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Contents

ERASME: An Expert System for Pavement Maintenance

F. ALLEZ, M. DAUZATS, P. JOUBERT, J. P. LABAT, AND M. PUGGELLI

To facilitate decision making in the area of road maintenance, the Directorate of Roads in France decided to use artificial intelligence techniques and to rapidly make available to various government agencies an expert system serving as an aid to decision making on maintenance (*1*). ERASME (a French acronym for road maintenance assisted by a multiexpert system) aims to produce an operational expert system by mid-1988 for flexible pavements, by mid-1989 for bituminous pavements, and by the end of 1989 for hydraulic binder-treated pavements. This article reviews its present status of development.

Very swift development of artificial intelligence techniques and, more precisely, of expert systems has led to their progressive integration, during the past years, within all human activities.

The field of civil engineering very seldom calls for these incredible performing tools called expert systems. As shown in a recent American report (*2*), a large number of teams around the world are working on the elaboration of products meant for the road sector, which represents a market that must not be neglected.

The diagnosis and selection of the maintenance solution for a defective pavement present the main characteristics that make the use of an expert system interesting. Hundreds of decision makers in the field of road maintenance can be found at the national, regional, or local service levels. Only a few pavement specialists are able to define the right pavement rehabilitation technique. Those experts are working essentially in government technical services. They use the following kinds of data:

- technical and accurate data such as produced by laboratory tests,
- qualitative data, such as surface condition,
- incomplete and uncertain data, such as traffic volumes and loads, and
- redundant and contradictory data, as frequently occur in the real world.

Some aspects of the pavement maintenance problem are poorly understood or stated. In these cases, experts use empirical methods or "rules of thumb" derived from experience or collective practice.

Confronted by an incompletely defined problem and a partially formalized theory, experts trust their own experience to assess the real state of pavement and select appropriate rehabilitation techniques. This decision making is partly reflexive and irrational.

The economic stakes are important. In France, annual road maintenance expenditures range around 5 billion francs.

This field thus has a well-identified need that the Road Directorate has decided to fill by supplying services with a "maintenance" expert system. This product will be developed under the supervision of an Owners Committee associating several dedicated representatives of system users and the central administration. The system must be considered an *assistance* tool for decision making. Within this scope, its functions include guiding the user in the collection of the data needed for an accurate diagnosis and proposing technically equivalent alternatives to users, providing the elements needed to enable them to reach sensible selections.

ERASME will, of course, benefit from the qualities inherent to expert systems:

- a great possibility for updating, ensuring the permanence of the product,
- teaching potential: explanation of the thinking path and justification of the thinking upon request. These features will make it a teaching tool with no match in classical data processing.

ERASME PROJECT OBJECTIVES

Subject Definition

Homogeneous Section

ERASME assists the user in selecting among pavement diagnosis and rehabilitation techniques for homogeneous sections that are declared such when all their significant parameters are homogeneous:

- deflection signal (deflection analysis involves no destructive measurement of the surface deflection under a standard load),
- pavement structure,
- nature and date of pavement repairs-traffic, and
- surface condition.

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Homogeneous section lengths vary from a few hundred meters to a few kilometers. ERASME deals strictly with section problems, not network problems. It is in fact complementary with tools developed in the field of pavement management systems.

Diagnosis and Design

In the first stage, ERASME assists pavement engineers in assessing the pavement condition. The information necessary to establish the diagnosis are gathered from data files or input interactively by the user. ERASME tries to reproduce the expert thinking process; it collects only the relevant data and can provide explanations about the questions it asks the user.

In the second stage, after problem assessment, ERASME seeks successful rehabilitation techniques; the selection is linked to the initial diagnosis. Several alternatives are generally proposed to the user. Each solution is evaluated in terms of service life, costs, and short-term serviceability. (Serviceability can be predicted in the long term at the network level but not at the section level, because the dispersion is too large.)

Calculations

Like pavement engineering specialists, ERASME makes some calculations:

- whether to validate or invalidate current hypotheses during problem assessment, and
- whether to define design parameters such as overlay thickness during the conception stage.

ERASME will be interfaced with several algorithmic subroutines:

- ALIZE3, which computes stresses and strains in pavement structure (*3*),
- a model predicting rut depth resulting from asphalt concrete flow,
- a model predicting cracking due to the aging of asphalt concrete,
- a model for evaluating pavement resistance to frost thaw cycles, and
- an economic model (cost estimation and volume and surface calculations).

Incomplete Data

Information is sometimes scarce, especially for low-traffic roads. Pavement structure and traffic should be known. ERASME will manage cases where laboratory tests and measurements are missing, however. The expert system will show the user how the absence of a certain type of information can lead to the selection of an unsuccessful rehabilitation technique. The user will be able to require some laboratory tests or choose a relatively unreliable rehabilitation technique knowledgeably.

ERASME's Users

ERASME users should be primarily engineers in charge of pavement management at local, district, or regional levels and members of the national technical services working in the field of pavement engineering, such as LCPC, SETRA, and CETE. To a lesser extent, they will be at engineering schools (expert systems are valuable tools for lifelike teaching).

ERASME's Operational Version

The native version will be available on Unix workstations such as SUN 3/140. The portability of ERASME depends on that of LE-LISP (INRIA-ILOG) and X-WINDOWS. These choices should warrant very good portability.

Studies are being made to assess the possibilities of transferring the system for use on equipment of the IBM PC type. According to their outcome, distribution of the product will be ensured either by teleprocessing from service centers fitted with a workstation or by supplying the software to PC users. In any case, users will have access to a runtime version that will not allow them to modify the software or the knowledge bases.

PROJECT EXPERTS

Representative Expertise

The expert system integrates various competencies. Its stored, encoded expertise derives from a knowledge elicitation process conducted with pavement laboratory specialists and pavement-management-oriented engineers. This collaboration between pavement engineers with two different kinds of experience should enhance the encoded knowledge's quality (*4*).

Concentric Expertise

About ten experts will be associated with system development. From the beginning, two experts have been involved in knowledge elicitation. Two expert teams with specialized backgrounds (drainage and pavement resistance to frost effects) are assisting them. Other experts will use ERASME's successive prototypes to validate, criticize, and develop the expert system's encoded knowledge.

Validation Procedure

Validation is costly and time-consuming (30 to 40 percent total cost). A few dedicated future users will validate the expert system. Their remarks will be gathered into related fields and sent to the development team.

DIAGNOSIS

Subproblems

The knowledge in the diagnosis system is structured with prototypes inspired by Aikins (*5*) and by those in a French expert system project called DIVA (*6*). Each prototype is associated with a subproblem involved in the decision-making process. One prototype defines the part of knowledge required to solve a subset of the problem; it consists of procedures, collections of rules, and problem domain attributes. Examples of prototypes are "subgrade assessment," "representativeness of deflection," and "deflection measurement conditions."

Decentralized Decision

The structure of the selected knowledge leads to development of a decentralized system: each one of the subproblems is taken care of by a specialized expert subsystem (Figure 1). A control modulus—a supervisor—is in charge of the cooperation of these different subsystems or knowledge moduli. This supervisor is equipped with a high-level expertise that allows it to decide, during the process, either to carry on with the thinking process while assigning an analysis to a subsystem, to conclude, or to invalidate a hypothesis (*7*).

Finally, the supervisor is fitted with a local data structure that is fed with the expert subsystems proceedings. These proceedings are high-level abstractions of the state of the problem. For example, if one does not take the action of water into account, the pavement shows no fatigue.

Reentry and Nonmonotonous Subsystems

In the course of thinking, each one of the specialized expert subsystems may be called upon by the supervisor several times. Each one of these calls is the subject of a special analysis. The first analysis, performed during the first call, consists of a "quick general view" of the problem. It is generally completed with a series of hypotheses produced by the subsystem and eventually questioned on the occasion of later stages (nonmonotonous thinking process).

For example, as it was called for the first time, the "deflection analysis" modulus supposes that it refers to the "representative deflection." It will question this hypothesis if the supervisor makes such a suggestion and will then evaluate the "conditions of the deflection measurement."

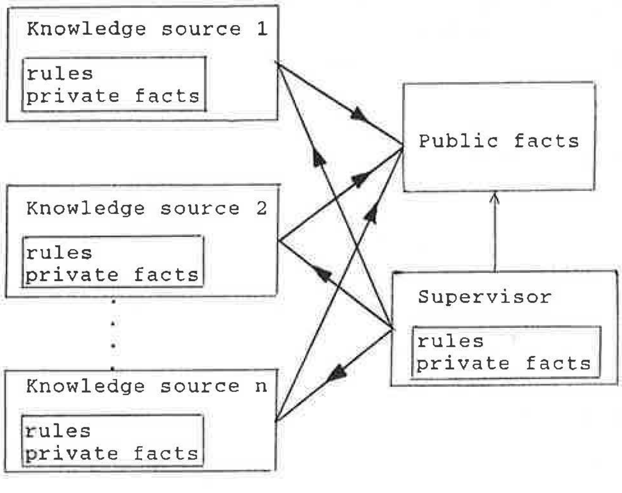

FIGURE 1 A decentralized structure.

Analysis

During the thinking process, pavement specialists use expertise of various types. For a given subproblem, they usually develop several relatively independent analyses that are subsequently synthesized. For example, structure fatigue can be evaluated by two separate analyses: elastic analysis (traffic, structure) and surface condition analysis (surface condition, date, and nature of repairs).

Models

A pavement specialist also reasons with models that are abstracted from the real pavement. Hence, when he or she focuses on surface cracking, the stages of the reasoning process are as follows:

- forgets traffic action,
- evaluates surface course cracking that results from aging,
- integrates the dynamic action of traffic on these cracks, and
- compares the obtained cracks with the real ones, and so on.

DESIGN

Having assessed the pavement problem, the expert system tries, as a second stage, to select successful rehabilitation techniques.

Generate-and-Test Expertise

Part of the encoded expertise is of the generate-and-test type. Some production rules state the concurrent alternatives in a given situation. For example, if pavement rehabilitation is to be realized, then the following techniques can be used:

asphalt concrete + bituminous base

asphalt concrete + granular base

surface dressing + granular base

Some other production rules state the constraints that constructed solutions must meet. For example, if a pavement surface course is subjected to snow removal, then surface dressing cannot be used as a long-term solution.

Procedural Expertise

Procedural knowledge is implemented as procedural attachments to objects. These procedural attachments are expressed along inheritance trees. Intensive use is made of object programming style, in particular, for interfacing ERASME with FORTRAN subroutines.

Problem Breakdown

Complex problems are broken down into simpler subproblems. Final solutions are the synthesis of more elementary solutions. For example, defining a rehabilitation technique consists of pavement structure improvement and complementary constructions (e.g., drainage).

Multicriteria Decision

Constructed solutions must satisfy several requirements (durability, serviceability, cost, and construction duration). ERASME makes no choice among solutions; rather, it evaluates them in terms of the foregoing criteria, enabling users to select their own solution.

LABORATORY TEST MANAGEMENT

For a low-traffic pavement network, generally limited data are available (laboratory tests such as deflection tests or in situ materials tests).

ERASME will generate a hypothesis and thus use hypothetical reasoning. The main stages of the solution process should be

- definition of concurrent diagnosis,
- indication of laboratory tests that would reduce the number of these concurrent diagnoses, and
- selection of rehabilitation techniques for each diagnosis.

Then the user would either make some laboratory tests or knowingly select a hypothetical rehabilitation technique.

This difficult aspect is now under development with SMECI by authors of INRIA at Sophia-Antipolis.

PROJECT CURRENT STATE

Expert System Shell

ERASME's first prototype was developed (April 1986, December 1986) with CRIQUET (*8*), an expert system shell developed by INRIA at Sophia-Antipolis. For product development, SMECI (*9, 10*) (a high-level expert system shell developed at Sophia-Antipolis by INRIA) has been chosen for the following reasons:

- It has knowledge encoding techniques (objects, methods, state graph, and production rules) facilitating knowledge maintenance.
- It includes tools for construction of user-friendly interfaces (icons, mouse, windows, various editors).
- SMECI is a commercial tool (marketed by ILOG Inc., a subsidiary of INRIA).

First Prototype

The first prototype assists local engineers in analyzing and designing flexible pavement sections. Knowledge encoded in the system is limited to the principal distresses of flexible pavements.

Interaction with this first prototype allows users, with their own defined data (e.g., surface condition, deflection test, laboratory test), to assess the problem and to select one or several rehabilitation techniques. This first prototype includes 210 rules and 50 decision and computation tables; it is interfaced with ALIZE3 (10,000 FORTRAN lines) (*3*).

A powerful feature of this prototype is that it enables users to record sessions. Sessions can be modified and rerun, automatically or not. If user changes necessitate that the expert system obtain further information not defined in the session, these are requested by the program. This feature enables the user to make sensitivity studies.

Present Prototype

This prototype (April 1987, June 1987) developed with SMECI diagnoses pavement structure fatigue and builds rehabilitation design according to four different techniques. Each solution is assessed in terms of costs. Particular efforts were made to construct a user-friendly interface.

CONCLUSION

The first prototype of ERASME (210 rules), similar to projects now developed in North America (*2,11–13*), shows that knowledge-based expert system technology should benefit pavement maintenance.

The presence within the Owner's Committee of user representatives warrants that their needs and wishes will be taken into account from the elaboration stage onward.

The interfacing of the expert system with the calculation codes will make it possible to supply all users with a complete line of software that, up to now, was scarcely distributed outside the laboratories.

A compromise remains to be found between the system products (e.g., calculation speed, graphic output), the equipment likely to receive them and the group of potential users.

The development and maintenance of such a tool are powerful encouragement to validate the national and regional research in the road field.

The setup of the expert systems makes them a very valuable complement to pavement management systems.

Five billion francs are now spent each year for French highway network maintenance. ERASME should generate savings of about 100 million francs each year. Economies are high, although still only anticipated at the moment.

ACKNOWLEDGMENTS

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Preventive Maintenance of Asphalt Concrete Pavements

E. R. Brown

Preventive maintenance of asphalt concrete can often extend the pavement life for a number of years at relatively low costs. The types of preventive maintenance discussed in this report include rejuvenators, slurry seals, surface treatments, and crack sealing. The report's emphasis is directed toward the use of asphalt rejuvenators. The maintenance procedure should be selected for a specific project to be maintained, and the treatment should be designed for the project. Random selection of maintenance procedures may be ineffective, resulting in loss in performance and additional life-cycle costs. This report provides some guidance into the selection process for maintenance procedures, problem areas to consider, and expected performance of various procedures.

Maintenance of most asphalt pavements involves repairing localized problem areas, such as potholes or badly cracked pavement sections and sealing cracks. This type of maintenance is needed to prolong the pavement life and prevent rapid damage to the pavement from water penetration and other causes.

Some problems with asphalt pavements can be prevented or delayed by using good maintenance practices. Unfortunately, there is very little guidance available concerning when to perform maintenance, what type of maintenance to perform, and how long its benefit will last. All of these questions need to be addressed in order to set up an acceptable maintenance schedule.

The objective of this paper is to discuss preventive maintenance procedures used to prolong the life of asphalt concrete pavements. The procedures discussed include rejuvenators, slurry seals, surface treatments, and crack sealing. Emphasis is directed toward the use of asphalt rejuvenators.

The most important step in minimizing maintenance costs is to properly design and construct the pavement initially. To do this requires satisfactory specifications and adequate quality control procedures during construction. A little extra money spent during the construction process to ensure that quality is obtained will reduce the life-cycle cost of the pavement and reduce maintenance costs in subsequent years.

REJUVENATORS

There are a number of rejuvenators on the market today that are being used to seal and rejuvenate asphalt concrete. Most of these rejuvenators are proprietary materials and, thus, are often difficult to specify using a generic specification. Very little information is available that describes the expected performance when using rejuvenators to maintain pavements.

The rate of oxidation of asphalt concrete is highly dependent on the voids in the total mixture (VTM). If the VTM is below 7 to 8 percent in place, then the effects of oxidation will be greatly minimized. Oxidation causes the asphalt mixture to stiffen and crack at low temperatures. The purpose of the rejuvenator is to penetrate into the asphalt concrete somewhat and soften (rejuvenate) the asphalt binder. The rejuvenator also helps to seal the pavement and minimize future oxidation.

For a rejuvenator to be effective, it must penetrate into the asphalt concrete. If it does not penetrate, it cannot soften the asphalt, and it will cause the surface to become slick, especially in wet weather. The VTM must be about 7 to 8 percent or more to provide sufficient permeability to allow for penetration of the rejuvenator into the asphalt mixture.

A study was conducted by the U. S. Army Corps of Engineers to evaluate the performance of pavement sections treated with rejuvenators (*1*). These treated sections were compared to untreated (control) sections to determine relative performance. Five rejuvenators were selected for this study. One rejuvenator was selected to be SS-1 asphalt emulsion, while the remaining four rejuvenators were proprietary materials. The rejuvenators are identified in this report as materials A, B, C, D, and E. Material E was the SS-1 asphalt emulsion.

The rejuvenators were evaluated to determine their ability to penetrate oxidized pavements, to soften the asphalt binder, to reduce the amount of surface cracking, to reduce the loss of surface fines, and to minimize reduction in skid resistance. Three locations in the United States were selected for application of the test sections. One was located in the Southeast, one in the Southwest, and one in the North to allow for evaluation in each of the three major climatic areas.

The amount of each rejuvenator to be applied was determined by covering a 1-square-yard section with various amounts of each rejuvenator. The amount that would penetrate into the pavement and cure within 24 hours was selected as the optimum amount. For purposes of comparison, two application rates were applied to the test sections—one at the selected optimum and one lower than optimum. In most cases, the application amount was approximately 0.05 gallons per square yard.

