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More Effective Cold, Wet-Weather Patching Materials for Asphalt Pavements

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FOREWORD

This report presents the findings of a research study to evaluate improved cold-mix patching materials for asphalt pavements. Five binders were selected for evaluation in mixtures after initial laboratory testing. Both standard and new test methods were used to evaluate the mixtures in the laboratory prior to field trials. Over 400 patches were placed during the field installations over a winter season, and their performance was monitored for the next 13 months.

This report will be of interest to engineers involved in designing or using cold-mix patching mixtures for the repair of asphalt pavement during cold, wet weather.

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16. Abstract

To the motoring public, potholes are one of the most visible and annoying forms of pavement distress. Most pothole repairs made during the winter months are short-lived. Potholes that must be filled repeatedly are expensive to repair. One reason for the short life of repairs done during the winter is that the commonly used repair mixtures cannot withstand the cold, wet weather. The overall objective of this project was to develop and test improved cold-mix, stockpiled patching mixtures. To satisfy this objective, the predominant failure mechanisms and concomitant performance requirements were established. Binder performance was identified as the most promising area of study. More than 40 experimental binders were evaluated in the laboratory, and five of these binders were chosen for field trials. It was found that current mix designs for cold-mix, stockpiled patching materials were inadequate, and, therefore, a new mix design procedure was adopted for use in the study. Field trials were conducted, in which 410 repairs were made, and were monitored over a 1 -year period. Mixtures employing certain high-float medium-set emulsion binders performed demonstrably better than companion control mixtures. These binders, used in mixtures designed with the procedures described herein, are therefore recommended for trial installation by interested highway agencies.

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1. INTRODUCTION

To the road user, potholes are one of the most visible and annoying forms of asphalt pavement deterioration. Potholes have always been a problem for highway-maintenance organizations because their treatment is very costly and time-consuming. The problem can reach enormous proportions during cold, wet periods of the year, when pothole repair is made more difficult because of adverse weather and the large number of potholes that seem to appear at one time.

Pothole repairs conducted by most highway agencies during the cold, wet winter and spring months are typically short-lived. Potholes that must be filled repeatedly are expensive to repair. A value engineering study conducted in 1975 indicates that a patch repaired with a "dump and run" procedure has a serviceable life of 1 month and, on an annualized basis, a direct agency cost of $308 per ton ($340 per Mg).[1] According to that study, a properly compacted repair made by cutting out the deteriorated pavement will last more than 12 months and has an annualized cost per ton of $65 per ton ($72 per Mg). A more recent finding shows that the uniform annual cost of repairing a pothole correctly, including manpower, material, and equipment, is about $100 per ton ($110 per Mg), whereas the "dump and run" procedure costs about $310 per ton ($340 per Mg).[2] These figures have been normalized to represent the cost on the basis of the unit weight of material placed in the pothole at the initial time of repair. The cost can also be translated to a cost per repair. For example, assuming an average pothole volume of 3 ft^3 ($2.3\ m^3$) and a compacted unit weight of 133 lb/ft^3 ($2.1\ Mg/m^3$), a ton of mix will repair five average potholes. On this basis, the cost of repairing a pothole with the "do it right" procedure would be approximately $20 per repair and the "dump and run" procedure would cost $62 per repair.

Repair longevity is the secret to a cost-effective procedure since repeated repairs cost almost as much as the initial repair. Material costs were found to constitute less than 10 percent of the total cost of repair when the correct procedure was used. Thus, a more expensive material can be justified if it provides increased repair life.

One reason for the short life of a repair made during the cold, wet period of the year is that commonly available cold-mix patching materials cannot withstand the cold, wet weather. The objective of this study was to develop and test an improved cold-mix, stockpiled patching material that could be used for the repair of asphalt pavements during cold, wet weather conditions. The material had to be suitable for winter stockpiling, not require specialized equipment or handling, and be cost-effective with a minimum price differential compared with conventionally engineered cold-mix materials.

This report describes the laboratory testing, production, placement, and field evaluation of the more promising laboratory mixes. The field evaluations included an assessment of parameters that could be readily determined at the time of placement, such as workability, degree of binder coating on the aggregate, and nuclear density measurements. Longevity and long-term performance were documented with four inspections of the repairs conducted after approximately 40, 70, 200, and 400 days of service.

The research plan was completed by accomplishing five major tasks:

1. Definition of Performance Requirements. The first task of the research team was to define early failure mechanisms and to develop performance requirements for pothole repairs. In determining failure mechanisms, the researchers relied on several sources. First, an extensive literature search was conducted in which particular emphasis was given to those agencies that had conducted recent evaluations of nonconventional materials. The failure mechanisms of these materials were particularly relevant to this study. The researchers also used their extensive experience gained from an earlier 2-year field study of more than 1,000 potholes. Mechanisms occurring in the stockpile, during transport and placement, and while in service were documented.

Once the failure mechanisms were established, the research team developed performance requirements. In developing these requirements, it was realized that some of them were contradictory and that there are interactions and trade-offs among binder properties, aggregate gradation, equipment requirements, and repair philosophy.

2. Laboratory Development of Patching Materials. A list of candidate binders was developed on the basis of a review of the properties of commercially available binders, and limited laboratory studies. A more comprehensive series of laboratory studies was then used to select the binders for the field studies. Conventional mix-design procedures were applied, and workability, freeze-thaw resistance, stripping resistance, and several other tests were performed. After these tests were completed, five candidate materials remained.

3. Production and Stockpiling. Approximately 7 to 10 tons (6.4 to 9.1 Mg) of material were produced using each of the five binders. In addition, 45 tons (40.8 Mg) of a control mix (PennDOT 485) were produced. The materials were produced at a local facility and transported to a stockpile area, where they remained until the following spring.

4. Placement of Materials. The objective of this task was to conduct a controlled experiment in which the materials were placed and compacted using standard repair methods. A smaller number of repairs were made using the dump and run procedure. Certain parameters related to the repair procedure were controlled to reduce the number of variables that might affect the results, but actual field conditions were not controlled. Numerous attributes and parameters characterizing each repair were documented. Nuclear density measurements were made for most of the repairs made with the standard repair procedure. More than 400 repairs were included in the study.

5. Field Evaluation. The purpose of the field evaluation was to evaluate the long-term performance of each repair. A rating scheme was developed to document the condition of the repair relative to dishing, raveling, bleeding, and shoving. Statistical analysis was then applied to compare each mix with the control mix.

The flowchart shown in figure 1 depicts the sequence for the selection and testing of the patching mixtures developed in the study.

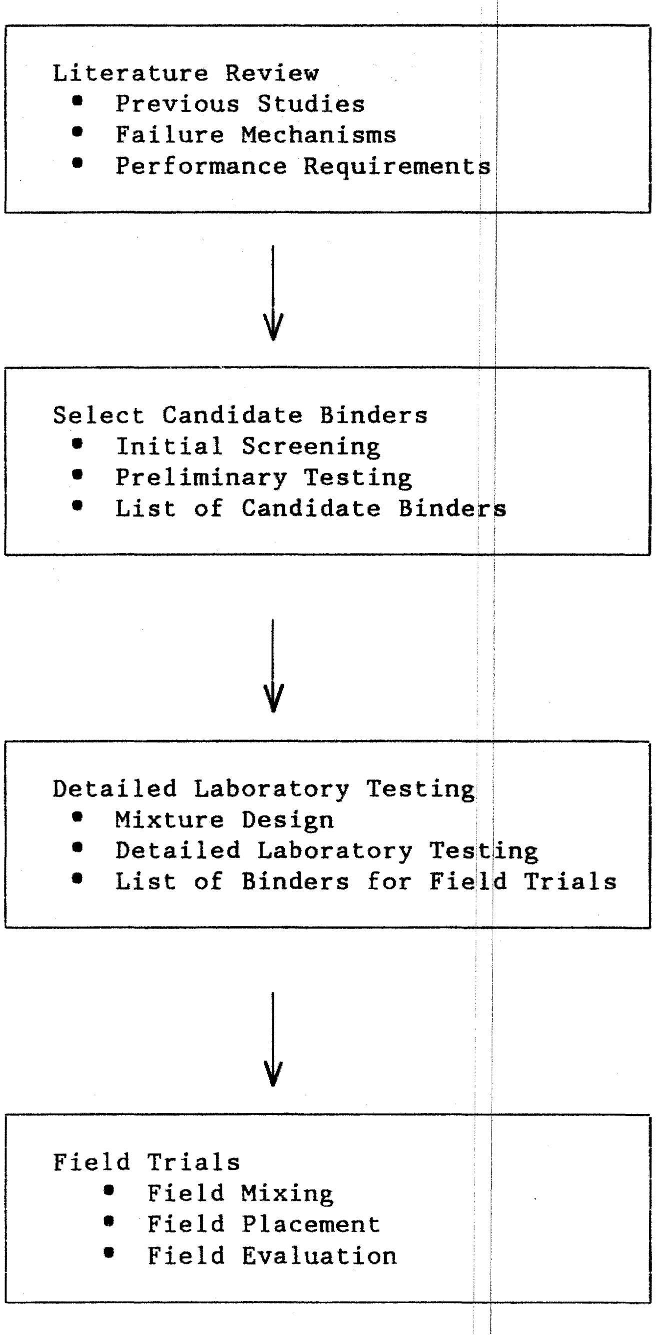

Figure 1. Flowchart for selection and testing of patching mixtures.

2. LITERATURE REVIEW

The major reasons that pothole repairs conducted in the winter and spring months fail prematurely are (1) the inability of stockpiled cold mix to resist wet-weather conditions, both before and after placement, and (2) the use of improper procedures by repair crews. This research focuses on the properties of the cold mix, assuming that the associated installation procedures are readily available, cost-effective, and properly executed by the repair crew.

The first objective of this project was to identify the mechanisms leading to the premature failure of pothole repairs made in cold, wet weather with cold-mix, stockpiled patching mixtures. Although many of these mechanisms have been discussed in the literature, the symptoms, or effects, of premature failure (pushing, dishing, etc.) are often confused with the causes or mechanisms of failure (stripping, lack of stability, etc.). In this report, a distinction is made between the symptoms of failure and the mechanisms of failure. By identifying the mechanisms of premature failure, it is then possible to establish a set of performance criteria that can be used to develop improved patching materials.

Pothole repair strategies and procedures have not received a great deal of attention in the literature. The primary emphasis in recent pothole repair research, much of which is unpublished, has been on the evaluation of proprietary cold mixes. Studies conducted in New Jersey, Indiana, New York, Colorado, Connecticut, Delaware, and Pennsylvania will be briefly reviewed.

NEW JERSEY STUDIES

The New Jersey Department of Transportation conducted a study to identify patching materials for rapid, durable, and economical winter patching of portland cement concrete (PCC) and asphalt cement concrete (ACC) pavements.[3] In addition to hot-mix asphalt, three types of cold-mix patching mixtures were evaluated. The State's standard winter mix (RR) was used as the control. The methods employed to place and compact the bituminous materials ranged from simply dumping the mix into the pothole and tamping the patch with the back of a shovel to reheating the material in a portable pugmill (McConnaughay HTD-10) and compacting it with a small vibratory roller. It was found that the standard cold-mix patching material (RR) performed better than the other patching mixtures tested. The other two cold-mix patching mixtures studied (a proprietary patching material and the asbestos-modified RR mix) proved unsuitable because of their shorter patch life and higher cost. In addition, the asbestos-modified RR mix presented potential health hazards. The use of asbestos has been banned for environmental reasons. It should be noted that the conventional hot-mix asphalt outperformed the standard RR mix, but hot mix is not readily available during the winter months.

Another investigation conducted by the New Jersey DOT utilized the McConnaughay HTD-10 mixer to produce hot-mix patching material.[4] As a part of the study, New Jersey's standard cold-weather patching material (designation RR) was evaluated with four different patching procedures. The RR mix, which is no longer in use, consisted of a 1 to 1 blend of stone and sand and an MC-800 binder. In technique No. 1, the mix was compacted by hitting it with the back of the shovel. Hole preparation was not required. Technique No. 2 called for the use of tacking material and compaction of the mix with a hand tamper. Again, cutting was not required, but loose debris was removed with a broom. Technique No. 2 was used as the control. Technique No. 3 included cutting and cleaning the hole before filling it with RR mix preheated (at the job site) in the McConnaughay unit. In this case, the material placed in the hole was compacted with a vibratory roller. Technique No. 4 was the same as technique No. 2 except that the vibratory roller was used for compaction.

It was found that RR mix used with technique No. 2 and technique No. 4 had similar patch life, whereas patches repaired with technique No. 3 (reheated and rolled) lasted 75 percent longer. In high traffic volume locations, the average number of replacements (per winter season) for patches repaired with techniques 2, 4, and 3 was 2.9, 3.0, and 1.7, respectively. However, patching operations with technique No. 3 incurred a higher cost per ton than operations using the other three techniques.

INDIANA STUDY

In 1980, the State of Indiana completed an extensive pothole repair study.[5] The study compared the performance of heated and unheated, stockpiled patching mixtures. A total of 324 potholes were repaired and several patching techniques were investigated. As in the case of the New Jersey investigation, the cold mix was heated and transported in hot boxes. The cold mix was also heated in a Porta-Patcher with the intent of removing

The Indiana study concluded that heating the cold mix resulted in improved durability compared with using unheated cold mix and that the best durability was obtained when cold mix was heated to 200 °F (93 °C) in a Porta-Patcher. This conclusion was verified in a study sponsored by the Federal Highway Administration, in which it was also found that heated stockpiled mix performed well.[6] Another finding in the Indiana study was that tacking and sealing were detrimental because they contributed to patch failures such as rutting, shoving, and bleeding resulting from poor application control and excessive use of tack material.

NEW YORK STUDY

The studies discussed above dealt mainly with conventional bituminous patching materials. Other investigations have focused on new materials for patch repair. One such investigation was conducted in New York State under the FHWA HPR program.[7] The New York study was based on the premise that the cold-mix patching material commonly used in winter is a temporary solution because it does not produce a good bond with the surrounding pavement, it tends to ravel, and it cannot withstand more than a few freeze-thaw cycles.

Repairs made with the standard New York cold mix and a proprietary product were evaluated for two winters. The New York DOT cold-mix, stockpiled patching mixture is relatively coarse graded, and the binder may be an emulsion or a cutback. Gradation requirements (percent passing) are shown in table 1. The type and content of the binder in the cold-mix used in the study were not provided in the report.

Table 1. Gradation of cold mix used in New York study.

Sieve Size	Percent Passing	
	Specification	Job-Mix
1/2 in (12.7 mm)	100	100
1/4 in (6.4 mm)	90-100	92
1/8 in (3.2 mm)	10-30	12
No. 80	0-5	7.3

Source: Reference 7.

Five potholes were repaired with the State's cold-mix versus 44 repairs made with the proprietary mix. All of the patches made with the State specification mix failed within four weeks, but only 2 of the 44 repairs made with the proprietary mix failed. The failed repairs were at sites where vehicle tires exerted lateral forces, resulting in the shoving of the mix. The study recommended that the proprietary mix not be used in locations of frequent vehicle acceleration and deceleration. Another conclusion of this research was that the high cost of the proprietary mix may be offset by longer patch life and reduced necessity for repatching.

COLORADO STUDY

A study conducted by Swanson et al. in Colorado, between December 1979 and July 1980, focused on the field testing of a variety of materials and techniques for repairing bituminous concrete.[8] The investigation included Colorado's standard hot mix (with AC-10), the standard cold mix (with MC-800), and a cold mix containing MC-70. Cold mix made with MC-800 was also compared with cold mixes containing polypropylene fibers and an antistripping agent.

In one repair technique, a rubberized emulsion was used to tack the sides and the bottom of a pothole. Then, layers of aggregate were placed in the hole, and each layer was covered with the emulsion. The patch was then covered with a layer of masonry sand and compacted. In some cases, a slightly different technique was used. The pothole was first tacked with the rubberized emulsion, and then the aggregate and the emulsion (thinned to two parts emulsion and one part water) were mixed inside the hole. More of this mix was added to fill the pothole. The patch was covered with a layer of sand, and a truck or a roller was used to compact the patches.

The following patching procedure was adopted when foamed asphalt was employed. MC-70 was used to tack the hole. The hole was then filled with a foamed asphalt mix. Compaction was done with a truck or a roller. Finally, MC-70 was poured on the patch and blotted with fine aggregate.

Several potholes were repaired with a hot mix produced by mixing sulflex and aggregate in an improvised drum mixer. The sulflex binder and the aggregate were preheated to 250 °F (121 °C) and 310 °F (154 °C), respectively. The patches were compacted with a roller. The other six patching mixtures--a proprietary cold mix, a conventional hot mix with AC 10, a standard cold mix with MC-800, a cold mix with MC-800 and polypropylene fibers, a cold mix with MC-800 and an antistripping agent, and a cold mix with MC-70--were employed, separately, to fill several potholes.

By July 1980, 7 months after the study began, all the asphalt patching materials (with the exception of the sulflex and the hot mix) had failed and had to be replaced with the standard hot mix. Common failures were raveling and dishing. Also in July, the sulflex patches began to strip. The use of sulflex mixtures in portable mixers may be dangerous without proper temperature control. When sulflex is heated above 310 °F (154 °C) toxic gases are released.[9]

CONNECTICUT STUDY

In 1980, the Connecticut Department of Transportation conducted an FHWA study to develop and evaluate a number of commercial and nonproprietary patching mixes.[10] During the month of January, bituminous patching material was placed in 35 test holes, 18 in (0.46 m) by 18 in (0.46 m) by 3 in (76 mm) deep. These test holes were cut out in an asphalt concrete pavement at a location with an average daily traffic (ADT) of 25,700 vehicles per day.

In the study, the aggregate gradation, the binder type, and the use of antistripping agents were varied in an effort to produce an optimum bituminous patching mixture. The researchers selected five aggregate gradations and four binders consisting of two cutback asphalts (MC-800 and MC-250) and two emulsions (table 2). Three antistripping agents also were incorporated.

Table 3 shows the total distribution of failures observed in the bituminous patches based on aggregate gradation and binder type. Failure was defined as mechanical breakup, development of depressions, flushing, and freezeouts. The report concluded that:

Table 2. Gradation of mixtures used in Connecticut study.

Size	Percent Passing				
	Proprietary A Class 14	Mix B Open Graded	Mix C Open Graded	Class 5	Dense Graded
3/4 in (19.1 mm)	90-100	---	---	---	---
1/2 in (12.7 mm)	70-100	---	---	100	---
3/8 in (9.5 mm)	60-82	100	100	90-100	96
No. 4	40-65	31.2	85	65-90	60
No. 8	28-50	20.2	24	45-75	41
No. 50	6-26	9.3	3.2	12-40	17
No. 200	2-8	2.0	2.2	3-10	3.6

Source: Reference 10.

Table 3. Distribution of failures in bituminous patches in the Connecticut study.

Mixture Type[1]	Failures: No. of Patches	Failures: Percentage of Total	Asphalt Type	Failures: No. of Patches	Failures: Percentage of Total
Dense Graded	10	77	MC 250	8	50
Class 5	9	53	MC 800	1	20
Class 14	0	0	Emulsion A	4	57
			Emulsion B	4	50

Source: Reference 10.

[1] See table 2.

- When a bituminous patch failure takes place, it generally occurs early in the life of the patch, especially in the presence of rain.

- Aggregate gradation plays a major role in the performance of bituminous patching mixtures.

The report recommended an ideal bituminous patching material consisting of an open gradation (class 14) with a 3/8-in (9.5 mm) maximum aggregate size, less than 2 percent fines, an MC-250 binder content between 4 and 6 percent, and an antistripping agent in a quantity of about 1 percent.

DELAWARE STUDY

In May 1984, the Delaware Department of Transportation completed the field evaluation of two cold-mix, stockpiled asphalt patching materials, one modified with the addition of a polypropylene fiber and the other made with a latex-modified emulsion.[11] Patches were placed during the winter season. The performance of these materials was compared with the known performance of Delaware's standard cold mix and with a proprietary cold mix. The objective of the study was to determine the cost-effectiveness, mixability, workability, durability, and stockpile weathering. However, the stockpiled proprietary cold mix experienced stripping problems, and the performance of the standard mix was unusually poor. In light of these problems, a fair comparison was not possible. Therefore, the evaluation was based on visual observations. The results of this study showed the following:

- All four patching materials had a satisfactory plant mixability.

- At temperatures below 40 °F (4 °C), the latex-modified mix had poor workability. The other three mixtures, hot or cold, had satisfactory workability.

- The heated, fiber-modified, cold mix had the best durability.

PENNSYLVANIA STUDIES

A series of comprehensive pothole repair studies was completed in Pennsylvania. In the first of these, mixture design requirements were evaluated,[12] and a new specification, PennDOT 485, for cold-mix, stockpiled patching mixtures was established.[13] Subsequently, PennDOT adopted a specification for fiber-modified mixtures, PennDOT 481, and these mixtures are now used routinely in the State.[14]

As part of the Pennsylvania studies, the standard for repairing potholes was reviewed and a guide for repairing potholes was developed.[15,16] This procedure is referred to as the "do-it-right" or standard method and includes provisions for cutting out deteriorated material, using a plant-mixed, cold, stockpiled patching mixture, and compacting the filled hole by mechanical means. The do-it-right procedure, which has been adopted by others,[17] was used as the standard procedure in the present study.

The effectiveness of a standard procedure used in conjunction with a well-designed and controlled cold-mix, stockpiled patching mixture was verified in another Pennsylvania study.[18] As part of this study more than 1,000 repairs were performed on both asphalt concrete and portland cement concrete pavements. Two patching materials were investigated: PennDOT ID-2 and PennDOT 485. ID-2 is a dense-graded, hot-mix asphalt concrete normally used for wearing courses in Pennsylvania. PennDOT 485 is a stockpiled cold mix, which is discussed in detail later in this chapter.

The repairs were monitored for rutting, shoving, dishing, raveling, and cracking. After two winters more than 70 percent of the repairs were rated as being in good to excellent condition. There was no significant difference in the survival rate of repairs made with cold mix or hot mix.

The following findings were reported from the Pennsylvania field evaluation study:[18]

- A properly designed and installed cold-mix, stockpiled patching mixture can give an excellent repair.

- The cost of high quality materials and a standard procedure is considerably less than the cost of the repeated repairs associated with the short-lived throw-and-go repairs.

- Aggregate gradation and aggregate crush count are important factors in determining mixture stability.

- An open-graded crushed aggregate mix with less than 2 percent passing the No. 200 mesh sieve and with a maximum particle size of 3/8 in (9.5 mm) is required for an optimum mix.

OTHER STUDIES

A 1984 study published by the Federal Highway Administration describes pavement and shoulder maintenance guidelines for selected maintenance activities.[19] Pothole repair was not specifically addressed. Using value engineering concepts, the report describes the materials, equipment, and procedures to be used. Optimum crew sizes and daily output are suggested, and appropriate safety precautions are recommended.

Methods for improving the patching of potholes on high-volume roads was the subject of a 1986 study sponsored by the Federal Highway Administration.[20] The researchers visited 30 sites in nine States and documented the types of distress, procedures, equipment, and materials being used. The report concludes that the greatest single improvement in the overall operation would result from better management. Other recommendations were made in the areas of materials, equipment, and traffic control.

Other studies conducted in Pennsylvania have focused on the productivity of repair crews and the relative cost of different repair operations and materials.[21,22] In these studies various types of equipment and procedures were evaluated and optimum repair strategies and equipment complements were identified. Small vibratory compactors were found to be the optimum choice for small-scale pothole repair, a conclusion supported by other studies.[23]

MIX DESIGN

NCHRP Synthesis of Highway Practice No. 64, published in 1979, deals with the design, testing, and control of bituminous patching materials in considerable detail.[24] The report discusses the common failures of bituminous patching mixtures and the mix properties related to these problems. Table 4 summarizes this information. According to the report, the performance of conventional, stockpiled patching mixtures in many States has been generally unsatisfactory. The report further states that many of the conventional mixes are poorly designed or are simply the result of past practice. The primary reason for this problem is the lack of a rational design procedure for these mixtures.[24]

A 1981 study reviewed the challenges of designing a cold-mix, stockpiled patching material and then used a rational approach to design an improved bituminous mixture.[12] The study presents an excellent discussion of the compromises that are necessary in selecting the aggregate, the aggregate gradation, the binder type, and the binder content for cold-mix, stockpiled patching mixtures. On the basis of this approach, Pennsylvania developed a specification for a plant-mix, stockpiled cold mix. The gradation of the aggregate in this mixture is given in table 5.[13] Depending upon the time of the year, one of the binders shown in table 6 is used. The aggregate is dried in a hot-mix asphalt plant, and both the aggregate and the binder are heated (table 7) before they are mixed (also in a central hot-mix plant). An important part of the PennDOT 485 specification is the requirement that the job-mix aggregate be tested in advance with the emulsion or cutback to ensure adequate resistance to stripping.

The performance of the PennDOT 485 mix was compared with a proprietary at various locations in Pennsylvania.[12] The mixes were placed cold, without any heating. The first group of potholes was repaired in April 1977. More patches were placed in March 1978. Both patching materials were placed in wet potholes without any preparation. The air temperature when the repairs were made ranged from 21 °F (-6 °C) to 36 °F (2 °C), and there were occasional snow flurries. After one year, most of the patches were performing well. The performance of the PennDOT 485 mix design was verified in a subsequent study

Table 4. Failures, handling problems, and related mix properties common to bituminous patching mixtures.

Failure[1] or Handling Problem	Principal Related Mixture Property
Shoving (rutting)	Stability
Lack of adhesion to sides and bottom of hole	Stickiness
Binder stripping from aggregate	Resistance to water action
Raveling	Durability
Slick surfaces	Skid resistance
Excess binder tracking and sticking to surfaces	Bleeding
Mix difficult to handle and shovel	Workability
Mix hardened in stockpile	Storability

Source: Reference 24.

[1] This list does not include failures produced by improper construction practices, such as bumps caused by placing too much mixture in the hole.

Table 5. Aggregate gradation specified for PennDOT 485 cold mix.

Sieve Size (mm)	Percent Passing	
	Specified	Preferred
3/8 in	100	100
No. 4	40-100	85-100
No. 8	15-40	10-40
No. 16	---	0-10
No. 200	0-2	0-2

Source: Reference 12.

Table 6. Binder materials specified for PennDOT 485 cold mix.

Class of Material	Type of Material
MC-400	Cutback petroleum asphalt
MC-800	Cutback petroleum asphalt
ME-800	Emulsified cutback asphalt
E-10	Emulsified asphalt (high-float residue)
E-12	Cationic emulsified asphalt
RT-4	Coal tar
RT-6	Coal tar

Source: Reference 12.

Table 7. Mixing temperatures specified for PennDOT 485 cold mix.

