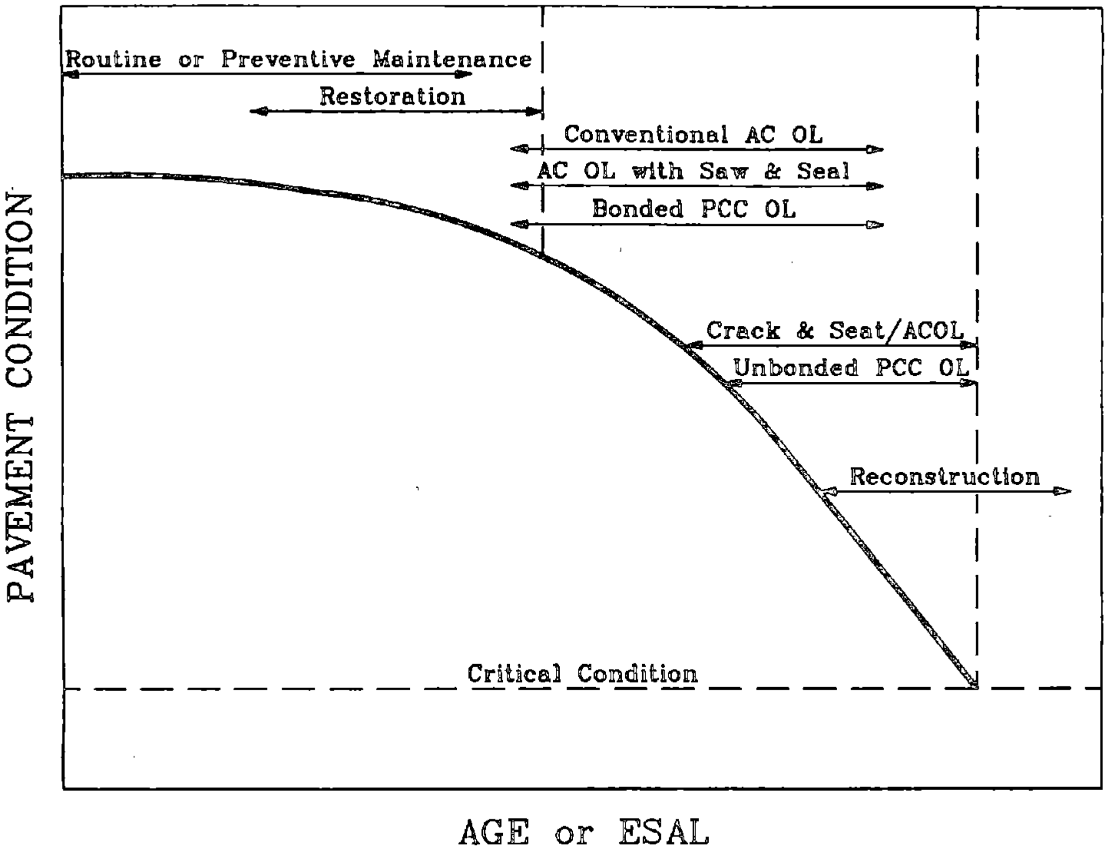
PB91-100628

Structural Overlay Strategies for Jointed Concrete Pavements

Volume IV, Guidelines for the Selection of Rehabilitation Alternatives

Publication No. FHWA-RD-89-145
June 1990



REPRODUCED BY
U.S. DEPARTMENT OF COMMERCE
NATIONAL TECHNICAL
INFORMATION SERVICE
SPRINGFIELD, VA 22161

U.S. Department of Transportation
Federal Highway Administration

Research, Development, and Technology
Turner-Fairbank Highway Research Center
6300 Georgetown Pike
McLean, Virginia 22101-2296

FOREWORD

This report is one volume of a four volume set of interim reports documenting a major field study and evaluation of the effectiveness of three structural overlay types for jointed portland cement concrete pavements and guidelines for their use. The three overlay types are sawing and sealing joints in asphalt concrete (AC) overlays of PCC pavements, cracking and seating PCC pavements prior to AC overlay and constructing a thin bonded PCC overlay on top of the existing PCC pavement. Condition survey, deflection testing and roughness measurements were performed on a total of 60 sections. It should be noted that the small sample of projects and the unknown condition of the pavement prior to overlay limit the conclusions that can be drawn from the study. Volume V (Summary of Research Findings) and the technical summary will be given widespread distribution in the near future. These reports will be of interest to those involved in design, construction and rehabilitation of jointed concrete pavements.

Sufficient copies of this report are being distributed by FHWA memorandum to provide one copy to each FHWA Region and Division and two copies to each State highway agency. Direct distribution is being made to the division offices. Additional copies for the public are available from the National Technical Information Service (NTIS), U.S. Department of Commerce, 5285 Port Royal Road, Springfield, Virginia 22161. A small charge will be imposed for each copy ordered from NTIS.

Thomas J Pasko Jr

Thomas J. Pasko, Jr., P.E.
Director, Office of Engineering and
Highway Operations Research and Development

NOTICE

This document is disseminated under the sponsorship of the Department of Transportation in the interest of information exchange. The United States Government assumes no liability for its contents or use thereof. The contents of this report reflect the view of the contractor who is responsible for the accuracy of the data presented herein. The contents do not necessarily reflect the official policy of the Department of Transportation. This report does not constitute a standard, specification, or regulation.

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein only because they are considered essential to the object of this document.

Technical Report Documentation Page

1. Report No.
FHWA-RD-89-145

2. Government Accession No.

3.
PB91-100628

4. Title and Subtitle
STRUCTURAL OVERLAY STRATEGIES FOR JOINTED CONCRETE PAVEMENTS - Volume IV; Guidelines for the Selection of Rehabilitation Alternatives

5. Report Date
June 1990

6. Performing Organization Code

7. Author(s)
M. I. Darter and K. T. Hall

8. Performing Organization Report No.

9. Performing Organization Name and Address
ERES Consultants, Inc.
1401 Regency Drive East
Savoy, Illinois 61874

10. Work Unit No. (TRAIS)
3C1A2012

11. Contract or Grant No.
DTFH61-86-C-00079

12. Sponsoring Agency Name and Address
Office of Engineering and Highway Operations R&D
Federal Highway Administration
6300 Georgetown Pike
McLean, VA 22101-2296

13. Type of Report and Period Covered
Interim Report
Oct. 1986 - Jan. 1990

14. Sponsoring Agency Code

15. Supplementary Notes
FHWA Contracting Officer's Technical Representative (COTR)
Mr. Roger M. Larson, HNR-20

16. Abstract

A major field study and evaluation has been conducted into the effectiveness of three structural overlay types for portland cement concrete (PCC) pavements. These include sawing and sealing asphalt concrete (AC) overlays of PCC pavements, cracking and seating PCC pavements prior to AC overlay, and constructing a thin bonded PCC overlay on top of the existing PCC pavement. Condition surveys, deflection testing, and roughness measurements were performed on a total of 55 sections. The performance of these sections was evaluated and the effectiveness of each overlay type analyzed. Based on the field data, guidelines were developed for the use of these structural overlays.

This volume provides detailed guidelines and case studies prepared specifically for the practicing engineer as an aid in the evaluation and rehabilitation of jointed concrete pavements. Feasibility guidelines are given for restoration, resurfacing, and reconstruction alternatives in terms of constructability, future life and life-cycle costs. New prediction models are developed for bonded PCC overlays, sawing and sealing and AC overlay, and cracking and seating and AC overlay. The EXPEAR program was extensively modified to include the above rehabilitation alternatives and improved predictive models and to provide for much easier usage by the practicing engineer for evaluation and rehabilitation. Detailed rehabilitation case studies are presented that will be of interest to the practicing engineer.

This volume is the fourth in a series. The other volumes are:

FHWA No.	Vol. No.	Short Title
FHWA-RD-89-142	I	Sawing and Sealing of Joints in AC Overlays of Concrete Pavements
FHWA-RD-89-143	II	Cracking and Seating of Concrete Slabs Prior to AC Overlay
FHWA-RD-89-144	III	Performance Evaluation and Analysis of Thin Bonded Concrete Overlays
FHWA-RD-89-146	V	Summary of Research Findings
FHWA-RD-89-147	VI	Appendix A - Users Manual for the EXPEAR Computer Program

17. Key Words
Jointed concrete pavement, evaluation, rehabilitation, overlays, expert system.

18. Distribution Statement
No restrictions. This document is available through the National Technical Information Service, Springfield, Virginia 22161.

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
92

22. Price

Form DOT F 1700.7 (8-72)

Reproduction of completed page authorized

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

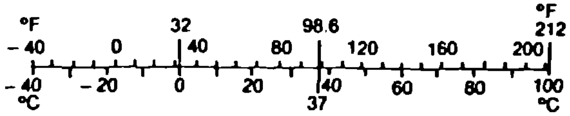
Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
		AREA		
in²	square inches	645.2	millimetres squared	mm²
ft²	square feet	0.093	metres squared	m²
yd²	square yards	0.836	metres squared	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	kilometres squared	km²
		VOLUME		
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.028	metres cubed	m³
yd³	cubic yards	0.765	metres cubed	m³

NOTE: Volumes greater than 1000 L shall be shown in m³.

Symbol	When You Know	Multiply By	To Find	Symbol
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
		AREA		
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
ha	hectares	2.47	acres	ac
km²	kilometres squared	0.386	square miles	mi²
		VOLUME		
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
		TEMPERATURE (exact)		
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

TABLE OF CONTENTS

VOLUME I SAWING AND SEALING OF JOINTS IN AC OVERLAYS OF CONCRETE PAVEMENTS

PART I

PART II

PART A. DESIGN AND CONSTRUCTION GUIDELINES

PART B. GUIDE SPECIFICATIONS

VOLUME II CRACKING AND SEATING OF CONCRETE SLABS PRIOR TO AC OVERLAY

PART I

PART II. CRACKING, SEATING, AND OVERLAY OF PORTLAND CEMENT CONCRETE PAVEMENTS

PART A. DESIGN AND CONSTRUCTION GUIDELINES

PART B. GUIDE SPECIFICATIONS

VOLUME III PERFORMANCE EVALUATION AND ANALYSIS OF THIN BONDED CONCRETE OVERLAYS

VOLUME IV GUIDELINES FOR THE SELECTION OF REHABILITATION ALTERNATIVES

VOLUME V SUMMARY OF RESEARCH FINDINGS

VOLUME VI APPENDIX A—USERS MANUAL FOR THE EXPEAR COMPUTER PROGRAM

LIST OF FIGURES

VOLUME I SAWING AND SEALING OF JOINTS IN AC OVERLAYS OF CONCRETE PAVEMENTS

VOLUME II CRACKING AND SEATING OF CONCRETE SLABS PRIOR TO AC OVERLAY

VOLUME III PERFORMANCE EVALUATION AND ANALYSIS OF THIN BONDED CONCRETE OVERLAYS

VOLUME IV GUIDELINES FOR THE SELECTION OF REHABILITATION ALTERNATIVES

VOLUME V SUMMARY OF RESEARCH FINDINGS

LIST OF TABLES

VOLUME I SAWING AND SEALING OF JOINTS IN AC OVERLAYS OF CONCRETE PAVEMENTS

VOLUME II CRACKING AND SEATING OF CONCRETE SLABS PRIOR TO AC OVERLAY

VOLUME III PERFORMANCE EVALUATION AND ANALYSIS OF THIN BONDED CONCRETE OVERLAYS

VOLUME IV GUIDELINES FOR THE SELECTION OF REHABILITATION ALTERNATIVES

VOLUME V SUMMARY OF RESEARCH FINDINGS

VOLUME VI APPENDIX A—USERS MANUAL FOR THE EXPEAR COMPUTER PROGRAM

CHAPTER 1 INTRODUCTION

1. BACKGROUND

Most of the high-volume pavements constructed over the past 30 years in the United States have carried volumes and weights of heavy truck traffic far in excess of those for which they were designed. In one State, for example, the pavement sections constructed on the Interstate system in the 1960's and 1970's received on average three times their design traffic (in terms of 18-kip [80 kN] equivalent single-axle load [ESAL] applications) over their 20-year design lives.(1) Eventually, this heavy overloading takes its toll and results in rapid deterioration. Extending the lives of these pavements through cost-effective rehabilitation, as opposed to more costly reconstruction, has become a major activity and cost to all State highway agencies, and promises to be so for many years to come. In fact, the situation is likely to get much worse due to the compounding effect of having many previously rehabilitated pavements requiring additional rehabilitation.

Selecting and designing rehabilitation strategies for individual pavement sections requires both planning/programming and engineering activities, and is performed within the framework of management of a State's entire pavement network. Every agency has its own unique process for assessing highway network needs, prioritizing projects, and allocating funds among the projects, and this process usually involves both planners and engineers. The programmer's responsibility is to distribute the limited available funds among the selected projects to maximize the benefits to the overall highway network, which may require selecting less-than-optimal strategies for some projects. The design engineer's responsibility is to evaluate each individual pavement section, and develop feasible cost-effective rehabilitation alternatives within the available limited funding level. Those pavements exhibiting structural deterioration are among the most difficult to rehabilitate and achieve significant life extensions significantly with limited available funding.

2. RESEARCH OBJECTIVE

This work is part of a two-phase research study entitled *"Performance/Rehabilitation of Rigid Pavements,"* conducted for the Federal Highway Administration (FHWA). The first phase of this study addresses key design features which influenced the performance of new concrete pavements. The second phase of this study addresses concrete pavement rehabilitation, with special emphasis on three structural overlay types:

1. Bonded portland cement concrete (PCC) overlay.
2. Asphalt concrete (AC) overlay on cracked and seated PCC slabs.
3. AC overlay with sawed and sealed joints.

The results of the field studies of the performance of each of the above three overlay types are documented in volumes I, II, and III.

The purpose of this report is to provide practical guidelines for engineers on selection of rehabilitation strategies for jointed plain concrete pavements (JPCP) and jointed reinforced concrete pavements (JRCP). This includes guidance on selecting appropriate structural overlay types, as well as identifying when other rehabilitation alternatives such as restoration and reconstruction should be considered.

3. RESEARCH APPROACH

This report consists of five chapters. Chapter 2 describes the basic concepts of concrete pavement rehabilitation, outlines a practical process for assessing the feasibility of alternatives, and details the key problem of recognizing the need for a structural improvement. Chapter 3 presents guidelines on pavement rehabilitation selection for restoration, AC conventional overlays, bonded PCC overlays, AC overlays with cracked and seated slabs, AC overlays with sawed and sealed joints, unbonded PCC overlays and reconstruction.

A useful tool for illustrating the process of evaluating a concrete pavement and developing feasible rehabilitation strategies is the computer program EXPEAR (EXpert system for Pavement Evaluation And Rehabilitation), developed for the FHWA.(2) Chapter 4 gives a brief description of EXPEAR, and identifies improvements which have been made as a result of the findings of this research study.

Chapter 5 presents 13 detailed case studies in rehabilitation strategy development, using actual design, construction, and performance data from in service pavement sections covering a broad range of conditions and distributed among the four major climatic regions of the United States.

CHAPTER 2 BASIC CONCEPTS OF PAVEMENT REHABILITATION

1. THE SPECTRUM OF REHABILITATION ALTERNATIVES

Concrete pavement rehabilitation encompasses a broad range of activities that are grouped in three main approaches:

1. Restoration.
2. Resurfacing.
3. Reconstruction (including recycling).

Several specific rehabilitation alternatives exist within each of these main three approaches.

Although the full spectrum of rehabilitation alternatives could theoretically be considered for every potential rehabilitation project, the conditions which apply to a specific project typically result in some alternatives being infeasible. Although many factors are involved, the performance and cost-effectiveness of each type of rehabilitation depends heavily on the existing pavement condition. The general relationship between pavement condition and optimum rehabilitation need is shown in figure 1. This figure illustrates several issues related to rehabilitation type and timing.

Some agencies specify only a single "policy" rehabilitation strategy (e.g., a 3-in [76 mm] AC overlay), without weighing alternatives and without considering pavement condition or traffic. This approach to rehabilitation results in unnecessarily high rehabilitation costs on pavements which are not in need of the "policy" rehabilitation, and more frequently, results in rapid deterioration and premature failure of pavements in need of more substantial work.

The Pavement Performance Curve

Figure 1 is a schematic illustration of a typical "performance curve" for an individual pavement section, in which pavement condition declines over time and with accumulated traffic until it reaches some unacceptably low level. The more common ways to express pavement condition are by extent of visible distress (e.g., cracking, joint deterioration), by a composite index representing several distresses, or by serviceability (or equivalently, roughness). The performance of the pavement is often defined as the area under the curve over the pavement's life, that is, from initial condition to unacceptable condition.

