REHABILITATION OF PCC PAVEMENTS USING FRACTURE TECHNIQUES AND HMA OVERLAYS

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This paper describes the technical development of relatively new and innovative methodologies for rehabilitation of Portland Cement Concrete (PCC) pavements involving the fracturing of the pavement slab prior to the placement of an asphalt concrete (HMA) overlay with the objective of eliminating or minimizing the occurrence of reflective cracks in the overlay. As used in this paper, the term "Fractured Slab," refers to an element of PCC pavement rehabilitation techniques generally known as crack and seat, break and seat, and rubblize followed by an HMA overlay. The information and findings contained in this paper are based on an extensive nationwide research study conducted by PCS/Law Engineering, Inc. for the National Asphalt Pavement Association (NAPA) and the State Asphalt Pavement Association Executives (SAPAE).

INTRODUCTION

The use of HMA overlays for the rehabilitation of deteriorating PCC pavements has been a common rehabilitation option for many decades. However, performance of these overlays is often hampered by the occurrence of reflective cracks over existing joints and cracks in the PCC pavement. This type of distress constitutes the most frequent cause of the loss of HMA overlay performance.

Reflective cracks in the HMA overlays are caused by a complex interaction of both thermal and traffic induced stresses. Expansion and contraction of the PCC pavement results in cyclic horizontal movements that produce strains in the overlay exceeding its resistance. In addition, traffic loads cause vertical differential movements at the location of joints and working cracks in the PCC slab and induce tensile strains at the bottom of the HMA layer. The overlay immediately over the joints and working cracks in the PCC is not able to accommodate these localized movements resulting in the development of reflective cracks as illustrated in Figure 1.

The engineering profession has attempted a wide variety of rehabilitation techniques principally aimed at eliminating the reflective crack problem associated with HMA overlays over PCC pavements. Table 1 is a summary listing of the various approaches which have been tried by the pavement community. The more recent innovative category that has been used increasingly over the last 5 to 10 years has been the "Fractured Slab" approach.

The probability of reflective cracking is directly proportional to the horizontal

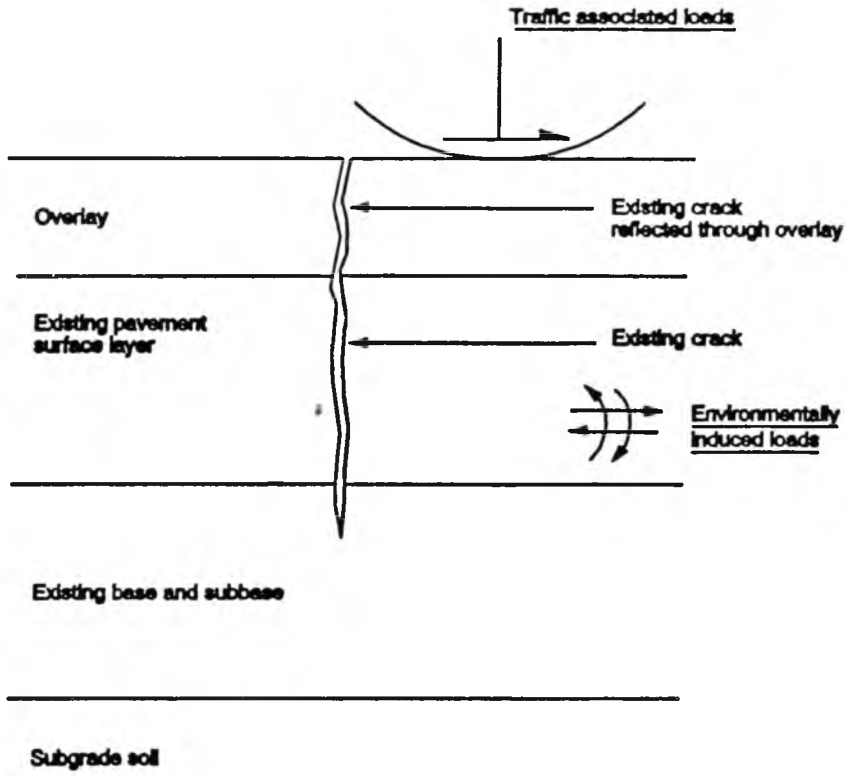

FIGURE 1. SCHEMATIC DIAGRAM OF REFLECTION CRACKING

TABLE 1
MAJOR CATEGORIES OF AC OVERLAYS TECHNIQUES OVER EXISTING PCC PAVEMENTS

- "No" Reflective Crack
  - Thick (Conventional) AC Overlays
  - Crack Relief Layers
    - Open Graded Asphalt Base
    - Unbonded Granular Base
- Saw/Seal AC Overlays
- Special Overlay Materials
  - Rubberized AC Overlay
  - Modified AC Overlay
- Special Interface Materials
  - Stress Absorbing Membrane Interface (SAMI)
  - Geotextiles/Fabrics/Masties
- Reduction of Effective Slab Length (Fractured Slab)
  - Rubblize
  - Crack/Seat - No Reinforcing Steel Present
  - Break/Seat - Reinforcing Steel Present

movement at joints and cracks, which in turn are directly proportional to the spacing between joints and cracks. The major objective of the "Fractured Slab" approach is aimed at reducing the effective in-situ slab length before the overlay is placed. If this is effectively accomplished, the likelihood of having reflective cracks appear is significantly reduced.

The Fractured Slab category is generally subdivided into three major types of rehabilitation; rubblize, crack/seat, and break/seat. Rubblize is a fractured slab process intended to transform the existing PCC layers into fragments having the textural/gradational characteristics of a large aggregate size crushed stone base. It is most effectively accomplished with a Resonant Pavement Breaker (PB-4 type) and has been found to be successfully used on any type of existing PCC pavements (i.e., Jointed Plain; Jointed Reinforced; and Continuously Reinforced).

Crack/seat and break/seat are fractured slab techniques intended to produce very short rigid slabs whose effective lengths vary from 12 in. to 48 in. Both construction techniques (i.e., crack/seat and break/seat) are similar with Guillotine or Spring-Arm (Whip) Hammers being used to develop the reduced crack spacings in the existing PCC pavement. While the construction techniques are similar, there is a very major and important distinction between the two techniques.

As used in this paper (and the prior study), the definitions of rubblize, crack/seat, and break/seat are consistent with the Federal Highway Administration (FHWA) terminology. The term crack/seat is associated with the fractured slab process conducted solely on Jointed Plain Concrete (JPC) pavements. For these pavements, the objective of the crack/seat process is to develop closely spaced, tight cracks which permit load transfer across the crack through aggregate interlock with little loss of structural value. Fracture or cracking through the entire depth of the PCC layer is the ultimate goal. The term break/seat is associated with the fractured slab process on Jointed Reinforced Concrete (JRC) pavements. The ultimate objective of the break/seat process is to physically fracture the distributed steel and/or completely debond the steel from the concrete. While cracking may result through the entire PCC layer depth, if steel fracture and/or debonding is not accomplished; the effective slab length is not reduced in the construction process and what remains is a series of smaller slabs tied together into a longer effective slab by the bonded distributed steel.

A co-requisite to the slab fracturing process is the Seating portion of the construction. For both cracking and breaking, it is customary practice to have 5-7 passes of a 35 ton to 50 ton roller "seat" the fractured slab fragments. This provides a relatively smooth and uniform grade for paving operations and also serve as an excellent means of proof-rolling before the HMA overlay is placed. For rubblized projects, steel vibratory rollers are normally used for the compaction or seating process.

