REPAIR OF JOINT RELATED DISTRESS IN PCC PAVEMENTS

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A comprehensive study on the repair of joint and crack related distress in Portland cement concrete (PCC) pavements is presented. Procedures for project evaluation and selection of cost-effective repair and preventative techniques were developed. Detailed "Design And Construction Guidelines" and "Guide Specifications" were developed and field tested for seven different techniques for repairing and preventing the deterioration of joints and cracks including void detection.

Introduction

The primary objective of NCHRP Project 1-21 was to develop effective guidelines and criteria for repairing and preventing deterioration of joints and cracks in Portland cement concrete (PCC) pavements. This study was limited to the repair and prevention of deterioration of joints and cracks in both jointed plain concrete pavements and jointed reinforced concrete pavements.

This objective was accomplished by first identifying the most promising techniques that are needed to both repair and prevent the deterioration of joints and cracks. Only the top seven of these were chosen for consideration in this project due to funding limitations (2):

1. Full-depth repair of joints, cracks and shattered slabs,
2. Partial-depth repair of spalls,
3. Subsealing of voids (or slab stabilization),
4. Restoration of load transfer of joints and cracks,
5. Diamond grinding of faults at joints and cracks,
6. Resealing of joints and cracks, and
7. Slab edge support improvement.

Development Of Repair/Preventative Procedures

Design and construction guidelines were developed using the state-of-the-art experience of numerous engineers from Federal and State government and also from industry (contractors and materials suppliers), laboratory testing, analytical analyses and subsequent field testing of the techniques.

Each of these seven rehabilitation techniques is described by two separate documents (see Ref. 1):

Part 1 -- Design and Construction Guidelines Provides detailed guidelines for each technique on the type of distress to be repaired or prevented, when to apply, limitations, effectiveness, other rehabilitation work that should be performed concurrently, design concepts, construction guidelines (materials, equipment, procedures) and preparation of plans and specifications.

Part 2 -- Guide Specifications Provides recommended guide specifications that may be adopted in part or total, or utilized by an agency to update their current specifications.

Each of the documents for the seven restoration techniques has gone through several major reviews by numerous experienced Federal, state and industry engineers and has been modified from the results of several field demonstration projects.

Evaluation Of The Pavement

An adequate pavement evaluation is absolutely essential to the ultimate selection of cost-effective and reliable rehabilitation techniques. Pavement evaluation essentially involves a "definition of the problem" to determine the cause and extent of the existing deterioration.

The following data is considered necessary for an adequate pavement evaluation (See Ref. 1):

- distress types, severities and amounts
- design, materials, and soils properties
- past and future traffic loadings
- climatic information

- deflection testing at mid-slab and joint/crack corners
- cores taken from selected joints and cracks
- surface profile measurements (for grinding)

A summary of the data which may be required for each rehabilitation technique is given in Figure 1. The amount of information required will vary depending upon the type of repair work being contemplated, the size of the project under consideration, and the truck traffic level.

The above data is then analyzed to determine the causes and extent of the deterioration in the pavement. Each component of the pavement must be evaluated: transverse joints, longitudinal joints, the concrete slab, base/subbase, subgrade, and shoulders. A detailed list of questions that should be answered is provided in Ref. 1 for each pavement component. It is important to determine the extent of load associated damage as opposed to climatic or materials associated damage.

Selection Of Repair/Preventative Techniques

Once the causes and extent of the deterioration are determined, the design engineer can select one or more repair/preventative techniques that (in combination) both repair existing deterioration and prevent or minimize future similar deterioration. Normally, two or more techniques must be selected to both repair existing deterioration and prevent its reoccurrence. Figure 2 presents a summary of the major types of jointed concrete pavement deterioration along with the capabilities of each of the rehabilitation techniques to repair and prevent future deterioration. For example, faulting can be repaired or removed by:

- o diamond grinding, or
- o placement of a structural overlay.

Note: If voids exist at the faulted joints, then the voids must be "repaired" by subsealing.

Faulting of transverse joints can be prevented or retarded by:

- subsealing to restore support,
- reestablishing load transfer across the joint with mechanical devices,
- resealing the transverse and longitudinal joints and cracks, and
- ensure adequate subdrainage.

Each of the two repair methods (grinding and overlay) and each of the four preventative methods (see above) generally meet the pavements needs and could be selected as feasible alternatives. One of the repair methods must be selected along with one or more of the preventative methods to provide a complete rehabilitation alternative.

It is emphasized that nearly always a combination of different repair and preventative maintenance methods will be required to return a deteriorated pavement to serviceable condition and maintain it in that condition for a substantial period of time.

After two or more feasible rehabilitation alternatives have been identified, the final selection is based upon a life-cycle cost analysis to see which alternative is the most cost-effective. Practical procedures for doing this are described.

Design And Construction Guidelines

Detailed design and construction guidelines as well as guide specifications were developed. These procedures were initially based on the best state-of-the-art methods in 1980 at the initiation of this project. They were then tested through field trials and demonstrations and improved over a four year period. Many improvements were also suggested by the Industry/Agency panel and by the NCHRP Project 1-21 panel.

The following represents the major findings related to each of the seven repair and preventative techniques included in this project.

Full-Depth Repair

(1) Full-depth repairs must be customed designed to meet the project conditions. The pavement design, desired life extension, and traffic loadings will dictate the structural design of the repair. The lane closure time will impact on the design, particularly the mixture design and curing considerations.

(2) Field layout is critical and the field engineer must have training in this aspect. All of the surficial and underlying deterioration must be included within the repair boundaries. Particularly, the extent of loss-of-support beneath the existing slab must be investigated as described in "Subsealing" to determine if subsealing should be performed at joints/cracks that were full-depth repaired.

Many times, inadequate funds have been allocated to repair the existing pavement. This results in many areas needing repair being neglected. These areas then become the first failures in the rehabilitated pavement. Example layouts of full-depth repairs are given in Ref. 1.

(3) Adequate load transfer at the transverse joints is the most critical aspect of the design of the full-depth repair. This can best be achieved using dowels having sufficient diameter and numbers placed in the wheel paths to prevent faulting and spalling. The recommended design is given in Figure 3 for heavily trafficked pavements.

Mechanical load transfer must be used in most full-depth repairs placed on heavily trafficked routes to prevent faulting and spalling of the repair. The only situation where dowels may not be needed is for jointed plain non-doweled concrete pavements (short joint spacing) with stabilized bases in dry climates.