The "Maintenance Only" Alternative

In the first phase of a pavement's life, its condition is excellent and its rate of deterioration is normally low (this corresponds to the relatively flat portion of the performance curve). The "routine or preventive maintenance only" alternative

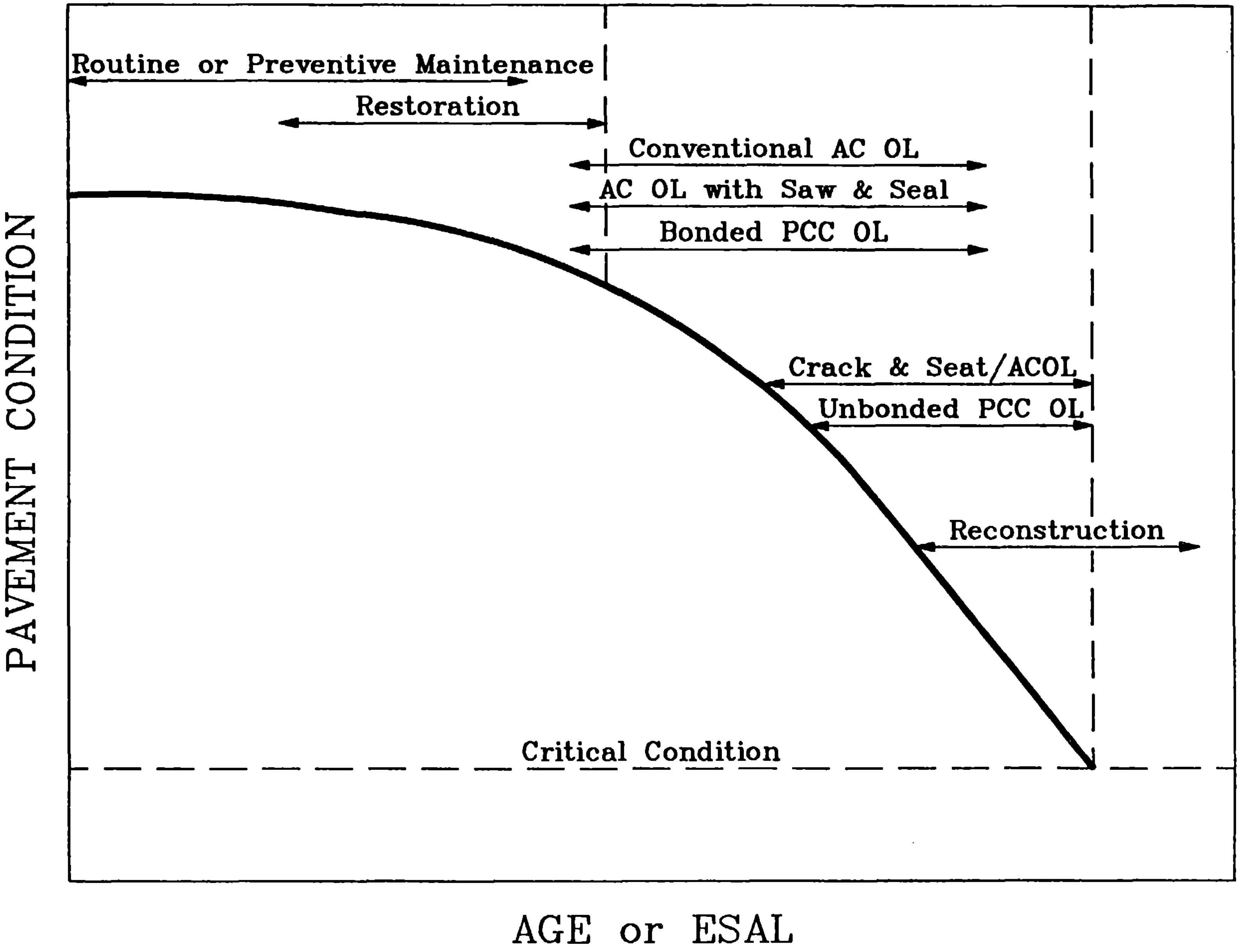


Figure 1. The spectrum of pavement rehabilitation alternatives.

is more cost-effective than any rehabilitation activity. Preventive maintenance would be beneficial during this phase, such as retrofitted subdrains for a pavement with poor drainage capabilities, or joint sealing for a pavement whose joints were not adequately sealed during initial construction. This sort of preventive maintenance work generally yields the greatest benefit when performed early in the life of the pavement, before moisture-related and joint-related distresses can develop to significant levels.

Restoration

Restoration activities are warranted when pavement condition has declined somewhat, particularly when distresses such as cracking, faulting, and joint spalling are detracting from the pavement's serviceability. Restoration techniques for concrete pavements include:

- Full-depth repair of joints, cracks, and corner breaks.
- Partial-depth repair of small spalls.
- Grinding to remove faults and studded tire ruts and to improve surface friction.
- Grooving to improve surface friction.
- Undersealing to fill voids under slab corners.
- Slabjacking to improve the pavement's profile.
- Load transfer restoration at joints and cracks.
- Joint resealing.
- Crack sealing.
- Subdrainage improvement.
- Shoulder improvement.

Concrete pavement restoration (CPR) may involve one of these techniques or a combination of several. As figure 1 illustrates, there is no clear boundary between the time when "maintenance only" is appropriate and when restoration is appropriate; this depends on the effect that the restoration activities will have on reducing the rate of deterioration of the individual pavement section or in providing a smoother ride.

Successful restoration work typically achieves one or more of the following: it repairs the existing distress, improves rideability, and slows subsequent pavement deterioration by arresting the mechanisms causing the distress. In weighing restoration against "maintenance only," the life extension attainable with restoration must justify its expense in order for it to be judged cost effective. When annual maintenance costs equal or exceed the equivalent annual cost of restoration, the restoration work is justified.

Restoration must be performed while the pavement exhibits fairly low levels of distress and a fairly slow rate of deterioration in order to be cost-effective. The rate of deterioration observed for 2 to 3 years prior to restoration provides one indication of the degree to which restoration will cost-effectively extend the pavement's life.

Structural Resurfacing (Overlays)

As a pavement accumulates traffic loadings it also accumulates fatigue damage, which eventually manifests itself in the form of slab cracking. Of course, not all slab cracking is caused by fatigue damage from repeated traffic loadings. Other causes of slab cracking include thermal curling stresses, shrinkage stresses, late sawing of joints, and settlement of the foundation. In many cases the pavement also develops serious distresses such as D-cracking, joint deterioration, and poor load transfer, which, while not directly caused by repeated load fatigue, diminish the pavement's structural integrity and its ability to support loads.

In contrast to the mutual overlap between the appropriateness of "maintenance only" and that of restoration, figure 1 illustrates that there is no forward overlap between restoration and a structural overlay. That is, at some point in the pavement's life the amount of accumulated structural damage becomes so substantial that restoration can never compete with structural improvement in either performance or cost effectiveness. Thus, a key issue in rehabilitation selection is determining when a pavement requires structural improvements. Trying to determine exactly when this point is reached on the basis of observed distress, measured deflections, core results, past and future traffic, and other factors is a very difficult and very project-specific task. The important issue of recognizing when a pavement requires a structural improvement is discussed in section 2.

Figure 1 does illustrate some backward overlap between structural improvement and restoration, meaning that it is possible for an overlay to equal or exceed restoration in cost effectiveness even when performed during the time frame when restoration is still feasible. This is due to the potentially greater life extension achievable by a structural overlay when placed on a pavement that is not badly deteriorated. Whether this life extension justifies the additional cost of the overlay can only be determined by a comparison of life-cycle costs.

Several different types of structural overlays can be applied to concrete pavements, including:

- Conventional thick AC overlay (with or without reflection cracking treatments).
- Thick AC overlay with sawed and sealed joints.
- Thick AC overlay on cracked and seated PCC slabs.
- Bonded PCC overlay.
- Unbonded PCC overlay.

Conventional AC overlays sometimes incorporate techniques that attempt to control reflection cracking, which is a major mode of failure for AC overlays.

Reflection crack control treatments tried over the years, with varying degrees of success, include various fabric and fiberglass interlayers, "band-aid" type crack treatments, and layers of open-graded stabilized granular material, such as the Arkansas base. Although control of reflection cracking is very important to the performance of an asphalt overlay, discussion of the relative merits of these crack control treatments is beyond the scope of this report. Here special emphasis is placed on two other treatments which show particular promise: sawing and sealing joints in the AC overlay above the joints in the underlying concrete pavement, and cracking and seating the concrete pavement prior to placing the AC overlay.

Sawing and sealing, which attempts to control the formation and severity of reflective cracks rather than inhibit their occurrence, is more appropriate on pavements in fairly good condition, and may not be as cost effective as other overlay alternatives on either short-jointed pavements or on long-jointed pavements with many deteriorated transverse cracks which require extensive full-depth repair. Good performance has been reported for this type of reflection crack control.

Cracking and seating reduces the longitudinal movements which contribute to reflection cracking by reducing the spacing of working cracks and joints. Cracking and seating is more appropriate for pavements in poor condition, and depending on how it is done, results in a reduction in structural integrity of the existing slabs ranging from noticeable to substantial. Controversy exists over whether or not this technique increases or decreases structural capacity. At its most extreme, cracking and seating takes the form of turning the existing concrete pavement to rubble. In this situation the AC "overlay" must be very thick, since it is essentially a reconstructed AC surface on a "granular" base.(3) The cracking and seating operation is usually more effective on JPCP than on JRCP, since considerable force is necessary to shear the reinforcing steel in JRCP and allow horizontal movement of the cracked pieces. Additional efforts by FHWA are underway to evaluate the effectiveness of cracking and seating on JRCP.

Bonded PCC overlays are most cost-effective when applied to pavements in relatively good condition; that is, when good load transfer, good drainage, good concrete durability, and little cracking or joint deterioration is present. Any cracking or joint deterioration present should be full-depth repaired completely prior to placement of the overlay. Bonded PCC and AC overlays can be thought of as "condition-sensitive," since their cost and future performance depend on the amount of existing distress which needs to be repaired.

Compared to bonded PCC overlays and AC overlays, unbonded jointed PCC overlays require less preoverlay repair and their performance is generally much less sensitive to preoverlay condition. This is not true, however, for thinner unbonded CRCP overlays, which require uniform support and good joint/crack load transfer in order to perform well.

Crack and seat AC overlays fall between these two extremes. Field results presented in volume II have shown that some types of distress will reflect through the AC overlay if left unrepaired.

Reconstruction

A pavement that is allowed to deteriorate eventually reaches a state of such advanced deterioration that even thick overlays cannot compete in cost-effectiveness with reconstruction. Whether this point is inevitably reached by all pavements or whether it can be forestalled indefinitely by repeated overlays is a much-argued point. Repeated resurfacing eventually becomes unfeasible from a construction standpoint for many pavements, when required overhead clearances can no longer be met. This may be avoided in some situations by milling off and recycling the overlay (AC overlays only). Repeated overlaying also tends to provide a diminishing return; that is, second and third and fourth overlays may achieve progressively smaller life extensions. This is particularly true under conditions of heavy traffic, poor drainage, and poor foundation support.

Extremely poor concrete durability, as evidenced by extensive D-cracking or reactive aggregate distress, may also tip the scales in favor of reconstruction. Although an unbonded PCC overlay may perform reasonably well over even a badly D-cracked pavement, it can do nothing to restrain the longitudinal expansion of a pavement with highly reactive aggregate. There is also evidence to suggest that AC overlays (and ostensibly unbonded PCC overlays) may retain moisture in a pavement structure and thereby accelerate the development of D-cracking or reactive aggregate distress.(4) When pavements with poor concrete durability are reconstructed, recycling the concrete can be effective in achieving better performing new concrete. However, due to poor performance observed on some recent CRCP and JRCP reconstruction projects using 1-in (25 mm) maximum size coarse aggregate, caution is advised. When concrete is recycled to a small coarse aggregate maximum size to reduce susceptibility to D-cracking, poor load transfer at cracks and contraction joints may result. Not only does the smaller coarse aggregate provide less mechanical interlock, but recycled concrete aggregate also appears to be less abrasion-resistant than virgin aggregate and therefore may experience wear at crack interfaces faster than virgin aggregate.

Reconstruction may require more lane closure time than resurfacing, since time for pavement breakup and removal operations is included. The difference might not be significant, however, when compared to a resurfacing option which requires extensive preoverlay repair. Other concerns include the condition of the base, subbase, and subgrade. If these layers can be left in place, surface removal and reconstruction may be conducted reasonably quickly. However, if these layers are in poor condition (i.e., saturated) and must be replaced or reworked, excessive costs and delays may result. An unbonded PCC overlay might be preferable to reconstruction under such conditions.

A variety of concerns not directly related to the condition of the pavement may come into play when considering reconstruction. These include improving geometric conditions, changing the roadway realignment, adding traffic lanes, constructing a pavement with a better design (perhaps including a drainage layer), and reducing maintenance needs. On some high-volume routes, reconstruction may be the only rehabilitation alternative which can provide the performance life an agency requires (e.g., 20 or more years). The expressway system in Chicago, for example, is one such case in which reconstruction, despite its substantial first cost, has been the rehabilitation method of choice.

2. DETERMINING THE FEASIBILITY OF REHABILITATION ALTERNATIVES

The pavement design engineer is continually faced with the problem of determining the most effective rehabilitation alternative for a given section of pavement that is within the agency's overall network pavement management resources. This section provides practical guidance to the engineer in making this selection.

The general rehabilitation selection process is shown in figure 2. There are three major phases:

> Phase 1: Problem Definition. A pavement evaluation is conducted to identify the causes and extent of deterioration. Constraints for the project must be identified. Typical constraints include available funding, construction feasibility, and minimum performance period (life over which the rehabilitation alternative must perform).
>
> Phase 2: Potential Problem Solutions. Based upon the pavement evaluation, several candidate alternatives are identified. They are then tested for feasibility considering three main constraints:
>
> 1. Construction feasibility.
> 2. Minimum performance period.
> 3. Available funding.
>
> After this analysis, several feasible solutions are typically available for further consideration.
>
> Phase 3: Selection of Preferred Solution. A life-cycle cost analysis is conducted and non-monetary considerations are identified. Finally, the preferred rehabilitation alternative is selected and a detailed design is developed.

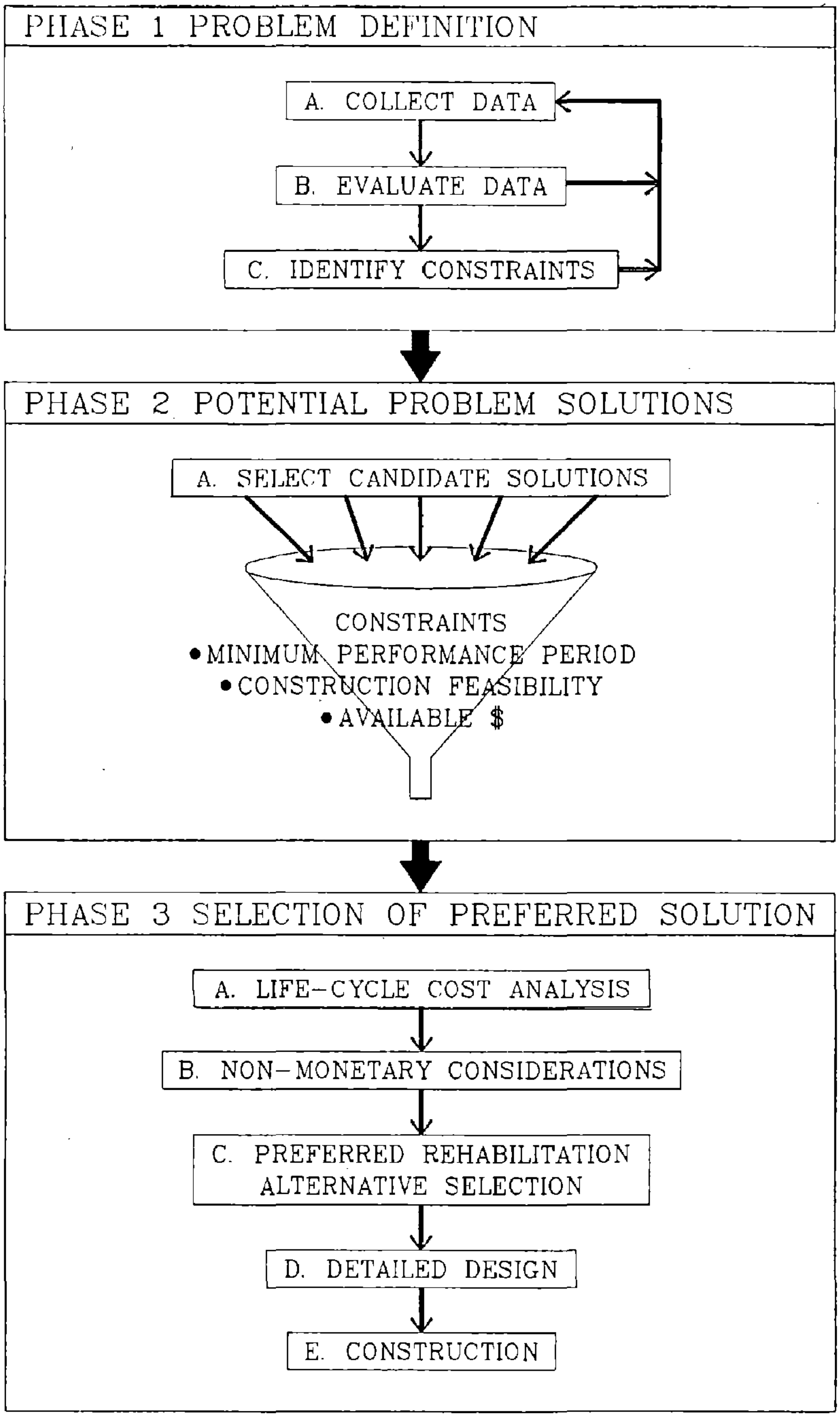


Figure 2. The pavement rehabilitation selection process (Adapted from the AASHTO Guide for Design of Pavement Structures, 1986).

Each candidate rehabilitation alternative is evaluated by first considering its construction feasibility. If the alternative is constructable, an estimation of its future performance period (life) is made. If the predicted performance period is acceptable, an estimate of its initial construction cost is made to ensure that the initial construction cost is within the funds available for the project. If so, then the alternative is "feasible." A comparison of the life-cycle costs of all feasible alternatives can then be made and the most cost-effective alternative can be identified. There may still be other considerations that may make it desirable to choose an alternative other than the one with the lowest life-cycle cost, as indicated in figure 2.

Construction Feasibility of the Rehabilitation Alternative

The ability to construct a rehabilitation alternative is the first consideration in determining feasibility, because if it cannot be constructed under prevailing conditions, it is obviously not feasible. Constraints often exist at a given site that present major problems for construction of specific alternatives. The major factors in construction feasibility are described below.

