A FRAMEWORK FOR REPAIR AND REHABILITATION TREATMENT SELECTION FOR PORTLAND CEMENT CONCRETE PAVEMENTS

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Abstract
In order to ensure that pavement investment decisions are made in an optimum manner, the State highway agencies (SHAs) are continually examining their pavement maintenance, rehabilitation, and reconstruction (MRR) strategies and their repair and rehabilitation (R&R) techniques to maintain and preserve the nation's highways. As the economy has grown in recent years, highways in the United States are being subjected to more and more vehicles with heavy loads. This effect along with the variety of climatic conditions has caused the vast network of the nation's highways to deteriorate in a number of different ways. Consequently, current decisions associated with the repair of this deterioration have long reaching implications for many future generations.

With respect to portland cement concrete (PCC) pavements, the state of practice of MRR is good, but it can be better. In the last 10 to 15 years, significant improvements have been made in our understanding of PCC pavement failure mechanisms, pavement condition evaluation techniques, repair materials, equipment, and techniques for MRR. The challenge is how to use this information to preserve the highway investment that has been made over the years while maintaining pavement structures in a serviceable condition. These and other factors have caused SHAs greater concern regarding the effectiveness of their maintenance, rehabilitation, and reconstruction (MRR) strategies and their repair and rehabilitation (R&R) treatments in maintaining and preserving the nation's highways. Consequently, techniques are sought after in repair treatment selection that will enhance the effectiveness of strategies for maintenance, rehabilitation, and reconstruction of concrete pavements and to develop better decision-making processes to select MRR strategies and R&R treatments. These types of devices will help highway agencies and engineers select treatments that will ensure expected performance.

Introduction

It has been known for several years, as funds for highway construction have become more and more limited, that decisions to repair highways that are being subjected to more and more vehicles and trucks are becoming more and more critical. The impact of vehicle loading along with the variety of climatic conditions has caused the vast network of the nation's highways to deteriorate in a number of different ways that further complicates the decision to repair, rehabilitation, or restore a pavement system. Preservation is of high importance since the total investment in our nation's highway network is staggering, easily into the trillions of dollars.

Consequently, SHA's are challenged as how to maintain the highway investment in an optimum manner while maintaining the pavement condition at an optimum level which have caused SHAs to examine more carefully their maintenance, rehabilitation, and reconstruction (MRR) strategies and their repair and rehabilitation (R&R) treatments to maintain and preserve the nation's highways. Consequently, an increased interest has developed in finding effective means to select treatments within the overall framework of a strategy development process. New and fresh examinations of ways to improve current R&R treatment selection have always been sought and are needed today to ensure that the most appropriate treatments are identified.

Present practices of selecting pavement R&R treatments tend to consider two factors: construction cost (first cost) and performance (life and expected maintenance cost). The decision-maker often considers these two factors in a quantitative way while considering, in a subjective (qualitative) way, secondary factors such as traffic inconvenience, public acceptance, cost-effectiveness, and accident risk. It is evident that a strategy for repair includes both pavement and non-pavement related factors. Pavement engineers today are challenged to consider these factors in an equitable manner in almost any given rehabilitation project that addresses the timeliness of the repair and its cost effectiveness. Although this is a difficult challenge for SHA decision-makers to meet, the use of improved practices and new tools that are capable of considering these characteristics are needed in order accomplish the enormous task of efficiently maintaining and improving our highways.

A decision-making tool for treatment selection was outlined several years ago in a report to the Federal Highway Administration (FHWA) entitled, "Techniques for Rehabilitating Pavements without Overlays - A Systems Analysis" [Ledbetter et al. 1977]. A process for rehabilitation was described in this report along with a systematic decision-making tool referred to as utility theory. It was shown how utility theory can consider a multitude of decision criteria to optimize the incorporation of a variety of repair methods to address a particular situation, and additionally is suggested in this paper to be useful for pavement condition assessment.

Rehabilitation Decision Process and Tools

Over the years, the American Concrete Pavement Association (ACPA) has published extensively on the topic of concrete pavement rehabilitation. In one publication entitled "Pavement Rehabilitation Strategy Selection" [ACPA 1993], guidelines for selecting cost-effective rehabilitation strategies are presented in terms of a systematic decision-making process that is illustrated in Figure 1. As one of the first steps in the process, detailed project information (such as pavement construction details, traffic levels, drainage conditions, and distress levels) is collected to formulate the causes of any pavement distress that may be evident. In some cases

the pavement system has simply worn out from repetitive loading but in other instances, the mode of distress is premature in nature. Whatever the situation, it is important not to rely on assumed conditions to provide an effective and durable solution that addresses the root causes of the distress. An engineering evaluation is necessary to assess the functional and structural condition of the pavement in addition to determining if the prevailing causes of distress are materials or drainage related.