	Temperature Range (°F)		
Material	Aggregate	Bituminous Material	Mixture
MC-400	40-140	150-190	--
MC-800	40-140	165-205	--
ME-800	40-140	175 max	--
E-10 and E-12	Appropriate for specified mix temperature	140-175	190-250
RT-4	100-200	130-150	100-190
RT-6	100-200	130-175	100-190

°F = 9/5 (°C) + 32.

Source: Reference 12.

in which more than 70 percent of nearly 400 cold-mix repairs were intact after two winters.[18]

SUMMARY

The experience with conventional cold, stockpiled patching mixtures as well as with proprietary mixes has been varied. Many agencies are searching for a cold mix that can be placed in the hole without prior preparation or subsequent compaction. None of the mixes, conventional or proprietary, have performed well under these conditions. When proper hole preparation and compaction are provided, properly designed conventional cold mixes can give satisfactory performance under many circumstances. However, improved materials are needed that

- Are more resistant to high-volume traffic and heavy axle loads
- Are more tolerant of cold, wet weather conditions
- Are more tolerant of placement procedures
- Have better workability at low temperatures
- Develop their strength or cure more rapidly in the hole, especially before the onset of hot weather.

The literature supports the concept of an open-graded cold-mix, stockpiled patching mixture. Requirements include a maximum of 2 percent passing the No. 200 mesh sieve and a maximum aggregate size of 3/8 in (9.5 mm). The use of tacking materials is cited as being detrimental to performance. The heating of cold-mix, stockpiled patching mixtures to remove some of the solvent in the binder is considered beneficial, which verifies the need for a stiffer binder. Finally, a mix design procedure for cold-mix, stockpiled patching mixtures with conventional binders was described, and this procedure was adopted for use in the present study.

3. FAILURE MECHANISMS AND PERFORMANCE REQUIREMENTS

In order to develop an improved patching mixture for cold, wet weather conditions, it is first necessary to identify the deficiencies of the mixtures that are in current use. These deficiencies are reflected in poor performance or premature failure, which may be initiated in the stockpile, during handling and placement, or in service.

A list of the types of inadequate performance and their probable causes is given in table 8. This information is based on the literature review, the authors' experience, and discussions with transportation officials and with material and equipment suppliers. From the information in table 8, it is apparent that, in the development and evaluation of new mixtures, performance during stockpiling, placement, and service must be considered as well as the properties of the aggregate and the binder.

MECHANISMS IN THE STOCKPILE

Poor workability, drainage of the binder, and stripping were the most commonly cited mix deficiencies at the stockpile (table 8). Mix workability is affected by a number of factors including the gradation of the aggregate, the stiffness of the binder, the quantity of the binder, and premature curing. Any appreciable quantity of minus No. 200 mesh material adversely affects workability because it stiffens the binder. The minus No. 200 mesh dust in the mix should be no greater than 1 to 2 percent to ensure adequate workability.[12] Moreover, mixtures with a maximum aggregate size greater than 3/8 to 1/2 in (9.5 to 12.7 mm) are hard to handle, work, and finish.[12]

A soft binder enhances workability. However, a soft binder is undesirable with respect to stripping and drainage. Stripping can occur in the stockpile because the aggregate is not properly coated during mixing or through the washing action of rainfall and snow. Although stripping could be minimized by covering the stockpile with a tarpaulin, if the mix strips in the stockpile, it is likely that it will strip in service. In order to minimize the occurrence of stripping, aggregate-binder compatibility should be checked

Table 8. Problems and failure mechanisms in cold-mix patching materials.

Problem or Symptom of Failure	Probable Causes - Failure Mechanisms
	In Stockpile
1. Hard to work	1.1 Binder too stiff
	1.2 To many fines in aggregate, dirty aggregate
	1.3 Mix too coarse or too fine
2. Binder drains to bottom of pile	2.1 Binder too soft
	2.2 Stockpiled or mixed at too high a temperature
3. Loss of coating in stockpile	3.1 Stripping
	3.2 Inadequate coating during mixing
	3.3 Cold or wet aggregate
4. Lumps - premature hardening	4.1 Binder cures prematurely
5. Mix too stiff in cold weather	5.1 Binder too stiff for climate
	5.2 Temperature susceptibility of binder too great
	5.3 Too many fines in aggregate, dirty aggregate
	5.4 Mix too coarse or too fine
	During Placement
6. Too hard to shovel	6.1 Binder too stiff
	6.2 Too many fines, dirty aggregate
	6.3 Mix too coarse or too fine
7. Softens excessively upon heating (when used with hot box)	7.1 Binder too soft
8. Hard to compact (Appears "tender" during compaction)	8.1 Insufficient mix stability
	8.2 Too much binder
	8.3 Insufficient voids in mineral aggregate
	8.4 Poor aggregate interlock
	8.5 Binder too soft
9. Hard to compact (Appears stiff during compaction)	9.1 Binder too stiff
	9.2 Excess fines
	9.3 Improper gradation
	9.4 Harsh mix - aggregate surface texture or particle shape

Table 8. Problems and failure mechanisms in cold-mix patching materials. (continued)

Problem or Symptom of Failure	Probable Causes - Failure Mechanisms
	In Service
10. Pushing, shoving	10.1 Poor compaction
	10.2 Binder too soft
	10.3 Too much binder
	10.4 Tack material contaminates mix
	10.5 Binder highly temperature-susceptible, causing mix to soften in hot weather
	10.6 Inservice curing rate too slow
	10.7 Moisture damage--stripping
	10.8 Poor aggregate interlock
	10.9 Insufficient voids in mineral aggregate
11. Dishing	11.1 Poor compaction
	11.2 Mixture compacts under traffic
12. Raveling	12.1 Poor compaction
	12.2 Binder too soft
	12.3 Poor cohesion in mix
	12.4 Poor aggregate interlock
	12.5 Moisture damage--stripping
	12.6 Absorption of binder by aggregate
	12.7 Excessive fines, dirty aggregate
	12.8 Aggregate gradation too fine or too coarse
13. Freeze-thaw deterioration	13.1 Mix too permeable
	13.2 Poor cohesion in mix
	13.3 Moisture damage--stripping
14. Poor skid resistance	14.1 Excessive binder
	14.2 Aggregate not skid resistant
	14.3 Gradation too dense
15. Shrinkage or lack of adhesion to sides of hole	15.1 Poor adhesion
	15.2 No tack used, or mix not self-tacking
	15.3 Poor hole preparation

Note: In some instances items appear as both symptoms and causes. It is difficult to separate the symptoms from the causes in some cases.

as part of the mix design. This can be done by performing a moisture sensitivity test with the job mix aggregate and binder.[13] A much more important reason for covering the stockpile is that ice in the stockpile adversely affects the workability of the mix.

Drainage, which occurs when the binder drains from the aggregate and becomes concentrated on the bottom of the pile, can be caused by improper stockpiling temperatures, excessive binder in the mix, or the selection of a binder that is too soft. Stockpiles that are higher than 6 ft (2 m) may result in an excess of drained binder at the bottom of the pile.[12]

The curing characteristics of the binder are also very important during stockpiling. Although some "skinning" may be expected in the stockpile, it should not be so pronounced that the mix is hard to work or lumpy. Finally, the viscosity-temperature characteristics of the binder must permit the mix to be worked over the range of temperatures encountered during handling and placement.

MECHANISMS DURING TRANSPORT AND PLACEMENT

Workability of the mix is the primary concern during transport and placement. Additional considerations include compactability and drainage in hot boxes used for transporting the mix. Hot-box drainage usually occurs when the mix is heated excessively and, therefore, is a procedural rather than a mix design problem. This project is concerned with mixes that will be handled or placed with no heating or minimal heating (less than 140 °F (60 °C)). Mixes used in reclaimers or portable mixers where temperatures exceed 140 °F (60 °C) require different mix design criteria and are outside the scope of this project.[18]

Compactability and workability are related. Workability refers to the ease with which a mix can be shoveled and handled. Although a workable mix is not necessarily easy to compact, a mix with poor workability is generally difficult to compact. A workable mix can usually be compacted without difficulty unless the workability is gained by using an excessive amount of binder or a very soft binder; neither case will result in a stable repair.

Immediately after compaction, the mix must be stable and not susceptible to pushing or shoving even though there is no appreciable curing of the binder. Therefore, the stability immediately after compaction is primarily obtained through careful attention to aggregate properties.

INSERVICE MECHANISMS

The most commonly encountered inservice failures are pushing or shoving, raveling, and dishing. Other failure mechanisms may include freeze-thaw deterioration, poor skid resistance, and lack of adhesion to the side or bottom of the repair (see table 8).

Pushing and Shoving

Pushing and shoving under traffic may be caused by a number of factors, all of which reduce the stability of the mix. In order to maximize stability the aggregate should be crushed, open-graded, and contain no more than 2 percent passing the No. 200 mesh sieve.[12] Inadequately compacted mixes also are susceptible to pushing and shoving, because compaction is required to develop the aggregate interlock that is primarily responsible for mixture stability.

A soft binder may contribute to mixture instability, and, therefore, the binder should not be too soft nor should the binder soften excessively in hot weather. In order to maximize stability the binder should cure as quickly as possible once the patch is made. Stripping or emulsification of the binder as a result of the action of traffic and water can reduce mix stability and cause pushing or shoving. Bleeding, caused by inadequate voids, compaction under traffic, or excessive binder, can have the same results.

Shoving and pushing can be caused by a nonstable mix resulting from the contamination of tacking or sealing materials that have migrated into the mix. Unless the tacking material is applied in a very thin film, it will contribute to the binder content of the patch. It may soften the binder and thus result in an excess amount of soft binder. Ideally, cold mixes should be self-tacking, thus eliminating the need for tacking material and equipment and thereby precluding its misapplication.

Ideally, once the mix is placed in the hole, the binder should cure immediately, leaving a stiff binder. Open-graded mixes allegedly facilitate early curing, thereby promoting mix stability; however, the researchers' experience in exhuming two-year-old open-graded patches (PennDOT 485) made with MC binders refutes this. The binder in the patches examined after several years of service was soft and still exhibited a considerable kerosene-like odor. A cured patch that is more flexible than the existing pavement is desirable to accommodate shrinkage, reflection cracking, and frost heaving in the pavement. To this extent, cold mixes are to be preferred over conventional hot mixes.

Dishing

Dishing occurs when the mix compacts under traffic, leaving a depression in the repaired surface. Dishing is invariably the result of inadequate compaction, assuming that the mix has been properly designed and has not cured prematurely in the stockpile. Therefore, the dishing mechanism is not responsive to new and improved binders but is properly addressed through mixture design and proper compaction.

Raveling

Raveling is defined as a progressive loss of aggregate from the surface of the repair and is due to inadequate cohesion within the mix. Inadequate aggregate interlock or poor compaction may reduce cohesion sufficiently to allow raveling to occur. Perhaps the most prevalent cause of raveling is the loss of adhesion between the binder and the aggregate, although most of the factors that cause pushing and shoving may also contribute to raveling.

Absorptive aggregate, or aggregate that selectively absorbs the cutter stock from the binder, can reduce the stickiness and self-tacking character of the mix, which may lead to raveling. An excessive amount of fines (minus

No. 200 mesh) may have the same effect because the fines become incorporated into the binder, causing it to become stiffer and less tacky. Mixes with thick binder films tend to be "stickier" or more cohesive. This requires a gradation that is open (low in fines), so that there is sufficient space within the aggregate to prevent the mix from bleeding. Modification of the rheology of the binder to enhance thixotropy (shear thinning) will allow the use of mixes with thicker films.

Freeze-Thaw Resistance

Freeze-thaw deterioration has been reported as a problem by some researchers. The most commonly cited mechanism is the delamination of the patch from the original pavement as a result of the freezing of water at the bottom of the repair. The deleterious effects of freezing water in open mixes have been cited as a potential problem, but this is not well supported by field observations. Much of the freeze-thaw damage is undoubtedly due to the improper adhesion of the patch to the bottom of the hole, which in turn may be the result of improper compaction, tacking, or hole preparation.

Skid Resistance

Poor skid resistance can result from a flushed or bleeding surface or from polished aggregate. Nonpolishing aggregates that retain adequate microtexture during service should be employed where high levels of skid resistance are needed. The 3/8- to 1/2-in (9.5 to 12.7 mm) maximum aggregate size and the open gradation specified for cold stockpiled patching mixtures should ensure adequate macrotexture. Macrotexture may deteriorate in service because of flushing or bleeding, which can be caused by excess asphalt, inadequate voids, or stripping. These factors can be controlled with an appropriate mix design. Stripping and the subsequent movement of the binder to the surface of the mix have been observed by the authors. This occurrence is facilitated by a relatively soft, uncured binder.

SUMMARY

In summary, the binder, the aggregate, and the binder-aggregate interactions (moisture damage) must be considered as factors in the failure of cold-mix patching materials. Little latitude is available in the gradation of the aggregate: a crushed, angular aggregate ranging in size from No. 8 to 1/2 in (12.7 mm) is the optimum size aggregate to maximize stability and workability and yet obtain sufficient voids to hold thick binder films without bleeding. Improved binders offer the best opportunity for upgrading cold-mix performance. The binder must be resistant to moisture damage in the stockpile; in service it must be workable during transport and placement; and it must produce stability after placement.

A summary of the design considerations required with cold mixes is given in table 9. In addition, worker safety, environmental implications, and cost must be considered. This discussion has been predicated on conventional cold-mix design. Other approaches may be viable, such as filling the hole by successive applications of aggregate and binder, much as in a multiple seal coat or a voidless mix that is poured into the hole. These nonconventional approaches require other design considerations that are material- or system-specific. Such approaches were outside the scope of this study.

PERFORMANCE REQUIREMENTS

In order to develop improved patching materials for use in cold, wet weather, a series of performance requirements is needed that can be used as a developmental guideline. These performance requirements should reflect the underlying mechanisms that are responsible for premature failure. A summary of the desired performance requirements is given in table 10. Suggested laboratory procedures to ensure these qualities are discussed below. Details of the laboratory procedures used in the project are given in chapters 4 and 5, where acceptance criteria are also discussed.

Drainage resistance is necessary in the stockpile and during transport in a heated box. This requirement can be tested simply by placing a quantity of the mixture on a plate and observing the amount of binder that drains to the

Table 9. Design considerations for cold mixes.

Design Considerations	Effect on Mixture
1. Binder consistency (before and during placement)	1.1 Too stiff may give poor coating during mixing 1.2 Too stiff makes mix hard to shovel, compact 1.3 Too soft causes drainage in stockpile or hot box 1.4 Too soft may cause stripping in stockpile 1.5 Too soft may contribute to "tenderness" during compaction
2. Binder consistency (after placement)	2.1 Too soft accelerates stripping, moisture damage inservice 2.2 Too soft accentuates rutting, shoving 2.3 Too soft may lead to bleeding, which causes poor skid resistance 2.4 Must cure rapidly to develop cohesion 2.5 High temperature susceptibility causes softening and rutting in summer
3. Binder content	3.1 Maximize to improve workability 3.2 Excess causes drainage in stockpile or hot box 3.3 Excess may lower skid resistance (bleeding) 3.4 Excess may cause shoving and rutting 3.5 Low binder content gives poor cohesion
4. Antistripping additive	4.1 Correct type and quantity may reduce moisture damage
5. Aggregate shape and texture	5.1 Angular and rough aggregate gives good resistance to rutting and shoving but is hard to work 5.2 Rounded and smooth gives good workability but poor resistance to rutting and shoving
6. Aggregate gradation	6.1 Reduced fines improves workability 6.2 Excess fines can reduce "stickiness" of mix 6.3 Coarse (>1/2 in) mixes are hard to shovel 6.4 Open-graded mixes can cure rapidly but allow water ingress 6.5 Well-graded mixes are more stable 6.6 Dirty aggregate may increase moisture damage 6.7 Too dense a gradation will lead to bleeding or thin binder coating, and a dry mixture with poor durability 6.8 Open or permeable mix may be poor in freeze-thaw resistance
7. Other additives	7.1 Short fibers increase cohesion, decrease workability

Table 10. Performance requirements of patching materials.

1. Drainage Resistance
2. Workability
3. Stripping Resistance (uncured)
4. Self-Tacking
5. Complete Curing (at the proper time)
6. Stability
7. Bleeding Resistance
8. Nonraveling
9. Freeze-Thaw Resistance
10. Safe for Workers
11. Environmentally Acceptable
12. Skid Resistance

surface of the plate. A hot-box can be simulated by placing the plate in an oven heated to 140 °F (60 °C). The length of time for evaluating hot-box drainage should be equivalent to the storage time, typically no more than 8 hours.

Workability is required during handling operations at the stockpile and during placement. The mix must be workable over its design temperature range, and therefore the test procedure should be conducted at the working temperatures. Workability has been simulated by others by cooling the mix to the appropriate temperature and working a small quantity with a hand spatula.[12] This test is fairly unsophisticated but quite discerning to the trained observer. A more sophisticated test based on penetration resistance may be warranted. A new test procedure based upon the pocket penetrometer was developed for use in the project.

The stripping resistance of the uncured mix was evaluated with a heated immersion test used by PennDOT.[12] Although it may be argued that an immersion or boiling test is unsophisticated, the scope of this project did not provide for the development of new test procedures for stripping resistance. Moreover, it is important that a relatively simple test procedure be adopted so that it can be readily performed in the field.

The tacking characteristics of the mix were evaluated by placing a pavement core on the bottom of a compaction mold and compacting the cold mix on top of the core. The mix was then sheared from the face of the core, and the maximum force required to cause failure was recorded. A moisture-conditioning step was also included in the test procedure.

It is important that the mix cure after it has been placed in the hole but that it not become skinned-over in the stockpile. Skinning was evaluated by placing a thin layer (approximately 2 in (50 mm) thick) of the mix in a pan in an oven and observing subjectively the stiffness of the cured mix.

One of the key performance characteristics is the stability of the compacted material. No accepted test procedure exists for the evaluation of the stability of cold mixes. The Marshall design procedure was developed for dense-graded hot mixes and is inappropriate for open-graded, cold-mix stockpiled mixtures. Limited use was made of the Hveem stabilometer to measure mix stability. Resistance to shoving was measured with a modified penetration test in which the cold mix was compacted in a 6-in-diameter (150 mm) mold, and a 1/2-in (13 mm) loading foot was applied to the surface of the compacted mix in a repeated mode.

Stability is also enhanced by proper attention to aggregate gradation and aggregate properties. Aggregate gradation plays an important role in many of the performance requirements for cold mixes and was given particular attention during the developmental stages of this project.

The proper amount of binder in the mix was established by the maximum amount that the aggregate can hold without any measurable drainage. Once the mix is compacted in the hole, there should be sufficient voids within the mineral aggregate to hold this quantity of binder, with at least 5 to 8 percent air voids to ensure resistance to bleeding. No direct test for bleeding resistance was conducted other than a simple voids analysis.

One of the most commonly cited performance requirements is the resistance to raveling. Raveling is caused by such different factors as poor compaction, lack of moisture resistance, and improper binder characteristics. If the other performance requirements discussed in this section and listed in table 10 are met, the researchers believe that the mixture will contain sufficient resistance to raveling. Therefore, no direct test procedure for raveling was conducted.

The lack of freeze-thaw resistance has been cited by some researchers as contributing to premature failure. There is no standard freeze-thaw test for dense, bituminous hot mixes because they are not susceptible to freeze-thaw damage. However, freeze-thaw resistance was evaluated by the repeated freezing and thawing of saturated, compacted mixes. A 2 1/2-in-thick (64 mm) specimen was compacted in a 6-in-diameter (150 mm) mold. The specimen was saturated and repeatedly frozen and thawed. If the freeze-thaw mechanism is indeed valid, the openness of the cold mixes should cause expansive forces in the mix, resulting in an observable loss of material from the sample surface.

Several other considerations must be addressed in the development of new mixes. First, worker safety is of paramount importance. The binder materials and solvents must not create a fire hazard nor be toxic as defined by safety and environmental control agencies such as OSHA and EPA. This requirement precluded the use of such materials as asbestos fibers, sulfur, and other organic additives. The patching material must also not release any toxic chemicals to the environment that can cause roadside pollution or other environmental degradation. In most States, cutbacks are permitted in winter maintenance work; however, their use is restricted in some States.

Satisfying the above requirements necessitates a trade-off among many different factors. For example, the open gradation that facilitates workability also causes the mix to be permeable. A binder that improves workability may lower mix stability. The design of cold patching mixes is a continuing compromise among the desired engineering properties.

4. BINDER SELECTION

The primary objective of this study was to select and test new or improved binders that can be used for cold, wet weather patching. In accordance with the requirements of the contract, the binders were developed using only current, readily available technologies. It was further required that the cost of these binders be compatible with the cost of the conventional emulsions or cutbacks.

The selection of the candidate binders was based upon a review of the literature, the experience of the research team, and a series of small trial batches of binder manufactured in the subcontractor's laboratory in Tulsa, Oklahoma. Approximately 40 binders were initially screened in the laboratory, using small beaker-scale batches. These binders were evaluated subjectively for their workability and drainage. They were then compared for potential cost, ease of production and handling, and availability. Based on the initial screening, 11 different binder systems were recommended for detailed laboratory study and were identified as candidate binders.

A detailed laboratory test program was conducted with the 11 binder systems and, based on this testing, 4 binder systems plus 1 system modified with fibers were selected for field study. This chapter summarizes the materials that were considered in the initial screening process and describes the results of the detailed laboratory studies on the 11 binders that were selected as candidate binders.

CONVENTIONAL MATERIALS

Most cold, wet weather, stockpiled patching materials are produced with cutback asphalt cement. The grade of the cutback varies according to the climate and the season.[20] Typically, MC-250 is used for winter patching although intermediate grades, such as the MC-400 used in Pennsylvania, are sometimes specified. The diluent or solvent used to make the MC-400 or MC-800 cutback is typically gas oil or kerosene, which is supposed to evaporate after placement. However, much of the solvent remains in the patch for a relatively long period of time, thereby imparting a certain degree of flexibility to the patch. Depending upon the source of the aggregate, it may be necessary to add an antistrip additive to the cutback to promote adhesion in the presence of water. These antistrip additives are useful in promoting adhesion in the stockpile as well as during service. Other than the selection of the appropriate antistrip additive, little additional formulation is done with the cutback asphalts used for cold, wet weather, patching materials.

The primary advantages of the cutback asphalts are their relative simplicity of use and low cost. Without any additional modification, little can be done to improve the workability of these mixtures or to improve their resistance to deformation under traffic. The main disadvantage of cutback-based stockpiled materials is their potential for air pollution because of the release of solvent.

Emulsions are sometimes used as alternatives to cutback asphalt cement. To obtain the necessary workability in the stockpile, mixing-grade emulsions are generally used. These emulsions are often made with cutback asphalt; however, the percentage of solvent is considerably reduced, typically two-thirds of the solvent required for an MC cutback. As with cutback asphalt cement, it is necessary to formulate the emulsion so that it will have adequate adhesion in the stockpile and during service. Although asphalt emulsions are slightly more expensive than the cutback asphalts, they offer the advantage of reduced air pollution.

Asphalt emulsions may be modified with the use of surfactants to produce high-float emulsions (ASTM D 977). High-float emulsions exhibit thixotropic or shear-thinning characteristics that allow the retention of much thicker films of residual asphalt on the aggregate. This shear-thinning effect is also an aid in workability because the asphalt becomes more fluid as it is worked. Thus, the asphalt will appear to be relatively stiff while it is in the stockpile, but with working, the asphalt will shear thin, yielding an improvement in workability. After placement, the thixotropy allows the retention of a thicker film on the aggregate without drainage. Although high-float emulsions have been used for cold, wet weather patching, their use has been rather limited. Because they offer promise for cold, wet weather, stockpiled patching mixtures, they were ultimately included in the field trials.

MODIFIED BINDERS

In recent years considerable attention has been given to the use of modified asphalt in hot-mix asphalt and in seal coats. Relatively little attention has been given to the modification of cold-mix, stockpiled patching mixtures because these mixtures are generally considered low-cost, low technology applications. However, asphalt modifiers offer opportunities for enhancing the performance of pothole repair mixes.

Plastics

Plastics are organic polymers that are rigid at room temperatures. They generally impart stiffness and decreased flexibility when added to asphalt cement. Although plastics may be manufactured in a variety of different ways, they can be summarized briefly with respect to their properties as follows.

Epoxy-based materials are two-component systems with excellent tensile strength but very little ductility. They are difficult to melt into the asphalt. Consequently, they are poor candidates as modifiers for cold, wet-weather, patching materials. Although polyesters are easily melted into asphalt cement, they have the same shortcomings as the epoxies.

Urethanes, which are multicomponent systems, do not readily formulate in asphalt, and they are very sensitive to the oily phase in the asphalt cement. Therefore, their compatibility with asphalt cement depends upon the source and composition of the asphalt. Urethane materials are discussed further, below, with liquid butadiene.

Atactic polyethylene/polypropylenes are rigid plastics that are used in roofing asphalts and hot-mix asphalt systems. These materials improve the long-term durability of asphalt cement but offer little improvement in low-temperature ductility. The equipment needed to shear and mix these polymers into asphalt cement is very expensive, and, to the knowledge of the research team, the polymer base has not been successfully emulsified. Therefore, the use of these materials was not considered.

Ethylene vinyl acetate (EVA) is easily mixed with asphalt cement and is easily emulsified. This class of polymers is currently being evaluated by industry for use in seal coat emulsions and hot-mix asphalt concrete, but it does not impart significantly improved low-temperature ductility or workability. Therefore, the EVA polymers are not beneficial modifiers for cold-mix, stockpiled mixtures.

A great many other plastics are potential candidates, including silicones or thio (sulfur) systems. These are generally very expensive and require special process and handling equipment and formulating expertise. As noted above, plastics generally impart stiffness or decreased flexibility when added to asphalt cement. This characteristic is undesirable. Because the plastics do not, as a group, show promise as modifiers for cold, wet weather, stockpiled patching mixtures, they were not included in the list of candidate binders for this study.

Elastomers

This group of polymers is currently receiving the most attention in the asphalt industry as asphalt modifiers. It includes a great number of materials and offers rather diverse enhancements to asphalt cement. Elastomers are organic polymers that can withstand large degrees of elongation without rupture and, when unloaded, return to their original shape. The rubber in an elastic band and natural rubber are examples of elastomers.

Neoprene. Neoprene rubber is an elastomer that has excellent weatherability and adheres tenaciously to aggregate, but its compatibility with asphalt cement is sensitive to the crude source. Neoprene is very hard to disperse in asphalt because of its high resistance to solution by oils. Neoprene rubber is often used in the shoe industry for heels and soles because of its oil resistance.