1. Vertical clearances. The distance between the pavement surface and the bottom of the bridge beams is normally restricted to a certain minimum clearance for specific routes, which limits the allowable thickness of overlays. There are, however, four ways to overcome this limitation.

- Extensively repair the area under and near the bridge and do not overlay this area. This may require removal and replacement of a significant portion of this area, depending on the amount of deterioration.

- Remove the pavement beneath the bridge and reconstruct a new full pavement structure within a few hundred feet with the proper clearance.

- Reduce the thickness of the overlay under the bridge. This alternative usually results in a much more rapid deterioration of the overlay within the thinned area, however, and is not recommended.

- Raise the bridges to increase the clearance. This will require additional work for the bridge approaches.

At least one of the above alternatives should be physically possible, but the feasibility then depends on the costs involved. If many overhead bridges exist along the project, any of the above alternatives with a thick overlay may result in prohibitively high costs.

2. Traffic Control. Most projects must be built under traffic due to a lack of available detours. This may require having one or more lanes open at all times, or having all lanes open during certain times of the day or week. However, it may be possible to detour traffic onto the opposing traffic lanes, which permits the closure of traffic lanes in one direction at a time. This traffic control option is not limited in applicability to rural areas; this technique was successfully employed in the reconstruction of urban freeways such as the Edens expressway in Chicago and the Lodge freeway in Detroit. Zero-clearance concrete pavers and "fast-tracking" (early opening) of concrete overlays have increased their construction feasibility. Many creative traffic control plans have been developed which have made seemingly impossible traffic control situations possible.

3. Construction. Lack of equipment, materials or skilled contractors in a given area may limit the feasibility of certain rehabilitation alternatives.

Future Life of the Rehabilitation Alternative (Performance Period)

This is the period of time that the rehabilitation will last before the pavement will again require some type of rehabilitation. The AASHTO Guide defines this as a performance period. Highway agencies have typically designed new pavements for a performance period of 20 to 40 years. Rehabilitation projects have usually been designed for a shorter periods, with the exception of urban freeways with heavy traffic flows.

It is nearly always more desirable to have a rehabilitation alternative last many years to avoid all of the problems of frequently disrupting traffic flow. Because of the difficulty and hazards of closing traffic lanes, especially for routes which carry high volumes of traffic, some minimum life generally must be attainable with the proposed rehabilitation in order for it to be considered acceptable from a practical, policy, or political standpoint. For example, the new FHWA pavement policy specifies a minimum performance period of 8 years for most rehabilitation projects.(5) However, in some cases traffic volumes and traffic control difficulties may be such that the agency may require a much longer life, such as 20 years.

The life of a rehabilitation alternative depends upon many factors. These factors vary for different alternatives. The following is a list of the major factors which influence how well and how long a rehabilitation alternative will perform.

1. Existing Pavement Condition. The type, severity and extent of distress present in the existing pavement normally have a large effect on the future life of the rehabilitation alternative. This is particularly true for restoration and for certain types of overlays which require extensive repair of the existing pavement. Furthermore, serious progressive deterioration of the concrete pavement, such as that caused by D-cracking or reactive aggregate, has a large effect on the future life of most rehabilitation alternatives. Poor base or subgrade support or the presence of a high water table must be considered.

2. Extent of Repair Performed. The amount of repair performed, either as restoration or as preparation for an overlay, has a substantial impact on the future life of the rehabilitation. Of particular importance are:

- Full-depth repairs of working cracks, deteriorated joints, and corner breaks.
- Steps to reduce pavement deflections, including subsealing and load transfer restoration.

The proper design and construction of full-depth repairs and other restoration work is also critical. If the restoration requires extensive full-depth or partial-depth repairs, this may limit the future life of certain alternatives due to either repair failure or deterioration of the surrounding slab, both of which have occurred commonly in the past as a result of improper repair construction.

3. Subdrainage of the Existing Pavement. Poor subdrainage may be a major reason for deterioration of the existing pavement. Longitudinal subdrains can be installed in a pavement structure which was not originally constructed with drains, but if the permeability of the base and subgrade is so poor that water requires long periods of time to reach the drains, their installation may have little or no effect on future performance. However, the subdrain may remove water that infiltrates the outside lane/AC shoulder joint, where up to 80 percent of the water in the pavement section enters.

4. Structural Adequacy. If the existing pavement is suffering from significant structural deterioration, the life of any rehabilitation alternative that does not increase the structural capacity of the pavement will be severely limited.

5. Future Traffic Loadings. Truck traffic volumes are currently growing at such a rapid rate that it is not unthinkable for a pavement to receive as many 18-kip (80 kN) ESAL loadings in the first 5 years after rehabilitation as it received in the previous 20 or 30 years of its life. Obviously, this will have a dramatic effect on the future life of the rehabilitated pavement.

6. Reliability. The reliability of a rehabilitation technique depends upon the performance of each of the individual techniques involved, such as full-depth repairs, subdrainage and the overlay, and on the potential for deterioration of areas that were not repaired. Either unsuccessful or inadequate repair can cause failure of the rehabilitated pavement.

The future life of the rehabilitation alternative can be estimated using available performance results from similar projects, available predictive models and engineering judgement.

The EXPEAR program contains many predictive models based upon extensive field surveys of over 400 conventional concrete pavements and 350 concrete pavement rehabilitation projects.(2) Other models were developed using the Illinois pavement feedback database for continuously reinforced concrete pavements (CRCP). In addition, a few improved predictive models were developed under Phase II of this contract for crack and seat with AC overlays, bonded concrete overlays, and saw and seal of AC overlays on PCC pavements. These new prediction models are described in appendix A of this volume. Models for the following distress types and serviceability are used in the EXPEAR program:

- **Faulting of transverse joints for:**
  - non-diamond ground projects.
  - diamond grinding projects.
  - full-depth repairs.
  - bonded concrete overlays.
  - unbonded concrete overlays.

- **Spalling of transverse joints for:**
  - conventional jointed pavements.
  - full-depth repairs.

- **Cracking of slabs for:**
  - conventional jointed pavements.
  - bonded concrete overlays.

- **Reflection cracking for:**
  - crack and seat AC overlays.
  - saw and seal AC overlays.
  - conventional AC overlays over jointed pavements.
  - conventional AC overlays over CRCP.

- **Rutting for AC overlays of concrete pavements.**

- **Punchouts for CRCP.**

- **Spalling of transverse joints for:**
  - full-depth repairs..
  - conventional jointed concrete pavements.

- **Serviceability index based on cracking, joint deterioration and faulting for JPCP and JRCP.**

These predictive models use information on the pavement's existing design, rehabilitation design, climate, and past and future traffic loadings to estimate future distress. The prediction curves are shifted vertically upward or downward so that the intersect the actual distress quantities corresponding to the pavement's current condition. This greatly improves their accuracy for future prediction. These models have significant limitations of accuracy, but are adequate in most cases for making preliminary estimates of rehabilitation performance.

The use of predictive models to estimate future life of a rehabilitation alternative requires setting limits for key distresses such as faulting and cracking. When one of these critical distress levels is reached, the pavement's condition is unacceptable in some way and further rehabilitation is needed. This provides a way to define the life of the rehabilitation. Establishing these critical distress levels is not an easy task. Some suggested values are provided in table 1. Individual agencies should review these values and revise them in accordance with their own experience.

Initial And Life-Cycle Costs

If a rehabilitation alternative is constructable, the future life of the alternative is acceptable, and the initial rehabilitation construction cost is within the available funds, then by definition, the alternative is feasible. It may not, however, be the most cost-effective alternative available; this can only be determined after a comparison of the life-cycle costs of all of the feasible alternatives.

Engineers frequently make premature and subjective judgments of the relative cost effectiveness of various rehabilitation strategies. Such judgments tend to be strongly influenced by conscious or unconscious biases for or against certain alternatives, based on the engineers own past experiences or the experiences of others. Although there is certainly a place for experience in evaluating alternatives, the engineer is usually wise to withhold judgment until after a life-cycle cost comparison has been conducted.

The EXPEAR program includes a routine for estimating the life-cycle cost of a rehabilitation alternative. The initial cost of rehabilitation is computed on the basis of existing distress quantities and unit costs provided by the engineer. This initial cost is annualized over the life of the alternative using an input discount rate. Other costs which are not directly related to improvement of the pavement but which should be considered in the cost of the rehabilitation project include:

- Guardrail and sign raising or replacement.
- Widening of slopes due to a thick overlay.
- Extension of culverts due to a thick overlay.
- Traffic control (unless included in unit cost of repairs, overlay, etc.).
- Bridge raising.
- Interchange work.
- Safety work required to bring highway up to standards.
- Bridge and other structure work.
- Noise barriers.
- User delay costs due to traffic control.

Table 1. Suggested limiting distress values for determining rehabilitation life.

	LIMITING CRITERIA	
DISTRESS TYPE	JPCP	JRCP
Faulting of transverse joints		
- non-diamond ground projects	0.10 in	0.25 in
- diamond grinding projects	0.10 in	0.25 in
- bonded concrete overlays	0.10 in	0.25 in
- unbonded concrete overlays	0.10 in	0.25 in
- total faulting of joints, cracks, and full-depth repairs	30 in/mi	30 in/mi
Spalling of transverse joints for		
- conventional jointed pavements	50 M-H joints/mi	25 M-H joints/mi
Cracking of slabs for		
- conventional jointed pavements	800 L-H ft/mi	800 M-H ft/mi
- bonded concrete overlays	800 L-H ft/mi	800 M-H ft/mi
Reflection cracking for		
- crack and seat and AC overlays	75 M-H cracks/mi	75 M-H cracks/mi
- saw and seal AC overlays	75 M-H cracks/mi	75 M-H cracks/mi
- conventional AC overlays on JCP	75 M-H cracks/mi	75 M-H cracks/mi
- conventional AC overlays on CRCP	25 M-H cracks/mi	
Rutting for AC overlays	0.4 in	0.4 in
Punchouts for CRCP	25/mi	

1 in = 25.4 mm
1 ft = 0.3048 m
1 mi = 1.609 km

The cost estimate produced by EXPEAR also does not include future maintenance costs or user costs associated with such things as lane closures and pavement roughness.

3. RECOGNIZING THE NEED FOR STRUCTURAL IMPROVEMENT

This section defines the concept of structural damage of jointed concrete pavements as used in the context of determining feasible rehabilitation alternatives. Structural damage is normally defined as slab cracking (primarily transverse cracking) caused by repeated traffic loads. This definition is too limiting when it comes to determining feasible rehabilitation alternatives because all slab fractures (or cracks) are important, even those not caused by fatigue. Repeated loads will nearly always cause increased deterioration of any type of fracture in the slab, no matter what the cause.

"Structural damage" for rehabilitation purposes, then, is defined as any type of slab fracture (cracking). This ranges from transverse and longitudinal cracks to very fine fractures or spalls that may exist near joints and linear cracks. This definition makes it possible to consider all slab fractures that may deteriorate in the future that would result in a structurally deficient slab.

Structural damage begins to accumulate as soon as a concrete pavement is constructed and opened to traffic. The type and amount of structural damage depends upon many factors, including slab and joint design, subdrainage capability, initial quality and subsequent erosion of slab support, applied traffic, climatic conditions, maintenance activities and material properties of the concrete, bases and subgrade. Based on this definition, at least four broad categories of structural damage exist.

Slab Cracking Caused By Fatigue (Repeated Load) Damage

Repeated load fatigue damage results in transverse cracks and corner breaks, and also may include some longitudinal cracks. Other contributing causes which are often present include thermal curling stresses, drying shrinkage stresses and increase in load stresses due to erosion of supporting layers.

The critical fatigue damage location for conventional JPCP and JRCP pavements is along the outer lane edge. This is the location at which the magnitudes of truck wheel load stresses and thermal curl stresses, combined with the frequency of loading, produce the greatest fatigue damage. As the damage accumulates, cracks eventually develop at the bottom of the slab and work their way up and across the slab to form a transverse crack. The development of transverse cracks as a function of fatigue damage at the slab edge is shown in figure 3.(6) The extent of fatigue damage accumulated in the pavement is expressed by the ratio of applied loads (n) to allowable loads (N) to cracking. This curve eventually becomes S-shaped as cracking approaches a maximum value (e.g., all slabs cracked). These cracks may then deteriorate further under repeated

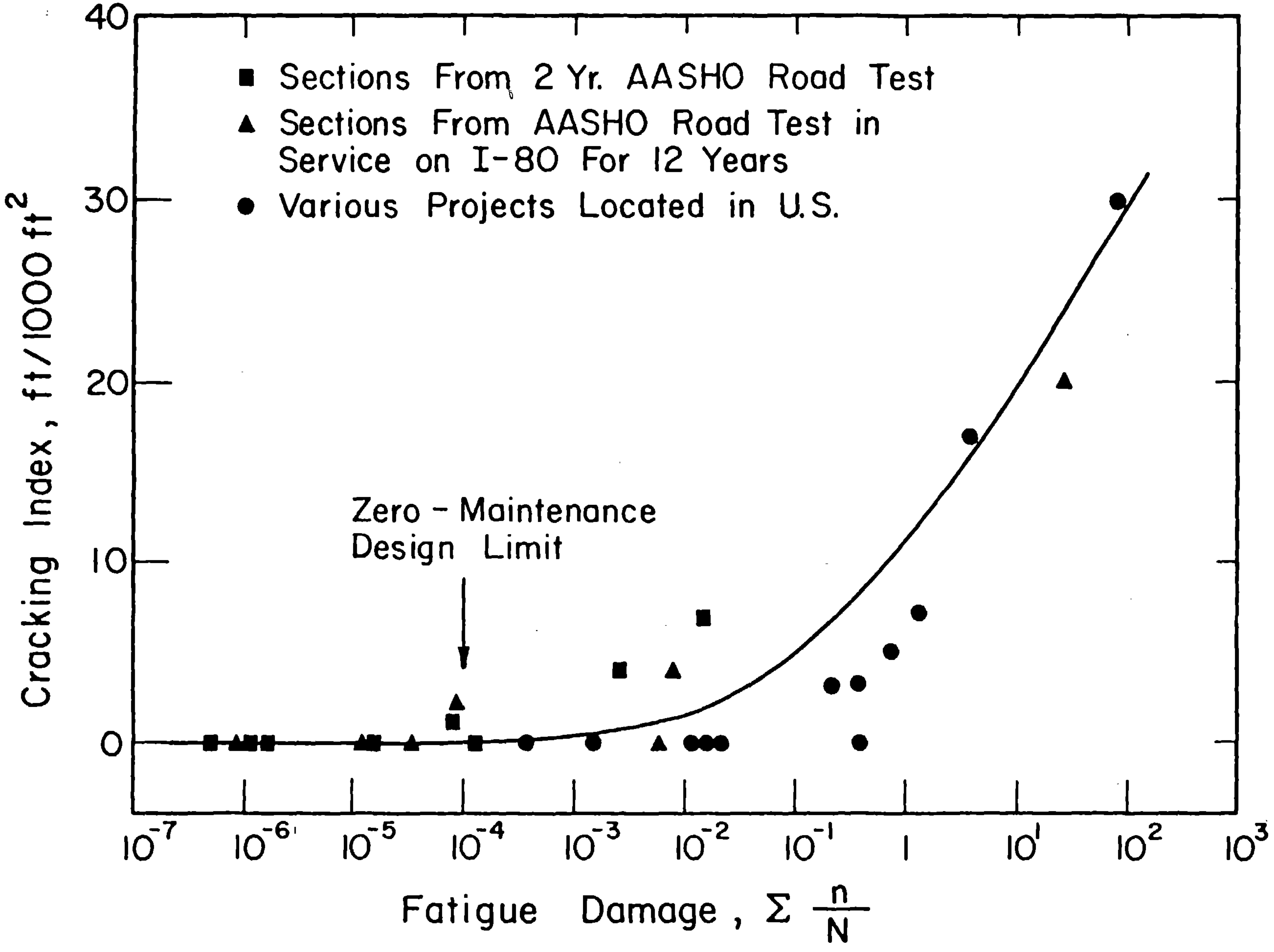


Figure 3. Effect of fatigue damage on development of cracking in JPCP.

loadings, resulting in spalling and faulting. Reinforcement in the slab normally reduces the rate of deterioration of the cracks. By the time a significant amount of cracking is visible at the surface, exists, the pavement generally has accumulated a large amount of structural damage.

Corner breaks occur when support is eroded beneath slab corners by the interaction of water, poor load transfer, and wheel loads. The critical stress under a corner loading occurs at the top of the slab, along a radius which intersects the transverse joint and longitudinal slab edge. Fatigue damage accumulation eventually results in a corner break (not to be confused with a corner spall caused by incompressibles in the joint). Corner breaks rarely occur on pavements that have doweled joints due to the increased shear support. Widened lanes or tied concrete shoulders may also significantly reduce this type of distress.

Fatigue damage can be estimated using Miner's law.(7) The ratio of applied loads to allowable loads ranges from 0 (no damage) to 1.0 (about 50 percent cracked slabs), and even above 1.0 for more slab cracking. Past traffic history using the pavement must be estimated to use this approach.

Deterioration Of Slab Cracking Caused By Nonload Factors

Transverse cracks in long-jointed JRCP are caused by a combination of thermal curling and shrinkage and drying shrinkage stresses. The reinforcement is supposed to hold these cracks tight so that they will have high aggregate interlock resistance to shear stresses caused by passing wheel loads. If the cracks open up more than 0.025 to 0.035 in (0.6 to 0.9 mm) for any reason, the interlock is lost and the crack will break down and spall and fault.(8) Cracks may open for a variety of reasons, including:

- Daily or seasonal temperature changes.
- Relief of compression in the slab as a result of full-depth repair or expansion joint installation.
- Lock-up of transverse joints due to dowel corrosion or misalignment.