NATIONWIDE EVALUATION STUDY

Objectives and Approach

Over the past 15 years, there has been a rather dramatic increase in the use of the fractured slab category of PCC rehabilitation. Much field experience has been gained during this time. However, little technical guidance relative to the design and construction of these techniques has become available to adequately predict their performance in terms of minimizing reflective cracking under specific traffic and climatic conditions for a particular pavement structure and existing condition. As a consequence, the major objective of the NAPA/SAPAE jointly funded project with PCS/LAW was to develop guidelines and methodologies for these rehabilitation techniques, based upon state-of-the-art principles suitable for nationwide implementation. This comprehensive study was initiated in 1988 and a final report provided to NAPA/SAPAE in June 1991 entitled Guidelines and Methodologies for the Rehabilitation of Rigid Highway Pavements Using Asphalt Concrete Overlays. Reference is made to this comprehensive document for further details of the overall study. The following portions of this paper are intended to provide a condensed summary of the study findings.

The study report contains information dealing with the saw and seal type of PCC pavement rehabilitation. For purposes of brevity, this rehabilitation option is excluded from further discussion in the paper and only those rehabilitation options noted as Fractured Slab approach are addressed.

In recognition of the critical need for a sound technical basis to support the extensive use of HMA overlays as the primary rehabilitation process for deteriorating PCC pavements, the national research study conducted was based upon the following major work activities.

1. Development of a General Data Base
2. Selection of Field Test Sections
3. Development of a Detailed Data Base
4. Collection of Field Performance and Layer Responses
5. Data Analysis
6. Development of Design Methodologies

The development of the General Data Base utilized an extensive synthesis of current practice as obtained from a comprehensive literature review. This review resulted in the identification of 487 pavement sections applicable to the study. The breakdown by rehabilitation type was:

Crack and Seat	250
Break and Seat	150
Rubblize	19
Saw and Seal	33
Unknown*	35
	487

(* Unknown if steel was present or not)

Based upon the results of this literature search, a detailed list of specific projects (test sections) were selected to represent the four rehabilitation types in as many climatic zones as possible and covering ranges of overlay thickness, rehabilitation age, and age of existing PCC pavement prior to overlay. These sections formed the Detailed Data Base and were the focus of additional field surveys by PCS/LAW relative to both detailed pavement condition index (PCI) surveys as well as nondestructive (NDT) deflection testing conducted with a Falling Weight Deflectometer (FWD). This deflection data was used to backcalculate an effective modulus for the fractured PCC layer of the test section. Table 2 summarizes the breakdown by rehabilitation type of the actual number of sections investigated in the study. Except for the saw/seal, both PCI and NDT measurements were made on most sections. In addition, other sources (non PCS/LAW) of NDT data were found in several states and this information was included within the Detailed Data Base. Figure 2 shows the locations of the field test sections used by PCS/LAW and Table 3 is a summary of the NDT program for the overall study. From this table, it can be observed that 4700 NDT test points were obtained and subsequently used in computerized solutions to backcalculate the

TABLE 2
DISTRIBUTION OF FIELD TEST SECTIONS
(DETAILED DATA BASE RECORDS) BY REHABILITATION TYPE

REHABILITATION TYPE	NDT/PCI (PCS/LAW)	NDT ONLY (PCS/LAW)	PCI ONLY (PCS/LAW)	NDT ONLY (STATES)
Break & Seat	34	2	5	16 (5)*
Crack & Seat	33	1	1	30 (3)*
Rubblize	16	0	1	8 (1)*
Saw & Seal	0	0	18	0
Control	4	2	1	0
TOTALS	87	5	26	54

( )* Number of records that represent sections for which NDT data was also collected by PCS/LAW and included as a separate record.

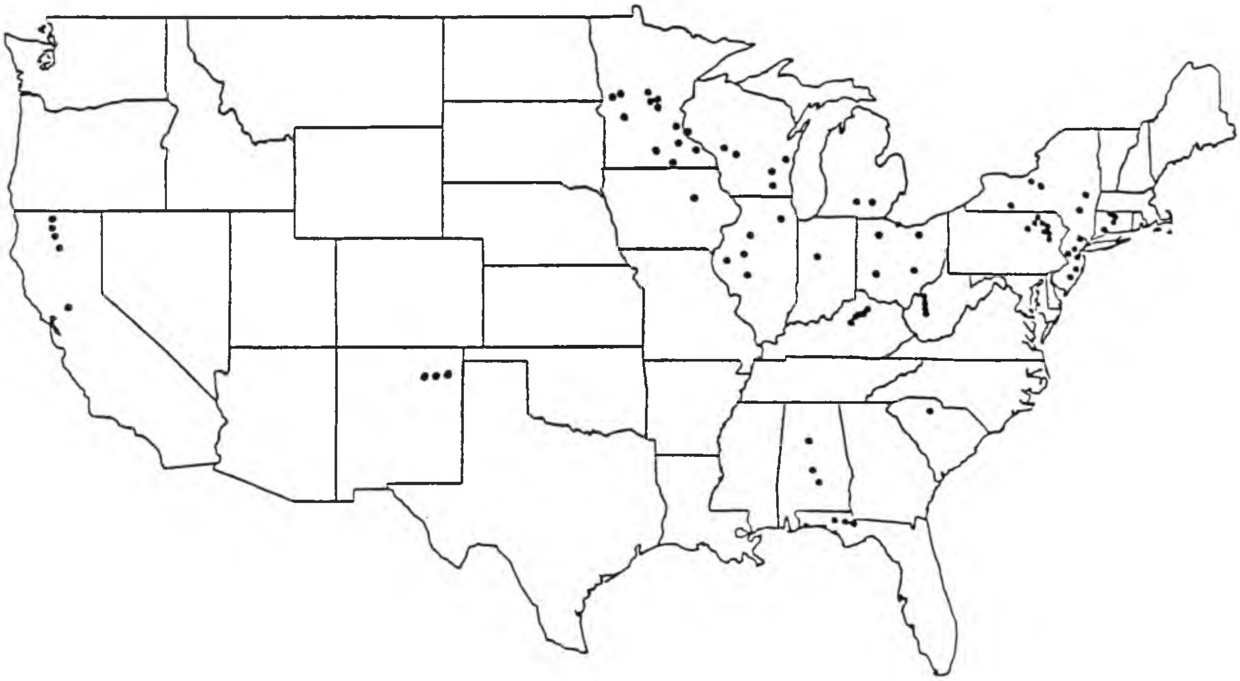

FIGURE 2. LOCATION OF FIELD TEST SECTIONS WITH RECORDS IN DETAILED DATA BASE

TABLE 3
DEFLECTION TESTING PROGRAM SUMMARY

DEFLECTION TESTING PROGRAM SUMMARY			
Type of Rehabilitation	No. of Sections	Total No. of NDT Locations	Average No. of NDT Points/Section
Rubblized	24	1019	43
Crack/Seat	64	1776	28
Break/Seat	52	1905	37
Total	140	4700	34

TABLE 4
SUMMARY OF AVERAGE STATISTICS OF
FIELD TEST SECTIONS

Rehabilitation Type	Average Date of Rehabilitation	Average AC Overlay, in.	Average PCC Thickness, in.
Crack and Seat	1984	4.4	8.3
Break and Seat	1985	5.6	9.4
Rubblize	1986	6.0	8.9
Saw and Seal	1983	3.4	8.3

effective in-situ modulus of the fractured slab layers (E_{PCC}).

Based upon the contents of the Detailed Data Base sections; analysis of the data was conducted, results generated, and the final report design guidelines and methodologies determined.

Major Study Results

While this paper cannot address all of the results and findings presented in the final report, several key results are presented which form the basis of the design methodologies described in the next section of this paper.