There are still questions as to the most efficient design of the load transfer devices:

- Many installations of dowels and rebars have been inadequate. For example, epoxy has not set up properly and both epoxy and grout have not been inserted adequately to completely cover the bar. Research is needed to develop reliable cost-effective means for providing load transfer.
- Slightly over drilling the diameter of the holes (1/16 in.) and inserting the bars without any bonding material is working in one state and should be investigated further.
- The number of dowels, their diameter and spacing is not fully resolved at this point. The recommendation for heavy traffic and soft subgrades is to place 5 dowels of 1.50 inches diameter in each wheel path as shown in Figure 3.

(4) A minimum size of patch of six feet long and 12 feet wide is recommended for heavy traffic to avoid rocking and pumping of the repair. The joint deflection of a 4 ft. long full-depth repair is significantly greater than a 6 ft. long repair. General experience indicates that 6 ft. is a minimum when load transfer is provided and heavy

traffic exists. It must be noted that 4 ft. length repairs have worked satisfactorily in some states, but there have also been significant problems in other states under heavy traffic and wet climates.

(5) Equipment exists to cut and lift out pieces of the deteriorated concrete slab. The lift-out method is highly recommended over the breakup-and-clean-out method whenever possible. The lift-out method avoids disturbing the base/subgrade material which is a common problem with the break-up and clean-out method of slab removal. This is believed to be a very important factor in subsequent performance of the repair to reduce deflections. The cost of either method appears to be approximately the same.

(6) Mixture designs including high cement factors, low water cement ratios, high early strength cement (Type III), and the use of insulation blankets over the repair can provide a repaired slab that can be opened rapidly to traffic with acceptable fatigue damage. Figure 4 presents recommended opening times for different mixtures, slab thickness and curing conditions to minimize cracking of the repair. The use of insulation blankets has a dramatic effect on opening times, particularly at cooler temperatures.

(7) The so-called inverted "T" repairs caused differential frost heave in deep frost areas. Measured load transfer was also poor due to underconsolidation of the concrete in the undercut areas. The inverted "T" type of repair is not recommended, except perhaps when coupled with dowels. It should definately not be used in deep frost areas due to differential frost heave.

(8) The sawing/forming of a transverse joint sealant reservoir at the repair boundaries is highly recommended. A high quality sealant should be used. The sealed transverse joint at the repair boundaries reduces spalling and water infiltration into the pavement.

Partial Depth Patching

(1) Partial depth patching is used to repair spalls and other partial depth distress. It is essential that the patch be isolated from the adjacent slab by some type of fiberous material to prevent compression or shear failures as illustrated in Figure 5. Compression failure is one of the most common causes of partial depth patch failures. Sawing the joint to the anticipated depth of the spall will facilitate the use of these inserts.

(2) The repair area must be properly prepared to develop good bond between the patch and the base concrete. Proper bonding of patches is essential for good performance. The use of proper size removal equipment (15 lb. maximum chipping air hammers) to prevent damage to the slab is essential. After removal, the patch area should be sandblasted to remove any loose material caused by removal operations. Bonding agents used in patching have been cement grouts, epoxies and other proprietory materials. Where patches are protected from traffic for 24 to 72 hours, Portland cement grout mixtures have provided adequate bonding when used with Type III Portland cement mixtures. Epoxy bonding agents are generally used when patches are opened to traffic within 4 to 6 hours.

(3) When using a proprietary patching material it is essental that the handling, mixing, placement and consolidation, finishing, and curing of the patch material be in accordance with the manufactuers written instructions. The working tolerances of some of the proprietary patch materials are too tight for most repair projects.

(4) Type III Portland cement concrete, with and without admixtures, has been used for patch mixtures longer and more extensively than other patch materials. It is low cost, readily available and simple to use.

A high percentage of repair projects require patches to be opened to traffic within 4 to 6 hours. Under hot weather conditions, a patch mixture using Type III cement with 2% $CaCl_2$ by weight of cement has been used successfully when an epoxy bonding agent is used.

(5) When spalls extend deeper than one-half the slab thickness, full depth repairs should be utilized. Partial depth patches that extend below mid depth of the pavement have exhibited variable performance, particularly with doweled pavements.

Subsealing

(1) Pavement subsealing is used to restore support by filling small voids (e.g., 0.010-0.250 ins. thick) beneath the slab and/or stabilized base that have been cuased by pumping action. Subsealing could also be called slab stabilization. The loss of support results in a large increase of deflections and stresses that cause pumping, spalling, faulting and slab breakup. Figure 6 shows a profile of corner deflections on a pavement with serious pumping and loss of support/void development under the leave corner. When grout has sufficiently filled the voids, the corner deflection will be reduced to full support conditions as illustrated in Figure 7 for the leave corner. The approach corner did not have any loss of support. The failure to restore support to a slab, whether or not an overlay is placed, will result in rapid deterioration of a pavement under heavy traffic.

(2) The determination of joints/cracks that need subsealing has been a controversial question. The findings of this study conclusively show that only those joints/cracks that exhibit loss of support (voids) should be subsealed. It is a waste of effort and can even be detrimental to subseal joints/cracks with existing full support. The joints/cracks with loss of support can be identified using deflection testing procedures described in Refs. 1 and 12. The common practice of "blanket" subsealing (every joint and crack) may result in damaging slabs that already have full support by lifting them unevenly.

(3) The estimation of grout quantities is extremely difficult, but can be accomplished using deflection testing. A procedure was developed which provides estimates of the horizontal size of voids at a given joint (detailed method) or an indication of the existence of a void (rapid method). Deflection testing should also be used (perhaps most importantly) to evaluate the effectiveness of the subsealing by retesting after subsealing (see Figure 7 for a joint that was properly subsealed).

(4) The grout used in subsealing can have a significant influence on its effectiveness in stabilizing the slab. The use of pozzolanic (fly-ash) cement grouts are recommended due to their ability to flow into voids and also their measured strength. The water content of the grout must be controlled through the flow cone test. When fly-ash grouts are used, a colloidal mixer must be used to achieve adequate mixing.

(5) The subsealing procedures must be carefully controlled in the field. Slab lift must be closely controlled to avoid overgrouting, which may result in premature slab breakup. The down force exerted during the drilling of grout injection holes must be controlled so as to not cause deterioration or spalling at the bottom of the slab near the hole. Pumping pressures must be limited to avoid damage to the pavement from excessive slab lift. Consideration should be given by agencies to pay for subsealing by the square yard instead of by the cubic foot of dry grout to avoid the tendency for over grouting.

(6) The long-term effectiveness of subsealing depends on preventing free moisture from accumulating in the pavement structure. All joints and cracks should be sealed and/or subdrains should be placed to remove the moisture rapidly.

(7) Pavements should be continually monitored by deflection to determine if loss of support is reoccurring so that appropriate action can be taken.