Once the distress types have been evaluated, the mechanisms can be identified such that adequate treatment combinations can be determined. Treatment types are referenced by the ACPA relative to three categories: restoration, resurfacing, and reconstruction. Restoration is described as treatments that restore the structural condition and rideability of a pavement to an acceptable level. Resurfacing is described as either concrete or asphalt overlays. Reconstruction includes both inlays and recycling. Once feasible treatment combinations within the framework of these categories are selected, preliminary designs can be formulated to provide information for the final selection.

The preferred alternative is selected by comparing the life-cycle costs of the possible combinations. This includes relevant cost items such as user delay and vehicle operator cost since they can often dominate the cost of a given strategy. Non-monetary factors, such as construction time, traffic control constraints, and design reliability, may also be considered in the evaluation process. Once selected, the preferred alternative then undergoes detailed design, estimating, and construction. Part III of AASHTO's pavement design guide [1993] also provides a general layout of the pavement rehabilitation process broken down into phases that is similar to the ACPA process.

Table 1 lists the primary pavement repair types as maintenance, rehabilitation, or reconstruction. The various treatment types available for the distresses are grouped according to the function they perform or the course of action adopted. Maintenance strategies are appropriate for distresses in the initial stages. The function of such treatments is corrective in nature to

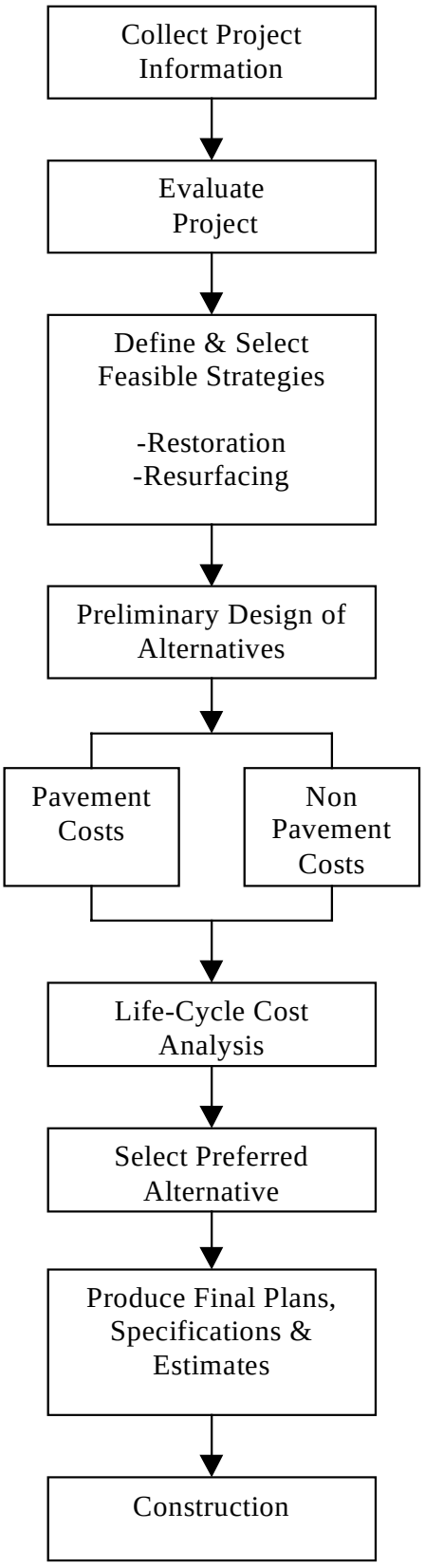


Figure 1 ACPA Decision Process. [ACPA 1993]

prevent or retard further deterioration of the pavement structure. However, the degree to which this is accomplished depends on the timeliness of their application. The treatments serve in rectifying defects in the initial stages, so that major repairs may be minimized.

Rehabilitation refers to the repair of distresses at a greater level of severity. Application of rehabilitation treatments is intended to extend the life of the pavement structure and include treatments that can restore the pavement to a satisfactory condition. Consequently, rehabilitation strategies may further be classified as restoration and resurfacing. Resurfacing refers to the application of an overlay in order to improve the structural capacity and ride quality of the pavement, and includes various slab preparation techniques (such as crack and seat or rubblization).

Reconstruction is generally carried out when the pavement has deteriorated to such an extent that major repairs would not be a suitable or economical option. Either an entirely new pavement is constructed, or the existing pavement material is recycled in place, and used as a base material.

Table 1 Framework of MRR Classification.

Classification	Function	Treatment Types
Maintenance	Preventative/Routine/Corrective	Fill/seal cracks and joints Clean and shape drainage Isolated partial depth repair Isolated full depth repair
Rehabilitation	Restoration (CPR) or Repair	Diamond grinding or grooving Retrofitted edge support Retrofitted load transfer (RLT) Partial depth repair (PDR) Full depth repair (FDR) Slab undersealing Slab jacking
	Resurfacing	Unbonded concrete overlay (UCOL) Bonded concrete overlay (BCOL) Asphalt concrete overlay (ACOL)
Reconstruction	Reconstruction	Remove and replace (R&P) Remove and recycle (R&C)

It should be noted that the term “Concrete Pavement Restoration (CPR)” is also widely used to designate a series of non-overlay techniques used to repair isolated areas of distress in PCC pavements. CPR is undertaken to restore the pavement to a condition close to original and to significantly delay the need for resurfacing or reconstruction.

