Where the 117/215-kN limit is imposed, the user cost would increase by 7 percent, whereas the maintenance cost would decrease by about 35 percent.

System Evaluation

The total system costs were computed for two sets of parameters. Three axle-load limit alternatives were tested: the no-limit case, the 140/255-kN-limit case, and the 117/215-kN-limit case, since a limit less than the latter one would yield a considerably higher total system cost. The highway network of 1493 km (933 miles), including existing highways, highways under construction, and highways to be constructed, was divided into 32 sections. Maintenance and construction costs and user costs were estimated for each section, then added together to obtain total system costs. Table 7 summarizes the results in terms of percentage changes.

CONCLUSIONS

General conclusions drawn from the study are as follows.

1. The axle-load limit that gives the minimum total combined costs of highway maintenance and user costs depends on pavement strength and traffic level. For a given highway, the optimum axle-load limit is no limit for the very low traffic level, a certain value for the intermediate traffic level, and again no limit for the high traffic level.
2. Although the total cost may not vary significantly by axle-load limits, public and private sectors share the total cost in considerably different proportions under different axle-load limits.
3. An axle-load limit may have significantly different effects on different types of vehicles depending on their weight and current loading characteristics. Thus, it may change the relative competitiveness of vehicles and consequently that of vehicle operators.
4. The actual level of the optimum axle-load limit depends a great deal on local conditions of existing pavement strength, present and anticipated traffic, traffic composition, loading practices, and unit costs of pavement maintenance and vehicle operation. The procedure presented in this paper, however, can be applied to any country that has a sufficiently simple highway network and vehicle fleet.

ACKNOWLEDGMENT

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Evaluation of Patching in Continuously Reinforced Concrete Pavements

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An evaluation of concrete patching in continuously reinforced concrete pavements (CRCP) located in Illinois was made. Problems in designing and constructing permanent concrete patches were identified; the costs of patching were estimated; and the performance of typical patches was evaluated. Illinois has constructed over 4827 two-lane km (3000 miles) of CRCP, major portions of which are displaying increasing occurrence of distress that requires patching. Patches placed in recent years are performing inadequately. A survey of over 800 CRCP patches showed one-fourth requiring replacement and one-fifth requiring an adjoining patch. Constructing a typical 3x3.7-m (10x12-ft) patch is labor intensive, time consuming, and expensive. Between six and eight people can only place a patch a day at a cost of $1000-1600. The poor performance of many patches can be attributed to inadequate design specifications and poor construction techniques. The information in this paper can be used to improve the design specifications and construction techniques for CRCP patching. Many experimental patches have been placed and are being evaluated.

In this paper, current problems in designing and constructing permanent concrete patches in continuously reinforced concrete pavement (CRCP) are identified. In addition, the costs of patching are estimated, and the performances of typical patches are evaluated. This information can be used to improve future CRCP patches.

Illinois has now constructed nearly 4827 equivalent two-lane km (3000 miles) of CRCP, having begun constructing CRCP as a result of the excellent performance of several experimental sections in both Illinois (e.g., the Vandalia test section in 1947-1948) and other states. The excellent performance was specifically revealed in the low maintenance requirements of the pavement, that is, no joint sealing, corner breaks, blowups, or joint deterioration and very little patching.

However, in recent years CRCP in Illinois and

Figure 1. Typical edge punchout.

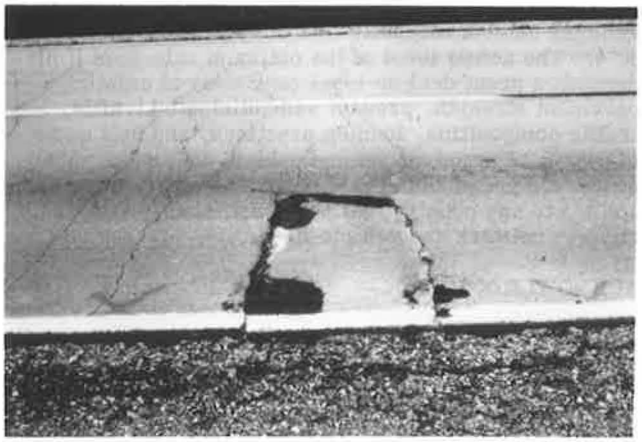


Figure 2. Effect of traffic loadings on mean edge punchouts per kilometer.

