Case Studies in Rehabilitation Strategy Development

by Michael I. Darter and Kathleen T. Hall

Restoration is a rehabilitation strategy that involves a combination of methods for repairing distress, improving ride quality, and extending pavement life without a structural overlay. Restoration techniques for jointed concrete pavements include the following:

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

Concrete pavement restoration typically involves a combination of several of these techniques. Over the past 25 years, many states have gained experience with restoration, and detailed information on design, construction, and performance of various restoration techniques is available from a variety of sources.[1,2,3,4]

Little guidance is available, however, to assist the practicing engineer in determining whether a particular pavement is a good candidate for restoration, or whether another rehabilitation strategy would be more appropriate. Restoration has been applied to many pavements that really were in need of structural improvement. The result, even if the restoration is a well designed and well constructed, is short rehabilitation life, high life-cycle costs, and diminished confidence in the effectiveness of restoration among engineers and highway users. Practicing engineers can be shown that it is possible to assess the appropriateness of restoration using information available about the design and condition of a particular pavement section, rehabilitation performance prediction models, and rehabilitation cost data. This is demonstrated using the EXPEAR computer program to compare rehabilitation strategies for 13 pavement projects from across the United States and representing a wide range of pavement conditions.

Pavement performance and rehabilitation needs

Maintenance versus restoration

The success of restoration depends on good design and construction, but it also depends on application of restoration at the appropriate time in the performance life of a pavement. The earliest time that restoration should be done is relatively easy to identify. Early in a pavement's life, its condition is excellent and its rate of deterioration is slow. For several years, routine or preventive maintenance is more cost-effective than any rehabilitation strategy. Restoration is generally not warranted until distresses such as cracking, faulting, and joint spalling have developed to the point that they detract from the pavement's serviceability. When annual maintenance costs equal or exceed the equivalent annual cost of restoration, the restoration work is justified.

Restoration versus resurfacing

It is more difficult to identify the latest point in the pavement's life at which restoration is likely to be cost-effective, i.e., the point at which the pavement has carried so much traffic and sustained so much structural damage that an overlay is needed. It is conceivable that resurfacing may be done before this point and be more cost-effective than restoration, primarily because of an overlay's ability to reduce deflections and slow deterioration in the slab. Early resurfacing seldom occurs however, due to funding limitations. More frequently, restoration is performed some years after the time when it has the greatest potential to cost-effectively extend the pavement's life, and in some cases, after the time when a structural improvement is warranted. The longer the delay, the less likely it is that restoration will be able to compete with resurfacing in performance and cost-effectiveness.

Indicators of structural deficiency

The following is a list of key distresses and levels that should be considered in assessing structural damage in

Table 1 — Case studies selected from the RPPR database

Section	Climate	Type	Condition	Cracking (no/mile)	Joint deterioration	Joint faulting (in.)	Pumping	PSR
AZ 1-6	DNF	JPCP	Good	0	5	0.01	None	3.5
FL 2	WNF	JPCP	Good	0	0	0.01	None	3.7
MI 3	WF	JRCP	Good	0	0	0.02	None	4.8
MN 3	DF	JRCP	Good	0	0	0.00	None	3.8
MN 2-3	DF	JRCP	Good	0	5	0.05	None	4.0
CA 6	DNF	JPCP	Fair	0	2	0.15	None	3.4
NC 1-8	WNF	JPCP	Fair	20	5	0.22	None	3.3
NC 2	WNF	JPCP	Fair	0	0	0.02	High	4.2
NJ 2	WF	JRCP	Fair	24	14	0.06	None	3.8
CA 1-3	DNF	JPCP	Poor	30	10	0.10	Medium	3.0
MI 4-1	WF	JRCP	Poor	222	0	0.12	None	2.4
MI 1-10b	WF	JPCP	Poor	0	219	0.19	Low	2.8
MN 1-8	DF	JRCP	Poor	102	141	0.09	None	3.4

Notes: Condition rating (good, fair or poor) is subjective assessment of overall pavement condition, based on vivible distress and PSR in outer traffic lane.
Sections CA 6 and CA 1-3 have low-severity reactive aggregate distress.

jointed concrete pavement. The critical values suggested are based upon observations of jointed reinforced concrete pavements (JPCP), and jointed plain concrete pavements (JRCP) performance in previous studies [4,5,6] and from use of EXPEAR[7] to predict the performance of restoration on pavements with varying levels of deterioration.