Of interest from a practical viewpoint, is a summary of several key variables (average date of rehabilitation, average HMA overlay thickness, and average PCC thickness) shown in Table 4 for each of the four rehabilitation types. As can be observed, the average dates of the rehabilitation options clearly show the relative "youthfulness" of the methods discussed, particularly for the rubblize technique. The table also shows that the average PCC thicknesses range between 8 in. and 10 in., which are very typical of highway pavements. Finally, the resulting average statistics for the HMA overlay thicknesses are quite revealing. The thinnest HMA overlay is shown for the saw/seal option. This is consistent with the fact that this rehabilitation option is normally placed on existing PCC pavements which are in relatively good condition. In contrast, the rubblize technique provides the largest average overlay thickness. Again this is consistent with the fact that the rubblization process is intended to truly transform an existing "rigid" layer into a conventional "flexible" layer.

While many factors influence the performance of each rehabilitation technique studied, overall general trends and models relating the PCI to the time from rehabilitation were developed. Although the R^2 values of these equations were not high they, nonetheless, provide a global ranking of each rehabilitation procedure. The general equations for predicting PCI are shown in Table 5. Also shown in this table are the average times to reach typical failure conditions (i.e., PCI levels when major rehabilitation would be required) for each rehabilitation type.

While several multivariate predictive equations for PCI and E_{PCC} (effective in-situ fractured PCC modulus) were developed and presented for each rehabilitation type; one of the more important predictive models developed is for the E_{PCC} of the crack/seat technique. This equation was:

$$E_{PCC} = -968.39 + 20.34E_{sub} + 34.89CS + 5.37SL \qquad R^2=0.776$$

where E_{PCC} = effective in-situ fractured slab PCC modulus (in ksi); E_{sub} = composite foundation modulus of pavement below the existing PCC layer (in ksi); CS = specified crack spacing in the crack/seat operation (in inches); SL = seating load applied (in tons).

This model (and others as well) clearly illustrate the importance of crack spacing and the foundation support of the existing PCC pavement. As both of these variables are increased, the E_{PCC} value likewise increases. While historic construction information has shown that crack spacings from 12 in. to 60 in. have been used, recommended crack spacings for the crack/seat process are shown in Table 6. It can be observed that the target crack spacings decrease as the stiffness of the underlying foundation is increased.

Numerous other researchers have shown that the effective E_{PCC} value is dependent upon the nominal crack spacing/fragment size after slab fracturing. A study of this was also conducted in the report. A comparison of the general

TABLE 5
PCI PREDICTIVE MODELS AND TIMES TO FAILURE

Type/Rehabilitation	General PCI-Time Model
Rubblize	$PCI_t = 100 - 1.613t + 0.092t^2$
Crack/Seat	$PCI_t = 100 - 0.343t - 0.136t^2$
Break/Seat	$PCI_t = 100 - 0.050t - 0.316t^2$
All "Fractured" Slabs	$PCI_t = 100 - 0.149t - 0.252t^2$
Saw/Seal	$PCI_t = 100 - 6.519t + 0.172t^2$

	Time to Reach PCI	
Type/Rehabilitation	PCI = 50	PCI = 40
Rubblize	*	*
Crack/Seat	18.0 years	19.8 years
Break/Seat	12.5 years	13.6 years
All"Fractured" Slabs	13.8 years	15.2 years
Saw/Seal	10.7 years	15.5 years

(*) Unable to project time as PCI>90 at t=8 to 10 years.

TABLE 6
RECOMMENDED CRACK SPACINGS FOR CRACK-SEAT

Type of Foundation	Recommended Crack Spacing, in.
Subgrade Soils	30
Granular Subbase	24
Stabilized Subbase	12

relationships between these variables show relatively good agreement with the 1986 AASHTO Guide for Design of Pavement Structures relationship for both rubblize and crack/seat techniques. In contrast to these rehabilitation types, a poor (unconservative) relationship for the break/seat option was found. These results are clearly shown in Figure 3.

The final, and most important, area of study dealt with the distribution of the E_{PCC} values found from the field section evaluations. Detailed analysis of this data led to the important conclusions regarding two major forms of variability encountered; the "between project" variability and "within project" variability. The "between project" variability reflects the variation between the average project predicted E_{PCC} values. As such, the standard deviation (σ_b) or variance (σ_b^2) reflects the variations attributable to each construction project on a national scale. Specifically, factors such as the type of equipment, specific breaking energy, specified crack spacing, and the specific site factors and pavement cross section are all reflected within the $\sigma_b(\sigma_b^2)$ parameter.

In contrast to the "between project" variability, the "within project" variability (σ_w or σ_w^2) reflects the resultant variation of the E_{PCC} values obtained within a given rehabilitation project. As such, the magnitude of this variation in the in-situ E_{PCC} values, within a given site, reflect the overall ability of the contractor to develop a uniform (or non-uniform) fractured slab product after cracking, breaking, or rubblization has taken place.

Figure 4 presents the between project E_{PCC} frequency distributions results for: rubblize; crack/seat; and break/seat, respectively while Table 7 summarizes the between project E_{PCC} statistics. From this figure, it can be observed that the distributions for the rubblize and crack/seat option are very similar. However, the frequency distribution of the break/seat E_{PCC} values indicate that results are extremely variable and highly indicative of the variable success in fracturing/ debonding distributing steel in the concrete.

The study dealing with the "within project" E_{PCC} variability as shown in Figure 5 indicates that regardless of the average project E_{PCC} value and the type of rehabilitation option investigated, the average coefficient of variation (CV_w) was approximately 40% and normally distributed. This result gives way to defining guidelines for project construction uniformity for all Fractured Slab options.

The recommended construction control guidelines for various levels of project uniformity are shown in Table 8. Approximately 22% of the sections were found by this study to be in each of the "Good to Excellent" (i.e., $CV_w < 30\%$) and the "Poor to Fair" (i.e., $CV_w > 50\%$) categories. Therefore, the "Fair to Good" category contains about 56% of all computed within project CV_w values found in this study.

HMA OVERLAY DESIGN

Design Philosophy

This study, as well as other researchers, has shown that general relationships exist between the effective modulus (E_{PCC}) of fractured PCC pavement and the resulting nominal fragment size. Because of this, the effective in-situ modulus of fractured PCC is directly related to the probability of reflective cracking in HMA overlays. As the E_{PCC} increases (i.e., the nominal slab size or length is increased), the probability of reflective cracking in a given HMA overlay also increases; or as the HMA overlay thickness increases for a given E_{PCC}, the probability of reflective cracking decreases. On the other hand, it must be recognized that the fracturing of the PCC pavement, when taken to the extreme