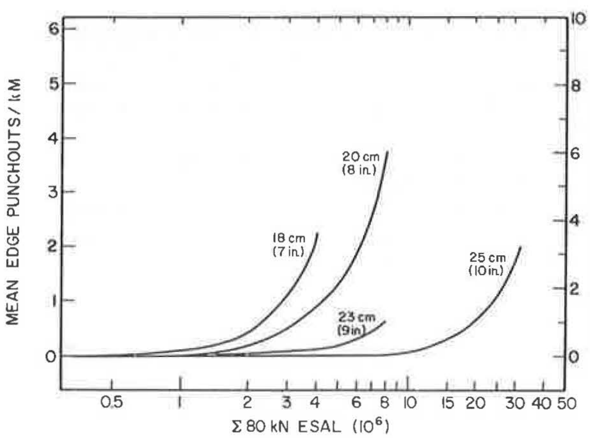
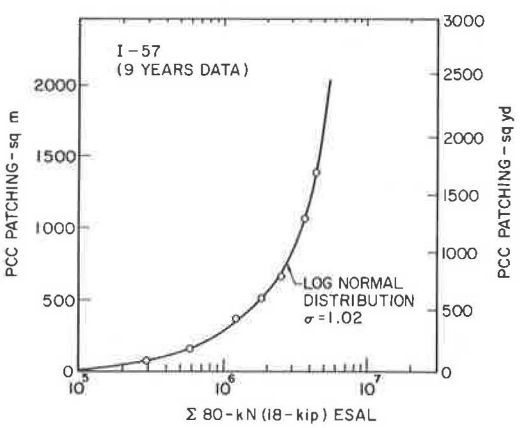


Figure 3. Cumulative patching requirements versus cumulative traffic loading.



other states has displayed increasing distress that requires permanent patches. It has also become clear that CRCP is perhaps the most difficult pavement type to repair because of its unique characteristics such as large amounts of steel and closely spaced transverse cracks. For these reasons, a research project was initiated by the Illinois Department of Transportation (IDOT) to (a) develop guidelines to assist maintenance personnel in identifying the types and causes of CRCP distress, (b) evaluate current practice and develop improved maintenance procedures and materials for repair of localized failures, (c) develop preventive maintenance procedures to reduce the rate of distress occurrence, and (d) formulate recommendations for design and construction that will reduce CRCP maintenance requirements.

This paper deals primarily with point b, evaluating current practice and developing improved maintenance procedures and materials.

CRCP DISTRESS REQUIRING PATCHING

In the initial phase of the project the types and mechanisms of distress in Illinois CRCP were studied (1). An extensive field survey was conducted of 1979 km (1230 miles) of Interstate (132 construction projects) ranging in age from 5 to 14 years. Many distress types that required pavement patching were identified.

1. Edge punchout: A block of pavement that has been depressed or punched down relative to the surrounding pavement is an edge punchout. It almost always develops at the pavement edge between two closely spaced transverse cracks (Figure 1).
2. Wide cracks: Originally tight transverse cracks widen, fault, and spall into wide cracks. Loss of aggregate interlock, corrosion, and rupture of the steel often follows.
3. Lane settlement: This entails faulting of the outside lane or separation of the two lanes at the centerline joint for a distance of 3.05-15.24 m (10-50 ft) and usually occurs along with punchouts and wide cracks.
4. Construction joint failures: The appearance near a CRCP construction joint of any of the distress types previously mentioned is such a failure. The underlying cause is poor construction techniques.
5. Blowups: A blowup is a crushing or buckling of the slab caused by thermal and moisture expansive forces. Once believed to be a nonexistent distress in CRCP, the occurrence of blowups has been increasing in recent years, especially where wide cracks exist.
6. D-cracking or reactive aggregate distress: This is a distress that originates in the concrete aggregate from undesirable chemical and physical reactions. Depending on the aggregate properties and local environment, D-cracking can eventually result in the complete disintegration of the pavement in 10-15 years.

The mechanism of development of these distress types is described in detail elsewhere (1). The importance of recognizing the various distress types and having a basic knowledge of their nature and extent cannot be understated. If properly applied, this knowledge can be used to improve the design and construction of patches. In addition, one or several of the factors causing premature patch failure may be identified and eliminated to improve patch performance.

An estimate of CRCP patching requirements, in terms of the effects of time and traffic, was determined from distress data collected from the 132 projects surveyed. A summary graph is shown in Figure 2 for 18-, 20-, 23-, and 25-cm (7-, 8-, 9-, and 10-in) CRCP. The rate of occurrence of edge punchouts for 18- and 20-cm slabs is very high. These pavements constitute a majority of the Interstate length in Illinois. It is important to note that many of the pavements have been subjected to large amounts of traffic that in many cases have exceeded the 20-year design life of the 18- and 20-cm (7- and 8-in.) slabs.

The cumulative patching requirements versus the

Figure 4. Overall performance of 831 CRCP patches in Illinois.

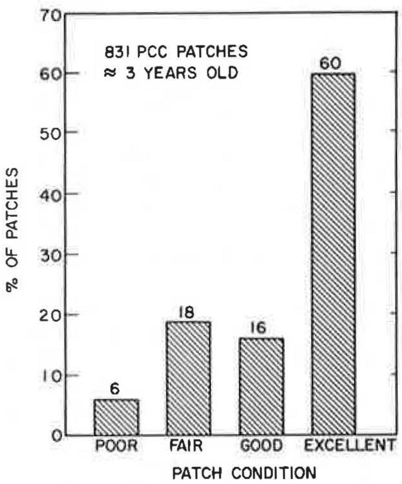
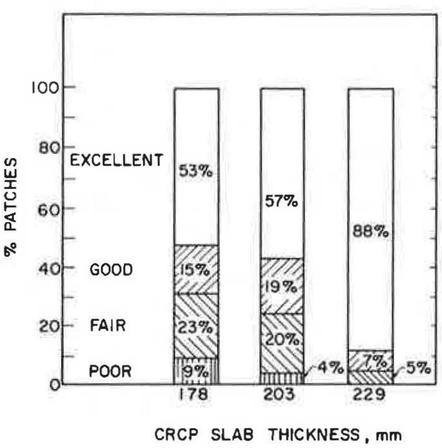


Figure 5. Performance of patches according to thickness.



cumulative traffic loadings for a given Interstate CRCP project are shown in Figure 3. The increase in patching over several years has been fitted to a log-normal distribution curve. The data indicate that distress requiring patching is greatly influenced by the fatigue damage created by large traffic loadings. Other factors, such as the environment, local pavement characteristics, and maintenance crew performance can greatly influence the amount of patching needed.

