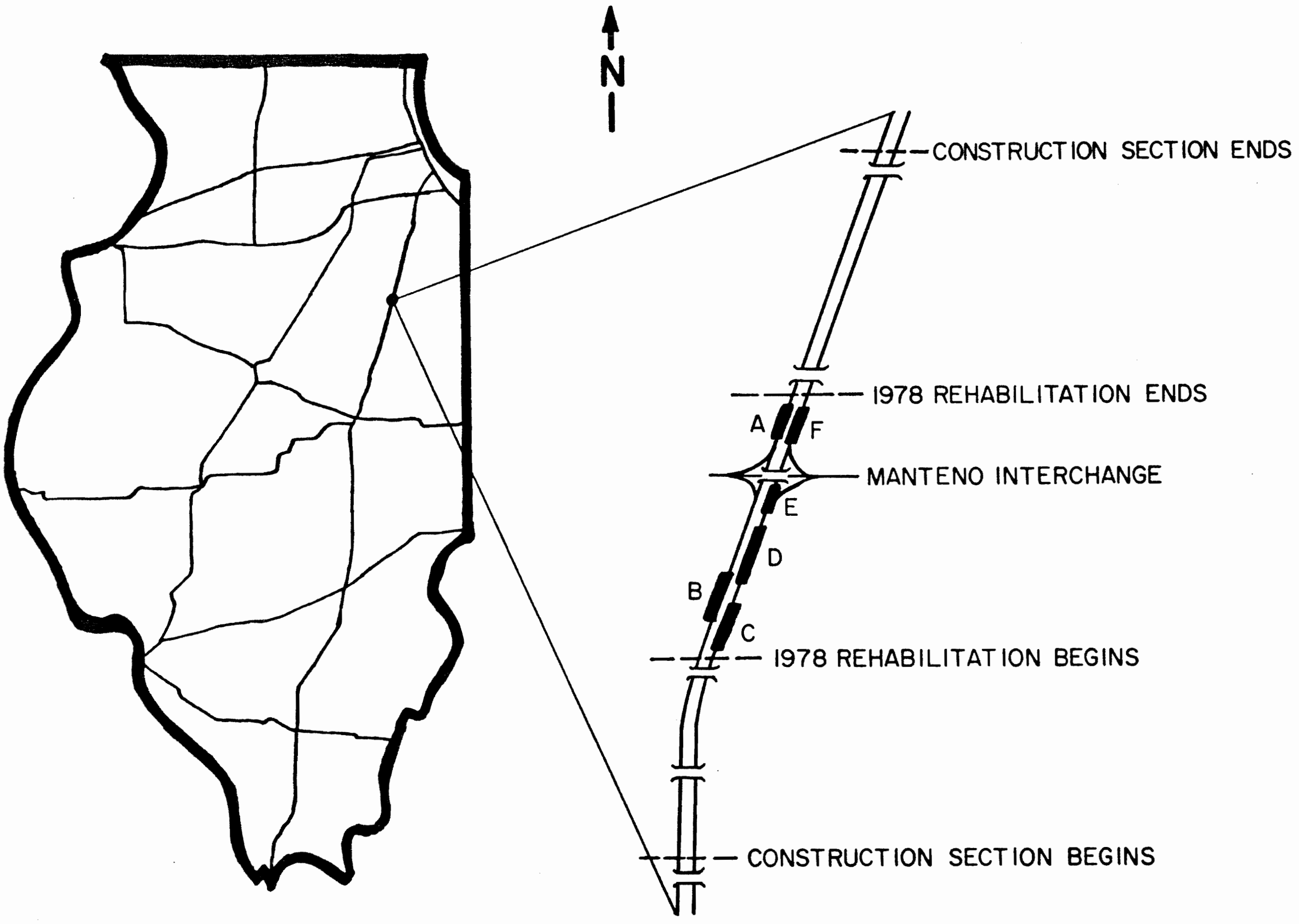

FIGURE 1 Location of I-57 Manteno rehabilitation project and test sections.

condition, although deterioration of the CRCP had occurred adjacent to many of them, requiring additional patching. Aside from the extent of structural damage evident in the preceding numbers, the quantity of unrepaired failures (punchouts plus wide cracks) gives an indication of the pavement's poor ride quality: 87 and 60 failures in the northbound and southbound lanes, respectively, or 13.2 and 9.1 failures per mile. Serviceability of CRCP tends to be poor when the number of unrepaired failures exceeds about 10 per mile.

Not included in the aforegoing quantities are failures in the CRCP adjacent to joints in the JRCP ramps. Such failures appear to be due to joints in the ramps opening and forcing otherwise tight cracks in the CRCP to open. Although not caused strictly by load, the cracks deteriorate rapidly under traffic. This distress is difficult to repair: often when such failures are patched, the ramp joint forces a crack in the patch. Failures adjacent to ramp joints have been frequent occurrences on many CRCP sections of the Illinois Interstate system built before 1967, when design specifications permitted CRCP to be built with either JRCP or CRCP ramps. Around 1967, the specification was changed to restrict ramps for mainline CRCP to be CRCP also (*2*). This section of I-57 at Manteno, however, was constructed prior to that time. During the 1978 distress survey, twenty failures adjacent to ramp joints were observed in the northbound lanes and nine in the southbound lanes.

The other major distress observed during the 1978 distress survey was pumping, which was rated as extensive in both directions. The pavement was not originally constructed with underdrains. The pumping, as well as the variability in condition along the project and between directions, suggests generally poor and possibly variable support, which is typical for the topography and soil of the area.

PREOVERLAY REPAIR AND AC OVERLAY

Based on the 1978 survey results, the Manteno section was selected to be among the first CRCP rehabilitation projects conducted in Illinois. Sufficient funds to repair the entire 6.6 miles of the project were not available, however, so the rehabilitation was limited to the middle 3.1 miles of the project in the vicinity of the Manteno interchange. Figure 2 illustrates that the majority of the distress was located in these middle 3.1 miles. The rehabilitation techniques applied are briefly described in this paper. Complete details are given elsewhere (*1*).

Test Sections

Within the rehabilitation project limits, six test sections were established to evaluate combinations of the techniques. The

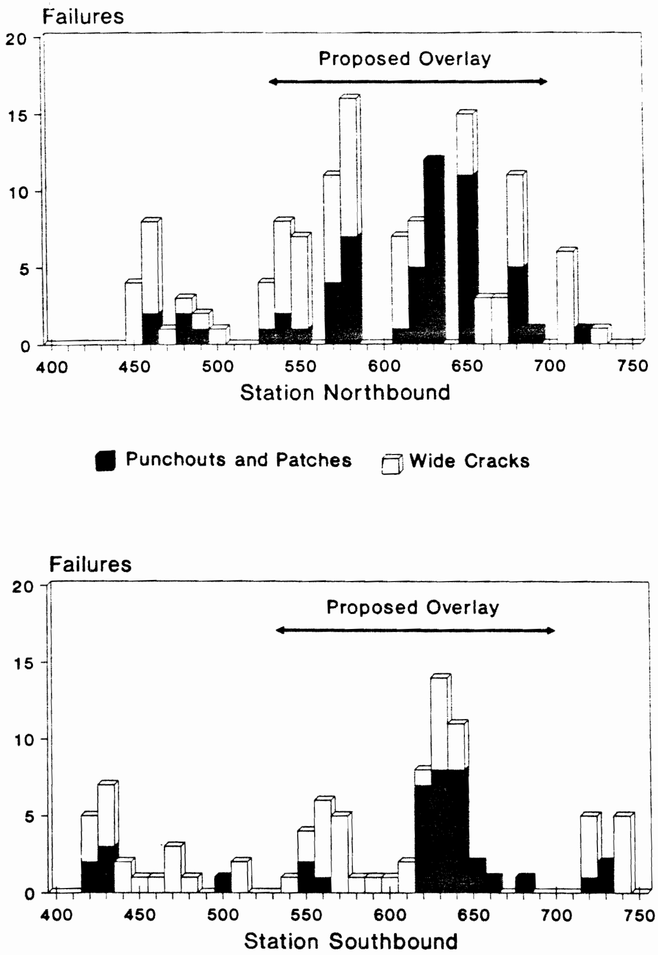

FIGURE 2 Distribution of distress along length of I-57 Manteno project.