A partial treatment selection scheme is shown in Appendix A in a tabular format as an example of the decision process behind the selection of MRR treatments. This table yields a variety of treatment combinations depending upon the condition of the pavement. The thought process behind the screening of a multitude of treatment alternatives involves four types of choices,

namely whether to conduct routine maintenance, to conduct CPR, to consider the use of some type of an overlay, or to undertake total reconstruction. Table 2 provides a list of the pavement condition attributes that are considered to be important in making such a choice in terms of structural, functional, and material-related distress factors. This table suggests how various rating indexes relative to these distress types can be formulated.

Table 2 also shows how both structural and functional condition ratings are formulated. The structural condition rating is derived from individual distress types whereas the functional condition rating is represented by such attributes as ride, skid, and noise quality. An overall condition rating of a given pavement segment can be derived from a weighted rating of each decision attribute noted the table. This weighted-value is compared to the decision criteria to determine the decision type to be made. It is certainly expected that the lowest level of rating that is allowed to occur will dictate the life cycle economics behind the decision of the optimal MRR strategy.

The table in Appendix A was developed from a decision-tree representing a treatment selection process. To ensure the development of suitable treatment alternatives within the decision tree, limits were established for the following attributes to constraint to the decision process and ensure the integrity of resulting treatment combinations:

1. Distress type and level
2. Traffic level
3. Pavement condition
4. Climatic region
5. Desirable performance life.

Project information associated with each of these categories in effect serves to 'qualify' each rehabilitation alternative. Note that budget is not included in the above list. However, patching area (this could be determined to be 1% of the pavement area less the current level of patching) and pavement age could perhaps be added to the above list. Treatment combinations not meeting the constraint criteria are eliminated from further consideration. .

Table 3. Material-related distress (MRD) rating.

		MRD Severity		
		Low	Medium	High
Extent over length of project	Less than 1/3	**1**	**1**	**2**
	Between 1/3 and 2/3	**1**	**2**	**3**
	Greater than 2/3	**2**	**3**	**3**

Although the table of treatments shown in Appendix A is not all encompassing, it does demonstrate how different distress types are considered in treatment selection (i.e. the table considers material-related distress (MRD), along with functional distress, and structural related distress). If MRD is a factor, then treatments such as HMA overlay with slab fracturing, unbonded overlay (which requires minimal pre-overlay repair), or reconstruction may be appropriate. The choice of treatment is governed to some extent upon the severity of MRD, which is defined in Table 3. Under functional condition, different treatments may be recommended such as diamond grinding.

Table 5.1 Treatment combination/strategy selection decision indices.

Strategy Type	**Decision Attribute**	**Weighted Attribute Component****	**Suggested Decision Criteria Limits** (% of scaled value)
To Conduct Routine Maintenance (*Cost driven solution*)	Structural Condition (SC)	Distress Type Distress Level Remaining Life (RL)	If SC Rating > 50% If RL Rating > 50%
	Functional Condition (FC)	Ride Profile Skid Resistance Tire Noise+	If FC Rating > 25%
	MRD Condition (DC)+	D-Cracking ASR Dowel/Steel Corrosion	Provided in table 4.4
To Conduct Repair (CPR) (*Engineering driven solution*)	Structural Condition (SC)	Distress Type Distress Level Remaining Life	If SC Rating < 50% If RL Rating < 50%
	Functional Condition (FC)	Ride Profile Skid Resistance Tire Noise	If FC Rating < 50%
	MRD Condition (DC)	ASR Steel Corrosion	Provided in table 4.4
To Use Overlay	Suitability for Overlay	Life Extension (LE)+	LE Rating > 50% (Jointed) LE Rating > 70% (CRC) LE Rating > 80% (HMA)
To Reconstruction	Suitability for Reconstruction	Lane Capacity (LC)+ Remaining Life (RL)+ Life Extension (LE)	LC Rating < 50% RL Rating < 50% LE Rating < 25%

** *Weighting criteria is suggested in appendix G.*

+ *Ratings are user defined*

Structural Condition (SC) Rating = $U_{SC} = \sum W_{D_i} U_{D_i} + W_{Pat} U_{Pat}$

- U_{D_i} *is the rating for individual distress types and level (U_{SC} does not include faulting (F) distress for jointed pavements but does include thermal and reflective cracking for HMAC pavements)*
- W_i *represents the weight given to each rating*

Functional Condition (FC) Rating = $U_{FC} = W_P U_P + W_{SKID} U_{SKID} + W_{NOISE} U_{NOISE}$