Restoration of Load Transfer

(1) The ability of a joint or crack to transfer load (shear) from the loaded side to the unloaded side is very important to the pavements performance. Poor load transfer results in the following:

- High deflections causing increased pumping and subsequently faulting, and
- loss of support beneath the slab and/or base that results in slab breakup.

The load transfer of a joint or crack cannot be visually "observed", it must be measured with special NDT equipment. The measurement of load transfer should be a standard procedure for any PCC pavement evaluation. Load transfer is defined as the deflection of the unloaded side divided by the deflection of the loaded side times 100. Thus, 100 percent represents perfect load transfer while 0 represents a free edge.

(2) Load transfer restoration should be considered whenever it is less than 50% during a cool temperature period. Load transfer can be measured using deflection equipment with at least two sensors, one placed on each side of the joint. This must be performed during cool weather. There is excellent equipment available for measuring the deflection load transfer of a joint or crack. Two commercially available devices that can apply reasonably heavy loads include the Road Rater and the Falling Weight Deflectometer. Both of these devices can rapidly measure deflection load transfer across joints/cracks.

(3) Plain jointed PCC pavements without mechanical load tranfer invaribly have low load transfer during all but hot weather periods. These pavements tend to develop slab cracking near the joints much more readily than those pavements with dowels. Pavements with dowels or other mechanical load transfer devices can also loose good load transfer as a result of high bearing stresses wearing away the hole around the dowel. The specific load transfer conditions at the time of rehabilitation must be measured.

(4) Two types of retro-fit mechanical load tranfer devices are available:

- Dowel Bars
- Shear Devices

Short term experience with load transfer restoration of a joint/crack indicates that both techniques can be used successfully. There have been several failures of the shear type of device on several projects due to lack of bonding between the patch material and the PCC slab. Research is continuing and improvements have been made for this design.

Dowel bars installed and grouted into slots cut into the surface of the pavement have performed well in the few projects where they have been installed (8). This is a new rehabilitation technique that has not yet been fully developed. Improvements in the design and construction of shear devices and dowel installation are made on every project where they are used. The devices should be placed on an experimental basis before being incorporated into a major project so that successfull procedures can be determined. The best recommendations availabe to date are given in Ref. 1.

(5) Recommendations for the layout of the dowels and shear devices have been developed. The placement of two shear devices and three to five dowels in the wheel paths has worked satisfactory. Structural analysis shows this to be adequate for a minimum dowel diameter of 1.50 ins.

(6) The slab must be subsealed prior to the placement of any load tranfer device if loss of support exists. The occurrence of voids beneath the slab near the joint could result in very high shear stresses on the devices causing them to debond with the PCC slab. The dowels may result in very high bearing stresses and spall out the patch material used to fill their slots.

(7) Placement recommendations for the load transfer devices are given in Ref. 1. These designs will ensure adequate load transfer across the joint as long as the devices remain in place. The decrease in deflection and stress in the slab as a result of load transfer restoration will contribute to a substantial increase in the life of the joint/crack due to reduced pumping, faulting, spalling and cracking.

Diamond Grinding

(1) Continuous diamond grinding over the entire project length is often required to restore a suitable ride to a pavement, particularly to remove faulting at joints and cracks. Intermittent grinding of faulted joints and cracks has been specified on a few projects and the resulting ride is usually not that much improved.

(2) The smoothness of a diamond ground pavement should be equal to or better than a newly constructed surface. The grinding equipment available today is designed to act as a long wheel base plane. Faulted joints and other roughness are eliminated by diamond grinding without damage to joints. The smoothness specified is usually that for new pavement construction and in some cases a higher tolerance is specified.

(3) Acceptance testing for smoothness is accomplished by repeatable measuring devices (e.g., profilographs, profilometers). The use of a profilograph has proved satisfactory for acceptance testing. Response type devices such as the Mays Ride Meter must be carefully calibrated against a known standard frequently to assure that proper readings are being taken.

(4) Skid resistance of diamond ground pavements is substantially improved over the existing worn surface. The skid resistance of a diamond ground pavement is substantially improved because of the corduroy type of texture developed by grinding. The ridges are composed of rock and mortar and provide an escape route for moisture under the

tire. The use of the lock-up type ASTM Skid Trailer may not be an accurate evaluation of the skid resistance of this type of texture particularly for the treaded tire. The use of a smooth tire shows definite improvement in the skid number after grinding.

(5) Slab stabilization prior to grinding is essential to provide the smoothest ride with diamond grinding. The weight of the new grinders will deflect unstable slabs making it difficult to grind the pavement smooth and to match adjacent cuts.

(6) The pavement joints/cracks should either be sealed to waterproof the pavement or subdrains should be installed to rapidly remove infiltrated moisture, or both should be done to prevent re-occurance of faulting of the pavement as a result of pumping action.

(7) Spacing of the diamond blades must be varied depending upon the hardness of the aggregates to provide a durable surface texture. In general the harder the coarse aggregate the closer the diamond blades must be spaced to result in breakoff of the coarse aggregate fins developed by grinding, particularly on the approach side of a faulted joint. If blades are spaced too wide the fins will not break off when cutting through the coarse aggregate. It is recommended that the maximum spacing be used consistent with the aggregate hardness to improve the service life and friction factor of the texture.

(8) An advantage of diamond grinding is that only the area where roughness is present needs treatment. Normally, diamond grinding is required only in the heavy traffic lane where roughness, due to faulting, is present. In some cases other lanes require grinding due to faulting or poor skid resistance.

(9) The cost of diamond grinding is primarily dependent upon the amount of roughness (faulting) to be removed, the hardness of the aggregate, and the job size. In a diamond grinding operation, the planing action of the present day grinder blends the high areas with the low areas of a pavement surface to obtain a smooth ride. Therefore the amount of material that must be removed to blend the approach and leave slab will depend upon the depth of faulting. As more material is removed the cost of grinding increases. The size of the project also influences grinding costs due to such considerations as mobilization or move in cost, equipment utilization, etc.

Resealing Joints

(1) An effective joint seal will prolong the life of a PCC pavement (Ref. 9). During this operation the incompressibles in the joint are removed and a new long lasting seal is provided to reduce further infiltration. Distress caused by infiltration of imcompressibles include joint spalling and blowups. Jointed reinforced concrete pavements in particular show this type of distress because of the large joint movements associated with the longer joint spacing. An effective seal will also reduce water infiltration into the joint. Free water beneath the slab or subbase can lead to pumping of fines which will lead to joint faulting, corner breaks, and slab breakup (Ref. 9).

