Economic Considerations of Faulting and Cracking in Rigid Pavement Design

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The results of several pavement studies and road tests have been compared to determine the significance and interaction of design variables with respect to distress. The design variables studied are pavement rein forcement, thickness, joint spacing, and subgrade material. The distress modes studied are faulting, transverse cracking, and pumping. To compare faulting between pavement designs with different joint spacings, researchers developed a method for estimating serviceability from faulting and joint spacing data. This method is based on amplitude-wavelength relationships to serviceability that were established in Texas. An extension of this method allows comparisons of reinforced and unreinforced concrete pavements that consider both cracks and joints in concrete pavements to be "faulting opportunities." The expected faulting per length of pavement for various designs is then computed by using the number of joints and cracks and the probability of faulting for each type of joint or crack. Load transfer is used as a criterion for estimating the probability of faulting. A method for considering the relative cost of pavements per vehicle is presented that is based on expected faulting and effect of faulting on serviceability. This method is illustrated by an example problem.

This paper investigates the major problem area of jointed concrete pavements, interactions of problem areas, design parameters that may minimize problems, and economic trade-offs for selecting an optimum pavement design. The use of various design parameters to limit or minimize the effect of pavement distress on serviceability is compared on an economic basis.

TYPES OF PAVEMENT

Jointed concrete pavements (JCPs) consist of any combination of portland cement concrete slabs, reinforcing steel, and load transfer devices. To conveniently describe these combinations, we adopted the following abbreviations for use in this paper:

1. JPCP is jointed plain concrete pavement without load transfer devices at the joints or reinforcing steel,
2. JPCP/D is jointed plain concrete pavement with dowel bars for load transfer at the joints,
3. JRCP is jointed reinforced concrete pavement, and
4. JRCP/D is jointed reinforced concrete pavement with dowel bars for load transfer at the joints.

DISTRESS MODES OF JOINTED CONCRETE PAVEMENTS

The U.S. Army Corps of Engineers (1) lists 18 specific forms of rigid pavement distress. To discuss all of these distress modes in this paper is obviously impossible. Therefore, only 3 major forms of distress have been selected for discussion: (a) faulting, (b) cracking or breakup, and (c) pumping.

Faulting

Faulting, described by Spellman, Stoker, and Neal (2) as the vertical displacement of concrete slabs at joints or cracks, is often considered to be the main weakness of JCP (3) because the vertical dislocation of short pavement sections at transverse joints can lead directly to serviceability loss. Two mechanisms have been identified as being associated with faulting (4). One cause is the loss of slab support, especially under the leave slab (the slab past the joint), which is due to settlement or erosion of the underlying layers. The other cause is the buildup of fine materials under the approach side of the slab (2, 4) when the subbase is very stiff, such as in cement-stabilized subbases. This buildup is a result of the carrying by pressurized water of fine particles of subbase or shoulder material under the approach slab when a heavy axle load passes over a joint (2, 4). For these mechanisms to result in faulting the following conditions must be present:

1. Free water on top of the base,
2. Differential deflection across the joint (inadequate load transfer across the joint), and
3. Heavy axle loads (resulting in high pavement deflections).

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Cracking

Cracking, which may take several forms in JCP, results from a combination of environmental forces (such as thermal contraction forces) and fatigue due to traffic loads. The forms of cracking of interest in this report are corner cracks, transverse cracks, and longitudinal cracks. Cracking associated with construction problems, such as double cracking at joints (4), is not considered in this report.

Corner cracking is usually associated with excessive corner deflections resulting from heavy axle loads, loss of slab support, and inadequate load transfer across the joint. Because one of the primary catalysts of corner cracking is loss of slab support due to pumping of the underlying layers, conditions related to pumping may also be considered to be associated with corner cracking.

Transverse cracks are generally associated with environmental forces, especially thermal contraction resulting from a temperature drop. The amount of force (or stress) generated in this manner is a function of slab thickness, joint spacing, amount and rate of temperature drop, concrete shrinkage and slab-subbase or slab-subgrade interaction (friction). Although environmental effects are usually considered the primary factor for transverse cracking, the effect of traffic loading cannot be ignored. This was discovered at the American Association of State Highway Officials (AASHO) (now American Association of State Highway and Transportation Officials) Road Test (5) where pavement sections on the traffic loops developed cracks and sections on the nontraffic loop had no apparent cracks.

Longitudinal cracks generally occur in a manner similar to that of transverse cracks. The effect of longitudinal cracks on pavement serviceability should be somewhat less than the effect of transverse cracks because longitudinal cracks are parallel with traffic flow and therefore are encountered less often than transverse cracks.

