

PREDICTION OF FAULTING OF JOINTS IN CONCRETE PAVEMENTS

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INTRODUCTION

In 1984 the Portland Cement Association (PCA) published *Thickness Design for Concrete Highway and Street Pavements*. (1) For the first time in any thickness design procedure the concept of pavement component erosion was introduced. The erosion criteria was added to the traditional concrete flexural fatigue criteria because heavy-axle loads cause deflections at slab corners and edges, which cause pumping, erosion of the subgrade, subbase, and shoulder materials, voids under and adjacent to the slab, and faulting of the pavement joints.

The erosion criteria correlated well to all of the in-service performance data available at the time, including data from the AASHO Road Test and several states. These criteria were viewed as first-generation general guidelines that could be refined as field performance data became available on specific climatic and drainage conditions.

The objective of this study was to collect performance data that have become available since 1984 and refine the existing erosion criteria to represent different climatic areas and drainage conditions.

EROSION CRITERIA DEVELOPMENT

Prior to 1984, mechanistic thickness design procedures for concrete pavements were based on the principal of limiting the flexural stresses in a slab to avoid flexural fatigue cracks due to load repetitions. The erosion criteria was incorporated into the 1984 PCA procedure since some modes of pavement distress, such as pumping, faulting, and shoulder distress, are unrelated to fatigue. Distress due to erosion are considered to be more closely related to slab deflections than to flexural stresses. At slab corners and edges in the presence of water and many repetitions of heavy axle loads; pumping; erosion of subgrade, subbase, and shoulder materials; voids under and adjacent to the slab; and faulting of pavement joints, especially in pavements with undoweled joints, can occur.

In order to relate these particular distresses to deflections, it was decided to develop a mechanistic-based erosion criteria taking into account the placement and number of heavy-axle loads and the magnitude of deflection occurring at the slab joints, edges, and corners.

For erosion analysis, the worst case involves deflections at the corner with truck wheel loads placed at the outside pavement edge, without concrete shoulders. At increasing distances inward from the pavement edge or with tied concrete shoulders, the frequency of load applications increases while the magnitude of stress and deflection decrease. Studies on pavement edge encroachment show that most trucks are driven with the outside wheels placed about 0.6 m (2 ft) from the edge. Only approximately 6 percent of all the trucks run with their wheels placed at the edge. For the erosion criteria development of pavements without concrete shoulders, the most severe condition noted in encroachment studies of 6 percent of trucks at pavement edges was assumed. For pavements with concrete shoulders, the most severe condition of 94 percent of truck loadings at the pavement joint was assumed. (2)

Attempts to correlate corner deflections to AASHO Road Test (3) performance data, where all pavement sections were doweled were not successful. It was found that to be able to predict the AASHO Road Test performance, different values of deflection criteria would have to be applied to different slab thicknesses, and to a smaller extent, different slab support values.

Better performance prediction was obtained by multiplying the slab-foundation interface pressure (p) by the slab corner deflection (w). Power, or rate of work, incorporates the product of pressure and deflection divided by a measure of the length of the deflection basin (radius of relative stiffness, l_e in inches) to account for the amount of erosion that can occur. The concept is that a thinner pavement with its shorter deflection basin receives a faster punch than a thicker slab causing greater erosion. At equal products of deflection and pressure, the thinner slab is subjected to a greater rate of work or power.

Successful correlation to AASHO Road Test performance data was developed in which the number of load repetitions (N) decreases with power (P) as defined in the following equation: (2)

$$P = \frac{p \text{ (unit area)} * w * \text{constant} / k^{0.0633}}{l_e / (\text{truck speed})} \quad (1)$$

$$P = 268.7 * p^2 / l_e / k^{0.73} \quad (2)$$

where P = power (rate of work)
 p = pressure at slab-foundation interface, psi
 w = corner deflection, in.
 t = slab thickness, in.
 l_e = radius of relative stiffness for elastic subgrade, in.
 k = modulus of subgrade reaction, pci

Truck speed is not a design variable but is used to introduce length of deflection basin in time units.

The development of the 1984 design erosion criteria also included correlations to studies on joint faulting and serviceability by Brokaw⁽⁴⁾ and Packard⁽⁵⁾ of undoweled pavements. In these studies, the degree of joint faulting of the pavements were related to pavement thickness, heavy truck counts, and other factors. These studies included pavements in Wisconsin, Minnesota, North Dakota, Georgia, and California, and included a range of variables not found at the AASHO Road Test such as increased amounts of truck traffic, undoweled pavements, a wider range of pavement service life, and stabilized subbases.