(2) The proper shape factor is essential for long term performance of sealants. Although the need for a proper shape factor has been recognized for many years, many resealing projects are not providing the proper shape factor for the existing pavement design and environment. The shape factor recommended by the manufacturer should be used. This will vary with the characteristics of the sealant used. Figure 8 shows recommended dimensions for a silicone sealant.

(3) Joint walls must be clean for proper adhesion of sealant material. All old sealant not compatible with the new sealant material must be removed by sawing or other means. Joints should be flushed out after sawing, sandblasted (required) and air blown prior to sealing.

(4) Life cycle costs should be considered in the selection of sealant materials. When one considers the life of a sealant and all the costs of joint preparation, traffic control, user delay etc. the cost of a good sealant with an extended service life is a good investment. This is especially true for heavily trafficked routes.

(5) Resealing should be done at the proper time, normally much sooner than the current practice in many areas of the United States. Many pavements across the country have open joints and/or ineffective joint seals. The service life of these pavements can be prolonged with a proper job of joint resealing (Ref.9). This would delay such forms of distress as pumping, faulting, corner breaks, slab breakups, and slab blowups.

(6) Thorough inspection of all aspects of the resealing operation is essential to obtain good sealant performance. Detailed inspection procedures are given in Ref. 1. A thorough inspection is required on resealing projects to determine if the joints are satisfactorily cleaned, the backer rod is at the proper depth, and the sealant is properly placed to the specified depth below the surface.

Edge Support Improvement

(1) Many concrete pavements exhibit distress resulting from loss of support beneath the slab edges and transverse joints. The major cause of this loss of support is heavily loaded, repeated truck loads and the infiltration of water into the pavement system (particularly along the longitudinal joint) and the subsequent erosion of the base and/or subgrade material. This causes an increase in the corner and edge deflections and stresses which results in corner breaks, transverse and longitudinal cracking and transverse joint faulting. Pavement design procedures such as the PCA (6) and the UI/FHWA Zero-Maintenance design (7) recognize the edge stress as the critical location for structural design. The impact of a securely tied shoulder is very significant on the thickness required and on the life of the pavement. Figure 9 shows the expected decrease in deflection from a tied edge beam.

(2) Increased edge support can be obtained from tieing a relatively narrow PCC edge beam (e.g., 24 ins.) or a wider standard PCC shoulder to the lane slab. The effectiveness of the edge support depends upon the reduction in deflections and stresses in the traveled lane slab. This reduction depends on the adequacy of the tie system and the width and thickness of the PCC edge beam or shoulder. Design recommendations are provided in Ref. 1 which will provide at least 70 percent deflection load transfer between the traffic lane and the edge support. Another benefit is the tight seal at the lane edge that greatly reduces water infiltration.

(3) An important factor that must be considered is that the longitudinal joint must maintain good load transfer for many years. Tests from 10 year old retro-fit PCC shoulders in Illinois show that where an adequate tie system was provided, over 70 percent load tranfer was achieved. Where an inadequate tie system was used, load tranfer was reduced to 50 percent or less due to pullouts and corrosion of the ties (5). Thus, it is possible to achieve a long term load transfer if proper design and construction techniques are used as described in Ref. 1.

(4) Only one test site of an edge beam was found in Minnesota. There are, however, several projects across the U.S. where full width PCC shoulders were tied onto an existing jointed concrete traffic lane. No significant difficulties were encountered in construction of either the edge beam or the PCC shoulders.

(5) The long-term effectiveness of the edge support has not been established through field performance. However, where shoulders were tied onto existing CRCP in Illinois, a substantial improvement in performance was noted after 10 years (5). This improvement did not occur in one experimental project in Indiana where either a deficient tie system is suspected, or a significant loss of support already existed along the edge and was not stabilized before or after placing the PCC shoulder. However, it is believed that the two beneficial effects of edge support (reduced water infiltration and increased edge support) will add a substantial service life to a PCC pavement.

(6) The cost-effectiveness of improved edge support depends in part on the condition of the AC shoulder, the thickness of the slab, the amount of heavy truck traffic, and the amount of moisture available. A deteriorated AC shoulder would need to be replaced anyway. The thinner the slab the more beneficial effect of the edge support. Heavy traffic and excess free water always causes problems in pavements.

Selection of Most Cost-Effective Alternative

Once two or more feasible rehabilitation alternatives have been selected, a decision must be made as to which one is the most cost-effective for the project under consideration.

Life-Cycle Cost Analysis

The overall life-cycle cost of each alternative is generally considered the "cost" factor that should ideally be used in determining cost-effectiveness. The major life-cycle cost factors are:

1. Initial construction costs
2. Future maintenance and rehabilitation costs
3. Salvage value - what the pavement is worth when its service life has expired
4. Extra user costs resulting from rougher pavements and lane closures .
   a. Delays from traffic control during intial construction, maintenance and rehabilitation
   b. Discomfort costs
   c. Extra vehicle operation costs
   d. Extra accident costs

Life-cycle costs can be expressed in terms of "present worth," or in terms of an "equivalent uniform annual cost" (EUAC) (Ref. 10,11). The procedure for calculating both present worth and EUAC for a detailed life-cycle cost analysis is given in Figure 10.

It is important to realize that any given pavement has an associated cost that can be expressed on an average annual basis. This "equivalent uniform annual cost" for a pavement depends greatly upon the maintenance and rehabilitation policies and designs. For example, a "failure-type" policy of letting a pavement deteriorate badly and then reconstructing it currently varies in annual cost from $20,000 to $40,000 per two-lane mile of Interstate-type roadway. The application of rehabilitation work such as described in this document at the appropriate times may result in average annual costs that are much less than those of the "failure" policy, and would thus be considered very cost-effective.

The application of a detailed life-cycle cost analysis that considers all of the above cost factors is normally beyond the capability of the design engineer. Therefore, an approximate life-cycle cost procedure is recommended that can be performed manually by the design engineer that considers the most important cost factors:

(1) the cost of initial construction of the rehabilitation, and

(2) the extension of service life of the pavement due to the application of the rehabilitation.

An approximate average annual cost can be computed with this information, by dividing the cost by the extension of service life of the pavement caused by the rehabilitation work.

Where unusually heavy traffic is involved, the impact of high user costs may need to be considered in more detail in making the final selection of rehabilition method for joints and cracks.

Pavement Life Extension

The expected extension in service life of a pavement caused by the application of a repair or preventative technique must be estimated before the average annual cost can be computed. <u>This extension is the increase in life beyond that obtained if no rehabilitation work is performed</u>. An illustration of this life extension definition is shown in Figure 11. Defining life extension in this way is essential to insure that the average annual cost computed is due solely to the effect of the rehabilitation technique.

It must be recognized that when a pavement is rehabilitated, there are two different "lives" that are of importance:

(1) the life of the individual repair or preventative technique (e.g., full-depth repair or joint sealant), and

(2) the life of the pavement as a whole.