Pumping

Pumping of materials from under a jointed concrete pavement does not directly lead to loss of serviceability, but pumping is such a major contributor to other pavement distress that it should be considered a major design problem. Pumping was defined at the AASHO Road Test (5) as "the ejection of water and subbase material or embankment soil from beneath the pavement surfacing." The result is a loss of slab support. Pumping may occur at the pavement edge, joints, or cracks. In general, more material is ejected during edge pumping than during crack or joint pumping (5). The conditions required for pumping are pumpable material underlying the slab, free water under the slab, and high deflections.

DESIGN PARAMETERS FOR MINIMIZING JCP DISTRESS

The design parameters for jointed concrete pavement are well known; therefore, they will only receive a brief review here. The purpose of this review is to discuss the reasons for applying the various design parameters to minimize the previously discussed problem areas and to introduce the concept of the interactions of the various design parameters.

Pavement Thickness

Pavement thickness is perhaps the most obvious design parameter. Proponents of JRCP support the concept that a pavement of adequate thickness can be designed so that minimum distress will occur during the design life of the pavement (3). Critical stresses in JPCP are a result of corner loading; critical stresses in JRCP are the result of edge loading if there is good load transfer at the joints. Pavements designed to withstand corner loading must be thicker than pavements designed for edge loading.

Reinforcement and Load Transfer Devices

Internal pavement reinforcement, such as is used in JRCP, is not used as a direct measure to increase the pavement strength, but rather is used as a measure to ensure that pavement strength is maintained. The method for maintaining pavement strength is to provide sufficient reinforcement to ensure aggregate interlock across cracks that form in the concrete. Proponents of JRCP claim that the "slightly" greater cost of reinforcement is offset by the need for fewer joints, lower maintenance cost, and higher serviceability during the life of the pavement (6). Load or shear transfer devices at joints are usually in the form of dowel bars.

Subbase and Subgrade

Subbase design varies according to the desired objectives for the design agency. Originally, subbases were placed under concrete pavements to provide drainage and reduce pumping. In the 1940s Hveem recommended the use of treated or chemically stabilized subbase materials to reduce damage to the subbase (2).

Joint Design

Joint design plays an important role in how a pavement will perform. Four basic types of joints are currently being used: construction, expansion, contraction, and warping joints. Joints are necessary for the proper design of jointed concrete pavements because of volume changes in the concrete that are due to shrinkage and temperature changes. Early experiments with long sections of continuous plain concrete pavement proved that joints are necessary. The two most important design considerations are joint spacing and load transfer.

Drainage

The earlier discussion of distress showed that the presence of free water under a pavement is one of the most important catalysts for pavement distress. Therefore, providing proper drainage under the pavement should be an important design parameter, especially in wet climates.

Interactions

Although a discussion of the individual design parameters is useful for understanding the basic concepts of these parameters, an understanding of the interaction of these parameters is equally important. For example, the thickness of the pavement should reflect the subbase design used. A pavement on a strong cement-treated subbase may conceivably be thinner than a pavement placed directly on a weak subgrade if all other design factors are equal. A summary of other important interactions is given in Table 1. In this table, interactions are described as being either primary or secondary. A primary interaction occurs when a change in one variable causes a direct effect on another variable. A secondary interaction is defined as a change in the variable that causes an indirect effect on another variable. This table was used as a guideline for a literature review of the effectiveness of the various design factors. If the design factor interactions are not recognized, results of the literature survey could be misleading.

OBSERVATIONS OF DISTRESS MODES WITH RESPECT TO DESIGN STRATEGIES

This section summarizes the findings of laboratory studies and field observations about the relative merits of three design strategies used for jointed concrete pavements:

1. Plain concrete pavements without dowel bars for load transfer at joints,
2. Plain concrete pavements with dowel bars, and
3. Jointed reinforced concrete pavements with dowel bars.

The pavement distresses studied were faulting, transverse cracking, and pumping.

Faulting at Joints and Cracks

As mentioned earlier, faulting of JCP leads directly to a loss of serviceability. Therefore, to compare the design concepts of interest, one needs a method to compare the effects of faulting on serviceability. Such a method may be developed based on the results of an amplitude-wavelength-serviceability study reported by Walker and Hudson (8). Figure 1 shows how the amplitude-wavelength data may be used to determine present serviceability ratings (PSR) levels (8). This figure was developed in a manner similar to that used to develop the original present serviceability index (PSI) at the AASHO Road Test (5). A surface dynamic profilometer was used to measure the amplitudes and wavelengths of several pavements throughout Texas. These measurements were then correlated with road users' opinions of pavement serviceability. Use of the amplitude-wavelength measurements provides a good measure of PSI because only amplitude-wavelengths that are highly correlated with PSR are included in the relationship.