locations of the test sections are shown in Figure 1. The length of each section and its condition before rehabilitation follow:

Section	*Direction*	*Length (ft)*	*Existing Failures*	*Existing Failures/Mile*
A	South	2,000	0	0.0
B	South	2,250	16	37.5
C	North	2,800	25	47.1
D	North	2,100	27	67.9
E	North	2,000	7	18.5
F	North	2,600	13	26.4
Total:			88	

Since the sections are of different lengths, failures per mile are given for comparison. Except for section A, which was chosen as a control section, the number of failures per mile is very high for all of the test sections, considerably higher than the average distress levels over the project reported before. This is a reflection of the earlier statement that the middle portion of the project that was rehabilitated was in much worse condition than the two end portions. Note also that the sections vary widely in condition, which is a reflection of the variability in condition even within the rehabilitation project limits. Section D, for example, has almost four times as many failures per mile as section E.

Deflections were measured within the test sections before rehabilitation with IDOT's heavy-load Road Rater. A statistical analysis of the deflection data showed that failure occurrence within a test section was not well correlated with mean deflection but was strongly correlated with the coefficient of variation of deflections (*1*). This was explained by way of the analogy of a chain being only as strong as its weakest link. High variability in deflections within a test section indicates that many localized areas have deflections considerably higher and considerably lower than the section average. Localized areas with unusually high deflections are prime locations for structural failure.

Full-Depth Repairs

The standard IDOT design for CRCP full-depth repair in 1978 was PCC with reinforcing steel tied into the existing slab with 36-in. laps on each side. The specified minimum repair length was 10 ft. Design details are shown in Figure 3. Several such repairs, placed by maintenance crews, were already in place on the project.

Two experimental, full-depth repair designs were developed and tested on this project. The first design used 20-in. tied laps, and the second used two 4-in. welded laps, together with a 16-in. tied center lap. Details for the two experimental repair designs are shown in Figure 4. The purpose of both designs was to reduce the cost of a repair by reducing repair size and lap length. The specified minimum length for the 20-in. tied-lap repair was 5 ft, and the minimum for the 4-in. welded-lap repair was 3 ft. The shorter repair lengths reduce the material costs for the repairs. More important, however, is that the shorter lap lengths greatly reduce the length of concrete that must be broken out by hand around the existing reinforcing steel. That process is a very labor-intensive and time-consuming task that adds quite a bit to the cost of full-depth repair for CRCP.

Two less expensive repair designs were also used in a few locations. One was PCC in which the repair itself contained no reinforcement, although the reinforcement in the existing slab extended about 10 in. into the repair area on both sides. Partial extension of the reinforcement into the repair area contributes to load transfer across the repair joints; since the steel is not carried through the repair, however, continuity of the CRCP is not restored, and repair or repair-adjacent distress is more likely. This repair design is not well suited for

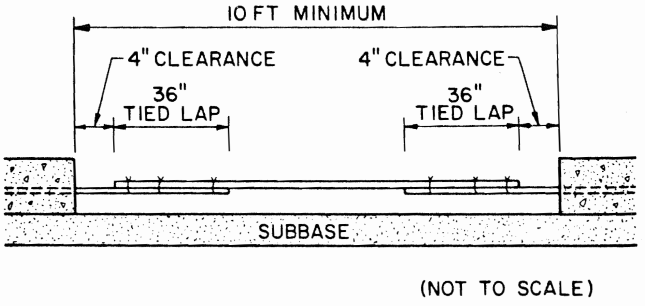

FIGURE 3 Design details for IDOT's old standard CRCP repair with 36-in. tied laps.

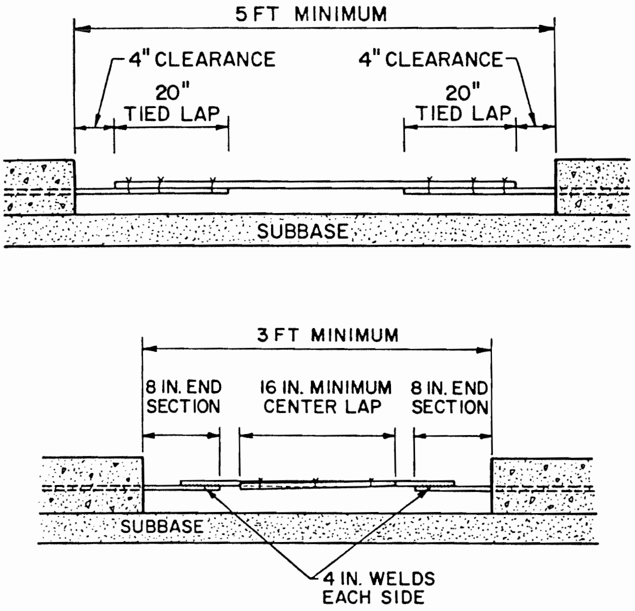

FIGURE 4 Design details for experimental CRCP repairs with 20-in. tied and 4-in. welded laps.

CRCP except for short-term use, as in the case of a severely deteriorated pavement that will be replaced within a few years. The Illinois DOT has placed a number of these unreinforced PCC repairs on CRCP under these circumstances with satisfactory results (*3*).

The second type of inexpensive repair used was full-depth AC. This repair design provides neither continuity nor load transfer and is therefore highly susceptible to repair or repair-adjacent distress. Furthermore, expansion of the CRCP into the repair area in hot weather can compress the AC and create a sizeable hump, which reduces serviceability and may even pose a safety hazard. Full-depth AC is not well suited for repair of CRCP, except for temporary use, as in the case of a blowup (*3*).

Of the 88 repairs placed on the project, 45 were located within the test sections: 30 welded repairs, 10 tied repairs, 2 unreinforced repairs, and 3 full-depth AC repairs. The test sections also included 11 old (36-in. tied-lap) repairs placed by maintenance crews. Welded repairs were placed in test sections B, C, and D; and tied repairs were placed in sections E and F. No repairs were placed in section A. Repair locations are given in Table 1.

Epoxied Cracks

Since funds for this project were limited, full-depth repairs were placed only at punchouts and at high-severity, deteriorated transverse cracks. The remaining deteriorated cracks were repaired with epoxy. The intent of the epoxy treatment was to bond the sides of the cracks back together and restore continuity to the slab at a much lower cost than that of full-depth repair.

Cracks were prepared for epoxy sealing by airblasting. The epoxy was a two-component, high-modulus, moisture-insensitive material, mixed in small quantities at the locations where it was used. It was applied to the cracks in two steps. The

TABLE 1 SUMMARY OF REHABILITATION WORK DONE IN TEST SECTIONS

	A	B	C	D	E	F	Total
Welded FDRs	0	8	15	7	0	0	30
Tied FDRs	0	0	0	0	1*	9	10
AC FDRs	0	0	1	1	1	0	3
No-steel FDRs	0	1	0	0	1	0	2
Existing FDRs	0	0	1	6	4	1	11
Epoxied Cracks	0	7	8	17	5	6	43
Unrepaired Cracks	0	0	1	1	0	0	2
Undersealing	NO	NO	CG	AS	CG	AS	
AC Overlay	YES	YES	YES	YES	YES	YES	

* Four tied repairs placed adjacent to ramp joints are not included.

** CG - cement grout undersealing
AS - asphalt cement undersealing

first application was epoxy alone, to coat the crack walls. For the second application, the epoxy was mixed with an oven-dry silica filler to fill up the cracks.