- *Profile (P) Rating =* $U_P = W_{RIDE} U_{RIDE} + W_F U_F + W_{Spall} U_{Spall} + W_{Rut} U_{Rut}$
- *Skid Rating =* U_{SKID}
- *Noise Rating =* U_{NOISE}
- *Patching Rating =* U_{Pat}
- *Rutting Rating =* U_{Rut}
- *Spalling Rating =* U_{Spall}

Overall Condition (OC) Rating = $U_{OC} = W_{SC} U_{SC} + W_{FC} U_{FC}$

If CPR is determined to be feasible, three different levels of rehabilitation are considered:

- Short-term – less than 5 years
- Intermediate-term – 5 to 10 years (typical CPR)
- Long-term – 10 years or more

The target design life determines the level of repairs and preventive measures required ensuring that the design life will be reached. The optimum design life depends on many factors. However, in practice the target design life will often be dictated by agency policy constraints. In some cases a short design life may be more cost-effective, but lane-closure considerations may preclude the use of the optimum rehabilitation frequency. In some cases a long design life may be more cost-effective, but budget constraints should not force the use of a short-term solution, which has a lower initial cost.

Utility Theory as a Condition Assessment Tool

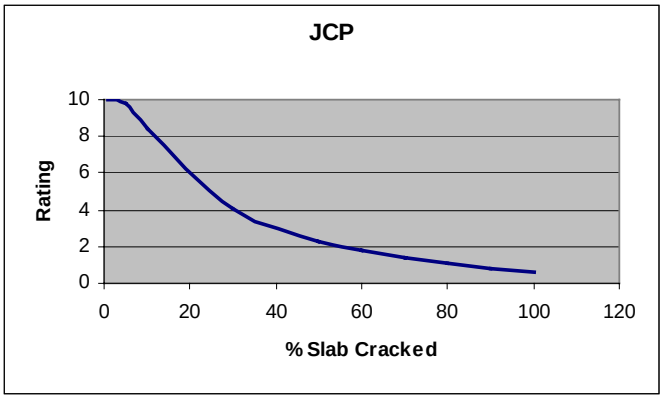
The process of treatment selection previously described requires a decision analysis tool configured for condition assessment to allow a variety of R&R techniques to be selected from a set of feasible alternatives. The tool that is proposed for this purpose is utility theory. As previously stated, utility theory can be used to synthesize and account for a variety of factors that play a role to varying degrees in decision-making processes. In the previously cited FHWA study, Ledbetter et al. [1977] developed a systems methodology for decision analysis in the selection of pavement rehabilitation strategies and treatments for asphalt and concrete pavements using utility theory to account for factors associated with cost, performance, safety and energy usage.

Utility theory, simply stated, facilitates a way to compare dissimilar things (apples and oranges) based on the following concepts:

Value - the worth attached to an object or a service

Utility - capability of a practice or measure to satisfy a particular need or provide a desirable result

The basic idea in utility theory is that decisions are made on a rational basis. In other words, there is a set of prerequisite preferences associated with the end results of the possible courses of action (COA) or combinations of R&R treatments, and the best combination can be chosen on the basis of maximizing some objective (such as pavement performance or cost). Furthermore, such preferences can be rated in terms of their relative utility (typically on a scale from 0 to 1) or ability to satisfy a decision-maker's desires or criteria [Ledbetter et al. 1977].



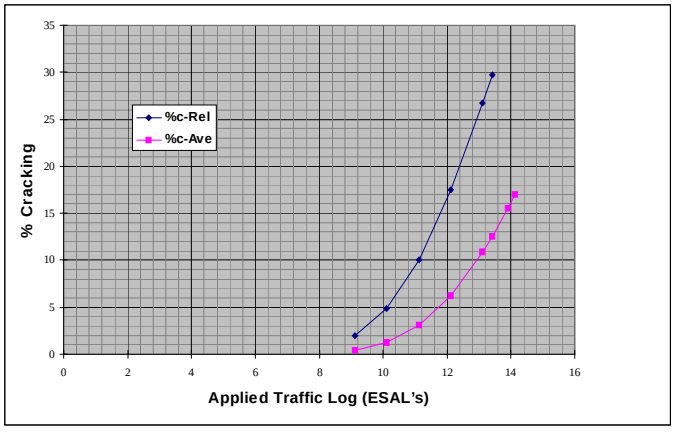


Figure 2 Example Utility and Pavement Performance Curves (for Slab Cracking).

As previously indicated, utility is a measure of preference and typically is assigned a value between 0 and 1 but can be adjusted to any desirable scale (such as 10 as noted in Figure 2) to make it suitable to characterize, for instance, pavement distress types. The cracking trends shown in Figure 2 for a given pavement section vary in utility from a value of 10 at the low traffic level down to a value of 6.5 at the higher traffic level. Repair of the cracked slabs would of course increase the utility or structural rating at any traffic level.