This information may be used to estimate PSR levels of pavements given joint spacing and faulting data. If faulting is assumed to equal amplitude and joint spacing is assumed to equal wavelength, the results of faulting studies may be plotted directly on Figure 1 to estimate PSR levels. For example, assume that the amplitude-wavelength measurements for a pavement with 9.14-m (30-ft) slabs are shown by the dashed line in Figure 1. The "hump" in the dashed line would represent the occurrence of faults at the joints. The penetration of the 2.0 to 2.5 PSR line by the faults indicates that this is the critical wavelength for the pavement. The PSR of the pavement then would be governed by faulting; therefore, measurements of faulting and joint spacing are useful for estimating PSR.

Assuming that PSR may be estimated in this manner is somewhat inaccurate because the curves were developed for smooth variation in the road profile and faults are abrupt variations in the profile. This becomes especially critical for the long wavelength or joint spacings. For example, the curve shows that an amplitude of 3.43 cm (1.35 in) and a wavelength of 24.38 m (80 ft) corresponds to a PSR of 4.0 to 4.5. A fault of 3.43 cm (1.35 in) obviously could not be tolerated on a roadway every 24.38 m (80 ft). This problem is offset by two factors. First, the curves are plotted for the 99 percent level of amplitude. Therefore, on the average, the 3.429-cm (1.35-in) amplitude would only occur once every 100 joints, which corresponds to once every 2438 m (8000 ft). Second, the high side of the fault usually occurs on the approach side of the joint (2); therefore, the traffic is dropping off the fault. This is less severe than if the approach slab were lower than the leave slab and the traffic was hitting a "bump."

Faulting criteria cited by Brokaw (3) for JPCP with 4.5 to 6.1-m (15 to 20-ft) slabs have been plotted on Figure 1. It appears that there is good agreement between the faulting criteria and the wavelength-amplitude curve. Unfortunately, similar criteria do not exist for pavement with longer slabs.

Two hypotheses may be developed from Figure 1. First, tolerable faulting levels for a given PSR increase with slab length. Second, minor increases in faulting of a pavement with short slabs result in a significant drop of PSR. This method of analysis allows comparison of faulting in pavements with different slab lengths.

Observations of pavement performance with respect to faulting tend to support these hypotheses. In a 5-year progress report of a New York rigid pavement study (4), faulting of pavement sections with 6.1-m (20-ft) unreinforced and 18.54-m (60-ft, 10-in) reinforced slabs was studied. Because of the limited amount of traffic during the 5-year period, faulting had not developed to a significant degree. All sections except for one had less than 0.16-cm ($^1/_{16}$-in) average faulting; therefore, variation between sections was too limited for forming statistically significant conclusions. The following trends were observed from averages of the observations:

1. Sections on granular bases had more faulting than sections on stabilized bases had;
2. The 18.54-m (60-ft, 10-in) slabs had more faulting than the 6.1-m (20-ft) slabs had; and
3. Higher roughnesses were measured on the sections with short slabs.

Because of the limited amount of faulting, plotting results of this study on Figure 1 would not be significant.

De Young (9) reported the results of a joint spacing study of plain concrete pavements in Iowa. Pavements were constructed with joint spacings of 6, 15.2, and 24.4 m (20, 50, and 80 ft). After 8 years of traffic, transverse cracking had reduced the sections to average slab lengths of 5.8, 8.8, and 11.3 m (19, 29, and 37 ft) respectively. Faulting on these sections at the 99 percent level was approximately 0.64, 0.86, and 0.79 cm (0.25, 0.34, and 0.31 in) respectively. As shown on Figure 1, the section with the longest joint spacing would be expected to have the highest PSR. Roughness measurements with the BPR roughometer verified that the sections with the long joint spacings were the smoothest.

Even though these data do not allow definite conclusions to be drawn, they do indicate that there is a trend for pavements with long slabs to be smoother than pavements with short slabs. Regardless of the slab length used, faulting needs to be controlled.

In this paper, load transfer is defined as the leave slab deflection divided by the sum of the approach and leave slab deflections and converted to a percentage. Load transfer by aggregate interlock requires that joints remain very "tight" to maintain contact on the bearing faces. Observations at a Michigan test road (10) verified that, when joints without dowel bars separate, load transfer drops off significantly. For example, average load transfer across 10 joints changed from 46.2 to 36.1 percent when the joint width changed from 0.11 to 0.16 cm (0.045 to 0.064 in) due to temperature changes. A California faulting study (2) found similar results.

Studies of joint openings at the Michigan test road (10) showed that contraction joints opened as much as 0.51 cm

(0.20 in) at -17.78°C (0°F) for 6.1-m (20-ft) joint spacings. Furthermore, all contraction joints were found to sustain permanent openings that gradually increased after 10 to 15 years of service. This means that there is a high probability, especially in colder climates, of loss of load transfer across joints with only aggregate interlock. Average load transfer across nine doweled joints on the Michigan test road was 48.8 percent; average joint width was 0.16 cm (0.063 in).