Undersealing

Undersealing was done in both lanes to fill voids under the pavement that were indicated by pumping and located by deflection testing. Two materials were used for undersealing: cement grout and asphalt cement. Blanket undersealing was performed in areas in poor condition overall. Selective undersealing was performed in areas in better condition, at specific locations identified by observed pumping and high deflections.

Underdrains and AC Overlay

After the preoverlay repair work was completed, pipe underdrains were placed on both sides of the pavement throughout the length of the project, and a 4-in. AC overlay was placed on the lanes and shoulders.

10-YEAR PERFORMANCE RESULTS

Five sets of data have been collected on the condition of the project at different times: in 1978 just before and just after the overlay was placed, at 10 months (1979), at 5 years (1983), and at 10 years (1988). Visual condition surveys were performed, and all distresses observed within the test sections were mapped and photographed. Strip maps showing test section limits, stationing, and exact locations of all full-depth repairs and epoxied cracks were used for mapping distresses and recording the locations of all photographs taken. Nondestructive deflection testing was performed by IDOT personnel with the IDOT Road Rater, at locations marked out by the project team. Deflections were typically taken at 50-ft intervals to coincide with stations along the project length. In several selected locations of interest (e.g., in the vicinity of a full-depth repair or epoxied crack showing significant distress) a series of closely spaced deflections was taken.

Performance of Full-Depth Repairs

The welded and tied repairs have both given excellent performance. Only two welded repairs and one tied repair have failed (as evidenced by high-severity reflective cracking) at the present time and need to be replaced. The only other reflective cracking associated with the repairs is of low severity. The performance of the various types of repairs is summarized in Table 2.

The performance of the welded repairs is illustrated by the series of photos in Figure 5. The first photo was taken in 1978 at a deteriorated construction joint. The pavement had actually blown up in the inner lane and been temporarily patched with AC. The next two photos were taken at the same location just after welded repairs P30 and P31 had been placed. The last photo was taken in 1988.

These photos illustrate the excellent performance of the welded repairs. The performance of the tied repairs has also been excellent. Throughout the test sections, 80 percent of the welded repairs (24 of 30) and 70 percent of the tied repairs (7 of 10) have not reflected through at all in 10 years. Likewise, 91 percent (10 of 11) of the old tied repairs, which are all more than 10 years old, have not reflected through. This clearly demonstrates that tied or welded repairs can be placed on CRCP without causing subsequent reflective cracking in an AC overlay.

The less expensive repairs have not performed well. Two of the three full-depth AC repairs have experienced rutting and shoving as well as reflective cracking. Figure 6 provides a series of photos taken where full-depth AC repair P60 was placed. The first photo shows a working crack to be repaired. The newly placed AC repair is shown in the second photo, taken in 1978. The third and fourth photos were taken during the 1983 and 1988 surveys.

One of the unreinforced PCC repairs is intact and exhibits no distress at this time, but the other one has caused a medium-severity reflective crack at one joint. This is better perfor-

TABLE 2 PERFORMANCE OF FULL-DEPTH REPAIRS IN TEST SECTIONS

	DISTRESS SEVERITY				
REPAIR TYPE	NONE	LOW	MEDIUM	HIGH	TOTAL
36-inch tied PCC	10	1	0	0	11
20-inch tied PCC	7	2	0	1	10
4-inch welded PCC	24	4	0	2	30
Unreinforced PCC	1	0	1	0	2
Full-depth AC	1	0	0	2	3

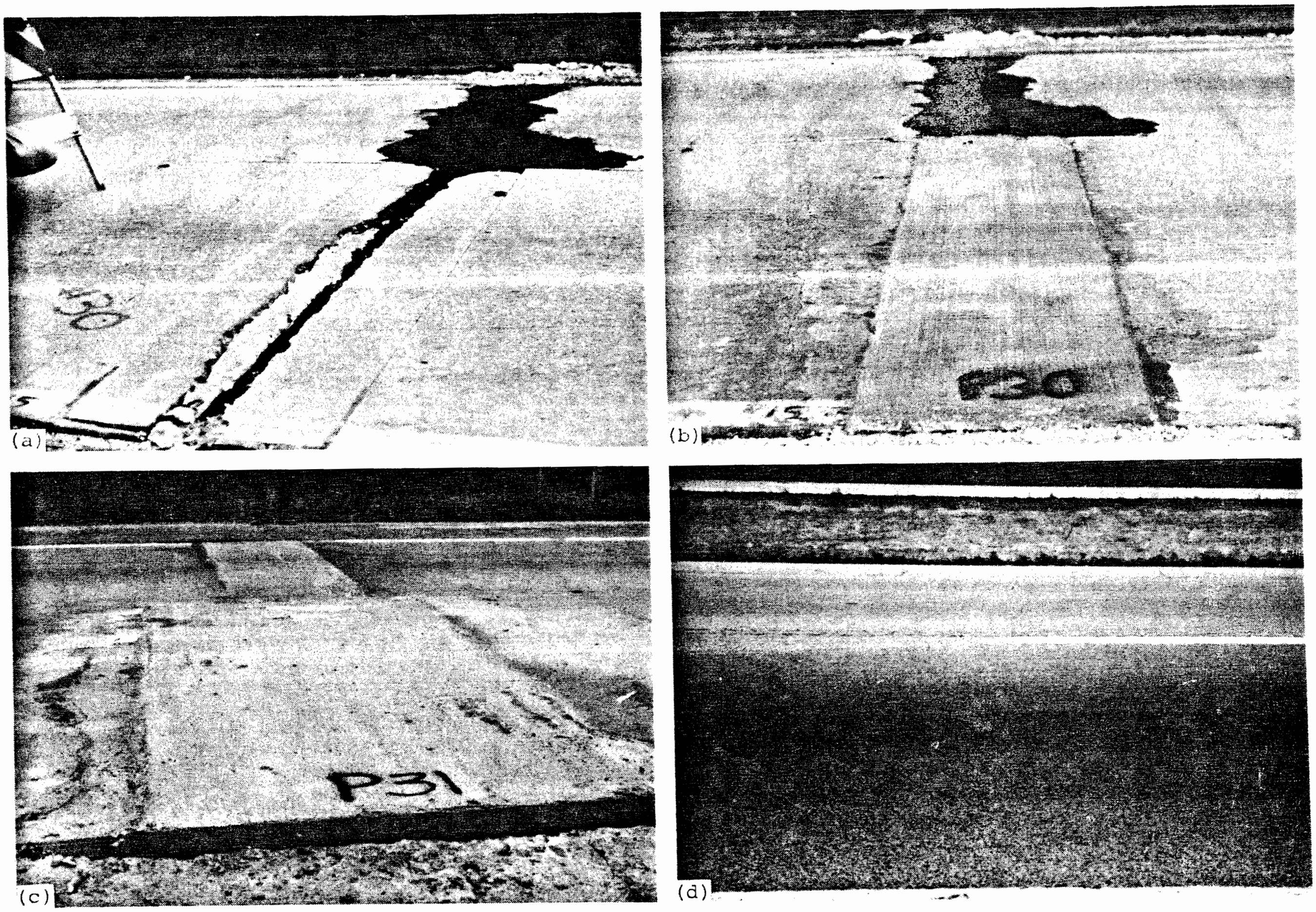

FIGURE 5 Performance of welded full-depth repairs. (a) Deteriorated construction joint before repair. (b) Welded repair P30 placed in outer lane. (c) Welded repair P31 placed in inner lane. (d) No reflection cracking in overlay in 1988.

mance than was expected from the unreinforced PCC repairs but still is not satisfactory.