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. Suggested critical levels for transverse cracking are 10 percent slabs cracked or 70 cracks per mile (all severities) for JPCP, and 70 cracks per mile (medium or high severity) for JRCP.

Longitudinal cracking in highway pavements is almost always caused initially by factors other than traffic (e.g., poor joint construction, foundation movement), but under traffic it can deteriorate to such an extent that it constitutes structural damage. More than 500 feet of longitudinal cracking per mile is suggested as a critical level for both JPCP and JRCP.

Joint faulting and pumping are not generally considered structural distresses, but they are caused by traffic loads and are visible indications of progressive loss of joint load transfer and erosion of slab support. Suggested critical levels of joint faulting are 0.10 in. for JPCP and 0.25 in. for JRCP.

Corner breaks, which occur as a result of substantial erosion of slab support and high corner deflections, are definite indications of structural damage. The suggested critical level for corner breaks is 25 per mile for both JPCP and JRCP.

Transverse 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 poor joint construction, dowel bar corrosion, "D" cracking, or reactive aggregates. Suggested critical levels for joint spalling are 50 spalled joints per mile (medium or high severity) for JPCP and 25 spalled joints per mile (medium or high severity) for JRCP.

If JRCP or JPCP exhibits levels of structural damage beyond those given above, 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 is likely to provide a relatively short performance life 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.

Although visible distress is a good indicator of structural damage, it cannot give a complete picture of the extent of underlying deterioration. Coring and deflection testing are recommended on any project being considered for rehabilitation.

EXPEAR pavement evaluation, rehabilitation

EXPEAR is a computerized system to assist highway engineers in project-level evaluation of concrete highway pavements, development of feasible rehabilitation strategies, and prediction of rehabilitation performance and cost-effectiveness. EXPEAR is intended for use in rehabilitation planning and design for high-volume (e.g., Interstate) conventional concrete pavements (JRCP, JPCP, and continuous reinforced concrete pavement). EXPEAR was originally developed for the Federal Highway Administration (FHWA)[7] and was developed further with the support of the Illinois Department of Transportation.

Additional work on EXPEAR was supported by the FHWA under the "Performance and rehabilitation of rigid pavements" research study.[8] Additional information on the development of EXPEAR is available in References 9, 10, and 11. The current version is EXPEAR 1.4, which pos-

Table 2 — EXPEAR analysis results of AZ 1-6

Pavement design	
Highway:	Route 360 near Phoenix
Pavement type:	9 in. JPCP
Year constructed	1981
Joint spacing:	15-13-15-17
Dowels:	Undoweled
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/ mile
Deteriorated joints:	5/ mile 20/ mile
Joint faulting:	0.01 in.
Longitudinal cracks:	0 ft/ mile
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	

Future condition without rehabilitation		
Some joint deterioration is present, but no significant increase of any type of deterioration is predicted over the next 20 yr period.		
Consequence of delaying rehabilitation		
Rehabilitation may safely be delayed. Some joint resealing and joint spall repair is recommended.		
Predicted life of rehabilitation		
Alternative	Years	Unacceptable
Restoration	20+	
3 in. ACOL	7	Ref. cracking
5 in. crack/ seat AC OL	6	Rutting
3 in. saw/ seal AC OL	8	Rutting
3 in. bonded PCC OL	20+	
8 in. unbonded PCC OL	20+	
9 in. reconstruction	20+	
Results of life-cycle cost analysis		
Alternative	Initial cost	Annual cost
Restoration	59,200	3,800
3 in. AC OL	274,600	41,500
5 in. crack/ seat AC OL	273,200	47,500
3 in. saw/ seal AC OL	284,300	38,200
3 in. bonded PCC OL	368,800	23,400
8 in. unbonded PCC OL	514,200	32,600
9 in. reconstruction	506,000	32,000
Cost per 2-lane mile, based on predicted lives shown above (20 yr for bonded overlay, unbonded overlay, and reconstruction) 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.		
Rehabilitation techniques		Quantity
Full-depth repair of joints		200 sy
Reseal transverse joints		9450 ft
Reseal lane/ shoulder		10560 ft
Quantity per 2- lane mile and shoulders		