Load transfer across several joint designs was studied by the Portland Concrete Association (PCA) (11) by using repeated load tests on slabs. Results from these tests are given in Table 2. Note that both the 15.24-cm (6-in) and 20.32-cm (8-in) slabs with dowel bars and 0.635-cm (0.25-in) joint width performed better than the joints without load transfer devices.

It is apparent that dowel bars provide good load transfer at joints and that joints with only aggregate interlock tend to lose their load transfer capability. Several pavement studies confirm this statement.

At the AASHO Road Test (5), all joints had dowel bars. As a result, "faulting at joints was notably absent throughout the project." Observations in Georgia (7) of plain concrete pavements without dowel bars at joints found that "all projects on the Interstate Highway System in Georgia with plain concrete pavements exhibited faulting." Findings at a test pavement in Kentucky (12) were that "sections having load transfer dowels in all joints have shown less faulting of the joints." Similar results were reported at the Michigan test road (10): "Plain concrete pavements with dowels at contraction joints performed better than plain concrete pavements without dowels at contraction joints." Sufficient variation in pavement designs and environmental and traffic conditions exists among these pavement studies to allow the general conclusion that dowel bars are an effective means for limiting faulting.

Subbase design also affects faulting of jointed concrete pavements. Two alternate approaches to subbase design are currently being practiced: (a) use of stabilized subbase to reduce differential deflection or (b) use of free-draining subbases to remove free water.

Findings of the Georgia faulting study (7) with respect to subbase design were that "plain concrete pavements (without dowels at joints) on a cement stabilized subbase tend to have less faulting than those constructed on a bituminous stabilized or soil-cement subbase for the same traffic parameter." At the New York pavement experiment (4), more faulting was observed on granular subbases than on stabilized subbases.

Based on these findings, faulting appears to decrease as subbase stiffness increases. This trend cannot be so firmly established as the conclusions about the effectiveness of load transfer devices can be because of a lack of data.

Part of the problem in comparing results of several road tests is that the design of the experiments generally is aimed at obtaining results for a specified set of design parameters over a fixed range of values. The interactions of design parameters often prevent the specific results determined during one pavement study from being compared to the results of other pavement studies. For example, no faulting was observed at the AASHO Road Test (5) where the rigid pavements were built either directly on the subgrade or on granular subbases. In contrast, the Georgia faulting study showed that faulting does occur on pavements with cement-stabilized subbases. The conclusion that granular subbases are more effective than stabilized subbases for limiting faulting would be incorrect because dowel bars were used in the AASHO pavements but not in the Georgia pavements.

Transverse Cracking

One of the most important factors determining the amount of transverse cracking is the spacing of contraction joints. The Michigan test road results showed that a joint spacing of approximately 3.1 m (10 ft) was necessary to completely prevent transverse slab cracking (10). Joint spacings of 4.5 to 6.1 m (15 to 20 ft) are more commonly used to minimize transverse slab cracking. Figure 2 shows the development of transverse cracking with respect to time as a function of joint spacing in JPCP (9). Transverse cracking developed in JRCP would be similar because the reinforcing steel does not prohibit the formulation of transverse cracks. This was verified at the Michigan test road (10) where the amount of transverse cracking was not significantly different for reinforced and unreinforced test sections whose design was the same in other respects.

A significant factor at the Michigan road test is that the pavements with reinforcement were generally in much better condition than the nonreinforced pavements (10). This occurred because the reinforcement held the cracks close enough that the aggregate interlock was maintained across the crack for load transfer. This is not really a fair comparison of the performance of reinforced versus nonreinforced pavements because of the interaction between reinforcement and joint spacing. Plain concrete pavements are generally designed to have shorter slabs than reinforced pavements.

Because of the shorter slab lengths of plain concrete pavements, much less transverse cracking occurs than with reinforced concrete pavements. In the New York pavement study (4), twice as many transverse cracks formed in the 18.54-m (60-ft, 10-in) reinforced slabs as in the 6.1-m (20-ft) unreinforced slabs. This appears to be an advantage of shorter unreinforced slabs. However, when one considers that the criteria for joint spacings of unreinforced slabs were developed from crack spacing data, one is not surprised that only limited transverse cracking occurs on these sections.