These two lives are interrelated. The future life of the overall pavement depends on the life of the individual repair or preventative techniques <u>and</u> on the deterioration of the rest of the pavement that was not repaired. Also, the lives of the individual repair or preventative techniques depend somewhat on the performance of the existing pavement. For example, a joint sealant material may perform for ten years, but if the joint spalls at five years it is essentially failed at five years.

The life of an individual repair or preventative technique depends on the following major factors:

- type of technique,
- adequacy of construction,
- proper selection of the repair or preventative technique,
- concurrent rehabilitation work being performed,
- truck traffic level,
- climate conditions (moisture, temperature, freeze-thaw), and
- existing pavement design, materials and subgrade.

A summary of the estimated range of lives of individual techniques is given in Figure 12. These values were estimated by the NCHRP Project 1-21 staff based upon results from field demonstrations, experience on other projects, and information from other agencies.

The life of the overall pavement after rehabilitation depends on the following major factors:

- life of specific repair and preventative techniques placed,
- condition of the rest of the pavement which was not repaired (that is, how much of the existing deterioration was actually repaired),
- truck traffic level,
- climate conditions, and
- existing pavement design, materials and subgrade.

It is extremely difficult to give estimates for overall project life because of the many interacting and complex factors involved. However, some general guidance is provided in Figure 13 for some general conditions. These estimates are for the entire pavement and it is assumed that certain restoration techniques will need to be repeated during the extended life of the pavement.

The design engineer should not use any of these estimates without modification to the specific project under design. It must be remembered that these are only estimates and that local conditions and many other factors may change these estimates considerably. Thus, the final selection of the life extension of a repair or preventative method must be made by the design engineer for the specific project under design.

Step-by-Step Example Procedure

The following is a step-by-step procedure for selecting a cost-effective joint and crack rehabilitation techniques.

Step 1. Collect Important Pavement Data and Conduct Pavement Evaluation. A brief summary of the important information for a hypothetical example pavement is as follows:

Design:

Age: 15 years
Jointed plain concrete pavement
Joint spacing: 12 to 19 feet
Slab thickness: 9 inches
Four-lane divided highway
Lanes 12 feet wide and AC shoulders 4 and 10 feet wide
Subgrade: fine-grained soil (impermeable)

Evaluation:

Major distresses: Pumping fines, serious faulting (0.17 inches, PSR = 3.2) and a few broken slabs all in outer truck lane. Outer AC shoulder needs repair also.
Major causes: Free water beneath slab and stabilized base caused by "bathtub" design and poor load transfer at joints.
Extent of loss of support problem: Loss of support beneath approximately 50 percent of slabs confirmed by deflection testing.

Step 2. Select Feasible Alternatives to Repair And Prevent

Figure 2 is utilized to develop the following summary of repair and preventative alternatives.

Distress	Repair	Prevent
Pumping(Loss of Support)	Subseal	Restore Load Transfer Reseal Joints PCC Shoulder Subdrains
Faulting	Grind Thick OL	Subseal Reseal Joints PCC Shoulder Subdrains
Cracking	Full-Depth Repair	Subseal Prevent pumping(above)

One repair method and one or more preventative methods are selected for each distress to develop a specific rehabilitation alternative. Both the "seal out water" and the "drain out water" approaches were used to develop the following alternatives:

Alternative	Repair Methods	Preventative Methods
A	Subseal joints Full-depth repair Grind faults	Reseal all joints Add tied PCC shoulder
B	Subseal joints Full-depth repair Grind faults AC shoulder repair	Subdrains(outer edge)
C	Subseal joints Full-depth repair Grind faults AC shoulder repair	Reseal all joints Restore load transfer

Other alternatives could be developed.

Step 3. Conduct Annual Cost Analysis. Estimate the construction costs and the expected life extension of each feasible alternative using Figures 12 and 13 and other experience and information available to the design engineer. Then compute the approximate average annual cost of the life extension for each alternative.

Feasible Alternative	Expected Life Extension	Expected Cost	Annual Cost
A. Subseal, grind, PCC shoulder full-depth repair, reseal joints	15	115,230	7,682
B. Subseal, subdrains, full-depth repair, grind, AC shoulder, shoulder repair	10	79,168	7,917
C. Subseal, full-depth repair, grind, restore load transfer, AC shoulder repair, reseal joints	10	102,230	10,223

These results show that Alternatives A and B are the most cost-effective. Their annual costs are very close and in light of the possible errors in cost and life extension estimation, they have essentially the same cost. The final choice of which to construct must then be based on some other criterion such as expected life extension, which would favor Alternative A. However, if only, say, $80,000 were available, then alternative B would be selected.

Conclusions

The following general conclusions have been determined from this study.

(1) The successful rehabilitation of PCC pavement joints is a complex problem that requires comprehensive evaluation, custom design and well defined construction procedures.

(2) This study started with state-of-the-art techniques in 1980 and identified many different improvements during the succeeding 4 years. A substantial improvement in the state-of-the-art for the seven selected repair and preventative techniques was achieved through interaction with numerous experienced engineers and contractors, results from various studies, and in the conduct of several field test projects.

(3) There are five major steps in rehabilitating joints and cracks in PCC pavements.

1. Pavement data collection and evaluation
2. Identification of feasible alternatives that both repair and prevent the deterioration
3. Selection of the most cost-effective alternative
4. Detailed design of the individual repair and preventative techniques
5. Construction of the alternatives in accordance with plans and specifications

The procedures contained in Reference 1 provide the current state-of-the-art procedures for the seven techniques studied. The results of short term field testing performance is given in Ref. 1. However, there are many aspects of each technique that need further research and development.

(4) The timing of the construction of these seven techniques on many projects is deferred too long, typically until very serious deterioration has already occurred. This has often resulted in a decreased life of the rehabilitated project. The timely application of their repair and particularly preventative methods is of considerable importance.

Acknowledgements

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   Appendix B: "Field Demonstration Projects Of Joint/Crack Repairs"
   Appendix C: "Void Detection Procedures"
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Figure 1. Data required for determing feasibility and developing designs of several repair and preventive methods.