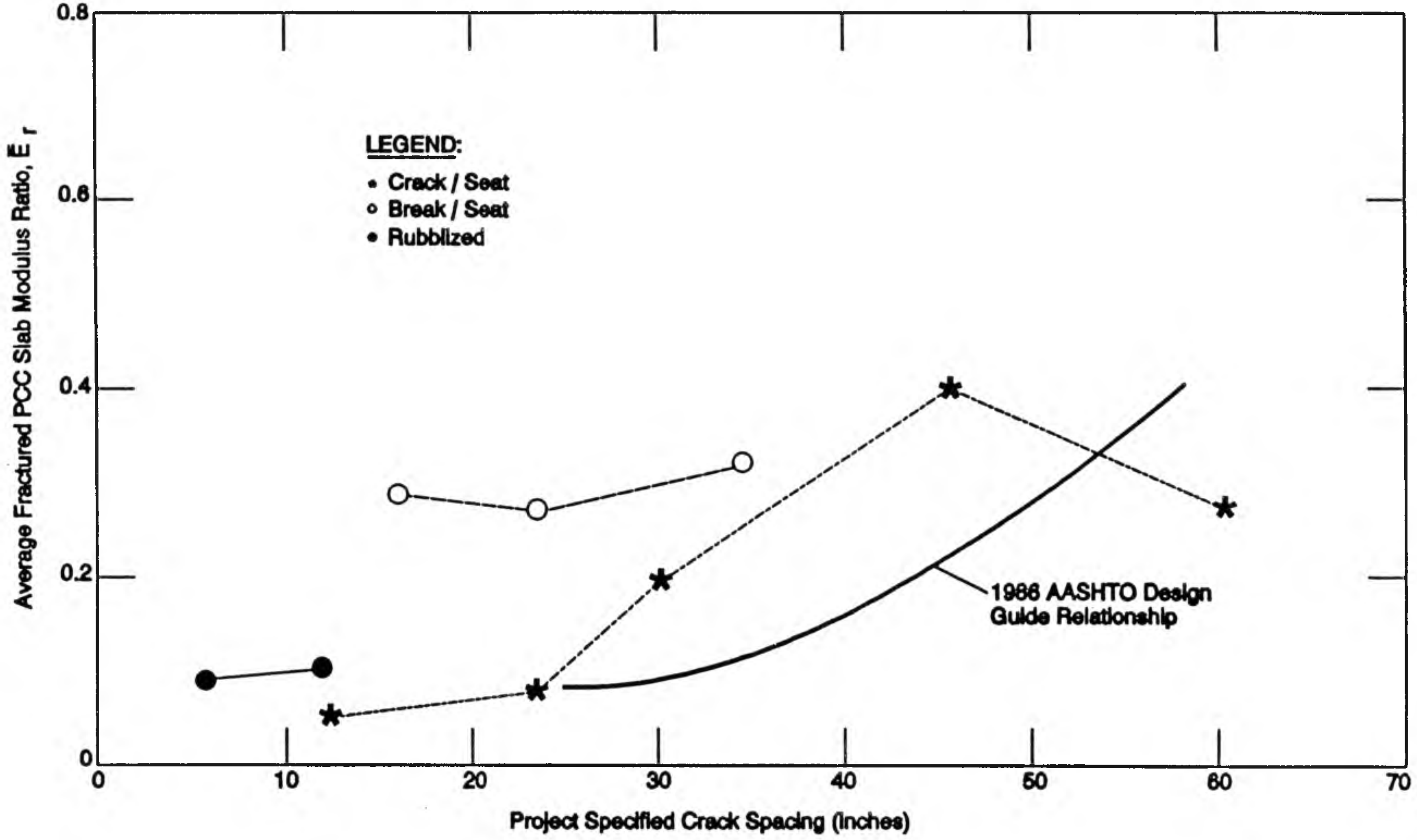

FIGURE 3. RELATIONSHIP OF AVERAGE PCC MODULUS RATIO VERSUS SPECIFIED PROJECT CRACK SPACING FOR FRACTURED SLAB TECHNIQUES

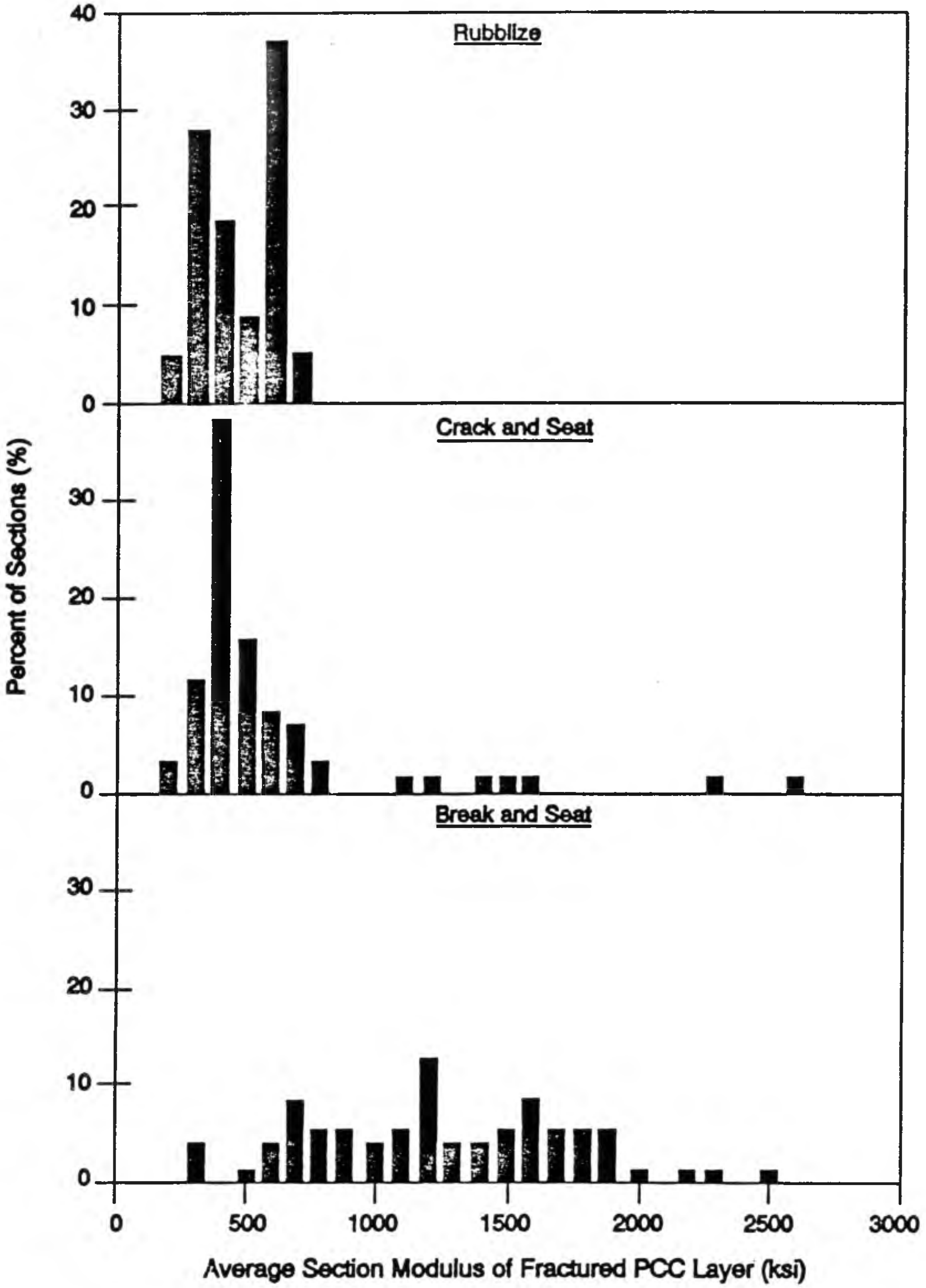

FIGURE 4. FREQUENCY DISTRIBUTION OF IN - SITU PCC MODULUS VALUES BY REHABILITATION TYPE

TABLE 7
SUMMARY OF BETWEEN PROJECT E_{PCC} STATISTICS

Type of Rehab	No. of Sections	Between Project Results			Remarks
		E_{PCC}	σ_b	CV_b(%)	
Rubblized	22	412.5 ksi	154.4 ksi	37.4%	Recommended (excludes 2 outliers)
	24	501.8 ksi	338.9 ksi	67.5%	All data
Crack/Seat	46	409.0 ksi	140.7 ksi	34.4%	Recommended (excludes all values greater than 1000 ksi i.e., Crack spacings 48" or greater)
	54	584.7 ksi	482.8 ksi	82.6%	Excludes California data
	64	780.6 ksi	665.6 ksi	85.3%	All data
Break/Seat	52	1271.5 ksi	548.7 ksi	43.2%	All data; Recommended
Combined	120	783.4 ksi	377.4 ksi	48.2%	All Recommended results
	140	915.1 ksi	578.0 ksi	63.2%	All data