Because slab lengths for reinforced and nonreinforced pavements are considerably different, to compare the number of cracks per slab or per length of pavement for these two design concepts is inappropriate. The most logical comparison that can be made is comparing the number of faulting opportunities per length of pavement and the likelihood of faulting. To make this comparison, one considers joints and transverse cracks to be faulting opportunities. A comparison of this type has been made by using the New York data (4). Figure 3a shows a 36.6-m (120-ft) pavement with 6.1-m (20-ft) slab lengths; Figure 3b shows a 36.6-m (120-ft) pavement with 18.3-m (60-ft) joint spacings. The pavement with 6.1-m (20-ft) slab lengths has five internal joints and two transverse cracks, or a total of seven faulting opportunities. The pavement with 18.3-m (60-ft) slabs has one joint and four transverse cracks, or a total of five faulting opportunities. The ratio of faulting opportunities for the two slab lengths would decrease as pavement length increases, but, for the conditions reported at the New York test road (4), the number of faulting opportunities for the pavement with long slabs will be equal to the number of joints in the pavement with short slabs, as would be expected if the joints in the JPCP are considered to be preformed cracks.

If the concept of faulting opportunity is used, JRCP appears to have an advantage over JPCP if transverse cracks and joints have the same probability of faulting. Unfortunately, there are no data available on the probability of faulting by joints and cracks. Laboratory studies of load transfer of various joints have been performed (11) that can be used to postulate the relative

Table 1. Interactions of pavement design variables.

Design Factor	Design Factor Code	Interaction[a] Primary	Secondary
Pavement thickness	1	2, 3, 4, 5, 6, 7, 8, 9	
Steel load transfer	2	1, 5, 6, 7, 8	4
Steel reinforcement	3	1, 5, 6	4
Subbase thickness	4	1, 2, 3, 5, 6, 8	7, 9
Type of subbase material	5	1, 2, 3, 4, 6, 8, 9	7
Subgrade stabilization	6	1, 2, 3, 4, 5, 7, 8	
Joint spacing	7	1, 2, 3, 5, 6	4, 9
Joint load transfer	8	1, 2, 3, 5, 6, 9	4
Drainage	9	1, 2, 3, 5, 6, 8	4, 7

[a] Numbers refer to design factor codes.

Figure 1. Amplitude-wavelength relationships for two PSR levels.

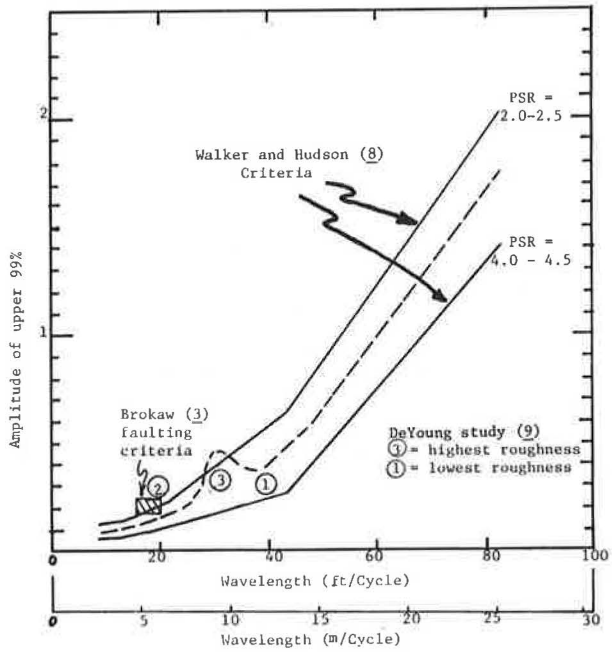


Figure 2. Reduction of slab length over time due to transverse cracking.

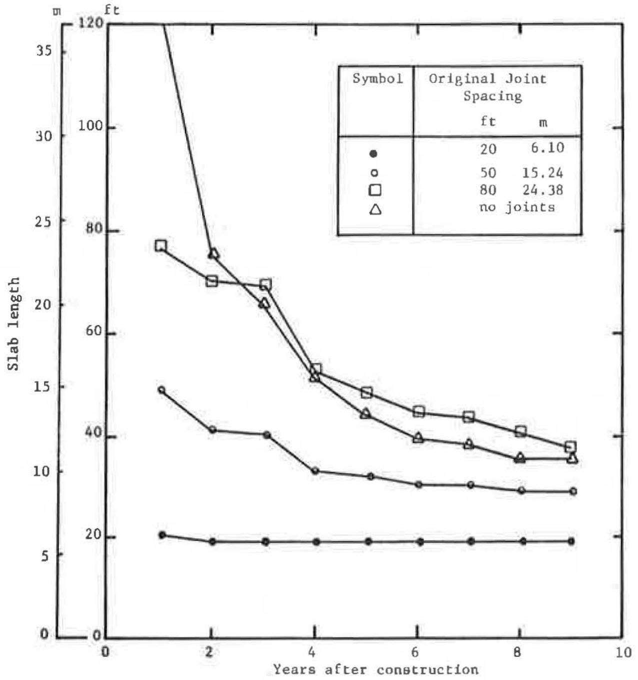


Table 2. Summary of PCA joint study.