Neoprene may be produced as a latex in a post-blended or co-milled form. The water can be flushed off to make a polymer base for hot-mix applications, or the emulsified latex can be added directly to the asphalt during emulsification. Neoprene latex emulsions are generally produced in the anionic form, but in this form they suffer from the same compatibility and solubility problems as neoprene. Only one cationic/nonionic is marketed in the United States at this time. The results of the initial screening and the previous experience of the researchers showed that the anionic neoprene latex would have drainage problems and would exhibit poor low-temperature workability. As a consequence, neoprenes were not included in the list of candidate binders.

Polyolefins. The polyolefins are a loosely defined group of polymers without styrene, which generally exhibit rubbery characteristics. Polyolefins may be produced as solids, in a liquid form, or as a latex.

In the solid form, polyolefins are usually delivered as bales, as crumb, or as ground rubber. They generally have a very high molecular weight and are made by solution polymerization.

1. Ethylene polypropylene diene monomer (EPDM) is very popular in roofing applications because of its resistance to weathering. It is used in specialty compounds, requires special handling techniques and equipment, and is very expensive. Therefore, it is not appropriate for cold, wet-weather, patching mixtures.

2. Styrene ethylene butylene styrene (SEBS) is being manufactured in only one form in the United States at the present time. It exhibits very good resistance to weathering but requires special handling equipment and, therefore, was not included as a candidate binder.

3. Butyl/isoprene polymers are usually solids and are used in adhesives. However, they need special handling equipment and were, therefore, eliminated as candidate binders.

4. Butadiene is compatible with asphalt but provides little enhancement in properties. It also requires special handling equipment and, therefore, was eliminated as a candidate binder.

Liquid polyolefins are usually lower in molecular weight than their solid counterparts. When heated, these materials pour readily and are easily mixed or dissolved with asphalt cement.

1. Butyl rubber is particularly noted for its adhesion-promoting characteristics. It is commonly used and was chosen as one of the modifiers for that reason. There are two sources of butyl rubber in the United States. Kalene 800 was chosen because it has the higher molecular weight and was the most promising in the initial screening tests.

2. Butadiene is another liquid polyolefin polymer that has considerable promise as an asphalt modifier. A hydroxy-terminated liquid butadiene is available that could be used as a viscosity enhancer through urethane linkages. Although the initial screening showed some potential in this regard, the results were not as promising as with the liquid butyl rubber and, therefore, it was not used. Other liquid butadienes are currently available but were not available when the initial survey tests were conducted (1984).

3. A third option within the liquid polyolefins is isoprene. From prior experience, it is known that this polymer is not a good emulsion viscosity builder and, therefore, it was dropped in favor of the liquid butyl rubber.

The polyolefins can also be manufactured in latex form, but they have not been used in this form as asphalt modifiers. Because considerable development work would be required, they were dropped from the list of candidate binders.

Natural Rubber. Natural rubber has been used for many years in asphalt cement. It exhibits poor storage stability when used in emulsions and has poor heat stability. Most of the natural latex is imported into the United States. Natural latex may be supplied in a solid, liquid, or latex form. The latex form is most commonly used in asphalt cement. Because other polymers offer greater enhancement potential than the natural rubbers, the natural rubbers were dropped from the list of candidate materials.

Reclaimed Tire Rubber. Reclaimed tires, when used in asphalt paving binders, are generally ground and added to hot asphalt. Extremely hot temperatures are required to depolymerize the rubber and to dissolve it into the asphalt cement. The use of these materials was beyond the scope of the project.

Styrene-Butadiene Polymers. These polymers are the ones used most frequently in asphalt systems. Their compatibility with asphalt may vary from poor to excellent depending on specific type, molecular weight, polymerization mechanism, and other factors. They may be supplied in solid, latex, or liquid form. The dry form is made by polymerizing styrene and butadiene. The solution styrene-butadiene polymers are made by polymerizing styrene and butadiene in a solvent. The solvent is then removed by evaporation. These polymers may be randomly polymerized with no attempt to structure the polymer. For this reason, the polymer obtains a high molecular weight. Consequently, the resulting polymers are difficult to dissolve in asphalt cement and are very sensitive to asphalt source.

Block polymerization results in highly structured polymers. These materials have received considerable attention as asphalt modifiers because of their relatively low price and excellent performance potential. At the time of the initial screening (1984), SBR latex was the most commonly used asphalt modifier and this is still true. There are several sources of SBR latex. The latex is added to the hot asphalt cement and, with gentle stirring, the water is flushed off. This is in contrast to the block copolymer (SBS), for which special equipment is required.

The SBR latex imparts low-temperature ductility, reduces temperature susceptibility, and improves tackiness and adhesion. For these reasons, and because of its lower cost, it was included in the study.

SELECTION OF CANDIDATE BINDERS

On the basis of the initial screening tests and the literature review, the following systems and modifiers were identified as candidate systems that warranted further laboratory study:

- MC-800, wich is typical of current practice and therefore used as a control.
- Mixing grade MS emulsions, which also is typical of current practice and therefore used as a control.
- HFMS emulsions, which, because of their thixotropic nature, allow potentially thicker asphalt films and an extended workability range.

Modifiers that were selected for further study included:

- SBR latex, which is the most commonly used polymeric modifier of asphalt cement. It also reduces the stiffness of asphalt cement and has the potential for improving low-temperature workability.
- Liquid butyl rubber, which has many of the same attributes as the SBR latex, but is noted especially for its adhesion-promoting properties.
- SBS block copolymer, which is the most costly of the candidate modifiers, but also potentially offers the greatest improvements in properties. At the time the binders were selected, the SBS block copolymer was difficult to disperse in asphalt cement.

Each of the base systems and modifiers that were chosen for study represents existing technology and will not require extensive development to implement. No special handling equipment or environmental or safety precautions are needed to use them in the field. The preliminary list of candidate binders is given in table 11.

Table 11. Preliminary list of candidate binders.

Additive	Basic System	Designation
Styrene Butadiene Rubber (SBR) Latex	CMS, Cationic Medium-Set Emulsion	CMS-2L
	HFMS, High-Float Medium-Set Emulsion	HFMS-2L
	MC-400, Medium-Cure Cutback	MC-400L
Butyl Rubber	CMS, Cationic Medium-Set Emulsion	CMS-2B
	HFMS, High-Float Medium-Set Emulsion	HFMS-2B
	MC-400, Medium-Cure Cutback	MC-400B
Block Copolymer	CMS, Cationic Medium-Set Emulsion	CMS-2BC
	HFMS, High-Float Medium-Set Emulsion	HFMS-2BC
	MC-800, Medium-Cure Cutback	MC-800BC

TEST PROCEDURES

The next step in the selection process was to evaluate the candidate binders by mixing them with three lithologically different aggregates: crushed limestone, traprock, and gravel. The limestone was obtained from central Pennsylvania, while the traprock and gravel were collected from the eastern and western parts of Pennsylvania, respectively. A brief description of these aggregates is given in table 12. The gradation used to produce the experimental mixes, along with the PennDOT 485 specification for cold, wet weather, stockpiled patching materials, is shown in table 13.[13] The same gradation was used in the laboratory studies and for the field mixes.

The preliminary evaluation of the candidate binders was done by the subcontractor and consisted of an evaluation of coating during mixing, potential for stripping, drainage, and workability. The subcontractor has developed a simple test to evaluate the coatability of cold-mixed emulsion mixtures. This test, which is routinely used in their laboratory, was applied to the candidate mixes. This test is used to determine the percentage of the aggregate that is coated after 5 minutes of hand mixing and was used to evaluate the coatability characteristics of each binder. In this procedure, approximately 200 g of aggregate is placed in a glass beaker, the emulsion or cutback is added to the aggregate, and the mixture is stirred for 5 minutes. After 5 minutes of mixing, the contents of the beaker are poured onto a paper towel, and the percentage of aggregate that is coated is evaluated visually. The test is conducted with two different aggregate moisture contents: oven-dried and 3 percent moisture by weight of dry aggregate. In order to pass this test, at least 90 percent of the aggregate must be coated at the end of the test.

The standard PennDOT water resistance test was used to evaluate stripping.[13] This test, which is designed especially for cold-mix, stockpiled patching mixtures, consists of submersing 100 g of the prepared patching mixture in distilled water in a 1-quart (1 L) jar and placing it in the oven for 16 to 18 hours at a temperature of 140 °F ± 5 °F (60 °C ± 3 °C). After the submersion period, the mixture is shaken vigorously in the jar, the water is poured off, and the mixture is spread on absorbent paper. Then the

Table 12. Aggregates used in laboratory mixes.

Generic Name	Rock Type	Specific Gravity	Absorption (%)
Limestone	Dolomite	2.82	0.49
Traprock	Argillite	2.67	1.25
Gravel	Complex glacial deposit, reworked by river	2.58	1.93

Table 13. Aggregate gradation used in experimental mixes.

Sieve Size	PennDOT 485 Spec. limits (% Passing)	Penn State Mix Design (% Passing)
3/8 in (9.5 mm)	100	100
No. 4	40-100	85
No. 8	10-45	15
No. 200	0-2	1.0

Note: When fibers were incorporated in the mix, it was done at the rate of 0.125% of total mix (by weight).

mix is evaluated visually to determine the percentage of the aggregate that remains coated. The mix is rejected if less than 90 percent of the aggregate retains its coating.

The drainage test used in this study is a simple modification of the test procedure that was originally used for open-graded friction courses.[24] In this test procedure, 1000 g of prepared mix is placed on a glass plate; the plate is then placed in a 140 °F ± 5 °F (60 °C ± 3 °C) oven for 24 hours. At the end of the 24-hour period, the plate is removed from the oven, and the binder residue remaining on the plate is weighed. The drainage is reported in grams of residual asphalt remaining on the plate after the curing period in the oven. There is no accepted criterion for this nonstandard test procedure. The researchers found that the drainage was excessive when the residue on the pan exceeded 5 to 6 percent of the weight of the binder in the sample. Therefore, 4 percent was established as a maximum limit for drainage. During the initial screening of the candidate binders, a smaller 200-g sample was used because of the limited amount of material that was available. In the later testing a full 1000-g sample was used. A 10-in (250 mm) disposable aluminum pie plate was used instead of a glass plate.

The standard PennDOT workability test was used to measure the workability of the candidate mixtures.[13] In this test procedure, approximately 5 lb (2.3 kg) of mix is placed on a tray and cooled in a freezer at 20 °F (-7 °C). After the mix has cooled, it is worked with a spatula and the workability is rated subjectively. A subjective rating of strong pass, pass, marginal pass, marginal fail, or fail was assigned to each mix according to the ease with which it could be worked with a spatula.

PRELIMINARY TEST RESULTS

The initial testing of the candidate binders was done using dolomite as the aggregate because dolomite would be used for the field trials. The results of the testing for the emulsion and cutback type binders are shown in tables 14 and 15. Except for the MC-800BC cutback mixed with wet aggregate, all of the cutback systems showed acceptable coating after mixing. When a commercial antistripping agent was added to the MC-800BC, the percentage coated after mixing increased from 30 percent to 100 percent. In all

Table 14. Initial design mixtures, 6.4 percent emulsion, limestone aggregate.

Emulsion Type	Polymer Type	Residual Asphalt (%)	Aggregate Moisture (%)	% Aggregate Coated after 5 min. Mixing	% Aggregate Coated after Immersion[1]	Drainage[2] (%)	Workability
CMS-2L	SBR Latex	4.4	0	97	97	0.9	Strong Pass
			3	85[3]	85	1.7	Marginal Fail
CMS-2B	Butyl	4.4	0	100	90	0.9	Pass
			3	85	80	1.5	Marginal Fail
CMS-2BC	Block Copolymer	4.5	0	100	85	3.0	Pass
			3	85	80	4.2	Pass
HFMS-2L	SBR Latex	4.6	0	97	97	1.3	Strong Pass
			3	97	97	0.2	Pass
HFMS-2B	Butyl	4.5	0	100	99	2.0	Marginal Pass
			3	95	95	3.1	Marginal Pass
HFMS-2BC	Block Copolymer	4.5	0	100	95	1.7	Marginal Fail
		4.5	3	100	95	10.1	Marginal Fail

[1] The mix is said to "pass" if the aggregate is at least 90% coated with a bituminous film.
[2] Reported as percentage of residual asphalt in the sample. Drainage greater than 4.0% is not acceptable.
[3] Underscored values indicate that the mix did not pass the acceptability criterion.

Table 15. Initial design mixtures, 6.1 percent cutback, limestone aggregate.

Cutback Type	Polymer Type	Residual Asphalt (%)	Aggregate Moisture (%)	% Aggregate Coated after 5 min. Mixing[1]	% Aggregate Coated after Immersion Test[1]	Drainage[2] (g)	Workability
MC-400	None	5.0	0	100	75[3]	2.5	Strong Pass
			3	90	10	4.5	Marginal Pass
MC-400 with BA-2000	None	5.0	0	100	98	2.3	Pass
			3	95	15	1.9	Marginal Pass
MC-400L	SBR Latex	4.5	0	100	65	5.6	Strong Pass
			3	95	0	5.2	Marginal Pass
MC-400B	Butyl	4.5	0	100	70	5.1	Strong Pass
			3	90	15	6.0	Fail
MC-800BC	Block Copolymer	4.5	0	100	30 (100)[4]	3.0	Pass
		4.5	3	30	15	1.6	Pass

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[1] The mix is said to "pass" if the aggregate is at least 90% coated with a bituminous film.

[2] Reported as percentage of residual asphalt in the sample. Drainage greater than 4.0% is not acceptable.

[3] Underscored values indicate that the mix did not pass the acceptability criterion.

[4] 100 percent after addition of antistripping additive.

fairness, the cutbacks should not be mixed with wet aggregate, and the water resistance test results on the cutback mixes made with 3 percent aggregate moisture should not be used as a basis for rejecting the cutback binders.

The coating and water resistance tests were conducted with both dry aggregate and aggregate containing 3.0 percent moisture. Ideally, cold-mix, stockpiled patching mixtures should be made with dry aggregate, and the results with the dry aggregate were used for selecting the binders for the field trals. The moist aggregate was used to simulate the effect of aggregate that has not been properly dried, which may occur in practice.

Each of the emulsion and cutback mixes passed the coating test when dry aggregate was used. The wet aggregate slightly reduced the percentage of coated aggregate particles for both the emulsion mixes and the cutback mixes except for the block copolymer modified cutback, where there was a very large reduction in the coating after mixing.

For the emulsion mixtures the severity of the coating and immersion tests was approximately the same. For the cutback mixes, the water resistance test was consistently more severe than the coating test. Although the results for some of the emulsion-based binder systems showed less than 90 percent coating of particles, the data did not show any trends according to modifier type. The moisture tests with the modified cutbacks also showed some systems with less than 90 percent coating, but, except for the the MC-800BC cutback, the results were not unexpected since no antistripping additive was used. When a commercial additive was added to the MC-800BC emulsion, the water resistance test results increased from 30 percent to 100 percent. Therefore, all of the binder systems were considered promising with respect to resistance to moisture damage.

There are no accepted standards for judging the drainage test results. None of the emulsions were judged as having drained excessively except for the HFMS-2BC binder mixed with 3.0 percent moisture. The drainage data for the emulsion mixes show that the presence of moisture in the aggregate appears to increase binder drainage, although the increases were slight in all cases except for the HFMS-2BC binder (table 14). No explanation can be given for this trend; however, it should be pointed out to field personnel and may warrant closer control of aggregate moisture in the field.

The drainage experienced with the latex- and butyl-modified MC-400 was judged to be marginal. The drainage for the unmodified MC-400 was 2.5 percent, whereas the drainage for the latex- and butyl-modified MC-400 was 5.6 percent and 5.1 percent, respectively (table 15). For this reason, MC-800 was chosen for use with the modifiers. The block copolymer was therefore added to MC-800; the drainage for this system was 3.0 percent versus 5.6 percent and 5.1 percent, respectively, for the latex- and butyl-modified binders (table 15). In the later testing, the MC-400L and MC-400B were replaced by MC-800L and MC-800B.

The workability of all the mixes was acceptable when the mixing moisture was 0.0 percent. The reduced workability that was obtained when 3.0 percent water was added to the aggregate was due to the freezing of the water. The workability tests on the mixes that were made with the wet aggregate illustrate the problem that may occur if there is excessive moisture in the mix.

The initial screening tests of the candidate binders were extended to the glacial sand and gravel and traprock mixes; the results for these mixes are shown in tables 16 and 17, respectively. As was expected, poor moisture resistance was evident with the glacial sand and gravel. Stripping was particularly evident with the latex-modified binders. The butyl modification improved the resistance to stripping in several cases. Antistripping additives would be necessary for mixes made with the silicious aggregates. The selection of the appropriate additive depends upon the job-mix aggregate. Antistripping additives were not used, however, because the silicious aggregate mixtures were not used in the field studies. Stripping resistance was generally good for the traprock mixes.

The drainage that occurred with the gravel mixes was much greater than with the limestone or traprock mixtures. No consistent pattern is demonstrated in the drainage results by aggregate type or binder type. The absorptivity for the gravel was the largest (1.93 percent) followed by 1.25 and 0.49 percent for the traprock and limestone, respectively. The largest

Table 16. Initial design mixtures, 6.4 percent emulsion, glacial sand and gravel aggregate.

Binder Type	Polymer Type	Residual Asphalt (%)	Aggregate Moisture (%)	% Aggregate Coated after 5 min. Mixing	% Aggregate Coated after Strip Test[1]	Drainage[2] (%)	Workability
CMS-2L	SBR Latex	4.4	0	100	100	2.8	Marginal Pass
			3	100	100	3.5	Marginal Pass
CMS-2B	Butyl	4.4	0	100	100	2.6	Marginal Fail[3]
			3	100	90	19.4	Marginal Fail
CMS-2BC	Block Copolymer	4.5	0	100	85	3.1	Pass
			3	95	95	10.1	Pass
HFMS-2L	SBR Latex	4.6	0	70	15	6.6	Marginal Fail
			3	30	10	1.5	Fail
HFMS-2B	Butyl	4.5	0	100	40	5.7	Pass
			3	100	40		
HFMS-2BC	Block Copolymer	4.5	0	100	30	7.1	Marginal Fail
			3	25	25	9.8	Fail
MC-400L	Latex	4.7	0	100	5	--[4]	
			3	60	5	--	
MC-400B	Butyl	4.7	0	100	10	--	Pass
			3	95	5	1.7	Marginal Fail
MC-800BC	Block Copolymer	4.5	0	100	25	5.9	Pass
			3	50	5	1.8	Pass

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[1] The mix is said to "pass" if the aggregate is at least 90% coated with a bituminous film.
[2] Reported as percentage of residual asphalt in the sample. Drainage greater than 4.0% is not acceptable.
[3] Underscored values indicate that the mix did not pass the acceptability criterion.
[4] Insufficient material to complete testing.

Table 17. Initial design mixtures, 6.4 percent emulsion, traprock aggregate.

Binder Type	Polymer Type	Residual Asphalt (%)	Aggregate Moisture (%)	% Aggregate Coated after 5 min. Mixing	% Aggregate Coated after Strip Test[1]	Drainage[2] (%)	Workability
CMS-2L	SBR Latex	4.4	0	80[3]	80	0.0	Marginal Pass
			3	80	80	0.0	Marginal Pass
CMS-2B	Butyl	4.4	0	100	95	0.0	Pass
			3	100	95	0.0	Pass
HFMS-2L	SBR Latex	4.6	0	90	90	0.0	Pass
			3	95	90	0.0	Marginal Pass
HFMS-2B	Butyl	4.5	0	95	95	0.0	Pass
			3	95	90	0.0	Pass
MC-400L	Latex	4.7	0	90	95	--[4]	Pass
			3	100	95	--	Pass
MC-400B	Butyl	4.7	0	90	90	0.0	Pass
			3	100	90	0.0	Pass

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[1] The mix is said to "pass" if the aggregate is at least 90% coated with a bituminous film.
[2] Reported as percentage of residual asphalt in the sample. Drainage greater than 4.0% is not acceptable.
[3] Underscored values indicate that the mix did not pass the acceptability criterion.
[4] Insufficient material to complete testing.

amount of drainage occurred with the gravel mixtures and the least amount with the traprock mixes. The same binder content and gradation was used for each mix. Optimizing the binder content through a mix design, as outlined in the next chapter, might have reduced the drainage with the gravel mixes to an acceptable level.

In general, the workability for the glacial sand and gravel mixes was not as good as for the dolomite mixes (tables 14 through 16). This difference may be explained in part by differences in the shape and surface texture of the aggregates. Overall, the test results for the traprock aggregate were very favorable (table 17). Each of the mixes passed the workability test, showed very little drainage, and was well coated after mixing and after the stripping test. Except for the drainage that occurred with the gravel mixes, the test results indicated that further study of each of the binders was warranted.

COST OF MIXES MADE WITH MODIFIED BINDERS

None of the modified binders or the mixes made with the modified binders require any special handling. The increased cost of producing and placing these binders is primarily due to the cost of adding the modifier or the fibers. A summary of the costs for the various systems is shown in table 18. These costs are based upon the present cost of an MC-800-based PennDOT 485 mix. This locally produced mix is made in a hot-mix asphalt plant using dry aggregates that conform to the gradation specifications given in tables 5 through 7. As shown in table 18, the cost of the high-float emulsion is approximately the same as that of the MC-800 cutback. A surcharge of approximately $10 per ton ($11 per Mg) is required for the latex-modified binder, and approximately $12 per ton ($13 per Mg) for the butyl-modified binder. When fibers are added to the mix, the surcharge is approximately $5 per ton ($5.50 per Mg). A full discussion of the effect of material costs on the life-cycle cost of pothole repairs is given in chapter 8.

Table 18. Estimated cost of mixes made with modified binders.

Unmodified Binder	Modification	Surcharge/Gal[1] ($)	Cost/Ton for Mix ($)[2]
MC-800	None	None	30 (PennDOT 485)
MC-800	Fibers	None	35 (PennDOT 486)[3]
MC-800	Latex	0.78	40.22
HFMS-2	None	0.03	30.39
HFMS-2	Butyl	0.86	41.66
HFMS-2	Butyl + fibers	0.86	46.66
HFMS-2	Latex	0.78	40.61

[1] Due to addition of polymer.
[2] Based on 5.5% (residue) of binder by weight of mix.
[3] PennDOT 486 includes 5 lb of fibers/ton (2.5 kg/Mg) of mix.
1 ton = .9 Mg; 1 gal = 4.4×10^{-3} m^3

5. DETAILED LABORATORY EVALUATION OF CANDIDATE MIXES

The nine binders listed earlier in table 11 were chosen as the candidate binders and were tested as described in chapter 4. After further review of current processing technology, it was decided to drop the block-copolymer modifier because specialized equipment was required at that time for its manufacture. Because the SBR latex-modified cutback, MC-400B, showed excessive drainage, an MC-800B system was added to the list of binders. The modified list of candidate binders is given in table 19.

Because fibers had been identified in the literature survey as a promising addition to cold, wet-weather, patching mixtures they were used with the high-float, medium-set emulsion modified with butyl rubber. On the basis of the test results and its overall handling characteristics, this binder was considered the most promising of the various candidate binders and, therefore, was selected for use with the fibers. It was judged that, by combining the most promising binder with the fibers, an optimal binder system would be produced.

The testing of the candidate binders proceeded in two phases. In the first phase, mix design, testing was conducted for drainage, water sensitivity, and workability. The final list of binders for the field trials was selected on the basis of these three criteria. These binders were then subjected to the second phase of testing which included stability under load, freeze-thaw, and tacking.

MIXTURE-DESIGN CONSIDERATIONS

There are no accepted design procedures for cold-mix, stockpiled patch mixtures. Although PennDOT has a specification for cutback and emulsified cold-mix, stockpiled mixtures, the specification does not include a specific design procedure for selecting the optimum binder content. Instead, a recommended binder content is given in the specification with provisions for an increase in the binder content according to the moisture absorption of the aggregate. Therefore, the research team was faced with a dilemma in the selection of the binder content for the field mixtures that incorporated the

Table 19. Modified list of candidate binders used in detailed laboratory study.

System	Modifier	Residue	Used in Field Trials
MC-400	None	81.5	No
MC-400L	SBR Latex	73.6	No
MC-400B	Butyl Rubber	73.8	No
MC-800	None	85.0	Yes
MC-800L	SBR Latex	78.0	Yes
CMS-2	None	69.4	No
CMS-2L	SBR Latex	68.8	No
CMS-2B	Butyl Rubber	68.8	No
HFMS-2	None	69.5	Yes
HFMS-2L	SBR Latex	72.0	Yes
HFMS-2B	Butyl Rubber	70.0	Yes

modified binders. Consequently, the researchers adopted their own design procedure that consisted of a water-sensitivity test, a test for drainage, and a workability test. The laboratory mix-design work was done with the job-mix gradation used to produce the field mixtures (table 13). The mixture design consisted of preparing a series of mixtures with three different binder contents. Each of the mixtures was then subjected to the drainage, workability, and moisture-sensitivity tests. The optimum binder content was based on the results of these tests.

Materials

The aggregates used in this phase of the study came from the same batches of aggregate used in the preliminary testing (table 12). Mixes were prepared with the three aggregates and the eleven binder materials shown in table 19. The same base asphalt was used in all the binders, and the binders reported in this chapter were from the same batches of material reported in chapter 4.

Preparation of Mix

In order to select the optimum asphalt content for the mixes, one aggregate type (limestone) and three levels of binder content were studied: 5.0 percent, 5.5 percent, and 6.0 percent (residue) by weight of the total mix. When fibers were used in the mix, the asphalt content was increased by 0.2 percent following the recommendation of the fiber producer. A 0.2 percent increase in binder content is typically used by PennDOT and other agencies when fibers are added to cold-mix, stockpiled patch mixtures.[14]

The aggregate was first dried in the oven at 230 °F (110 °C) to remove moisture. After cooling, it was sieved into four fractions: passing the 3/8-in (9.5 mm) sieve and retained on No. 4 sieve, passing the No. 4 sieve and retained on the No. 8 sieve, passing the No. 8 sieve and retained on the No. 200 sieve, and passing the No. 200 sieve. The different sizes were recombined during mixing according to the job-mix formula (table 13).

When an emulsion was used in a mix, both the emulsion and the aggregate were preheated to a mixing temperature of approximately 145 °F (63 °C).

Cutbacks were heated (in a separate oven) to approximately 170 °F (77 °C) prior to mixing with the aggregate, which was preheated to 145 °F (63 °C). These temperatures were selected in accordance with the PennDOT 485 specification (table 7).

The aggregate and the emulsion or cutback were mixed in a Hobart mixer Model A200 equipped with a 20-quart (18 L) mixing bowl and wire whip. In order to have sufficient mix for the tests, approximately 3500 g of mix was prepared at a time. PennDOT's standard procedures for evaluating the workability and water resistance of bituminous cold mixes were adopted.