Data Required	Full Depth Patching	Partial Depth Patching	Overlay	Grinding	Recycling	Underseal	Slab Jacking	Underdrains	Reseal Jts.	Pressure Relief Jts.	Load Transfer Restoration
Pavement Design	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗
Traffic Load & Volume	⊗		⊗	⊗	⊗	X		⊗	X	X	⊗
Distress	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗
Skid			X	X	X						
Accidents			X	X	X						
Age	X	X	X	X	X			X	X	X	X
Materials Properties	X	X	⊗	⊗	⊗	X		⊗			
Subgrade			⊗		⊗	X	X	⊗	⊗		
Climate			⊗		X	⊗		⊗	⊗	X	
Vertical Clearance			⊗		⊗						
Geometrics			X		X						
NDT	X	X	⊗		X	⊗					⊗
Destructive Testing (coring)	⊗	⊗	⊗	X	⊗	X					X
Overall Roughness			X	X	X		X				
Profile of Surface				⊗			X				
Previous Maintenance	X		X	X	X	X		X	X	X	
Pushing of Bridges									X	⊗	
Utilities (underground)	X				X	X	X	X			
Original Construction Data	X		X	X	X			X			
Traffic Control Options	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗	⊗
Drainage	X		⊗	X	⊗	X		⊗	X		

Key: ⊗ - Definitely needed. X - Desirable.

Figure 2. Candidate repair and preventative methods for specific joint and crack distress.

Joint/Crack Distress	Repair Methods	Preventative Methods
Pumping	**1. Subseal** **2. Full-Depth Repair**	**1. Reseal Joints** **2. Restore Load Transfer** **3. Subdrainage*** **4. Edge Support(PCC Shoulder/Edge Beam)**
Faulting	**1. Grind** **2. Structural Overlay**	**1. Subseal** **2. Reseal Joints** **3. Restore Load Transfer** **4. Subdrainage*** **5. Edge Support**
Slab Cracking	**1. Full-Depth Repair** **2. Replace/Recycle Lane**	**1. Subseal loss of support** **2. Restore Load Transfer** **3. Structural Overlay**
Joint Spalling	**1. Full-Depth Repair** **2. Partial-Depth Repair**	**1. Reseal Joints**
Blowup	**1. Full-Depth Repair**	**1. Pressure Relief Joint** **2. Resealing Joints/Cracks**

*** Drainage analysis required for specific situation to determine need and benefit.**

Figure 3. Recommended design of full-depth repair for heavy traffic.

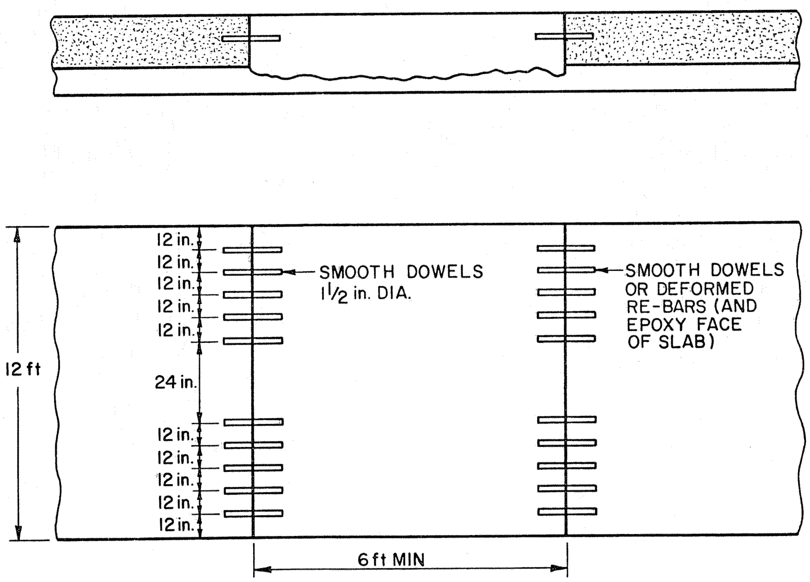


Figure 4. Early opening Guidelines for full-depth repairs.

Slab Thickness (inches)	Ambient Temperature At Placement (°F)	Full-Depth Repair Mixtures/Curing* (Hours after placement) A	B	C	D	E	F
7	40	203	90	69	29	28	7
	50	125	60	41	21	20	5
	60	80	45	28	17	16	4
	70	60	38	21	14	13	3
	80	48	35	17	13	11	3
	90	40	30	13	13	9	3
8	40	145	59	55	24	24	6
	50	82	40	35	18	17	5
	60	58	31	24	13	13	4
	70	42	26	17	11	10	3
	80	35	23	13	10	9	3
	90	29	22	11	9	8	3
9	40	82	34	37	15	16	5
	50	51	25	23	12	13	3
	60	28	19	16	9	9	3
	70	25	16	12	8	7	3
	80	20	14	10	6	6	3
	90	17	12	8	5	5	3
10	40	45	18	23	9	9	3
	50	30	14	14	7	7	3
	60	20	10	9	5	5	3
	70	15	9	7	4	4	3
	80	12	7	5	4	4	3
	90	9	6	4	3	3	3

* All mixtures contain 650 pounds cement per cubic yard and 2% CaCl.

Mixture Characteristics:	A	B	C	D	E	F
water/cement ratio	0.42	0.42	0.35	0.42	0.35	0.35
cement type	I	I	I	III	I	III
superplasticizer	no	no	yes	no	yes	yes
fiberglass insulation	no	yes	no	yes	yes	yes

Note: These results are based on research done at the University of Illinois, Department of Civil Engineering, using a computer program written in the Microsoft BASIC language. They are intended as guidelines and should only be used after careful evaluation (Reference 6).

Figure 5. Partial-depth spall repair recommendations.

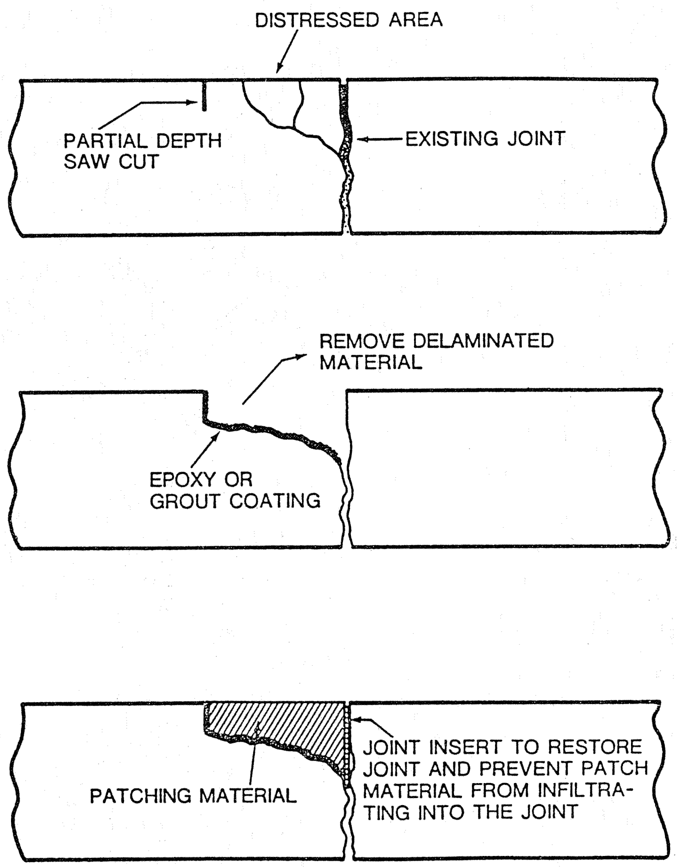


Figure 6. Corner deflection profile.