Longitudinal cracks may occur as a result of inadequate longitudinal joint design or construction procedures, or foundation settlement. After they occur, repeated heavy wheel loads can break down longitudinal cracks until they also spall and fault.

Sometimes, longitudinal cracks occur near the outer wheelpath due to high compressive stresses in the slab caused by infiltration of incompressibles in the transverse joints. Longitudinal cracking near transverse joints may also be caused by expansion of reactive aggregate. Repeated traffic loads can propagate these longitudinal cracks further into the slab and also cause spalling.

Slab Spalling Fractures From Repeated Loadings

When the faces of a joint or crack are fairly tight, but still experience some differential deflection as loads pass, high shear stresses can cause spalling at the top of the slab. A sealant reservoir cut 2 in (51 mm) or more into the top of the slab and properly sealed can inhibit spalling at transverse joints. This type of spalling is common at transverse cracks.

Dowel/concrete bearing stresses can become excessive for small dowel bars (1-in [25 mm] diameter) which can lead to spalling of the concrete above or below the dowel after many heavy loads. This can also be a problem due to cracking of the green concrete under the dowel due to construction loading or if the pavement is opened to traffic quickly after poor curing conditions (e.g., late fall).

Repeated Load Deterioration of Spalls Initially Caused By Other Factors

This is further deterioration of joint spalls that were originally caused by incompressibles, misaligned dowels, corrosion of dowels, concrete durability problems (D-cracking, reactive aggregate cracking), or other nonload causes.

Deterioration of longitudinal and transverse joints and cracks due to the causes listed above is very common. The most serious of the causes is D-cracking, which is manifested by small, fine fractures within about 2 ft (0.61 m) on each side of joints and cracks. Badly D-cracked concrete is extensively fractured throughout its aggregate and its cement matrix, and thus has little structural integrity to resist deterioration under repeated heavy loads.

Structural Damage Identified In An Existing Pavement

The extent of structural damage present can be partially determined from observations of the extent of cracking visible at the slab surface. However, the extent of cracking at the bottom of the slab may be greater and will definitely manifest itself in additional visible cracking if allowed to progress.(9) The way in which structural distress progresses is also important. It tends to start slowly and accelerate rapidly as the pavement's fatigue life is reached and exceeded, as illustrated in figure 3. This accelerating progression of load-related distress is characteristic of both concrete and asphalt pavements. Both may exhibit relatively little visible structural distress until near the end of their fatigue lives.

For example, a concrete pavement that is 25 years old and has been subjected to some heavy loadings may not exhibit any transverse cracking, but that does not mean its structural capacity is as good as that of a new concrete slab just opened to traffic. The old pavement has certainly accumulated some fatigue damage, and if loadings continue, will eventually begin cracking. On the other hand, it is a mistake to assume that just because the pavement is old, it could "go any minute." It is the slow-starting nature of fatigue damage manifestation that ensures that cracking will initially develop slowly and provide some warning that the end of the pavement's fatigue life is approaching.

As any of the above types of damage occurs in a jointed concrete pavement, the pavement is said to accumulate structural damage. As the level of structural damage increases, it eventually reaches a point where rehabilitation of the pavement is necessary to continue carrying traffic at current and projected future load levels.

There is no general agreement on the point at which a pavement should be rehabilitated, nor the point at which the pavement cannot be restored and should receive a structural improvement. The following is a list of items to consider in assessing structural damage in jointed concrete pavement:

- Transverse cracking provides direct evidence of fatigue damage. In JRCP, low-severity cracks are considered a normal consequence of drying shrinkage after construction, and are not considered structural distresses. In JPCP, unless the joint spacing is too long, transverse cracking of any severity is evidence of structural damage.
- Longitudinal cracking that exhibits deterioration is definitely a sign of structural damage.
- Corner breaks indicate erosion of slab support which is a definite indication of structural damage.
- Extensive transverse or longitudinal joint spalling that reduces the thickness of the slab at the joints should be considered structural damage since it diminishes the structural integrity of the slab and is progressive in nature. This is often caused by D-cracking or reactive aggregates.

Although visible distress is a good indicator of structural damage, it cannot give a complete picture of the extent of underlying deterioration. Nondestructive deflection testing and coring are strongly recommended on any project being seriously considered for rehabilitation. Additionally, under certain circumstances, the use of "test pits" may be useful to provide an indication of the condition of the underlying paving materials.

Limits for these types of structural damage can be established so that the pavement evaluation indicates the extent of the damage and the remaining life of the pavement. The values for visible distress shown in table 2 are suggested based upon observation of JPCP and JRCP performance from the database, and from use of the EXPEAR program to predict the performance of restoration on pavements with varying levels of existing deterioration.

Table 2. Suggested visible distress criteria for judging significant structural damage.

STRUCTURAL DISTRESS	JPCP	JRCP
Transverse Cracking	10 percent slabs cracked or 70 cracks/mi	70 deteriorated cracks/mi
Longitudinal Cracking	500 ft/mi	500 ft/mi
Corner Breaks	25/mi	25/mi
Deteriorated Joints (medium-high spalling)	50/mi	25/mi
D-cracking or Reactive Aggregate Cracking	medium-high severity	medium-high severity

1 ft = 0.3048 m
1 mi = 1.609 km

If a JRCP or JPCP exhibits levels of structural damage beyond these values, the pavement has probably reached or passed the point at which the rate of deterioration begins to accelerate rapidly. This is the stage at which a structural improvement is most appropriate. Restoration work performed on a pavement that has deteriorated past this point will almost always perform poorly (life less than 8 years) under medium to heavy traffic conditions. Attempting to delay a structural improvement by continued patching may result in annual maintenance costs so high that they completely offset any savings achieved by the delay.

The above guidelines were tested using the EXPEAR program and found to be quite reliable in identifying pavements on which restoration would perform well for 8 years or more.

A pavement that is exhibiting low severity D-cracking is a much more difficult problem. Here, cores of the joints and cracks would provide knowledge of the extent of deterioration beneath the surface. Also, a knowledge of the source of the aggregate in the concrete and its performance in other pavements in the area would give some insight into the rate at which the D-cracking is likely to progress. This additional information would be very useful to the design engineer in determining the feasibility of restoration. The age of the pavement and the rate of D-cracking development will also influence the rehabilitation decision.

CHAPTER 3 REHABILITATION SELECTION GUIDELINES

This section provides guidelines for selection of the major type of concrete pavement rehabilitation. The guidelines are presented in a series of tables that summarize construction, performance period and cost-effectiveness feasibility of each rehabilitation approach:

• Table 3	Restoration.
• Table 4	Bonded concrete overlays.
• Table 5	Conventional AC overlays.
• Table 6	AC overlay with sawed and sealed joints.
• Table 7	Crack and seat and AC overlay.
• Table 8	Unbonded PCC overlay.
• Table 9	Reconstruction.

Further information on the design and construction of each of these rehabilitation approaches can be found in several recent publications:

- Restoration—references 10, 11, and 12.
- Overlays—references 3, 10, 11, 13 and volumes I, II, and III.
- Reconstruction—references 14 and 15.

Table 3. Feasibility guidelines for restoration.

CONSTRUCTABILITY	
Vertical Clearance	No problem.
Traffic Control	Construction under traffic is common. Rapid repair possible.
Construction	Trained personnel required for agency inspector and contractor. Specialized equipment often needed.
PERFORMANCE PERIOD	
Existing Condition	Existing pavement must be in relatively good condition. Limited transverse and longitudinal cracking, D-cracking, or reactive aggregate distress.
Extent of Repair	Must repair deteriorated cracks and joints.
Subdrainage	Must improve if deficient and truck traffic volume is high.
Structural Adequacy	Only limited amount of structural deterioration present.
Future Traffic Level	Presence of high truck traffic volume may cause rapid deterioration where structural deterioration exists.
Reliability	Fair. Success depends upon the performance of each restoration technique, particularly full-depth repairs.
COST-EFFECTIVENESS	
Initial Cost	Usually lower cost than other alternatives, especially if most deterioration exists in outer lane, and shoulders are in good condition.
Life-Cycle Cost	Usually low if structural adequacy is not a problem.

Table 4. Feasibility guidelines for bonded PCC overlay.

CONSTRUCTABILITY	
Vertical Clearance	Thin (3-in [76 mm]) overlay usually not problem. See section 2 for solutions to clearance problems.
Traffic Control	Somewhat difficult to construct under traffic. Rapid placement and curing techniques (fast-track paving) are available.
Construction	Trained personnel required. Special cleaning equipment needed. Achievement of bond critical. Not widely used so construction experience limited.
PERFORMANCE PERIOD	
Existing Condition	No D-cracking or extensive cracking.
Extent of Repair	Must repair deteriorated cracks and joints.
Subdrainage	Must improve if deficient.
Structural Adequacy	PCC overlay thickness can be provided to increase structural adequacy.
Future Traffic Level	Used under any traffic level.
Reliability	Fair. Success depends primarily upon achieving permanent bond and proper jointing.
COST-EFFECTIVENESS	
Initial Cost	Usually relatively high. Depends on preoverlay repair needs.
Life-Cycle Cost	Competitive with other overlays if future life is substantial.

Table 5. Feasibility guidelines for conventional AC overlays.

CONSTRUCTABILITY	
Vertical Clearance	Required AC thickness may pose a problem. See section 2 for solutions to overhead clearance problems.
Traffic Control	Not difficult to construct under traffic. Can be opened to traffic quickly.
Construction	Common rehabilitation procedure. AC mixture design critical. Proper construction critical to achieve density.
PERFORMANCE PERIOD	
Existing Condition	The more deterioration present, the thicker the AC overlay required for any given performance period.
Extent of Repair	Must repair deteriorated cracks and joints and must provide load transfer across transverse joints to limit reflection crack deterioration.
Subdrainage	Must improve if deficient.
Structural Adequacy	AC overlay thickness can be provided to increase structural adequacy, but may be substantial.
Future Traffic Level	High traffic level may result in excessive rutting, particularly if overlay is thick or mix design is poor.
Reliability	Fair. Success depends primarily upon preventing excessive rutting and deterioration of reflection cracks.
COST-EFFECTIVENESS	
Initial Cost	High compared to restoration. Depends greatly on preoverlay repair needs.
Life-Cycle Cost	Competitive with other overlays if future life is substantial.

Table 6. Feasibility guidelines for AC overlay with sawed and sealed joints.

CONSTRUCTABILITY	
Vertical Clearance	Required AC thickness may pose a problem. See section 2.
Traffic Control	Not difficult to construct under traffic. Can be opened to traffic rapidly. Joint sawing requires additional time.
Construction	Common rehabilitation procedure, except for joints which must be very accurately sawed. AC mixture design critical. Proper construction critical to achieve density.
PERFORMANCE PERIOD	
Existing Condition	The more deterioration present, the thicker the AC overlay required for any given performance period.
Extent of Repair	Must repair deteriorated cracks and joints and must provide load transfer across transverse joints to limit reflection crack deterioration.
Subdrainage	Must improve if deficient.
Structural Adequacy	AC overlay thickness can be provided to increase structural adequacy, but may be substantial.
Future Traffic Level	High traffic level may result in excessive rutting, particularly if overlay is thick or mix design is poor.
Reliability	Good. Success depends primarily upon preventing excessive rutting and locating sawed joints accurately above underlying joints and cracks.
COST-EFFECTIVENESS	
Initial Cost	Somewhat higher than conventional AC overlay due to joint sawing. Depends greatly on preoverlay repair needs.
Life-Cycle Cost	Competitive with other overlays if future life is substantially greater than conventional AC overlays.

Table 7. Feasibility guidelines for AC overlay with cracked and seated slab.

CONSTRUCTABILITY	
Vertical Clearance	Required AC overlay thickness usually a problem. See section 2.
Traffic Control	Not difficult to construct under traffic. Can be opened to traffic rapidly. Cracking and seating operations requires additional time.
Construction	Fairly difficult to crack existing slab sufficiently. AC mixture design critical. Proper construction critical to achieve density.
PERFORMANCE PERIOD	
Existing Condition	Can be applied to more deteriorated concrete pavements. However, if the cracking and seating process does not produce uniform support, with good load transfer across the cracks, serious reflection cracking may develop around the broken pieces.
Extent of Repair	Must repair deteriorated cracks and joints and must provide load transfer across transverse joints to limit reflection crack deterioration.
Subdrainage	Must improve if deficient.
Structural Adequacy	Cracking and seating process reduces concrete slab's structural capacity. Substantial AC overlay thickness must be provided to achieve structural adequacy.
Future Traffic Level	High traffic level may result in excessive rutting, particularly if overlay is thick or mix design is poor. High traffic also may result in rocking pieces of concrete, causing reflection cracks in the AC overlay.

Table 7. Feasibility guidelines for AC overlay with cracked and seated slab (continued).

Reliability	Poor to fair. Success depends primarily upon preventing excessive rutting and ensuring that PCC slab is properly cracked. Field performance results to date show that initial delay in onset of reflection cracking is overcome within 6 to 8 years; beyond that time reflection cracking levels equal or exceed those for conventional AC overlays of the same thickness.(3)
COST-EFFECTIVENESS	
Initial Cost	Higher than conventional AC overlay due to cracking and seating and thicker AC overlay required. Depends somewhat on preoverlay repair needs.
Life-Cycle Cost	Not competitive with other overlays unless preoverlay repair can be reduced to offset cost of cracking and seating. Life, in terms of rutting and reflection cracking, less than or equal to that of conventional AC overlays of the same thickness.

Table 8. Feasibility guidelines for unbonded PCC overlay.

CONSTRUCTABILITY	
Vertical Clearance	Required PCC thickness usually a problem. See section 2.
Traffic Control	Difficult to construct under traffic, but can be done using new techniques (zero-clearance paver). Normally cannot be opened to traffic rapidly, except when high-early-strength concrete and special curing techniques used (i.e., fast-track paving).
Construction	Does not require any special equipment.
PERFORMANCE PERIOD	
Existing Condition	This overlay can be applied to very deteriorated concrete pavements.
Extent of Repair	Very little repair of deteriorated crack and joints is needed.
Subdrainage	Improvement recommended if deficient.
Structural Adequacy	Substantial PCC overlay thickness must be provided to increase structural adequacy. Minimum thickness of 5 in (127 mm) recommended for low-volume routes, 7 in (178 mm) for higher-volume routes. Joint design is critical.
Future Traffic Level	Use under any level of traffic.
Reliability	Very good. Can be designed for any desired performance period.
COST-EFFECTIVENESS	
Initial Cost	Higher than conventional AC overlay.
Life-Cycle Cost	Not competitive with other overlays unless existing deterioration is significant.

Table 9. Feasibility guidelines for reconstruction.

CONSTRUCTABILITY	
Vertical Clearance	Reconstructed pavement can be built to any desired grade.
Traffic Control	Difficult to construct under traffic, but can be done using new techniques (zero-clearance paver). Normally cannot be opened to traffic rapidly, except when high-early-strength concrete and special curing techniques used (i.e., fast-track paving).
Construction	Does not require any special equipment except for removal of old pavement. Recycling of existing slab is an option. Condition of existing base, subbase and subgrade should be considered.
PERFORMANCE PERIOD	
Existing Condition	Generally not a factor in reconstruction performance. Recycling D-cracked or reactive aggregate PCC may require mix design modifications (maximum aggregate size, admixtures).
Extent of Repair	None.
Subdrainage	New subdrainage system recommended.
Structural Adequacy	Can be designed to handle any traffic level.
Future Traffic Level	Use under any level of traffic.
Reliability	Very good. Can be designed for any desired performance period.
COST-EFFECTIVENESS	
Initial Cost	Normally higher than conventional overlays.
Life-Cycle Cost	Not competitive with overlays unless existing deterioration is substantial.

CHAPTER 4 EVALUATION AND REHABILITATION WITH EXPEAR

1. INTRODUCTION

EXPEAR is a practical and comprehensive computerized system to assist practicing engineers in evaluating concrete highway pavements, developing feasible rehabilitation alternatives, and predicting the performance and cost effectiveness of the alternatives. EXPEAR was originally developed for the FHWA and has been further developed with the support of the Illinois Department of Transportation.(2) Additional work on EXPEAR has been supported by the FHWA under this research study.

EXPEAR is intended for use by State highway engineers in project-level rehabilitation planning and design for high-volume (i.e., Interstate) conventional concrete pavements (JRCP, JPCP, and CRCP). EXPEAR does not perform thickness or joint design; the engineer must use existing design procedures to determine these details.

EXPEAR has been developed in the form of a knowledge-based expert system, which simulates a consultation between an engineer and an expert in concrete pavements. EXPEAR uses information about the pavement to guide the engineer through evaluation of a pavement's present condition and development of one or more feasible rehabilitation strategies. The procedure was developed through extensive interviewing of authorities on concrete pavement performance. In addition, predictive models are included to show future pavement performance with and without rehabilitation.

Evaluation of a pavement and development of feasible rehabilitation alternatives is performed according to the following steps:

1. Project data collection.
2. Extrapolation of overall project condition.
3. Evaluation of present condition.
4. Prediction of future condition without rehabilitation.
5. Recommendations for physical testing.
6. Selection of main rehabilitation approach.
7. Development of detailed rehabilitation strategy.
8. Prediction of rehabilitation strategy performance.
9. Cost analysis.
10. Selection of preferred rehabilitation strategy.

A computer program has been developed for each of the three pavement types addressed. The programs operate on any IBM-compatible personal computer. The current version is EXPEAR 1.4, which possesses the capabilities to do life-cycle cost analysis and delay rehabilitation up to 5 years. Many revisions were made in EXPEAR 1.4 to improve the user friendliness of the program.