Given the type of distress, a utility rating curve may be configured to represent cracking, spalling, faulting or any of the distresses that change with time or traffic. Since the rating varies with the severity of the distress, the utility approach can be integrated into the decision making process because the severity of distress is a decision factor. In this manner, each distress type can be compared and weighted on a scale that is universal through out the decision making process.

Pavement Condition and Remaining Life

Various approaches have been used for pavement condition assessment. Pavement condition assessment should consider both the functional and structural quality of the pavement. Functional performance is the ability of the pavement to serve the traveling public and is represented by such attributes as ride quality and friction quality. Structural performance is determined by the ability of the pavement to carry the required loads and maintain requisite stiffness at the joints.

A condition assessment is the first step in determining appropriate strategies for a specific pavement. This should include an evaluation of the existing pavement condition as demonstrated by key distress levels and characterized by behavioral responses. The assessment of the condition of an existing rigid pavement must identify both existing functional and structural deficiencies. A few SHAs consider structural distress types in their procedures but most SHA databases contain less than 10 years of historical information since a systematic method for assessing pavement performance did not exist for the most part prior to 1986.

As an example of remaining life determination, a brief outline detailing a series of performance relationships that incorporate key structural condition components, is presented although functional remaining life and non-pavement factors are recognized as important considerations as well. To further narrow the focus of this outline, the following discussion will only address jointed concrete pavement performance relative to the characterization of joint stiffness and load transfer relative to overlay design.

Structural Characterization of Pavement Layers

Pavement condition and remaining life assessment often involves non-destructive testing (NDT). NDT is useful to create deflection basin data that are used to characterize the support conditions of concrete pavements. In characterizing these support conditions, the following types of field information regarding the existing pavement structure is necessary:

a. Foundation modulus or k-value,
b. Thickness and elastic modulus of each layer, and

c. Falling weight (FWD) or rolling heavy wheel deflectometer data (tests normally conducted in the morning hours) at cracks, joints, and other locations in the existing pavement.

The use of deflectometer data plays a key role in concrete pavement evaluation since it provides a measure of the deflected slab profile under load. The use of a FWD to evaluate pavement support conditions has been previously used [Zollinger and Barenberg, 1990] but use of a rolling dynamic deflectometer [McNerney et al, 1997] for evaluating CRC pavements is a promising possibility as well. Data of this nature are used to calculate the deflection basin area and the load transfer efficiency across joints or cracks. The calculated basin area and the load transfer efficiency are then used in the analysis to characterize support conditions provided by the pavement system.

Foundation modulus or subgrade k-value

The k-value of a soil or its modulus of subgrade reaction is indicative of the support provided by the subgrade and is important along with its associated variability or coefficient of variation (cv) in a rehabilitation or overlay design process. The conventional method of using the plate-bearing test is what is used to characterize the modulus of subgrade reaction, but this method is very rarely used. Various strength tests performed on the subgrade soils are often used to estimate the subgrade k-value but may suffer similar limitations as the plate-bearing test. Non-destructive testing (NDT) may be the most practical approach to determine a subgrade k-value at specific slab locations by back-calculation methods based upon Westergaard-type formulations. This approach can provide acceptable foundation support data. When a subbase or a stabilized subbase is used under the pavement, the k-value determined by NDT represents the entire foundation support as a composite layer. [Darter et al, 1995].

Thickness and Modulus of Each Layer

The type, thickness, and modulus of each layer in the existing pavement section must be known to facilitate effective modeling of the system layer configuration. From the as-built plans and profiles of the existing subgrade, it should be possible to obtain details of the thickness of each layer in the pavement section. The type and the thickness of the sub-base material may also be noted. The elastic modulus of the existing concrete may be most suitability determined (in the opinion of the authors) by testing available cores taken from the original slab. Other means, such as the cross-hole seismic method, may also product suitable results. The modulus is used as an input to the NDT analysis. The modulus of the sub-base can also be determined using compression tests on field or laboratory samples depending upon the type of stabilizer used.

Characterization of Joint or Crack Stiffness

Both joints and cracks (mid-slab, corner, etc.) have been recognized as a major focal point for pavement distress in jointed concrete pavements (and overlays placed on jointed pavements), and transverse cracks are similarly recognized in many instances as the source of problems that develop in CRC pavement. Discussion provided by Jeong and Zollinger [2001] detailed the characterization of the ‘effective’ stiffness of a joint or crack using FWD data in terms of the radius of relative stiffness (P) and is not elaborated here other than to note that the relative stiffness is theoretically determined by the following equation:

$$\ell = \left[\frac{Eh^3}{12(1-\nu^2)k} \right]^{\frac{1}{4}}$$

where

E = concrete modulus of elasticity (psi)
h = Thickness (in)
< = Poisson's ratio
k = Foundation modulus (psi/in)

The P-value is a key factor in remaining life determination since it can serve as an indicator of slab stiffness at joints or cracks. This makes it useful for assessment of *insitu* stiffness of the existing pavement structure or a transverse crack and the assessment of the improvement of pavement stiffness due to rehabilitation treatments such as CPR or overlays. Consequently, the 'effective' P-value is useful for overlay design as well. The root of the utility of the 'effective' P-value is derived from the fact that it is calculated from deflection basin data as measured in the field using an FWD. Matching the measured deflection basin across a joint or crack allows for the determination of an 'effective' stiffness (P) of the transverse crack. Subsequent discussion will briefly demonstrate how the 'effective' P-value of a joint or crack affects overlay design and is related to load transfer efficiency (LTE) or joint stiffness (J).