Performance of Epoxied Cracks

The crack-epoxying treatment did not perform as intended. Even before the overlay was placed in 1978, observers noted that the epoxy bond had failed at many of the cracks within 2 days to 3 weeks after treatment. Some had failed at the epoxy-concrete interface, which may have been due to insufficient cleaning of the sides of the cracks. Many others, however, had failed within the epoxy, suggesting it was not capable of withstanding the large horizontal movements resulting from daily temperature cycling in the CRC slab. Figure 7 shows a series of photos taken at epoxied crack E4. The first photo was taken in 1978 before the crack was filled. The second photo was taken during the 1979 survey (10 months after the overlay was placed) and shows the low-severity reflected crack that had already come through the overlay. The third and fourth photos, which were taken during the 1983 and 1988 surveys, show the progression of the reflected crack to medium and high severity.

The AC overlay reduced deflections at the epoxied cracks, but the deflections have gradually increased as the cracks have reflected through, as illustrated by the deflection profile for a typical epoxied crack shown in Figure 8. The rate at which the epoxied cracks have reflected through the overlay is illustrated in Figure 9.

Effect of AC Overlay on Deflections

The 4-in. AC overlay reduced mean deflections in the six test sections to an average of 55 percent of their preoverlay levels. The mean deflections have gradually increased over time, however, as illustrated in Figure 10, and are now, on average, at 88 percent of their preoverlay levels. The following is a comparison by test section of preoverlay deflections and 1988 deflections:

Section	*Mean Deflection Before Overlay*	*Mean Deflection in 1988*	*Percent of Preoverlay Deflection*
A	7.74	5.43	70
B	10.05	6.16	61
C	7.82	6.80	87
D	6.17	6.55	106
E	5.50	5.09	92
F	7.02	7.90	113

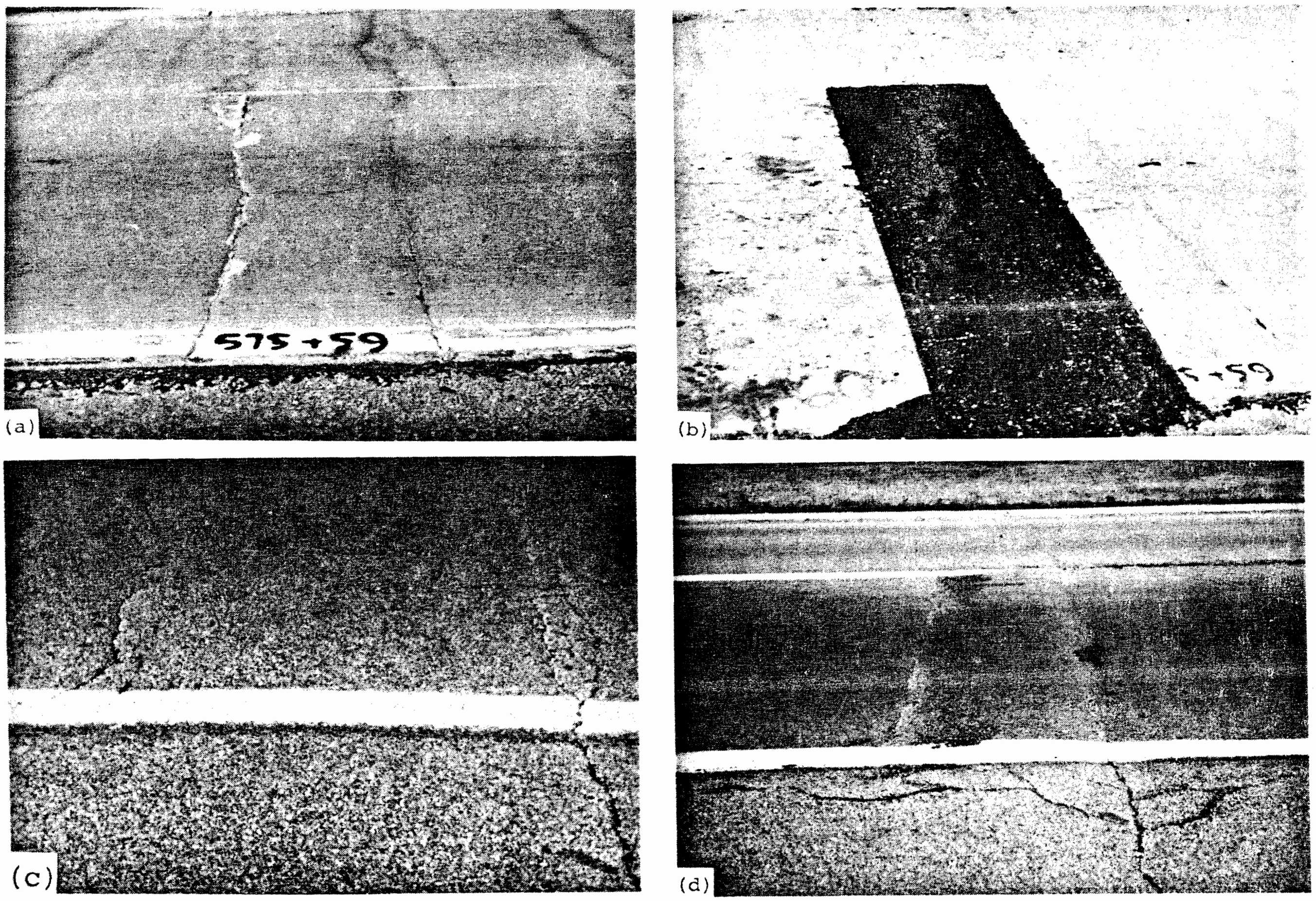

FIGURE 6 Performance of full-depth AC repair. (a) Wide transverse crack before repair. (b) Full-depth AC repair P60 placed in outer lane. (c) Reflection cracking in 1983. (d) Reflection cracking in 1988.

Mean deflections (reported in mils) were taken at 50-ft intervals with the IDOT Road Rater using a 5-kip, 15-Hz load.

Averaging the results from the six test sections together, deflections have steadily increased since 1978, which suggests that progressive deterioration of the overlay and/or underlying concrete slab is taking place. However, the pavement does not appear to have experienced any "new failures" since the overlay was placed. After 5 years (1983), 15 medium- and high-severity reflective cracks not associated with underlying full-depth repairs or epoxy crack treatments were observed in the six test sections, but only those same fifteen cracks were rated at medium or high severity during the 1988 survey. It is likely, therefore, that those cracks were low- to medium-severity cracks that were not repaired in 1978 before the overlay was placed. Despite the nearly 5 million ESALs applied to the pavement between 1983 and 1988, fatigue damage has not yet been manifested in any additional cracking.

Reflective Crack Occurrence

An examination of the data by test section shows that reflective crack occurrence on the overlay after 10 years of service is a function of (1) the number of high-severity failures full-depth repaired prior to overlay, (2) the number of low- to medium-severity cracks not repaired prior to overlay, and (3) whether or not undersealing was performed.

Section	*Preoverlay Full-Depth Repairs/Mi*	*Preoverlay Unrepaired Failures/Mi*	*Undersealed*	*Reflective Cracks/Mi After 10 Yr*
A	0.0	0.0	No	0.0
B	3.4	3.4	No	7.2
C	8.5	5.3	Yes	2.6
D	5.2	7.2	Yes	1.6
E	1.9	2.3	Yes	0.8
F	4.4	3.0	Yes	1.0

The relationship among these factors is expressed by the following multiple regression equation:

$$\text{REFCRK} = 2.18 + 0.42\ \text{FDR} + 0.42\ \text{CRACKS} - 4.67\ \text{UNDERSEAL}$$

where

REFCRK = deteriorated reflection cracks per mile in AC overlay;
FDR = number of full-depth repairs placed per mile;
CRACKS = number of previously unrepaired cracks per mile;