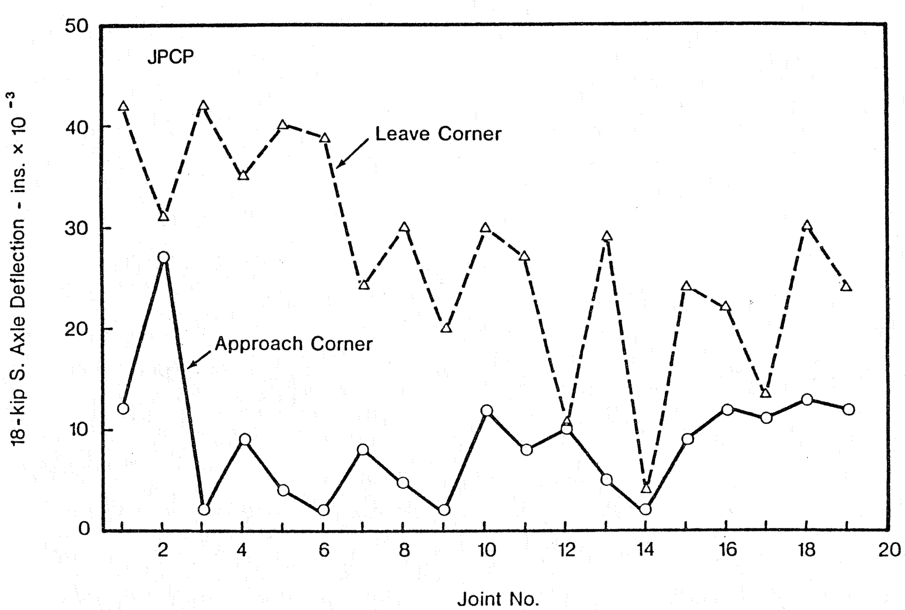


Figure 7. Void detection procedures--rapid field method.

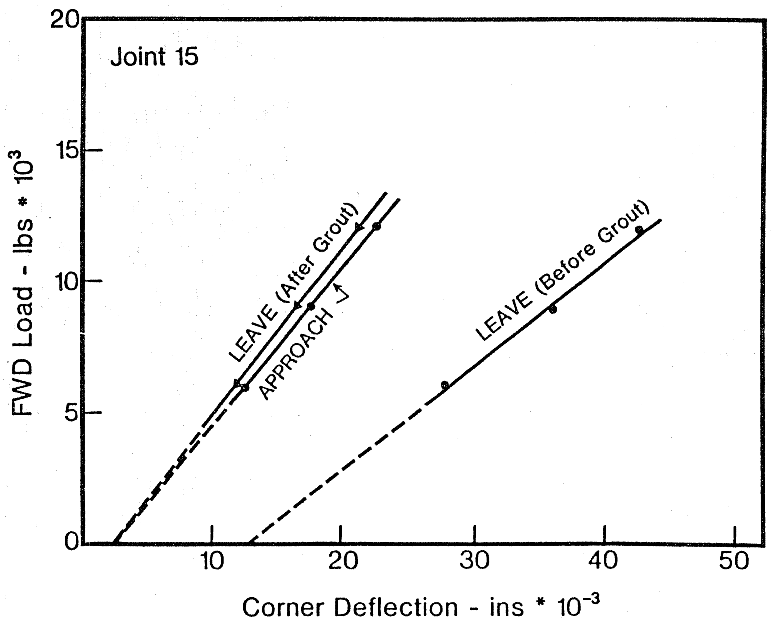
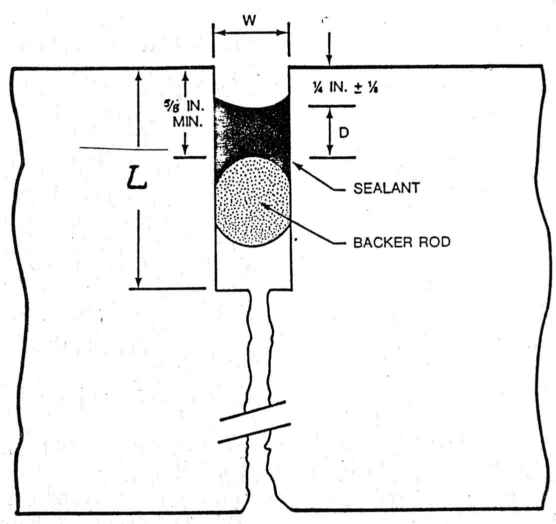


Figure 8. Joint sealant reservoir for silicone sealants recommendations.



JT. SPACING (FT.)	D (INS.)	L (INS.)	FREEZE AREA W (INS.)	NON-FREEZE AREAS W (INS.)
≤ 20	1/4	1-1/4	1/4	1/4
21- 40	1/4	1-1/2	1/2	3/8
41- 60	3/8	1-3/4	5/8	1/2
61- 80	1/2	2	3/4	5/8
81- 100	1/2	2-1/2	1	3/4

Figure 9. Influence of edge support on slab edge deflections.