Joint Type	Joint Ties	Slab Depth (cm)	Cement-Stabilized Subbase Depth (cm)	Cycles[a] ($\times 10^6$)
Aggregate interlock	None	15.24	0	0.10
	Two 0.635 cm[b]	15.24	0	1.33
Dowel	Two 1.905 cm	15.24	0	2.00
Aggregate interlock	None	15.24	7.62	0.42
Dowel	Two 1.905 cm	15.24	7.62	2.37
Aggregate interlock	None	20.32	0	0.24
Dowel	Two 1.905 cm	20.32	0	0.90
Aggregate interlock	None	15.24	15.24	0.24
	Two 0.635 cm[b]	15.24	15.24	3.98
Dowel	One 2.54 cm	15.24	15.24	1.58

Note: 1 cm = 0.394 cm.

[a] Number of load cycles required for load transfer to drop from initial value to 44 percent. Load transfer decreases with number of applications.

[b] No. 2 size.

Figure 3. Faulting opportunities for (a) JPCP and (b) JRCP.

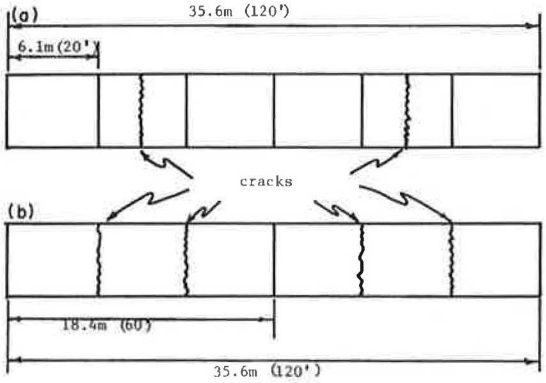


Figure 4. Estimating probability of faulting from load transfer.

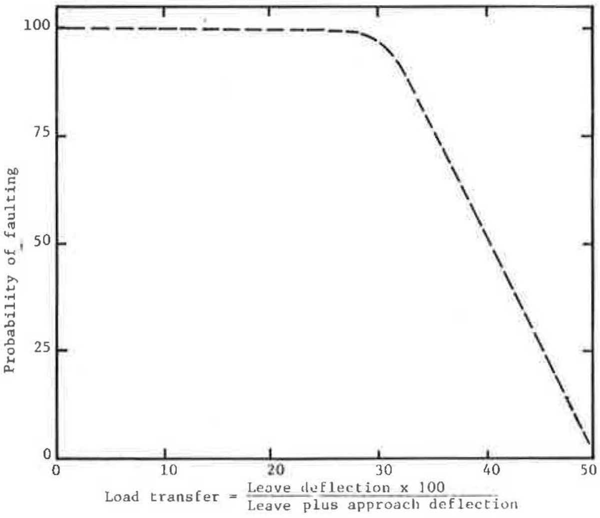


Table 3. Probability of faulting for joints and cracks.

Type A Pavement	Type of Fault	Load Transfer	Probability of Faulting	Number of Joints or Cracks/ Kilometer	Expected Faulting
JRCP/D	Joint	45	0.25	55	22
	Crack	44	0.30	109	53
	Total				75
JPCP/D	Joint	45	0.25	164	66
	Crack	36	0.70	55	62
	Total				128
JPCP	Joint	36	0.70	164	185
	Crack	36	0.70	55	62
	Total				247

Note: 1 joint/km = 1.609 joints/mile.

probabilities of faulting because faulting is largely dependent on load transfer. Use of the PCA data (11) to determine the relative probability of faulting for joints and cracks requires the following assumptions:

1. The laboratory study of joints may be extended, in a relative fashion, to field conditions;
2. The aggregate interlock joint with no tie (11) is representative of cracks in unreinforced pavements and joints that do not have load transfer devices;
3. The dowel joint tested represents a dowel joint in a pavement; and
4. The aggregate interlock joint with tie bars is representative of cracks in reinforced pavement.

An additional factor that should be considered is the fact that the PCA tests were run at joint widths of zero for the aggregate interlock joints with and without reinforcement and 0.635 cm (0.25 in) for the doweled joints. Therefore, the performance of the aggregate interlock joints would probably decrease and the performance of the dowel joints would probably increase. The results of the PCA joint study (11), given in Table 2, indicate that in all cases the unreinforced aggregate interlock joint did not perform as well as the other joints did. Comparison of reinforced aggregate interlock joints and dowel joints is confounded by the change in type of subbase and dowel design.