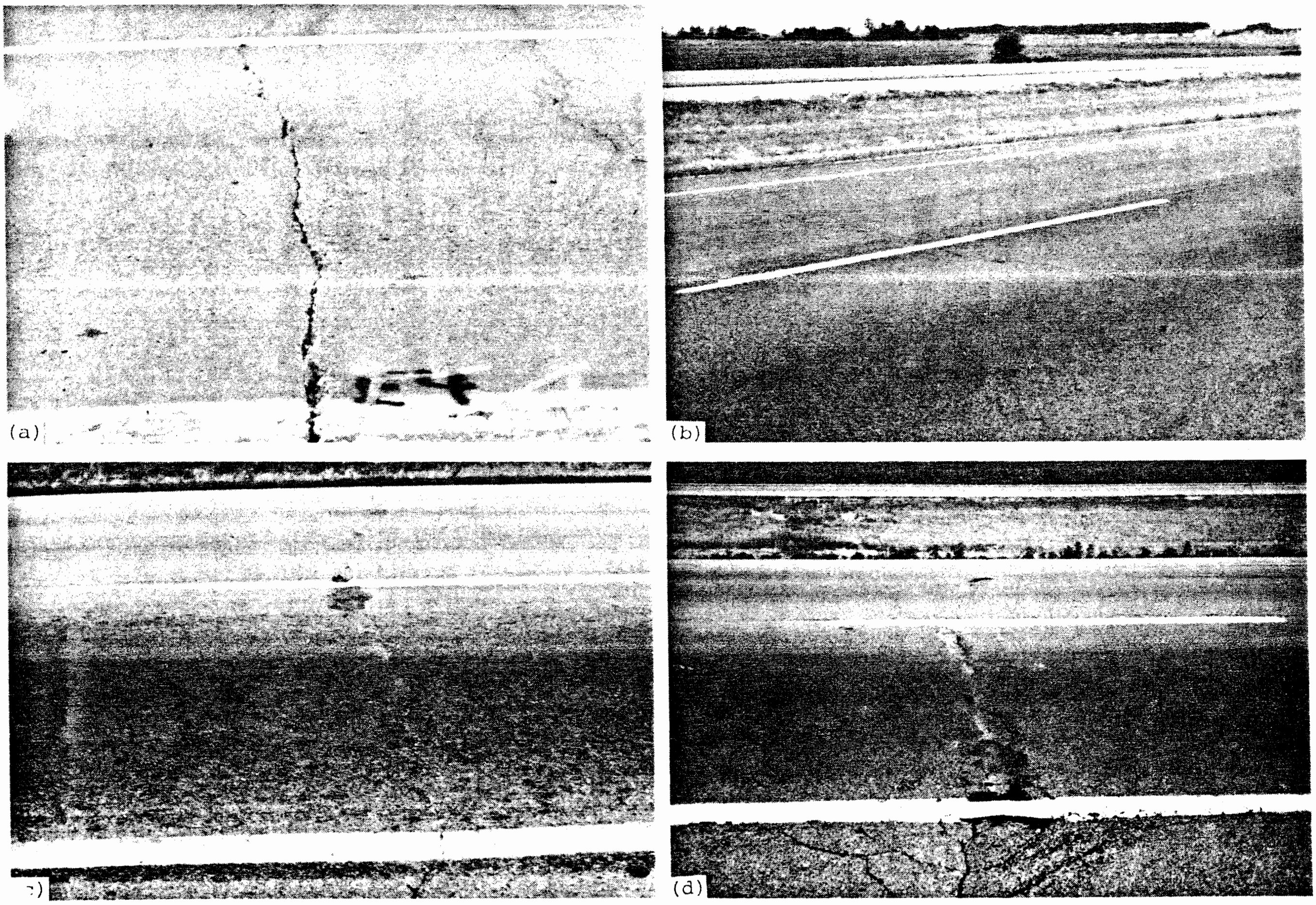

FIGURE 7 Performance of epoxied cracks. (a) Wide transverse crack before repair. (b) Reflection cracking at epoxied crack E4 after 10 months. (c) Reflection cracking at E4 in 1983. (d) Reflection cracking at E4 in 1988.

UNDERSEAL = 0 if no cement grout or asphalt undersealing done and = 1 if cement grout or asphalt undersealing done;
R^2 = 0.60; and
SEE = 2.6 failures/mile.

Effect of Undersealing

The regression equation demonstrates that undersealing had a substantial impact on the occurrence of reflective cracking in the overlay. Type of undersealing did not enter significantly into the regression analysis; that is, no significant difference was found in terms of reflection cracking between cement grout undersealing and asphalt undersealing.

Asphalt undersealing in test sections D and F was found in the 1978 preoverlay survey actually to increase rather than decrease deflections. This was attributed to pumping too much asphalt, which resulted in lifting of the slab and may have created new voids or enlarged existing ones. Regardless of this effect of asphalt undersealing on preoverlay deflections, wever, a statistical analysis of preoverlay versus postoverlay deflections was dominated by the substantial reduction in deflections achieved by the AC overlay (*1*). After the overlay was placed, there was no significant difference between the reduction in deflections for control sections and asphalt undersealed sections.

The cement grout undersealing performed in sections C and E was found in the 1978 preoverlay survey to reduce above-average deflections in the vicinity of failures but had little or no effect on average and below-average deflections. This was taken as evidence that blanket undersealing is not as cost-effective as selective undersealing of areas with particularly poor support. As with the asphalt undersealed sections, the substantial reduction in deflections resulting from the AC overlay was not significantly different in the cement grout undersealed sections than in the control sections (*1*).

Effect of Underdrains

Because underdrains were placed throughout the entire rehabilitation project length, including the control sections, it is not possible to compare the actual performance of the rehabilitated pavement with drains to what it would have been without drains. Visual observations, however, attest to

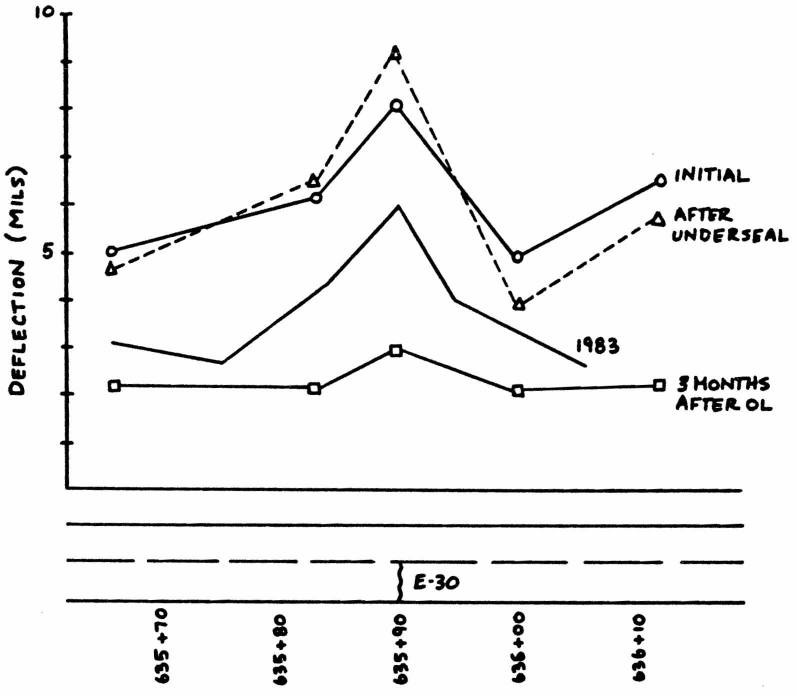

FIGURE 8 Deflection profiles at epoxied crack.