The workability of each mix was evaluated at room temperature and at 20 °F (-7 °C), 30 °F (-1°C), and 40 °F (4 °C), rather than only at 20 °F (-7 °C) as specified in the test procedure. The last three temperatures were attained by storing the mix in a controlled-environment chamber prior to and during testing. Otherwise the details of the test were the same as for the initial screening tests.

The drainage test used in this phase of the study was the same as that used in the intial screening except that a 1000-g sample was used for all of the testing. The PennDOT water resistance test was used to evaluate moisture sensitivity. The test was conducted in accordance with the PennDOT specification,[13] following the same procedure used by the subcontractor.

RESULTS OF MIX-DESIGN TESTING

Workability

The results of the workability tests are summarized in table 20. It was expected that for a given gradation and temperature, the workability would improve with an increase in bitumen content. In general, this was found to be true. However, in the case of the latex- and butyl-modified emulsions, HFMS-2B and HFMS-2L, the workability of the mix seemed to decrease with increased binder content. Mixes made with MC-800 failed to pass the PennDOT workability test at all three levels of bitumen contents when evaluated at the two lower temperatures. For this reason, sections 485 and 486 of the PennDOT specifications do not permit the use of MC-800 in stockpiled mixes intended for use between November 1 and March 1. The addition of the butyl and SBR latex modifiers to the cutbacks improved the workability at 20 °F (-7 °C), 30 °F (-1 °C), and 40 °F (4 °C) so that the modified MC-400 (MC-400B) cutbacks yielded a strong pass at all temperatures and binder contents.

The addition of the SBR latex to the CMS-2 emulsion (CMS-2L) offered improvements in workability at 20 °F (-7 °C), 30 °F (-1 °C), and 40 °F (4 °C) but actually decreased the workability of the HFMS-2 emulsion at 20 °F (-7 °C) and 30 °F (-1 °C). When the butyl rubber was added to the CMS-2 emulsion, there was a loss of workability at 20 °F (-7 °C) and 40 °F (4 °C) with 6.5 percent binder. Some loss in workability was also noted with the HFMS-2 emulsion when the butyl rubber was added. However, the HFMS-2 mixes tended to be very workable before modification, allowing the modified high-float emulsion mixes to be significantly more workable on the whole than the modified CMS-2 mixes. From the results shown in table 20, the amount of binder in the mix clearly has a large effect on workability and is an important design variable.

Drainage

The drainage test results for the limestone mixes are shown in table 21. Except for two anomalies, MC-400 at 4.5 and 5.5 percent binder and MC-800 at 5.5 and 6.5 percent binder, the drainage increased with increasing binder content. In the drainage test, a small amount of binder is transferred to the test pan at the aggregate contact points. This amount is approximately 1 to 2 percent of the binder, and thus at the smaller binder contents some apparent drainage (approximately 1 to 2 percent) is reported. As the binder content is increased, the amount of reported drainage increases, and obvious drainage of binder occurs when the residue on the test pan is above 4 to 5 percent of the total binder in the mix. Based on visual observations, an upper limit of 4 percent was selected as the maximum allowable drainage.

Based upon an upper allowable limit of 4 percent, except for the MC-800 and the MC-400L at 4.5 percent residual binder, none of the cutback mixes passed the drainage test. Addition of the latex and the butyl polymer to the

Table 20. Results of PennDOT workability test for limestone mixes.

Binder in Mix		Workability at Temperature (°F)			
Type	% (by residue)	20	30	40	Ambient
MC-400	4.5	F[1,2]	--	--	SP
	5.5	P	--	--	SP
	6.5	SP	SP	SP	SP
MC-400B	4.5	SP	SP	SP	SP
	5.5	SP	SP	SP	SP
	6.5	SP	SP	SP	SP
MC-400L	4.5	SP	SP	SP	SP
	5.5	SP	SP	SP	SP
	6.5	SP	SP	SP	SP
MC-800	4.5	F	F	F	SP
	5.5	F	F	P	SP
	6.5	F	F	SP	SP
CMS-2	4.5	F	F	P	SP
	5.5	F	F	P	SP
	6.5	P	P	SP	SP
CMS-2L	4.5	F	P	SP	SP
	5.5	P	SP	SP	SP
	6.5	P	SP	SP	SP
CMS-2B	4.5	F	F	P	SP
	5.5	F	F	P	SP
	6.5	F	P	P	SP
HFMS-2	4.5	F	SP	SP	SP
	5.5	P	SP	SP	SP
	6.5	P	SP	SP	SP
HFMS-2L	4.5	P	P	SP	SP
	5.5	F	F	SP	SP
	6.5	F	F	SP	SP
HFMS-2B	4.5	P	SP	SP	SP
	5.5	F	P	SP	SP
	6.5	F	P	SP	SP

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[1] P = pass, SP = strong pass, F = fail.

[2] Underscored values indicate that the mix did not pass the acceptability criterion.

°F = 9/5 (°C) + 32.

Table 21. Results of drainage test for limestone mixes.

Binder in Mix		
Type	% (by residue)	Drainage (%)
MC-400	4.5	10.9[1]
	5.5	7.4
	6.5	10.4
MC-400B	4.5	12.4
	5.5	16.7
	6.5	18.7
MC-400L	4.5	1.8
	5.5	11.4
	6.5	22.0
MC-800	4.5	3.4
	5.5	15.3
	6.5	13.4
MC-800L	5.5	9.4
CMS-2	4.5	1.2
	5.5	2.5
	6.5	3.3
CMS-2L	4.5	2.5
	5.5	4.7
	6.5	7.8
CMS-2B	4.5	1.6
	5.5	3.5
	6.5	4.7
HFMS-2	4.5	1.9
	5.5	1.9
	6.5	3.6
HFMS-2L	4.5	2.2
	5.5	3.7
	6.5	9.8
HFMS-2B	4.5	1.4
	5.5	2.2
	6.5	4.9

[1] Underscored values indicate that the mix did not pass the acceptability criterion.

MC-400 cutback increased the drainage in all cases. Drainage increased slightly when the latex and butyl polymer were added to the CMS and HFMS emulsions, but the increase was very slight. The tendency of the latex-modified binders to drain more readily is confirmed by comparing the drainage of the latex-modified mixtures at 6.5 percent binder with the unmodified binders.

Water Resistance

The binders used in the study were formulated for use with the limestone aggregate. The results of the testing are shown in table 22. In general, there was no tendency toward stripping except for the CMS-2 and CMS-2B binders. Ultimately these binders were not used, and, therefore, no attempt was made to correct the stripping observed with these binders.

Some stripping was noticed with the MC-400B but not with the control MC-400. The latex modified cutback, MC-400L, also showed some stripping at the smaller binder content, 4.5 percent; but stripping resistance improved with increased binder contents, 5.5 and 6.5 percent respectively. The MC-400B was judged unsatisfactory from a drainage standpoint and was reformulated as MC-800B. The stiffer MC-800B passed the stripping test.

Fiber-Modified Mixes

Fiber-reinforced mixes made with limestone aggregate and three binders--MC-400F, CMS-2BF, and HFMS-2BF--were subjected to the three laboratory tests discussed earlier. The results are summarized in tables 23 through 25. It should be noted that the bitumen content of these mixes was increased by 0.2 percent in order to account for the addition of the fibers.

The workability of all the fiber-reinforced mixes studied was found to be acceptable (table 23), and the addition of the fibers provided dramatic improvement in workability for the MC-400 and CMS-2B mixes. The reason for the improvement is not apparent, but it cannot be attributed to the slight increase in binder content that was used with the fiber-modified mixes.

Table 22. Results of water-resistance test for limestone mixes.

Binder in Mix		Bitumen Coating on Aggregate (%)
Type	% (by residue)	
MC-400	4.5	>90
	5.5	>90
	6.5	>90
MC-400L	4.5	<90[1]
	5.5	90
	6.5	>90
MC-400B	4.5	<90
	5.5	<90
	6.5	<90
MC-800	4.5	>90
	5.5	>90
	6.5	>90
CMS-2	4.5	<90
	5.5	<90
	6.5	<90
CMS-2L	4.5	>90
	5.5	90
	6.5	>90
CMS-2B	4.5	<90
	5.5	<90
	6.5	<90
HFMS-2	4.5	>90
	5.5	>90
	6.5	>90
HFMS-2L	4.5	>90
	5.5	>90
	6.5	>90
HFMS-2B	4.5	>90
	5.5	>90
	6.5	>90

[1] Underscored values indcate that the mix did not pass the acceptability criterion.

Table 23. Results of PennDOT workability test for fiber-reinforced mixes.

Binder in Fiber-reinforced Mix		Workability at Temperature (°F)[1]			
Type	% (by residue)	20	30	40	Ambient
MC-400	4.5	F[2]	--	--	SP
	5.5	P	--	--	SP
	6.5	SP	SP	SP	SP
MC-400F	4.7	SP	SP	SP	SP
	5.7	SP	SP	SP	SP
	6.7	SP	SP	SP	SP
CMS-2B	4.5	F	F	P	SP
	5.5	F	F	P	SP
	6.5	F	F	P	SP
CMS-2BF	4.7	SP	SP	SP	SP
	5.7	P	SP	SP	SP
	6.7	P	SP	SP	SP
HFMS-2	5.5	P	SP	SP	SP
HFMS-2BF	5.7	P	SP	SP	SP

[1] P = pass, SP = strong pass, F = fail.

[2] Underscored values indicate that the mix di not pass the acceptability criterion.

°F = 9/5 (°C) + 32.

Table 24. Results of drainage test for fiber-reinforced mixes.

Binder in Mix		Drainage (%)
Type	% (by residue)	
MC-400	4.5	10.9[1]
	5.5	7.4
	6.5	10.4
MC-400F	4.7	4.0
	5.7	5.2
	6.7	6.5
CMS-2B	4.5	1.2
	5.5	2.5
	6.5	3.3
CMS-2BF	4.7	1.9
	5.7	3.3
	6.7	5.2
HFMS-2B	5.5	2.2
HFMS-2BF	5.7	2.4

---

[1] Underscored values indicate that the mix did not pass the acceptability criterion.

Table 25. Results of water-resistance test for fiber-reinforced mixes.

Binder in Mix		Bitumen Coating on Aggregate (%)
Type	% (by residue)	
MC-400	4.5	>90
	5.5	>90
	6.5	>90
MC-400F	4.7	>90
	5.7	>90
	6.7	>90
CMS-2B	4.5	<90[1]
	5.5	<90
	6.5	<90
CMS-2BF	4.7	<90
	5.7	90
	6.7	90
HFMS-2B	5.5	>90
HFMS-2BF	5.7	>90

[1] Underscored values indicate that the mix did not pass the acceptability criterion.

The addition of the fibers reduced the drainage for the MC-400 mix but had little effect on the CMS-2B and the HFMS-2B mixes (table 24). A slight increase in drainage was noted for the two emulsion mixes when the fibers were added. The increase was approximately equal to the added binder (0.2 percent) in the fiber-modified mixes.

The water resistance of the fiber-modified MC-400 and HFMS-2B mixes was the same as that of the mixes made with the unmodified binder (table 25). Some improvement in water resistance was noted with the CMS-2B, but the improvements were not large and are not, in themselves, a sufficient basis for selecting a binder. More significantly, the addition of the fibers did not deleteriously affect the water resistance of the mixtures.

Selection of Design Mixtures

During the course of the laboratory evaluation of the mixes, and based on a periodic review of results as they became available, it was decided to select 5.5 percent (by residue) as the binder content for further evaluation of laboratory mixes and for field trials of candidate binders. This decision was based upon the desirability of maximizing the quantity of binder in the mix without causing excessive drainage. A binder content of 5.5 percent appeared to be appropriate for all of the binders. The test proceedures were not sufficiently sensitive to indicate different percentages for different binder types.

Five experimental binders were required for the field trials. The high-float emulsion offered the best workability of all the systems, and, therefore, both the butyl-modified HFMS-2 emulsion and an SBR latex-modified HFMS emulsion were chosen for the field trials. An unmodified HFMS emulsion was also included as a control. The fibers were added to the butyl-modified HFMS emulsion since the butyl-modified HFMS was the most promising of the modified binders. Because cutbacks are still widely used for cold, wet-weather, stockpiled patching materials, it was decided that at least one modified cutback system should be included in the field trials. A latex-modified MC-800 was chosen for this purpose on the basis of its workability and drainage characteristics. In order to provide a basis of comparison, a locally produced PennDOT 485 mix was included in the field trials. This mix was made with MC-800, yielding the six binder systems used in the field trials (table 26). Test data for the binders used in the field trials are given in table 27. The gradation of the aggregate used in the field trials was given in table 13.

Tests on Traprock and Gravel Mixes

The three preliminary screening tests--drainage, stripping, and workability--were also conducted on laboratory mixes prepared with traprock and gravel aggregate. These aggregates were not used in the field trials and therefore were not included in the binder selection or mixture design considerations, and, therefore, only one binder content level (5.5 percent) was evaluated. In the case of the fiber-reinforced mixes, the binder content was increased by 0.2 percent. The results of these tests are given in tables 28 and 29. The results point out the need to tailor the binder and the binder content to each aggregate type. From the drainage and workability results, it can be concluded that both the gravel and the traprock require additional binder. Absorption of solvent in the gravel mixes also caused lowered workability in those mixes. The improvement in workability afforded by the fibers was evident for both the traprock and the gravel mixes.

ADDITIONAL TESTING ON MIXES SELECTED FOR FIELD TRIALS

Workability, drainage of the binder, and water resistance are the key factors that affect mix design. Similarly, the mix should be able to resist freeze-thaw deterioration during service and after compaction the mix should be stable and not susceptible to pushing, shoving, or dishing. Finally, the mix should be self-tacking so as to adhere to the bottom and sides of the hole. In the light of these requirements, the candidate mixes were further evaluated for stability, self-tacking, and freeze-thaw resistance. In addition, a more objective mix workability test (referred to as the PTI Workability Test) developed by the research team was conducted on the selected mixes. The equipment and procedure for each of these tests are briefly described here.

Table 26. Binders selected for field evaluation.

Designation	Emulsion or Cutback Type	Modification	Residual Binder Content (%)[1]	Gal of Liquid Binder Per Ton of Mix
HFMS-2	HFMS-2	None	5.5	13.1
HFMS-2L	HFMS-2	SBR Latex	5.5	13.1
HFMS-2B	HFMS-2	Butyl	5.5	13.1
HFMS-2BF	HFMS-2	Butyl + Fibers[2]	5.7	13.6
MC-800	MC-800	None	5.5	13.1
MC-800L	MC-800	SBR Latex	5.5[3]	13.1[3]

[1] Based on weight of total mix.

[2] Fiber added at rate of 5 lb/ton (2.5 kg/1000 kg) of mix or 0.25% by weight of total mix.

[3] Based on mixing performance this was later reduced to 5.2% and 12.4 gal/ton.

Table 27. Test data on binders for field mix.

Test	Binder Types			
	HFMS-2 Control	HFMS-2L Latex	HFMS-2B Butyl	MC-800L Latex
Viscosity at 120 °F, (D 88) SFS	749	>800	313	1241[1]
Residue by Dist. (D 244), wt. %	72.9	75.3	72.7	78.8
Oil in Dist. (D 244), Volume %	4.0	4.0	3.25	21.3
Float at 140 °F (D 139), s	>3600	>3600	>3600	--
R & B Softening Point (D 36), °F	134	124	133	--
Penetration (D 5), mm/10	>230	201	>230	119
Absolute viscosity (D 2171), 140 °F, P	1358	1684	1552	1286
Ductility at 39 °F, 5 cm/min, cm	118.0	>150	54.0	24.5

[1] Kinematic viscosity, D 2161, 140 °F, P
°F = 9/5 (°C) + 32; 1 P = 0.1 Pa•s.

Table 28. Laboratory test results for traprock mixtures.

Binder in Mix		Workability at Temperataure (°F)				Bitumen Coating on Aggregate (%)	Drainage (%)
Type	% by residue	20	30	40	Ambient		
MC-400	5.5	F[1]	F	P	SP	90	1.97
MC-400L	5.5	SP	SP	SP	SP	<90	2.44
MC-400B	5.5	F	P	P	SP	90	0.52
MC-800	5.5	F	F	F	SP	<90	0.75
MC-800L	5.5	P	P	P	SP	<90	4.13
CMS-2	5.5	SP	SP	SP	SP	<90	7.77
CMS-2L	5.5	F	F	P	SP	<90	1.63
CMS-2B	5.5	F	F	P	SP	>90	0.75
HFMS-2	5.5	P	P	SP	SP	<90	0.33
HFMS-2L	5.5	F	F	P	SP	<90	0.32
HFMS-2B	5.5	F	F	P	SP	<90	0.53
HFMS-2BF	5.7	F	F	P	SP	<90	0.17

[1] P = pass, SP = strong pass, F = fail; Underscored values indicate that the mix did not pass the acceptability criterion.
°F = 9/5 (°C) + 32.

Table 29. Laboratory test results for gravel mixtures.

Binder in Mix		Workability at Temperataure (°F)				Bitumen Coatings on Aggregate (%)	Drainage (%)
Type	% by residue	20	30	40	Ambient		
MC-400L	5.5	SP[1]	SP	SP	SP	<90[2]	9.50
MC-400B	5.5	P	P	P	SP	90	0.97
MC-800	5.5	F	F	P	SP	<90	4.00
MC-800L	5.5	P	SP	SP	SP	<90	7.42
CMS-2	5.5	SP	SP	SP	SP	<90	13.14
CMS-2L	5.5	F	F	P	SP	90	1.23
CMS-2B	5.5	F	F	P	SP	90	1.77
HFMS-2	5.5	F	F	F	SP	<90	1.50
HFMS-2L	5.5	F	F	F	SP	<90	1.30
HFMS-2B	5.5	F	F	F	SP	<90	1.13
HFMS-2BF	5.7	P	P	SP	SP	<90	1.18

[1] P = pass, SP = strong pass, F = fail.

[2] Underscored values indicate that the mix did not pass the acceptability criterion.

The PTI Workability Test

The workability test developed by PennDOT results in a subjective evaluation of the workability of the mix. This subjective evaluation is undesirable from the standpoint of test repeatability and, in particular, the between-laboratory repeatability of the test procedure. Therefore, the research team sought a quantitative measure of workability that could be readily performed in the field with minimal expense. The test needed to be simple to perform; require low-cost, readily available equipment; reliably measure mix workability; and provide a rapid return of the test results.

After considerable review of various testing techniques, a simple penetration test was chosen. The apparatus is shown in figure 2 and consisted of a model CL-70 Soiltest pocket penetrometer that is usually used for testing cohesive soils and a steel box with holes on each side. The penetrometer was modified by attaching a 3/8-in by 3-in (9.5 mm by 75 mm) extension to the penetrometer foot. Material was placed loosely, by dumping it from a scoop, into the 4-in by 4-in by 4-in (102 mm by 102 mm by 102 mm) steel box. The workability was measured by pushing the penetrometer foot through one of the holes in the box and then into the mix until a peak load was obtained. The peak load required to penetrate the mix was recorded as a measure of workability. The penetrometer is used to determine the bearing capacity of fine-grained soils and is calibrated in units of tons/ft^2 (Pa). These units were disregarded in reporting the test results.

Table 30 summarizes the results of the PTI Workability Test conducted on the candidate mixes. A comparison of these test results with results obtained from the PennDOT Workability Test (table 22) is shown in figure 3. A reasonable correlation between the two test procedures is shown. Based on the figure, a penetration number greater than 4 would indicate a mix with unacceptable workability, whereas penetration numbers of 3 or less would ensure good workability.

This workability test warrants further consideration as a quick, simple, low-cost test that can be used in the field to judge the workability of cold, wet-weather, stockpiled patching mixtures. Before the test can be adopted, it

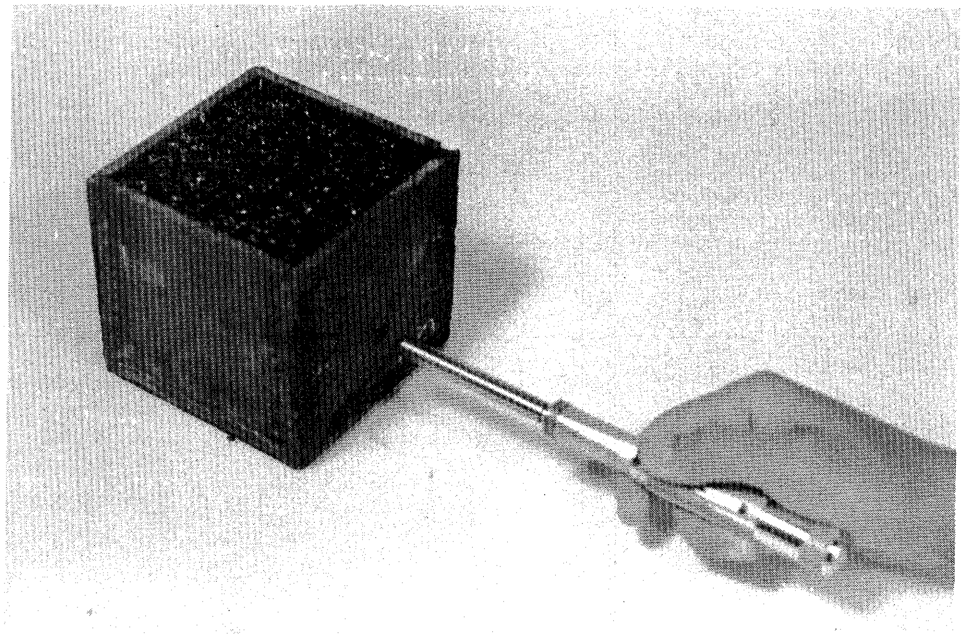

Figure 2. Pocket pentrometer used for workability test.

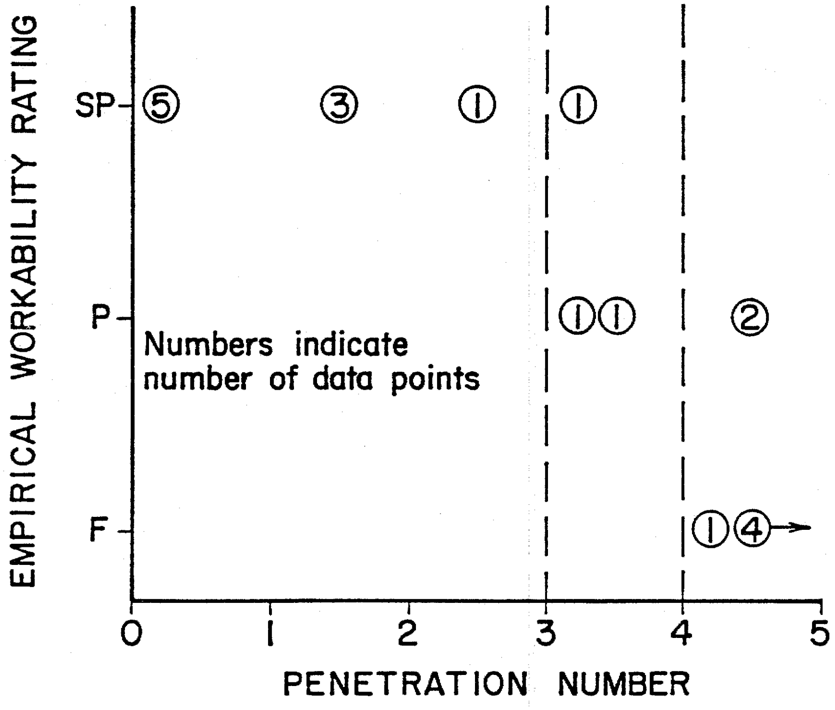

Figure 3. Rating from the PennDOT Workability Test versus penetration number.

Table 30. Results of PTI workability test for candidate mixes.

	Penetration Resistance ($tons/ft^2$) at Temperature (°F)			
Binder in Mix	20	30	40	Ambient
HFMS-2	>4.5	2.75	1.5	0.25
HFMS-2L	>4.5	4.25	2.5	0.25
HFMS-2B	>4.5	3.5	1.5	0.25
HFMS-2BF	>4.5	3.25	1.5	0.25
MC-800L	2.5	2.5	2.5	0.25
MC-800	>4.5	>4.5	3.25	0.25

1 ton/ft^2 = 96 kPa; °F = 9/5 (°C) + 32.

must be calibrated by comparing test results with ratings of workability during mix placement. Additional testing is required to validate the relationship in figure 3 and to extend the relationship to aggregates other than the limestone used for the study.

The Freeze-Thaw Test

Freeze-thaw resistance was measured by compacting the experimental mixes into a cylindrical steel mold and then exposing the compacted mix to alternating cycles of freezing and thawing. The change in thickness of the specimens after repeated freezing and thawing was measured. The uncured mix prepared in the laboratory was compacted in a 6.25-in-diameter (159 mm), 4-in-deep (102 mm) steel mold equipped with a 12-in (305 mm) by 12-in (305 mm) by 1/2-in-thick (12.7 mm) steel base plate. The mix was compacted in three (approximately equal) lifts with a hand-held, electric vibratory hammer (Milwaukee Model No. 5361) with a 4-in-diameter (102 mm) tamping foot. Each lift was compacted at room temperature (approximately 70 °F (20 °C)) for 1 minute with the weight of the hammer as the only surcharge. The surface of the first and second lift was scarified before the next lift was placed and compacted. The overall depth of the compacted specimen was 2.5 to 3 in (64 to 76 mm). The compacted mix in the mold was then subjected to a 15,000-lb (6.8 Mg) static load to level the surface. After the load was applied, water was poured into the mold to form a thin layer, approximately 1/8 in (3 mm), on top of the specimen. A vacuum (28 mm Hg) was then applied to the specimen for 30 minutes until it was saturated.

A steel ruler was placed diametrically across the top of the mold, and the distance from the top of the specimen to the top of the mold was measured with another steel ruler marked with 0.02-in (0.508 mm) divisions. Three such readings were obtained and the average was computed. The points where the readings were taken were marked with paint so that future readings could be taken at the same points. Next, the mold with the specimen was placed in a chest-type food freezer and subjected to a below-freezing temperature at -20 °F (-29 °C) for 24 hours. Then the frozen specimen was allowed to thaw at room temperature. The depth to the top of the specimen was measured as before, and the average of three readings was determined. This procedure was repeated after 2, 4, and 8 or 16 days of freeze-thaw cycling. From these data the change in thickness of the specimens was determined. The results are summarized in table 31.

The purpose of the freeze-thaw test was twofold: to determine if the freezing of water in the voids would cause disintegration in the mix through the splitting of the bond between aggregate and binder and to determine if the specimen would expand under the pressure of the freezing water at the bottom of the specimen. No raveling or disintegration was observed on the surface, and the specimens did not separate from the base of the mold.

For the most part, the tests were inconclusive. Freeze-thaw failure due to the mechanism represented by this test has not been reported as a problem in the field and was not observed in the laboratory. No criteria for pass-fail were established, and further development of the test is probably not warranted. The increase in thickness that occurred with the MC-800L sample was somewhat greater than the increase that occurred with the other mixes, but nothing indicated that it was any cause for concern.