As an illustration of the concept of considering both the number of faulting opportunities and the probability of faulting, the following example problem was conceived. Graphical relationships and numerical data used in this example were contrived based on limited field data.

Based on some data from the Michigan test road (10), Figure 4 was drawn to show the relationship between load transfer and the probability of faulting. By using this relationship and the number of faulting opportunities occurring for each type of fault or joint, one can calculate the expected faulting on a section of JCP as

$$E(f) = \sum_{i=1}^{k} P(f)_i \cdot n_i \tag{1}$$

where

$E(f)$ = expected number of faults,
k = number of types of joints and cracks occurring in the pavement,
$P(f)_i$ = probability of the ith type of crack or joint faulting, and
n_i = the number of ith type of cracks or joints.

Equation 1 may be applied to compare expected faulting for the sections in the New York study; three pavement designs are evaluated in the New York study: (a) JPCP with 6.1-m (20-ft) slabs, (b) JPCP/D with 6.1-m (20-ft) slabs, and (c) JPCP/D with 18.3-m (60-ft) slabs. The joints and cracks per length of pavement can be calculated from the data shown in Figure 3; these calculations are given in Table 3.

The probability of faulting for each type of joint or crack was obtained by assuming load transfer values and by using Figure 4. These calculations show that, for the assumed conditions, the jointed reinforced concrete pavement would have considerably less faulting than either of the plain concrete pavements would have and that the plain concrete pavement with doweled joints would have less faulting than the one without dowel bars would have.

Pumping of Rigid Pavements

Concrete pavements were originally placed directly on the subgrade. As axle loads increased (which caused higher pavement deflections), the subgrade material under the pavement began to mix with free water and formed mud. Deflection of the pavement then forced the mud out from under the pavement, or mud pumping, which was a serious problem. To stop the problem, granular subbases were placed under the pavements. These worked well for many years, and it was thought that the granular subbase was not a pumpable material. Then, at the AASHO Road Test, heavy axle loads on the thinner test sections resulted in pumping of the granular subbases (5).

Cement- and asphalt-stabilized subbases have been used for many years as a means of reducing deflections. In general, pumping is not a problem when stabilized subbases are used, but at a New York experimental pavement (4) pumping has occurred on pavement sections with stabilized subbases; however, the water pumped was free of subbase materials.

California has recently started building cement-stabilized subbases that extend 0.3 m (1 ft) beyond the pavement edge (2). This is being done in part to eliminate or reduce edge pumping. Faulting of California pavements has been attributed to erosion of the subbase under the leave side (2); therefore, the possibility of pumping exists. When a stabilized subbase is used, it should be of high quality to resist erosion caused by rapid movement of free water under the pavement.

ECONOMIC CONSIDERATIONS FOR PAVEMENT DESIGN

The previous sections demonstrated that pavements with stabilized subbases, reinforced slabs, and load transfer devices at joints generally perform better than plain concrete pavements. However, the decision to use JRCP or JPCP is based on economic trade-offs. To make this decision, the designer must determine whether the benefits of using a more expensive pavement design are worth the extra expense. By using the concepts presented, we developed an approach for economic trade-off analysis of different designs.

For the three designs considered in the previous example, the expected wavelengths between faults would be $[1/E(f)] \times 1609$ m, or 6.6, 12.6, and 21.5 m (21.5, 41.3, and 70.4 ft) for designs a, b, and c respectively. If the data in Figure 1 are used, the corresponding 99 percentile fault levels would be 0.51, 1.45, and 3.94 cm (0.20, 0.57, and 1.55 in) for a PSR level of 2.0 to 2.5. The average faulting for these designs may now be estimated from Figure 5. This figure was extrapolated, by use of engineering judgment, from the limited amount of data available on the standard deviation of faulting. The average faulting for designs a, b, and c is 0.25, 0.38, and 5.8 cm (0.1, 0.15, and 0.23 in) respectively.

These allowable average faults may be converted to allowable traffic by using Figure 6. The curve for pavements without dowel bars is based on data collected for Georgia pavements (7). The curve for plain concrete pavements with dowel bars was drawn by using the same shape and slope as were used in the Georgia data, but the curve passed through a point estimated from Michigan test road (10) data. The JRCP curve was estimated based on a conservative evaluation of the PCA joint study (2).

The allowable number of truck-semitrailer combinations for the designs is estimated at 11 000 for the plain concrete pavement without dowel bars, 45 000 for the plain concrete pavement with dowel bars, and 190 000 for JRCP. The ratio of allowable traffic for the designs may be used to estimate the cost efficiency of each design. For these designs the ratios are

1. JPCP/D:JPCP = 4.1,
2. JRCP/D:JPCP = 17.3, and
3. JRCP/D:JPCP/D = 4.7.

Figure 5. Determining average faulting from 99 percentile faulting.