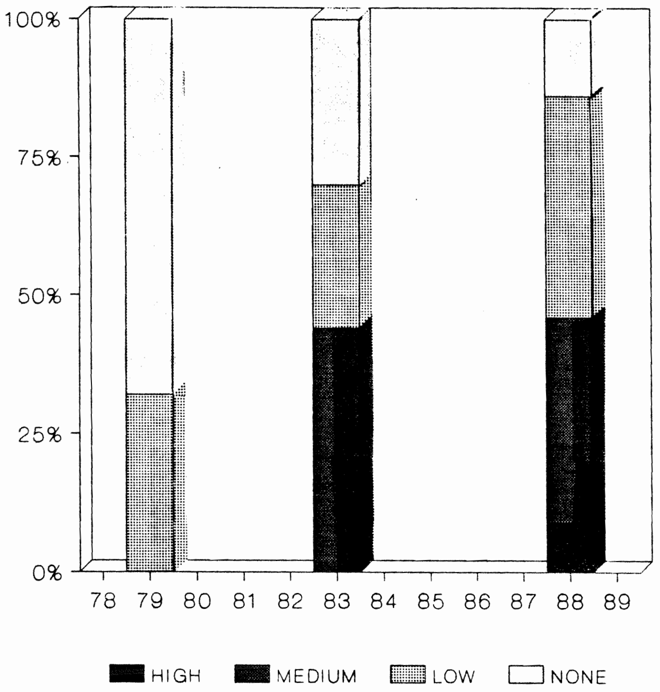

FIGURE 9 Reflective cracking of epoxied cracks.

improved drainage conditions. Immediately after the underdrains were installed, water was observed flowing from the drainage outlets. The drains were observed to be functioning during the 1988 survey, although the need for cleaning some outlets was noted.

More significantly, extensive pumping was observed on the project during the initial distress survey of the project in 1978, but no visible evidence of pumping was noted during the 1988 survey. The fact that this pavement had experienced extensive pumping for the first 10 years of its life before rehabilitation, but that no pumping was observed 10 years after the pavement was rehabilitated, demonstrates that the rehabilitation arrested most of the erosion that was occurring before. However, whether the erosion would have been halted by the undersealing and AC overlay alone, had the drains not been placed, is impossible to say.

COST-EFFECTIVENESS OF REHABILITATION

The cost-effectiveness of rehabilitation depends on performing appropriate and adequate rehabilitation at the appropriate time in the life of the pavement. This raises the following questions:

1. How does repair plus an overlay compare in cost-effectiveness with repair only?
2. What quantity of preoverlay repair is most cost-effective?
3. What is the most appropriate time to perform rehabilitation to maximize cost-effectiveness?

A quantitative comparison of the relative cost-effectiveness of different rehabilitation alternatives requires the selection of an analysis period to serve as a frame of reference. The results of such a comparison are necessarily dependent upon the length of time arbitrarily selected for that analysis period. The analysis period selected for this study was 20 years, from 1978 to 1998. A discount rate (interest minus inflation) of 3 percent was used in the analysis. This value was selected after consulting a recent *NCHRP Synthesis* on life-cycle cost analysis (*4*).

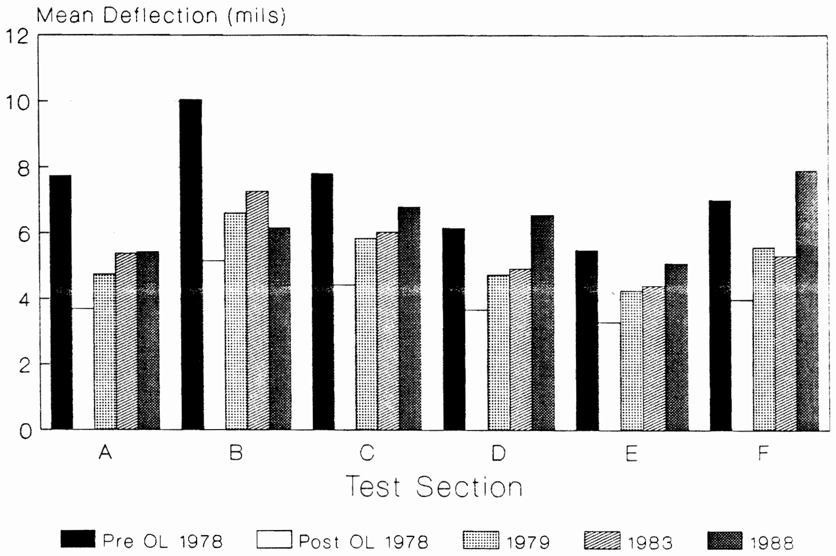

FIGURE 10 Effect of AC overlay on mean deflections in test sections.

Cost-Effectiveness of Overlay Versus Full-Depth Repair

The first of the three questions addressed is the relative cost-effectiveness of repair alone versus the repair plus overlay actually performed.

In 1978, maintenance records were examined to determine how much full-depth repair had been performed on the project in each year since its construction (*1*). The relationship of cumulative area repaired to cumulative 18-kip ESALs was found to follow closely a log-normal distribution, as shown in Figure 11. This is not surprising, since the full-depth repair requirements reflect the rate of deterioration, which accelerates as fatigue damage accumulates.

In 1983, the projected rate of deterioration was verified by determining the percent area repaired in the two end sections of the original project that had not yet been overlaid. These sections have since been overlaid, unfortunately, so it was impossible to check the actual versus the predicted percent area repaired during the 1988 survey. The good fit of the curve to the data through 1983, as shown in Figure 11, is considered to be sufficient for validation.

On the basis of this deterioration curve, it is possible to project the future hypothetical repair needs (in square yards) through 1998 for the middle portion of the project if a repair-only strategy had been adopted. These repair requirements can be translated into repair costs. The actual unit cost of CRCP full-depth repair in 1978 was $100 per square yard. Using a discount rate of 3 percent, all repair expenditures up to 1978 were converted to equivalent 1978 costs. Then, using the log-normal deterioration curve, predicted repair needs for each year through 1998 were computed and their costs converted to equivalent 1978 costs. Based on IDOT's prior experience with tied repairs on nonoverlaid CRC pavements, the life of a full-depth repair was assumed to be 5 years.

The cumulative total of the full-depth repair costs incurred over the analysis period is given by the 1978 present worth (PW) of the repair-only alternative, which can also be expressed as an equivalent uniform annual cost (EUAC) over the analysis period, as shown below:

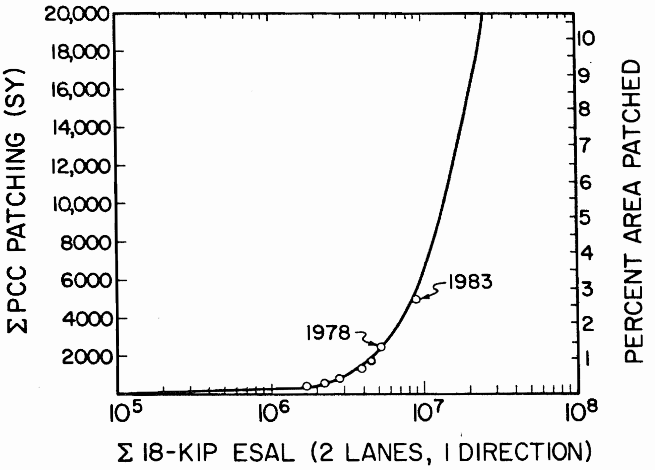

FIGURE 11 Log-normal relationship of cumulative repair requirements to cumulative traffic.

Alternative	*Repair Only*
1978 PW	$ 1,030,684
20-yr EUAC	$ 69,278

The repair-plus-overlay alternative had the same cumulative cost up to 1977 as the repair-only alternative. The techniques performed in the rehabilitation effort had the following 1978 costs:

Activity	*Cost* ($)
AC overlay	699,926
Underdrains	137,738
Full-depth repair	67,814
Cement undersealing	32,600
Asphalt undersealing	14,220
Epoxy cracks	5,892
Total	958,190

No rehabilitation work was performed on the project between 1978 and 1988. The 1988 survey showed that the project had an immediate need for 790 yd^2 of full-depth repair to repair medium- and high-severity, reflective cracking caused by repair deterioration, failed epoxied cracks, and previously unrepaired failures. The unit cost of full-depth repair now that the 4-in. overlay is in place was assumed to be increased by 20 percent over the cost of repairing bare 8-in. CRCP.