2. PAVEMENT EVALUATION

Data Collection and Entry

The engineer collects inventory and monitoring data for the project. Inventory data, which should be available from office records, includes design traffic, materials, soils and climate. Monitoring data includes distress, drainage characteristics, rideability, and other items collected during a field visit to the project. Monitoring data is collected by sample unit; a sufficient number of sample units distributed throughout the projects's length should be surveyed to obtain an accurate representation of the project's condition.

It is recommended that a team of two engineers perform the project survey together. They should drive over the entire length of the project and rate the present serviceability in each lane. They should also note the number and location of settlements and heaves. They should then return to the start of the project and perform the distress survey by sample unit. It is convenient to start sample units at mileposts.

Either the pavement distress identification manual provided in NCHRP Report No. 277 or the Strategic Highway Research Program's (SHRP's) Long-Term Pavement Performance (LTPP) distress identification manual should be used for reference (see references 16 and 17, respectively). These provide standard definitions for distresses by type, severity, and unit of measurement. They also provide photographs of distresses to assist the engineers in rating their severity. The engineers must also measure faulting at joints, cracks, and full-depth repair joints.

In the office, the data are entered into a personal computer using a full-screen editor. The format of the data entry screens is very similar to that of the field survey sheets. The editor provides function keys for moving forward and backward through the data items and screens. The editor will provide screens for the project inventory data and monitoring data (1 set for each sample unit, up to a maximum of 10).

Extrapolation of Overall Project Condition

Using the project length and lengths of the sample units, EXPEAR extrapolates from the sample unit distress data to compute the overall average condition of the project. The project is then evaluated on the basis of this average condition.

Evaluation of Present Condition

EXPEAR utilizes a set of decision trees to analyze all of the data and develop a specific detailed evaluation in the following major problem areas (for JRCP and JPCP):

- Roughness.
- Drainage.
- Foundation movement.
- Joint construction.
- Load transfer.
- Concrete durability.
- Structural adequacy.
- Joint deterioration.
- Skid resistance.
- Loss of support.
- Joint sealant condition.
- Shoulders.

The same problem areas are examined for CRCP, with the exception of those related to transverse joints (construction, deterioration, load transfer, and loss of support), and with the addition of a decision tree for construction joints and terminal treatments.

From the decision trees, a set of evaluation conclusions is produced for each traffic lane and each shoulder.

Prediction of Future Condition Without Rehabilitation

Based on the current traffic level (annual 18-kip [80 kN] ESAL) and the anticipated ESAL growth rate, the future condition of the pavement without rehabilitation is predicted. Faulting, cracking, joint deterioration, pumping, and present serviceability rating are projected for jointed pavements (and punchouts for CRCP) and the years in which they will become serious problems are identified. The predictive models used are calibrated to the existing condition of the pavement at the time of the survey.

Physical Testing Recommendations

The initial data collection does not require physical testing. Based upon the available information, the program identifies types of physical testing needed to verify the evaluation recommendations and to provide data needed for rehabilitation design. Testing may include nondestructive deflection testing, destructive coring, material sampling and laboratory testing, test pits, and roughness and friction measurement. Types of deficiencies which may warrant physical testing include structural inadequacy, poor rideability, poor surface friction, poor drainage conditions, poor concrete durability (D-cracking or reactive aggregate distress), foundation movement (due to swelling soil or frost heave), loss of load transfer at joints, loss of slab support, joint deterioration, and evidence of poor joint construction.

3. PAVEMENT REHABILITATION

Selection of Main Rehabilitation Approach

Based upon the evaluation results, the system interacts with the engineer to select the most appropriate main rehabilitation approach for each traffic lane and shoulder. These include all 4R options: reconstruction (including recycling), resurfacing (with concrete or asphalt), or restoration. The major factors in determining whether a pavement needs reconstruction, resurfacing, or merely restoration are the extent of structural distress (e.g., cracking and corner breaks) and the extent of deterioration due to poor concrete durability (D-cracking or reactive aggregate distress).

Development of Detailed Rehabilitation Strategy

Once an approach is selected for each traffic lane and shoulder, the engineer proceeds to develop the detailed rehabilitation alternative by selecting a feasible set of individual rehabilitation techniques to correct the deficiencies present. This may include such items as subdrainage, shoulder repair, full-depth repairs, joint resealing, etc. This is performed for each traffic lane and shoulder by interaction with the program. EXPEAR displays each of the evaluation conclusions reached earlier and recommends one or more appropriate rehabilitation techniques. A set of decision trees has been developed to guide the rehabilitation strategy development process for traffic lanes and for adjacent shoulders. Where more than one choice exists for an appropriate technique to repair a specific distress, the system presents the engineer with the choice to make.

Computation of Rehabilitation Quantities

EXPEAR computes needed quantities for the rehabilitation techniques selected based on the data in the project survey and additional information provided by the engineer. In general, the program assumes that 100 percent repair will be performed; that is, that the quantity of a certain type of distress to be repaired is equal to the quantity of that distress observed during the field survey.

If the rehabilitation work is being delayed, the quantities are increased where appropriate for each year of delay. Predictive models are used where available to increase the quantities. For distresses which do not have predictive models available, the quantities are increased by some constant amount (e.g., 5 percent per year).

When rehabilitation is delayed on a project which does not currently have any cracking or joint deterioration but which is predicted to develop some of either of these distresses between now and the time that the rehabilitation work will be done, appropriate quantities of full-depth repair are added to the rehabilitation strategy.

Prediction of Rehabilitation Strategy Performance

The future performance of the developed rehabilitation strategy is predicted in terms of key distress types for 20 years into the future, based upon the traffic growth rate entered by the engineer. The JRCP and JPCP EXPEAR programs contain prediction models for the following key distresses for the various rehabilitation approaches:

• Reconstruction:	Faulting Cracking Pumping Joint deterioration PSR
• Bonded PCC overlay, and Unbonded PCC overlay:	Faulting Cracking Joint deterioration
• AC structural overlay, AC nonstructural overlay, AC overlay/crack & seat, and AC overlay w/saw and seal:	Reflective cracking Rutting
• Restoration:	Faulting: - with grinding - without grinding Full-depth repair faulting Cracking Pumping Joint deterioration PSR

The models are calibrated to the assumed condition of the pavement immediately after the rehabilitation is performed. If, for example, diamond grinding is not included in a restoration strategy, joint faulting after restoration is assumed to be the same value as was measured during the field survey, but if grinding is performed, joint faulting is assumed to be zero after the restoration.

EXPEAR evaluates the predicted performance of the rehabilitation strategy with respect to critical distress levels selected by the engineer, and determines in which years in the future these critical distress levels will be reached. From this information the predicted life of the rehabilitation strategy is determined.

Cost Analysis of Rehabilitation Strategy

The first version of EXPEAR which was developed for the FHWA (EXPEAR 1.1) did not include the capability to perform a life-cycle cost analysis of the rehabilitation strategy developed. The most recent version of the program (EXPEAR 1.4) performs the cost analysis for the engineer. It uses the computed repair quantities and determines the rehabilitation alternative's life from the performance predictions. The engineer must specify the discount rate to be used in the analysis (values between 0 and 7 percent are permitted), and must also specify whether or not the rehabilitation will be delayed. Delays up to 5 years are permitted; considering the margin of error on some of the predictive models used by the program, it is not reasonable to assume the models can give meaningful predictions of the cost of rehabilitation postponed longer than that.

The engineer is given the opportunity to override the predicted life determined by the program. This may be desirable if the engineer has good reason to believe that the predicted life does not accurately reflect the performance of that type of rehabilitation under the specific local conditions which apply to the pavement being considered. The cost analysis output indicates whether the life used in the computations was that predicted by the program or another value provided by the engineer.

EXPEAR also provides default unit costs for all of the rehabilitation techniques involved in the strategy being considered. The engineer may use these default costs or enter other values. Any number of sets of modified unit costs may be saved by the engineer and retrieved for future use.

EXPEAR computes the present cost and the equivalent annual cost of each technique over the entire project length, and summarizes the total present and annual costs of the strategy being examined. In the case of delayed rehabilitation, the program also computes the actual dollar cost of the rehabilitation in that year, that is, the "present cost" in the year the work is performed.

The cost analysis period is restricted to be the same as the first rehabilitation performance period. Thus it is not possible to include subsequent rehabilitation in the strategy in order to fill out a desired analysis period. This is largely due to the lack of availability of predictive models for performance of such things as second overlays. It is also not possible to attach a salvage value to strategy with a predicted life in excess of 20 years. When interpreting the results of the cost analyses for several strategies, the engineer must keep in mind that the analysis periods will in most cases be unequal. These limitations will be addressed in future improvements to EXPEAR.

The cost analysis in EXPEAR is a simple and approximate procedure, the primary purpose of which is to facilitate rapid generation and comparison of rehabilitation alternatives. It should help the engineer identify alternatives which are comparable in cost effectiveness and deserve further investigation, and also eliminate alternatives which are clearly not cost-effective. It does not, however, take the place of the detailed evaluation and cost analysis which is required for preparation of plans, specifications, and bid estimates. It also does not consider cost items not directly related to improvement of the pavement (e.g., traffic control, bridge and guardrail work, etc.) though these costs may be incorporated into the engineer's unit costs if desired.

4. EXPEAR OPERATION

System Requirements

Running EXPEAR requires an IBM DOS-compatible computer with approximately 350 Kbytes of free memory, and one of the following:

- Hard disk.
- Two 360 K, 5.25-in (133 mm) floppy disk drives.
- One 720 K, 3.5-in (89 mm) disk drive.

Hard disk operation is recommended both for speed of execution and storage of output files. EXPEAR will display on any type of monitor (monochrome, CGA, EGA or VGA), and does not require a math coprocessor.

Each of the three EXPEAR versions (for the three pavement types: JPCP, JRCP, and CRCP) is distributed on a set of two 360 K, 5.25-in (133 mm) floppy disks. One disk contains the executable program (EXPEAR.EXE) and the other disk contains several other files needed to run EXPEAR. The file names (EXPEAR.EXE, DISPLAYS.REC, STNDRD.DAT, etc.) are common to the programs for all three pavement types (JRCP, JPCP, and CRCP), so it is important that the programs for different pavement types be kept on separate floppy disks or separate directories of a hard disk.

Running EXPEAR

The program is started by typing "EXPEAR" from DOS. After the EXPEAR title screen and a few screens of introductory information, the system displays the main menu, which has four options:

MAIN MENU

1. ENTER OR EDIT PROJECT DATA
2. CONDUCT PROJECT EVALUATION
3. DEVELOP REHABILITATION STRATEGY
4. QUIT, RETURN TO DOS

Enter or Edit Project Data

When this option is selected, a menu will appear to ask whether you want to create a new data file or edit an existing file. A new data file is created by modifying the STNDRD.DAT file. If an existing data file is to be modified, the program will ask for the name of the data file without the .DAT extension.

A full-screen data editor is incorporated into the system for data entry and editing. Function keys for moving through the data items and screens are defined at the bottom of the screen. Some data items are defined as "toggle variables," meaning that available values (such as low, medium, high) can be selected using the tab key. After a file is edited, SHIFT-10 will exit the editor. This command does not however, save the file on disk. The program will prompt the user to save the file before continuing.

Conduct Project Evaluation

When this option is selected, the program asks for the name of the data file to be evaluated. It also asks whether the user wants to use the default critical distress levels incorporated in the program, or his or her own values. These may be selected each time the program is run, or may be saved to disk and retrieved when needed. The program will prompt the user for a file name under which to store critical distress values and save the file with a .CVL extension. Whether the default values or user-defined values are used, critical distress levels must be selected before proceeding with the evaluation.

The evaluation runs very quickly. When it is done, EXPEAR displays the results of the evaluation, which consists of evaluation conclusions for the traffic lanes and shoulders, predicted performance of each lane without rehabilitation, and physical testing recommendations. If the user desires, the data summary file and the project evaluation summary file may be printed from within the program. These files are saved on disk (with .REP and .TXT extensions) and may also be printed from DOS at a later time. However, if the user exits the program at this point and enters it again, the evaluation process must be repeated in order to proceed, since EXPEAR must have a current evaluation in memory in order to develop a rehabilitation strategy.

When the evaluation is completed, a menu appears with the following options:

EVALUATION MENU

1. DISPLAY EVALUATION CONCLUSIONS
2. DISPLAY PHYSICAL TESTING RECOMMENDATIONS
3. DISPLAY FUTURE DISTRESS AND PSR PREDICTIONS
4. PRINT EVALUATION SUMMARY
5. RETURN TO MAIN MENU

This permits the user to examine any part of the evaluation results, print the evaluation results, or bypass viewing the evaluation results and proceed directly to developing a rehabilitation strategy.

Develop Rehabilitation Strategy

When this option is selected, EXPEAR interacts with the user to select the main rehabilitation approach (reconstruct, overlay, or restore) and the specific rehabilitation techniques needed to correct the deficiencies identified in the evaluation. EXPEAR recommends appropriate rehabilitation approaches and techniques and gives the user the option to choose whenever more than one appropriate technique exists. EXPEAR does not have the capability to permit the user to enter options other than the ones given. When the list of techniques making up the rehabilitation strategy has been developed, it will be displayed along with approximate quantities. For some quantity calculations additional user input is required, for which a prompt appears on the screen. The rehabilitation techniques and quantities may be printed from EXPEAR or from DOS; the output file has an .STS extension.

After a strategy has been developed, the rehabilitation menu appears with the following options:

REHABILITATION MENU

1. REVISE REHABILITATION STRATEGY
2. PREDICT REHABILITATION PERFORMANCE
3. PERFORM LIFE-CYCLE COST ANALYSIS
4. RETURN TO MAIN MENU

The second option will predict the performance of the rehabilitation strategy developed, using predictive models for key distresses. EXPEAR prompts the user for any additional information needed, such as overlay thickness. The predictions are displayed for each lane and may be printed from EXPEAR or from DOS (the output file's extension is .RHB).

Only after a rehabilitation strategy has been developed and its performance predicted can a cost analysis of the strategy be performed. EXPEAR prompts the user for a discount rate and the number of years that the rehabilitation will be delayed, and also asks the user to select unit cost values for the rehabilitation techniques. Default unit costs are provided, or (in the same manner as for critical distress levels), user-defined unit costs can be saved to disk (the file extension will be .UCC), and retrieved when needed.

The program computes the present and equivalent annual costs over the project length for the rehabilitation strategy analyzed. The annual cost is computed on the basis of the predicted life of the strategy, which is computed by EXPEAR but which may be overridden by the user if desired. The cost analysis results are displayed on the screen and may be printed from EXPEAR or from DOS (the extension is .LCC).

CHAPTER 5 CASE STUDIES IN REHABILITATION STRATEGY DEVELOPMENT

1. INTRODUCTION

Sections Evaluated

The database developed under this contract includes 95 sections of JPCP and JRCP in their first performance period.(18) Thirteen of these sections were selected for evaluation with the EXPEAR program. Their general characteristics are shown in table 10. These sections include a range of conditions from poor to good, are located in all major climatic zones, and include both JRCP and JPCP types. They represent a wide diversity of designs and conditions.

Table 10. Identification of 13 sections evaluated with EXPEAR.

Section ID	Climate	Type	Condition
AZ 1-6	Dry-Nonfreeze	JPCP	Good
CA 6	Dry-Nonfreeze	JPCP	Fair
CA 1-3	Dry-Nonfreeze	JPCP	Poor
FL 2	Wet-Nonfreeze	JPCP	Good
NC 1-8	Wet-Nonfreeze	JPCP	Fair
NC 2	Wet-Nonfreeze	JPCP	Fair
MI 3	Wet-Freeze	JRCP	Good
NJ 2	Wet-Freeze	JRCP	Fair
MI 4-1	Wet-Freeze	JRCP	Poor
MI 1-10b	Wet-Freeze	JPCP	Poor
MN 3	Dry-Freeze	JRCP	Good
MN 2-3	Dry-Freeze	JRCP	Fair to Good
MN 1-8	Dry-Freeze	JRCP	Poor

Evaluation Procedure

All EXPEAR input data required for each section were obtained from the database. The following steps were carried out for each of the 13 projects:

1. Input data were verified by State employees and project team members familiar with the section.

2. A pavement evaluation was conducted and future performance was predicted without any rehabilitation.

3. Feasible pavement rehabilitation alternatives were considered:

   - Restoration (except where structural inadequacy or concrete durability problems existed).
   - AC conventional overlay.
   - AC overlay and crack and seat.
   - AC overlay and saw and seal above joints.
   - PCC bonded overlay.
   - PCC unbonded overlay.
   - Reconstruction with JPCP or JRCP.

4. Life-cycle costs were estimated using Illinois statewide average costs. The cost analyses should be considered as examples only, due to the highly variable nature of pavement costs throughout the United States.

2. RESULTS OF THE EVALUATIONS

The predicted life, initial and annual costs were estimated for each rehabilitation alternative. Since the complete output from EXPEAR is very comprehensive, the results were summarized in a single page for each project. These summaries are presented as tables 11 to 23. During the process of running these 13 projects, several problems with the EXPEAR code were identified and corrected.

EXPEAR was found to do a reasonable job of evaluating the 13 widely different pavement sections and projecting their condition into the future without rehabilitation. On a few sections, the program did not appear to predict future deterioration as might be expected. EXPEAR's analysis of the rehabilitation alternatives showed some interesting and varied results. The information in tables 11 to 23 must be studied carefully to determine overall trends. Some observations from these case studies are given below.

1. Restoration is the most cost-effective alternative for pavements that are structurally adequate and do not have a concrete durability problem (D-cracking or reactive aggregate). This is shown by sections MI 3, NJ 2, MN 3, MN 2-3, AZ 1-6, FL 2, NC 2, and NC 1-8.

2. A conventional AC overlay (3 in [76 mm]) typically does not perform as well as the same thickness of AC overlay where the joints have been sawed and sealed. This is shown by sections MI 4-1, CA 6, and NC 1-8.