In addition to the increase in structural distress, CRCP is plagued by D-cracking in about one-sixth of the projects surveyed. Once the deterioration of the concrete pavement has progressed beyond a certain point, an extensive amount of patching is required. Many projects containing this D-cracked concrete will require major rehabilitation long before the ends of their design lives.

PERFORMANCE OF TYPICAL PATCHES IN CRCP

A field performance study of the existing patches on Interstate CRCP in Illinois was conducted. The procedures and techniques used in placing these patches will be discussed in what follows.

Nearly all of the patches surveyed were placed by either an IDOT district maintenance crew or a roving IDOT crew known as "day labor". The day labor crew travels from district to district placing patches. A few of the patches surveyed were placed by contractors repairing construction defects that appeared very early in the pavement's life. All patches placed by IDOT crews were reinforced portland cement concrete (PCC) patches.

A rating system was developed for evaluating patches on a structural basis. Each patch was evaluated and then placed in a category based on the presence of cracking, spalling, faulting, etc. In addition, records were kept of the number of patches that had severely distressed concrete adjacent to the patch. When two or more adjoining patches were found (which indicated that an adjacent distressed area had already been patched), it was counted as adjacent slab distress. Most patches surveyed were between one and seven years old, with an average of about three. As would be expected, new patches displayed fewer of the distress features. Also, some patches had been replaced one or more times. More than 800 patches located in all parts of the state were surveyed. The rating categories for PCC patches are as follows.

1. Excellent: No visible cracks are evident within the boundaries of the patch, which is smooth and flush with the adjacent pavement, and all joints are tight, although a very slight amount of joint spalling may be present in older patches.
2. Good: One or more tight transverse cracks exist within the boundaries of the patch, but no longitudinal or diagonal cracks are present and the patch is smooth and flush with the adjacent pavement. Moderate joint spalling or raveling may exist.
3. Fair: Transverse cracks within patch boundaries and joints at the patch ends display considerable spalling or faulting or both. Longitudinal or diagonal cracks that will eventually cause the patch to break up into blocks may exist. The patch may appear to rock and pump as truck loads pass over it. Replacement will probably be required within the year.
4. Poor: The patch is severely damaged and requires the removal and repatching of a major portion in the near future.

Figures 4, 5, and 6 summarize the overall results for the patch performance survey. It is interesting to note that a major proportion of the patches did not contain any cracks and were rated excellent. About one-quarter of the patches were rated fair to poor and will soon require replacement (Figure 4).

The effect of CRCP slab thickness on the patch and adjacent slab performance can be seen in Figures 5 and 6. The thinner CRCP slabs and patches exhibit more frequent occurrence of distress than the thicker slabs and patches. This seems reasonable, considering that nearly all patches were placed at the same thickness as the slab and that stresses and deflections decrease with increased slab thickness.

In summary, the data show that at least one out of every four concrete patches must be replaced with another patch and that about one out of every five patches will have adjacent slab distress that requires the construction of an adjoining patch. This high rate of patch replacement will result in excessive and unnecessary maintenance expenditures on CRCP. As will be explained, patching CRCP presents many problems not found in other pavement types.

Figure 6. Distress adjacent to CRCP patches.

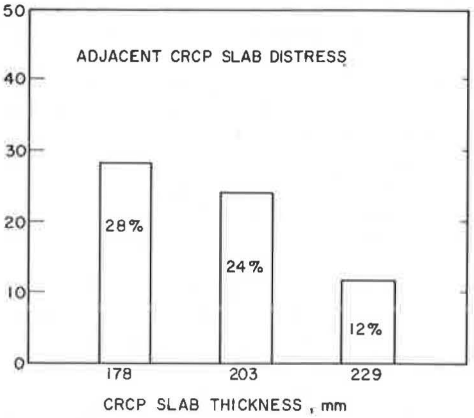
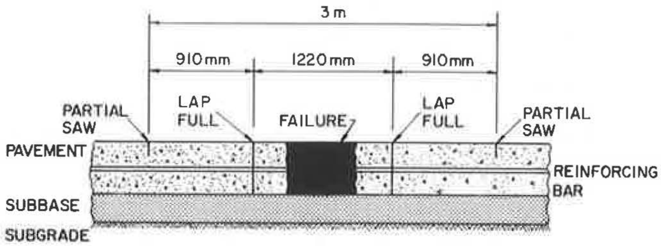


Figure 7. Section of a standard Illinois CRCP patch.