The future repair needs through 1998 can be estimated by drawing some inferences from the observed performance through 1988. With respect to the repairs that currently show no reflective cracking (after 10 or more years of service and approximately 5 million ESALs), the following assumption is made: since these repairs appear to have been completely successful at restoring the continuity of the CRC slab, they are not expected to exhibit any reflective cracking over the remainder of the analysis period. The repairs that are exhibiting reflective cracking were unsuccessful in completely restoring slab continuity and load transfer. The repairs that currently have low-severity reflective cracking may progress to medium and high levels of cracking but at a rate that is uncertain. They do not warrant repair now, but it is difficult to imagine them withstanding 10 more years of traffic before reaching medium- to high-severity levels of cracking. For purposes of this analysis, it was assumed that they would require repair in 1993, or halfway through the time remaining in the analysis period. Likewise, it was assumed that the epoxied cracks that currently exhibit low-severity reflection cracking will need to be repaired in 1993. As Figure 9 illustrates, 14 percent of the epoxied cracks still have not reflected through in 10 years. Most of these were at the outer edge of the traffic lane and were typically less than 6 ft long. These are not expected to reflect through before 1998.

The third potential need for future repair is new failures (not associated with existing repairs, epoxied cracks, or currently unrepaired cracks) that may arise from fatigue damage in the CRC slab. It is evident from the 10-year performance results that the AC overlay substantially reduced deflections and slowed the rate of failure. Of course, fatigue damage is still accumulating in the pavement, and the rate of development of new failures will likely accelerate in the same manner as (albeit much more gradually than) deterioration of the original slab accelerated from construction through 1978. As described previously, no new failures appear to have occurred in the 10 years since the rehabilitation was done. If a relationship does exist between new failures after overlay and traffic or time, it evidently has a very flat slope as of 1988. It is not anticipated that any significant quantity of full-depth repair due to new failures will be needed between now and the end of the analysis period.

The costs of full-depth repair in 1988 and 1993 were converted to equivalent 1978 costs and added to the cumulative total cost of this alternative. The 1978 present worth (PW) and equivalent uniform annual cost (EUAC) of the repair-plus-AC overlay alternative are shown below:

Alternative	*Repair + Overlay*
1978 PW	\$1,156,061
20-yr EUAC	\$77,705

Over the 20-year analysis period, the repair-plus-overlay alternative (EUAC = \$77,705) appears to be less cost-effective from an agency cost standpoint than the repair-only alternative (EUAC = \$69,278). This is illustrated by the accumulation of costs associated with the two alternatives shown in Figure 12. Several points must be made, however, before drawing any conclusions about the relative cost-effectiveness of the two alternatives.

- The overlay is in good condition with respect to reflective cracking but may or may not last the remainder of the analysis period. Rutting of the overlay is currently between ¼ and ⅜ in. and may reach an unacceptable level (½ in.) before 1998. The possible need for a second overlay or a milling operation in the future is not included in this analysis.
- Because the repair-only alternative was not actually done, its performance, in terms of years of pavement life extension

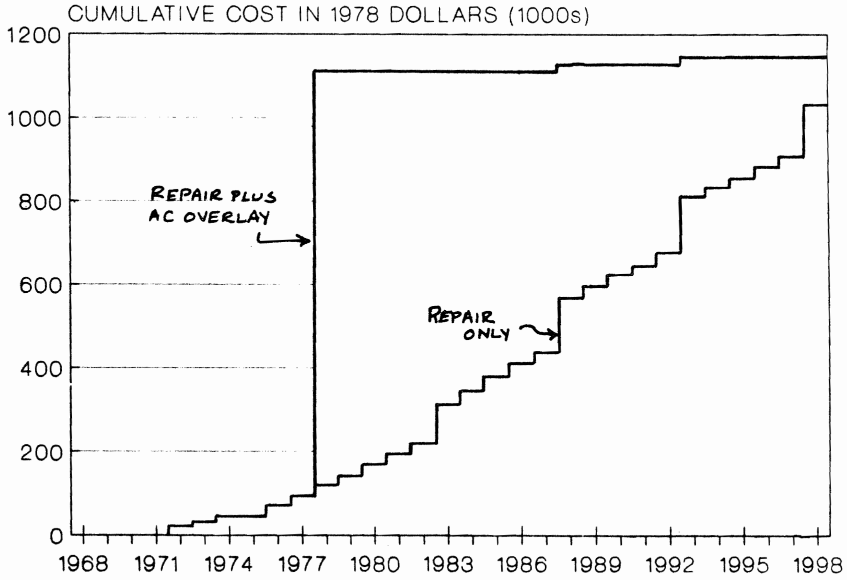

FIGURE 12 Cumulative costs of repair-plus-overlay and repair-only alternatives (in 1978 dollars).

provided before additional major rehabilitation would have been needed, is difficult to assess. Continual patching of a deteriorating pavement without placement of an overlay will at some point result in an unacceptably rough pavement surface. This point might well have occurred before the end of the 20-year analysis period, had this alternative actually been selected.

- This is an analysis of agency costs only, not a cost-benefit analysis, and does not consider some important factors in addition to agency expenditures, such as user costs associated with lane closure time, roughness, and accidents.

Whenever two hypothetical alternatives are equal in *cost*, the one that has kept the pavement condition at the highest average level provides the greater *benefit* to the traveling public. For this project, the repair-plus-overlay alternative probably provided greater benefit to the agency, as well as lower user costs, than the repair-only alternative could have provided. It is not known, however, whether this difference in benefit and user costs, if quantified, would offset the difference in the alternatives' annual costs shown earlier.

Cost-Effectiveness of Preoverlay Repair

The second question addressed is what quantity of preoverlay repair is most cost-effective. On this project, funding limitations prevented the repair of all of the distress present in 1978. In fact, the full-depth repairs placed at all high-severity and some medium-severity distress locations repaired only 55 percent of all the failures present. The remaining failures (45 percent), which were all of medium severity, were treated with epoxy or left untreated. Although the rehabilitated pavement has performed well and 55 percent repair of the worst areas appears to have been, in one sense of the word, "adequate," it would be interesting to know whether it would have been more cost-effective in the long run to perform more repairs.

On this project 100 percent repair would have included all the repairs that were placed, plus repairs for the cracks that were epoxied, plus the cracks not repaired (the 15 failures that reflected through by 1983). This increase in the cost of full-depth repair ($64,600) minus the cost savings without the epoxy ($5,892) would have raised the total cost of the rehabilitation by $58,708, or about 6 percent, to $1,016,898.

If construction quality for the additional repairs were the same as for the repairs actually placed, the same proportion of them would have to be replaced in 1988 and in 1993. There should be no other costs associated with this alternative over the analysis period. The 1978 PW and EUAC of the two preoverlay repair alternatives are shown below:

	Alternative Cost	
	1978 PW	*20-Year EUAC*
Overlay with 55 percent repair	$1,156,061	$77,705
Overlay with 100 percent repair	$1,148,477	$77,196

The surprising result is that the two alternatives have very similar agency costs; 100 percent repair is actually slightly cheaper. Although both alternatives involve performing repairs at the same three times (1978, 1988, and 1993), longer lane closure times might be expected with the 55 percent repair alternative, since there would be more deterioration to repair. From an agency cost standpoint, the two alternatives are essentially equal, although maintenance costs would be lower with the 100 percent repair approach.

Optimal Timing of Rehabilitation

The third issue addressed in rehabilitation planning is the optimal timing of rehabilitation. Highway agencies need to know when in the pavement's life rehabilitation will be most cost-effective and, if adequate funding is not available at that time, what the consequences of delaying the rehabilitation will be. Although the answers to these questions are different for each project, the data available from the Manteno project can be used to illustrate how such an analysis may be conducted.