sesses the capabilities to do life-cycle cost analysis and delay rehabilitation up to five years.

EXPEAR was developed in the form of a knowledge-based expert system, that simulates a consultation between an engineer and an expert in concrete pavements. EXPEAR uses information about the pavement to guide the engineer through an 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 used to estimate future pavement performance with and without rehabilitation.

Sections evaluated

The database developed for the RPPR study includes 95 sections of JPCP and JRCP in their first performance period.[6] Thirteen of these sections were selected for evaluation with the EXPEAR program. The sections, both JRCP and JPCP and located in all four major climatic zones, are listed in Table 1. The condition of each section was subjectively assessed as good, fair, or poor on the basis of observed distress and serviceability.

Pavements rated as "good" had little or no cracking or joint deterioration, minimal joint faulting, no pumping, and a Present Serviceability Rating (PSR) of 3.5 or more. "Fair" pavements had at least one of the following: moderate cracking and/or joint deterioration (due to "D" cracking or reactive aggregate distress), moderate to high faulting (exceeding the critical level), visible pumping, or serviceability less than 3.5.

Pavements rated as "poor" had at least two and in most cases three or four of the following: substantial cracking and/or joint deterioration (exceeding critical levels), high faulting (exceeding the critical level), visible pumping, and PSR less than 3.0.

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.

Table 3 — EXPEAR analysis results of NC 1-8

Pavement design	
Highway:	I-95 near Rocky Mount
Pavement type:	9 in. JPCP
Year constructed	1967
Joint spacing:	30 ft
Dowels:	Undoweled
Base:	4 in. untreated aggregate
Subgrade:	A-2
Shoulders:	AC
Drains	No drains
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/ mile
Deteriorated joints:	5/ mile
Joint faulting:	0.22 in.
Longitudinal cracks:	0 ft/ mile
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 serviceability.	
Physical testing recommendations	
Deflection test for structure analysis and void detection. Core at center slab to obtain material samples. Core representative deteriorated joints. Test strength of PCC cores.	

Future condition without rehabilitation		
Serviceability:		PSR < 3.0 in 1994
Faulting:		> 0.10 in. in 1987
Joint deterioration:		5/ mile for 20 yr
Cracking:		24/ mile in 20 yr
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	Ref. cracking
5 in. crack/ seat AC OL	14	Ref. cracking
3 in. saw/ seal AC OL	15	Ref. cracking
7 in. unbonded PCC OL	20+	
11 in. reconstruction	20+	
Results of life-cycle cost analysis		
Alternative	Initial cost	Annual cost
Restoration	105,000	6,000
3 in. AC OL	303,000	28,900
5 in. crack/ seat AC OL	428,000	23,100
3 in. saw/ seal AC OL	313,000	21,400
7 in. unbonded PCC OL	635,000	30,200
11 in. reconstruction	506,000	29,300
Cost per 2-lane mile, based on predicted lives shown above (20 yr for unbonded overlay, unbonded overlay, and reconstruction) and discount rate of 3 percent.		
Recommended rehabilitation (1989)		
Technique		Quantity
Grinding		7040 sy
Full-depth repair of cracks		210 ft
Full-depth repair of joints		80 ft
Reseal transverse joints		4106 ft
Reseal lane/ shoulder joint		10560 ft
Quantity per 2-lane mile and shoulders.		