PATCHING TECHNIQUES AND COSTS

Typical Illinois Patching Procedures

Most of the IDOT maintenance crews attempt to follow a standard procedure for CRCP patching, although some have developed variations adapting to their own particular equipment, time, or crew requirements. The maintenance engineer or technician is guided by the specifications set forth in the IDOT standard specifications (2), many of which are illustrated in Figure 7. A brief list of the more important specifications dealing with CRCP patching is given below.

1. All CRCP patches must be of PCC (620.01).
2. The edges of all patches shall be sawed to a depth just above the reinforcing bar (620.05 b.1.).
3. The saw cuts shall be no closer than 45.7 cm (18 in) from an existing crack and shall not cross an existing crack (620.06 b.1.).
4. Reinforcing steel shall not be removed for patches less than 3 m (10 ft) long (620.05 b.1.).
5. For patches longer than 3 m (10 ft) (Figure 7), the steel may be cut and removed, provided that a 91-cm (36-in) length of steel is left for lap at both ends of the patch (620.05 b.2.).
6. The concrete in the area of the 91-cm (36-in) lap may only be removed by hand, so as not to damage the steel (620.05 b.2.).
7. Not more than 10 percent of the existing 91-cm (36-in) lap steel may be damaged; otherwise the patch must be lengthened (620.05 b.2.).
8. Before opening a patch to traffic, a minimum modulus of rupture of 4200 kPa (600 lb/in^2) or a compressive strength of 22 000 kPa (3200 lb/in^2) at age two days will be required (630.06 b.).

A typical patching job is performed by a district maintenance crew of from six to eight people using equipment such as a dump truck, front-end loader, air compressor, and jackhammers. Permanent patches are generally placed between April and September.

Steps in CRCP Patch Construction

From one day to several weeks before CRCP distress is to be patched, a maintenance engineer or technician surveys the project and marks off the boundaries of the distressed area. Consideration is given to the shape and size of the distressed area and to pertinent IDOT specifications (e.g., minimum distance from a crack). Regardless of the width of the distressed area, all patches are one full lane wide and 3 m (10 ft) long.

Sawing the premarked boundaries of a patch may be performed from one to several days before the actual breakout and removal of the pavement. However, some crews are able to saw the first thing in the morning and then perform the other patching operations later the same day.

The next patching operation is the removal of the distressed pavement. Removal is done in two steps: (a) the breakout and removal of the center section and (b) the breakout and removal of the end lap areas. The center section is usually broken into small pieces with jackhammers and then removed with hand tools. However, the day labor crew and some contractors have available specialized pavement-breaking equipment (drop hammers or hydrahammers) that is used on the center section (Figure 8). At least one maintenance crew completely cuts the steel around the center section and removes the pavement in one large block. A chain is then wrapped around the piece of concrete, and it is carefully lifted up and placed in a nearby dump truck.

The two end sections of the patch are supposed to be carefully broken out using only jackhammers, prying bars, picks, shovels, and other hand tools. Breaking around the reinforcing steel is a difficult, time-consuming process, especially when the required lap length is 91 cm (36 in). Because this is such a hard job, there is an irresistible urge on the part of most crews to use the drop hammers or hydrahammers to speed up their work.

After all of the distressed concrete has been removed, an attempt is made to dress and level up the subbase. Deteriorated subbases are usually not replaced with new material or compacted before placement of the concrete. If the patch was longer than 3 m (10 ft) and the old steel was removed, new reinforcing steel is installed and tied lapped to the 91 cm (36 in) of old steel to make a continuous steel connection into the adjacent slab. The new steel is matched with the existing steel in number (percentage of steel), quality, and grade. To keep the bars at the right depth in the patch, they are supported by chairs.

By this time, the patch is ready to be filled with PCC. A nearby ready-mixed concrete producer is contacted and a low-slump, seven-bag, rich mix is ordered. When the ready-mix truck arrives, the sides of the patch are wetted down in preparation for the concrete. The plastic concrete is spread from one end of the patch to the other in one lift. If a vibrator is available, it is used to consolidate the concrete around the patch ends and edges and in between the bars. The patch is then struck off, floated, and surfaced. About half the crews apply a liquid membrane-forming compound, while the rest use no curing method. Curing times range from 3 to 72 h before the patch is opened to traffic. Strength tests to determine whether the patch concrete will sustain traffic loadings are rarely conducted.

A simplified flowchart of a typical PCC patching operation is shown in Figure 9. Information con-

cerning the durations and procedures were obtained by field checks and a questionnaire was sent to maintenance personnel in each district. The usual production rate for an IDOT maintenance crew is one large 3-m (10-ft) full-lane-width patch per day. Most crews place patches on the first three or four days of the week. The last one or two days are reserved for patch curing so that all traffic lanes can be open over the weekend. Often the maintenance crews will use this time to saw the next week's patches.

Cost of a Typical Patch

The average costs for constructing a 3x3.7-m (10x12-ft) PCC patch in CRCP are shown in Table 1. The 1977 cost data were obtained from a survey of the IDOT district maintenance engineers and from observations at several patching sites. The average cost for a patch, including traffic control, labor, equipment, and materials, was found to be \$102/m^2 (\$85/yd^2). An estimate of the range of cost (1977 prices) would be \$102-\$143/m^2 (\$85-\$120/yd^2). This results in total costs of from \$1067 to \$1600 for a single CRCP standard patch.