For this analysis, the repair quantities and costs associated with the 100 percent repair-plus-overlay alternative were used as a starting point. The repair-only alternative was extended 1 year at a time beyond 1978. The repair quantity required for each year of delay was determined using the log-normal deterioration curve shown in Figure 11. The total cost of all other rehabilitation work actually performed in 1978 except full-depth repair was deferred 1 year at a time. It was assumed that future full-depth repair replacements would be done at the same time intervals as before, 10 and 15 years after placement of the overlay. All the deferred costs were discounted 3 percent per year to convert them to equivalent 1978 dollars. The analysis period was kept at 20 years, from 1978 to 1998. The following results were obtained:

Year to Place Overlay	*1978 Present Worth ($)*	*20-Year EUAC Cost ($)*
1978	1,148,477	77,196
1979	1,118,526	75,182
1980	1,111,483	74,709
1981	1,111,244	74,693
1982	1,107,781	74,462
1983	1,100,035	74,447

Delaying the overlay provides a diminishing return in savings: the savings achieved by deferring the overlay is mostly offset by the costs of keeping up with full-depth repairs, with the result that smaller reductions are achieved every year. The annual cost appears to be approaching a minimum somewhere around $74,000, which is still more than the annual cost of continual repair only ($69,278). Rehabilitating the pavement in 1978 appears in retrospect to have been more cost-effective than delaying rehabilitation would have been. Agency maintenance costs associated with rehabilitating in 1978 would also have been lower than if the rehabilitation had been delayed.

Again, this cost analysis does not take into account user costs, which would be higher for the repair-only alternative and would increase, as pavement roughness increased, every year that the overlay was delayed. It may be true that if user costs were included in the analysis, the gap in costs between 1978 rehabilitation and delayed rehabilitation might narrow more quickly. Without user cost data available, however, it is impossible to say.

These findings are reinforced by the log-normal deterioration curve shown in Figure 11. Recall that this pavement was designed for 4.8 million ESALs, a traffic level that Figure 11 shows was reached around 1977. The point on the curve corresponding to 1978 is very close to the elbow between the relatively flat portion and the steeply sloped portion of the curve. Repair requirements, which are a reflection of structural damage, accelerate dramatically beyond this point. In fact, examination of Figure 11 raises the question of whether repairing and overlaying the pavement a year or two earlier might not have been even more cost-effective. This question was not addressed in the analysis reported in this paper but could easily be investigated with the cost and performance data available.

CONCLUSIONS AND RECOMMENDATIONS

This paper documents a case study of rehabilitation performance and cost-effectiveness conducted over a 10-year period. The project represents one of the oldest rehabilitated CRC pavements in Illinois. The performance of this project provides a great deal of valuable information about the performance and cost-effectiveness of rehabilitation.

Rehabilitation Performance

1. The experimental tied and welded full-depth repairs placed before the overlay have performed extremely well. The vast majority of these repairs have not even reflected through the overlay after 10 years of service and traffic of nearly 8 million ESALs. The data from this project suggest that, for CRCP at least, a well-constructed concrete repair that fully restores the continuity of the slab and the reinforcing steel can perform for 10 years or more beneath an AC overlay without causing any reflective cracking, even in a cold climate under heavy traffic.
2. The cost of CRCP full-depth repair can be significantly reduced with no sacrifice in repair performance by using shorter overall repair lengths and shorter lap lengths. The experimental repair designs with shorter tied laps (20 in.) and welded laps (4 in.) were almost 50 percent less expensive than the then-standard IDOT repairs (36-in. tied laps) and performed the same.
3. Full-depth AC repairs and unreinforced PCC repairs performed very poorly. After 10 years, nearly all of these repairs must be replaced. Full-depth AC and unreinforced PCC are both unsuitable for permanent repair of CRCP, and are not used for this purpose by IDOT. Their performance on this project shows that they also perform poorly even under an AC overlay.
4. Crack epoxying was not successful. Many of the epoxied cracks failed rapidly, even before the overlay was placed, and reflected through the overlay within a year. After 10 years nearly half of them need to be repaired again. Crack epoxying is not recommended for repair of wide cracks that extend across the full lane width of CRCP. The epoxy cannot withstand the large crack openings caused by thermal cycling in the pavement. Crack epoxying may be useful in slowing the rate of propagation of partial-lane-width cracks when at least some of the reinforcing steel across the width of the pavement is still intact.
5. Undersealing with cement grout or asphalt cement reduced deflections before overlay and reduced reflective cracking in the overlay. Sections that were undersealed had about 50 percent fewer medium- to high-severity reflection cracks than sections that were not undersealed, despite the fact that the undersealed sections had many more failures prior to rehabilitation. Blanket undersealing did not prove to be cost-effective. Selective undersealing at locations of poor support, as indicated by deflection testing, was more effective.
6. The 4-in. AC overlay reduced deflections to 55 percent of their preoverlay levels. After 10 years, deflections have increased to 88 percent of their preoverlay levels, indicating that some deterioration is taking place. The overlay is in good condition with respect to cracking, although a thin overlay or milling may be warranted sometime in the next several years to correct rutting. Tied and welded full-depth repairs of the CRCP resulted in practically no reflection cracks in the overlay after 10 years. Deteriorated cracks that were not adequately repaired have reflected through the overlay and now require full-depth repair.
7. Underdrains continually drained water from the pavement section over the 10 years of service. No pumping was evident after 10 years. Although a comparison of performance with and without drains is not possible since drains were placed through the entire project length, the elimination of pumping and the absence of any new failures attest to the improved drainage and support conditions.

Rehabilitation Cost-Effectiveness

1. Analysis of the hypothetical repair-only alternative versus the actual repair-plus-overlay alternative showed that, from the standpoint of agency rehabilitation costs, it would have been more cost-effective to continue the full-depth repair option for several years. The repair-only alternative would have higher maintenance costs, however, as well as higher user delay and accident costs resulting from the frequent lane closures. Pavement roughness would also be significantly greater with the repair-only alternative. A more detailed cost analysis that quantified these factors might show that the lower maintenance costs and user costs associated with repair plus overlay offset the higher agency costs.
2. The amount of preoverlay repair done determines the amount of repair needed after overlay. Repairing the worst 55 percent of the deteriorated areas was about as cost-effective as 100 percent repair would have been. Again, consideration of maintenance costs and user costs might favor the 100 percent repair alternative.
3. Delaying the overlay a few years beyond 1978 would have made it more cost-effective, from an agency cost standpoint, but apparently not enough to offset the maintenance costs of continued full-depth repair, which would have increased every year that the overlay was delayed. Consideration of user costs may change the results and reduce the cost difference. Performance data that illustrate the rate of deterioration with respect to traffic can be very valuable in determining the best time to perform major rehabilitation. Structural deterioration accelerates rapidly beyond the point at which the pavement's fatigue life is consumed, and as deterioration accelerates, so do the annual expenditures for full-depth repair. It is doubtful whether delaying a structural improvement significantly beyond the end of a pavement's structural life can

compete in cost-effectiveness with applying the structural improvement within the flat portion of the deterioration curve.

None of the conclusions contained in this paper concerning performance of rehabilitation techniques or cost-effectiveness of various alternatives should be construed as criticism of the rehabilitation work actually performed by the Illinois DOT on this project. The analyses described in this paper were conducted with the benefit of 10 years of detailed performance data. No such performance data were available to IDOT at the time the rehabilitation was done, since this was among the first full-scale CRCP rehabilitation projects ever undertaken in the state. The Illinois DOT is to be commended for its efforts in planning and executing this rehabilitation project and closely monitoring its performance.

Furthermore, it must be emphasized that this is only one project monitored over 10 years and these results apply only under these specific field conditions. Long-term monitoring of rehabilitation projects, collection of cost and performance data, and careful analysis of data are all greatly needed to improve rehabilitation planning decisions. User costs are an important part of life-cycle cost analysis and should be considered if possible. It is not impossible to conduct a cost analysis without information on user costs, but it requires that decision makers make qualitative judgments about the relative benefits of various rehabilitation alternatives to users.

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