3. A crack and seat and 5-in (127 mm) AC overlay alternative performed better than a conventional 3-in (76 mm) AC overlay. However, the cost of cracking and seating and the cost of the additional 2 in (51 mm) of AC resulted in a higher life-cycle cost about half the time.

4. The sawed and sealed AC overlay alternative was usually the most cost-effective type of AC overlay. Rutting, not reflective crack deterioration, usually ended the life of this type of overlay.

5. The bonded PCC overlay provided good performance on the MI 4-1 section, and was cost-competitive with the 3-in (76 mm) saw and seal AC overlay and the 7-in (178 mm) unbonded PCC overlay.

6. The unbonded PCC overlay provided the longest life of all overlay alternatives and was found to be cost effective in several cases where the existing pavement was badly deteriorated, for example, MI 1-10b and MN 1-8.

7. The reconstruction alternative was cost effective if the existing pavement exhibited extensive deterioration and the shoulders were in good condition and did not need to be replaced. This was shown by sections NJ 2, NC 1-8, and CA 1-3.

The cost data used in the evaluations were obtained from the Illinois DOT and represented statewide averages. The costs include average traffic control and other miscellaneous costs normally associated with the alternative (guardrails, signs, etc.). Costs from other states vary greatly, and thus the actual costs computed for these examples should only be considered as examples.

Table 11. Results of EXPEAR analysis of AZ 1-6.

EXPEAR CASE STUDY: AZ 1-6

PAVEMENT DESIGN

Highway:	Route 360 near Phoenix
Pavement type:	9-in JPCP
Year constructed:	1981
Joint spacing:	15-13-15-17 ft
Dowels:	Nondoweled
Base:	4-in lean concrete
Subgrade:	A-6
Shoulders:	Tied PCC outer, AC inner
Drains:	No drains

TRAFFIC

Current 2-way ADT:	97,770
Percent trucks:	3.8
Lanes each direction:	3
Accumulated ESAL:	2.01 million (outer lane)

EXISTING PAVEMENT CONDITION

Year surveyed:	1987
PSR:	3.5
Deteriorated cracks:	0/mi
Deteriorated joints:	5/mi (outer lane) 20/mi (middle lane)
Joint faulting:	0.01 in
Longitudinal cracks:	0 ft/mi
Pumping:	None
PCC surface:	Tined, not polished
Joint sealant damage:	Medium severity (resealed 1986)
D-cracking	None
Reactive aggregate:	None
Settlements/heaves:	None
Shoulder condition:	Excellent
Lane/shoulder joint:	Fair

PHYSICAL TESTING RECOMMENDATIONS

No physical testing warranted.

1 in = 25.4 mm
1 ft = 0.3048 m
1 mi = 1.609 km

FUTURE CONDITION WITHOUT REHABILITATION

Some joint deterioration is present, but no significant increase of any type of deterioration is predicted over the next 20-year period.

CONSEQUENCE OF DELAYING REHABILITATION

Rehabilitation may safely be delayed. Some joint resealing and joint spall repair is recommended.

PREDICTED LIFE OF REHABILITATION

20 years or more

RESULTS OF LIFE-CYCLE COST ANALYSIS

Technique	Initial Cost	Annual Cost
Restoration	51,200	3,243

* Based on 20-year predicted life and discount rate of 3 percent.

RECOMMENDED REHABILITATION (1989)

Minor restoration work (spall repair and joint resealing) could be done to improve rideability and prevent water and incompressible infiltration. Success of prior joint resealing was short-lived (medium severity again after 1 year).

Restoration Technique	Quantity*
Full-depth repair of joints	50 sy
Reseal transverse joints	3985 ft
Reseal lane/shoulder joint	10560 ft

*Quantity per 2-lane mile and shoulders.

Table 12. Results of EXPEAR analysis of CA 6.

EXPEAR CASE STUDY: CA 6

PAVEMENT DESIGN

Highway: Route 14 near Solemint
Pavement type: 9-in JPCP
Year constructed: 1980
Joint spacing: 12-13-15-14 ft
Dowels: Nondoweled
Base: 4.2-in lean concrete
Subgrade: A-2
Shoulders: AC
Drains: Drains present

TRAFFIC

Current 2-way ADT: 46,000
Percent trucks: 9.0
Lanes each direction: 3
Accumulated ESAL: 4.43 million (outer lane)

EXISTING PAVEMENT CONDITION

Year surveyed: 1987
PSR: 3.4
Deteriorated cracks: 0/mi
Deteriorated joints: 2/mi
Joint faulting: 0.15 in
Longitudinal cracks: 51 ft/mi
Pumping: None
PCC surface: Tined, not polished
Joint sealant damage: High severity (not sealed)
D-cracking None
Reactive aggregate: Low severity
Settlements/heaves: None

Shoulder condition: Excellent
Lane/shoulder joint: Poor

PHYSICAL TESTING RECOMMENDATIONS

Coring at representative deteriorated transverse joints. Coring at longitudinal joint and crack.
Test strength of PCC surface and lean concrete base.
Observe erosion at top of lean concrete base.
Petrographic exam of PCC for aggregate reactivity.

1 in = 25.4 mm
1 ft = 0.3048 m
1 mi = 1.609 km

FUTURE CONDITION WITHOUT REHABILITATION

Faulting: > 0.12 in in 1987
Cracking: No problem
Joint deter. No problem

CONSEQUENCE OF DELAYING REHABILITATION

Faulting is currently unacceptable.

PREDICTED LIFE OF REHABILITATION

Alternative	Years	Unacceptable
Restoration	6	Joint deterioration
3-in AC OL	8	Rutting and refl. crk.
5-in AC OL (crack & seat)	9	Rutting
3-in AC OL (saw & seal)	12	Rutting and refl. crk.
7-in UB PCC OL	20+	

RESULTS OF LIFE-CYCLE COST ANALYSIS

Alternative	Initial Cost	Annual Cost
Restoration	248,843	43,299
3-in AC OL	312,893	42,015
5-in AC OL (crack & seat)	406,812	49,249
3-in AC OL (saw & seal)	335,809	31,799
7-in UB PCC OL	619,443	39,246

Based on predicted lives shown above and discount rate of 3 percent.

RECOMMENDED REHABILITATION (1989)

3-in AC overlay with sawed and sealed joints is the most cost-effective alternative with a life of about 12 years (rutting reaches 0.5 in 11 years and reflection cracking reaches 75/mi in 15 years).

Rehabilitation Technique	Quantity*
Full-depth repair of joints	434 sy
Full-depth repair of cracks	10 sy
Reseal transverse joints	9910 ft
Reseal lane/shoulder joint	10560 ft
3-in AC OL and saw & seal jts.	22293 sy

Table 13. Results of EXPEAR analysis of CA 1-3.

EXPEAR CASE STUDY: CA 1-3

PAVEMENT DESIGN

Highway: I-5 near Tracy
Pavement type: 8.4-in JPCP
Year constructed: 1971
Joint spacing: 12-13-19-18 ft
Dowels: Nondoweled
Base: 5.4-in cement-treated
Subgrade: A-1
Shoulders: AC
Drains: No drains present

TRAFFIC

Current 2-way ADT: 13,000
Percent trucks: 19.0
Lanes each direction: 2
Accumulated ESAL: 7.62 million (outer lane)

EXISTING PAVEMENT CONDITION

Year surveyed: 1987
PSR: 3.0
Deteriorated cracks: 30/mi
Deteriorated joints: 10/mi
Joint faulting: 0.10 in
Longitudinal cracks: 500 ft/mi
Pumping: Medium
PCC surface: Tined, not polished
Joint sealant damage: High severity (not sealed)
D-cracking None
Reactive aggregate: Low severity
Settlements/heaves: None

Shoulder condition: Excellent
Lane/shoulder joint: Poor

Overall: Significant joint deterioration, slab cracking and joint faulting causes roughness. Subdrainage deficiency exists.

PHYSICAL TESTING RECOMMENDATIONS

Deflection test for structure analysis and void detection. Core PCC surface and stabilized base at center of slab.
Core representative deteriorated joints and cracks.
Core longitudinal joint and crack.
Test strength of PCC surface and stabilized base.
Evaluate drainability (gradation, permeability) of subgrade.
Petrographic exam of PCC for aggregate reactivity.

FUTURE CONDITION WITHOUT REHABILITATION

Poor rideability: PSR = 3.0 in 1987
Faulting: = 0.10 in 1987
Pumping = Medium in 1987

CONSEQUENCE OF DELAYING REHABILITATION

Condition is currently unacceptable

PREDICTED LIFE OF REHABILITATION

Alternative	**Years**	**Unacceptable**
Restoration	5	Joint deterioration
3-in AC OL	8	Reflective cracking
Crk/seat, 5 in ACOL	10	Rutting
7 in unbnd PCCOL	20 +	
9 in reconstruction	20 +	

RESULTS OF LIFE-CYCLE COST ANALYSIS

Alternative	**Initial Cost**	**Annual Cost**
Restoration	$ 180,000	$37,100
3-in AC OL	419,000	56,300
Crk/seat, 5 in ACOL	442,000	48,800
7 in unbnd PCCOL	600,000	38,000
Reconstruction	603,000	38,200

Based on predicted lives shown above (20 years for unbonded PCC overlay and reconstruction) and discount rate of 3 percent.

RECOMMENDED REHABILITATION (1989)

Restore only if petrographic analysis indicates low aggregate reactivity. Otherwise, overlay with unbonded PCC or reconstruct.

Rehabilitation Technique	**Quantity***
Full-depth repair deteriorated joints	207 sy
Full-depth repair deteriorated joints	634 sy
Reseal transverse joints	10440 ft
Seal longitudinal cracks	940 ft
Reseal lane/shoulder joint	10560 ft
Install subdrains	5280 ft

* Quantity per 2-lane mile and shoulders.

1 in = 25.4 mm
1 ft = 0.3048 m
1 mi = 1.609 km

Table 14. Results of EXPEAR analysis of FL 2.

EXPEAR CASE STUDY: FL 2

PAVEMENT DESIGN

Highway: I-75 near Tampa
Pavement type: 13-in JPCP, 14-ft lanes
Year constructed: 1986
Joint spacing: 13-12-18-19 ft
Dowels: Doweled, 1.25-in diameter
Base: 6-in untreated aggregate
Subgrade: A-3
Shoulders: Tied PCC
Drains: No drains present

TRAFFIC

Current 2-way ADT: 28,700
Percent trucks: 20.0
Lanes each direction: 2
Accumulated ESAL: 2.00 million (outer lane)

EXISTING PAVEMENT CONDITION

Year surveyed: 1987
PSR: 3.7
Deteriorated cracks: 0/mi
Deteriorated joints: 0/mi
Joint faulting: 0.01 in
Longitudinal cracks: 0 ft/mi
Pumping: None
PCC surface: Tined, not polished
Joint sealant damage: Low severity
D-cracking None
Reactive aggregate: None
Settlements/heaves: None

Shoulder condition: Excellent
Lane/shoulder joint: Good

Overall: The only deficiency is an inadequate joint sealant reservoir width for the existing sealant type.

PHYSICAL TESTING RECOMMENDATIONS

No physical testing warranted.

1 in = 25.4 mm
1 ft = 0.3048 m
1 mi = 1.609 km

FUTURE CONDITION WITHOUT REHABILITATION

Rideability: > 3.5 for 20 years
Faulting: < 0.10 for 20 years
Joint deterioration: 0/mi for 20 years
Cracking: 1/mi in 20 years

CONSEQUENCE OF DELAYING REHABILITATION

Other than resealing transverse joints, no major rehabilitation is required now or over the next 20 years. Resealing may be delayed a few years with no adverse effects.

PREDICTED LIFE OF REHABILITATION

Alternative	Years Unacceptable
Restoration	20 +

RESULTS OF LIFE-CYCLE COST ANALYSIS

Alternative	Initial Cost	Annual Cost
Restoration	\$ 19,900	\$ 1,100

Based on predicted lives shown above (20 years) and discount rate of 3 percent.

RECOMMENDED REHABILITATION (1989)

Reseal transverse joints to correct sealant reservoir shape factor.

Rehabilitation Technique	Quantity*
Reseal transverse joints	11372 ft

* Quantity per 2-lane mile and shoulders.

Table 15. Results of EXPEAR analysis of NC 1-8.

EXPEAR CASE STUDY: NC 1-8

PAVEMENT DESIGN

Highway:	I-95 near Rocky Mount
Pavement type:	9-in JPCP
Year constructed:	1967
Joint spacing:	30 ft
Dowels:	Nondoweled
Base:	4-in untreated aggregate
Subgrade:	A-2
Shoulders:	AC
Drains:	No drains present

TRAFFIC

Current 2-way ADT:	19,100
Percent trucks:	9.0
Lanes each direction:	2
Accumulated ESAL:	9.14 million (outer lane)

EXISTING PAVEMENT CONDITION

Year surveyed:	1987
PSR:	3.3
Deteriorated cracks:	20/mi
Deteriorated joints:	5/mi
Joint faulting:	0.22 in
Longitudinal cracks:	0 ft/mi
Pumping:	None
PCC surface:	Tined, not polished
Joint sealant damage:	Low severity
D-cracking	None
Reactive aggregate:	None
Settlements/heaves:	None
Shoulder condition:	Good
Lane/shoulder joint:	Poor

Overall: Excessive faulting indicates a load transfer deficiency. Some joint and crack deterioration present, reducing rideability.

PHYSICAL TESTING RECOMMENDATIONS

Deflection test for structure analysis and void detection. Core at center of slab to obtain material samples. Core representative deteriorated joints. Test strength of PCC cores.

1 in = 25.4 mm
1 ft = 0.3048 m
1 mi = 1.609 km

FUTURE CONDITION WITHOUT REHABILITATION

Rideability:	3.0 in 1994
Faulting:	0.22 in 1987
Joint deterioration:	5/mi in 20 years
Cracking:	24/mi in 20 years

CONSEQUENCE OF DELAYING REHABILITATION

Faulting is already high, but PSR is rated above 3.0. A few years of delay can be tolerated.

PREDICTED LIFE OF REHABILITATION

Alternative	**Years**	**Unacceptable**
Restoration	14	Faulting
3-in ACOL	10	Reflective cracking
3-in saw/seal ACOL	15	Reflective cracking
5-in crk/seat ACOL	14	Reflective cracking
7-in unbnd PCCOL	20 +	
11-in reconstruction	20 +	

RESULTS OF LIFE-CYCLE COST ANALYSIS

Alternative	**Initial Cost**	**Annual Cost**
Restoration	$105,000	$ 8,000
3-in ACOL	303,000	30,700
3 in saw/seal ACOL	313,000	22,600
5-in crk/seat ACOL	428,000	32,700
7-in unbnd PCCOL	635,000	36,800
11-in reconstruction	506,000	29,300

Based on predicted lives shown above (20 years) and discount rate of 3 percent.

RECOMMENDED REHABILITATION (1989)

Technique	**Quantity***
Grinding	7040 sy
Full-depth repair of cracks	210 sy
Full-depth repair of joints	198 sy
Reseal transverse joints	3928 ft
Reseal lane/shoulder joint	10560 ft

* Quantity per 2-lane mile and shoulders.

Table 16. Results of EXPEAR analysis of NC 2.

EXPEAR CASE STUDY: NC 2

PAVEMENT DESIGN

Highway: I-85 near Greensboro
Pavement type: 11-in JPCP
Year constructed: 1982
Joint spacing: 19-18-25-23 ft
Dowels: Doweled, 1.38-in diameter
Base: 5-in lean concrete
Subgrade: A-4
Shoulders: Tied PCC
Drains: Drains present

TRAFFIC

Current 2-way ADT: 26,000
Percent trucks: 17.0
Lanes each direction: 2
Accumulated ESAL: 5.76 million (outer lane)

EXISTING PAVEMENT CONDITION (outer lane)

Year surveyed: 1987
PSR: 4.2
Deteriorated cracks: 0/mi
Deteriorated joints: 0/mi
Joint faulting: 0.02 in
Longitudinal cracks: 0 ft/mi
Pumping: High
PCC surface: Tined, not polished
Joint sealant damage: Low severity
D-cracking None
Reactive aggregate: None
Settlements/heaves: None

Shoulder condition: Excellent
Lane/shoulder joint: Poor

Overall: Although drains are present, high-severity pumping and poor joint sealant conditions indicate a drainage deficiency.

PHYSICAL TESTING RECOMMENDATIONS

Deflection test slab corners for void detection.
Core at center of slab to obtain material samples.
Examine stabilized base cores for erosion.
Evaluate drainability (gradation, permeability) of subgrade.

1 in = 25.4 mm
1 ft = 0.3048 m
1 mi = 1.609 km

FUTURE CONDITION WITHOUT REHABILITATION

Rideability: = 3.0 in 20 years
Faulting: < 0.10 for 20 years
Joint deterioration: 0/mi for 20 years
Cracking: 7/mi in 20 years

CONSEQUENCE OF DELAYING REHABILITATION

Subdrainage and slab support improvements are required now.

PREDICTED LIFE OF REHABILITATION

Alternative	Years	Unacceptable
Restoration	20 +	

RESULTS OF LIFE-CYCLE COST ANALYSIS

Alternative	Initial Cost	Annual Cost
Restoration	$ 29,300	$ 1,900

Based on predicted lives shown above (20 years) and discount rate of 3 percent.

RECOMMENDED REHABILITATION (1989)

Technique	Quantity*
Repair longitudinal subdrains	5280 ft
Subseal at joints	208 cf grout
Reseal lane/shoulder joints	10560 ft

* Quantity per 2-lane mile and shoulders.

Table 17. Results of EXPEAR analysis of MI 3.