After the pavements were rejuvenated, cores were taken and observed to determine approximate penetration of rejuvenator. Materials A, B, and C appeared to penetrate the

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TABLE 1 MTO-DESIGNATED SOURCES LIST FOR ENGINEERING MATERIALS: PRODUCTS SUITABLE FOR USE IN ALL DISTRICTS

Material	Penetration at 77 Degrees Fahrenheit, 0.1 mm				
	48 Hour	6 Month	1 Year	2 Year	3 Year
A - Control	21	21	21	18	18
A - Treated	57	30	38	24	26
B - Control	21	21	21	18	18
B - Treated	31	30	29	22	22
C - Control	21	21	21	18	18
C - Treated	28	25	24	20	21
D - Control	27	27	27	21	22
D - Treated	18	19	18	18	18
E - Control	26	26	26	19	20
E - Treated	23	23	20	18	20

surface about ⅜ inch on the average, while materials D and E showed no significant penetration. For this reason, the top ⅜ inch of all cores was removed and evaluated during this study to determine the effect of rejuvenators.

The ability of the rejuvenator to soften asphalt was measured by extracting the asphalt from the top ⅜ inch of each core and measuring the penetration and viscosity. The recovered asphalt from each treated area was compared with the asphalt recovered from an adjacent untreated area. The results of penetration at 77 degrees Fahrenheit during the three-year evaluation period are shown in Table 1. The results of viscosity tests at 275 degrees Fahrenheit for the same time period are shown in Table 2. The viscosity was measured at 275 degrees Fahrenheit since the viscosity at 140 degrees Fahrenheit was too high to be measured for some of the asphalts being tested.

The relative penetration (ratio of penetration of treated asphalt to untreated asphalt) of the five rejuvenated sections is shown in Figure 1. Materials A, B, and C provided some rejuvenation to the asphalt cement for the three-year evaluation period, while materials D and E actually stiffened the asphalt during this evaluation time. The viscosity data in Figure 2 show the same relative results. These data clearly show that the application of the materials being evaluated modified the asphalt properties for at least three years.

The skid resistance can be significantly reduced for a substantial period of time when rejuvenators are applied, especially when the rejuvenators do not penetrate. A summary of skid tests as measured with a British Portable Skid Tester is shown in Table 3. The data show that most materials reduce the skid resistance for at least one year. The two- and three-year tests show that the skid resistance of the treated sections are approximately equal to the skid resistance of the untreated sections. This is shown in the summary of data presented in Figure 3. It is obvious from these data that judgment must be used when applying rejuvenators to ensure that a dangerous condition does not develop. Rejuvenators are most often used in areas of slow-moving traffic, such as parking lots.

When excess rejuvenator is applied or when the material does not penetrate the asphalt concrete, skid resistance can be greatly reduced. If excess rejuvenator remains on the surface after 24 to 48 hours, it should be sanded and removed.

TABLE 2 MTO-DESIGNATED SOURCES LIST FOR ENGINEERING MATERIALS: PRODUCTS SUITABLE FOR USE IN DISTRICTS 1–8 ONLY

Material	Viscosity at 275 degrees Fahrenheit, Centistokes				
	48 Hour	6 Month	1 Year	2 Year	3 Year
A - Control	1930	1876	2008	2142	2697
A - Treated	562	959	766	1072	1522
B - Control	1930	1876	2008	2142	2697
B - Treated	1167	1288	1388	1606	2062
C - Control	1930	1876	2008	2142	2697
C - Treated	1374	1487	1523	1974	2978
D - Control	1909	1851	1987	2123	2648
D - Treated	2783	2713	2978	3300	4305
E - Control	2330	2396	2480	2652	3456
E - Treated	2330	1758	3325	3493	4850

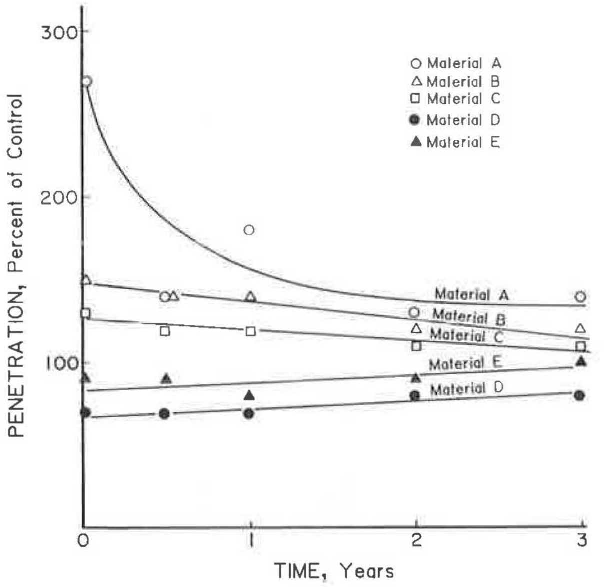

FIGURE 1 Relative penetration of asphalt recovered from sections treated with materials A–E during a three-year investigation.

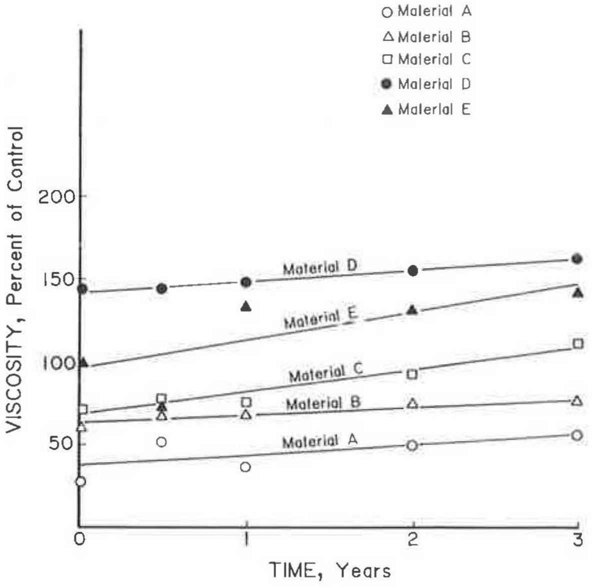

FIGURE 2 Relative viscosity of asphalt recovered from sections treated with materials A–E during a three-year investigation.

Rejuvenators should not normally be applied to a pavement surface, such as slurry seal or surface treatment, that has a large amount of asphalt near the surface. Applications of rejuvenator to these surface types may produce a sticky, soft surface.

After the rejuvenators had been in place for three years, the amount of cracking was evaluated. Results are presented in Table 4 and are shown graphically in Figures 4 and 5. Figure 4 shows that the total amount of cracking for each of the test sections is approximately equal to the total amount of cracking in the control sections. In most cases the cracking of the treated sections varied from 80 to 125 percent of the cracking in the control test sections. Figure 5 shows that the amount of cracking wider than ¼ inch is lower for materials A, B, and C than for the control test sections. The amount of cracking is reduced more inside the traffic lane than outside the traffic lane. For instance, the cracking varies from 12 to 30 percent of control inside the traffic lane, while it varies from 25 to 100 percent of control outside the traffic lane. The amount of cracking in sections D and E was higher for the treated sections than for the untreated sections. The amount of data for large cracks was limited. The results indicate, however, that the rejuvenators that softened the asphalt binder (materials A, B, and C) also resulted in a smaller amount of large cracks after three years; the rejuvenators that stiffened the asphalt binder (materials D and E) resulted in a greater amount of large cracks after three years.

Another property that was observed when the rejuvenated test sections were being inspected was the surface texture. After three years, it was noted that the untreated sections, in some cases, had lost surface fines, while the treated sections appeared to perform better. The loss in surface fines was measured by quantifying the surface texture. This was done by spreading a known amount of sand into the surface voids. The area was measured, and the average penetration into the asphalt mixture was calculated. A higher penetration indi-

TABLE 3 AVERAGE SKID RESISTANCE VALUES FOR AVERAGE APPLICATION RATES OF APPROXIMATELY 0.05 GSY

	Skid Resistance (Wet), Percent of Control				
Material	48 Hour	6 Month	1 Year	2 Year	3 Year
A	97	87	88	96	100
B	76	100	93	99	103
C	90	91	98	99	103
D	76	80	89	100	103
E	118	94	86	95	98

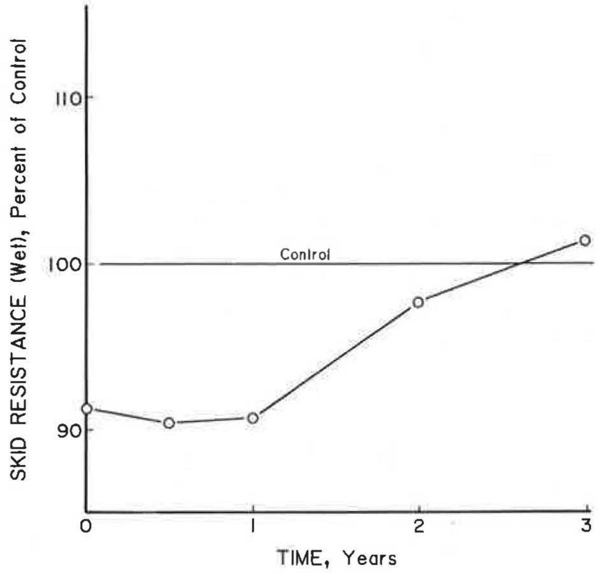

FIGURE 3 Average skid resistance of wet rejuvenated pavement during three years.

cated more loss in surface fines. The results of these tests are shown in Table 5. All five materials tested resulted in a reduction in sand penetration, which indicates that all five materials resulted in a reduction of fines being lost. At some locations, a difference in surface texture was noted visually. It was apparent in these areas that the untreated sections had lost some fines while the treated areas had not. The material that appeared to hold the surface fines best was material D, which did not penetrate but did seal the surface.

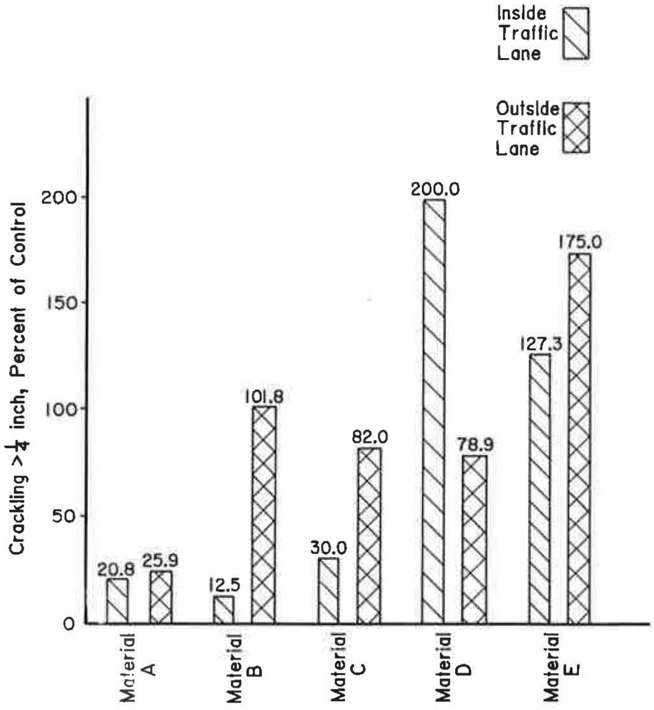

FIGURE 4 Relationship between material type and total cracking.

SLURRY SEALS

Slurry seal is a fluidlike mixture of fine aggregate, asphalt emulsion, and water. The slurry seal is used to seal an existing asphalt surface and to provide improved surface texture in

TABLE 4 EFFECT OF REJUVENATOR APPLICATION ON AMOUNT OF CRACKING (*1*)

Material	Amount of Traffic	Total Cracking	Total Cracking > 1/4 Inch Wide
A	Inside Traffic Lane	133	2.5
Control	Inside Traffic Lane	111	12
A	Outside Traffic Lane	157	14
Control	Outside Traffic Lane	148	54
B	Inside Traffic Lane	103	3
Control	Inside Traffic Lane	140	24
B	Outside Traffic Lane	82	57
Control	Outside Traffic Lane	92	56
C	Inside Traffic Lane	122	3
Control	Inside Traffic Lane	116	10
C	Outside Traffic Lane	101	41
Control	Outside Traffic Lane	120	50
D	Inside Traffic Lane	56	12
Control	Inside Traffic Lane	57	6
D	Outside Traffic Lane	62	30
Control	Outside Traffic Lane	61	38
E	Inside Traffic Lane	14	14
Control	Inside Traffic Lane	11	11
E	Outside Traffic Lane	14	14
Control	Outside Traffic Lane	8	8

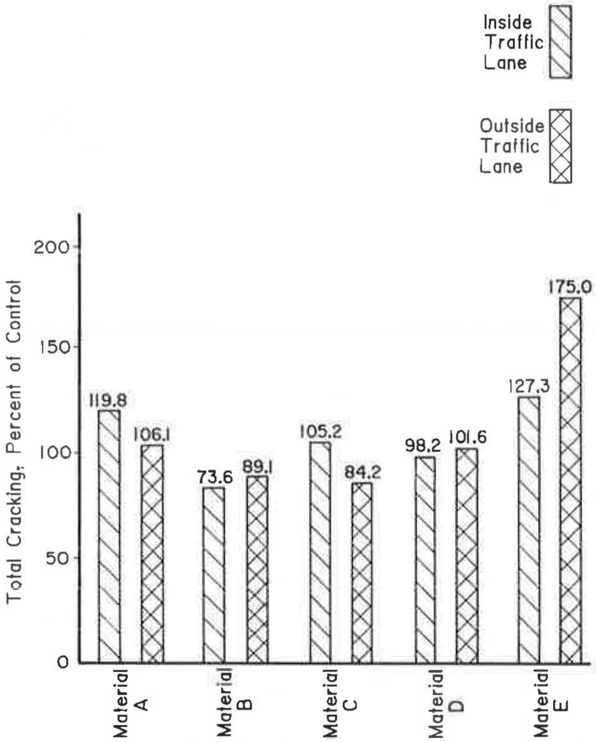

FIGURE 5 Relationship between material type and cracking wider than 1/4 inch.

some cases. When properly applied, it prevents penetration of water into the pavement and, therefore, prolongs the pavement life.

For most projects, a special rapid-set asphalt emulsion that has been specifically designed for slurry seals is used. The fine aggregate used should be crushed for best results.

Slurry seals are normally used on pavements subjected to low traffic volumes. When slurry seals are subjected to high traffic volumes, the life is greatly reduced. One of the biggest problems observed with slurry seals is the loss of bond between the slurry and the underlying asphalt mixture. This loss in bond can be a result of several factors that may occur simultaneously or separately. The underlying surface must be clean prior to application of a tack coat. Construction equipment operating on a pavement to be sealed can often track mud and other foreign material onto the pavement surface, preventing the development of a satisfactory bond. The tack coat is normally applied immediately before application of the slurry, so dust and other debris on top of the tack is not a problem. Many times the slurry is placed at a time when the temperature is relatively low, resulting in a poor bond. Slurry seal construction should be performed in hot weather. It generally should not be placed when the ambient temperature is below 50 or 60 degrees Fahrenheit. For best results, slurry seals should be rolled with a rubber tire roller after placement. A roller is often not required by the specifications, but failure to use one can result in a slurry seal that does not provide satisfactory performance. Another problem that sometimes affects the performance of slurry seals is water vapor. The slurry seal is watertight, preventing water from passing through the sealer and evaporating. Water that might be trapped in the existing pavement may vaporize during the hot summer months and exert sufficient pressure on the slurry to cause blisters or delamination.

Performance data determined from a number of Air Force bases has shown that slurry seals typically last from three to six years, depending on the construction quality and environ-

TABLE 5 SURFACE TEXTURE OF TREATED AND UNTREATED SECTIONS

Material	Amount of Traffic	Average Penetration of Sand Into Pavement (0.001 inches)
A	Inside Traffic Lane	18.7
Control	Inside Traffic Lane	24.5
A	Outside Traffic Lane	17.0
Control	Outside Traffic Lane	21.1
B	Inside Traffic Lane	20.6
Control	Inside Traffic Lane	24.8
B	Outside Traffic Lane	17.9
Control	Outside Traffic Lane	21.5
C	Inside Traffic Lane	20.1
Control	Inside Traffic Lane	24.3
C	Outside Traffic Lane	17.0
Control	Outside Traffic Lane	21.0
D	Inside Traffic Lane	22.3
Control	Inside Traffic Lane	28.8
D	Outside Traffic Lane	22.5
Control	Outside Traffic Lane	30.5
E	Inside Traffic Lane	24.8
Control	Inside Traffic Lane	25.9
E	Outside Traffic Lane	24.7
Control	Outside Traffic Lane	25.6

mental conditions (*2*). The cost for slurry seals based on 1985 data varies considerably but generally ranges from $1.00 to $3.00 per square yard.

SURFACE TREATMENT

Surface treatments are generally placed in one or two layers. A single bituminous surface treatment consists of one layer of asphalt followed by a layer of uniformly graded aggregate. The thickness of the surface treatment is controlled by the aggregate size. A double bituminous surface treatment consists of two layers of asphalt and two layers of aggregate. The top layer of aggregate is normally about one-half the size of the bottom aggregate layer.

All three types of asphalt (asphalt cement, cutback asphalt, and asphalt emulsion) can be used to construct surface treatments. The use of crushed aggregate provides better performance than that derived with uncrushed aggregate.

Surface treatments are normally used on existing pavements to improve skid resistance and to waterproof the underlying layers. When surface treatments are used in high-traffic-volume areas, surface life is relatively short. One of the biggest problems with surface treatments is the loose aggregate on the pavement surface that is often thrown into windshields, causing damage. Good design and construction techniques can minimize the loss of cover aggregate.