Test for Stability Under Traffic

There is no standard test that can be used to estimate the stability of cold, wet-weather, stockpiled mixes. In this context, stability is defined as the resistance to plastic deformation due to traffic loading. In order to simulate the repeated action of traffic, a repeated load was applied, with a steel foot, to the center of a 6-in-diameter (150 mm) sample. The objective of the test was to determine whether the mix would shove or push under the repeated loading.

For this test, compacted specimens were made in the same manner as for the freeze-thaw test except that before the mix was compacted, it was cured for 24 hours in an oven maintained at 140 °F ± 5 °F (60 °C ± 3 °C). The compacted specimen and the mold were placed on the platen of a model 810 Materials Testing System (MTS) testing machine. A 155-lb (70 kg) repeated haversine load was applied to the specimen through a 1-in-diameter (25 mm)

Table 31. Results of freeze-thaw test.

Binder in Mix	Duration of Cycles (days)	Height Measurement After Thawing (in)[1]	Increase in Thickness (in)
HFMS-2	Initial	1.69	----
	1	1.69	0.00
	2	1.69	0.00
	4	1.68	0.01
	8	1.67	0.02
	16	1.69	0.02
HFMS-2L	Initial	1.64	----
	1	1.65	-0.01[2]
	2	1.61	0.03
	4	1.63	0.01
	8	1.63	0.01
	16	1.63	0.01
HFMS-2B	Initial	1.55	----
	1	1.50	0.05
	2	1.55	0.00
	4	1.54	0.01
	8	1.49	0.06
	16	1.50	0.05
HFMS-2BF	Initial	1.50	----
	1	1.50	0.00
	2	1.47	0.03
	4	1.48	0.02
	8	1.48	0.02
MC-800L	Initial	1.14	----
	1	1.05	0.09
	2	1.01	0.13
	4	1.00	0.14
	8	1.00	0.14

[1] Average of three observations. 1 in = 25.4 mm.
[2] Negative value indicates that specimen decreased in thickness.

steel loading foot (figure 4). The plastic, or nonrecoverable, deformation in the mix was measured after 100 and 1,000 load cycles (table 32). All of the tests were conducted at 72 °F (22 °C).

General trends in the data reflect previous observations regarding the consistency of the binders, especially as reflected in the drainage tests. The HFMS-2L, MC-800, and MC-800L binders showed the largest amount of plastic deformation, 0.0545 in (1.38 mm), 0.0525 in (1.33 mm), and 0.0625 in (1.59 mm) respectively. In no case was there any visible shoving from the repeated loadings. The deformation, even for the MC-800 mix, was quite small. No acceptance criteria were adopted by the research team for this test. The test does not duplicate the action of traffic and is time-consuming to conduct. Consequently, the research team does not believe that this test warrants further development.

Test for Self-Tacking

Considerable thought was given to a simple, reliable test procedure that could be used to evaluate the self-tacking characteristics of the different mixes. A simple procedure was adopted in which the mix is compacted on the top of a field core, and the force required to shear the mix from the core is measured. As part of the test program, the mix was compacted against both wet and dry cores. Cores 6 in (150 mm) in diameter were obtained from an asphalt concrete pavement.

To perform the test, a core was placed in the 6.25-in (159 mm) steel mold and seated in plaster of paris so that its top surface was flush with the top of the mold (figure 5). A 6.25-in-diameter (159 mm) by 1/2-in-thick (12.7 mm) split spacer was placed on the mold. The spacer was then topped with a 4-in-high (102 mm) collar (figure 5). The three pieces (mold, spacer, and collar) were then clamped together. A sample of the mix to be tested was placed in the collar and compacted using the same procedure used for the freeze-thaw testing. After compaction, the base of the assembly was clamped to an I-beam bolted to the lower platen of the MTS machine (figure 6). A steel-wire rope was looped around the collar approximately 3/4 in (19 mm) from the bottom of the collar, and the wire was attached to the loading head of the

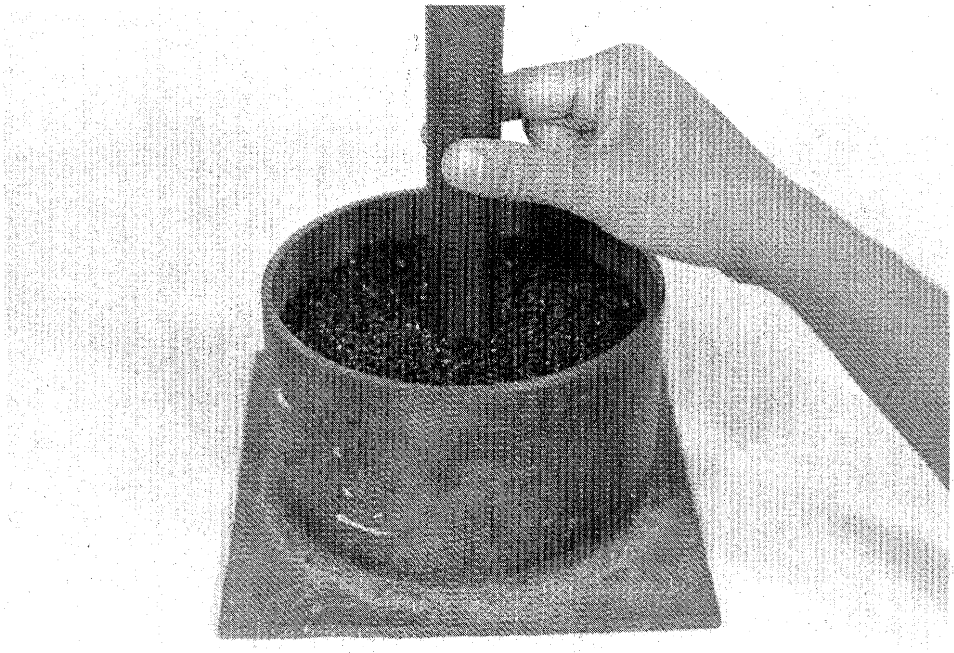

Figure 4. Stability test mold and loading foot.

Table 32. Results of repeated-loading penetration test.

Binder in Mix	Density of Sample (lb/ft3)	Deflection at 100 Cycles (in)	Deflection at 1000 Cycles (in)
HFMS-2	120.5	0.0350	0.0492
HFMS-2L	118.6	0.0420	0.0545
HFMS-2B	118.6	0.0275	0.0365
HFMS-2BF	119.9	0.0255	0.0338
MC-800L	122.2	0.0350	0.0525
MC-800	117.9	0.0438	0.0625

1 lb/ft^3 = 16 kg/m^3; 1 in = 25.4 mm.

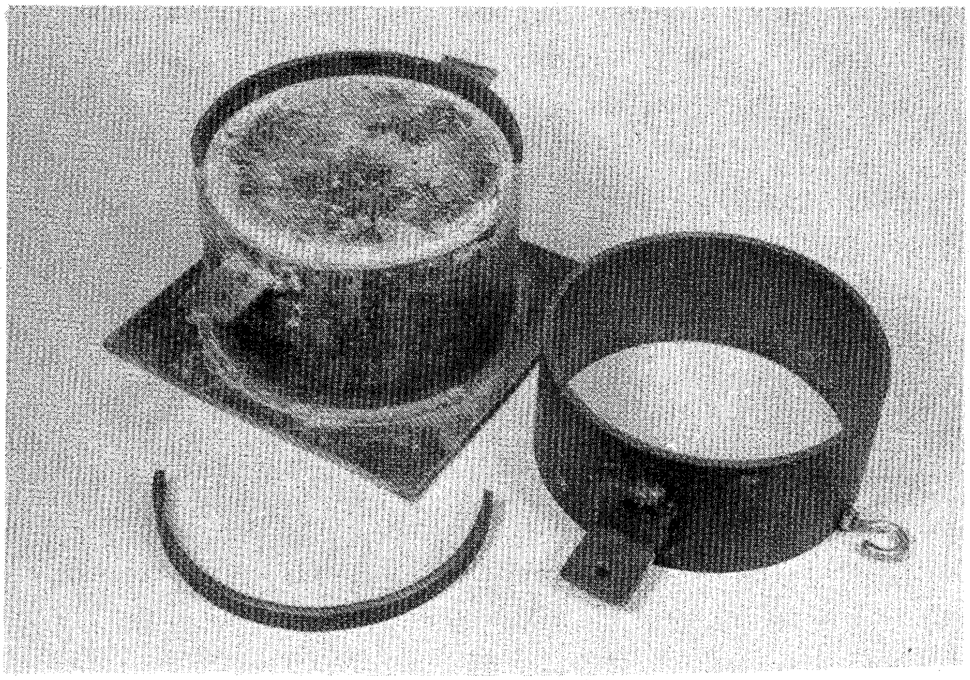

Figure 5. Mounting of specimen in mold for self-tacking test.

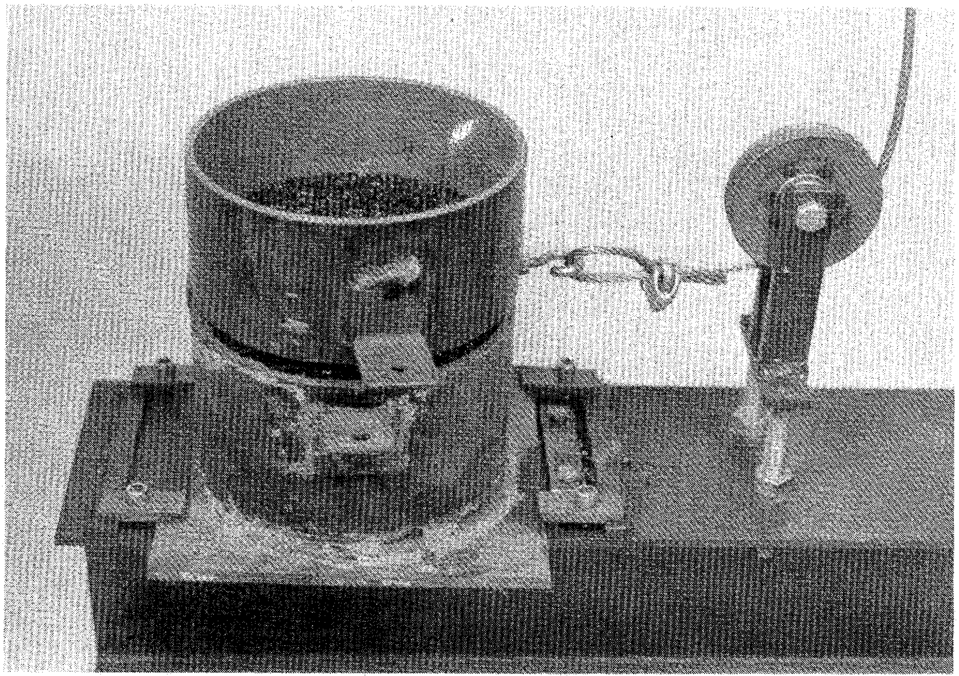

Figure 6. Self-tacking apparatus attached to MTS machine.

test machine. This procedure resulted in a horizontal shearing force on the interface between the core and the compacted sample. The peak load at which the bond between the surfaces failed was recorded.

The test procedure was repeated with a second set of new cores, but the surface was wetted with distilled water before the patching mixture was placed and compacted in the mold. This set of tests (dry surface and wet surface) was conducted on each candidate mix and on the PennDOT 485 control mix containing MC-800. The results are shown in table 33.

The results of the tacking study were somewhat inconclusive. Although there were some differences in the results, no trends were obvious and, in the process of selecting candidate binders, the researchers did not place any reliance on the test results. Further development is needed to produce a reliable test to measure tacking.

Table 33. Results of self-tacking test.

Binder in Mix	Load at Failure of Bond (lb)	
	Core Surface, Dry	Core Surface, Wet
HFMS-2	124.8 (<10%)[1]	27.2 (<1%)
HFMS-2L	60.0 (<5%)	31.2 (<1%)
HFMS-2B	134.0 (<5%)	38.0 (<1%)
HFMS-2BF	116.0 (<1%)	28.8 (<1%)
MC-800L	60.8 (<1%)	41.2 (<1%)
MC-800	43.2 (<1%)	36.8 (<1%)

[1] Numbers in parentheses indicate approximate area of core surface on which binder was observed after the test.
1 lb = 0.45 kg.

6. PRODUCTION AND PLACEMENT OF MIXES FOR FIELD TRIALS

PRODUCTION AND STORAGE

After the binders had been selected, the next step was to produce the quantity of binder that would be required for making the experimental mixes for the field trials. It was decided that approximately 60 patches would be placed and evaluated for each of the five experimental binders listed in table 26. Assuming an average volume of 3 ft^3 (0.085 m^3) per patch, a compaction density of 120 lb/ft^3 (1.9 Mg/m^3), and 15 percent wastage of mix during handling and stockpiling, it was estimated that 12 tons (11 Mg) of each mix would be required for the field trials.

Four 55-gal (0.21 m^3) drums each of HFMS-2, HFMS-2L, and MC-800L binder were manufactured in Springfield, MO, for study by the subcontractor. Since the HFMS-2B binder would be incorporated into two mixes, eight 55-gal (0.21 m^3) drums of this binder were produced. The binders were shipped to Pennsylvania in October 1985 and stored in a heated shed.

All five mixes were produced on the same day (November 14, 1985) in a conventional 100-ton (91 Mg) per hour McCarter batch plant. An Etnyre Model M3384 double-boiler, crack-sealer unit was used to heat, mix, and pump the binder into the weigh hopper. To prevent binder contamination, the tank of the unit was cleaned with kerosene before and after each binder was poured into it. The aggregate was double dried before it was conveyed to the weigh hopper. The fibers for the HFMS-2BF mix were separately weighed and dumped into the pugmill, where they were dry-mixed with the aggregate for 30 seconds before the binder was added. The mix data and the sequence in which the mixes were manufactured are summarized in table 34.

The temperature of the HFMS-2 mix at discharge from the pugmill was 75 °F (24 °C). A check of the hot-bin temperature revealed that the aggregate had cooled to 90 °F (32 °C). Although PennDOT specifications allow a temperature range of 40 to 140 °F (4 to 60 °C), the target mixing temperature was 120 °F (49 °C). The hot-bins were emptied, and freshly heated aggregate was used to produce the HFMS-2B and HFMS-2BF mixes. The coating and overall appearance of

Table 34. Mix data, November 14, 1985.

Mix Type	Residual Binder Content (%)	Temperature (°F)			No. of Batches	Total Quantity Manufactured (tons)
		Aggregate	Binder	Mix		
MC-800L	5.2	140	175	140	3	10.54
HFMS-2	5.5	90	110	75	3	8.02
HFMS-2L	5.5	140	140	112	2	7.39
HFMS-2B	5.5	150	115	140	3	8.55
HFMS-2BF	5.7	150	120	160	3	9.38

Note: °F = 9/5 (°C) + 32; 1 ton = 0.9 Mg.

the HFMS-2 and HFMS-2L mixes did not appear to be adversely affected by the reduced mix temperatures.

When the first batch of MC-800L was made, it appeared very fat and the binder was draining from the aggregate. The binder content was reduced to 5.2 percent, which greatly improved the appearance of the mix. All of the other mixes were acceptable in appearance, and no further corrections in binder content were made. A heavy rain prevailed throughout the day when the mixes were being made, and the stockpiling was done in the rain.

After mixing, the mixes were stockpiled on a bituminous-concrete pad on the premises of the batch plant. The depth of the stockpiles was less than 2 ft (0.6 m) to facilitate cooling and minimize drainage. In order to protect the freshly made mix from the rain, the stockpiles were covered with polyethylene sheets. Although considerable rain fell on the piles during the stockpiling operation, when the stockpiles were uncovered on the following day (November 15, 1985), no stripping or unacceptable drainage was observed.

On November 18, 1985 the experimental mixes were shipped to Ebensburg, PA, and stockpiled in the yard behind the office of PennDOT Maintenance District 9-3. The five stockpiles were then covered with tarps and cordoned off. It is standard PennDOT procedure to cover stockpiled patching material with tarps to prevent the infiltration of rain and snow, which adversely affects workability in freezing weather.

The research team intended to use the PennDOT 485 mix that would normally have been purchased by the local maintenance district (Cambria County). Instead, the maintenance district purchased PennDOT 486 fiber-reinforced, stockpiled mix made with gravel aggregate. This offered a sixth experimental mix, MC-800 modified with fibers.

The use of PennDOT 486 by the maintenance district left the research team without an appropriate control mix. Therefore, the research team purchased 45 tons (41 Mg) of PennDOT 485 patching material from the local contractor that produced the experimental mixes. This step ensured a control mix that contained the same aggregate as the experimental mixes. This material was shipped and stockpiled near the experimental mixes in Ebensburg. Before shipment, samples of each experimental mix and the PennDOT 485 control mix were tested for workability, water resistance, and drainage. The results are given in table 35. In general, the test results for the plant mixes were similar to (or better than) the test results for the laboratory mixes. The only exception was the HFMS-2 plant mix, which failed the drainage test with 6.20 percent drainage. However, no drainage problems were subsequently observed with this mix. It should be noted that the binders used in the field were manufactured in a full-scale emulsion plant with a different base emulsion and a different cutback than were were used in the laboratory batches. Therefore, the differences in the test results were not unexpected.

FIELD PLACEMENT

Particular care was given to the monitoring of the field trials. The assignment of the control mix or an experimental mix to a given repair was done randomly, and the repair procedures were thoroughly documented.

Site Selection

In coordination with county maintenance personnel, roadways with high traffic levels (ADT) were selected to begin the field experiment. Another criterion for selection was that the roadways should not be candidates for overlay or mechanized patching for at least 2 years after the potholes were repaired. As noted below, however, many of the patches were unexpectedly overlaid in the fall of 1985 when the local PennDOT office decided to accelerate its overlay program. Both rigid base and flexible base pavements were included in the study. Because Cambria County was frequently affected by snowstorms during the late part of the winter, the maintenance crews were busy plowing the roads and spreading salt and antiskid material until the end of February. Consequently, it was not until March 4, 1986 that the first potholes were repaired. On the first day of field placement, the air temperature was 33 to 34 °F (approximately 1 °C) and the mix temperature was 34 °F (1 °C). Cambria County lies on the peak of the Appalachian ridge in western-central Pennsylvania. The weather in this area is considerably colder than in many other parts of Pennsylvania, with late-season snowstorms and

Table 35. Laboratory test results for plant mixes.

Binder in Mix		Workability at Temperature (°F)[1]				Bitumen Coating on Aggregate (%)	Drainage (%)
Type	% (by residue)	20	30	40	Ambient		
MC-800L	5.2	SP	SP	SP	SP	>90	3.7
HFMS-2	5.5	P	P	SP	SP	>90	6.2[2]
HFMS-2L	5.5	F	P	SP	SP	--	3.2
HFMS-2B	5.5	F	P	SP	SP	>90	3.4
HFMS-2BF	5.7	P	P	SP	SP	>90	1.7
PennDOT 485 MC-800 Control	4.5	F	P	SP	SP	>90	3.1

[1] F = fail, P = pass, SP = strong pass.

[2] Underscored values indicate that mix did not pass acceptability criterion.

°F = 9/5 (°C) + 32.

freeze-thaw cycles. Heavy coal-hauling trucks are also common in the area, which made it an excellent site for the field trials.

As a safeguard against statistical bias, it was decided that the PennDOT 485 control mix would be used on the same day and under the same conditions as any given experimental mix. To facilitate the transport and use of two mixes the dump-truck bed was provided with a full-depth, longitudinal partition. The truck bed under the tailgate was color-coded to identify the mix in each half of the truck bed. Only one experimental mix was used on any given day.

Repair Procedure

Two different pothole repair strategies were adopted during the study: PennDOT's standard procedure for manual patching with stockpiled mix, often referred to as the "do-it-right" method, and the "throw-and-go" or nonstandard technique. In the standard procedure, illustrated in figures 7 through 9, the deteriorated pavement is removed with a mechanical cutting tool, leaving vertical edges. The debris is removed with a shovel and the hole is cleaned with a broom or compressed air.[18]

Before compaction, enough patching material is placed in the hole so that the compaction device does not "bridge" on the surrounding pavement. It is preferable to have the top of the compacted patch approximately 1/4 in (6 mm) higher than the surrounding pavement to ensure that the compaction device has fully compacted the patching mix. This minimizes the chance that there will be further densification under traffic. The compactive effort consisted of 14 passes with a model V30W2-R Essick vibrating roller.

The nonstandard strategy, illustrated in figure 10, does not involve cutting out the affected area. Loose material is removed with a shovel or broom, and patching material is shoveled into the hole. Compaction is usually accomplished by a few passes with the repair truck or a few blows with the back of a shovel. In this study, for the nonstandard method, compaction was performed with the truck.

Figure 7. Cutting operation for standard procedure.

Figure 8. Cleaning operation for standard procedure.

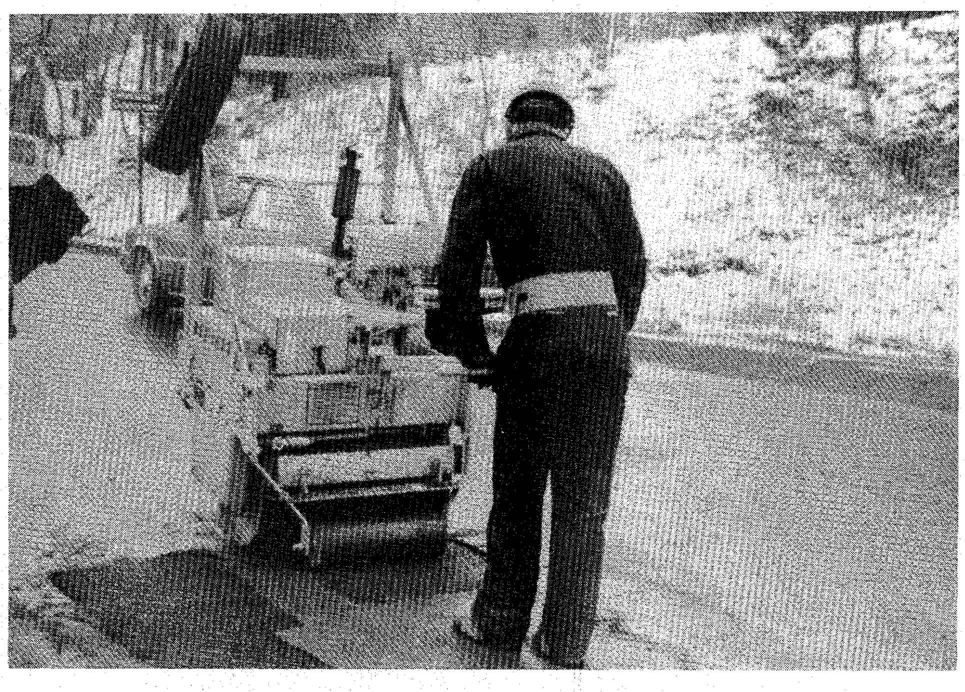

Figure 9. Compaction operation for standard procedure.

Figure 10. Nonstandard repair procedure.

The objective of the study was to improve the effectiveness of mixes in cold, wet weather. Therefore, if the sides and bottom of the pothole were not damp, water was sprinkled into the hole prior to filling it with patching mix. This practice (figure 11) was followed regardless of the repair procedure used. No edge sealing or tacking material was used in any of the repairs.

Monitoring of Repairs

All patching operations were performed under the supervision of a member of the research team, including loading the mixes into the appropriate compartment of the truck bed at the start of the day's work and returning any unused material to the appropriate stockpile at the end of the day. Once at the job site, a member of the research team (accompanied by the foreman) surveyed the section of the road earmarked for the day's operation. Repairs used in the study were always located in the traffic wheel path. Large holes, with dimensions greater than 2 to 3 ft (0.6 to 0.9 m), were avoided because they would have limited the number of repairs that could be made with each mix. A toss of a coin determined whether the first pothole patched on that day would be repaired with the PennDOT 485 control mix or the experimental mix. After the mix for the first repair was determined, the control and experimental mixes were used alternatively in subsequent repairs.

At the time of patching, each repair was thoroughly documented. Information collected for each repair included the repair number, the date, and the observer's initials. Location, hole size, traffic, environmental conditions, mixture characteristics, and pavement conditions surrounding the hole were documented. The procedure and equipment used in the repair along with mixture type and an evaluation of the suitability of the mix were recorded. Nuclear density readings were obtained for potholes repaired according to the standard procedure. In addition, a sketch of the repair was made, and a before-and-after photograph was taken for future identification.

Summary of Repairs

A total of 410 repairs were made during the period from March 4 to April 25, 1986. The standard procedure was used for patching 294 potholes,

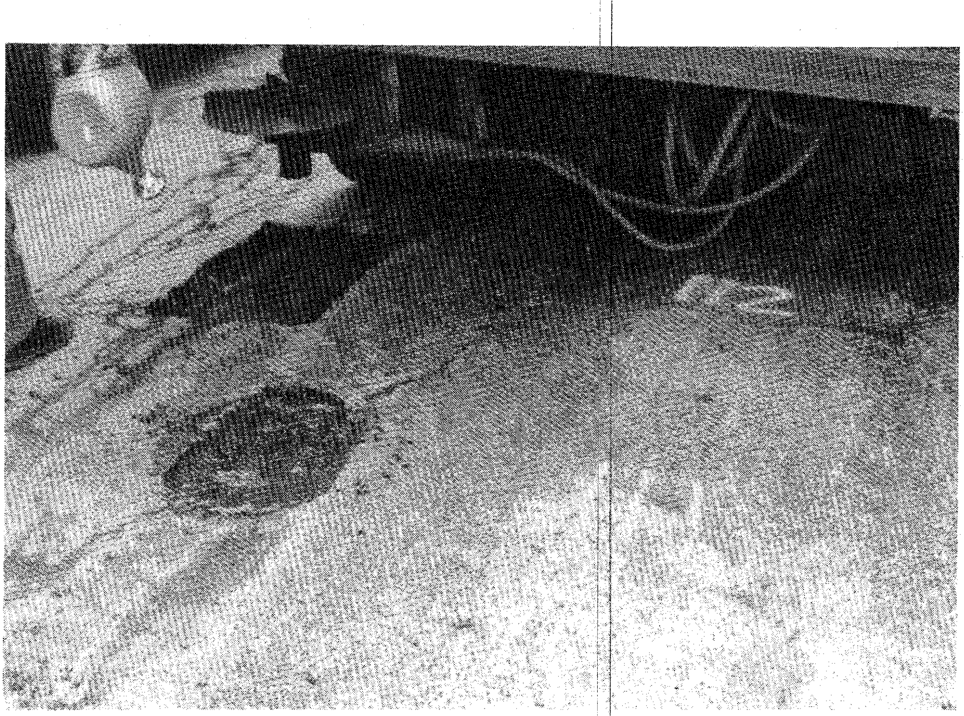

Figure 11. Watering the pothole before placing the mix.

while 122 repairs were made using the nonstandard method. Approximately one half of the repairs were made with the experimental mix, and the other half were made with the PennDOT 485 control mix. Except for the PennDOT 486 mix, all the mixes performed very well and were enthusiastically accepted by the crews.