EXPEAR CASE STUDY: MI 3

PAVEMENT DESIGN

Highway:	I-94 near Marshall
Pavement type:	10-in JRCP
Year constructed:	1986
Joint spacing:	41 ft
Joint sealant:	Preformed
Dowels:	1.25-in diameter
Reinforcement:	0.168 sq in / ft
Base:	4-in permeable nontreated aggregate
Subgrade:	A-4
Shoulders:	Tied PCC
Drains:	Yes

TRAFFIC

Current 2-way ADT:	31,300
Percent trucks:	22
Lanes each direction:	2
Accumulated ESAL:	2.77 million (outer lane)

EXISTING PAVEMENT CONDITION (outer lane)

Year surveyed:	1987
PSR:	4.8
Deter. trans. cracks:	0/mi
Crack faulting:	0.0 in
Deteriorated joints:	0/mi
Joint faulting:	0.02 in
Longitudinal cracks:	0 ft/mi
Long. joint spall:	0 ft
Pumping:	None
PCC surface:	Tined
Joint sealant damage:	Low
D-cracking	None
Settlements/heaves:	None

Shoulder condition:	Good
Lane/shoulder joint:	Good

Overall: Traffic lanes and shoulders show no deterioration.

PHYSICAL TESTING RECOMMENDATIONS

No physical testing warranted.

1 in = 25.4 mm
1 ft = 0.3048 m
1 mi = 1.609 km

FUTURE CONDITION WITHOUT REHABILITATION

Rideability:	PSR >3.0 over 20 years
Deteriorated joints:	> 27/mi in 2003
Deteriorated cracks:	> 75/mi in 1996
Faulting:	< 0.25 in over 20 years

CONSEQUENCE OF DELAYING REHABILITATION

None.

PREDICTED LIFE OF REHABILITATION

No rehabilitation needed for at least 9 years.

RESULTS OF LIFE-CYCLE COST ANALYSIS

None.

RECOMMENDED REHABILITATION

No rehabilitation is needed for at least 9 years. At that time, full-depth repair of joints and cracks will be needed. The pavement was underdesigned for the very heavy traffic on I-94.

Table 18. Results of EXPEAR analysis of NJ 2.

EXPEAR CASE STUDY: NJ 2

PAVEMENT DESIGN

Highway:	Route 130 near Yardville
Pavement type:	10-in JRCP
Year constructed:	1951
Joint spacing:	78 ft
Joint sealant:	Expansion
Dowel diameter:	1.25-in stainless steel clad
Reinforcement:	0.168 sq in / ft
Base:	5-in untreated aggregate
Subgrade:	A-4
Shoulders:	AC
Drains:	None

TRAFFIC

Current 2-way ADT:	24,650
Percent trucks:	22
Lanes each direction:	2
Accumulated ESAL:	34.8 million (outer lane)

EXISTING PAVEMENT CONDITION (outer lane)

Year surveyed:	1987
PSR:	3.8
Deter. trans. cracks:	24/mi
Crack faulting:	0.02 in
Deteriorated joints:	14/mi
Joint faulting:	0.06 in
Longitudinal cracks:	10 ft/mi
Long. joint spall:	14 ft
Pumping:	None
PCC surface:	Not polished
Joint sealant damage:	High severity
D-cracking	None
Settlements/heaves:	None
Shoulder condition:	Good
Lane/shoulder joint:	Good

Overall: Some transverse crack and joint deterioration. Some faulting at joints and cracks. Shoulders are in good condition. Subdrainage deficiency indicated due to dense-graded aggregate base, A-4 subgrade, inadequate ditch depth and heavy traffic. Joint seals are in poor condition.

PHYSICAL TESTING RECOMMENDATIONS

Deflection testing needed for structural analysis and void detection.

Coring and materials testing needed for assessing extent of deterioration. Materials testing for base permeability.

FUTURE CONDITION WITHOUT REHABILITATION

Rideability:	PSR <3.0 in 2003
Deteriorated joints:	> 27/mi in 1990
Deteriorated cracks:	> 75/mi in 1989

CONSEQUENCE OF DELAYING REHABILITATION

A very old pavement that has carried a large amount of traffic. Pavement is now deteriorating through cracking and joint deterioration and increased faulting from heavy traffic loadings. Pavement has some potential for restoration if done soon.

PREDICTED LIFE OF REHABILITATION

Type	Life (yr)	Major Deterioration
Restoration	8	Jt/crk. deterioration
3-in ACOL	6	Ref. crkng. & rutting
5-in ACCAS	10	Rutting
9-in UBPCCOL	14	Jt. deter. & cracking
12-in JRCP Rec	20	Jt. deter. & cracking

RESULTS OF LIFE-CYCLE COST ANALYSIS

Type	First $	Annual $
Restoration	181,995	24,438
3-in ACOL	423,937	73,765
5-in ACCASOL	488,281	53,956
9-in UBPCCOL	729,978	60,913
12-in JRCP Rec	618,822	42,728

Cost per 2-lane mile, based on predicted lives and discount rate of 3 percent. Since shoulders are in good condition, shoulder removal and replacement not included in cost of reconstruction.

RECOMMENDED REHABILITATION (at 2 years, 1990)

The rehabilitation life and cost analysis indicates that the restoration alternative is the most cost-effective. If a life of 8 years is acceptable, then restoration would be recommended. If not, then the reconstruction alternative would be recommended.

Restoration Techniques	Quantity*
Full-depth repair joints	337 sy
Full-depth repair cracks	701 sy
Reseal transverse joints	1108 ft
Install subdrains (both lanes)	10,560 ft

1 in = 25.4 mm
1 ft = 0.3048 m
1 mi = 1.609 km

Table 19. Results of EXPEAR analysis of MI 4-1.

EXPEAR CASE STUDY: MI 4-1

PAVEMENT DESIGN

Highway: I-69 near Charlotte
Pavement type: 9-in JRCP
Year constructed: 1973
Joint spacing: 71 ft
Joint sealant: Preformed
Dowel diameter: 1.25 in
Reinforcement: 0.162 sq in / ft
Base: 4-in untreated aggregate
Subgrade: A-4
Shoulders: Tied PCC
Drains: None

TRAFFIC

Current 2-way ADT: 13,700
Percent trucks: 11
Lanes each direction: 2
Accumulated ESAL: 4.37 million (outer lane)

EXISTING PAVEMENT CONDITION (outer lane)

Year surveyed: 1987
PSR: 2.4
Deter. trans. cracks: 222/mi
Crack faulting: 0.08 in
Deteriorated joints: 0/mi
Joint faulting: 0.12 in
Longitudinal cracks: 0 ft/mi
Long. joint spall: 0 ft
Pumping: None
PCC surface: Tined
Joint sealant damage: Medium severity
D-cracking Low
Settlements/heaves: None

Shoulder condition: Good
Lane/shoulder joint: Good

Overall: Traffic lanes show extensive transverse crack deterioration, but no joint deterioration. Some faulting exists at joints and cracks. Shoulders are in good condition. Subdrainage deficiency indicated by dense-graded aggregate base, A-4 subgrade, inadequate ditch depth and heavy traffic.

1 in = 25.4 mm
1 ft = 0.3048 m
1 mi = 1.609 km

PHYSICAL TESTING RECOMMENDATIONS

Deflection testing needed for structural analysis and void detection. Coring and materials testing needed for assessing extent of deterioration from D-cracking (both transverse and longitudinal joints). Materials testing for permeability.

FUTURE CONDITION WITHOUT REHABILITATION

Rideability: PSR >3.0 in 1987
Deteriorated joints: > 27/mi in 1997
Deteriorated cracks: > 75/mi in 1987

CONSEQUENCE OF DELAYING REHABILITATION

Pavement very rough and need immediate rehabilitation. All types of deterioration are predicted to increase in future. Pavement is too deteriorated for restoration now. AC overlay may not be feasible due to deterioration of PCC slab.

PREDICTED LIFE OF REHABILITATION

Type	Life(yr)	Major Deterioration
Restoration	5	Joint deterioration
3-in ACOL	10	Refl. cracking
5-in ACCAS	15	Rutting
3-in ACOLSAS	13	Refl. cracking
3-in Bonded PCC	15	Refl. cracking
7-in UBPCCOL	17	Jt. deter. & cracking

RESULTS OF LIFE-CYCLE COST ANALYSIS

Type	First $	Annual $
Restoration	718,250	143,524
3-in ACOL	611,867	67,612
5-in ACCASOL	736,404	58,145
3-in ACOLSAS	621,582	55,092
3-in Bonded PCC	706,062	55,749
7-in UBPCCOL	708,189	55,197

Cost per 2-lane mile, based on predicted lives and discount rate of 3 percent.

RECOMMENDED REHABILITATION (1989)

The rehabilitation life and cost analysis indicates that three alternatives are very similar. Further analysis is needed to determine the most preferred.
3-in AC overlay with sawed and sealed joints
3-in PCC bonded overlay
7-in PCC unbonded overlay

Table 20. Results of EXPEAR analysis of MI 1-10b.

EXPEAR CASE STUDY: MI 1-10b

PAVEMENT DESIGN

Highway: US 10 near Clare
Pavement type: 9-in JPCP
Year constructed: 1975
Joint spacing: 13-19-18-12 ft
Dowels: Nondoweled
Reinforcement: None
Base: 4-in asphalt-treated
Subgrade: A-2
Shoulders: AC
Drains: None

TRAFFIC

Current 2-way ADT: 5,100
Percent trucks: 8
Lanes each direction: 2
Accumulated ESAL: 0.88 million (outer lane)

EXISTING PAVEMENT CONDITION (outer lane)

Year surveyed: 1987
PSR: 2.8
Deter. trans. cracks: 0/mi
Crack faulting: 0.00 in
Deteriorated joints: 219/mi
Joint faulting: 0.19 in
Longitudinal cracks: 0 ft/mi
Long. joint spall: 1395 ft
Pumping: Low
PCC surface: Tined
Joint sealant damage: Medium severity
D-cracking Medium
Settlements/heaves: None

Shoulder condition: Good
Lane/shoulder joint: Good

Overall: Traffic lanes show extensive joint deterioration from D-cracking. Serious faulting exists. Shoulders are in good condition.

PHYSICAL TESTING RECOMMENDATIONS

Deflection testing needed for structural analysis and void detection. Coring and materials testing needed for assessing extent of deterioration from D-cracking (both transverse and longitudinal joints).
No roughness or skid testing needed.

FUTURE CONDITION WITHOUT REHABILITATION

Rideability: < 3.0 in 1987
Deteriorated joints: > 0.12 in in 1987
Deteriorated cracks: > 55/mi in 1987

CONSEQUENCE OF DELAYING REHABILITATION

Pavement too deteriorated for restoration. Transverse and longitudinal joint deterioration will increase. AC overlay may not be feasible due to deterioration of PCC slab.

PREDICTED LIFE OF REHABILITATION

Type	Life(yr)	Major Deterioration
Restoration	5	Joint deterioration
3-in ACOL	17	Refl. cracking
7-in UBPCCOL	20 +	

RESULTS OF LIFE-CYCLE COST ANALYSIS

Type	First $	Annual $
Restoration	718,250	143,524
3-in ACOL	929,502	64,607
7-in UBPCCOL	567,389	34,901

Cost per 2-lane mile, based on predicted lives and discount rate of 3 percent.

RECOMMENDED REHABILITATION (1991)

7-in unbonded PCC overlay with no additional repair is most cost-effective alternative due to extensive repair needed for other alternatives.

Unbonded PCCOL traffic lanes	14,080 sy
ACOL Shoulders	8,800 sy

1 in = 25.4 mm
1 ft = 0.3048 m
1 mi = 1.609 km

Table 21. Results of EXPEAR analysis of MN 3.

EXPEAR CASE STUDY: MN 3

PAVEMENT DESIGN

Highway: I-90 near Austin
Pavement type: 9-in JRCP
Year constructed: 1984
Joint spacing: 27 ft
Dowels: 1-in diameter
Reinforcement: 0.054 sq in / ft
Base: 4-in untreated
Subgrade: A-4
Shoulders: AC
Drains: None

TRAFFIC

Current 2-way ADT: 10,600
Percent trucks: 15
Lanes each direction: 2
Accumulated ESAL: 1.5 million (outer lane)

EXISTING PAVEMENT CONDITION (outer lane)

Year surveyed: 1987
PSR: 3.8
Deter. trans. cracks: 0/mi
Crack faulting: 0.00 in
Deteriorated joints: 0/mi
Joint faulting: 0.02 in
Longitudinal cracks: 0 ft/mi
Pumping: None
PCC surface: Tined
Joint sealant damage: Low severity
D-cracking None
Settlements/heaves: None

Shoulder condition: Good
Lane/shoulder joint: Poor

Overall: Only minor deterioration. A subdrainage deficiency is indicated by dense base, impermeable subgrade, inadequate ditches and heavy traffic.

PHYSICAL TESTING RECOMMENDATIONS

No deflection testing needed. Coring at center slab. Core examination and materials testing, including permeability of base. No roughness or skid testing needed.

FUTURE CONDITION WITHOUT REHABILITATION

Rideability: PSR < 3.0 in 2005
Deteriorated joints: > 0.27/mi in 2006+
Deteriorated cracks: > 75/mi in 2006+
Faulting: > 10 in in 2005
Pumping: > medium in 2001

CONSEQUENCE OF DELAYING REHABILITATION

Subdrainage improvement would delay future pumping and related distresses.

PREDICTED LIFE OF REHABILITATION (1992)

Type	**Life(yr)**	**Major Deterioration**
Restoration (subdrainage)	20 +	

RESULTS OF LIFE-CYCLE COST ANALYSIS

Type	**First $**	**Annual $**
Restoration (subdrainage)	37,831	2,193

Cost per 2-lane mile, based on predicted lives and discount rate of 3 percent.

RECOMMENDED REHABILITATION

Subdrainage improvement would extend life of pavement.

1 in = 25.4 mm
1 ft = 0.3048 m
1 mi = 1.609 km

Table 22. Results of EXPEAR analysis of MN 2-3.

EXPEAR CASE STUDY: MN 2-3

PAVEMENT DESIGN

Highway: I-90 near Albert Lee
Pavement type: 9-in JRCP
Year constructed: 1976
Joint spacing: 27 ft
Dowels: 1-in diameter
Reinforcement: 0.097 sq in / ft
Base: 5-in untreated
Subgrade: A-2
Shoulders: AC
Drains: None

TRAFFIC

Current 2-way ADT: 3,900
Percent trucks: 20
Lanes each direction: 2
Accumulated ESAL: 2.78 million (outer lane)

EXISTING PAVEMENT CONDITION (outer lane)

Year surveyed: 1987
PSR: 4.0
Deter. trans. cracks: 0/mi
Crack faulting: 0.00 in
Deteriorated joints: 5/mi
Joint faulting: 0.05 in
Longitudinal cracks: 0 ft/mi
Pumping: None
PCC surface: Tined
Joint sealant damage: Medium severity
D-cracking None
Settlements/heaves: None

Shoulder condition: Good
Lane/shoulder joint: Poor

Overall: Traffic lanes show some joint deterioration and faulting. Shoulders good condition, except the lane/shoulder joint.

PHYSICAL TESTING RECOMMENDATIONS

Deflection testing not needed. No coring or materials testing needed. No roughness or skid testing needed.

1 in = 25.4 mm
1 ft = 0.3048 m
1 mi = 1.609 km

FUTURE CONDITION WITHOUT REHABILITATION

Deteriorated joints: > 27/mi in 2004

CONSEQUENCE OF DELAYING REHABILITATION

Joint deterioration may increase if joint sealant not replaced. Excessive water may enter section if longitudinal lane/shoulder joint not resealed.

PREDICTED LIFE OF REHABILITATION (1992)

Type	Life(yr)	Major Deterioration
Restoration	20 +	Joint deterioration

RESULTS OF LIFE-CYCLE COST ANALYSIS

Type	First $	Annual $
Restoration	44,538	3,059

Cost per 2-lane mile, based on predicted lives and discount rate of 3 percent.

RECOMMENDED REHABILITATION (1992)

Minor restoration work in 5 years may extend life of pavement.

Restoration Technique	Quantity*
Full-depth repair joints	133 sy
Full-depth repair cracks	25 sy
Reseal transverse joints	4493 ft
Reseal lane/shoulder joint	10560 ft

*Quantity per 2-lane mile and shoulders.

Table 23. Results of EXPEAR analysis of MN 1-8.

EXPEAR CASE STUDY: MN 1-8

PAVEMENT DESIGN

Highway:	I-94 near Rothsay
Pavement type:	9-in JRCP
Year constructed:	1970
Joint spacing:	27 ft
Dowels:	1-in diameter
Reinforcement:	0.097 sq in / ft
Base:	5-in asphalt-treated
Subgrade:	A-2
Shoulders:	AC
Drains:	None

TRAFFIC

Current 2-way ADT:	5,000
Percent trucks:	21
Lanes each direction:	2
Accumulated ESAL:	5.5 million (outer lane)

EXISTING PAVEMENT CONDITION (outer lane)

Year surveyed:	1987
PSR:	3.4
Deter. trans. cracks:	102/mi
Crack faulting:	0.00 in
Deteriorated joints:	141/mi
Joint faulting:	0.09 in
Longitudinal cracks:	1775 ft/mi
Pumping:	None
PCC surface:	Tined
Joint sealant damage:	Low severity
D-cracking	Low severity
Settlements/heaves:	None

Shoulder condition:	Good
Lane/shoulder joint:	Good

Overall: Traffic lanes have a large amount of deteriorated transverse and longitudinal cracks and joints.

PHYSICAL TESTING RECOMMENDATIONS

Deflection testing for structural analysis and void detection. Coring at center slab, near trans. joints and longitudinal joints. Core examination and materials testing.