As also noted by Jeong and Zollinger, characterization of the effective joint stiffness in a existing pavement system may be affected by the degree of bond between the slab and the supporting layer below. The slab may either be bonded to the base or it may be unbonded. In either case, the most satisfactory results are obtained by considering the base or the sub-base as a part of the pavement system rather than part of the pavement support. For modeling an unbonded condition, a two-layer analysis may be used where the existing pavement is modeled atop a stabilized base (if one exists) and the subgrade. This approach can provide a back-calculated k-value or an effective layer modulus [Ioannides, et al, 1992]. In a bonded slab, the two layers may be treated as one equivalent layer with a composite layer thickness. If the existing slab has no stabilized base, two-layer analysis is most appropriate [Darter et al, 1995].

A back-calculated k-value (whether the pavement is bonded or unbonded) as approximated from a Westergaard analysis for an interior load condition is determined from the following equation:

$$k = \frac{P}{8D_0 \ell_m^2} \left[1 - \left\{ \frac{a}{\ell_m} \right\}^2 \left(0.217 - 0.367 \log \left\{ \frac{a}{\ell_m} \right\} \right) \right] \qquad (1)$$

The effective elastic modulus, if of interest, (E_e) may also be back calculated as:

$$E_e = \ell^4_m 12(1-\nu^2)\frac{k}{h^3}$$

where

P = load applied in lbs.
D_o = maximum deflection under the load
P_m = radius of relative stiffness corresponding to the measured basin area
= $a_1 + a_2 \cong \text{Area} + a_3 \cong \text{Area}^2$ where $a_1 = 74.32$, $a_2 = -4.185$, and $a_3 = 0.003163$ are regression constants with $r^2 = 0.9949$ and the SEE = 0.7548.

< = Poisson's ratio
k = back-calculated subgrade modulus.
a = loaded radius

The expression for P_m is applicable for the configuration of the pavement system that exists at the time of the FWD testing, whether it is a single or two layer system. This value is used to calculate the composite pavement stiffness with an overlay. The above can also be used to characterize the overall pavement behavior in terms of the structural parameters of the original pavement system. The overall composite pavement stiffness ($E_c h_c^3$) can be defined in terms of the existing pavement system and an unbonded overlay as:

$$E_c h_c^3 = E_1 h_1^3 + E_2 h_2^3 \qquad (2)$$

where,

$E_c h_c^3$ = composite pavement stiffness,
E_i = flexural moduli of the pavement layers (1 = Overlay, 2 = Existing Slab),
h_i = thickness of the pavement layers.

The subscript "c" denotes the properties of the composite pavement system imagined to rest on the same foundation as the original pavement. Although not shown here, a similar approach may be applied to the case of a bonded overlay. In this case, the flexural stiffness of the composite pavement is determined in terms of the properties of the original pavement system and a bonded overlay using the parallel axes theorem [Ioannides et al, 1992].

Therefore, an overall stiffness ($E_c h_c^3$) may be determined, for design purposes, for unbonded as well as bonded layer conditions relative to the basin area and the radius of relative stiffness of the existing pavement system. E_1 and h_1 are the elastic modulus and the thickness of the pavement surface (or overlay) and E_2 and h_2 are those of the lower pavement layer and may be considered to be effectiveness values since they may include the effect of the transverse cracks and joints.

Pavement Rehabilitation Design and Life Extension

Using the parameters relevant to the evaluation of concrete pavements described above, life extension relative to an overlay or any repair technique that improves the 'effective' stiffness can now be elaborated. Life extension is indirectly addressed through effects on load transfer efficiency (LTE) and the total joint stiffness factor (J). Jeong and Zollinger [2001] indicated the relationship between J and LTE and its dependence upon the opening of the joint or crack. If

$$\ell_c^4 = \frac{E_c h_c^3}{12(1-\nu)k}$$

then the joint stiffness factor can be defined as:

$$J_c = \frac{Agg}{k\ell_c}$$

providing a relation to LTE where Agg is the aggregate interlock spring stiffness. It is clear the effective or composite P-value and J factor have components consisting of the stiffness characteristics of the existing pavement layer and that of the rehabilitation treatment. The effect

of these components on life extension is indirectly manifested through the improvements on LTE.