In summary, patching CRCP is time consuming and expensive. That current design specifications and construction techniques are inadequate is reflected by the poor performance of many patches. Much confusion exists regarding when, where, and how to properly place a CRCP patch.

Figure 8. Hydrahammer breakout and mechanized pavement removal operation.

Figure 9. Flowchart of a typical PCC patching operation.

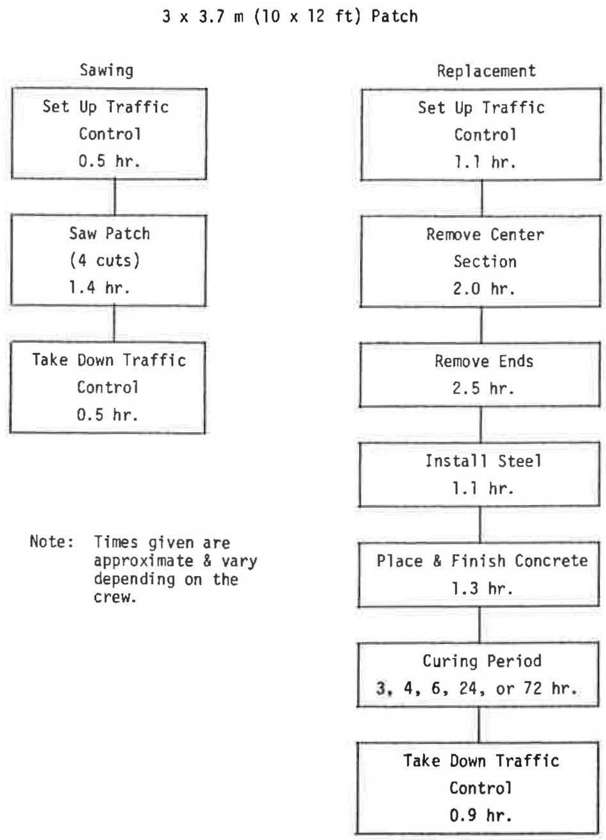


Table 1. Average costs for a typical 3.0x3.7-m (10x12-ft) CRCP patch.

Category	Costs (\$) Unit	For 3.0x3.7-m Patch	Reported Range	Percentage of Total
Traffic control				
Sawing	50/patch	50		
Set up or take down	25/time	50		
Equipment: barricades and light arrow	25/day	100		
Flagperson	60/day	60		
Subtotal		260	150-380	23
Materials				
Steel rebars	0.67/N	40		
Concrete	52.3/m^2	120		
Concrete hauling	35/truck	35		
Miscellaneous		5		
Subtotal		200	180-205	17
Equipment				
Concrete saw, dump trucks, pickup trucks, front-end loader or backhoe, compressor, jackhammers, vibrator, others		275	95-456	24
Labor				
Sawing (3 people, 2 h)				
Replacement (6 people, 8 h)	7/h	375	222-675	36
Total		1110		
Average	102/m^2			

Note: 1 m = 3.3 ft; 1 N = 0.225 lbf; 1 m^2 = 1.2 yd^2.

Figure 10. Extent of damage surrounding an edge punchout.

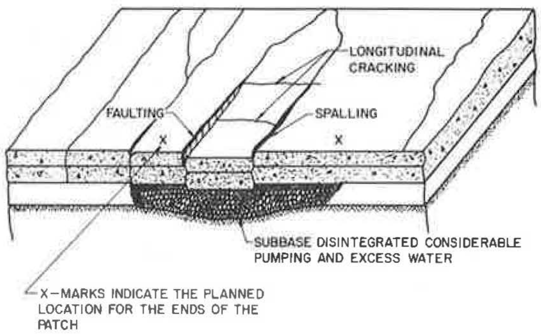
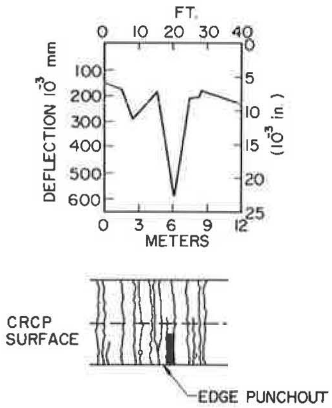


Figure 11. Deflection profile near edge punchout.



PROBLEMS ENCOUNTERED IN PATCHING CRCP

The initial step for improving the performance of CRCP patches is to identify those design features and construction techniques that contribute to patch distress. These problem areas are identified and discussed under the following patching operations.

Diagnosing Distress and Delineating Patch Boundaries

The first problem encountered in patching CRCP occurs when the engineer or technician must diagnose the distress. During this important operation, the nature and extent of the distress should be determined so that the boundaries of the patch may be delineated. Because patching CRCP is so expensive, the patched area should be kept at a minimum. At the same time, the length and width of the patch should not be so small as to adversely affect the performance of the patch or adjacent slab.