For best performance, construction should take place in warm weather, at least 50 to 60 degrees Fahrenheit. When asphalt cement is used, the aggregate must be placed immediately after the asphalt is placed and the surface must be rolled as soon as possible. Steel-wheel rollers are sometimes used, but they tend to break the aggregate and bridge over low spots. A rubber tire roller is desirable. The aggregate is often heated when asphalt cement is used.

The aggregate used in surface treatments must be clean to ensure a good bond between the asphalt and aggregate. The use of dirty aggregates will result in loss of aggregate and, hence, unsatisfactory performance.

Performance data from a number of Air Force bases has shown that surface treatments usually last for between three and six years, depending on quality and environmental conditions (*2*). Based on 1985 data, the cost for surface treatments varies from $1.00 to $3.00 per square yard, depending on location and other factors.

CRACK SEALING

When cracks occur in asphalt pavements, they must be sealed to prevent water infiltration and loss of load-carrying capacity. A number of materials are available for sealing cracks. These materials include cutback asphalt, emulsified asphalt, joint sealing materials, and proprietary materials. On occasion, large cracks are sealed with sand-asphalt mixtures.

Small cracks (less than ¼ inch) are difficult to seal. If these cracks are few, they may be routed and sealed or left unsealed. If there are many cracks, it is usually too expensive to route and seal them. In such cases, the entire area may be sealed with a slurry seal, surface treatment, or overlay. Liquid asphalt should not be painted on the surface over the cracks. This does not properly seal the cracks, and it can cause a skid problem, especially in areas with many cracks. This excess asphalt may also cause problems when overlaying the existing pavement. The asphalt on the surface often causes slippage of the overlay when it is rolled.

In 1985, the cost for crack sealing at a number of Air Force bases was $0.75 to $1.25 per linear foot (*2*). At that time, it was expected that crack sealing had to be performed every three to five years.

SUMMARY

There are a number of maintenance procedures, including rejuvenators, slurry seals, surface treatments, and crack sealing, that can be used to prolong the life of asphalt pavements. Construction quality will greatly decrease the need for maintenance and ensure years of satisfactory performance.

Preventive maintenance procedures can increase the pavement life significantly and reduce future reconstruction costs. Pavements to be maintained need to be investigated to allow the selection of the most appropriate maintenance procedures for optimizing performance and ensuring that the lowest life-cycle cost is obtained.

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Improved Preventive Maintenance: Sealing Cracks in Flexible Pavements in Cold Regions

G. J. CHONG AND W. A. PHANG

Cracking of asphalt pavements in cold regions has always presented a problem, because it can directly affect pavement rideability and material behavior and, therefore, service life. If left untreated, cracking will develop into more drastic distresses, such as spalling, potholes, deformation, and even structural failure. These distresses are irreversible and are a major factor in pavement surface roughness. A prime example is the transverse crack that, when left untreated, develops permanent and seasonal deformation in the form of lipping or cupping. Lipping is an upheaval, and cupping is a depression of the pavement profile at the transverse crack. The Ontario Ministry of Transportation has an ongoing preventive maintenance measure, a crack rout-and-seal program, to minimize the effects of cracking. The ministry also seeks to improve rout-and-seal methodology and discover sealant materials that perform better. This paper presents some up-to-date results from these investigations.

When very severe pavement distress results in a very rough surface or deteriorated surface condition that is hazardous for the traveling public, urgent corrective maintenance is undertaken to remedy the situation. Such rough and/or hazardous conditions need not exist, however, if timely preventive maintenance is undertaken. A case in point, sealing the initial transverse crack (Figure 1) at the appropriate time would have stopped or delayed the distress from developing into this impossible situation.

Cracking of asphalt pavement in cold regions has always been a problem because it can directly affect pavement rideability and, therefore, service life. A prime example is the transverse cracks that, if left untreated, will develop permanent deformation in the form of lipping or cupping at the crack. Lipping is the upheaval of the pavement profile at the crack (Figure 2), and cupping is a depression of the pavement profile at the crack (Figure 3). These deformations are irreversible, and they are a major factor in pavement surface roughness.

Until about ten years ago, maintenance of cracks was generally implemented in the Ontario Ministry of Transportation by sealing with "Spray Patch" treatment—that is, spraying emulsion over the crack and blotting with a sand aggregate or stone chips. The success rate of this treatment was much less than acceptable, however, not only because of the treatment itself but because it is inappropriate for the distress (Figure 4). In many instances, the presumed cure is worse than the disease; the treatment can, and generally will, create additional roughness on an otherwise acceptable pavement riding surface, thus lowering its serviceability (Figure 5).

During the early 1970s, the ministry began to seal cracks using the method commonly known as rout-and-seal, using as standard the same rout configuration of 19 mm wide and deep designed for concrete pavement joints and the hot-pour rubberized asphalt sealant developed for the same purpose. Requirements for sealing characteristics of concrete pavement and asphalt pavement, however, are substantially different. Therefore, the results of the early rout-and-seal programs were less than completely successful. This led to questioning the value of crack sealing as a viable maintenance treatment. Is it true, as some advocate, that it is merely a waste of money and time, as cracking will always be with us? Or is it truly beneficial and would it be penny wise and pound foolish to do nothing?

To answer this question, it is essential to know the consequences of deferring sealing of cracks and to know the cost-effectiveness of the rout-and-seal maintenance treatment. For the ministry, it is imperative to know how cost-effective the treatment is, because the ongoing rout-and-seal program has grown from an annual cost of mere tens of thousands to millions of dollars in the latest fiscal years. The ministry began to address this issue in 1980 through a series of studies to improve the rout-and-seal technology as well as to cooperate with the manufacturing sector to produce sealant materials that perform better. This paper provides some up-to-date results of these studies.

CONSEQUENCES OF DEFERRED MAINTENANCE ON CRACKING

Deferred maintenance of cracking is generally accepted, mainly because of budgetary constraints. The pavement designers in the ministry are beginning to be concerned, however, because the majority of asphalt pavement mileage with untreated transverse cracks is developing either lipping or cupping deformations, in many instances very severe. These pavement designers believe their concern is well justified because these deformations are costly to redress under the rehabilitation

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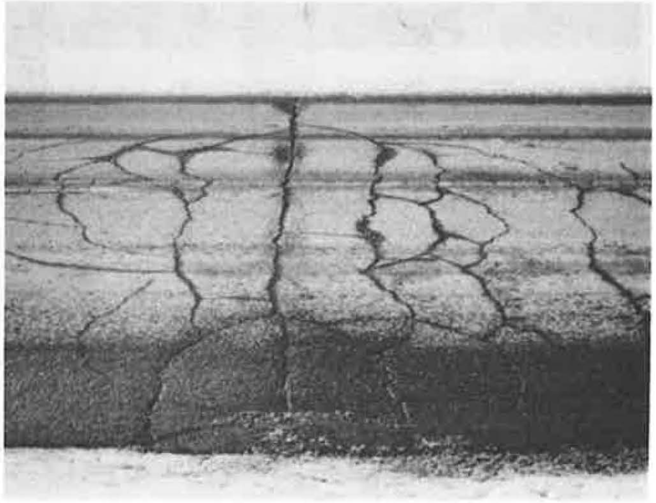

FIGURE 1 Consequence of deferred maintenance of transverse crack.

program, and simply resurfacing with hot-mix asphalt only perpetuates the cycle of reflection cracking and subsequent cupping or lipping.

Investigation shows that the surface condition of cracking does not necessarily indicate the degree of deterioration (*1*). Deterioration can take place at the bottom of the asphalt layers, as illustrated in Figure 6. On a heavily trafficked highway, deterioration can become so severe that half of the original asphalt layers or more will disintegrate from the bottom upward, creating a pavement of two different structural thicknesses within a matter of 1 m or 3 ft, plus or minus (Figure 7).

The consequences therefore of not sealing cracks are

1. Increased maintenance costs because deteriorated cracks are difficult (see Figure 1) and expensive to repair through corrective maintenance;
2. Increased user costs (vehicle repair and operation);
3. Increased rehabilitation costs, because deteriorated cracks demand special treatment from the designer when pavement rehabilitation is scheduled; and

FIGURE 2 Lipping of transverse cracks in winter.

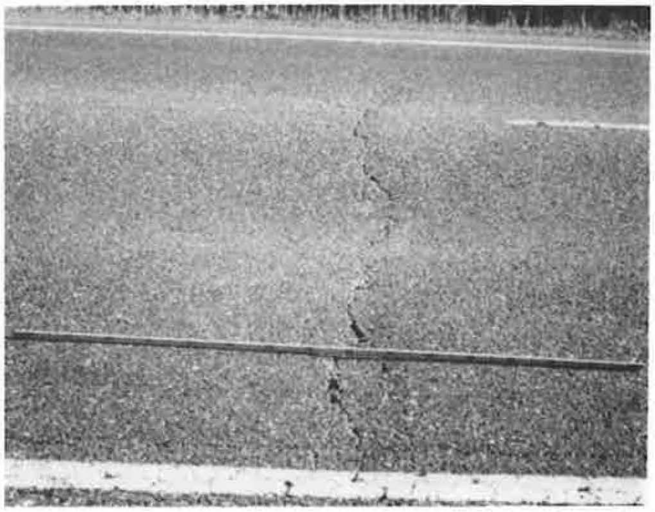

FIGURE 3 Cupping of transverse crack in summer.

4. Loss of serviceability and, therefore, service life (*1*).

COST-EFFECTIVE MAINTENANCE OF ASPHALT PAVEMENT CRACKING

The ministry employed two maintenance treatments for cracks—namely, sealing with emulsified asphalt and rout-and-seal with hot-pour rubberized asphalt sealant materials. Of these two treatments, it has been demonstrated that sealing with emulsified asphalt is not only ineffective but can also create undesirable side effects (*2*). On the other hand, rout-and-seal treatment has shown some success in effective maintenance of cracking, although it still is not known how cost-effective this particular maintenance alternative is.

The cost-effectiveness of a maintenance treatment depends on

1. How it will change the existing condition—that is, how effective it corrects the existing distress;

FIGURE 4 Spray patch of crack with emulsion and sand aggregate—crack remains unsealed.

FIGURE 5 Spray patch of cracks with emulsion and sand aggregate—created small ridges at cracks that are detrimental to rideability.

2. How well it can delay the distress's deterioration process and thereby extend the pavement service life; and
3. How much influence time has on its application against the existing distress using the particular maintenance treatment.

Therefore, the information needed to establish the cost-effectiveness of the rout-and-seal maintenance treatment must quantify:

1. The effectiveness of treatment, that is, (a) performance of sealant materials over time and (b) performance of various rout width and depth sizes over time to establish the most efficient rout configuration;
2. The extension of pavement service life that is, (a) retarding of additional crack development and (b) delaying the deterioration process of the existing distress; and
3. The influence of time—that is, at which point of the pavement's life cycle the treatment is applied most cost-effectively.

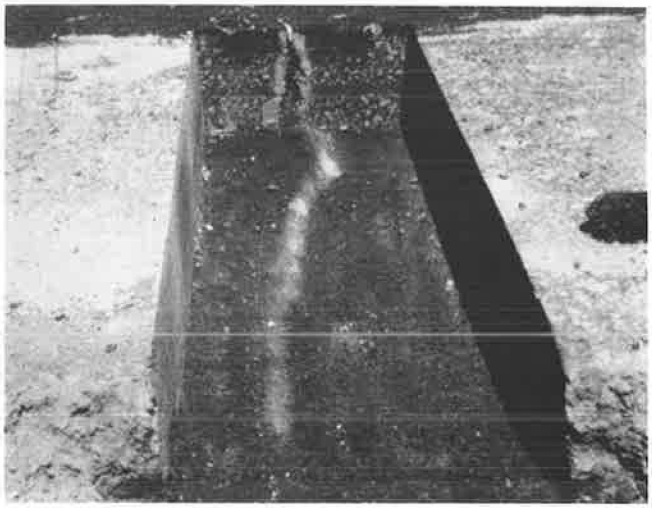

FIGURE 6 Highway 15 investigation site for unsealed transverse crack deterioration.

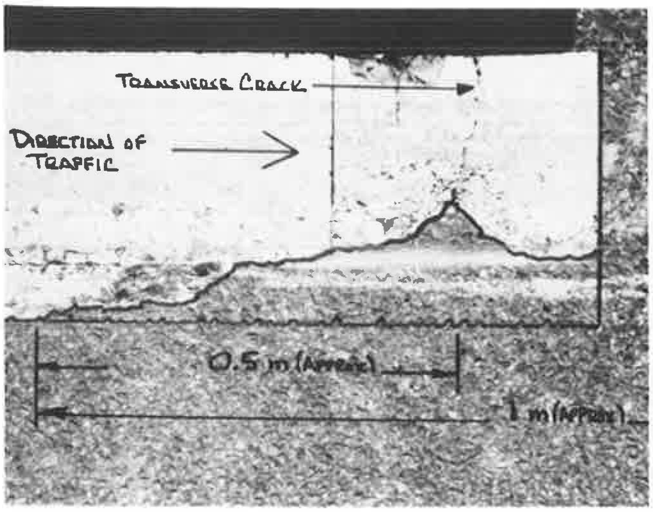

FIGURE 7 Highway 401 investigation site for unsealed transverse crack deterioration.

In Search of Effective Treatment

Effective Sealant Materials

Before 1980, the ministry maintained a designated source list of approved sealant materials that must conform to ASTM D-190 plus the Ministry Specification 1212 requirements. Opinions were expressed in the industry and within the ministry that these materials were evaluated and approved for use on portland cement concrete pavement, and that they were not necessarily effective when used to seal asphalt pavement cracks. In 1980, manufacturers of sealant materials were invited to participate in a field evaluation of their materials under identical and controlled conditions to identify the crack sealant best suited for sealing asphalt pavement cracks (*3–5*).

In 1983, the study identified eight sealant materials as approved products based on their mid-winter performance record. Four "premium" materials were approved for use in asphalt pavements throughout Ontario—namely,

1. Shell Cariphale ELT
2. Bemac Supergook
3. Meadows Hi-Spec
4. Hydrotech Sealz 6165

These materials are of low stiffness modulus and formulated to meet ASTM D-3405 (*6*).

Four other materials considered marginal were approved for use in asphalt pavement located in the southern part of the province only. These were

1. Bakelite 590-13
2. Hydrotech Sealz 6160
3. Meadows 164R
4. Paraseal 2065

These materials are of high stiffness modulus and are formulated to meet ASTM D-1190 (*6*). At this writing, the designated source list had a number of changes due to some additions and deletions (Tables 1 and 2). Deletion from the list means either that the product is no longer marketed by the manufacturer or has been dropped because of unsatisfactory performance observed in continuous monitoring by the Ministry.

Efficient Rout Configuration

Before 1980, the ministry maintained the 19 × 19-mm rout configuration as standard for portland cement concrete pavement joint sealing. This same standard was also used for asphalt concrete pavement joints and cracks (*7*). Opinions were expressed within the ministry that this rout configuration might not be the most efficient for asphalt pavement because of the extensibility. Adhesion at low temperature requirements are not the same for Portland cement concrete pavement and asphalt concrete pavement.

In 1981 and 1983, studies were initiated to identify the most efficient rout configurations from various combinations of width and depth (*2*, *6*, *7*). The result was that the new configuration of 40 mm width by 10 mm depth (Figure 8) was put into the Ministry *Maintenance Operation Instruction* guide as an option beside the standard 19 × 19-mm configuration for asphalt concrete pavement rout-and-seal guidelines (*8*).

The logic for this configuration is that the shape factor is at a ratio of 4 to 1 rather than the standard configuration of 1 to 1. Therefore, under low temperature the extensibility required of the sealant materials induced much less strain on the sealant and minimized the cohesion failure in the material. In addition, the shape factor provides a greater bonding area horizontally instead of the vertical bond faces for the standard square configuration. Therefore, since the extension force is less, it will in turn induce smaller adhesion stress on the sealant materials, thus minimizing the chance of bond failure.

Added benefits of the 40 × 10-mm configuration are that it is easier for the routing machine operator to follow the meandering cracks, which are the usual condition of asphalt pavement cracking. Also, there is less stress on the routing machine and router bits, which means higher productivity at lower cost. To date, although this configuration is optional, most of the in-house and contractual works were done using this 40 × 10-mm rout.

Efficient Work Procedures

Before 1980, rout-and-seal work procedure was the same standard as rout-and-seal Portland cement concrete pavement joints. That is, it was routed with a vertical router, cleaned with compressed air, and flush-filled with a hand pouring cone or garden watercan. The process is slow because of the vertical router's low productivity; considerable adhesion failure was also experienced from the flush-filled procedure. This was due to shrinkage of the sealant materials upon cooling, and it resulted in actual underfilling (*7*).

Since 1980, a number of studies were undertaken to establish the most efficient rout-and-seal procedure with the best possible long-term performance of sealing the cracks (*1*, *2*, *6*, *7*, *9*). The manufacturing sector also brought onstream some improved equipment designed for rout-and-seal operation (*6*, *7*, *9*). As a result, a number of processes were added or discarded based on their suitability. For example, the ministry

TABLE 1 MTO-DESIGNATED SOURCES LIST FOR ENGINEERING MATERIALS: PRODUCTS SUITABLE FOR USE IN ALL DISTRICTS

Manufacturer	Product	Supplier
Bakelite Thermosets Ltd 284 Watline Ave. Mississauga, Ontario L4Z 1P4 (416) 890-4800	590-13A Pouring Temp. 175-185°C	Manufacturer
Hydrotech Membrane Corp 100 Amber Street, Unit #12 Markham, Ontario L3R 3A2 (416) 475-3880	Hot Poured Sealz Sealz 6165 Pouring Temp. 190-215°C	Manufacturer
W.R. Meadows of Canada Ltd 130 Toryork Drive Weston, Ontario M9L 1X6 (416) 741-2220	Hi-Spec. Hot Poured Rubberized Asphalt Pouring Temp. 195-205°C	Manufacturer
Tremco (Canada) Ltd. 220 Wicksteed Ave. Toronto, Ontario M4H 1G7 (416) 421-3300	THC-200 Pouring Temp. 190-205°C	Manufacturer

NOTE: For all of the above products, method of application is either by pressure or gravity feed.