The only material that showed any signs of premature failure was the PennDOT 486 mix used by the local district. Of the seven repairs documented with PennDOT 486 in the early days of the field trials, two failed a few days after they were patched, and the others started showing distress as a result of stripping of the binder from the aggregate. Consequently, documentation of repairs conducted with PennDOT 486 was discontinued. These patches are not included in the data analyses discussed in chapter 7.

Table 36 summarizes the number of potholes repaired with each mix, the pavement type, the average ADT, and the repair procedure. As can be seen, the repairs were approximately equally divided between flexible and concrete composite pavements.

Table 36. Summary of potholes patched with each mix type.

	No. of Potholes Repaired							
	Flexible Pavement			Composite Pavement				
Mix Type	Standard Procedure	Nonstandard Procedure	Total	Standard Procedure	Nonstandard Procedure	Total	Total No. of Repairs	Average ADT
MC-800L	16	10	26	14	--	14	40	3853
HFMS-2	16	--	16	14	7	21	37	3406
HFMS-2L	14	16	30	14	--	14	44	7324
HFMS-2B	9	10	19	22	--	22	41	5812
HFMS-2BF	7	10	17	20	8	28	45	7821
PennDOT 485	61	46	107	81	15	96	203	6223
PennDOT 486	6	--	6	--	--	--	6	--
Total	129	92	221	165	30	195	416	

7. ANALYSIS OF FIELD RESULTS

This chapter describes the results obtained in the field as well as other results that are germane to the evaluation of the trial mixes. The repairs were made in a variety of environmental conditions (see table 37). Only one experimental mix was used during each working day, and, therefore, each mix was placed in a variety of weather conditions ranging from sunny and warm to snowy and cold (see table 38). The mix temperatures ranged from below freezing to above 77 °F (25 °C), as is shown in table 39. Although there is a general trend in the relationship between mix temperature and air temperature, (figure 12), the two temperatures are not interchangeable. For this reason, the mix temperature was used in subsequent analyses.

Average density, depth, and volume for the repairs made with each mix type are given in table 40. On the whole, there are few differences among the densities, depths, and volumes for each mix type except that the HFMS-2BF tended to be used more on smaller-sized holes, whereas the MC-800L was used more on larger ones.

EVALUATION OF MIXTURE CHARACTERISTICS

At the time of placement, various measurements and subjective evaluations were made on the mixtures and recorded using the construction documentation form devised for the project. The types of observations that were made are summarized in table 41 and are discussed below.

Drainage Resistance

During the temporary storage in the stockpile at the plant, no drainage in the stockpile was observed. The material was then transported to the winter storage area, where it remained for about 3 months until the end of February 1986. At that time, the stockpiles were again inspected, and there was no evidence of stockpile drainage. In May 1986, the material remaining in the stockpiles was re-evaluated. There was some evidence of drainage for the MC-800L mix, which verified the results obtained in the laboratory for this mix. It can be concluded, therefore, that although the SBR latex modifier

Table 37. Number of potholes patched under various weather conditions.

Weather Condition	Mix Type HFMS-2	HFMS-2L	HFMS-2B	HFMS-2BF	MC-800L	PennDOT 485	PennDOT 486
Sunny	15	4	7	15	24	60	--
Partly Sunny	2	10	21	15	4	50	--
Overcast	3	21	8	5	--	45	4
Drizzle	7	4	1	6	--	18	--
Steady Rain	2	--	1	1	--	3	--
Light Snow	2	5	3	3	10	22	2
Heavy Snow	5	--	--	--	2	6	--

Table 38. Number of potholes patched at various ambient temperatures.

Ambient Temp. (°F)	Mix Type HFMS-2	HFMS-2L	HFMS-2B	HFMS-2BF	MC-800L	PennDOT 485	PennDOT 486	Total
≦ 40	11	2	15	4	20	48	4	104
41-50	11	16	16	13	10	68	2	136
51-60	8	24	9	5	4	50	--	100
61-70	7	2	1	13	6	28	--	57
71-80	--	--	--	9	--	7	--	16
> 80	--	--	--	1	--	2	--	3

°F = 9/5 (°C) + 32.

Table 39. Number of potholes patched at various mix temperatures.

Mix Temperature (°F)	Mix Type						
	HFMS-2	HFMS-2L	HFMS-2B	HFMS-2BF	MC-800L	PennDOT 485	Total
≦ 40	16	6	5	12	30	66	135
41-50	16	22	36	22	10	104	210
51-60	5	16	--	--	--	24	45
> 60	--	--	--	11	--	9	20

°F = 9/5 (°C) + 32.

Table 40. Physical properties of repairs.

Mix Type	Average Density (lb/ft^3)	Average Depth (in)	Average Volume (ft^3)
HFMS-2	120.54	2.82	1.26
HFMS-2L	120.53	2.35	1.68
HFMS-2B	119.45	2.80	1.20
HFMS-2BF	119.65	2.30	0.83
MC-800L	118.74	2.42	2.12
PennDOT 485	119.63	2.46	1.46

1 lb/ft^3 = 16 kg/m^3; 1 in = 25.4 mm; 1 ft^3 = .03 m^3.

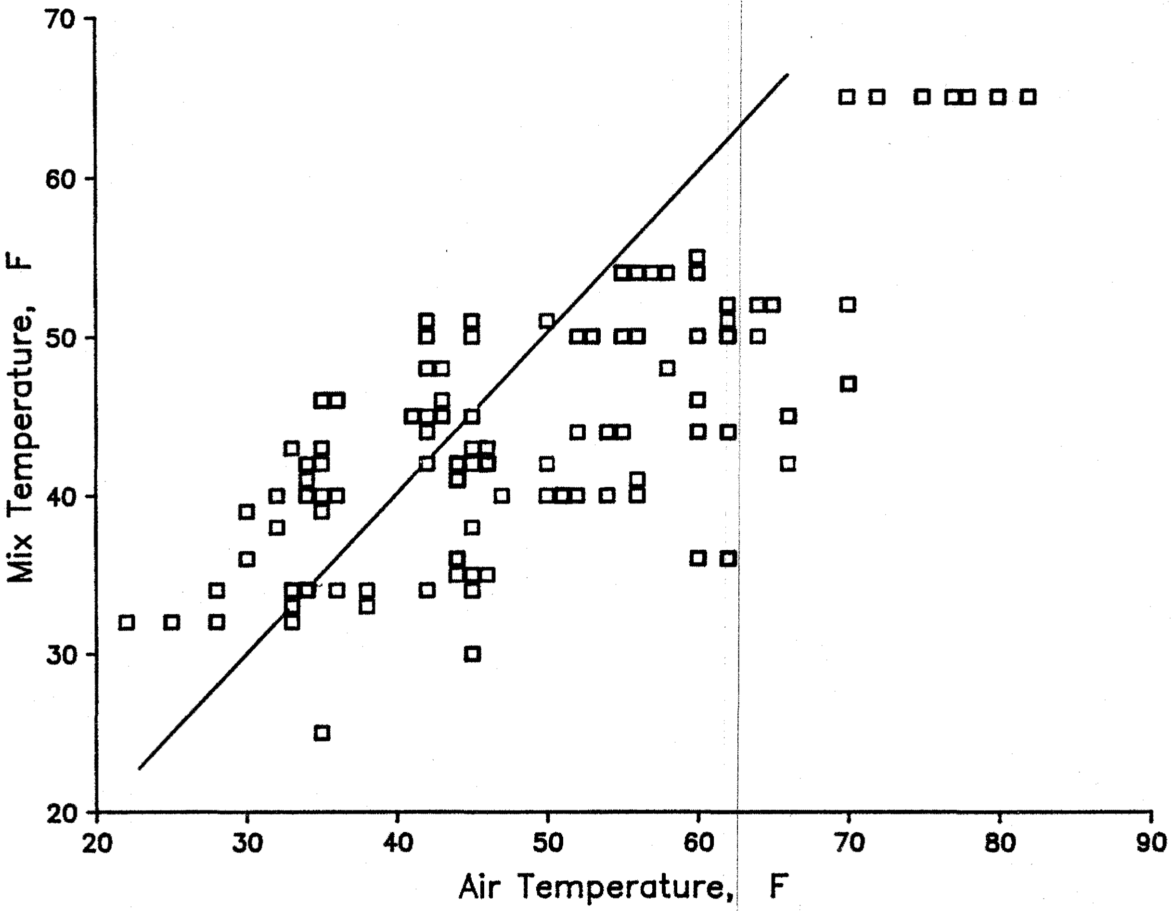

Figure 12. Mix temperature versus air temperature.

Table 41. Rating of mixture characteristics reported from the field.

Mix	Stockpile Drainage	Workability	Susceptibility to Stripping	Self-Tacking
HFMS-2	None	Excellent	None	Excellent
HFMS-2L	None	Excellent	None	Excellent
HFMS-2B	None	Satisfactory	None	Excellent
HFMS-2BF	None	Excellent	None	Excellent
MC-800L	Some	Excellent	None	Excellent
PennDOT 485	None	Excellent	None	Excellent

increased the workability of the mixes at low temperatures (table 37), it did so at the expense of increased drainage. The effect of the latex modification on drainage was less pronounced for the HFMS-2L emulsion.

Workability

The workability of the mixes in the field was subjectively evaluated in two ways. First, an assessment was made as to how easily the crust on the stockpiles could be broken and whether the materials could be easily loaded into a dump truck by a front-end loader. Except for the MC-800L mix, the crust on the candidate-mix stockpiles was observed to be thinner than the crust on the PennDOT 485 mix. PennDOT 485 and MC-800L stockpiles had surface encrustations 1 1/2 in (38 mm) to 2 in (50 mm) thick. All could be loaded satisfactorily; in no instance was the mix so lumpy that it did not break up during loading or shoveling.

The second evaluation of workability was made as the mix was placed in the pothole. Workability was rated as a strong pass, pass, or fail. Of the 410 observations, none failed, 13 were judged as passing, and the remainder were recorded as a strong pass. The 13 pass observations were for the HFMS-2B mix, which represents 32 percent of the repairs made with that mix. The mix temperature also was recorded, and all five repairs made when the mix temperature was less than 42 °F (6 °C) received a pass rating. These results are in agreement with the workability tests conducted on the plant mixes (table 35). The latex modification increased low-temperature workability, although the effect was more pronounced for the cutback (MC-800L) than for the emulsion (HFMS-2L).

Stripping Resistance

The susceptibility to stripping was determined at the time of placement by a subjective evaluation of the percentage of aggregate that was coated with bitumen. In all cases, more than 90 percent of the aggregate was coated, indicating no apparent susceptibility to stripping. These results were in agreement with the water resistance test results for the plant mixes (table 35). All of the experimental mixes, including the control PennDOT 485 mix (MC-800), were acceptable with respect to stripping. The PennDOT 486 mix (glacial gravel, MC-800, and fibers) purchased by the maintenance district stripped badly and did not pass the PennDOT stripping test which is used by PennDOT for acceptance purposes. Thus, it can be concluded that the local PennDOT 486 mix was not within specification and therefore did not merit inclusion as part of the field evaluation program.

Self-Tacking

In all cases, excellent self-tacking characteristics were observed. Even in cold, wet weather, the mixes adhered to the old pavement. No distress that could be attributed to a lack of self-tacking was observed in either the nonstandard or the standard procedure. No tacking materials were used, and all the repairs were done in damp or wet holes.

EVALUATION OF DENSITY

A nuclear gage was used to measure the density of the mix in the patches repaired in accordance with the standard procedure. Readings between 104.8 lb/ft^3 (1.69 Mg/m^3) and 132.8 lb/ft^3 (2.13 Mg/m^3) were obtained. The average density reading was 120 lb/ft^3 (1.93 Mg/m^3). Table 42 shows the average density obtained for each material and the average depth and average volume associated with patches repaired with that material. In the nonstandard procedure, the material in the patch was compacted with six passes of the truck. In this case, the density of the material in the patch was not measured, because these repairs were made on high-volume roads and traffic control was not available to protect the research team. For the repairs made according to the standard procedure, PennDOT provided traffic control as part of the repair operation.

The density of a mix compacted in the pavement is potentially affected by a number of factors including hole depth, hole volume, type of base, condition of base, and type of pavement, all of which were documented. Other aspects that were documented included the number of passes, whether the compaction tool bridged on the surrounding pavement, and whether the hole was filled with

Table 42. Summary of densities measured in the field for different mixes.

Mix	Number of Repairs Standard Procedure	Number of Repairs Nonstandard Procedure	Number of Density Measurements Standard Procedure	Number of Density Measurements Nonstandard Procedure	Density (lb/ft^3) Avg.	Density (lb/ft^3) Median	Density (lb/ft^3) Std. Dev.
MC-800L	30	10	29	0	118.7	119.5	--
HFMS-2	30	7	28	0	120.5	120.4	--
HFMS-2L	28	16	28	0	120.5	119.8	3.9
HFMS-2B	31	10	31	0	119.5	120.0	--
HFMS-2BF	27	18	22	0	119.7	120.7	6.0
PennDOT 485	142	61	135	0	119.6	119.6	3.6
Total	288	122	273	0	119.8	119.9	3.9

1 lb/ft^3 = 16 kg/m^3.

a sufficient amount of material. The data were plotted, and simple analysis of variance was used to test for relationships between density and the other variables. Each of these aspects is discussed below and is followed by a discussion of the relationship between density and type of mix.

Hole Dimensions

The average hole depth was 2.5 in (64 mm). The minimum depth was 0.9 in (23 mm), and the maximum was 6.4 in (163 mm). Five holes were less than 1.0 in (25 mm) deep, and 17 holes were deeper than 4.5 in (114 mm). Figure 13 and table 43 show the distribution of hole depth measurements. A plot of density versus hole depth was examined, but this plot showed no discernable relationship (figure 14). An analysis of variance was used to test the hypothesis that the density of holes less than 4 in (102 mm) in depth was equal to the density of holes deeper than 4 in (102 mm). For this analysis of variance, compaction density was studied at two levels of hole depth. The F-ratio was calculated as 4.46, and the probability that the observed relationship occurred by chance was 3.6 percent. The average densities were as follows:

Depth (in)	Sample Size	Average Density, lb/ft^3	Standard Error
≤4	241	119.9	0.249
>4	32	118.3	0.686

These statistics indicate that hole depth does have a statistically significant effect on the density measurements. However, the difference between the average densities for the two groups is relatively small from an engineering point of view and is not considered sufficient to affect the longevity of the repairs.

A similar analysis of variance was conducted for hole volumes greater than and less than 3.5 ft^3 (0.10 m^3). The F-ratio from the analysis of variance test was 22.68, and the probability of the results occurring on a chance basis was less than 0.1 percent. These statistics indicate that the

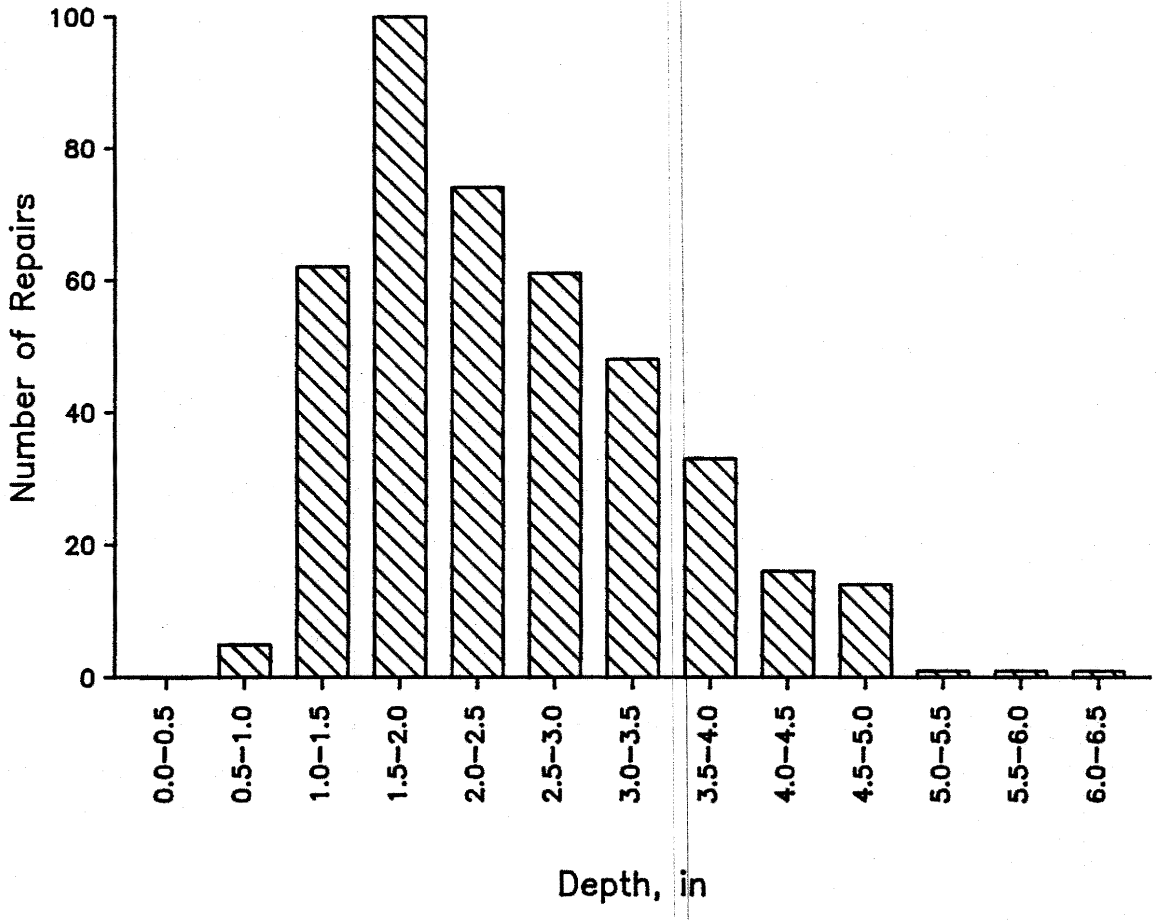

Figure 13. Frequency histogram for hole depth.

Table 43. Distribution of hole depths.

Lower Limit (in)	Upper Limit (in)	Midpoint (in)	Frequency	Relative Frequency
.50	1.00	.75	5	.012
1.00	1.50	1.25	62	.151
1.50	2.00	1.75	99	.241
2.00	2.50	2.25	73	.178
2.50	3.00	2.75	60	.146
3.00	3.50	3.25	46	.11
3.50	4.00	3.75	32	.078
4.00	4.50	4.25	16	.039
4.50	5.00	4.75	14	.034
5.00	5.50	5.25	1	.002
5.50	6.00	5.75	1	.002
6.00	6.50	6.25	1	.002

Mean depth = 2.49 in; 1 in = 25.4 mm.

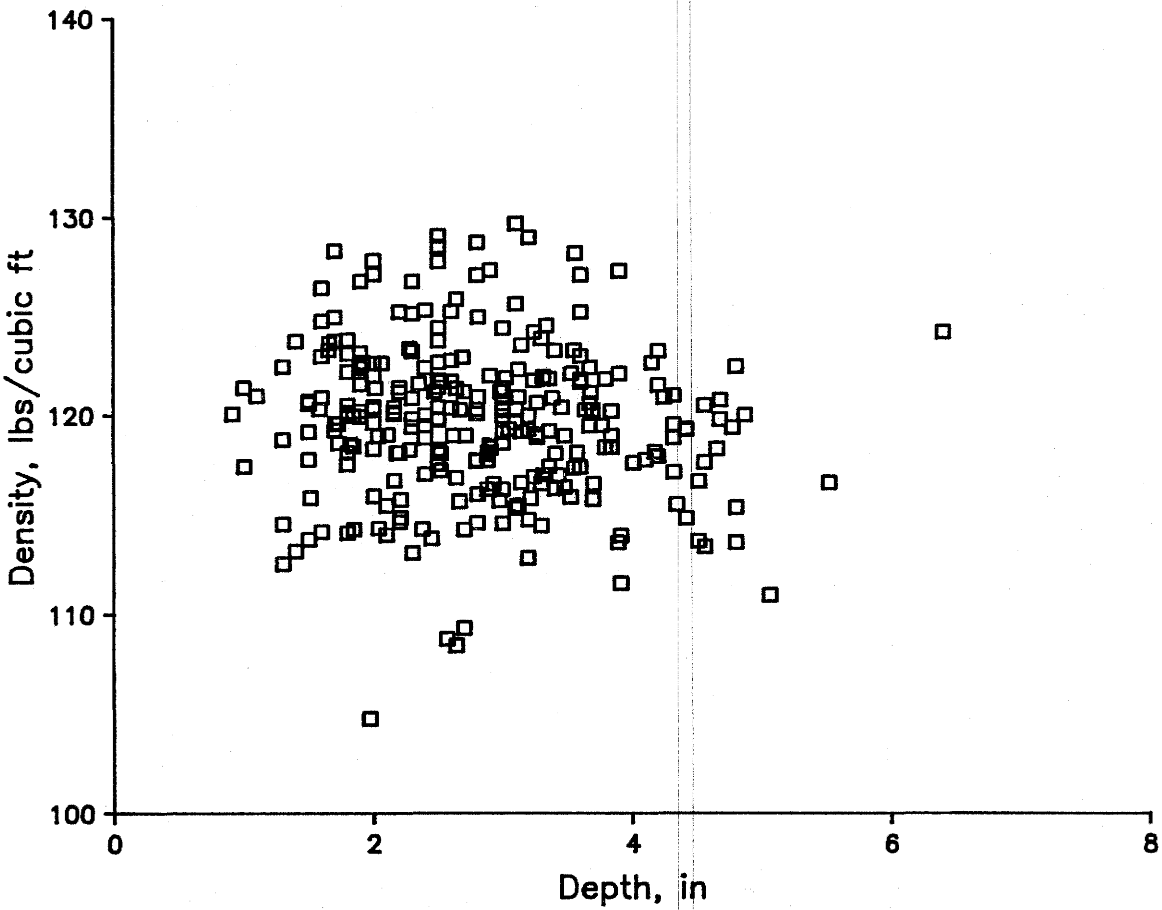

Figure 14. Density versus depth of repairs.

larger holes had, on the average, a lower density than the smaller holes. The average densities were as follows:

Volume, ft^3	Sample Size	Average Density	Standard Error
≤ 3.50	239	120.2	0.243
>3.50	34	116.8	0.643

The difference between the average densities appears to be significant, both statistically and from an engineering standpoint.

Results similar to those obtained for hole volume were obtained for hole area. The average densities for holes with areas greater than and less than 12 ft^2 (1.1 m^2) were as follows:

Hole Area, ft^2	Sample Size	Average Density, lb/ft^3	Standard Error
≤ 12	238	120.0	0.246
>12	35	117.3	0.642

These results show that, on the average, the density of the larger holes was 2.7 lb/ft^3 (43 kg/m^3) less than the average for the smaller repairs. These differences, while small, show that large, deep holes are more difficult to compact than small, shallow holes. Nonetheless, the reduced values of density for the larger or deeper holes are not considered sufficient to significantly affect the failure rate of the repairs.

Pavement Type

An analysis of variance was done to test the equivalence of the average densities for repairs made in the two predominant base types. The F-ratio was 4.30, and the probability of a chance relationship between the two variables was 3.9 percent. The average densities were as follows:

Base Type	Sample Size	Average Density	Standard Error
PCC	36	121.1	0.636
Asphalt Concrete	218	119.7	0.258

The significance of base type on density seems to be marginally important and may reflect the fact that the unit weight of portland cement concrete is larger than that of asphalt concrete. This difference would cause larger nuclear readings for the composite pavements, especially for the thinner repairs.

Two pavement types were included in the study. There were 121 density measurements on asphaltic concrete pavements, and 152 density measurements on composite pavements. The analysis of variance yielded an F-ratio of 3.29, and the probability of a chance occurrence of a significant relationship between the two variables was 7.1 percent. The average densities were as follows:

Pavement Type	Sample Size	Average Density	Standard Error
Asphalt Concrete	121	120.2	0.353
Composite	152	119.3	0.315

The results of this analysis indicate that pavement type does not have a particularly significant influence on the density of the compacted patches. Therefore, repair density, by itself, is not considered sufficiently different to affect the service life of repairs made in different pavement types.

Bridging of Compaction Device and Adequate Filling

During the repair process, data were collected on whether the compactor was bridging on the surrounding pavement. In 273 instances for which density values were available, bridging occurred only once, verifying that the crews performed the repairs in accordance with the PennDOT standard repair procedure. Because only one repair was made when the compactor bridged the repair, no conclusion can be drawn about the effect of bridging on density or repair longevity.

If the hole is underfilled, it is impossible to obtain full compaction. Only if the compacted repair is slightly above the pavement surface, can it be certain that full compaction has been achieved. When densities were recorded, only 3 times out of 273 was the repair flush with the pavement. Thus, there are insufficient data to draw a conclusion with respect to the effect of underfilling on density. However, it is worth noting that in these 3 instances, the average density was 115.3 lb/ft^3 (1.85 Mg/m^3), whereas the average density when the repair was slightly above the pavement was 119.8 lb/ft^3 (1.92 Mg/m^3).

Mix Temperature

The effect of mix temperature on density was evaluated using a simple linear regression. A significant relationship was found, although the correlation coefficient was very small (0.19). The plot of mix density versus mix temperature shown in figure 15 does not indicate a strong relationship between the two variables. To further analyze the data, three levels of the independent variable (temperature) were established. The average densities for these levels were as follows:

Temperature (°F)	Sample Size	Average Density, lb/ft^3
≤ 37	67	118.0
$38 < T \leq 47$	140	120.5
>47	66	119.6

Some decrease in density is shown for those repairs compacted at a temperature less than 37 °F (3 °C); however, the difference is small and is not significant from an engineering standpoint.

Summary

The installation variables, such as hole dimensions, pavement type, and mix temperature, had varying effects on the density of the repair. Although some statistically significant effects were found, they were small, and, from an engineering point of view, should not significantly affect the longevity of the repairs. Mix type did not have an effect on density. These findings support the conclusion that all of the mixes were sufficiently workable during placement and compaction.