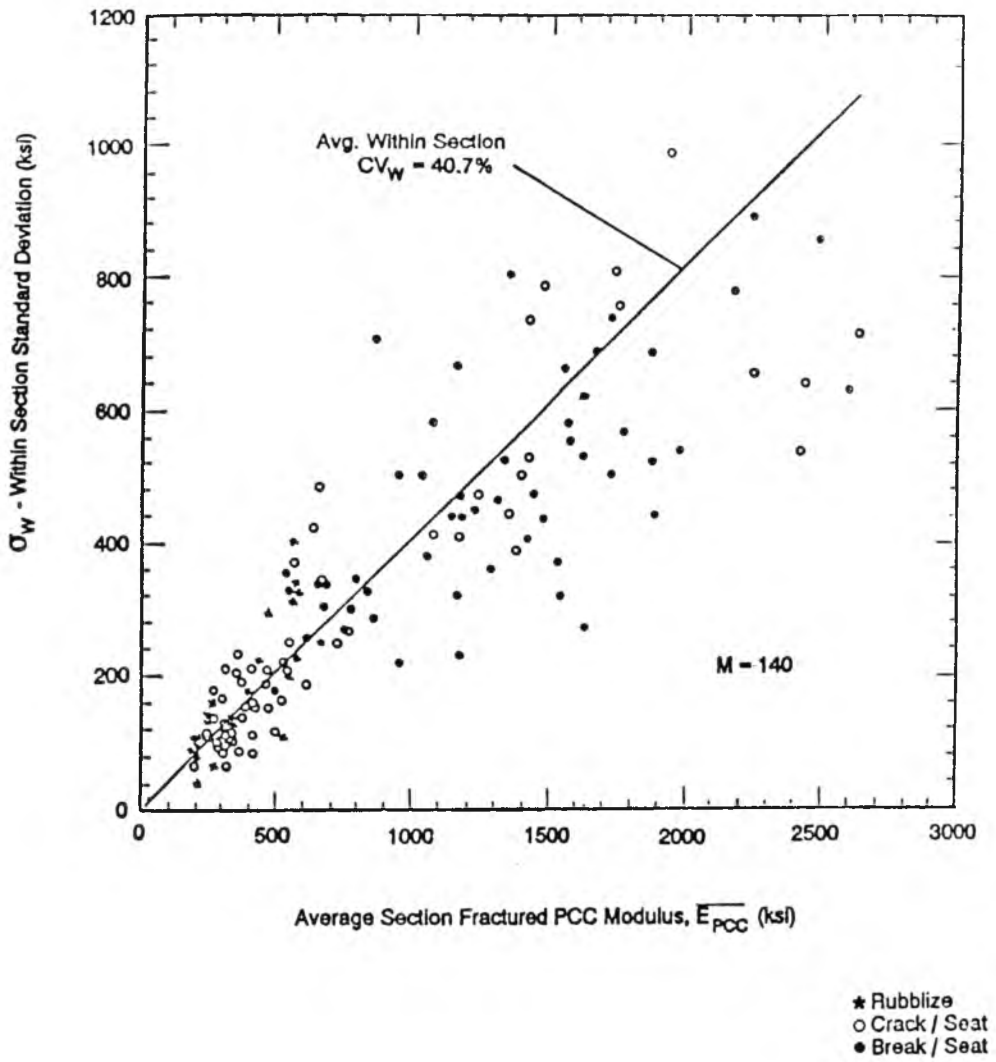

FIGURE 5. WITHIN SECTION VARIABILITY OF FRACTURED PCC SLAB MODULUS

TABLE 8
RECOMMENDED WITHIN PROJECT CONSTRUCTION UNIFORMITY LEVELS

Construction Control Quality	Proposed CV_w Limits
Good to Excellent	$CV_w < 30\%$
Fair to Good	$30\% \leq CV_w \leq 50\%$
Poor to Fair	$CV_w > 50\%$

degree of rubblizing, results in a "flexible" type pavement rather than a "rigid" type with structural slab action. Consequently, as E_{PCC} increases, the structural capacity of the pavement for a given HMA overlay increases and the probability of structural cracking distress decreases. Likewise, for a given E_{PCC} value the probability of structural cracking distress decreases as the HMA overlay thickness increases. When both of these relationships are considered together, a very important finding concerning the "Fractured Slab" rehabilitation technique is revealed in Figure 6. It can be seen that for a given HMA overlay thickness, the intersecting point of E_{PCC} vs distress (reflective and structural cracking) identifies a critical modulus (E_{α}) value that minimizes both distress modes.

While this E_{α} value may vary with the thickness of HMA overlay, it has been assumed in this study that the critical modulus is independent of the overlay thickness. Only further research will lead to the verification or modification of this assumption. For design purposes, a provisional critical value of E_{α} = 1,000 ksi has been established. Furthermore, in order to incorporate the influence of project variation, it is recommended that no more than 5% of the project's E_{PCC} value be greater than the E_{α} value.

The combination of both within project and between project variability of E_{PCC} values must now be considered to fully appreciate the design methodology being presented. In Figure 7, the average between project E_{PCC} and the within project modulus (E_{P1} and E_{P2}) for two typical projects are shown. For each project mean, it can be observed that the within project variability will affect the actual distribution of the E_{PCC} values for any given project. This is best illustrated by reference to Figure 8 which shows for each project, the three frequency distributions reflecting the range of project uniformity (i.e., Poor to Fair, Fair to Good, and Good to Excellent) along with the E_{α} value for minimizing HMA overlay distresses.

Because the average E_{PCC} value is small for Project 1, the probability of any combination of within project variation exceeding the critical threshold E_{α} value is non-existent. On the other hand, it can be observed for Project 2 (high E_{PCC} value) that as the project non-uniformity is increased, a significant portion of the modulus values exceed the E_{α} value. It can therefore be concluded that the ability of a given project to satisfy the E_{α} criteria is not only a function of the project average E_{PCC} value but also on the within project uniformity attained in the construction process.

It should also be recognized that from a structural viewpoint, a greater thickness of HMA overlay (and hence higher costs) would be required for Project 1 relative to Project 2, because Project 1 has a lower modulus. Thus, the optimal project is one that maximizes the average E_{PCC} value <u>and</u> minimizes the within project variability (i.e., Good to Excellent construction uniformity) so that the E_{α} criteria is satisfied.

While the previous discussion has primarily focused upon E_{PCC} distributions and their within project variability relative to the critical E_{α} for minimizing or eliminating reflective cracking, implications relative to the E_{PCC} distribution must also be considered relative to the structural overlay design. As discussed in the next section, the overlay methodology is based upon the utilization of the well known AASHTO Guide Structural Number (SN) concept for flexible pavements. An important parameter in SN computations is the AASHTO structural layer coefficient (a_i).