- Input data were verified by state employees and project team members familiar with the sections.
- A pavement evaluation was conducted and future performance was predicted without any rehabilitation.
- The following rehabilitation alternatives were considered:
  a. Restoration.
  b. Several resurfacing options (conventional AC overlay, crack and seat AC overlay, saw and seal AC overlay, bonded PCC overlay, and unbonded PCC overlay).
  c. Reconstruction with JPCP or JRCP.
- Rehabilitation performance was predicted using models contained in EXPEAR for distress after restoration (faulting, cracking, joint spalling, and PSR), resurfacing (rutting and reflective cracking for AC overlays; faulting, cracking, and joint spalling for PCC overlays) and reconstruction (faulting, cracking, joint spalling, and PSR).
- Life-cycle costs were estimated using Illinois statewide average costs. The costs include traffic control and other miscellaneous costs normally associated with the alternatives (guardrails, signs, etc.).

The cost analyses should be considered only as examples for comparison of the relative cost-effectiveness of various strategies, due to the highly variable nature of pavement rehabilitation costs throughout the United States.

It should be noted that all of the projects were surveyed in 1987 and analyzed using EXPEAR in 1989. This two-year delay is taken into account in the analyses: EXPEAR calibrated the performance prediction models to the 1987 distress and levels, predicted the distress levels in 1989, and used these levels to compute 1989 rehabilitation quantities and costs. For some projects in very good condition, the rehabilitation was delayed an additional few years in the analysis.

Good condition

Table 2 summarizes the results of the analysis of AZ 1-6, a section of 9 in. JPCP located on Rt. 360 near Phoenix, Ari-

Table 4 — EXPEAR analysis results of 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 in²/ ft
Base:	4 in. untreated aggregate
Subgrade:	A-4
Shoulders:	Tied PCC
Drains	No drains
Traffic	
Current 2-way ADT:	13,700
Percent trucks:	11
Lanes each direction:	2
Accumulated ESAL:	4.37 million (outer lane)
Existing pavement condition	
Year surveyed:	1987
PSR:	2.4
Deteriorated cracks:	222/ mile
Crack faulting:	0.08 in.
Deteriorated joints:	0/ mile
Joint faulting:	0.12 in.
Longitudinal cracks:	0 ft/ mile
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 transversion crack deterioration; no joint deterioration. Some faulting exists at joints and cracks. Shoulders are in good condition. Subdrainage deficiency indicated by densegraded aggregate base, A-4 subgrade, inadequate ditch depth and heavy traffic.	

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 (bothy transverse and longitudinal joints). Materials testing for permeability.		
Future condition without rehabilitation		
Serviceability:		PSR < 3.0 in 1987
Deteriorated joints:		> 27/ mile in 1997
Deteriorated cracks		75/ mile in 1987
Consequence of delaying rehabilitation		
Pavement already very rough and needs 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		
Alternative	Years	Unacceptable
Restoration	5	Jt. deterioration
3 in. ACOL	10	Ref. cracking
5 in. crack/ seat AC OL	15	Rutting
3 in. saw/ seal AC OL	13	Ref. cracking
3 in. bonded PCC OL	15	Ref. cracking
7 in. unbonded PCC OL	17	Jt. deterioration cracking
Results of life-cycle cost analysis		
Alternative	Initial cost	Annual cost
Restoration	718,200	143,500
3 in. AC OL	611,900 67,600	
5 in. crack/ seat AC OL	736,400	58,100
3 in. saw/ seal AC OL	621,600	55,100
3 in. bonded PCC OL	706,100	55,800
7 in. unbonded PCC OL	708,200	55,200
Cost per 2-lane mile, based on predicted lives shown above and discount rate of 3 percent.		
Recommended rehabilitation (1989)		
Three alternatives (3 in. saw/ seal AC OL, 3 in. bonded PCC OL, 7 in. unbonded PCC OL) are very similar in performance and cost. Further analysis is needed for selection		

zona, dry nonfreeze climatic zone. The pavement carried about 2 million 18 kip equivalent single-axle loads (ESALs) in the outer traffic lane since its construction in 1981 to 1987. When surveyed in 1987, its PSR was 3.5 and the only notable distress was some joint spalling. Joint resealing had been attempted unsuccessfully a year earlier.