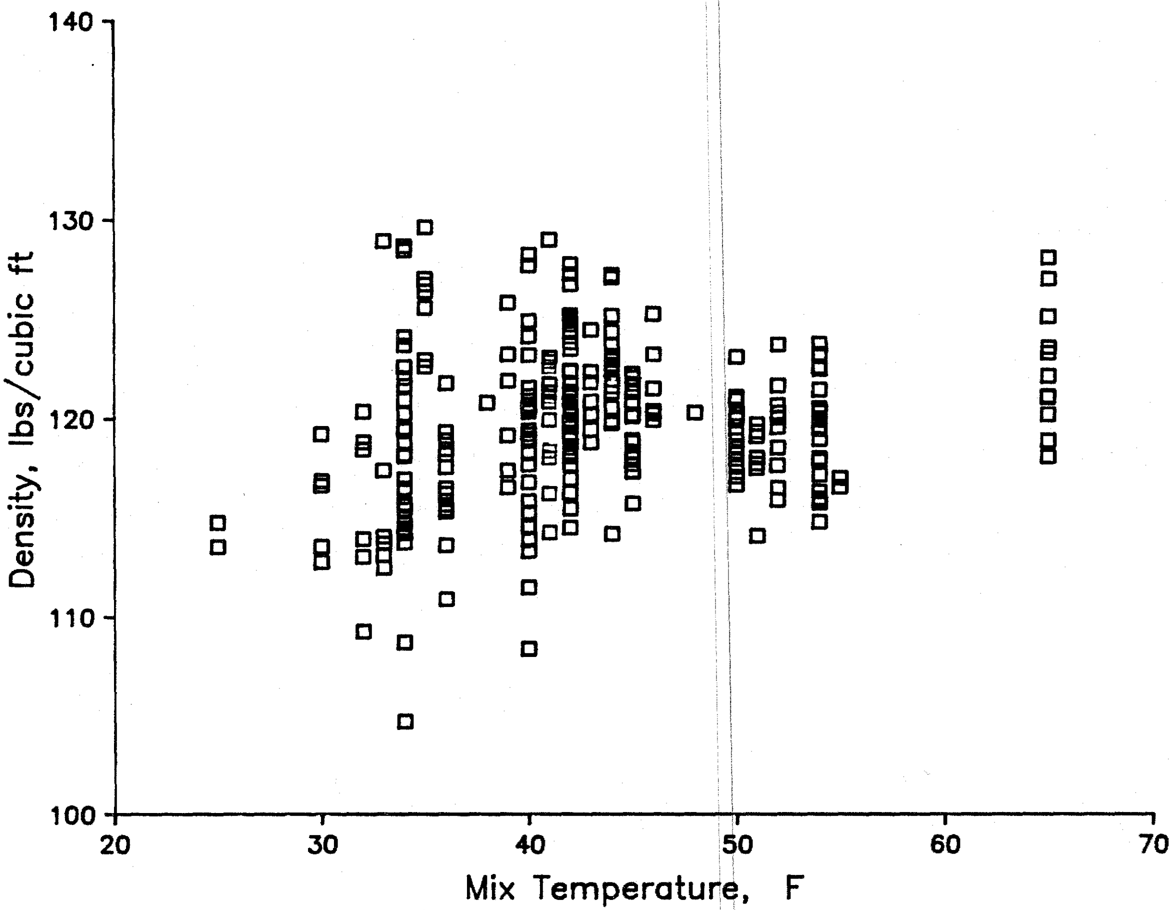

Figure 15. Mix density versus mix temperature.

Some drainage was noticed with the MC-800L mixture, but it did not adversely affect the other properties of the mix. The MC-800L was the most workable of the mixes, but this characteristic was the result of its soft consistency, which contributed to the excess drainage. There was no evidence of moisture damage during storage or placement. With this exception, all of the mixes performed well during placement and compaction. The repair crews were very receptive to the experimental mixes, preferring them to the control material.

MONITORING OF INSERVICE PERFORMANCE

The most commonly observed inservice failures are dishing, raveling, bleeding, and shoving. Each of the repairs was rated with respect to these failure modes during four different evaluations. The repairs were made during the period from March 7, 1986 through April 25, 1986. The first evaluation was conducted several weeks later, and three subsequent evaluations were done in the early summer of 1986, early winter of 1986, and late spring of 1987 as follows:

Evaluation No. 1

- March 17, 20, 1986
- April 14, 1986
- May 7, 13, 1986

Evaluation No. 2

- June 4, 5, 1986

Evaluation No. 3

- November 3, 6, 1986

Evaluation No. 4

- May 7, 1987

In order to provide a comprehensive rating of the performance of each repair, the patch surface was divided into three imaginary rows and columns, giving nine cells for each patch. Each of the nine cells was evaluated for dishing, raveling, bleeding, and shoving, according to the criteria given in table 44. The observations were tabulated on a field evaluation form together with a sketch of the patch outline, and notes were made of any visible signs of distress. Photographs were taken for future reference. The data from the field performance evaluations, along with the construction data, were assembled in a computer file for future analysis.

The repairs were considered to have failed if the repair had to be replaced or if any one of the nine cells received a rating of 3 or greater (see table 44). Using the presence of a single 3 rating as a failure criterion imposed rather strict performance criteria. Many agencies would probably consider the repair to have failed only when total or partial replacement was necessary.

A summary of the performance history of the standard and the nonstandard repairs is shown in tables 45 and 46. The excellent performance that was observed during the first spring evaluation can be clearly seen. Only 4 of 404 repairs failed after 3 months of service. Although careful planning was done by PennDOT county maintenance personnel and the research team to ensure that none of the repairs selected for this study would be overlaid during the evaluation period, changes in the local pavement management plan resulted in the loss of a number of repairs, particularly for the HFMS-2L and HFMS-2B nonstandard repairs, all of which were overlaid by November 1986. A sizable loss in the number of available patches also occurred for standard repairs made with the HFMS-2B mix. Some patches were lost from the other data sets through overlays, loss of markings, and other causes. Consequently, the percentage of failures calculated in tables 45 and 46 was based on the number of available patches, i.e., the number of patches for which observations could be made.

RESULTS OF FIELD SURVEY

The data in table 45 indicate that during the first evaluation there were no failures in either the experimental mix or the control mix. During the second evaluation the only repairs that had failed were those made with the

Table 44. Inservice rating criteria.

Distress Condition	Rating 1	2	3	4
Dishing	None	<1/4 in	>1/4 in, but <1/2 in	>1/2 in
Raveling	None	"pock marks" on surface due to loss of fine aggregate and binder	larger particles have come loose but damage limited to surface	damage no longer confined to surface
Bleeding	None	small, 1 1/2-in size bleeding	large patches of asphalt on surface	mass movement of asphalt to surface
Shoving	None	localized bulging <1/2 in	localized bulging >1/2 in but < 1 in	depth of corrugations >1 in

1 in = 25.4 mm.

Table 45. Comparison of mix performance using the standard repair procedure.

Mixture Type		Evaluation 1		Evaluation 2		Evaluation 3		Evaluation 4	
		Expt. Mix	Control Mix	Expt. Mix	Control Mix	Expt. Mix	Control Mix	Expt. Mix	Control Mix
HFMS-2	Repairs Avail.	30	31	30	31	24	22	24	21
	No. Failed	0	0	2^d	0	3^d	2^d	3^d	5^c
	% Failed	0	0	7	0	13	9	13	24
HFMS-2L	Repairs Avail.	33	40	30	37	26	28	26	27
	No. Failed	0	0	2^d	0	2^d	1^d	6^s	9^c
	% Failed	0	0	7	0	8	4	23	33
HFMS-2B	Repairs Avail.	31	27	31	27	9	7	9	7
	No. Failed	0	0	0	0	0	0	0	0
	% Failed	0	0	0	0	0	0	0	0
HFMS-2BF	Repairs Avail.	28	22	28	22	23	18	23	18
	No. Failed	0	0	0	0	0	0	0	1^d
	% Failed	0	0	0	0	0	0	0	6
MC800-L	Repairs Avail.	30	28	30	28	17	17	17	16
	No. Failed	0	0	0	0	4^c	3^c	8^c	4^c
	% Failed	0	0	0	0	24	18	47	25

d = patches failed due to dishing.
s = patches failed due to dishing or raveling.
c = patches failed due to dishing or raveling or unknown cause.
b = patches failed due to dishing, raveling or both.

Table 46. Comparison of mix performance using the nonstandard repair procedure.

Mixture Type		Evaluation 1		Evaluation 2		Evaluation 3		Evaluation 4	
		Expt. Mix	Control Mix	Expt. Mix	Control Mix	Expt. Mix	Control Mix	Expt. Mix	Control Mix
HFMS-2	Repairs Avail.	7	7	7	7	7	7	4	5
	No. Failed	0	0	0	0	0	0	1	1
	% Failed	0	0	0	0	0	0	25	20
HFMS-2L	Repairs Avail.	11	11	11	11	0	0	0	0
	No. Failed	0	0	0	0	-	-	-	-
	% Failed	0	0	0	0	-	-	-	-
HFMS-2B	Repairs Avail.	10	10	10	10	0	0	0	0
	No. Failed	0	0	0	0	-	-	-	-
	% Failed	0	0	0	0	-	-	-	-
HFMS-2BF	Repairs Avail.	17	17	17	17	7	7	7	7
	No. Failed	0	0	0	0	0	0	0	0
	% Failed	0	0	0	0	0	0	0	0
MC800-L	Repairs Avail.	10	10	10	10	10	10	10	9
	No. Failed	0	0	0	0	0	0	4[b]	2[s]
	% Failed	0	0	0	0	0	0	40	22

d = patches failed due to dishing.
s = patches failed due to dishing or raveling.
c = patches failed due to dishing or raveling or unknown cause.
b = patches failed due to dishing, raveling, or both.

HFMS-2 experimental mix. Two of the 30 repairs had failed by dishing even though they were still intact and serviceable. Data collected during the third and fourth evaluations are shown graphically in Figures 16 and 17, respectively. Given the different failure rates for the different control mixes it is obvious that, overall, the placement and service conditions varied between the mixes. Therefore it is important that the evaluations be made by comparing the experimental mixes with their respective control mix and not directly with each other.

At the time of the third evaluation the failure rate for the emulsion-based mixes was still very small. A higher failure rate was observed for the MC-800L mix and its control, but the difference between the experimental and control mix was not large (24 percent versus 18 percent). A better picture of potential performance emerged after the fourth evaluation. Over the winter there were no additional failures for the HFMS-2 mix (13 percent), but the failure rate for the control mix increased from 9 to 24 percent. The failure rate for the latex-modified emulsion was equal to that of the control mix, but the failures increased from 8 to 23 percent for the HFMS-2L mix and from 4 to 33 percent for the control mix, indicating that a greater percentage of the repairs made with the control mix failed over the winter. No failures were observed for the HFMS-2B mix or the HFMS-2BF mix, and only one failure was observed for the HFMS-2BF mix, making it difficult to reach a conclusion regarding their potential performance.

A much different picture emerges with respect to the latex-modified cutback, MC-800L. After the fourth evaluation the failure rate for the MC-800L mix had increased to 47 percent, nearly double that of the control mix (25 percent). The drainage problem encountered with the MC-800L mix has led the researchers to question the effectiveness of the latex modification. The incompatibility of the latex with the asphalt may be a possible explanation for the questionable performance of the latex-modified cutback and emulsion. Such incompatibility would explain the relatively soft nature, drainage, and resulting larger failure rate for the MC-800L mix.

In the nonstandard procedure no failures were recorded until the fourth evaluation, which was made after the first winter of service. Ordinarily, it

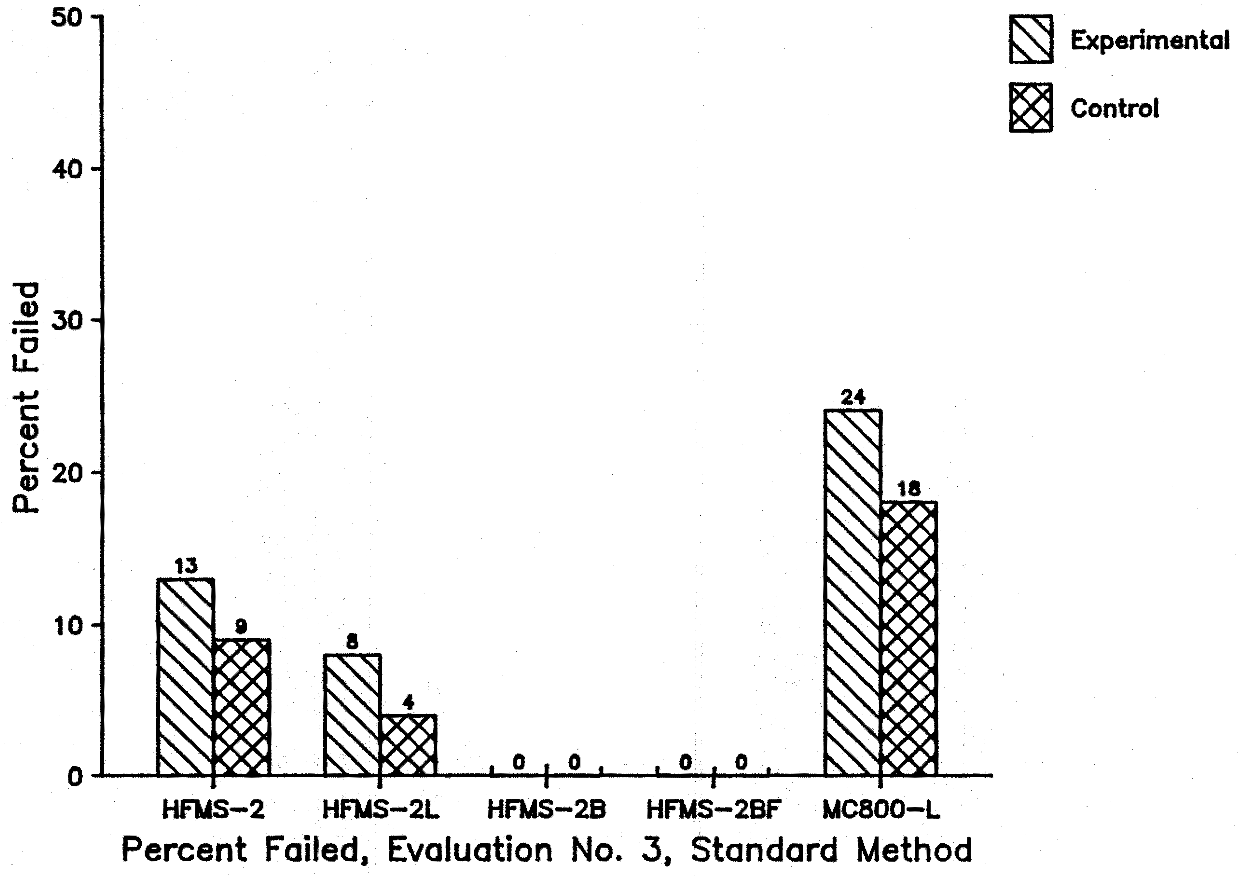

Figure 16. Performance of mixes, standard procedure, evaluation no. 3.

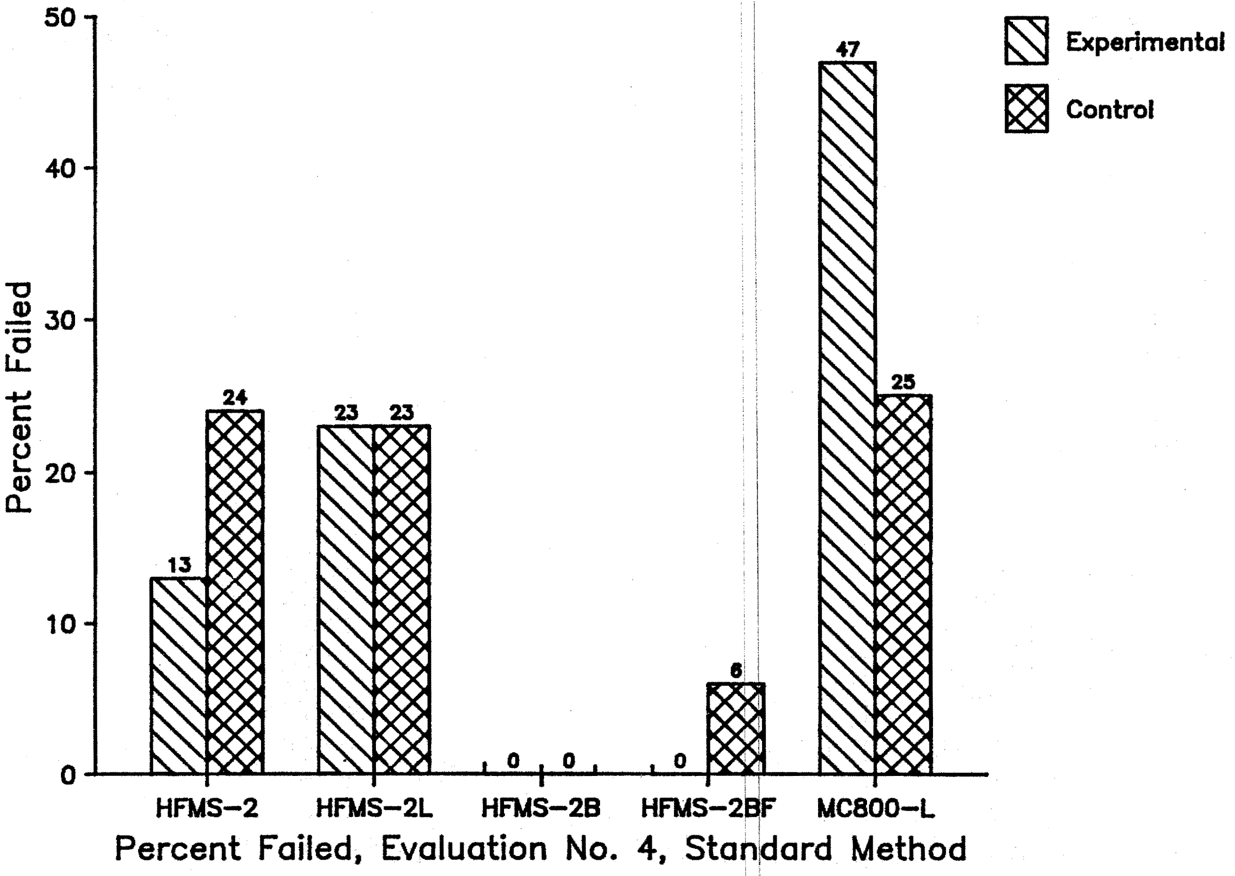

Figure 17. Performance of mixes, standard procedure, evaluation no. 4.

would be expected that the failure rate for the nonstandard procedure would be much greater overall than for the standard method. A comparison of Figure 17 and 18 shows that the failure rates were approximately equal except for the HFMS-2, which performed much better when the standard method was used (a failure rate of 13 percent versus 25 percent for the nonstandard method). The reason for the apparent anomaly was that the nonstandard repairs were made later in the season, when the weather conditions were more favorable. In addition, PennDOT services the more heavily traveled roads first, leaving the lower volume roads until later in the season. Therefore, the approximately equal failure rate for the two methods does not imply that they are approximately equal in terms of repair longevity.

No conclusions can be drawn relative to the failure rate for the nonstandard repairs made with the butyl-modified mixes (HFMS-2L and HFMS-2BF), because the repairs were lost as a result of a last-minute change in PennDOT's pavement overlay plans. Otherwise the trends in the repairs made according to the nonstandard procedure paralleled those made according to the standard procedure.

Raveling and shoving were both observed as failure modes for each procedure, although neither failure mode could be associated with a particular mix. In no case was failure associated with stripping of the mix. In many cases, the failures occurred in locations where there was poor drainage or severe reflection cracking, and a recurrence of the pothole was inevitable. Other failure modes were not observed on a recurring basis, even on the nonstandard repairs.

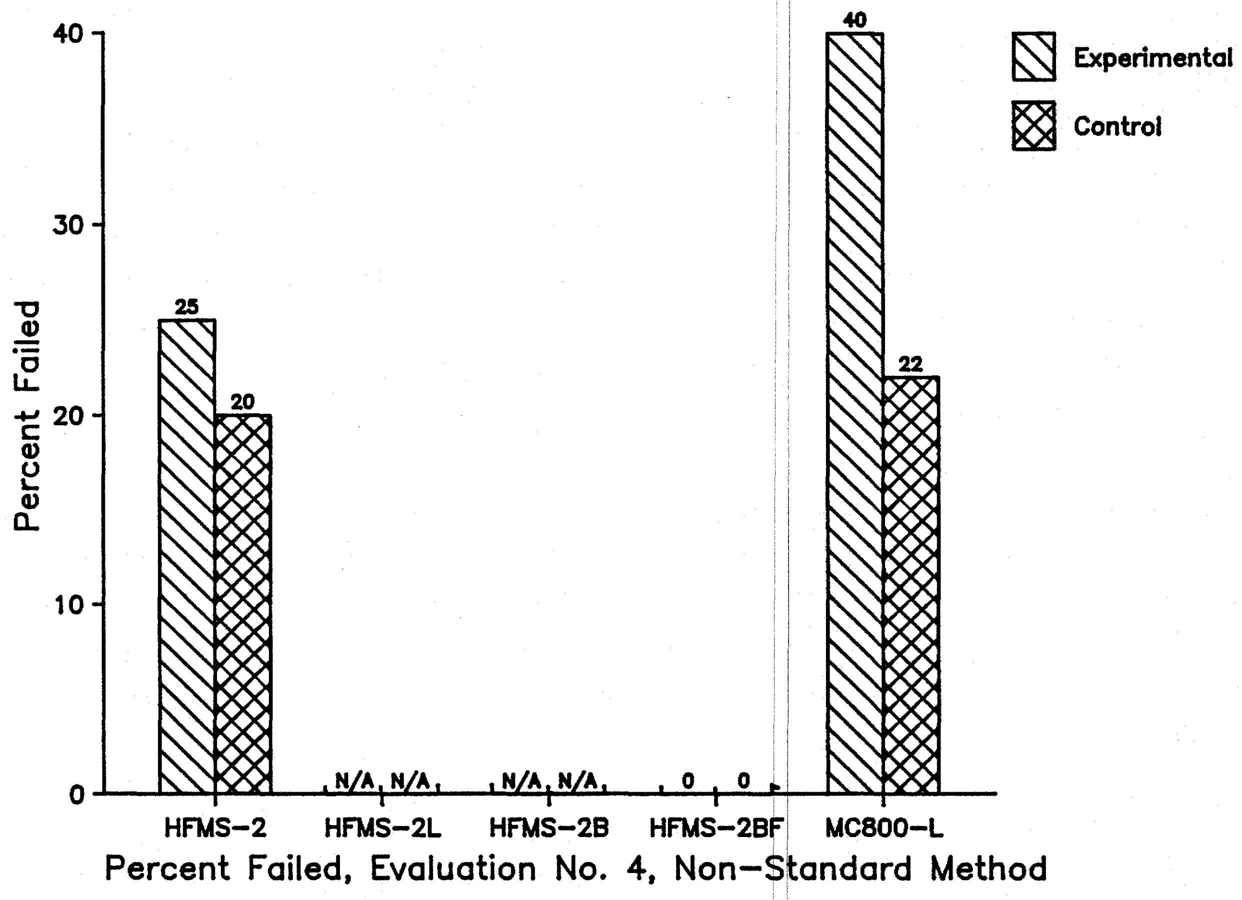

Figure 18. Performance of mixtures, nonstandard procedure, evaluation no. 4.

8. COST EVALUATION OF REPAIR METHODS AND MATERIALS

The difference in performance for some experimental mixes was apparent, but the question remains of whether the extra cost of the materials is justified. In this chapter, an example is presented which illustrates a procedure for evaluating the total cost associated with various cold-mix repair methods and materials. The objective is to impart a general understanding of the steps involved in the economic analysis. The procedures described in this chapter are similar to those used previously by the authors except that user costs have been added to the life-cycle cost, and the cost per repair is calculated instead of the cost per ton.[2,18]

IDENTIFICATION OF REPAIR METHODS

In this example, two alternatives or methods for cold-mix repair are considered. The first method is described in PennDOT performance standard 711-121-01 and is referred to herein as the standard method.[13] In this method, repairs in cold, wet weather consist of the following steps:

- Marking to delineate the repair area
- Cutting to remove weak and deteriorated material
- Cleaning to provide a surface to which the patch or tacking material can adhere
- Filling
- Compacting

Careful attention is given to each step to obtain a high-quality repair and to maximize productivity.

The second method is a nonstandard procedure referred to as the throw-and-go method. In this method, cutting is eliminated, and compaction is performed with a truck. Because there is no cutting or cleaning operation, the actual repair time for this method is considerably less than that for the standard method. Repair longevity with the nonstandard method is typically less than that achieved with the standard procedure.[1]

METHODOLOGY FOR EVALUATING REPAIR METHODS

Different costs are associated with the two repair methods presented. Since there are fewer operations involved with the throw-and-go method, initial placement costs are less than those for the standard method. However, the longevity of a repair must also be considered. If repairs made by one method provide longer service life, then that method may prove more economical even though the initial repair costs are higher. In particular, more expensive initial repair costs may be justified if the traffic volume is high and if there is significant truck traffic. Consequently, the evaluation of cold-mix repair alternatives should be based on a life-cycle cost analysis.

For the evaluation of alternatives, life-cycle cost may include costs associated with initial construction, user delay, user operation, and maintenance. Future costs are discounted using a selected interest rate so that comparisons can be made on the basis of value at a particular time. Costs are considered over some designated analysis period, which can vary in length depending on the type of analysis.

In the example provided, initial repair costs including those for materials, labor, and equipment plus user delay costs are considered. For repairs lasting more than one year, equivalent uniform annual costs were calculated for various repair longevities using the following equation:

$$A_n = P_o\ (A/P,\ i,\ n)$$

where

A_n = equivalent uniform annual cost for a repair longevity of n years

P_o = initial repair cost of a particular alternative

$(A/P,i,n)$ = capital recovery factor for converting the initial repair cost to a uniform series payment lasting n years at an interest rate of i percent

If the repair is made more than once annually, the calculations take on a slightly different form. In this case it is assumed that the repair season lasts for only four months. When a repair is made four times a year, it will be made at the end of months 0, 1, 2, and 3. The effective interest rate per month is i/12. Repairs made twice annually will be made at the end of months 0 and 3. In the example presented here, it is further assumed that subsequent repairs in the same year are made using the same procedure. This assumption is probably not entirely correct, and the model presented here should be adjusted to more closely match particular situations. Such refinement is beyond the scope of the present example but is discussed elsewhere.[18]

By determining the equivalent uniform annual costs for different repair longevities, a curve such as that shown in figure 19 can be obtained. If the estimated service life and cost per repair for a particular repair method and material is known, the equivalent uniform annual cost can be determined. For example, using figure 19, if the average repair longevity is 2 1/2 years, then the equivalent uniform annual cost is approximately $51 per repair.