DS: 143.4

Designated Sources for: JOINT SEALING COMPOUNDS FOR USE IN ASPHALTIC CONCRETE PAVEMENT - HOT-POURED RUBBERIZED ASPHALT

Specification(s): (1) EMO BITUMINOUS SECTION (ii) OPSS-1212

Standards: OPSD 508.01, 508.02, 508.03

TABLE 2 MTO-DESIGNATED SOURCES LIST FOR ENGINEERING MATERIALS: PRODUCTS SUITABLE FOR USE IN DISTRICTS 1–8 ONLY

Manufacturer	Product	Supplier
Bakelite Thermosets Ltd 284 Watline Ave. Mississauga, Ontario L4Z 1P4 (416) 890-4800	590-13M Pouring Temp. 175-185°C	Manufacturer
Hydrotech Membrane Corp 100 Amber Street, Unit #12 Markham, Ontario L3R 3A2 (416) 475-3880	Hot Poured Sealz 6160 Pouring Temp. 195-215°C	Manufacturer
W.R. Meadows of Canada Ltd 130 Toryork Drive Weston, Ontario M9L 1X6 (416) 741-2220	No. 164 Hot Poured Rubberized Asphalt Pouring Temp. 195-215°C	Manufacturer
Tremco (Canada) Ltd. 220 Wicksteed Ave. Toronto, Ontario M4H 1G7 (416) 421-3300	THC-205 Pouring Temp. 190-205°C	Manufacturer
Globe Asphalt Products Ltd. 3300 Steeles Ave. West Suite 201 Concord, Ontario L4K 2Y4 (416) 738-4306	W.I. 317 Pouring Temp. 195-210°C	Manufacturer
Koch Materials Co. 43 Industrial St. Toronto, Ontario M4G 1Z2 (416) 421-2252	#9001 Pouring Temp. 200-215°C	Manufacturer

NOTE: For all of the above products, method of application is either by pressure or gravity feed.

DS: 143.4

Designated Sources for: JOINT SEALING COMPOUNDS FOR USE IN ASPHALTIC CONCRETE PAVEMENT - HOT-POURED RUBBERIZED ASPHALT

Specification(s): (1) EMO BITUMINOUS SECTION (ii) OPSS-1212

Standards: OPSD 508.01, 508.02, 508.03

will not advocate a "Band-Aid" process because snow-plowing in the winter has made this process unacceptable. Similarly, the overfilled to 80 mm and squeezed method was also discarded because of additional labor, waste of sealant materials, and snowplow shearing of excess materials (*2*, *6*, *7*). The ministry recommends that whether 19 × 19 mm or the optional 40 × 10 mm is used, sealant materials should be overfilled sufficiently to cover both edges of the routed crack, leaving the sealing materials standing slightly proud of the pavement surface (Figure 9). This additional material will provide sufficient coverage to compensate for shrinkage during the cooling process (*6*, *7*).

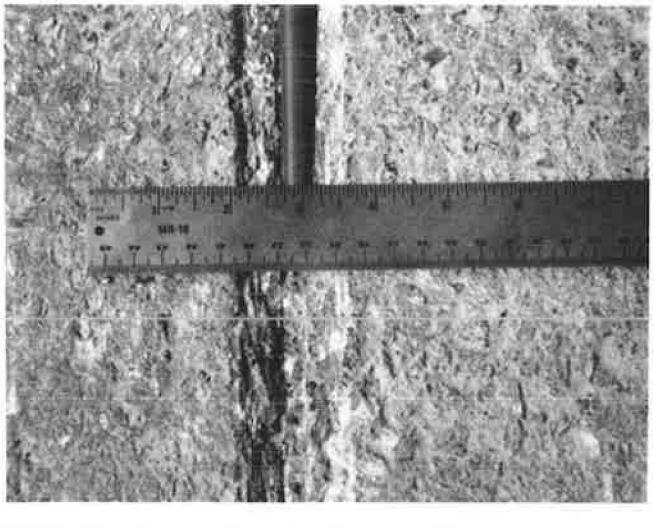

FIGURE 8 Rout configuration 40 mm × 10 mm.

For equipment, the ministry recommends the use of the Crafco and Marathon routers (both with cutter wheels) as the most efficient and productive of available routers. Use of a hot-compressed-air lance rather than compressed blowers is also recommended because it will remove dust and moisture efficiently to ensure a better bond between the pavement and the sealant materials (*6*, *7*, *9*).

The most efficient and productive operation arrangement was put together by the Ottawa District Maintenance staff of the ministry. Their method is now the standard for all in-house operations (Figure 9). The train of manpower and equipment is set up as follows. Two Crafco or Marathon routers with the operator operating ahead of the equipment train. A hot-compressed-air lance, connected to a tow-vehicle and supplied by the tow-vehicle with propane and compressed air, operates approximately 5 m (15 ft) for drying and clean-

FIGURE 9 Recommended sealant materials overfilled sufficiently to cover edges of routed crack.

ing the rerouted crack of dust and debris. A double-jacket oil kettle for sealant materials is towed behind the tow-vehicle; the heat is supplied by propane from the vehicle. Sealant is dispersed into routed crack by a pump-wand that maintains the sealant at a constant pouring temperature. The distance is approximately 5 m (15 ft) from the tow-vehicle. That is, the maximum distance between the cleaning and sealing phases is only about 20 to 25 m (60–80 ft), thus ensuring that no dust or debris will enter the routed crack prior to the sealant being poured.

Cost-Effectiveness of Rout-and-Seal Treatment as a Preventive Maintenance Measure

The cost-effectiveness of a treatment can be measured by how long it can delay the distress's deterioration process and by its additional ability to retard development of other distresses related to or consequent of the original distress.

In 1981, a small-scale study was initiated by the Ottawa District Maintenance Office to look into the consequences of sealing pavement cracks with rout-and-seal versus deferred maintenance (*1*, *7*). A section of Highway 17 near Ottawa was selected since it was originally constructed in 1965 with 115 mm (4 1/2 in.) of hot-mix asphalt and was rehabilitated in 1979 with 65 mm (2 1/2 in.) of hot-mix asphalt because of extensive cracking. In 1981, two years after resurfacing, extensive transverse cracks reappeared, and the pavement was rout-and-sealed as a preventive maintenance measure. Part of this pavement was used for the experimental study. In 1985, an investigation was made on the deferred maintenance control section and the rout-and-seal study section, which are adjacent to each other.

FIGURE 10 Standard ministry equipment train for in-house rout-and-seal operations.

A summary of the findings and observations (*1*) follows. When transverse crack maintenance was deferred in the control section, cupping deformation occurred and progressed to the "moderate" category six service years after rehabilitation (Figure 10). Deterioration of the transverse crack continues upward from the original pavement and into the base course of the resurfacing layers after six service years (Figure 11). Also, transverse cracks began to develop multiple cracks and spalling after six service years (Figure 12).

When transverse cracks were routed and sealed, cupping deformation developed after six service years but is in the "slight" category (Figure 13). Deterioration of the transverse crack upward from the original pavement was halted or retarded even after six service years (Figure 14), and the transverse crack surface condition remains static with no spalling or secondary crack development (Figure 15).

Therefore, although the project is still active and monitoring continues, the interim conclusions are as follows:

1. Rout-and-seal treatment of transverse cracks effectively retards internal and external deterioration.
2. Rout-and-seal treatment of transverse cracks effectively slows down the progress of cupping deformation.
3. Comparison of the treated sections with the control section indicates that rout-and-seal treatment of transverse cracks can extend the serviceability of the pavement by at least four years.

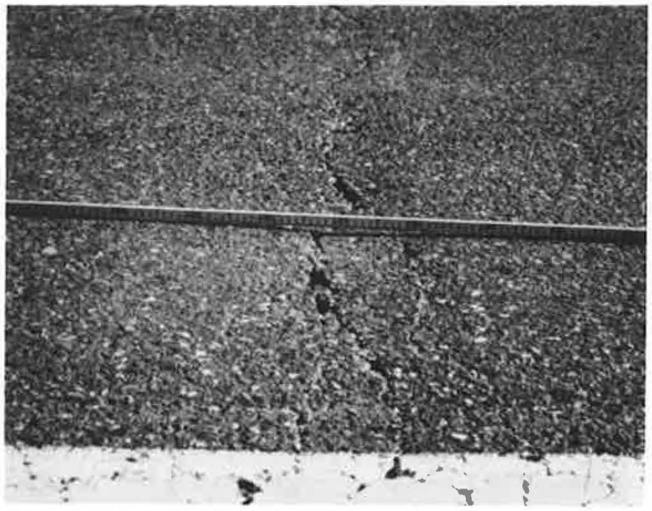

FIGURE 11 Moderate cupping of transverse crack on Highway 17, control section.

FIGURE 12 **Unsealed transverse crack deterioration continues upward unchecked on Highway 17, control section.**

Timing for Cost-Effective Application of Rout-and-Seal Treatment

In 1986, the ministry's Maintenance Branch initiated a comprehensive study program to further investigate the rout-and-seal treatment of cracks as a cost-effective preventive maintenance procedure (*1*). The scope of the study is provincewide to ensure complete coverage of the different climatic and environmental conditions that exist in Ontario. One of the objectives is to establish the influence of timing of treatment. That is, answers are sought to the question, At which point of the pavement's life cycle is the treatment most cost-effectively applied? To answer this question, pavement test sites were selected from several pavement age groups: those with less than 3 yr, 4 to 6 yr, and 7 to 9 yr of service life since last constructed or rehabilitated.

It is recommended, however, that rout-and-seal treatment of asphalt pavement cracking be carried out within the first five years of service life. Meanwhile, the ministry has also recently developed an expert system, with the acronym ROSE, for recommending rout-and-sealing of asphalt concrete pavement in cold areas (*10*). ROSE encodes expertise derived from recent research and development studies and from experience gathered within the ministry.

FIGURE 13 **Unsealed transverse crack develops multiple cracking and spalling on Highway 17, control section.**

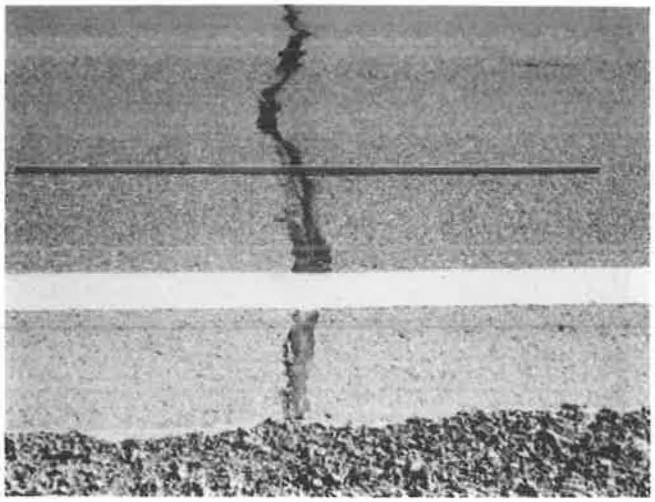

FIGURE 14 **Slight cupping of transverse crack on Highway 17, sealed test section with Hydrotech 6160.**

SUMMARY

The rout-and-seal treatment is designed to seal asphalt concrete pavement cracks to prevent water from entering and damaging the pavement structure. This is doubly important for pavements in cold areas because of the combination of low temperature-induced crack opening and the winter maintenance of snow and ice removal with salt.

Routing is used to open up the crack to accommodate enough sealant to provide an effective seal even after the pavement

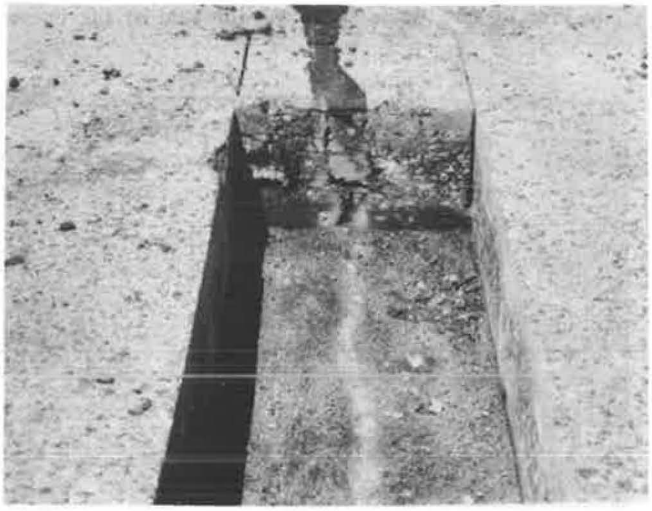

FIGURE 15 **Sealed transverse crack original deterioration stopped or retarded from progressing upward on Highway 17, sealed test section with Hydrotech 6160.**

crack opens due to contraction at low temperature during the winter months. Sealing is water-proofing the crack by bonding to the pavement surface and extending without fracture over the opened crack during the critical winter period. The ministry realized, however, that even the best sealant materials available would not perform in the field if they were not properly installed in clean, dry conditions and in the correct routing configuration. Therefore, the ministry has expended considerable effort to bring together the total package—that is:

1. The best performing sealant materials designed for the job,
2. The proper work procedure and equipment to ensure a well-laid seal, and
3. The proper timing for execution of this treatment.

The ministry considered these efforts worthwhile because past studies have indicated that rout-and-seal treatment, executed in a timely and proper fashion, can prolong pavement life by about five years for asphalt concrete pavement (*7*). This can be economically significant since the cost to rout and seal a two-lane highway is about $1,000 per kilometer, and typical resurfacing cost is about $40,000 per kilometer. The additional benefit is that when rehabilitation is scheduled, the pavement designer will not have a badly deteriorated pavement to deal with if timely maintenance has been performed.

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Effect of Routine Maintenance on Pavement Roughness

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This paper presents a study of the relationship between routine maintenance expenditure level and pavement roughness. A database by contract section was developed for the state highway system of Indiana. Covariance analysis was performed to test the effect of climatic region. Regression models were developed to examine the effect of routine maintenance expenditure level on rate of change in pavement roughness. Two highway classes and three pavement types were considered in the analysis. The database included a total of 550 pavement contract sections. The results can be used to develop an effective maintenance program.

Ideally, a maintenance management system (MMS) is an integral part of a pavement management system (PMS). An important purpose of the maintenance management component in a PMS is to monitor the costs associated with providing various levels of serviceability for any given situation. The costs are dependent on the type and level of maintenance activity, which can in turn affect pavement performance in terms of the rate of serviceability loss or the change in surface roughness for a pavement.

The interest in MMS is largely motivated by a desire to obtain a greater degree of control and approach standardization in order to manage better such resources as labor, materials, and equipment (*1*). Many factors make the task of managing routine maintenance activities difficult. First, it is difficult to quantify the benefit of changing existing practices or choice of treatment. Also, systematic data collection is rarely undertaken to evaluate the differences between alternative maintenance treatments for any given pavement defect in terms of overall cost-effectiveness. Furthermore, the scope of maintenance involves many activities over thousands of miles of roads that must be maintained every year.

Routine maintenance represents a large percentage of the total highway expenditures of the Indiana Department of Highways (IDOH). This level of routing maintenance expenditure is typical of other state highway departments in the United States and of regional and national highway authorities in most countries in Europe (*2*). For that reason, the IDOH has developed a MMS for programming, scheduling, and monitoring routine maintenance operations. Several studies have been conducted at Purdue University through the Joint Highway Research Project (JHRP) to improve the efficiency of the existing MMS (*3, 4*).

The purpose of the present research effort was to study the effect of various routine maintenance expenditure levels on pavement condition in terms of surface roughness. Pavement roughness was used as a direct quantitative measure of pavement performance instead of Present Serviceability Index (PSI). This was based on the results of several studies (*5, 6*) concluding that in many instances the use of roughness measurements alone is sufficient for predicting the serviceability index.

To accomplish the main objective, a database was developed for pavement routine maintenance, pavement condition, and pavement characteristics. The appropriate data were collected based on construction contract sections. A contract section is that portion of a highway pavement that is contracted out to one contractor for a specific activity such as resurfacing. The pavement characteristics within a contract section are generally uniform. In contrast, a highway section may stretch from county line to county line and may include a series of different contract sections with different pavement characteristics.

DEVELOPMENT OF DATABASE

Based on the findings of previous studies (*3, 4, 7, 8*) in Indiana, two regions, two highway classes, and three pavement types were considered. The two highway classes are interstate and other state highways (OSH). The three pavement types are flexible pavements, rigid pavements, and rigid pavements with bituminous overlay. The database was developed from three sources of information: routine maintenance records, roughness measurement records, and road life records.