Rational guidelines for determining patch boundaries do not now exist. In most cases, maintenance personnel follow rigid specifications that tend to predetermine the boundaries of the patch, regardless of distress type. If maintenance personnel are made aware of the various CRCP distress types and causes, they can better estimate the correct patch size.

As an example, consider the definition of wide-crack distress given above. From experience, it is known that this distress is confined to a small width. Instead of constructing a standard 3-m (10-ft) long patch, a smaller more economical 0.9-m (3-ft) patch may be used.

In most instances, the engineer will have to depend on a visual observation of the pavement surface to determine the nature and extent of the distress. Since one can only see the surface, sometimes the assumption that the distress is confined to a smaller region than it actually is will be made.

For example, consider the common edge punchout shown in Figure 1 and illustrated in Figure 10. Note carefully the Xs in the picture and in the illustration. These are the actual marks made by an engineer to designate the ends of the patch. From the surface appearance of the distress in the picture, the ends of the patch appear to be sufficiently far from the edge punchout. However, it has been learned through experience, core samples, and deflection studies that a region of disintegrated subbase often extends a couple of meters beyond the edge punchout. An example of this is shown in Figure 11, where the extent of the distressed area is greater than might be observed on the surface.

Inspection of core 1 showed that the crack had spalled and faulted 3 mm (0.12 in). If the condition shown in Figures 10 and 11 exists, the patch will be too short. Either the patch or the adjacent slab will soon break up from lack of sound support.

When marking the two ends of the patch, the engineer must also consider the effect that any nearby transverse cracks may have on the patch. From research studies, it is known that a debonded region of steel and concrete exists for 15-31 cm (6-12 in) on each side of a CRCP transverse crack (3). It is expected that the length of this debonded region will increase from the jarring and shaking the reinforcing bars experienced during breakout.

Currently, the effect of locating the patch joint near a transverse crack is unknown. There have definitely been instances of fractured concrete in the region between a transverse crack and a nearby patch joint. As an example, consider the left X in Figure 1. Adjacent slab distress (e.g., spalling) might occur because of the close proximity of the transverse crack and patch joint.

Some guidelines have been issued with this problem in mind. Illinois specifies that there be 46 cm (18 in) between the nearest transverse crack and the patch joint. A Texas report recommends the patch ends be located halfway between adjacent cracks where possible (4).

To make matters worse, problems arise when engineers and technicians try to follow Illinois specifications in regions of close crack spacing. If these specifications are rigidly followed and the crack spacing is very close, it can result in an unnecessarily long and expensive patch. The minimum distance from the saw cut to the nearest crack is under study but is believed to be at least 20 cm (8 in).

Sawing, Breaking Out, and Removing the Pavement

After the patch boundaries have been sawed, the distressed pavement inside must be removed. The method of removal will depend on the specifications, the available equipment, and the preferences of the maintenance crew. Through experience, it has been learned that rectangular patches are easy to construct and give better performance than any other shape. Diagonal patches inevitably cross transverse cracks and result in spalling and corner breaks. There is some doubt as to whether the boundaries of the patch need to be saw cut.

Several states and one or two districts in Illinois break out patches with jackhammers and use transverse cracks as boundaries where possible. The rest of the

Figure 12. Equipment damage to subbase and subgrade.

districts saw cut the boundaries as shown in Figure 7. While sawing can raise the cost of patching by 4-10 percent, it reduces spalling along the joint. A sawed joint provides a clean vertical face that gives a good bond between the patch concrete and the existing slab, and a tight joint will be formed. Field surveys of sawed joints show significant resistance to spalling, while nonsawed boundaries show considerable spalling.

Another important reason for sawing patches is to reduce the transmission of damaging shock waves into the adjacent pavement during break out. The hydrahammer and drop are particularly damaging. The gap made by both the partial- and full-depth saw cuts protects the adjacent pavement from fracturing and the steel from debonding.

Before the distressed segment of concrete can be removed, it is usually broken into small pieces that are easy to remove. The pavement-breaking job can be done with jackhammers or with specialized pavement-breaking equipment such as drop hammers or hydrahammers (Figure 8). If not operated carefully, however, this heavy equipment is capable of damaging the subbase, reinforcing steel, and the adjacent slab. In particular, the heavy equipment should never be used in the lap area because it generally fractures the adjacent slab and debonds the steel from the concrete. Undercutting of the adjacent slab also occurs. Poor breakout techniques are suspected of being a major cause of adjacent slab distress.

Evaluating the Condition of the Subbase and Subgrade

After the distressed concrete has been removed, the maintenance crew can examine the subbase and determine its condition. In many instances, the subbase will be saturated and badly disintegrated (Figure 12). The generally poor condition of the subbase can be expected whenever a patch is planned for an edge punchout or wide crack or when lane settlement suggested by faulting along the centerline between lanes exists. This is because the initiating factor in these two distresses and several others may be a localized loss of support. This loss of support can be caused by (a) a weak subgrade underneath the subbase, (b) accumulation of water in the subbase and subgrade, and (c) disintegration of the stabilized subbase and localized pumping of the stabilized granular subbase. Much foundation support is lost by allowing the distressed area to deteriorate and spread to a large area.