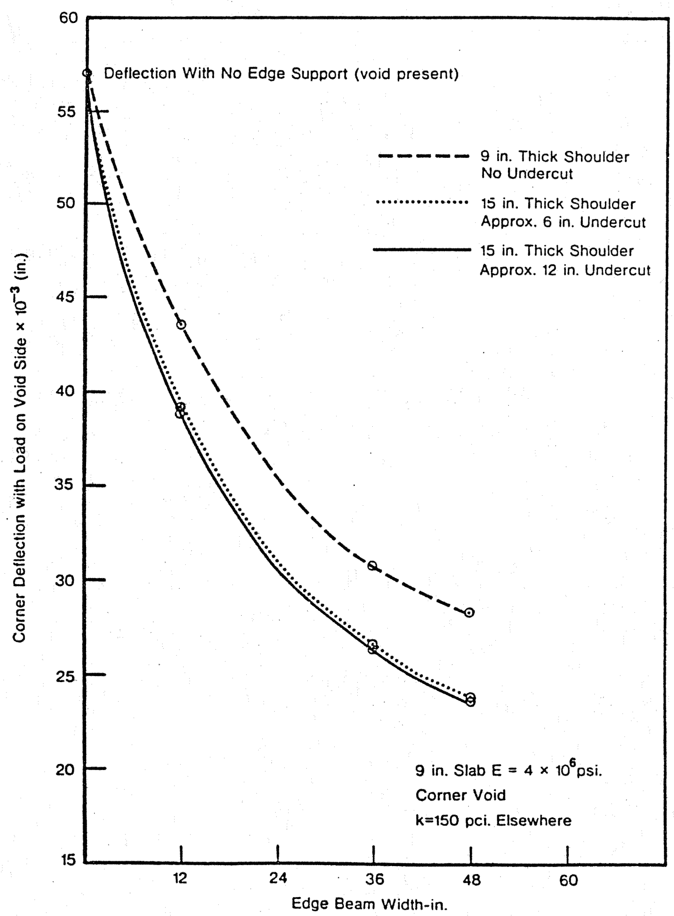


Figure 10. Life cycle cost analysis example.

Information Required

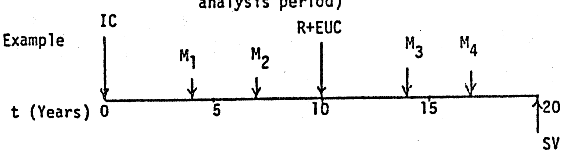
Analysis Period -- Life span over which alternatives will be compared. (Note: Analysis period must be the same for each alternative.)

Interest Rate -- Average annual interest rate appropriate for the alternatives being analysed. (Note: Rate is average anticipated over the analysis period.)

Inflation Rate -- Average annual rate of inflation anticipated over the period being analysed.

Cash Flows:
- IC - Initial Construction Cost
- Mi - Maintenance Costs
- R - Rehabilitation Costs
- EUC - Extra User Costs due to major rehabilitation activity
- SV - Salvage Value (pavements value at the end of the analysis period)

Example



IC = \$120,000
R = \$ 90,000
EUC = \$ 30,000
SV = \$ 50,000

M_1 = \$10,000
M_2 = \$12,000
M_3 = \$25,000
M_4 = \$20,000

Note: Costs have not been inflated. Inflation will be taken into account in the life cycle cost analysis by use of an inflation rate. An alternative method is to use inflated costs in the analysis procedure. The inflation factor can then be disregarded (i_R=0),

Figure 10 (cont.). Life cycle cost analysis.

All cashflows must first be brought back to time t=0. The present worth (PW) of the cashflows can be determined as follows:

$$PW = CASHFLOW \frac{(1+i_{INF})^n}{(1+i_{INT})^n}$$

where:

N = number of years to be discounted over
i_{INF} = inflation rate (assumed 6%)
i_{INT} = interest rate (assumed 10%)

CASHFLOW	N	$\frac{(1+i_{INF})^n}{(1+i_{INT})^n}$	PW of CASHFLOW
IC = \$120,000	0	1	120,000
M_1 = \$ 10,000	4	0.8623	8,623
M_2 = \$ 12,000	7	0.7716	9,259
R = \$ 90,000	10	0.6904	62,136
EUC = \$ 30,000	10	0.6904	20,712
M_3 = \$ 25,000	14	0.5954	14,885
M_4 = \$ 20,000	17	0.5328	10,656
SV = \$ 50,000	20	0.4767	(23,835)

Total Present Worth = 222,436

It is then possible to determine what series of equivalent uniform annual costs (EUAC) would be equivalent to this present worth lump sum. This is calculated as follows:

$$PW = EUAC \left(\frac{1-(1+i_{INT})^{-n}}{i_{INT}}\right)$$

$$EUAC = 222,436 \left(\frac{0.10}{1-(1.1)^{-20}}\right) = \$26,127$$

Figure 11. Definition of "life extension" resulting from restoration work.

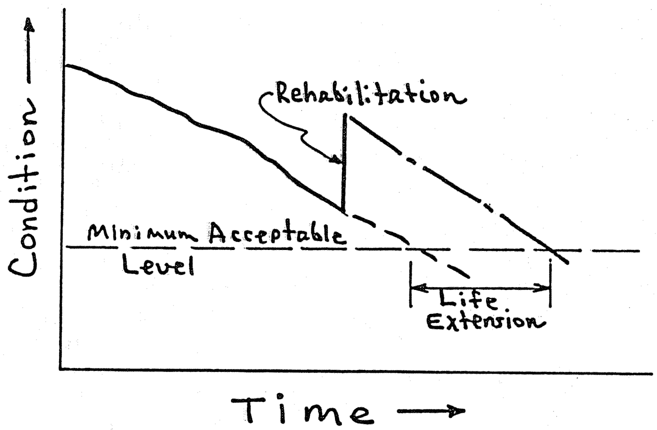


Figure 12. Tentative estimated lives of individual repair and preventative techniques (see assumptions below).

Technique	Conditions	Expected Life (yrs.)	Reliability
Full-Depth Repair	Sound PCC slab Prevent pumping	10	80%
Partial-Depth Patching	Sound PCC Slab	5 - 10	80
Subsealing	Prevent pumping	4 - 8	75
Restore Load Transfer	Prevent pumping	3 - 7	50 - 70
Edge Support (Beam or Shoulder)	Stabilize slab	10 - 20	85
Grinding	Stabilize slab Repair deterioration Prevent pumping	8 - 15	90
Reseal Joints	(a) Asphalt Rubber or Elastomer	4 - 6	80
	(b) Silicone or Compression Seal	8 - 15	80

Assumptions:

1. Traffic Load - for very heavy truck traffic (more than 1500 trucks per day in outer lane) reduce lives by 30 percent.

2. Adequate design and construction techniques are used as described in this document.

   Prevent pumping - Subdrainage, or reseal all joints, or tied edge support (PCC shoulder)

   Stabilize slab - Subseal slabs and full-depth repairs

   Repair deterioration - Full-depth and partial-depth repairs

   Sound PCC - No "D" cracking or reactive aggregate

Figure 13. Tentative expected project life extension due to application of repair and preventative techniques (see assumptions below).

Truck Traffic Level	Climate	Expected Life Extension (yrs.)
Medium to High	Dry	15 - 20
Very High	Dry	10 - 15
Medium to High	Wet	10 - 15
Very High	Wet	5 - 10

Assumptions: 1. Truck Traffic - Medium to High is less than 1500 trucks per day in outer lane.

Very High is more than 1500 trucks per day in outer lane.

2. Climate - Wet regions have a Thornthwaite Index greater than zero, or average annual precipitation greater than 20 inches (Ref. 9).