Design of Experiment

The IDOH has six districts. Five districts have six subdistricts each, and one district has seven subdistricts, for a total of thirty-seven subdistricts. In each subdistrict, there are three to four units that actually perform the field maintenance work. In the present study, the subdistrict was considered the appropriate management unit. Information had to be extracted from several thousand crew day cards recorded by subdistricts. The crew day cards provide a means of authorizing work to be done and a record of work completed (*9*). Each crew day card represents one eight-hour day of any maintenance activity. Ten subdistricts were selected for the analysis based on their fulfillment of the following criteria:

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1. to include sufficient sections from interstate highways;
2. to represent the administrative system so that at least one subdistrict was selected from each district;
3. to represent the entire state geographically;
4. to cover both climatic regions in the state (North and South); and
5. to avoid subdistricts that have a dense highway network, such as the Indianapolis subdistrict.

Finally, six subdistricts were selected from the South region and four subdistricts from the North region. Figure 1 shows the locations of the selected subdistricts.

Selection of Contract Sections

The two most recent roughness measurements (1984, 1985) in counts/mile were used. Only those contract sections that did not receive any major maintenance or resurfacing between the two roughness measurements were selected. The data on roughness measurement on each contract section for 1984 and 1985, along with such other information as contract number, contract length, surface type, landmarks, number of lanes in each direction, and date of construction or last major maintenance, were recorded in a newly created "roughness file."

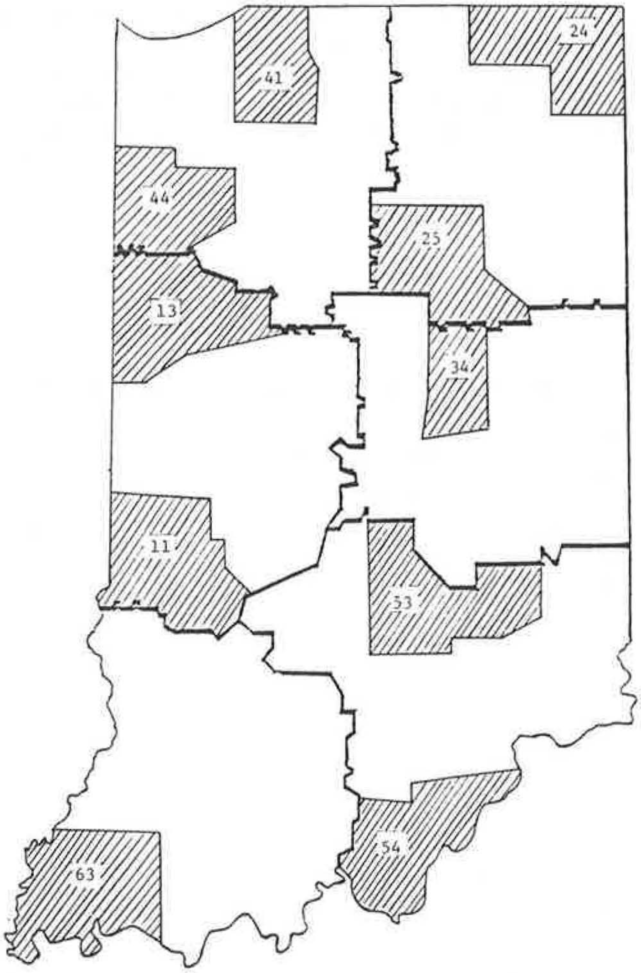

FIGURE 1 Locations of subdistricts included in the study.

A total of 550 contract sections were selected, including 126 sections in interstate and the remaining sections in other state highways (OSH).

Routine Maintenance Quantities

The amount of routine maintenance applied between two dates of roughness measurements was determined from crew day cards obtained from each subdistrict considered. A total of about ten thousand crew day cards were analyzed. Cards with missing information, such as highway number, county number, or location of the work, were excluded.

Pavement routine maintenance activities considered in this paper were categorized in two groups: (1) patching that consists of shallow patching (Activity 201) and deep patching (Activity 202); and (2) joint and crack sealing that consists of sealing longitudinal cracks and joints (Activity 206) and sealing cracks (Activity 207).

The relevant information extracted from the crew day cards included activity type, date of work, location of work, and the number of production units accomplished. The information was recorded in a newly created "routine maintenance file."

Routine Maintenance Amount by Contract Sections

Both roughness and routine maintenance records have generally the same inventory data, including the following common information:

1. highway class and number
2. county number
3. subdistrict number
4. district number

Using this information, it was possible to determine the amount of routine maintenance work done on a contract section. Two location demarcation scales were established for each highway in each subdistrict. The first scale was called the Contract Section Scale. It used the identified mileposts and determined contract length in lane-miles. The second scale, called Landmarks Scale, used mileposts and the distance between two successive landmarks. Landmarks included intersections, bridges, county lines, and rivers.

Having established the two scales, routine maintenance quantity on each card was distributed according to the contract length by activity. In most cases, the location of routine maintenance was recorded between landmarks containing more than one contract section. In such cases, the Landmarks Scale was applied, and the routine maintenance work was distributed in proportion to the length of the different contract sections. If the location of routine maintenance work was defined by mileposts within a contract section, then the quantity of the work was assigned directly to the corresponding contract section. This occurred mainly with interstate highways because in Indiana only interstates have mileposts.

Finally, the routine maintenance quantities were summed for each contract section and recorded along with roughness measurement and other information in a single file containing routine maintenance and roughness data. Information on average daily traffic (ADT) and percent of trucks obtained from the Division of Planning of the IDOH was added to the database.

Routine Maintenance Expenditure

After the quantity of each routine maintenance activity on each contract section was determined, the dollar values of maintenance activities performed on contract sections were obtained by multiplying the quantities by appropriate unit costs developed by Sharaf (*10*) and IDOH (*11*). The routine maintenance expenditure was calculated in dollars/lane-mile/year. The cost items considered were labor, materials, and the cost of motor fuel consumed by maintenance equipment and vehicles. These costs did not include those for overhead and equipment depreciation. Cutting relief joints (Activity 209), joint and bump burning (Activity 214), and other functions (Activity 219) were not considered because it was found that very few crew day cards had these activities for the selected subdistricts during the study period.

DATA ANALYSIS

One of the major factors causing pavement distresses is the climate. A pavement is affected not only by the weather but also by such related factors as deicing chemical agents. In this study, two climatic regions, the Northern region and the Southern region, were considered.

A statistical test was conducted to determine whether the data in both climatic regions can be analyzed as one data set or not. The two southernmost subdistricts (numbers 54 and 63) were selected to be tested against the two northernmost subdistricts (numbers 24 and 41) as shown in Figure 1. Since sufficient interstate sections were not available in these subdistricts, only other state highways were considered in the analysis. Pavement sections were grouped based on the type of routine maintenance that was applied during the study period. Table 1 shows the distribution of pavement contract sections by region and by routine maintenance category for each pavement type. The number of sections that received sealing or zero maintenance was very few, and in some cells no observations were available. Therefore, it was decided to use two routine maintenance categories (patching and patching plus joint and crack sealing) in the analysis.

Analysis of covariance technique was used to analyze data. Pavement age and cumulative equivalent single axle load (ΣESAL) were considered quantitative variables and climatic region and routine maintenance category as qualitative variables. Pavement roughness in 1985 was used as the dependent variable. As recommended by Anderson and McLean (*12*) and to develop the covariance models for different pavement types, the following two tests were made on the dependent variables.

1. *Normality Test*: Since the number of observations in each of the considered cells was less than 50, the Wilk-Shapiro (*12*) test was used. In some cases, the dependent variable was not found normally distributed even at the level of $\alpha = .01$. So, $\log_{10}$ transformation was tried on the dependent variable, and normality was indicated in all cases at $\alpha \geq .10$.
2. *Homogeneity of Variances Test*: Since the number of observations was different from cell to cell (unbalanced design), the homogeneity of variances was checked by performing the Burr-Foster (*12*) test. The variances of the dependent variable were found homogenous at the level of $\alpha = .01$ in all cases.

TABLE 1 DISTRIBUTION OF CONTRACT SECTIONS BY CLIMATIC REGION BY ROUTINE MAINTENANCE CATEGORY FOR EACH PAVEMENT TYPE

		Northern Region			Southern Region		
		Subdistricts			Subdistricts		
Pavement Type	Routine Maintenance Category	Angola (24)[a]	Laporte (41)[a]	Total Data Points	New Albany (54)[a]	Evansville (63)[a]	Total Data Points
Flexible	Patching	10	9	19	11	4	15
	Patching and joint & crack sealing	5	1	6	4	10	14
	Joint & crack sealing	1	1	2	2	1	3
	None	–	4	4	1	–	1
Rigid	Patching	2	8	10	6	4	10
	Patching and joint & crack sealing	–	3	3	–	12	12
	Joint & crack sealing	–	–	–	–	8	8
	None	–	1	1	–	–	–
Overlaid	Patching	10	7	17	1	4	5
	Patching and joint & crack sealing	1	7	8	1	11	12
	Joint & crack sealing	–	5	5	–	–	–
	None	–	–	–	–	–	–

[a] Code number of subdistrict.

Having met the normality and homogeneity tests, the following covariance model was adopted:

$$\log_{10}(RN_{85}) = \mu + R + RM + R * RM + \text{Age} + \Sigma\text{ESAL} + \varepsilon \tag{1}$$

where

RN_{85} = roughness measurement in 1985 in counts/mile;
μ = overall mean;
R = climatic region;
RM = routine maintenance category;
$R * RM$ = interaction between region and routine maintenance;
age = pavement age since construction or last major maintenance in years;
ΣESAL = total accumulated ESAL; and
ε = random error component.

Table 2 shows the statistical characteristics of covariance analysis for each pavement type. The major findings of this analysis are summarized below.

1. The regional effect was significant in all cases at the level of $\alpha < .10$. Based on this major finding, regression models were developed in the next section, and regional effect was considered as a main factor in these models.
2. Routine maintenance category (*RM*) was found to be not significant with respect to roughness measurements in 1985. This was because there were only two categories of maintenance considered and the measurements were only for one year. However, the interaction between climatic region and routine maintenance category was significant at $\alpha < .25$. This level of α was chosen because the recording of the location of routine maintenance work in most of the crew day cards was not precise. In addition, the initial data analysis was conducted as an overall test. Regression models were used to specify the trend of this interaction. The significance of the interaction between climatic region and routine maintenance category implies that effects of *RM* category differed between North and South regions.
3. The effects of pavement age and ΣESAL were significant at $\alpha \leq .10$, except for rigid pavements. A part of the reason could be that most rigid pavement sections are very old in both regions.

It should be noted that because of data limitations, the preceding analysis was conducted with only four out of ten subdistricts in the database.

REGRESSION MODELS FOR ROUTINE MAINTENANCE EXPENDITURE AND REGIONAL EFFECTS

Based on the results of covariance analysis, regression analysis was performed to study the effects of routine maintenance expenditure level and climatic region on pavement roughness. Rate of change in pavement roughness was used as the dependent variable in these models. Pavement sections with both negative and positive changes in roughness were considered in the analysis. Rate of change in pavement roughness was calculated as follows:

$$RRN = \frac{RN_{85} - RN_{84}}{RN_{84}} \tag{2}$$

where

RRN = rate of change in pavement roughness
RN_{84} = roughness measurement in 1984 (counts/mile); and
RN_{85} = roughness measurement in 1985 (counts/mile).

Since PSI is highly correlated to pavement roughness, *RRN* can be used as a measure of pavement deterioration. In Equation 2, RN_{84} represents the effect of past maintenance on pavement condition, while $RN_{85} - RN_{84}$ represents the effect of routine maintenance that was applied between the two roughness measurements.

The analysis included data from all the selected subdistricts in both regions. Only those pavement sections that received patching (*P*) or patching and joint and crack sealing (*PS*) were analyzed. Five categories of highway class pavement type were included: interstate rigid pavement, interstate overlaid pavement, OSH flexible pavement, OSH rigid pavement, and OSH overlaid pavement. Three criteria were considered in selecting the best model: (1) the general goodness-of-fit represented by the coefficient of multiple determination (R^2); (2) the general linearity test for the model through the application of the general *F*-test, and (3) the significance of individual coefficients of the model through the *t*- or *F*-tests. These criteria were applied, and an attempt was made to have the same model type for the five categories to facilitate consideration of the effects of different factors.

After several trials, the following regression model appeared to satisfy most of the required conditions.

$$RRN = a + b \log_{10}(RM) + c\,(R) + d \log_{10}(RM) * (R) \tag{3}$$

TABLE 2 STATISTICAL CHARACTERISTICS OF COVARIANCE ANALYSIS BY PAVEMENT TYPE

	Flexible Pavements (54)[a]		Rigid Pavements (35)[a]		Overlaid Pavements (42)[a]	
Variables	*F*-Value	α-Level	*F*-Value	α-Level	*F*-Value	α-Level
Region	3.70	0.060	4.02	0.054	5.66	0.023
RM	0.15	0.702[b]	0.36	0.551[b]	0.15	0.701[b]
Region * *RM*	1.61	0.211	6.19	0.019	2.48	0.124
Age	19.06	0.000	0.94	0.341[b]	4.52	0.040
ΣESAL	2.69	0.108	0.07	0.796[b]	4.48	0.041

NOTE: $\log_{10}(RN_{85})$ was used as the dependent or response variable.
[a] Number of observations.
[b] The variable is not significant at $\alpha < 0.25$.

where

RRN = rate of change in pavement roughness;
RM = routine maintenance expenditure level ($/lane-mile/Year) (this variable takes the symbol (P) for pavement sections that received patching and (PS) for sections that received patching and joint and crack sealing);
R = dummy variable to represent the region in which the pavement section is located: 0 for Northern region and 1 for Southern region; and
a,b,c,d = regression parameters.

A high level of confidence with $\alpha = .05$ was used to test the significance of all regression models. The following models were found significant.

For interstate rigid pavements:

$$RRN = 1.0 - 0.37 \log_{10}(PS) - 0.07R \quad (4)$$

For interstate overlaid pavements:

$$RRN = 1.83 - 0.81 \log_{10}(PS) + 0.11R \quad (5)$$

$$RRN = 0.27 - 0.20 \log_{10}(P) + 0.26R \quad (6)$$

For OSH flexible pavements:

$$RRN = 1.5 - 0.49 \log_{10}(PS) + 2.19R - 0.79 \log_{10}(PS) * R \quad (7)$$

$$RRN = 1.65 - 0.65 \log_{10}(P) - 0.94R + 0.43 \log_{10}(P) * R \quad (8)$$

For OSH overlaid pavements:

$$RRN = 5.44 - 2.04 \log_{10}(PS) - 3.8R + 1.5 \log_{10}(PS) * R \quad (9)$$

For OSH rigid pavements:

$$RRN = 0.62 - 0.15 \log_{10}(P) - 0.13R \quad (10)$$

Only Equations 7, 8, and 9 included the interaction term (between routine maintenance expenditure level and region). This is because the routine maintenance expenditure level on OSH had a wider range. For example, the expenditure level of PS on OSH overlaid pavements varies between 100 and 750 $/lane-mile/year, while on interstate overlaid, it varies between 150 and 400 $/lane-mile/year.

A summary of the characteristics of the regression models are given in Tables 3 and 4, respectively. As shown in these tables, a relatively higher R^2 was obtained for interstate than OSH models. This may be due to the fact that interstate highways are mile-posted; so it was easier and more accurate to match routine maintenance locations with roughness measurements. Furthermore, the significance test for the coefficient b for the variable RM (routine maintenance expenditure level) showed a high level of confidence. The levels of significance of the region and interaction term were lower than that of the expenditure level. These variables, however, could be considered significant at a 90 percent level of confidence, as shown in Tables 3 and 4.

Two observations can be made regarding the insignificant models: (1) the number of available sections in the Northern region in some cases was very small; and (2) routine maintenance records in the Southern region were less organized, and the location of maintenance on these records was less accurate. Therefore, regression models were developed separately for Northern and Southern regions. Table 5 shows these statistical models. As shown in this table, in general, a higher R^2 was obtained for all category models in the North. Most of the category models in the Southern region were insignificant. In all these insignificant models, however, there is a consistent trend indicating the significance at a higher level of α. The primary reason of these results is the inaccuracy in determining the exact location and amount of maintenance activity.

TABLE 3 STATISTICAL CHARACTERISTICS OF PATCHING AND JOINT AND CRACK SEALING MODELS

Criterion	Interstate Rigid ($N = 27$)[a]	Interstate Overlaid ($N = 10$)[a]	OSH Flexible ($N = 44$)[a]	OSH Rigid ($N = 43$)[a]	OSH Overlaid ($N = 57$)[a]
Coefficient of determination (R^2)	0.30	0.86	0.46	0.07	0.32
Adjusted coefficient (adj. R^2)	0.27	0.84	0.43	0.05	0.30
Linearity test					
F-value	5.14	20.96	11.23	1.48	8.37
α level	0.014	0.001	0	0.24[b]	0
Significance test for coefficients					
$\log_{10}(PS)$					
F-value	9.78	23.06	3.66	2.95	14.82
α value	0.005	0.002	0.063	0.093	0
Region					
F-value	1.15	7.71	6.20	0	7.86
α value	0.29[c]	0.028	0.017	0.95[c]	0.007
$\log_{10}(PS)$ * Region					
F-value	–	–	5.24	–	7.27
α value	–	–	0.027	–	0.009

[a] Number of observations.
[b] The model is not significant at $\alpha > 0.05$.
[c] The coefficient is not significant at $\alpha > 0.10$.