EXAMPLE COST EVALUATION OF REPAIR ALTERNATIVES

To illustrate the methodology discussed, three different scenarios are considered: (1) the standard method is employed, and repair can be productionized; (2) the standard method is employed, but repair work cannot be productionized; and (3) the nonstandard throw-and-go method is used. In the first scenario, it is assumed that the potholes are spaced so that the repair work can be productionized. In the second scenario, the standard procedure is used but the repairs are widely scattered. More travel and setup time is required, which significantly reduces daily production. The third scenario is similar to the first except that the standard procedure is not used. There is no cutting operation, and compaction is done with a truck. Table 47 summarizes the cost data assumed for calculating the initial repair cost for each scenario. The cost and production figures shown were obtained from a pothole repair project conducted for the Pennsylvania Department of Transportation.[2,18] User delay costs were based upon a traffic rate of 4000 vehicles per day. For each scenario, the lane closure is typically 1/4 mile (0.4 km) or less, and the delays are of short duration. Accordingly, a user delay cost of $0.05 per vehicle was used. The repairs are made during daylight hours, and, therefore, it is assumed that 2400 vehicle per day are

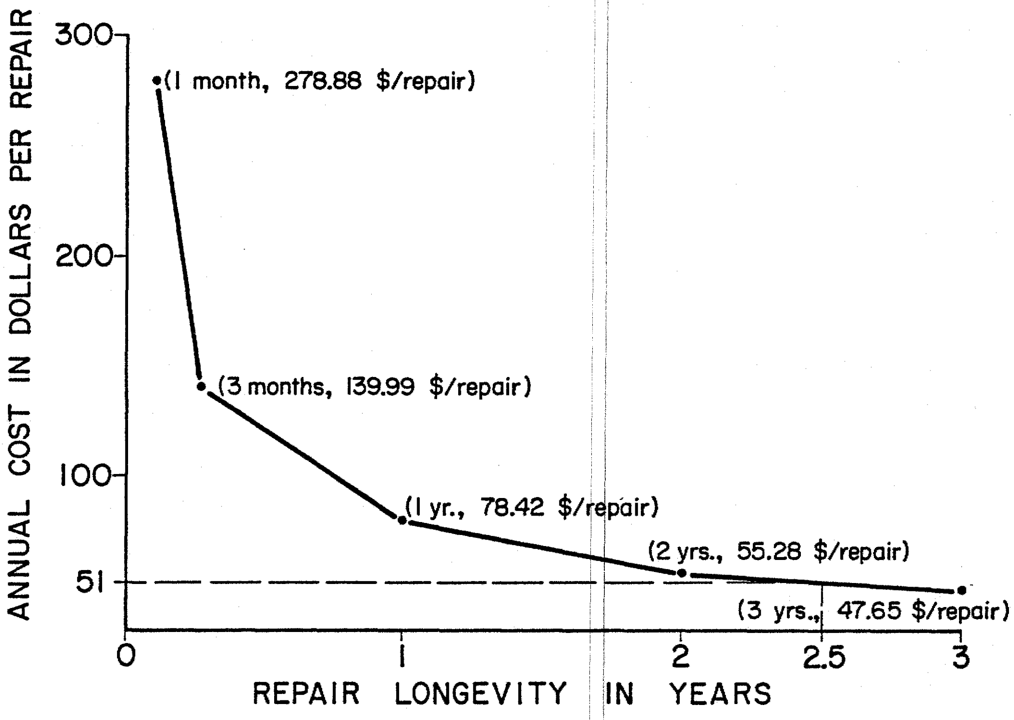

Figure 19. Variation in equivalent uniform annual cost with repair longevity.

Table 47. Variation in equivalent uniform annual cost as a function of repair longevity for a specific alternative.

	Standard (Productionized)	Standard (Not Productionized)	Nonstandard
Hole Volume (ft^3)	3.60	3.60	3.25
Density (lb/ft^3)	120	120	110
Production			
(tons/day)	6.00	2.32	5.34
(repairs/day)	28	11	30
Daily Crew Cost (\$/day)	646.28	461.25	461.25
Support Equipment Cost (\$/day)	267.30	156.30	156.30
Production Equipment Cost (\$/day)	123.15	74.18	
Subtotal			
(\$/day)	1,036.73	691.73	617.55
(\$/repair)	37.03	62.88	20.59
No. of Affected Vehicles	2,400	1,800	2,400
User Delay Cost			
(\$/vehicle)	0.05	0.05	0.05
(\$/day)	120.00	90.00	120.00
(\$/repair)	4.29	8.18	4.00
Total Cost Excluding Cost of Material (\$/repair)	41.32	71.06	24.59
Material Cost Per Repair If:			
\$ 30/ton	6.48	6.48	5.36
\$ 60/ton	12.96	12.96	10.72
\$ 90/ton	19.44	19.44	16.08
\$120/ton	25.92	25.92	21.44

affected. In the standard procedure, where holes are widely scattered, the time of closure is about 25 percent less. The pertinent data are summarized in table 47. The average size of a pothole and the material density after compaction were used to determine the number of repairs per day and to convert the material cost per ton to cost per repair.

Initial repair investments for material costs of 30, 60, 90, and 120 dollars per ton were determined for each scenario. Then, equivalent uniform annual costs, A_n, were determined for service life values ranging from 1 month to 5 years. An interest rate of 10 percent was assumed.

COMPARISON OF MATERIALS BASED ON ANNUALIZED COST

The costs per ton for the control mix and the five experimental mixes were shown earlier in table 18. Compared with the PennDOT 485 control mix, the cost of the experimental mixes ranged from approximately the same amount to 56 percent more. The important question is whether, on an annualized cost basis, the more expensive materials will result in a lower overall cost.

A review of figures 20 through 22 provides some insight into the influence of material cost on annualized costs. As can be seen, the annualized cost differential for various materials ranging in cost from $30 per ton to $120 per ton is relatively small. This is especially true for the range of costs shown in table 18, $30 to $46 per ton. The dominant influence on annualized cost is the longevity of the repair.

Figures 20 through 22 can be used to compare costs for different materials. Suppose an agency is presently using a material that cost $30 per ton, and the average repair life using the standard procedure is 1.0 year. The cost of each repair is $52.58 (figure 20). Figure 20 clearly shows that if the average service life can be extended to 2 years, then the use of material costing as much as $120 per ton would result in a significant cost saving. Even the HFMS-2BF at $46.66 per ton, which was the most expensive mix studied, is comparable to the $30 per ton mix if the average service life can be extended from 1.0 to 1.1 years or more. A similar pattern prevails with longer service lives. A $30 per ton mix lasting 2.0 years is comparable to a

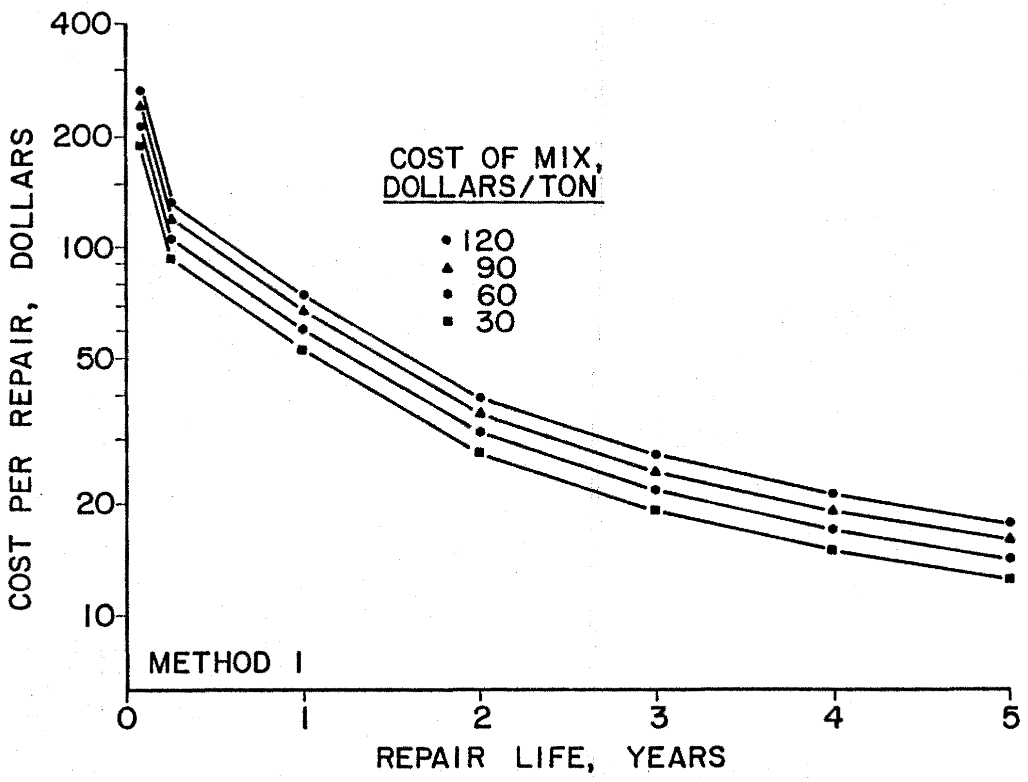

Figure 20. Equivalent uniform annual cost (dollars per repair) for the standard method when repairs can be productionized.

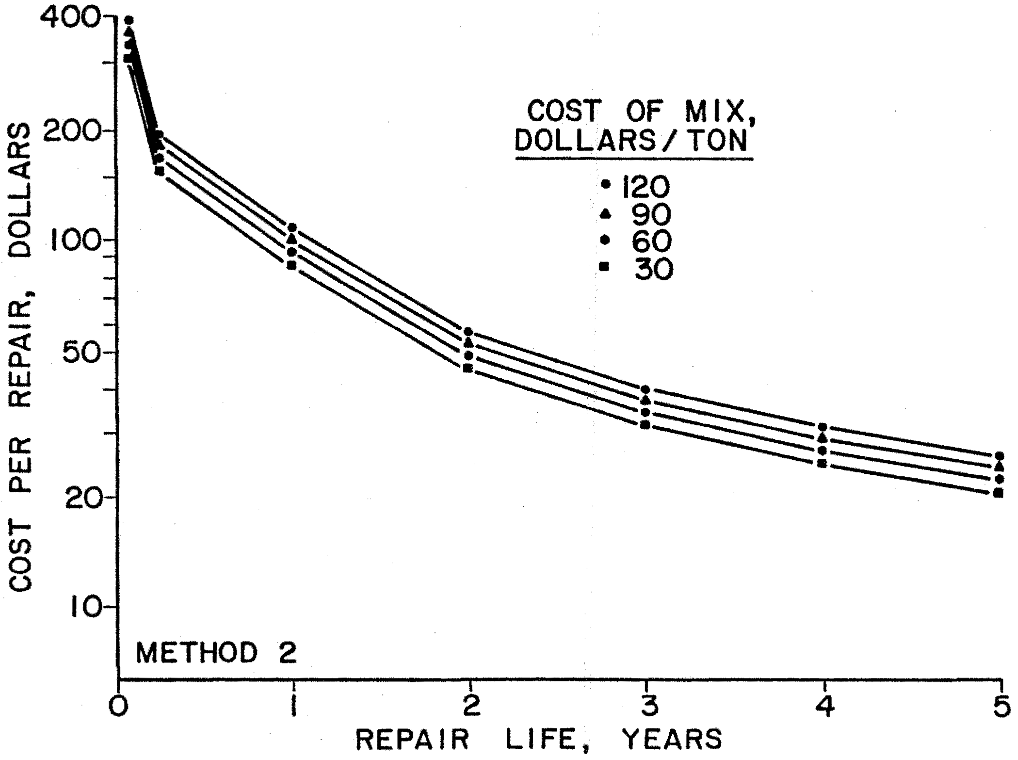

Figure 21. Equivalent uniform annual cost (dollars per repair) for the standard method when repairs cannot be productionized.

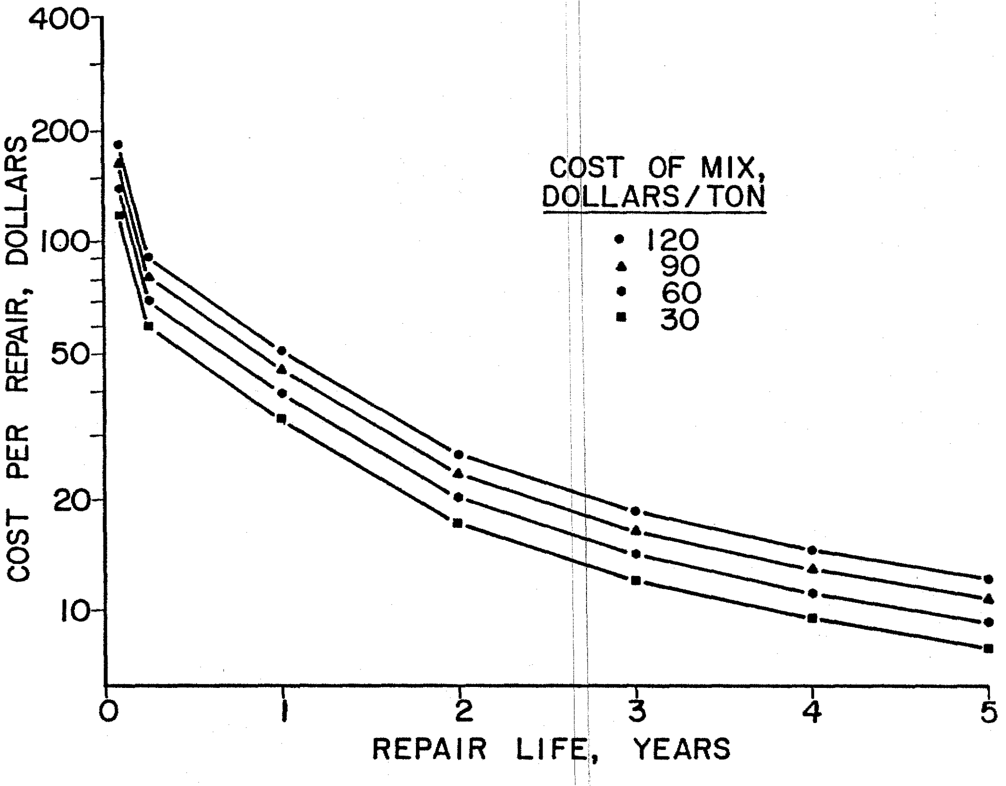

Figure 22. Equivalent uniform annual cost (dollars per repair) for the nonstandard method.

$120 per ton mix lasting 3.0 years. The HFMS-2BF mix is comparable to the $30 per ton mix if the service life can be extended to about 2.2 years. Similarly, mixes costing about $73 per ton or less that will last for 5 years have a lower annualized cost than mixes costing about $30 per ton that will last 4 years. It seems evident that premium mixes need only extend the average service life by a modest amount in order to provide a lower annualized cost than conventional mixes do.

The methods used to make a repair also have an important influence on annualized costs. By comparing the standard procedure (figure 20) with the nonstandard procedure (figure 22), it can be seen that a mix costing $30 per ton used in the nonstandard procedure and lasting one year is comparable to a mix costing about $60 per ton used in the standard procedure and lasting two years. However, certain limitations should be recognized when comparing different methods since there are several important factors not considered in the cost curves for the nonstandard procedure (figure 22). These are:

- Extending the service life decreases user costs resulting from rough pavements.
- Extending the service life improves the public image of the agency and enhances road user satisfaction.
- Compaction with a truck will likely increase vehicular maintenance costs.
- A truck will probably be unsatisfactory for compacting larger holes or compacting transverse repairs.
- Compaction with a truck may be unsafe when the repair is at or near the center line of the pavement.
- Compaction of any type is often not used in the nonstandard procedure, which would further shorten repair life.[1]

SUMMARY

This chapter has described a procedure for comparing materials on the basis of the annualized cost of a repair. The procedures can be easily tailored to various State highway agency practices and roadway situations. Nevertheless, the procedure demonstrates that material cost per ton is a relatively minor influence on annualized cost compared with the longevity of the repair. Generally, the more expensive materials need only extend the longevity of a repair by a modest amount in order to be more cost-effective. Caution needs to be exercised in evaluating the nonstandard procedure since there are hidden costs and other considerations not included in the analysis.

9. FINDINGS AND CONCLUSIONS

The primary objective of this study was to develop and test an improved cold-mix, stockpiled patching material for the repair of asphalt pavements during cold, wet weather conditions. The requirements were that the material be suitable for winter stockpiling, not require specialized equipment or handling, and be cost-effective with a minimum price differential compared with conventional cold-mix, stockpiled patching mixtures. To meet the objective of the study, the failure mechanisms and performance requirements for successful cold, wet-weather pothole repairs were reviewed. Once the failure mechanisms had been defined, the research team developed a set of performance requirements for cold-mix, stockpiled patching mixtures. These performance requirements were used to develop a series of experimental binders. The binders were evaluated in the laboratory, and five experimental binders were recommended for field trials.

A number of experimental cold-mix, stockpiled patching mixtures were produced for evaluation in the field. A total of 410 repairs were made with the different experimental mixtures and with a PennDOT control mixture. The performance of the repairs was monitored through the spring of 1987, and, except for one, all of the experimental binders performed satisfactorily. Several of the experimental mixtures showed notably better performance than the control mixture. Additional monitoring of the repairs might help to determine which of these successful experimental binders, if any, is superior. However, sufficient evaluation has been done to document the superior performance of the patching materials using the HFMS emulsion binders. Because of these results, State highway agencies are encouraged to evaluate these materials in their own areas.

FAILURE MECHANISMS AND PERFORMANCE REQUIREMENTS

Performance during stockpiling, placement, and service must be considered in the development and evaluation of new cold-mix, stockpiled patching mixtures. In the stockpile, poor workability, drainage of the binder, and stripping are the most commonly cited deficiencies. Mixture workability is affected by a number of factors including the characteristics of the aggregate, the consistency of the binder, the quantity of the binder, and any tendency for premature curing of the binder. Requirements for the aggregate have been studied by a number of researchers. The aggregate must contain crushed angular particles and a maximum of 1 to 2 percent passing the No. 200 sieve; the maximum aggregate size must be less than 1/2 in (13 mm). Limiting the amount of fine dust and the maximum aggregate size optimizes workability. Crushed angular particles are required to produce stability under traffic. A gradation that is relatively open provides sufficient space for the thick binder films that contribute to workability and water resistance. Since the aggregate requirements for a successful cold-mix, stockpiled patching mixture were well defined, the primary attention in this project was focused on improving the characteristics of the binder.

Lower binder viscosity contributes to workability in the stockpile and during placement. However, it is undesirable with respect to stripping, drainage, and resistance to pushing and shoving under traffic. The tendency of a binder to strip from an aggregate is a function of the aggregate type and the source as well as the binder. Tendencies toward stripping can be avoided by selecting the appropriate binder system or by adding an appropriate antistripping additive. Resistance to drainage is primarily a function of the consistency of the binder. The ideal binder must remain soft and flexible at low temperatures, be soft and flexible during placement and compaction, and "set up" rapidly after compaction. The ideal binder, therefore, has a low temperature susceptibility, will shear thin during working (i.e., be thixotropic), and will cure rapidly after placement without excessive hardening. Resistance to pushing and shoving under traffic must be developed primarily by the interlocking of the aggregate particles. Adequate aggregate interlock is developed by the proper compaction of angular crushed-aggregate particles.

There is no accepted mix design procedure for cold-mix, stockpiled patching mixtures. Four performance requirements were considered of primary importance with respect to mixture design: drainage resistance, workability, resistance to moisture, and stability. Stability can be ensured by using a properly graded, crushed aggregate. Drainage resistance, workability, and resistance to water are primarily functions of the binder. Therefore, test procedures for drainage, workability, and stripping were used as a guide in selecting the optimum binder content for the mixtures. Additional tests were conducted to evaluate stability under load, self-tacking characteristics, and freeze-thaw resistance.

The criteria for designing a cold-mix, stockpiled patching mixture are as follows:

- First, establish the maxium allowable binder content so that the mix will not drain excessively (not more than 4 percent of the binder content in the drainage test).
- Second, ensure adequate low-temperature workability by means of a workability test conducted at the lowest mix temperature expected in the field.
- Third, ensure water resistance by conducting the PennDOT water resistance test.

All of these tests must be conducted using the job aggregate and binder.

BINDER SELECTION

On the basis of the literature review and the experience of the researchers, it was concluded that the best opportunity for improving the performance of cold-mix, stockpiled patching mixtures was to focus on the characteristics of the binder. A wide variety of materials that can be used to modify cutback or emulsified asphalt cements were reviewed. These materials included plastics, elastomers, reclaimed tire rubber, and polymeric fibers. Consideration was given to the addition of these modifiers to conventional medium-curing cutback asphalt cements, anionic and cationic emulsions, and high-float emulsions.

A great number of polymeric additives have potential as modifiers for asphalt cements; however, many of these systems have never been used with asphalt cement. In addition, many of these materials require special processing and handling techniques and are relatively expensive. Because of the requirement that the study be confined to readily available, off-the-shelf technology, SBR latex, butyl rubber, and an SBS block copolymer were identified as the most promising modifiers. After further consideration, the block copolymer was dropped because additional developments in processing technology were required before it could be readily incorporated into asphalt systems. The recent development of SBS polymers that are dispersed in extender oils has eliminated this problem, and they now warrant further study. Short polyester or polypropylene fibers were also included in the experimental binder systems. Special attention was given to high-float emulsions because of the reduced temperature susceptibility and shear thinning, or thixotropic, properties offered by these emulsions.

The SBR latex modifier was chosen because of the improved low-temperature ductility and workability that it imparts to asphalt cement. SBR latex is perhaps the most widely used polymer modifier; it is low in cost and readily available. Although the SBR latex improved the workability of the binder, it reduced the consistency of the binder sufficiently to cause some drainage.

Butyl rubber was chosen because it is generally considered an adhesion promoter and also improves the low-temperature ductility of asphalt cement. The butyl rubber performed well in this regard except that it caused a decrease in low-temperature workability. This loss was compensated for by the general improvement in workability offered by the high-float emulsions.

Because the butyl-modified high-float emulsion offered the greatest promise as a modified binder, the fibers were added to this system. Surprisingly, the fibers improved the workability of the mixtures. This improvement in workability cannot be accounted for by the additional 0.2 percent binder that is recommended when fibers are added to a mix. The fibers appear to lubricate the mix when it is worked in a loose manner. Later, after compaction, the fibers offer a reinforcing effect, improving the cohesion of the compacted mass.

After a comprehensive laboratory evaluation, the following six binder systems were recommended for the field trials:

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

FIELD TRIALS

Although laboratory evaluations are important in the development of new materials, the final test of the product must be made in the field. Therefore, as part of the study, cold-mix, stockpiled patching mixtures were made with each of the binders listed above. A statistically designed experiment was developed so that each of the experimental mixtures could be compared individually with the MC-800 control mix.

A total of 410 repairs were made in Cambria County, Pennsylvania, in the spring of 1986. A different experimental mix was used on each successive day, and both the control mix and an experimental mix were used on any given day. Therefore, approximately one-half of the repairs were made with the control mix. The remaining repairs were divided equally among the five experimental mixtures. Detailed construction records were kept of the conditions at the time of placement of each of the repairs. These records included the equipment used to make the repair, the prevailing environmental conditions, the geometry of the repair, and the density of the compacted repair. Two different techniques were used to make the repairs. The PennDOT standard procedure was used for approximately two-thirds of the repairs; the remaining repairs were made according to a nonstandard procedure.

Each of the experimental mixtures and the control mix performed very well during stockpiling, transport, and placement. No problems were experienced with respect to stripping in the stockpile or during placement. Some drainage was observed with the MC-800L-based mixture, and its workability was better than that of the other experimental mixes. Some loss in low-temperature workability was noted with the butyl modifier, but this was offset by the addition of the fibers. The improvement in workability as a result of the addition of fibers, which was noted in the laboratory, was verified in the field. All of the experimental mixtures were preferred by the crews over the control PennDOT mix.

A detailed comparison of the density measurements indicated that the mixes were easy to compact and that the modifications did not adversely affect the compactability of the mixes. It was further found that adequate compaction can be obtained at mix temperatures as low as 20 to 30 °F (-7 to -1 °C), that hole depths as deep as 6 in (150 mm) can be reliably compacted, and that pavement base type has little effect on compacted density.

The patches were placed in the late winter/early spring of 1986. Four performance evaluations were made, approximately 30, 90, 240, and 400 days after the installation of the first patches. After 30 days, all of the patches were performing in an acceptable manner. Nothing was revealed during the first or second performance evaluation to indicate that there would be any future distress or failure in the patches. Although some dishing was observed in a few of the patches, the extent was relatively minor. Performance evaluations made in the fall of 1986 and spring of 1987 showed significant differences in the behavior of the different mixes.

The laboratory test data and the field handling and placement characteristics of the experimental mixes showed improved properties over the standard MC-800 cutback mix. The latex-modified binders, MC-800L and HFMS-2L, tended to have an excessive amount of drainage. This was attributed to a tendency of the latex to separate from the asphalt, which reduces the consistency of the latex-modified binder. From a longevity standpoint the MC-800L mix did not perform as well as the standard control in this study and cannot be recommended for future use in cold-mix, stockpiled patching mixtures. The most successful binders were those based on the HFMS-2 emulsion. The butyl modification should provide enhanced performance, although after one year of service the superior field performance expected by the research team was not yet definitively indicated. In the opinion of the research team, the butyl-modified high-float emulsion, especially with the addition of fibers, has the characteristics necessary to produce a mix with significantly improved performance and to be a cost-effective replacement for conventional cutbacks or emulsions.

CONCLUSIONS

Several conclusions can be drawn on the basis of the results of this study:

- The major mechanisms responsible for the early failure of cold-mix, stockpiled patching mixtures are the drainage of the binder from the aggregate, poor workability, stripping, inadequate stability under traffic, and inability of the mix to bond to the repair (self-tacking).

- A clean, crushed aggregate with less than 2 percent passing the No. 200 sieve and a maximum particle size of 1/2 in (13 mm) is needed for a successful cold-mix, stockpiled mixture.

- The binder is the most promising area for improvement in mixture performance. The required aggregate properties are well defined.

- An improved mixture design is required for cold-mix, stockpiled patching materials. A tentative procedure has been developed and is presented in this report.

- Two of the four experimental mixtures employing high-float medium-set (HFMS) emulsion binders performed demonstrably better than companion control mixtures in the field trials. The other two HFMS mixtures showed no failures in the field, but definitive conclusions could not be reached because their companion controls had only zero and one failure, respectively.

- Experimental mixtures using the latex-modified cutback binder did not perform as well as their companion controls.

RECOMMENDATIONS

- On the basis of the field performance, no further development of the latex-modified cutback mixture is recommended.

- Field trials of stockpiled cold mixtures employing the HFMS binders and designed according to the procedures described in this report are recommended to interested highway agencies.

- Continued monitoring of the existing patches placed during this study might further differentiate among the various HFMS mixtures, all of which are performing well.

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