Analytically, the a_i value can be related to the elastic modulus of a material (E_i) through the following relationship:

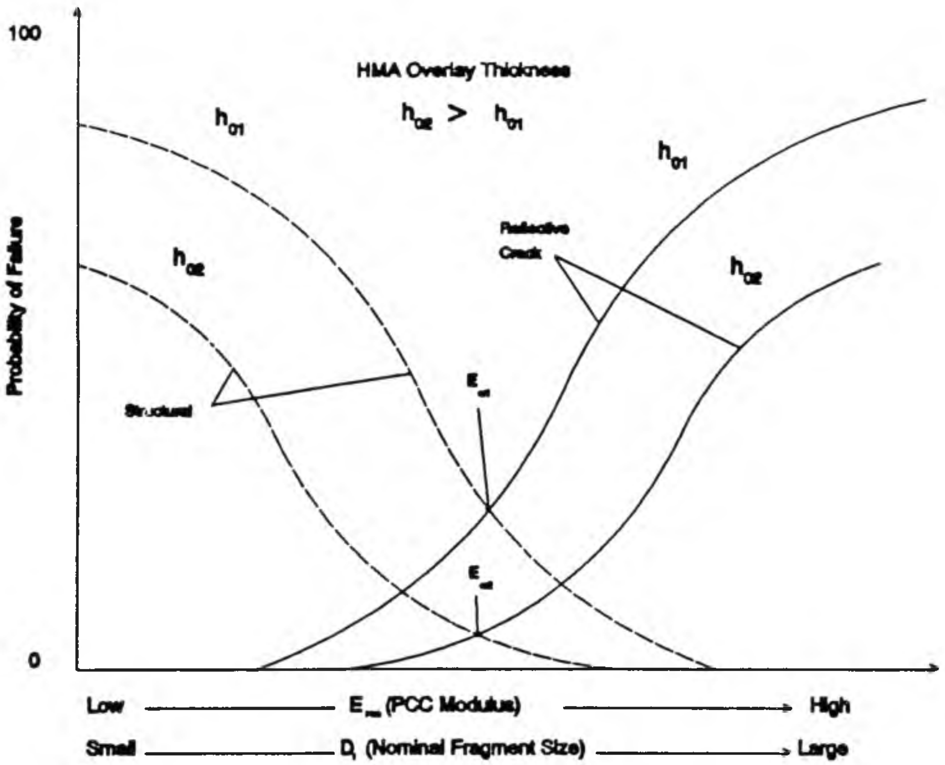

FIGURE 6. INFLUENCE OF PCC FRACTURED MODULUS AND HMA OVERLAY THICKNESS UPON STRUCTURAL AND REFLECTIVE CRACK FAILURE

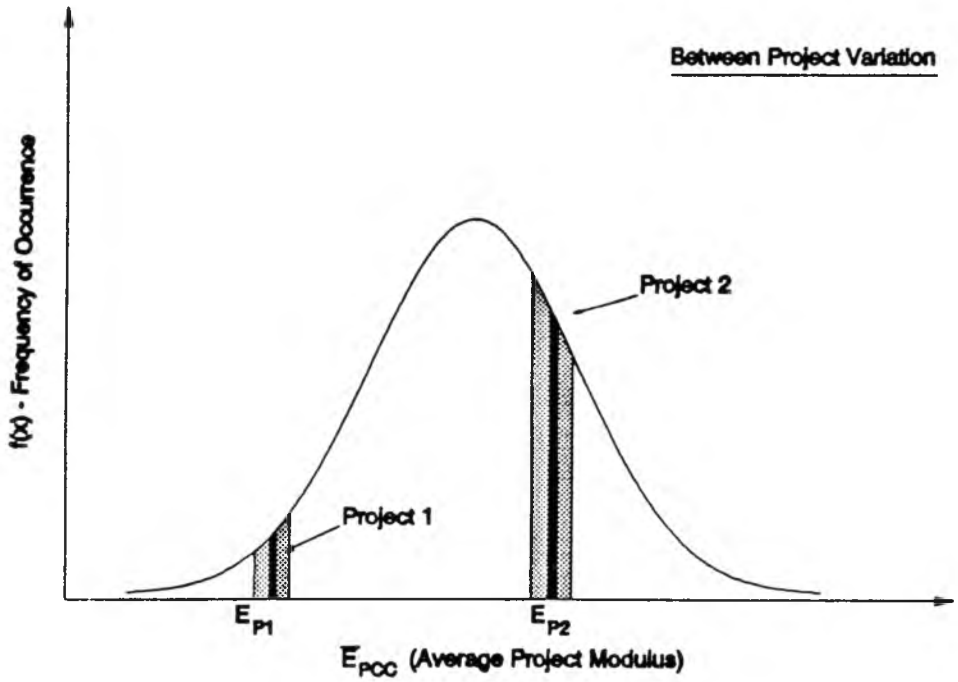

FIGURE 7. E_{PCC} FREQUENCY DISTRIBUTION OF AVERAGE PROJECT MEANS

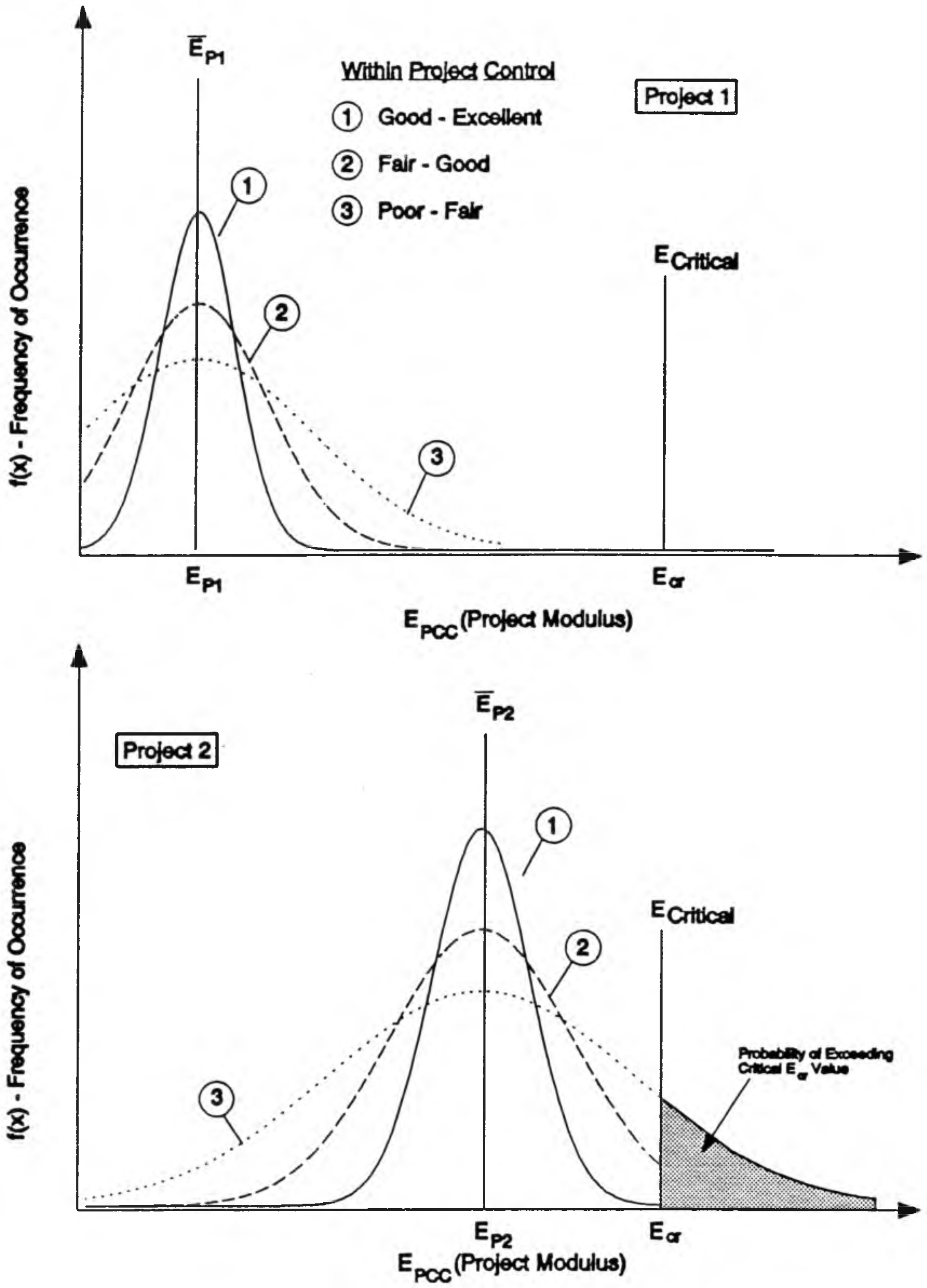

FIGURE 8. FRACTURED SLAB MODULUS FREQUENCY DISTRIBUTIONS REFLECTING BETWEEN AND WITHIN PROJECT VARIABILITY

$$a_i = a_s \sqrt[3]{\frac{E_i}{E_s}}$$

with the subscript "i" representing the material in question and the subscript "s" representing an arbitrary standard material whose a_s and E_s were established for AASHO Road Test materials. Using a dense graded crushed stone base as the standard it has been found that:

$a_s = 0.14$
$E_s = 30{,}000$ psi

Substituting these values into the a_i expression yields:

$$a_i = 0.0045 \sqrt[3]{E_i}$$

Thus, a direct transformation between the in-situ fractured modulus (E_i or E_{PCC}) and the AASHTO Guide layer coefficient, a_b, for the fractured material can be easily made.

Design Guidelines

All three procedures for rehabilitation of deteriorating PCC pavement using the "Fractured Slab" technique prior to placement of HMA overlay result in the converting of the original rigid type pavement to a condition more typical of a "flexible" type pavement. Consequently, for design purposes, it is appropriate to consider the HMA overlay of a fractured PCC pavement as being approximately equivalent to the new construction of an HMA surface course over aggregate base. This is particularly true for the rubblize fracture technique.

The HMA overlay methodology developed by this study is based on the widely used structural capacity deficiency approach. This overlay design methodology and the associated performance strategy is illustrated in Figure 9. The original structural capacity (SC_o) of the new pavement deteriorates with time and traffic to a value SC_{fs} at which time the pavement is fractured resulting in a further reduction in structural capacity to the SC_{FRAC} value. Placement of the HMA overlay increases the structural capacity by SC_{OL} to SC_{REQ}, at which time the pavement again begins to deteriorate with time and traffic. Thus, the overlay design equation is based on the following simple equation:

$$SC_{OL} = SC_{REQ} - SC_{FRAC}$$

where SC_{OL} = additional structural capacity required from the HMA overlay; SC_{REQ} = total structural capacity of a new flexible pavement constructed over the existing subgrade to accommodate the traffic within the life of the overlay; SC_{FRAC} = effective structural capacity of the existing pavement structure after the slabs have been fractured.

Furthermore, if the AASHTO Guide flexible performance model using the Structural Number (SN value) as the equivalent parameter of the structural capacity is used, the overlay design equation can be re-written as follows:

$$SN_{ol} = SN_{y} - SN_{eff}$$

where SN_{ol} = additional structural capacity required from the HMA concrete overlay; SN_y = future structural capacity (SN) of a new flexible pavement constructed over the existing subgrade to accommodate the traffic within the life of the overlay; and SN_{eff} = effective capacity (SN) of the existing pavement structure after fracturing has taken place.

Recognizing that:

$$SN_{ol} = a_{ol} h_o$$

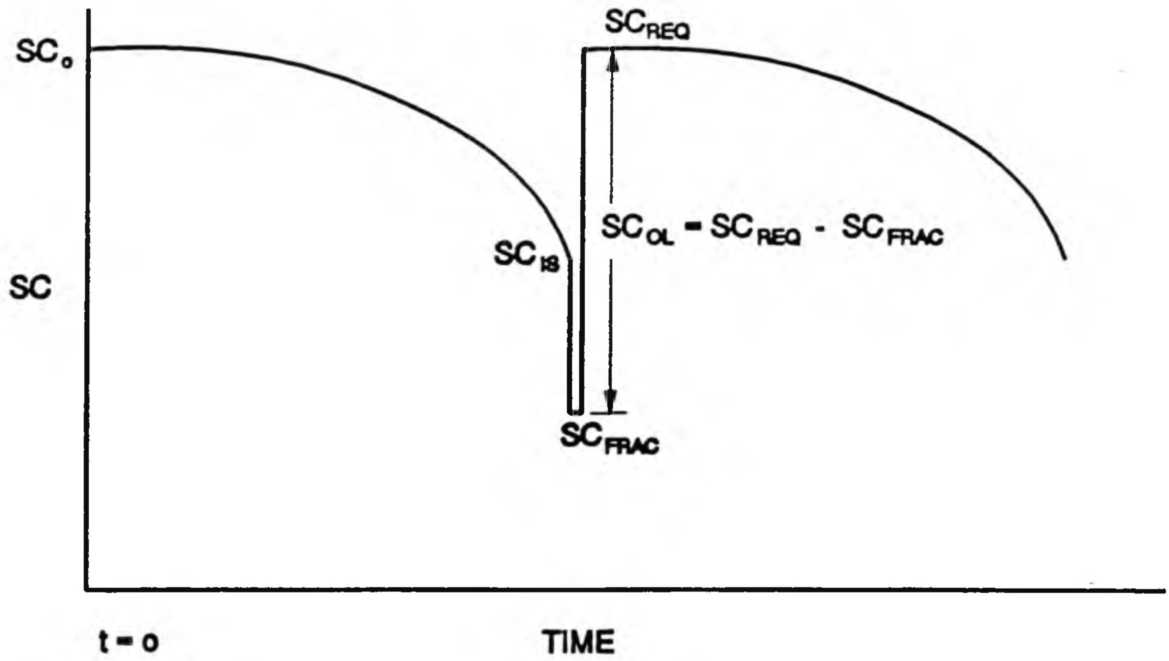

FIGURE 9. HMA OVERLAY DESIGN

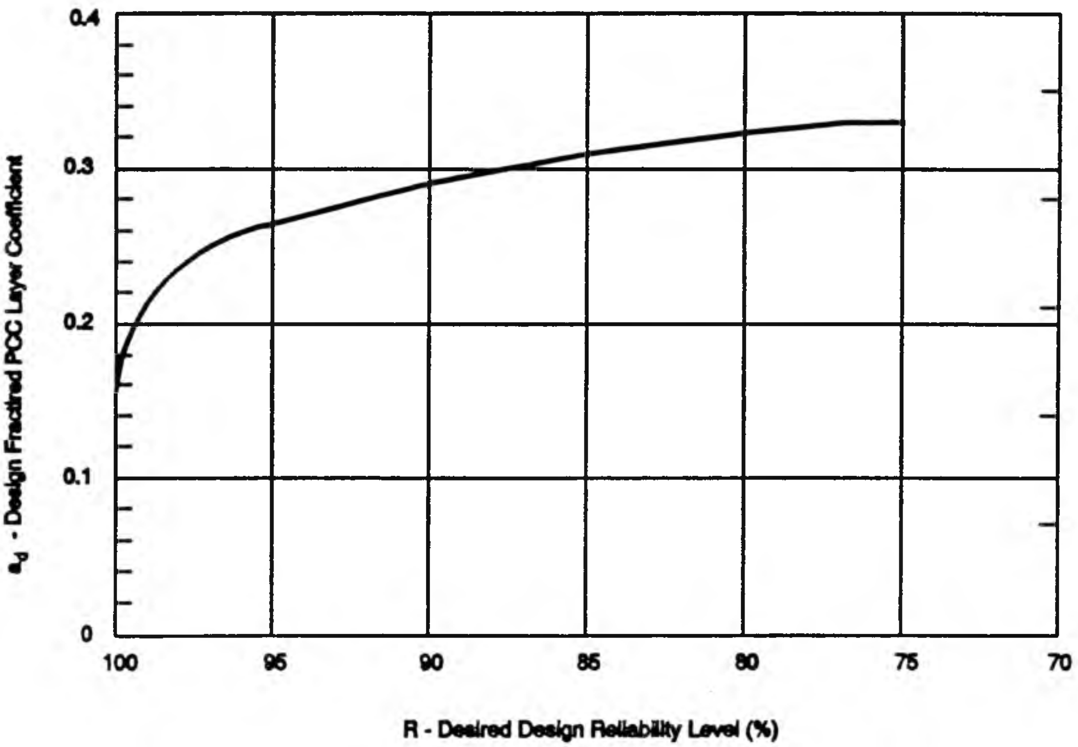

FIGURE 10. FRACTURED PCC LAYERS AS FUNCTION OF DESIRED RELIABILITY

and using a commonly accepted a_{ol} for HMA to be $a_{ol} = 0.44$, the required overlay thickness can be expressed by:

$$h_o = \frac{SN_y - SN_{xeff}}{0.44}$$

The solution of the h_o value involves the solution of the two variables: SN_y and SN_{xeff}. The solution of SN_y is very direct as it is based solely upon the AASHTO Guide flexible pavement solution for new pavements. In this solution, the design traffic value (W_{t18}) represents the future equivalent 18K SAL repetitions which will occur in the overlay period and the design subgrade modulus value (M_r) represents the design value for the existing subgrade. The reader is referred to the AASHTO Guide for details concerning this solution approach.

The second variable, SN_{xeff}, represents the structural capacity of the existing pavement after the slab fracturing process has taken place. The computation of the SN_{xeff} value should incorporate not only the fractured slab but any subbase layers present in the existing pavement. Thus:

$$SN_{xeff} = a_d D_o + a_{sb} h_{sb}$$

where a_d = design layer coefficient of the fractured PCC layer; a_{sb} = layer coefficient of any existing subbase layer material; D_o = original thickness of the PCC slab; and h_{sb} = subbase layer thickness

The reader is again referred to the AASHTO Guide for further details regarding the selection of the appropriate a_{sb} values for a variety of materials which may be present. Because layer thicknesses (both D_o and h_{sb}) can usually be found from historic construction data and/or obtained from drilling/ coring operations, the most significant factor to be determined involves the value placed on the a_d value for the fractured slab.

The selection of the appropriate a_d value is a very critical part of the overlay analysis. Because this parameter relates to the structural failure of the overlaid pavement system, it is necessary to apply design conservatism to the design process. However, it has also been pointed out that the within project variability (CV_w) also plays a key role in the design selection process of a_d in that the optimum construction process should yield an average E_{PCC} as large as possible, with as low a CV_w value as possible, to insure that the E_{cr} level is met.

Based on the between and within project variability results discussed earlier, an a_d relationship was developed as a function of the overall project reliability. This relationship is shown in Figure 10. For typical values of design reliability used in pavement construction, a value of $a_d = 0.28$ is recommended. This is equivalent to a reliability value of approximately 90%. However, the engineer must use his/her judgement in selecting the appropriate design reliability level for any given project. As the relative importance of the pavement section increases, a higher reliability value (and hence lower a_d value) may be selected.

Finally, it is emphasized once more that the proposed design methodology assumes the fracturing of the existing PCC pavement in accordance with the previously described criteria of achieving an effect E_{PCC} as close the to E_{cr} value of 1,000 ksi with no more than 5% of the project's E_{PCC} values exceeding the E_{cr}.

CONCLUSIONS

This paper presented the results of a nationwide study on new and innovative methodologies for rehabilitation of PCC pavement involving the fracturing of the slabs prior to the placement of an HMA overlay with the objective of eliminating or minimizing the occurrence of reflective cracks in the overlay.

Based on the results of this study, the following major observations were made:

- The relative ranking of the fracturing techniques, in order of decreasing performance life, appears to be: rubblization (best), crack/seat, and break/seat (worst).
- Reasonable predictive models for the fractured PCC modulus were obtained for the rubblized and crack/seat technique. These models clearly show the importance of crack spacing and the foundation support of the existing PCC pavement; As both of these variables are increased, the E_{PCC} value of the fractured slab likewise increases. The development of a similar model for the break and seat technique was not possible due to the extreme variation in PCC values resulting from inefficient fracturing and/or debonding of the distributed steel.
- Some of the most significant and important findings of the study revolve around the statistical frequency distributions of the effective E_{PCC} values for each rehabilitation technique. Both "between project" and "within project" variability were analyzed.
- For the crack/seat and rubblized pavement sections, the resulting frequency distributions of the project mean E_{PCC} value were found to be quite similar; average of E_{PCC} = 400-500 ksi and a between project coefficient of variation value of approximately 35%.
- In contrast, the break/seat distribution was found to be uniformly distributed across a wide range of E_{PCC} values (i.e., 250 to 2750 ksi). This clearly reinforces the conclusion that the break/seat process on JRC pavements is not uniformly efficient in fully debonding and/or fracturing the distributed steel.
- Based on the analysis results of the within project variability, guidelines for project uniformity were developed.

From these and other observations, the following major recommendations were developed:

- Rubblization of deteriorating PCC pavements followed by an HMA overlay is an excellent rehabilitation method that is equally effective for all types of existing PCC pavements. This technique is the preferred rehabilitation method for all PCC pavements containing any type of reinforcing steel. It has been determined during this study that a properly seated rubblized layer is between 1.5 and 3 times as effective as dense graded aggregate base course in terms of contributing to structural capacity of the rehabilitated pavement.
- The crack and seat technique followed by an HMA overlay is a very effective rehabilitation method for deteriorating Jointed Plain Concrete Pavements (JPCP; i.e., containing no reinforcing steel). However, the technique is only recommended if the suggested minimum crack spacing guidelines are met.
- The currently used construction techniques for break and seat rehabilitation of Jointed Reinforced Concrete Pavements (JRCP) result in a high degree of variability with

regard to the breaking or debonding of the reinforcing steel. Until improvements are made in the breaking technique, the use of this rehabilitation option is not recommended.

Finally, while much useful information was obtained from this initial nationwide study, additional research is required to further refine and improve the recommended guidelines and methodologies.

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REFERENCES

1. American Association of State Highway and Transportation Officials, "AASHTO Guide for Design of Pavement Structures", Washington, D.C., 1986.
2. Highway Statistics 1987, U.S. Department of Transportation, Federal Highway Administration, Washington, D.C., 1988.
3. Kilareski, W. and Bionda, R., "Performance/Rehabilitation of Rigid Pavements", Draft Final Report, FHWA Contract DTFHG1-86-C-00079, The Pennsylvania Transportation Institute, 1988.
4. Kilareski, W. and Stoffels, S., "Improved Design and Construction Procedures for Crack and Seat and Overlay of Rigid Pavements", Draft Final Report, Phase III, Task B, FHWA Contract DTFHG1-86-C-00079, The Pennsylvania Transportation Institute, 1988.
5. PCS/Law Engineering, Guidelines and Methodologies for the Rehabilitation of Rigid Highway Pavements using Asphalt Concrete Overlays", Final Report, prepared for the National Asphalt Pavement Association, June 1991.
6. Shahin, M. and Kohn, S., "Pavement Maintenance Management for Roads and Parking Lots", Final Report No. CERL-TR-M-294, U.S. Army Construction Engineering Research Laboratory, Champaign, Illinois, 1981.
7. Thompson, M.R., "Breaking/Cracking and Seating Concrete Pavements", NCHRP Synthesis 144, Transportation Research Board, Washington, D.C., 1989.