TABLE 4 STATISTICAL CHARACTERISTICS OF PATCHING MODELS

Criterion	Interstate Rigid $(N = 28)$[a]	Interstate Overlaid $(N = 21)$[a]	OSH Flexible $(N = 78)$[a]	OSH Rigid $(N = 44)$[a]	OSH Overlaid $(N = 47)$[a]
Coefficient of determination (R^2)	0.13	0.61	0.21	0.25	0.09
Adjusted coefficient (adj. R^2)	0.06	0.59	0.18	0.23	0.07
Linearity test					
F-value	1.20	14.07	6.33	6.70	2.07
α level	0.33[b]	0	0.001	0.003	0.14[b]
Significance test for coefficients					
$\text{Log}_{10}(P)$					
F-value	1.27	10.88	16.17	6.37	3.71
α value	0.27[c]	0.004	0	0.02	0.061
Region					
F-value	1.20	18.49	3.87	3.94	0.57
α value	0.28[c]	0	0.053	0.05	0.45[c]
$\text{Log}_{10}(P)$ * Region					
F-value	1.26	–	3.12	–	–
α value	0.27[c]	–	0.082	–	–

[a] Number of observations.

[b] The model is not significant as $\alpha > 0.05$.

[c] The coefficient is not significant at $\alpha > 0.10$.

IMPLICATIONS OF THE MODELS

The effects of routine maintenance expenditure level and climatic region on rate of change in pavement roughness (pavement deterioration) can best be demonstrated through examination of Figures 2 to 7. The *RRN* is positive in most cases, indicating that roughness increases regardless of maintenance expenditure level. The amount of this increase varies, however. It is clear that in most of the cases, *RRN* in the Northern region is higher than that in the Southern region, especially at a low expenditure level of routine maintenance. This may be because of a longer cold period and a greater amount of snowfall in the Northern region, requiring a higher level of maintenance. The validity of this conclusion can be supported by the fact, as reported by Fwa and Sinha (*4*), that the non-load-related damage responsibility in the Northern region is significantly higher than that in the Southern region. In some cases, as shown in Figures 3 and 4, *RRN* is higher in the Southern region. In these cases, it was found that the average pavement age of the analyzed sections in the Southern region was greater, and the average ESAL on these sections was also higher. For example, the average age of OSH flexible pavement sections in the Southern region that were patched and sealed was about twelve years, while it was nine years in the Northern region. The corresponding average traffic levels were 209,000 and 151,000 accumulated ESAL, respectively.

It is obvious in Figures 2 to 7 that, as routine maintenance expenditure level increases, *RRN* decreases and the difference in pavement deterioration between the two regions becomes less. In some cases, as shown in Figures 5 and 6, at higher expenditure levels *RRN* in the Northern region is lower than that in Southern region. In some cases, in the North, pavement roughness decreased even at lower expenditure levels. These results may possibly reflect the higher maintenance quality and degree of supervision in the Northern region.

The discussion of the results in this paper leads to the concept of routine maintenance effectiveness. Maintenance effectiveness in this study can best be represented by the reduction in *RRN* as routine maintenance increased from one expenditure level to another. In general, the reduction in *RRN* in the Northern region was more than that in the Southern region if maintenance increased from one expenditure level to another, regardless of pavement type or maintenance activity. Furthermore, this reduction was noticeable or higher when the increase in expenditure took place at lower levels of maintenance. For example, as shown in Table 6, if *PS* expenditure level increased from 50 to 100 \$/lane-mile/year, the reductions in *RRN* for interstate overlaid in the Northern and Southern

TABLE 5 STATISTICAL MODELS FOR THE EFFECT OF ROUTINE MAINTENANCE EXPENDITURE LEVEL BY REGION

Routine Maintenance Variable	Pavement Type	Northern Region			Southern Region		
		Model	R^2	Adj. R^2	Model	R^2	Adj. R^2
Patching and joint and crack sealing	Interstate rigid	$RRN = 1.14 - 0.43 \log_{10}(PS)$	0.50	0.46	$RRN = 0.79 - 0.30 \log_{10}(PS)$	0.15	0.06
	Interstate overlaid	$RRN = 2.20 - 0.97 \log_{10}(PS)$	0.94	0.90	$RRN = 1.63 - 0.63 \log_{10}(PS)$	0.63	0.54
	OSH flexible	$RRN = 1.50 - 0.49 \log_{10}(PS)$	0.21	0.17	$RRN = 3.68 - 1.28 \log_{10}(PS)$	0.53	0.51
	OH rigid	$RRN = 0.65 - 0.10 \log_{10}(PS)$	0.05[a]	−0.03	$RRN = 1.45 - 0.43 \log_{10}(PS)$	0.08[a]	0.05
	OSH overlaid	$RRN = 5.44 - 2.04 \log_{10}(PS)$	0.42	−0.38	$RRN = 1.63 - 0.54 \log_{10}(PS)$	0.24	0.22
Patching	Interstate rigid	$RRN = 5.10 - 2.30 \log_{10}(P)$	0.99	0.99	$RRN = 0.27 - 0.05 \log_{10}(P)$	0.02[a]	−0.02
	Interstate overlaid	$RRN = 0.47 - 0.31 \log_{10}(P)$	0.47	0.42	$RRN = 0.43 - 0.15 \log_{10}(P)$	0.38	0.29
	OSH flexible	$RRN = 1.64 - 0.65 \log_{10}(P)$	0.28	0.26	$RRN = 0.70 - 0.23 \log_{10}(P)$	0.05[a]	0.02
	OSH rigid	$RRN = 0.65 - 0.16 \log_{10}(P)$	0.33	0.28	$RRN = 0.46 - 0.13 \log_{10}(P)$	0.08[a]	0.04
	OSH overlaid	$RRN = 0.86 - 0.29 \log_{10}(P)$	0.11	0.07	$RRN = 0.65 - 0.23 \log_{10}(P)$	0.03[a]	−0.02

[a] The model is not significant at $\alpha > .10$.

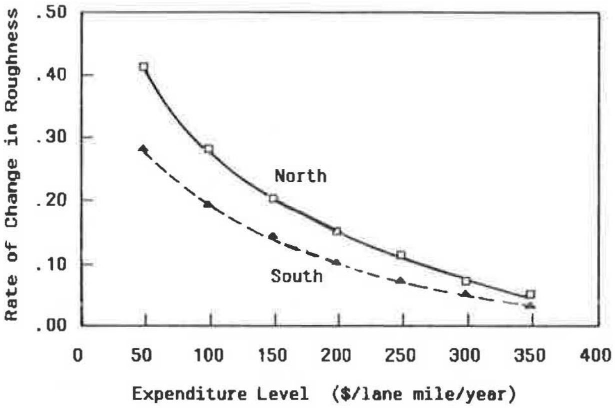

FIGURE 2 Effect of patching and joint and crack sealing expenditure level on interstate rigid pavement roughness.

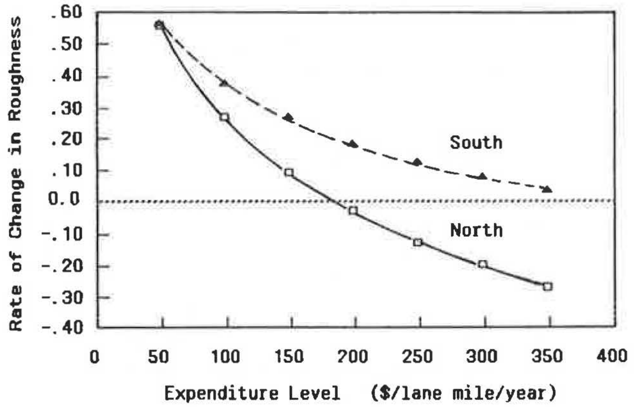

FIGURE 3 Effect of patching and joint and crack sealing expenditure level on interstate overlaid pavement roughness.

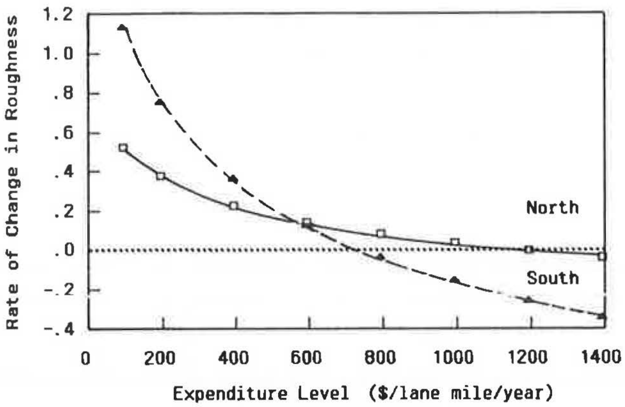

FIGURE 4 Effect of patching and joint and crack sealing expenditure level on OSH flexible pavement roughness.

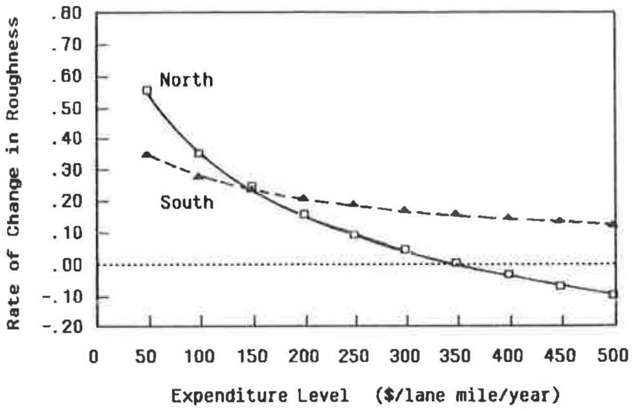

FIGURE 5 Effect of patching expenditure level on OSH flexible pavement roughness.

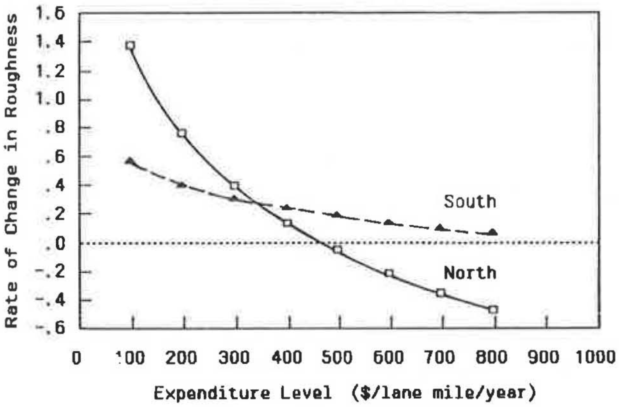

FIGURE 6 Effect of patching and joint and crack sealing expenditure level on OSH overlaid pavement roughness.

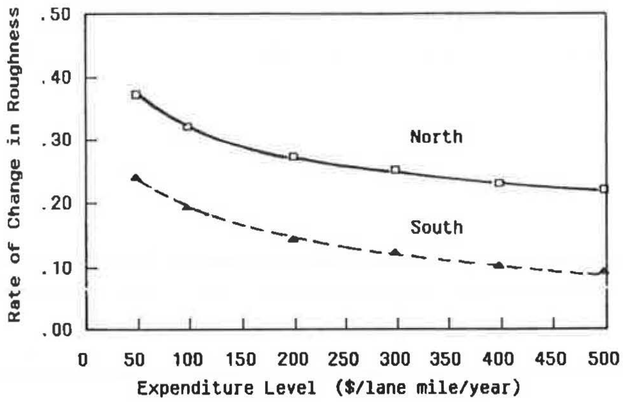

FIGURE 7 Effect of patching expenditure level on OSH rigid pavement roughness.

TABLE 6 REDUCTION IN RATE OF CHANGE IN PAVEMENT ROUGHNESS AS ROUTINE MAINTENANCE EXPENDITURE LEVEL CHANGES FOR INTERSTATE OVERLAID

Increase in Expenditure Level (from–to)	Reduction in Rate of Change in Pavement Roughness			
	Patching and Joint and Crack Sealing		Patching	
	North	South	North	South
50–100	0.29	0.19	0.09	0.05
100–150	0.17	0.11	0.05	0.03
150–200	0.12	0.08	0.04	0.02
200–250	0.10	0.06	0.03	0.01
250–300	0.07	0.05	0.03	0.01
300–350	0.07	0.04	0.02	0.01

TABLE 7 EFFECT OF CHANGES IN PATCHING EXPENDITURE LEVEL ON REDUCTION IN RATE OF CHANGE IN PAVEMENT ROUGHNESS FOR TWO PAVEMENT TYPES

Increase in Expenditure Level (from–to)	Reduction in Rate of Change in Pavement Roughness			
	OSH Flexible		OSH Rigid	
	North	South	North	South
50–100	0.20	0.07	0.05	0.05
100–150	0.11	0.04	0.03	0.03
150–200	0.09	0.03	0.02	0.03
200–250	0.06	0.02	0.01	0.01
250–300	0.05	0.02	0.01	0.01
300–350	0.04	0.01	0.01	0.01
350–400	0.04	0.01	0.01	0.01
				0.01

regions were 0.29 and 0.19, respectively. In contrast, if *PS* expenditure level increased from 200 to 250 $/lane-mile/year, the corresponding reduction values of *RRN* were 0.10 and 0.06, respectively.

A possible main conclusion is that maintenance effectiveness is higher in the Northern region than in the Southern region. This result confirmed what Fwa and Sinha (*4*) observed in an earlier study. They stated that the amount of pavement damage repaired (i.e., the amount of PSI-ESAL loss recovered) per dollar worth of maintenance work was greater in the Northern region.

The concept of maintenance effectiveness can be used to compare the effect of the same maintenance activity expenditure level on surface roughness of different pavement types. Table 7 shows the effect of changes in patching expenditure level on reduction in *RRN* for OSH flexible and rigid pavements. If patching expenditure level increased from 50 to 100 $/lane-mile/year, the reductions in *RRN* for OSH flexible and rigid pavement in the Northern region were 0.20 and 0.05, respectively. In general, it was found that regardless of climatic region, highway class, or maintenance activity, the response of rigid pavement to changes in expenditure level is less than that of flexible or overlaid pavements.

Figures 8 and 9 show the effect of expenditure level of two maintenance policies (*P* and *PS*) on *RRN* for interstate rigid and OSH flexible pavements, respectively, in the Southern

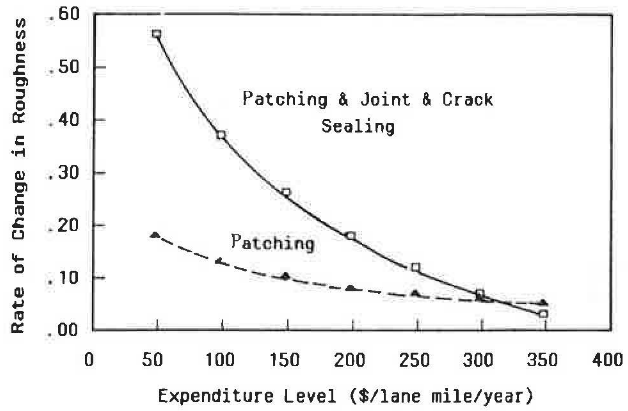

FIGURE 8 Effect of expenditure level of two maintenance policies on interstate overlaid pavement roughness.

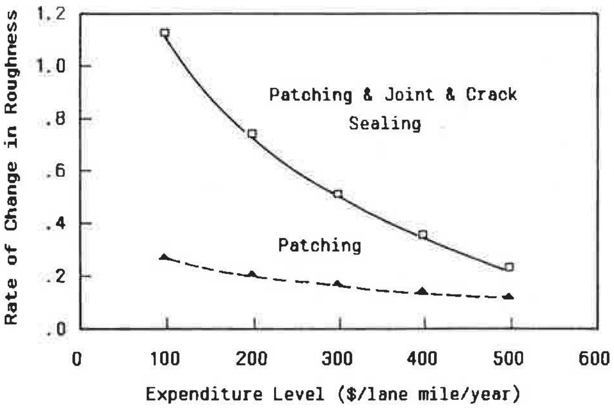

FIGURE 9 Effect of expenditure level of two maintenance policies on OSH flexible pavement roughness.

region. It is clear in these figures that regardless of highway class or pavement type, the effectiveness (slope of the curve) of using patching and sealing is higher than that of patching alone. The results show that adding joint and crack sealing to patching increases the maintenance effectiveness in reducing *RRN*. Hence, joint and crack sealing may have an important role as a preventive maintenance activity in improving pavement performance.

An important application of the results of this analysis is in assessment of the effect of climatic region, routine maintenance expenditure level, and their interaction on pavement performance in terms of surface roughness. The results can be used to help management at the central office monitor the surface condition of the highway network within a subdistrict on a periodic basis. In addition, with knowledge of the surface roughness of pavement sections, the models could be used by maintenance managers to determine the increase in maintenance expenditure level required to achieve a specified level of improvement in overall pavement condition.

Since most of the regression models in this study have low R^2, it is recommended that these models be applied for typical ranges of maintenance expenditure levels. To improve, it is necessary to introduce other factors, such as pavement age and traffic level, as well as to obtain maintenance expenditure data on a wider range. Research is continuing to investigate (1) the effect of pavement age and traffic level on routine maintenance expenditure level and, consequently, on pavement roughness and (2) the effect of routine maintenance expenditure level on pavement service life.

SUMMARY AND CONCLUSIONS

The main objective of this research was to study the effect of routine maintenance expenditure level on pavement roughness. An integrated database for pavement routine maintenance and pavement characteristics for the state highway system in Indiana was developed. Contract section instead of countywide highway section was used as a pavement section unit to develop this database. Results of covariance analysis revealed that the effect of climatic region was significant. Therefore, regression models for the effect of routine maintenance expenditure level on rate of change in pavement roughness were developed, and the climatic region was considered a main factor in these models. The effect of expenditure level was found significant in most of the developed models.

Based on these models, it was concluded that the rate of change in pavement roughness was more in the Northern region, especially at low expenditure levels. Thus, the cost-effectiveness of maintenance activity in the Northern region was higher than that in the Southern region. The results reflect not only the effect of maintenance quality but also the importance of organizing and classifying maintenance records, as noticed in the Northern region. Furthermore, it was found that the effectiveness of patching and sealing was higher than that of patching alone; and this supports the role of sealing as a preventive maintenance activity.