There are no known guidelines for inspecting and evaluating the condition of the subbases. These are needed so that the maintenance crews can apply corrective measures to improve the subbase and subgrade when necessary. The type of subbase (granular or stabilized), thickness of the slab, amount of free water present, subgrade condition, and planned patch thickness are important factors in evaluating the subbase and applying corrective measures.

Over the years, several corrective measures have been used to improve the subbase and subgrade for a patch. Examples would include (a) removing the entire thickness of subbase and replacing with concrete, (b) recompacting the existing subbase, or (c) installing a lateral drain beneath the patch for a path located in a low, wet area. These activities can usually be performed at moderate cost and time increases.

Installing and Splicing the Reinforcing Steel

There are four major unresolved problems associated with installing and splicing the reinforcing steel. First, the minimum length of lap splice required to provide a continuous connection between the patch and the adjacent slab is not known. The lap between the existing bars and the newly installed steel should be long enough to prevent a pullout when the adjacent slab contracts. If slippage does occur, the patch joint will either open up or a series of wide cracks will develop near the ends of the patch.

The current Illinois specification requiring a 91-cm (36-in) tied lap splice appears to be excessive and is not based on any data. Theoretical and experimental work (3) indicates that a 51-cm (20-in) tied lap would be reasonable for number 5 bars. In addition, shorter lap requirements result in much less damage to the steel during breakout.

The second problem encountered by maintenance crews is the occurrence of corroded, nicked, or bent rebars in the lap area. The cross-sectional area of the rebar is often reduced by corrosion or by careless removal operations. This might cause the steel rebar to yield excessively and result in a wide crack, usually at the patch joint. Also, some crews bend the lap bars up so they can easily remove pavement debris. The bars are then bent back to an S-curve. This has been identified as causing distress in some patches.

The third problem occurs when maintenance crews are patching in CRCP reinforced with welded wire fabric. It is difficult to match the new steel with this old steel because of differences in the size and number of bars.

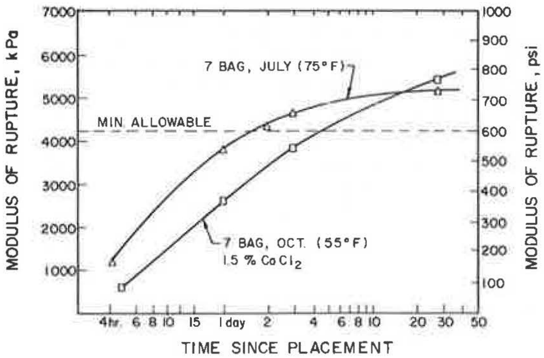
Finally, as an alternative to using the relatively long lap splice, some patching crews have attempted to use a short, 15-cm (6-in), single lap weld to make a continuous connection. Lap welding shows some promise for reducing the time of patching. However, welding equipment must be available at the patch site. Also, it is difficult to get high-quality welds on rebar.

Curing Time of Patch

The standard specified curing procedure is to allow the concrete to reach a modulus of rupture (center point loading) of 4100 kPa (600 lbf/in^2) or a compressive strength of 22 000 kPa (3200 lbf/in^2). Because of varying district policies, the curing time for patches before they are opened to traffic ranges from 3 to 72 h. If possible, most maintenance crews would prefer to open the patch the same day it is placed to avoid costly nighttime traffic control.

A question arises about what the minimum curing

Figure 13. Patch concrete strength gain.



time for a patch concrete is, in order that it not incur significant damage from traffic loading. Subjective evidence indicates that patches placed and opened the same day (about 4-5 h of curing) are replaced more often than those that cure from 24 to 72 h.

Data were collected from several patching sites to determine the typical strength-time relation for the concrete used in actual patching. A plot of some typical results is shown in Figure 13. The patches were placed during warm weather in July and during cool weather in October. The mean modulus of rupture over time is plotted from beam breaks. To achieve the 4100-kPa strength, the July patch should have been closed to traffic for 40 h and the October patch for 110 h. If the patches had been opened to traffic before these times, would any damage have resulted? Even if the patch had cracked, would not the crack have acted like a typical transverse crack in CRCP and have remained tight because of the amount of reinforcement present? The answer to the second question can be obtained from lab and field observations and the answer to the first from analytical analysis.

Tests are being conducted to determine the early strength of ready-mixed concrete used for patching. The effects of concrete mix design and curing procedures on the early strength of patch concrete are also being considered in these tests.

EXPERIMENTAL PATCHES

An experimental patching program is under way to field test various alternate patch design features and construction techniques. Discussions with IDOT maintenance personnel, analytical analyses, field observations, and information gained from other states were all considered in developing a comprehensive list of potential patching improvements.

Those design and construction alternatives that have the greatest potential were selected for field testing. Examples of these alternatives include (a) varying the length, width, and thickness of the patch, (b) undercutting the adjoining slab next to a patch, (c) shortening the length of tied lap splices, (d) welding splices, (e) varying the patch concrete mix design, (f) slab jacking patch ends, (g) placing subdrainage, and (h) constructing asphalt concrete patches. Many experimental patches were placed in 1977 and 1978 and are currently being field tested.