Application to Overlay Design

The utility of the above evaluation process can be demonstrated in the determination of overlay thickness as a function of the pavement condition from a structural stiffness and LTE perspective. For the purpose of structural analysis, it is important to consider whether the overlay is to be bonded or unbonded to the original pavement surface in the design process and whether or not the existing pavement layer is CRC or jointed concrete. The approach previously elaborated is used to represent a typical overlay condition (Figure 3) as an "effective" single layer pavement system.

Design Criteria

Concrete pavement overlay thickness design criteria may be formulated relative to fully supported pavement behavior. Lack or loss of pavement support may occur in several forms, such as poor load transfer across an underlying joint or crack or another condition at the joint location in the existing layer where the end result is usually a loss of deflection continuity. In other words, there are unequal deflection characteristics between adjacent slabs or segments of the supporting pavement which will cause the overlay and the original pavement to separate while under load, causing, in effect, a temporary void beneath the supported layer [Zollinger and Barenberg, 1990]. Thus, a concrete overlay would be forced to "bridge over" this void, causing highly localized shear stresses. This is a significant behavior defect (that can be represented by the 'effective' P-value), and the minimization of such is the basis for the design approach discussed below.

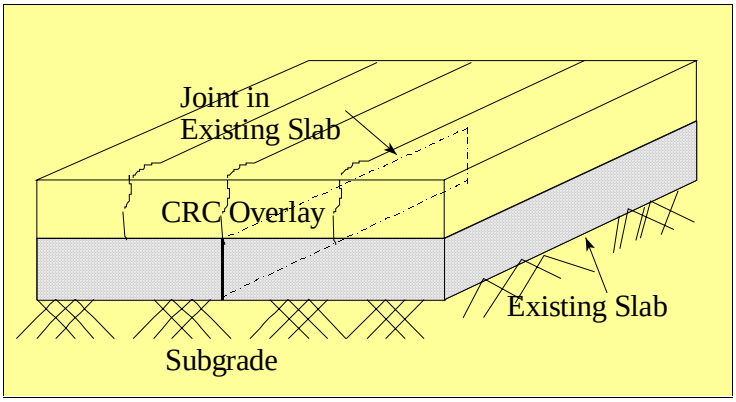


Figure 3 Section Overlay and Existing Pavement.

In terms of the effect of an overlay treatment, the level of stiffness of the existing concrete pavement system can be improved by placing an overlay on it. The benefit of an overlay can be assessed in terms of the increase in the overall stiffness of the pavement system. The effectiveness of an overlay can also be enhanced by improving the load transfer of the joints and cracks in the existing pavement layer prior to the placement of the overlay. Whatever the case may be, the load transfer must be increased or the overlay thickness placed great enough to cause the composite pavement system to behave as though it is fully supported and maintain deflection continuity within the pavement system under load. The effect or contribution of these improvements is quantified relative to the increased overall pavement stiffness. This is accomplished using the equations described above for either unbonded or bonded conditions.

In order to establish design criteria to maintain deflection continuity between different layers of the pavement system, limiting pavement stiffness for design purposes (Design Eh^3) must be defined for fully supported conditions. This can be done using equation 4 and the P-value for a fully supported slab:

Design $P_c \exists$ P for a fully supported system

and the required overlay thickness:

$$h_{OL} = \left[\frac{12k(1-\nu^2)(Design\ell_c^4 - \ell_e^4)}{E_{OL}} \right]^{1/3}$$

where E_{OL} is the elastic modulus of the overlay concrete. The difference between fully supported pavement P-value and the P-value of the existing pavement system determines what the required overlay thickness should be.

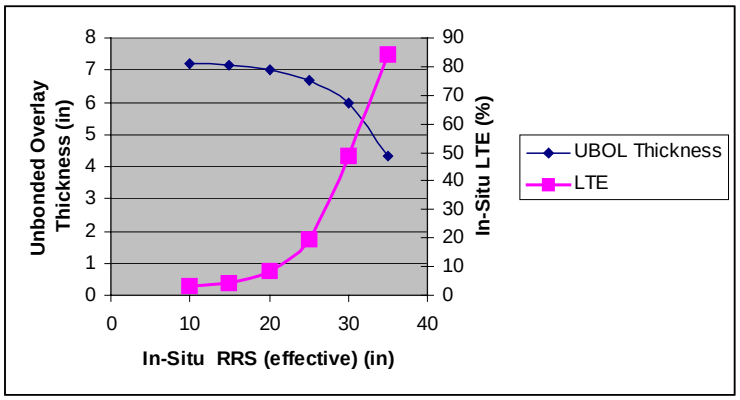


Figure 4 Unbonded Overlay Thicknesses as a Function of Existing Slab Conditions.

Improving the load transfer conditions of cracks and joints in the existing slab can increase the effective stiffness of the existing pavement system. The quality of the load transfer in the existing pavement system is reflected in the measured basin area. The basin area in turn affects the pavement "effective" stiffness where the effective stiffness may be found for different levels of load transfer across the joints/cracks in the original pavement layer. Improvement of the existing load transfer is represented in the design process by increasing the basin area and improving the "effective" pavement stiffness (equation 3) of the pavement system. A relation shown in Figure 4 between layer stiffness and load transfer illustrates this improvement. Jeong and Zollinger [2001] indicated in Figure 5 how LTE affects bending stresses in a CRC pavement. Consequently, the amount of slab repair, relative to LTE, can be directly reflected in the structural rating based on the resulting fatigue cracking.