ACKNOWLEDGMENTS

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Analysis of the Effect of Deferring Pavement Maintenance

ESSAM A. SHARAF, MOHAMED Y. SHAHIN, AND KUMARES C. SINHA

This paper presents a methodology for quantifying increased maintenance and rehabilitation (M&R) costs due to delaying M&R action. The methodology used data collected from several U.S. Army installations. These data included (1) pavement performance measured in terms of the Pavement Condition Index (PCI), (2) structural history, and (3) detailed costs. The methodology is based on applying life-cycle cost analysis to determine the Equivalent Uniform Annual Cost (EUAC) for various M&R alternatives. This was repeated at different pavement condition levels. The EUAC analysis for each M&R alternative included pavement surface preparation cost, initial cost of the M&R alternative, and future annual routine maintenance cost. The results of this study showed that considerable savings can be achieved if pavement sections are maintained while they are in good condition and are not allowed to deteriorate into poor condition.

Under budget constraints, highway agencies tend to delay pavement maintenance and rehabilitation (M&R) without analyzing, or sometimes realizing, the effects of such decisions on future M&R cost. The objective of this research was to quantify the effect of delaying pavement M&R based on life-cycle costing (LCC). The major task, then, was to relate LCC to pavement condition to determine the effect on LCC of moving from one condition state to another. Another important first step was to develop pavement performance models for each of the M&R alternatives considered in the analysis.

Pavement condition was expressed in terms of the Pavement Condition Index (PCI) used in the PAVER system developed by the Construction Engineering Research Laboratory (CERL) (*1*). The PCI is an index ranging from 0 to 100; 100 means excellent. The details of PCI development are included elsewhere (*1*). LCC was determined using the Equivalent Uniform Annual Cost (EUAC) procedure for all possible M&R alternatives at each PCI level.

PROCEDURE TO RELATE COST TO CONDITION

This section presents the procedure for relating M&R cost to pavement condition. This procedure was developed on the basis of data collected from five U.S. military installations (Tulsa District, Fort Eustis, Fort Knox, Great Lakes Naval Station, and Sierra Army Facility). Figure 1 is a flowchart of the procedure showing the steps applied for data analysis from each installation. The first step was to modify the database to make it suitable for the purpose of this study. The main sources of data used in the study were the PAVER databases from the five military installations. Several modifications were made, however, to reduce and screen the data for errors. The modified data from all five installations consisted of 2,517 records. Each record included the following main information categories:

1. Section Identification

- military installation code
- section number
- section length and width
- other related items

2. Pavement Rank (Primary, Secondary, or Tertiary); this item also indicated the traffic level.
3. Pavement Structure

- surface type, thickness, and date of construction
- base type, thickness, and date of construction
- other related items

4. Pavement Condition

- inspection date
- amount and severity level of each type of distress and the associated deduct points
- overall Pavement Condition Index (PCI)

The second step was to group different pavement sections into classes on the assumption that sections within each class are similar in structure and traffic use but have different ages. Sections were grouped in twelve classes (four pavement structure types by three pavement ranks). The four pavement structure types were (1) asphalt concrete, (2) surface treatment, (3) thin overlay (less than or equal to 2 inches), and (4) structural overlay (more than 2 inches). The three pavement ranks were primary, secondary, and tertiary. Also, the PCI values were grouped into five ranges: 81–100, 61–80, 41–60, 21–40, and 0–20.

The third step included the determination of maintenance and repair actions used at each installation. In selecting these actions, two items were considered. First, the selected M&R

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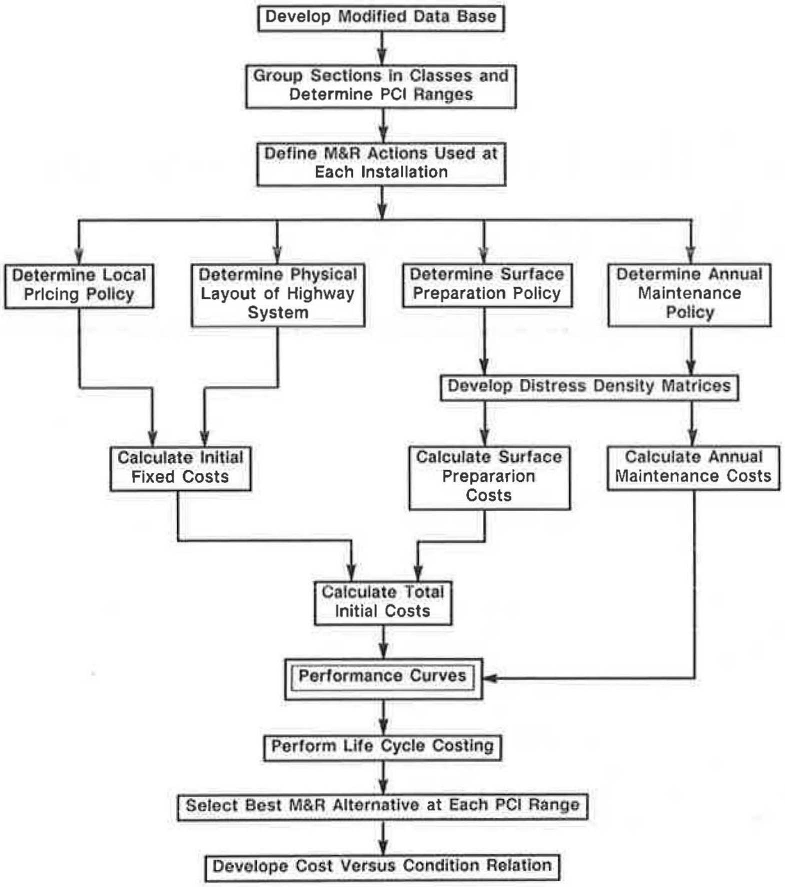

FIGURE 1 **Procedure used to relate M&R costs to condition.**

actions were comparable to those listed in the available database; it would otherwise have been impossible to obtain performance and cost information on any of the activities. Since the research was conducted at the network level, general groups of M&R activities were included rather than specific project level activities. The following M&R actions were found to be common at all installations:

1. Annual maintenance only,
2. Surface treatment,
3. Thin overlay (less than or equal to 2.0 inches),
4. Structural overlay (more than 2.0 inches), and
5. Reconstruction.

Discussion with installation engineers and reviews of past contract documents indicated that each installation's definition and description of various M&R actions were somewhat different. Therefore, it was necessary that unit cost estimates be derived separately from the work items that are commonly included in each M&R alternative at each installation. Table 1 is an example of the work items used to estimate initial cost of the different M&R alternatives at Fort Knox, Kentucky. As the work items for a particular M&R alternative are different at different installations, a weighted average approach was used to estimate unit activity costs by considering the percentage of times a particular work item was included in the data on a number of projects for a particular M&R alternative in an installation. These numbers are shown in parentheses in Table 1.

In the fourth step, intensive meetings with installation engineers took place to identify the following four items:

1. Physical characteristics of the network.
2. Determination of the local pricing patterns. This produced detailed, itemized costs of different M&R alternatives performed by each installation. Most of these costs were obtained from the records of the latest contracts.
3. Determination of the surface preparation policy. This included the identification of actions taken to prepare the pavement surface before applying any M&R activity (e.g., overlay). This was obtained in terms of what is called the surface preparation policy matrix. This matrix includes different combinations of distress types and their severity levels; for each of these combinations, the appropriate surface preparation action and its unit cost are listed. An example of such a matrix is shown in Table 2.
4. Determination of the annual maintenance policy. This included the identification of actions taken as day-to-day maintenance to repair different severity levels of distress types. This information was obtained in the same manner as in the surface preparation matrix. An example of an annual maintenance matrix appears in Table 3. Comparing Tables 2 and 3, it is evident that the actions taken in surface preparation policy were relaxed in the annual maintenance policy. This is

TABLE 1 M&R FIXED INITIAL COST ESTIMATION

		Fort Knox Square Yard Fixed Unit Costs (Frequency)			
Cost Items	$ Per Unit	Surface Treatment	1.5 Inch Overlay	2.0 Inch Overlay	3.0 Inch Recon-struction
Tack Coat	226 TN		0.15 (1.00)*	0.15 (1.00)	
Prime Coat	242 TN				0.36 (1.00)
Aggregate Base	8.5 TN				4.28 (1.00)
Bit. Concrete	31.50 TN		2.55 (1.00)	3.40 (1.00)	5.10 (1.00)
Install/Extend Culverts	32.00 LF		0.10 (0.20)	0.10 (0.20)	0.45 (0.25)
Roadbed Excavation	5.00 CY				1.94 (1.00)
Subbase Material	9.50 CY				2.11 (1.00)
Manhole & Utility Adjustments	150 EA		0.56 (0.90)	0.57 (0.95)	0.80 (1.00)
Cover Aggregate	14.00 TN	0.33 (1.00)			
Bituminous Binder	240 TN	0.58 (1.00)			
Upgrade Railroad Crossing	1025 EA		0.07 (0.60)	0.11 (0.80)	0.28 (0.55)
Pavement Milling	0.90 SY-IN		1.80 (0.08)		
Pavement Stripping & Marking	0.41 LF	0.17 (1.00)	0.17 (1.00)	0.17 (1.00)	0.17 (1.00)
Remove Existing Pavement	0.30 SF				2.70 (1.00)
Remove & Install Drop Inlet	872 EA				0.48 (0.58)
Remove & Replace Curb & Gutter	11.00 LF		2.06 (0.15)	2.26 (0.15)	8.25 (0.07)
Total Square Yard Unit Costs		$1.08	$3.97	$4.82	$18.58

* Numbers in parenthesis are the frequency of the cost item application obtained from previous projects.

natural, because the strict rules that are usually followed to prepare the surface are not necessarily required when it comes to day-to-day maintenance.

The fifth step included the manipulation of the available condition data to develop the distress density matrices. A distress density matrix includes different combinations of distress types and severity levels as its rows, while its columns include the average densities (percentage of section area with the particular severity level of a distress) at different PCI ranges. An example of part of a density matrix is shown in Table 4. A density matrix was developed for each pavement class within each installation.

In the sixth step, the cost models were developed. Simply, in these models, all costs were related to pavement condition (PCI level). That is, different cost items can be calculated, given the PCI level. Two major groups of costs were considered: initial cost and annual maintenance cost. The initial cost was further divided into two parts: fixed and variable. The fixed part is the cost of applying the M&R activity itself. This cost is independent of pavement condition at the time of application and is dependent only on the local pricing pattern (determined earlier). On the other hand, the variable part included the cost of preparing the surface to receive the M&R activity. This part is dependent on pavement condition at the time of activity application. To quantify this part, the distress density matrix provided the average quantity of each combination of distress types—severity levels at each PCI range; the surface preparation matrix provided the appropriate repair action and its corresponding unit cost. Thus the surface preparation cost of a specific pavement class at a specific PCI range at an installation was calculated as follows:

$$C_p = D_{ij} * C_{ij}$$

where

C_p = surface preparation cost of a specific pavement class at a given PCI range;
D_{ij} = average density of the ith distress type with jth severity level (from the appropriate distress density matrix); and
C_{ij} = unit cost of surface preparation required to repair the ith distress type with jth severity level (from the surface preparation policy matrix).

The annual maintenance costs were related to pavement condition levels the same way as in the surface preparation part except that the annual maintenance policy matrix was used instead of the surface preparation policy matrix.

User costs were not included because little information was available identifying the relationship between user costs and PCI level. Also, project results were directed primarily for budget estimates, so only the agency costs were considered.

From the foregoing steps, the fixed and variable parts of the initial cost and the annual maintenance cost can be determined if the PCI level is given. However, PCI change over time is required to be able to apply the life-cycle costing. Life-

TABLE 2 EXAMPLE OF A SURFACE PREPARATION POLICY MATRIX (FORT KNOX ARMY BASE)

Distress Type	Severity Level	Surface Preparation Action	Unit	Unit Cost
Alligator Cracking	H	Deep Patch	SF	2.98
	M	Shallow Patch	SF	1.78
	L	Seal Coat	SF	0.12
Bleeding	H	Seal Coat	SF	0.12
	M	Seal Coat	SF	0.12
Block Cracking	H	Shallow Patch	SF	1.70
	M	Seal Coat	SF	0.12
Bumps/Sags	H	Shallow Patch	SF	1.78
	M	Skin Patch	SF	1.01
Corrugation	H	Shallow Patch	SF	1.78
	M	Skin Patch	SF	1.01
Depressions	H	Shallow Patch	SF	1.78
	M	Skin Patch	SF	1.01
Edge Cracking	H	Deep Patch	LF	4.47
	M	Shallow Patch	LF	2.23
Lane/Shoulder Dropoff	H	Grade and Add Gravel	LF	0.38
	M	Grade and Add Gravel	LF	0.28
Long./Trans. Cracking	H	Crack Seal	LF	1.42
	M	Crack Seal	LF	1.01
	L	Crack Seal	LF	0.31
Patching and Utility Cuts	H	Replace Patch	SF	2.98
	M	Crack Seal	SF	1.68
Potholes	H	Deep Patch	Each	9.36
	M	Deep Patch	Each	2.32
	L	Shallow Patch	Each	1.39
Rutting	H	Deep Patch	SF	2.98
	M	Shallow Patch	SF	1.78
	L	Skin Patch	SF	1.01
Shoving	H	Shallow Patch	SF	1.78
	M	Shallow Patch	SF	1.78
Slippage Cracks	H	Shallow Patch	SF	1.78
	M	Shallow Patch	SF	1.78
Swell	H	Shallow Patch	SF	1.78
	M	Shallow Patch	SF	1.78
Weathering and Ravelling	H	Seal Coat	SF	0.12
	M	Seal Coat	SF	0.12
	L	Seal Coat	SF	0.12

TABLE 3 EXAMPLE OF AN ANNUAL MAINTENANCE POLICY MATRIX (FORT KNOX ARMY BASE)

Distress Type	Severity Level	Surface Preparation Action	Unit	Unit Cost
Alligator Cracking	H	Deep Patch	SF	2.98
	M	Skin Patch	SF	1.01
	L	No Action		
Bleeding	H	No Action		
	M	No Action		
Block Cracking	H	Shallow Patch	SF	1.70
	M	No Action		
Bumps/Sags	H	Shallow Patch	SF	1.78
	M	No Action		
Corrugation	H	Shallow Patch	SF	1.78
	M	No Action		
Depressions	H	Shallow Patch	SF	1.78
	M	No Action		
Edge Cracking	H	Deep Patch	LF	4.47
	M	No Action		
Lane/Shoulder Dropoff	H	Grade and Add Gravel	LF	0.38
	M	No Action		
Long./Trans. Cracking	H	Crack Seal	LF	1.42
	M	Crack Seal	LF	1.01
	L	No Action		
Patching and Utility Cuts	H	Replace Patch	SF	2.98
	M	Crack Seal	SF	1.68
Potholes	H	Deep Patch	Each	9.36
	M	Deep Patch	Each	2.32
	L	No Action		
Rutting	H	Skin Patch	SF	1.01
	M	No Action		
	L	No Action		
Shoving	H	Skin Patch	SF	1.01
	M	No Action		
Slippage Cracks	H	Skin Patch	SF	1.01
	M	No Action		
Swell	H	Skin Patch	SF	1.01
	M	No Action		
Weathering and Ravelling	H	No Action		
	M	No Action		
	L	No Action		

cycle costing requires the determination of pavement service life and rate of performance deterioration. Therefore, a substantial effort was made in the development of PCI versus age relationship for each pavement class. The expected life of an M&R alternative is often based on engineering judgment and experience, with consideration given to local materials, environmental factors, and traffic levels. This procedure usually leads to wide variation, however, in the estimated service life. In addition, because performance is so dependent on local materials and environmental factors, it would be difficult to relate service life for pavements from different locations. For this research project, it was decided to use the available database to develop aggregated estimates of pavement performance.

To model pavement performance, both the graphics capabilities of the microcomputer database manager KMAN (*2*) and the statistical procedures of the SPSS package (*3*) were used to test a large number of models. The best model, selected for this study, was in the following form:

$$C = 100 - bx^m$$

where

C = pavement condition expressed in terms of PCI,
b = slope coefficient,
x = pavement age (months), and
m = a parameter, the value of which controls the degree of curvature of the performance curve.