1 in = 25.4 mm
1 ft = 0.3048 m
1 mi = 1.609 km

FUTURE CONDITION WITHOUT REHABILITATION

Poor rideability: PSR < 3.0 in 2004
Deteriorated joints: > 27/mi in 1987
Deteriorated cracks:> 75/mi in 1987

CONSEQUENCE OF DELAYING REHABILITATION

Joint deterioration and crack deterioration are already unacceptable. Further delay in rehabilitation would substantially increase maintenance cost and the cost of rehabilitation.

PREDICTED LIFE OF REHABILITATION (1992)

Type	Life(yr)	Major Deterioration
Restoration	6	Faulting
3-in ACOL	10	Ref. Ck./Rutting
9-in JR Recon.	20	
7-in UBPCCOL	16	Joint deterioration

RESULTS OF LIFE-CYCLE COST ANALYSIS

Type	First $	Annual $
Restoration	599,000	104,000
3-in ACOL	748,000	83,000
9-in JR Recon.	748,000	83,000
7-in UBPCCOL	704,000	52,900

Cost per 2-lane mile, based on predicted lives and discount rate of 3 percent.

RECOMMENDED REHABILITATION (1992)

Unbonded PCC overlay provides acceptable life at lowest annual cost.

7-in unbonded PCC overlay with separation layer:
traffic lanes - 14,080 sy
shoulders - 9,387 sy

CHAPTER 6 CONCLUSIONS AND RECOMMENDATIONS

Detailed guidelines and case studies prepared specifically for the practicing engineer as an aid in the evaluation and rehabilitation of jointed concrete pavements have been presented.

1. Feasibility guidelines are prepared for restoration, resurfacing and reconstruction alternatives for jointed concrete pavements. Feasibility is defined in terms of:

    - Ability to construct the alternative.
    - Future life of the alternative.
    - Initial cost of the alternative.

2. A major section is included on recognizing the need for structural improvements. This includes information on slab cracking caused by fatigue damage, deterioration of slab cracking caused by nonload factors, slab spalling fractures from repeated loadings, and repeated load deterioration of spalls initially caused by other factors.

3. Guidelines are provided in the form of summary s for restoration, conventional AC overlay, AC overlay with sawed and sealed joints, AC overlay with cracked and seated slab, bonded PCC overlay, unbonded PCC overlay, and reconstruction.

4. New deterioration prediction models were developed for bonded PCC overlay, cracking and seat and AC overlay, and saw and seal with AC overlays based upon the latest field performance data.

5. The EXpert system for Pavement Evaluation And Rehabilitation (EXPEAR) was extensively modified to include the above rehabilitation alternatives and improved prediction models. EXPEAR was also modified to provide for much easier use by the practicing design engineer. The program now provides the following capabilities for assisting the engineer in pavement evaluation and rehabilitation.

    - Guidelines on project data collection.
    - Evaluation of present condition based on visual survey and other input data.
    - Recommendations for physical testing (deflection, coring, materials testing, roughness, friction) based upon the visual survey.
    - Prediction of future condition without rehabilitation.
    - Selection of the main rehabilitation approach (restoration, overlay, reconstruction).
    - Development of a detailed rehabilitation strategy including quantity estimation.

- Prediction of rehabilitation strategy performance.
- Life-cycle cost analysis.
- Selection of preferred rehabilitation strategy.

6. Thirteen of the sections were evaluated and analyzed to determine the most cost-effective rehabilitation. The 13 sections represent a wide range of designs, climates, traffic, and conditions. The revised EXPEAR 1.4 program provided realistic evaluations, future predictions, and selection of alternatives for most of the case studies.

7. EXPEAR is currently undergoing further field testing and development. The following are key items requiring additional investigation:

    - Improved predictive models.
    - Other rehabilitation techniques.
    - Physical testing recommendations.
    - Extension of the system to existing AC-overlaid PCC pavements.
    - Extension of the system to other pavement geometries.
    - More comprehensive subdrainage recommendations.

APPENDIX A

NEW PREDICTION MODELS FOR BONDED PCC OVERLAYS, CRACK AND SEAT WITH AC OVERLAY, AND SAW AND SEAL AC OVERLAYS

BONDED CONCRETE OVERLAY PERFORMANCE MODELS

Data was collected from 16 bonded concrete overlay projects at 10 locations in 6 States, as described in volume III. The first set of monitoring data were collected on most of these projects during 1984-85 and a second set during 1987-88.(13) The historical results show that there was an increase in faulting and cracking on most of the sections over this 2- to 3-year period. This historical data was very valuable in developing improved prediction models for faulting and cracking.

Joint Faulting

A predictive model was developed for the faulting of transverse joints of bonded PCC overlays. Linear and nonlinear regression techniques were utilized to determine which variables were significant and to determine the final set of coefficients.

$$\begin{aligned} \mathrm{FAULT} = \{ & \mathrm{ESAL}^{0.233} * [\, 3.198 - 2.532 * \mathrm{BASE} \\ & + 0.796 * (\, \mathrm{DIA}+1\,)^{-1.111}\,] \\ & + 0.0402 * [\, \mathrm{AGE} * (\, \mathrm{FI}+1\,) \,/\, 1000\,]^{2.299} \} \,/\, 100 \end{aligned} \tag{1}$$

where:

FAULT = Mean transverse joint faulting, inch

ESAL = Equivalent 18-kip (80 kN) single-axle loads in lane since overlay, millions

BASE = 0, if granular base (untreated)
1, if stabilized base (treated with asphalt or cement)

DIA = Diameter of dowel bars in original slab, inches

FI = Freezing Index, mean Fahrenheit freezing degree-days

AGE = Time since construction of overlay, years

Statistics: R^2 = 0.78
SEE = 0.022 in (standard error of estimate)
n = 45

Some examples of the prediction capability of the faulting model are given in table 24. The model fits the available data reasonably well, and also has the functional form of faulting occurrence.

Table 24. Predicted and actual joint faulting for bonded concrete overlay prediction model.

Section (years)	**Age** (millions)	**ESAL** (in)	**Predicted Faulting** (in)	**Actual Faulting**
NY60	0	0	0.00	0.00
	4	1.1	0.05	0.05
	6	1.9	0.07	0.07
WY1	0	0	0.00	0.00
	1	0.8	0.04	0.01
	4	1.9	0.05	0.04
IA1	0	0	0.00	0.00
	1	1.9	0.04	0.05
	4	6.3	0.06	0.02
IA2	0	0	0.00	0.00
	6	4.8	0.06	0.06
	9	7.9	0.08	0.10
IA4	0	0	0.00	0.00
	7	0.9	0.06	0.04
	10	1.3	0.10	0.07
IA5	0	0	0.00	0.00
	9	1.1	0.09	0.07
	12	1.3	0.13	0.12

Slab Transverse Cracking

A predictive model was developed for transverse cracking of bonded PCC overlays. Linear and nonlinear regression techniques were utilized to determine which variables were significant and to determine the final set of coefficients. The final model obtained is as follows:

$$\begin{aligned} TCRACK = \{ & 2.847 * ESAL^{0.384} * [AGE * (FI+1) / 1000]^{2.876} \\ & + ESAL^{1.773} * (5.016 * INDEXM + 50.836 * INDEXH) \} / 12 \end{aligned} \qquad (2)$$

where:

TCRACK = Transverse medium-high slab cracking, number/mile

ESAL = Equivalent 18-kip (80 kN) single-axle loads since overlay, by lane, millions

FI = Freezing Index, mean Fahrenheit freezing degree-days

AGE = Time since construction of overlay, years

JPCP INDEXM, INDEXH:	EXISTING CRACKING*	INDEXM	INDEXH
	Low 0 to 8	0	0
	Med 9 to 42	1	0
	Hi > 43	0	1

JRCP INDEXM, INDEXH:	EXISTING CRACKING*	INDEXM	INDEXH
	Low 0 to 16	0	0
	Med 17 to 83	1	0
	Hi > 83	0	1

* EXISTING CRACKING = Medium- to high-severity transverse cracks on original pavement prior to overlay and unrepaired, number/mile

Statistics: R^2 = 0.75
SEE = 42 cracks/mile
N = 24

The Clayton County, Iowa sections were not included, due to the large amount of cracking prior to overlay which was due to the unusual pavement design (40-ft [12.2 m] joint spacing without dowels or reinforcement). Some examples of the prediction capability of the cracking model are given in table 25.

Table 25. Predicted and actual slab cracking (medium-high severity) for bonded concrete overlay prediction model.

Section	**Age** (years)	**ESAL** (millions)	**Predicted Cracking** (cks/mi)	**Actual Cracking** (cks/mi)
NY6	0	0	0	0
	4	1.1	13	5
	6	1.9	53	20
WY1	0	0	0	0
	1	0.8	3	0
	4	1.9	20	42
IA1	0	0	0	0
	1	1.9	13	11
	4	6.3	118	210
IA2	0	0	0	0
	6	4.8	94	26
	9	7.9	266	217
IA4	0	0	0	0
	7	0.9	45	13
	10	1.3	142	60
IA5	0	0	0	0
	9	1.1	95	216
	12	1.3	231	240

CRACK AND SEAT AND AC OVERLAY

Data were collected from 55 crack and seat and AC overlay sections, as described in volume II. In addition, data obtained from a previous study that included most of these sections and several additional sections were added to the database, to provide a total of 120 sections. The first set of monitoring data were collected on most of these projects during 1984-85 and a second set during 1987-88.(13) Results for rutting and transverse cracking (mostly reflection cracking) show that there rutting and cracking increased on most of the sections over the 2- to 3-year period. This historical data was very valuable in developing prediction models for rutting and reflection cracking.

Rutting

$$\begin{aligned} \mathrm{RUTDEPTH} = [\, & -29.53 + 0.00688 * \mathrm{FI} + 1.63 * \mathrm{TRANGE} \\ & + 0.36 * \mathrm{ESAL} * \mathrm{AGE} + 0.0296 * \mathrm{PTRUCKS} * \mathrm{AGE}\,] \,/\, 100 \end{aligned} \tag{3}$$

where:

RUTDEPTH = Mean rut depth in outer and inner wheel path, inch

FI = Freezing Index, mean Fahrenheit freezing degree-days

TRANGE = Mean monthly temperature range, degrees Fahrenheit

ESAL = Equivalent 18-kip (80 kN) single-axle loads since overlay, by lane, millions

AGE = Time since construction of overlay, years

PTRUCKS = Percent trucks in average daily traffic

Statistics:
R^2 = 0.57
SEE = 0.07 in
n = 114

The model shows that as Freezing Index and monthly temperature range increase, rutting increases. The same is true for ESAL, percent trucks and age. This model was not considered to be an improvement over the one already existing in EXPEAR, and was not used.

Transverse Reflection Cracking

A predictive model was developed for medium- and high-severity transverse cracks. These cracks will have a major effect on pavement roughness. Linear regression techniques were used to develop many models. The following model was selected for use for both JPCP and JRCP.

$$\begin{aligned} \mathrm{TCRACK} &= [\ 1191.3 - 19.24 * \mathrm{ATEMP} + 7.72 * \mathrm{APREC} \\ &\quad + 0.50 * \mathrm{AGE}^{2.0} - 6.94 * \mathrm{SRW} + 2.97 * \mathrm{PCAREA} \\ &\quad - 2.69 * \mathrm{JTSPACE}\ ]\ /\ 12 \end{aligned} \tag{4}$$

where:

TCRACK = Medium- to high-severity transverse cracks, number/mile

ATEMP = Average annual temperature, degrees Fahrenheit

APREC = Average annual precipitation, inches

AGE = Age of overlay, years

SRW = Seating roller weight, tons

PCAREA = Approximate area of slab pieces, square feet

JTSPACE = Transverse joint spacing, feet

Statistics: R^2 = 0.56
SEE = 11 cracks/mile
n = 104

This model shows that transverse crack deterioration increases with age and ESALs. The large the pieces of cracked slab, the more deteriorated cracks that will exist.

SAW AND SEAL AC OVERLAY

Data were collected from 11 saw and seal AC overlay sections as described in volume I. A set of monitoring data were collected on these projects during 1987-88. Two types of transverse crack deterioration were considered: cracks not associated with the joints, and the deterioration of the sawed and sealed joints themselves over time.

Transverse Reflection Cracking

This is cracking that develops between sawed joints, plus some reflected cracks from missawed joints. A prediction model was developed using linear regression techniques. Only a very limited data set from 11 projects was available; however, a reasonable prediction model was developed.

$$\text{TCRACK} = 154.38 + 9.53 * \text{AGE} - 55.13 * \text{OLTHICK} + 0.8 * \text{JTSPACE} \quad (5)$$

where:

TCRACK = Transverse cracks (all severities), number/mile

AGE = Age of overlay, years

OLTHICK = Thickness of AC overlay, inches

JTSPACE = Joint spacing of existing slab, feet

Statistics: $R^2 = 0.64$
SEE = 2.4 cracks/mile
n = 11

This model shows that as age and joint spacing increase, transverse cracking in saw and seal projects also increases. As overlay thickness increases, cracking decreases. This model only predicts cracking not associated with the sawed and sealed joints (and perhaps some missawed joints). This model predicts all severities of cracks. It was multiplied be 0.7 to give an estimate of medium- and high-severity cracks that affect the life of the rehabilitation (this value is based upon the performance of conventional overlays)..

Deterioration of Sawed And Sealed Joints

These joints will also show some deterioration over time although the field surveys showed very good performance for up to 10 years. It is assumed that they will be resealed by maintenance forces to some extent, however, after a time some will to deteriorate to medium or high severities. To obtain an estimate of the number that might deteriorate over time, it was assumed that about 10 percent on short-jointed pavement (15 ft [4.5 m]), 30 percent on longer-jointed pavement (45 ft

(45 ft [13.5 m]), and 67 percent on long-jointed pavement (100 ft [30.5 m]) will deteriorate over a 20-year period. The number of joints to deteriorate at any given time is computed as follows:

TJOINTS = [2.0 * AGE]

where:
TJOINTS = Medium- to high severity joints, number/mile
AGE = Age of the AC overlay, years

Total Deteriorated Cracks and Sawed Joints

The total number of deteriorated transverse cracks and joints at any given AGE are then estimated from the following model.

TOTCRJT = TCRACKS + TJOINTS

REFERENCES

1. Dwiggins, M. E., M. I. Darter, C. C. Flowers, J. P. Hall, and J. B. DuBose, "Pavement Performance Analysis of the Illinois Interstate Highway System," Report No. FHWA-IL-UI-220, University of Illinois and Illinois Department of Transportation, July, 1989.

2. Hall, K. T., J. M. Connor, M. I. Darter, S. H. Carpenter, "Rehabilitation of Concrete Pavements, Volume III - Concrete Pavement Evaluation and Rehabilitation System," Federal Highway Administration Report No. FHWA-RD-88-073, July 1989.

3. Thompson, M. R., "Breaking/Cracking and Seating Concrete Pavements," NCHRP Synthesis of Highway Practice, No. 144, Transportation Research Board, March 1989.

4. Janssen, D. J., "The Effect of Asphalt Concrete Overlays on the Progression of Durability Cracking in Portland Cement Concrete," Ph.D. dissertation, University of Illinois at Urbana-Champaign, 1985.

5. "Pavement Policy for Highways," Federal Highway Administration, 23 CFR 625 and 626, Federal Register, Volume 53, Number 16, January 26, 1988, pp. 2041-2046.

6. Darter, M. I., "Design of Zero-Maintenance Plain Jointed Concrete Pavement - Volume I, Development of Design Procedures," Federal Highway Administration, FHWA-RD-77-111, 1977.

7. Miner, M. A., "Cumulative Damage in Fatigue," Transactions, American Society of Mechanical Engineers, Vol. 67, pp. A159-A164, 1945.

8. Colley, B. E. and H. A. Humphrey, "Aggregate Interlock at Joints in Concrete Pavements," Transportation Research Record No. 189, Transportation Research Board, 1967.

9. Hutchinson, R. L. and T. R. Wathen, "Strengthening Existing Airport Pavements," Proceedings, American Society of Civil Engineers, Volume 88, AT 1, August 1962.

10. "Techniques for Pavement Rehabilitation," NHI/FHWA 4R Training Course Manual, 4th edition, ERES Consultants, Inc., October 1987.

11. "Pavement Rehabilitation Manual," Federal Highway Administration, September 1985, supplemented through 1989, FHWA-ED-88-025.

12. Snyder, M. B., M. J. Reiter, K. T. Hall, and M. I. Darter, "Rehabilitation of Concrete Pavements, Volume I - Repair Rehabilitation Techniques," Federal Highway Administration Report No. FHWA-RD-88-071, July 1989.

13. Voigt, G. F., S. H. Carpenter, and M. I. Darter, "Rehabilitation of Concrete Pavements, Volume II - Overlay Rehabilitation Techniques," FHWA-RD-88-072, 1989.

14. "Pavement Design Principles and Practices," NHI/FHWA Training Course Manual, ERES Consultants, Inc., September 1987.

15. American Association of State Highway and Transportation Officials, Guide for Design of Pavement Structures, 1986.

16. Darter, M. I., J. M. Becker, M. B. Snyder, and R. E. Smith, "Portland Cement Concrete Pavement Evaluation System - COPES," NCHRP Report No. 277, 1985.

17. Smith, K. D., M. I. Darter, J. B. Rauhut, and K. T. Hall, "Distress Identification Manual for the Long-Term Pavement Performance (LTPP) Studies," Strategic Highway Research Program, 1987.

18. Smith, K. D., D. G. Peshkin, M. I. Darter, A. L. Mueller, and S. H. Carpenter, "Performance of Jointed Concrete Pavements, Volume I - Evaluation of Concrete Pavement Performance and Design Features," Federal Highway Administration, Report No. FHWA-RD-89-136, 1989.

*U.S. GOVERNMENT PRINTING OFFICE: 1990--717-000/27186