold mix. In most cases, the poorer performance associated with inexpensive cold mixes will result in greater overall costs for patching because of increased costs for labor, equipment, traffic control, and user delay.

- **Consider safety and user delay costs in calculating operation costs.** When justifying the purchase of a more expensive cold mix, consider the reduced user delay costs that will result when repatching is avoided. Also, consider the improved safety conditions that less crew time in traffic will allow.

- **Testing should be performed to ensure compatibility of aggregate and binder.** Whenever possible, the aggregate and binder to be used for producing a cold-mix material should be tested on a small scale to determine it the two are compatible. This testing is especially necessary when new combinations are being used and there is no record of the patching material's past performance.

7. REFERENCES

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