Given the low truck traffic level on this pavement section, joint spalling on this pavement section was not predicted to increase significantly over the 20 year analysis period considered, and no other distresses were predicted to reach critical levels. As Table 2 shows, the strategy with the lowest annual cost was restoration. Restoration could probably also safely be delayed for several years.

Fair Condition

Table 3 summarizes the results of the analysis of NC 1-8, a section of 9 in. JPCP located on I-95 near Rocky Mount, North Carolina, wet nonfreeze climatic zone. The pavement carried about 9.1 million ESALs in the outer traffic lane from its construction in 1967 to 1987. When surveyed in 1987, its PSR was 3.3, it had some transverse cracking (20 per mile), some joint spalling (5 per mile), and faulting of 0.22 in. at transverse joints.

Although faulting was already high, the PSR was acceptable, and was predicted by EXPEAR to remain above the critical level of 3.0 for another 5 years. Rehabilitation could be delayed a few years. As Table 3 shows, restoration and overlay alternatives had comparable predicted lives, but restoration had the lowest annual cost.

Poor Condition

Table 4 summarizes the results of the analysis of MI 4-1, a section of 9 in. JRCP located on I-69 near Charlotte, Michigan, a wet freeze climatic zone. The pavement carried about 4.4 million ESALs in the outer traffic lane its construction in 1973 to 1987. When surveyed in 1987, its PSR was 2.4, it had extensive transverse crack deterioration (222 per mile), moderate faulting (0.08 in. at cracks, 0.12 in. at joints), and medium-severity joint sealant damage.

The pavement needed immediate rehabilitation. As Table 4 shows, restoration was a poor rehabilitation choice, in terms of both performance life and annual cost. The crack and seat AC overlay, saw and seal AC overlay, and bonded and unbonded PCC overlay options were all very close in predicted life and annual cost.

Summary

The pavements examined here that were in "good" condition had minor faulting (average of 0.02 in.), little or no joint spalling or load-related cracking, and good ride quality (PSR greater than 3.5). For these pavements, restoration was consistently the most cost-effective rehabilitation strategy.

Pavements in "fair" condition had greater faulting (average of 0.11 in.), moderate joint spalling (average of 5 joints per mile) and load-related cracking (average of 11 cracks per mile), and fair ride quality (PSR greater than 3.0). Restoration was the most cost-effective rehabilitation strategy for four of the five case studies in fair condition. The exception was a pavement that had joint deterioration due to reactive aggregate.

The pavements in "poor" condition had high levels of faulting (average of 0.13 in.), a large number of spalled joints (average of 92 per mile) and load-related cracks (average of 88 per mile), and poor ride quality (PSR of 3.0 or less). In every case examined, overlay or reconstruction was more cost-effective than restoration.

The cost of rehabilitation is strongly tied to pavement condition, as shown below:

Condition	Average initial cost/ lane mile	Average annual cost/ lane mile
Good	$32,000	$2,000
Fair	163,000	16,000
Poor	605,000	45,000

It pays to maintain pavements in good condition and rehabilitate them before they exhibit substantial distress. In the case studies examined, an AC overlay with sawed and sealed joints was usually the most cost-effective AC overlay option.

The unbonded portland cement concrete overlay provided the longest life of all overlay alternatives and was determined cost-effective when the existing pavement was badly deteriorated. Reconstruction was cost-effective if the existing pavement exhibited extensive deterioration and the shoulders were in good enough condition that they did not need to be replaced.

Overall, the EXPEAR program provided realistic evaluations, future predictions, and selection of alternatives for the case studies.

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Selected for reader interest by the editors.

ACI member **Michael I. Darter,** Ph.D., P.E. is a principal of ERES Consultants, Inc. and a professor of civil engineering at the University of Illinois at Urbana-Champaign.

Kathleen T. Hall, Ph.D., P.E., also is an ACI member and also is a post-doctoral research associate in civil engineering at the University at Urbana-Champaign.