CONCLUSIONS

Constructing high-quality, economical CRCP patches is not an easy task. It is vitally important that the design and the construction methods for CRCP patching be improved so that the service life of CRCP pavements can be extended.

1. Considerable CRCP patching will be required on many projects in the future. This is because the load- and environment-associated distress is increasing on many CRCP projects.
2. Several of the more common distress types that require patching were identified. These include edge punchouts, wide cracks, centerline lane settlement and faulting, construction joint failure, blowups, and D-cracking. Patches should be designed by considering distress type and cause. Placing a standard patch for all distress types is not the solution.
3. CRCP patches suffer from an unacceptable rate of failure, and corrective measures to improve patch performance should be taken. At least one out of every four patches must be replaced with another patch, and one out of every five patches shows distress in the adjacent slab. This requires additional patching.
4. The standard Illinois patching procedure needs significant revision to better represent the conditions encountered by private contractors and state maintenance crews. The standard patch procedure was initially developed for contractor use in repairing defects in new construction.
5. CRCP patching is very expensive. Average costs for a typical 3x3.7-m (10x12-ft) patch are $102/m^2 ($85/yd^2) or more than $1000/patch.
6. Current patching procedures are labor intensive and time consuming. A six- to eight-person crew can only repair one single isolated patch per day. Traffic lanes are often kept closed for three days to allow the patch to cure.
7. There are many unresolved problems associated with CRCP patching. Major problems have been encountered in the following areas: diagnosing the distress and delineating the patch area; sawing, breaking out, and removing the pavement; evaluating and improving the condition of the subbase and subgrade; installing and splicing the reinforcement; and curing the patch concrete.
8. An experimental patching program is under way to evaluate costs, lane closure time, and patch performance. The object of this program is to develop maintenance guidelines so that long-lasting, economical CRCP patches can be easily constructed.

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Evaluation of Highway Maintenance Cost and Organization in Pennsylvania

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The analysis focuses on Pennsylvania's highway maintenance organization in its 67 counties and the cost of five maintenance activities common to all counties: manual patching, mechanical patching, shoulder repair, surface treatment, and snowplowing. In this analysis those counties and groups of counties that produce these activities at either very high or very low total costs relative to one another will be identified. Operational and environmental factors that cause maintenance costs to vary from county to county will be used in multiple regression techniques. Based on the comprehensive nature of the variables used to explain variation in maintenance costs, inferences are made about the relative efficiency of county maintenance organizations according to actual total costs compared to those predicted by the regression equations. These equations were based on data from 1976. The primary source of operational data was the highway maintenance management system developed for the Pennsylvania Department of Transportation. The study compares counties that produce unusually high- or low-cost maintenance and gives possible reasons for unexplained cost variations by examining operational characteristics. On-site management studies are recommended in order to identify areas for efficiency and cost savings.

In the last 30 years Pennsylvania has constructed a vast highway network. In 1977, the total state-maintained system amounted to 72 000 km (45 000 miles). Recently, because of the mounting cost of construction and debt service, the push for construction has diminished and increased emphasis has been placed on maintaining and improving the existing system. This trend is anticipated to continue.

This study was directed toward dealing with the problems of the efficient and effective use of resources in one area of the total highway maintenance operation, specifically, the operations of the 67 highway maintenance organizations located in the 67 counties of Pennsylvania.

The questions that prompted the study concern the comparability of maintenance work done in the county maintenance organizations in terms of cost, quality, quantity, efficiency, and effectiveness. Critical questions addressed concern which factors influence the total cost of various maintenance activities, which counties vary significantly from the statewide norm for costs of producing a particular maintenance activity, and why some counties do vary. It was hoped that identifying these counties would provide the impetus for an in-depth review of maintenance activities in them in order to determine the operational reasons for the variations.

Highway maintenance functions consist of a large number of individual activities. In order to make the study manageable in terms of length, only five maintenance activities were examined: surface treatment, manual patching, mechanical patching, shoulder operations, and snowplowing. They were selected because they represent a major share of the cost and time of highway maintenance and because they represent summer as well as winter maintenance activities.

Hypothesized cost functions, developed for each of the activities listed above, were estimated through the use of multiple regression analysis. The results were then used to determine which counties vary considerably from expected behavior. These counties were then singled out for a special analysis of the possible causes of their deviation.

This study was thus intended to be a first step in an effort to analyze highway maintenance in Pennsylvania and thus to increase efficiency and reduce costs. It did not provide definitive results in itself but did identify counties that may need on-site management studies. It should also be noted that the method employed was intended to be flexible enough to be applied to the management of highway maintenance on a yearly basis. The Pennsylvania Department of Transportation (PennDOT) is now using the study method and two recent years of management data to validate the models and results. This new study could serve to further refine the method and to provide conclusive evidence of the value of initiating management studies in the identified counties.

THEORETICAL CONSIDERATIONS

Economic theory states that the level of output is the major influence on the cost of production. Costs may rise at an increasing, constant, or decreasing rate as output increases. However, when one is examining behavior across many plants or counties it is necessary to consider other influences on costs that become important because of variations in conditions and practices across the counties. Werner Hirsch in his study of urban refuse collection provided a framework for this type of analysis (1).