TABLE 4 EXAMPLE OF A DISTRESS DENSITY MATRIX (FOR ALL OBSERVATIONS USED IN THE STUDY)

Distress Type	Severity	Density (%) by PCI Range				
		81–100	61–80	41–60	21–40	0–20
Alligator Cracks	L	0.32	1.15	5.54	11.36	9.46
	M	0.13	0.20	1.80	10.24	14.09
	H	0.03	0.04	0.39	1.05	14.02
Bleeding	L	0.30	0.89	1.04	1.02	1.25
	M	0.02	0.17	0.37	1.08	0.56
	H	0.00	0.00	0.00	0.01	0.01
Block Cracks	L	0.57	11.45	6.90	5.46	3.23
	M	0.06	0.93	5.80	8.01	7.42
	H	0.00	0.01	0.13	0.59	2.58
Bumps/Sags	L	0.01	0.01	0.03	0.02	0.01
	M	0.00	0.00	0.00	0.01	0.05
	H	0.00	0.00	0.00	0.00	0.02
Corrugation	L	0.01	0.17	0.15	0.03	0.07
	M	0.00	0.00	0.01	0.00	0.19
	H	0.00	0.00	0.00	0.00	0.00
Depressions	L	0.05	0.11	0.25	0.26	0.28
	M	0.01	0.03	0.15	0.17	0.47
	H	0.00	0.00	0.03	0.05	0.16
Edge Cracks	L	0.53	0.66	0.72	0.70	0.48
	M	0.22	0.88	1.51	1.26	1.10
	H	0.04	0.20	0.50	0.81	2.25
.....	.	....	....	....	....	....
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Weathering and Ravelling	L	4.49	12.44	17.15	19.57	11.25
	M	0.56	1.18	6.60	10.84	17.31
	H	0.06	0.08	0.42	6.04	23.74

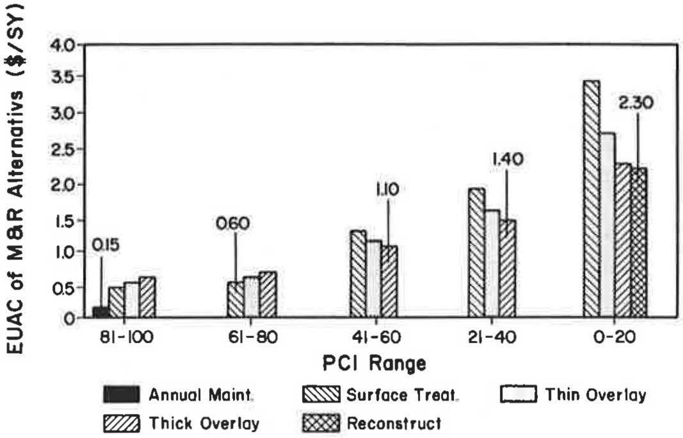

FIGURE 2 Example EUAC of different M&R alternatives for one pavement class by PCI range (Fort Eustis); SY = yd^3.

The best fit was determined by the highest R^2 value (coefficient of determination) using the least squares method. For all pavement classes at all installations, an exponent (m) of 1.5 resulted in the highest R^2 values. In this study, pavements were considered to have reached the end of their service life at a PCI level of 70. This value was chosen since the existing database indicated that most installations were performing some form of repair activity on a pavement once it dropped below that level.

Finally, a life-cycle costing was performed considering initial cost as well as annual maintenance costs throughout the expected service life of each pavement class. At each PCI level, all possible alternatives were considered, and the Equivalent Uniform Annual Cost (EUAC) of each was determined. The best alternative at a particular PCI level was considered to be the one with minimum EUAC value. Using this procedure, the cost (minimum EUAC) at each PCI level was determined for each pavement class at different installations.

TABLE 5 SUMMARY OF EUAC VALUES VERSUS PCI RANGES

Base Number	Pavement Class		EUAC ($/SY) by PCI Range				
	Pavement Type	Pavement Rank	81-100	61-80	41-60	21-40	0-20
1	Asphalt	Primary	0.10	0.55	0.60	0.95	1.75
1	Asphalt	Secondary	0.10	0.50	0.55	0.80	1.40
1	Asphalt	Tertiary	0.10	0.50	0.55	0.80	1.40
1	Surf. Tr.	Primary	0.20	0.60	0.90	1.60	3.00
1	Surf. Tr.	Secondary	0.22	0.55	0.80	1.35	2.10
1	Surf. Tr.	Tertiary	0.22	0.55	0.80	1.35	2.00
1	Thin Ovl.	Primary	0.10	0.55	0.85	1.50	2.45
1	Thin Ovl.	Secondary	0.10	0.50	0.70	1.25	2.15
1	Thin Ovl.	Tertiary	0.10	0.50	0.70	1.25	2.00
1	Thick Ovl.	Primary	0.10	0.55	0.75	1.30	2.30
1	Thick Ovl.	Secondary	0.10	0.50	0.65	1.05	1.85
1	Thick Ovl.	Tertiary	0.08	0.50	0.65	1.05	1.85
2	Asphalt	All	0.10	0.55	0.70	1.10	1.60
2	Thin Ovl.	All	0.20	0.50	0.65	1.75	1.95
2	Thick Ovl.	All	0.15	0.60	0.75	1.10	1.70
3	Asphalt	All	0.15	0.60	0.80	1.15	1.60
3	Thin Ovl.	All	0.15	0.60	1.10	1.40	2.30
3	Thick Ovl.	All	0.15	0.55	0.65	1.05	1.50
4	Asphalt	Primary	0.20	1.30	1.40	1.80	3.50
4	Asphalt	Secondary	0.20	1.15	1.25	1.65	2.95
4	Asphalt	Tertiary	0.20	1.10	1.20	1.60	2.80
4	Thin Ovl.	Primary	0.60	1.35	1.50	1.90	3.55
4	Thin Ovl.	Secondary	0.55	1.20	1.35	1.60	3.00
4	Thin Ovl.	Tertiary	0.55	1.15	1.30	1.58	2.90
4	Thick Ovl.	Primary	0.45	1.35	1.50	1.80	3.50
4	Thick Ovl.	Secondary	0.45	1.15	1.30	1.60	2.80
4	Thick Ovl.	Tertiary	0.45	1.10	1.20	1.50	2.70
5	Asphalt	Primary	NA	0.35	0.38	0.57	0.70
5	Asphalt	Secondary	NA	0.31	0.34	0.52	0.61
5	Asphalt	Tertiary	NA	0.27	0.30	0.45	0.53
5	Surf. Tr.	Primary	NA	0.40	0.55	0.85	1.60
5	Surf. Tr.	Secondary	NA	0.35	0.47	0.75	1.50
5	Surf. Tr.	Tertiary	NA	0.33	0.40	0.65	1.10
5	Thin Ovl.	Primary	NA	0.35	0.50	0.90	1.35
5	Thin Ovl.	Secondary	NA	0.30	0.43	0.78	1.15
5	Thin Ovl.	Tertiary	NA	0.26	0.39	0.70	1.00
5	Thick Ovl.	Primary	NA	0.40	0.45	0.75	1.10
5	Thick Ovl.	Secondary	NA	0.35	0.38	0.65	0.98
5	Thick Ovl.	Tertiary	NA	0.32	0.34	0.60	0.90

Figure 2 is an example of the calculated EUAC for one pavement class at different PCI levels. According to the figure, the minimum EUAC values at PCI levels of 81–100, 61–80, 41–60, 21–40, and 0–20 are 0.15, 0.60, 1.10, 1.40, and 2.30 \$/yd^3, respectively. The foregoing procedure was repeated for each pavement class at each installation. The resulting cost versus condition for all five bases is presented in Table 5.

ANALYSIS OF RESULTS

In Table 5, the minimum EUAC (\$/yd^3) values at each PCI range for different pavement classes within each base are shown. For example, at base number 3 (Fort Eustis) and thin overlay pavement (all ranks), the minimum EUAC at a PCI range of 81–100 is 0.15 \$/yd^3 and at ranges 61–80, 41–60, 21–40, 0–20 are 0.60, 1.10, 1.40, and 2.30 \$/yd^3, respectively. These values are the minimums of EUAC values of different M&R alternatives at each PCI range (see Figure 2). Similarly, the results are shown for all other pavement classes of other bases. It is clear that there are significant differences in 100; minimum EUAC of thin overlay pavements is 0.20 \$/yd^3 at base number 2, while this value ranges from 0.55 to 0.60 \$/yd^3 at base 4. This may be explained by the differences in unit costs, as well as in M&R policies. The results strongly indicate, however, a clear trend toward higher EUAC as the PCI range decreases. This trend emphasizes the fact that delaying pavement repair to a lower pavement condition results in higher costs in the long term (EUAC). Consider the example shown in Figure 2. If this pavement is left to reach a PCI level of 0–20, then it would cost about four times more to repair it than if it were repaired at a PCI level of 61–80.

To normalize the effect of the differences in unit costs and in M&R policies between bases, Table 6 was constructed. In Table 6, the EUAC values of Table 5 were converted to the ratios between the EUAC at any PCI range and those at a PCI range of 61–80. The 61–80 level was chosen because it was observed from both the collected data and from the interviews with base engineers that the PCI values of 65–75 usually mean that the section should be flagged as a candidate for M&R. Table 6 clearly shows the consequence of excluding a section with PCI values of 61–80 from the M&R list for any reason and letting it fall to a lower condition level. This effect is shown in terms of how many times higher the cost at the lower PCI level will be compared with that at the PCI range of 61–80. To illustrate, consider the case of base 3, thin overlay and all ranks (see Figure 2 and Table 6). The consequences of letting a section deteriorate without repair from a PCI level of 61–80 to levels 41–60, 21–40, or 0–20 will be additional M&R costs that equal 1.83, 2.33, or 3.83 times the M&R cost at the 61–80 level, respectively.

Figure 3 shows the overall average, minimum, and maximum values of these consequences (for all cases included in the study). For example, the consequence of delaying the repair of a pavement section from PCI level 61–80 to the 0–20 level will be, on average, \$3.20 for each \$1.00 required at the 61–80 level. The value 3.2, however, is the average value.

TABLE 6 SUMMARY OF EUAC RATIOS WITH RESPECT TO EUAC VALUE AT PCI RANGE 61–80

Base Number	Pavement Type	Pavement Rank	EUAC at PCI Range/EUAC at PCI at 61–80 Range				
			81–100	61–80	41–60	21–40	0–20
1	Asphalt	Primary	0.19	1.00	1.10	1.73	3.18
1	Asphalt	Secondary	0.20	1.00	1.10	1.60	2.80
1	Asphalt	Tertiary	0.20	1.00	1.10	1.60	2.80
1	Surf. Tr.	Primary	0.34	1.00	1.50	2.67	5.00
1	Surf. Tr.	Secondary	0.40	1.00	1.45	2.45	3.82
1	Surf. Tr.	Tertiary	0.40	1.00	1.45	2.45	3.64
1	Thin Ovl.	Primary	0.18	1.00	1.54	2.73	4.45
1	Thin Ovl.	Secondary	0.20	1.00	1.40	2.50	4.30
1	Thin Ovl.	Tertiary	0.20	1.00	1.40	2.50	4.00
1	Thick Ovl.	Primary	0.18	1.00	1.36	2.36	4.18
1	Thick Ovl.	Secondary	0.20	1.00	1.30	2.10	3.70
1	Thick Ovl.	Tertiary	0.16	1.00	1.30	2.10	3.70
2	Asphalt	All	0.18	1.00	1.27	2.00	2.91
2	Thin Ovl.	All	0.40	1.00	1.30	3.50	3.90
2	Thick Ovl.	All	0.25	1.00	1.25	1.83	2.83
3	Asphalt	All	0.25	1.00	1.33	1.92	2.67
3	Thin Ovl.	All	0.25	1.00	1.83	2.33	3.83
3	Thick Ovl.	All	0.27	1.00	1.18	1.91	2.73
4	Asphalt	Primary	0.15	1.00	1.08	1.38	2.69
4	Asphalt	Secondary	0.17	1.00	1.09	1.43	2.57
4	Asphalt	Tertiary	0.18	1.00	1.09	1.45	2.55
4	Thin Ovl.	Primary	0.44	1.00	1.11	1.41	2.63
4	Thin Ovl.	Secondary	0.46	1.00	1.13	1.33	2.50
4	Thin Ovl.	Tertiary	0.48	1.00	1.13	1.37	2.52
4	Thick Ovl.	Primary	0.34	1.00	1.11	1.33	2.59
4	Thick Ovl.	Secondary	0.39	1.00	1.13	1.39	2.43
4	Thick Ovl.	Tertiary	0.41	1.00	1.09	1.36	2.45
5	Asphalt	Primary	NA	1.00	1.09	1.63	2.00
5	Asphalt	Secondary	NA	1.00	1.10	1.68	1.97
5	Asphalt	Tertiary	NA	1.00	1.11	1.67	1.96
5	Surf. Tr.	Primary	NA	1.00	1.38	2.13	4.00
5	Surf. Tr.	Secondary	NA	1.00	1.34	2.14	4.29
5	Surf. Tr.	Tertiary	NA	1.00	1.21	1.97	3.34
5	Thin Ovl.	Primary	NA	1.00	1.43	2.57	3.86
5	Thin Ovl.	Secondary	NA	1.00	1.43	2.60	3.83
5	Thin Ovl.	Tertiary	NA	1.00	1.50	2.69	3.85
5	Thick Ovl.	Primary	NA	1.00	1.13	1.88	2.75
5	Thick Ovl.	Secondary	NA	1.00	1.09	1.86	2.80
5	Thick Ovl.	Tertiary	NA	1.00	1.06	1.88	2.81

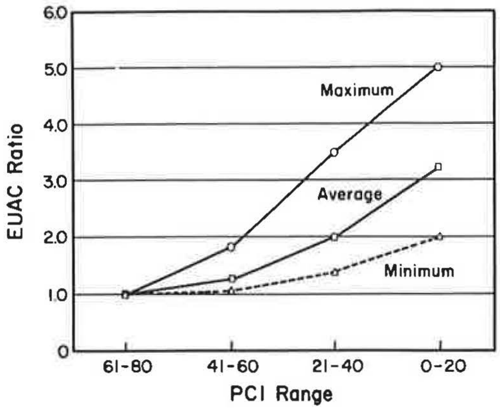

FIGURE 3 EUAC ratios for different PCI ranges.

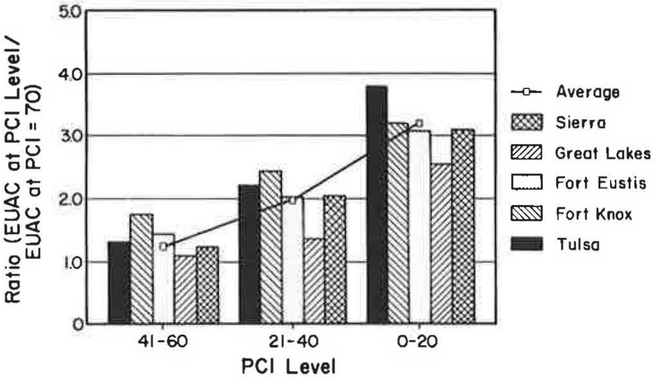

FIGURE 6 Effect of change in PCI level on EUAC for different installations.

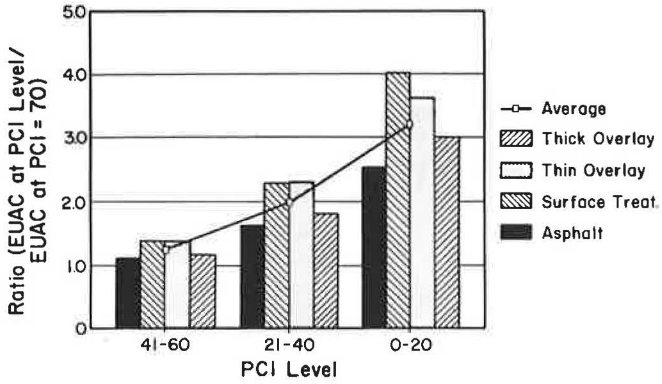

FIGURE 5 Effect of change in PCI level on EUAC for different pavement ranks.

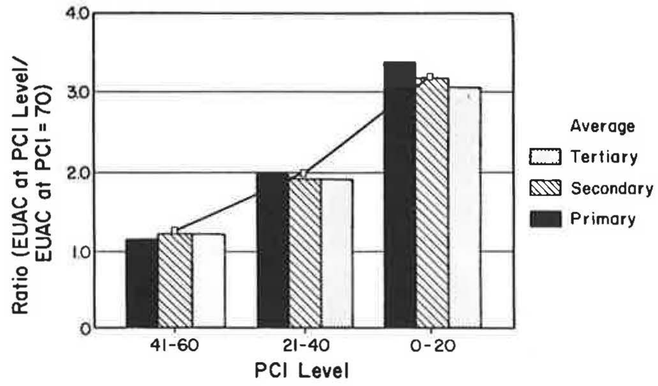

FIGURE 4 Effect of change in PCI level on EUAC for different pavement types.

The actual value may take any number from 1.99 to 5.0, as shown in Figure 3.

Figures 4, 5, and 6 summarize the results shown in Table 6 while considering the factors of surface type, pavement rank, and installation, respectively. These figures indicate that the factor with the most effect on the variation of the EUAC values is the surface type (Figure 4), followed by location (Figure 6); pavement rank (Figure 5) has the least effect.

Figure 4 indicates that the surface treatment pavements are the most sensitive to delaying M&R actions, followed by thin overlay, thick overlay, and then asphalt concrete. For example, if a surface-treated pavement were left to deteriorate without repair to a PCI level of 0–20, then the M&R cost would be about four times that of a 61–80 PCI level. The corresponding values for thin overlay, thick overlay, and asphalt concrete are 3.61, 3.00, and 2.55, respectively.

An important observation indicated by the results is that preventive maintenance can play a very important role in reducing the overall M&R cost by keeping pavement condition at or above the "good" level for a longer time.

SUMMARY AND CONCLUSIONS

This paper presented an effort to quantify the effect of delaying M&R actions on the life-cycle cost (LCC) of maintenance alternatives. The study was based on the development of a relationship between pavement condition level (represented by the Pavement Condition Index, PCI) and the corresponding M&R cost (represented by minimum EUAC of the M&R alternatives at each PCI level). The increases in EUAC values at lower pavement condition levels were considered the consequences of delaying M&R action.

The results showed that undertaking M&R actions on pavement in "good" condition may cost only $1.00 for every $4.00 that would be necessary for appropriate M&R if the pavements were left to deteriorate into "poor" condition.

The results also indicated that the pavement type most sensitive to delaying M&R actions is surface treatment, followed by thin overlay, thick overlay, and then asphalt concrete. Finally, the results of this study strongly emphasize the role of preventive maintenance in M&R cost savings through a reduction of the rate of deterioration of pavement structures.

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