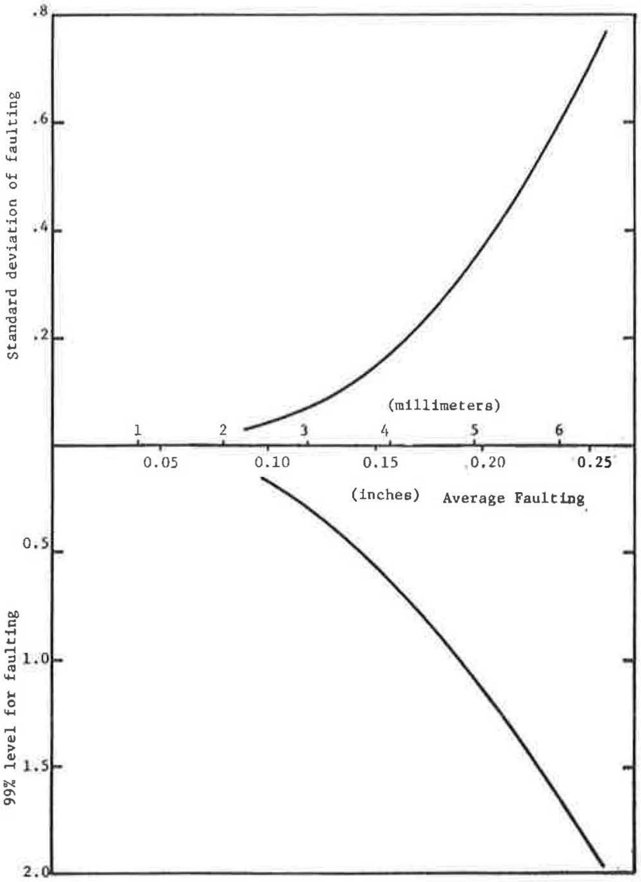
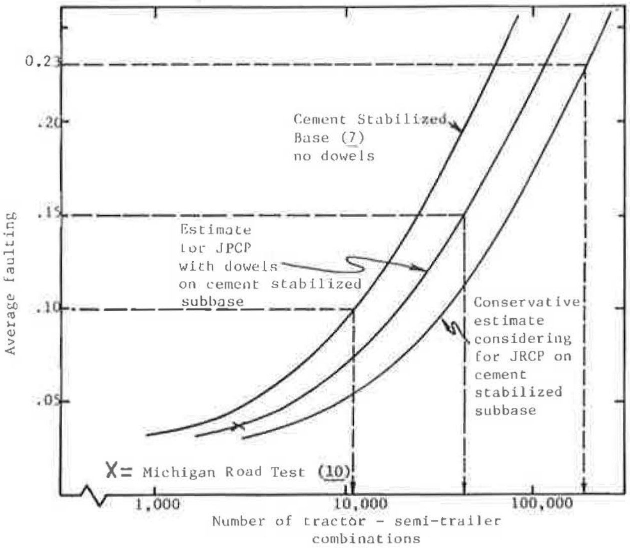


Figure 6. Faulting versus traffic for different load transfer at joints and cracks.



Interpretation of these results indicates that $4.10 could be spent for a plain concrete pavement with dowel bars for every $1.00 spent for plain concrete pavements without dowel bars without changing the cost of the pavement per vehicle served. This analysis is based on initial pavement cost only. If maintenance cost and salvage value were considered, the above ratios would probably be increased. This example was developed from the best available data, which are limited. New data are needed to verify or revise the figures in the paper before this technique can be used for practical pavement economic analysis.

SUMMARY

Research is needed for determining the interaction of design variables and pavement problem areas. Because of the problem of interactions, drawing definite conclusions from a comparison of the pavement studies and road tests is difficult, but several trends have been noted.

1. Dowel bars appear to be an effective means of limiting faulting.
2. Cracks and joints in JRCP tend to occur with the same frequency as do joints in JPCP; therefore, there are fewer faulting opportunities in JRCP.
3. There is a lower probability of faulting at a crack in JRCP than at a crack or unreinforced joint in JPCP.
4. Pavements with long slabs tend to be smoother than pavements with short slabs.
5. Faulting appears to decrease as subbase stiffness increases.
6. High-quality subbases are needed to resist erosion caused by pressurized free water under the pavement slab.

As the cost of pavement materials increases, it is becoming increasingly important for designers to use the most accurate methods available for designing pavements and to make cost comparisons of alternate pavement designs. Design methods used should be based on the best available theories and empirical data.

Analysis of pavement economics should consider not only the cost of the pavement, but also the benefits provided by the pavement. The pavement with the lowest initial cost is not always the most economical pavement.

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