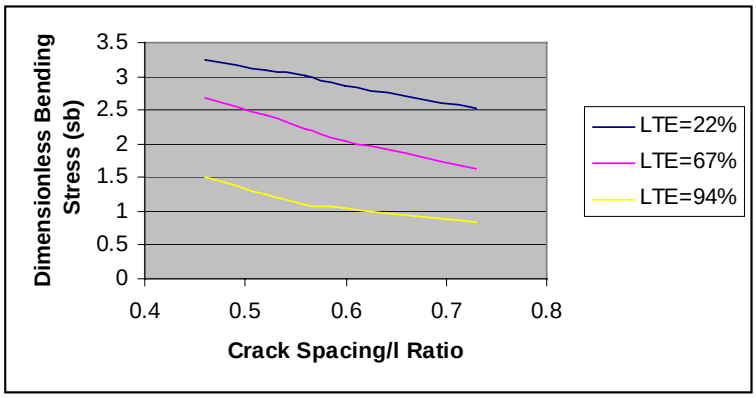


Figure 5 Dimensionless Stress - P value Relationships. [Jeong and Zollinger 2001]

Summary and Conclusions

Although the details are not elaborated, many of the key elements are, whereas the information represented in this paper provides a framework in which to

evaluate and select pavement treatment types as a function of their contribution to the structure of the pavement. An approach was presented to relate structural enhancement to the structural rating of the pavement system and ultimately to the expected performance. If selected R&R treatments were shown to sufficiently improve the stiffness of a given section, its overall condition would improve and result in extended pavement life. Although only briefly presented, in order to assess the value of a given R&R treatment type relative to its capability to extend pavement life and its associated life cycle cost, it will be important to develop prediction schemes for various distress types based upon the reduction in damage created by the original distress. The methodology presented in this paper further promotes a systematic approach to consideration of many factors that affect pavement rehabilitation decisions and hopefully enhance the effectiveness of strategies for maintenance, rehabilitation, and reconstruction of concrete pavements. These concepts will also enhance better decision-making processes to select MRR strategies and R&R treatments and assist highway agencies to select treatments that will ensure expected performance.

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Appendix A: Treatment Selection Process.

Type of Distress	Type of Treatment	Evaluation Criteria				
		Expected Life	Level of Severity	Pavement Condition	Traffic Level	Climate
Cracking: Midslab or Random	RLT	Med, Long	Low (JPCP)	LTE<90%	>500 ADTT	All
	FDR	Med, Long	Med to High	<1% crk/yr	All	All
		Short	High	<20% crk	>500 ADTT	DNF
		Short	High	<20% crk	<500 ADTT	All
		Short	Med to High	<20% crk	>500 ADTT	WNF, WF, DF
	FDR, $ACOL_S$	Short	High	<20% crk	<500 ADTT	All
		Med, Long	Med to High	All	All	All
		Long	Med to High	All	>500 ADTT	All
	FDR, BCOL	Med, Long	All	>1% crk/yr	All	All
	FDR, UCOL	Med, Long	Med to High	>1% crk/yr	All	All
Loss of Joint Stiffness (load transfer), Pumping, and Erosion	Under Sealing	Med, Long		Voids are present	>500 ADTT	All
	RLT	Med, Long	LTE < 90%		>500 ADTT	All
	Clean or Provide Edge Drains	Med, Long		Voids are present	>500 ADTT	All
Roughness (faulting)	Dia Grind		High	<20% crk	All	All
Spalling	Dia Grind	Med	Low	<20% crk	All	All
	PDR	Short	High	<20% crk	All	All
	PDR	Med, Long	Med, High	<1% per yr	All	All
	PDR, BCOL	Med, Long	High	>1% per yr	<500 ADTT	All
	PDR, BCOL	Med, Long	High	All	>500 ADTT	All
Loss of Skid Resistence or Excessive Noise	Dia Grind	Med	Low	<20% crk	All	All
	BCOL	Long	Med to High	<20% crk	All	All
	$ACOL_{NS}$	Med	Med to High	<20% crk	All	All
D - Cracking, ASR, or other Materials Related Distress	All	Short	MRD = 2	<20% crk	All	All
	All	Med	MRD = 1	<20% crk	All	All
	Rubblize, $ACOL_S$	Short to Long	MRD = 3	<20% crk	All	All
	UCOL, FDR	Short to Long	MRD = 3	<20% crk	All	All
	UCOL, Slab Fract	Short to Long	MRD = 3	<20% crk	All	All
	Nconst	Short to Long	MRD = 3	<20% crk	All	All