The erosion prediction criteria was developed from both the AASHTO Road Test data (doweled pavements) and the available faulting studies (undoweled pavements) with the constants being the best possible to fit both sets of data. This resulted in the following prediction equation:

$$\log N = 14.524 - 6.777 * (C_1 * P - 9.0)^{0.103} \quad (3)$$

where N = allowable load repetitions to end of design period
 P = power
 $C_1 = 1 - (k / 2000 * 4 / t)^2$

The constant C_1 is an adjustment factor that has a value close to 1.0 for normal granular subbases and decreases to approximately 0.90 for high strength subbases.

Using Miners hypothesis, the equation for erosion damage is:

$$\text{Percent erosion damage} = 100 * n_i * (C_2 / N_i) \quad (4)$$

where n_i = expected number of axle-load repetitions for axle-group i
 N_i = allowable number of repetitions for axle-group i
 $C_2 = 0.06$ for pavements without a shoulder and 0.94 for pavements with a tied concrete shoulder

Where there is no tied concrete shoulder, corner loadings (6 percent of trucks) are critical. When there is a concrete shoulder, the greater number of loadings inward from the pavement corner at the joint (94 percent of trucks) are critical.

Undoweled pavement thicknesses derived from the erosion criteria were compared with terminal roughness due to faulting (SVF), serviceability (PSI), and joint faulting. Commonly accepted terminal values are: SVF 11 to 14, PSI 2.0 to 3.0, and faulting 3.2 to 5.6 mm (4/32 to 7/32 in.). (6) Results are summarized in Table 1. The design thicknesses when incorporated as inputs into equations from other studies do approximately predict terminal conditions. Faulting studies of undoweled pavements indicate that climate and drainage are significant factors in pavement performance. The effects are summarized in Table 1 where the drainage terms "good" and "poor" refer to a free-draining or dry condition and a poorly drained wet condition, respectively.

The 1984 PCA erosion criteria was suggested for use as a general guideline. The criteria should be modified according to local experience since climate, drainage, local factors, and design innovations may influence the required slab thickness. The 100 percent erosion criteria, an index number correlated with general performance experience, can be increased or decreased based on available specific performance data in more favorable or adverse conditions.

REVIEW OF JOINT FAULTING, PUMPING, AND ROUGHNESS MODELS

literature review was conducted to evaluate pavement joint distress models for use in refinement of the PCA erosion criteria. Twenty concrete pavement joint faulting, pumping and roughness models were evaluated to determine which design and climatic factors to incorporate into the PCA criteria. (4,5,7-13). These nonlinear models combined several common variables which were considered for use in the design refinement. Variables could be generally grouped into traffic, age, design, and environmental categories. These parameters and associated variables identified in existing transverse joint erosion distress models are summarized in Table 2. Effects on pumping and faulting with increases or presence of variables are also listed.

Environmental variables which were significant in predicting transverse joint faulting and pumping include the amount of precipitation, freezing, and solar radiation. The amount of joint distress attributable to presence of moisture are reflected in the increase in faulting/pumping with an increase in freezing and precipitation and absence of longitudinal subdrains.

The use of the existing prediction models was not considered in the PCA erosion criteria refinement since:

- Traffic input is either in terms of the number of tractor-semi-trailers or the AASHTO Road Test equivalent single axle load (ESAL). The PCA method requires traffic input in terms of number of axle loads per axle load category.
- Faulting models do not incorporate any erosion accumulation criteria.
- Pumping models qualitatively rather than quantitatively predict pumping distress. Pumping is generally predicted in terms of four pumping severities ranging from none to severe.
- The predictability of models varied over a relatively wide range. The coefficient of determination (percent of explained variance in distress) ranged from 0.53 to 0.81.

RELATIONSHIPS BETWEEN PCA EROSION CRITERIA AND TRANSVERSE JOINT FAULTING

Data from existing performance databases was used to refine the PCA erosion criteria. Transverse joint data was collected from existing State DOT pavement management databases and pavement performance research databases. (9,13,14) Joint faulting measurements taken by Construction Technology Laboratories, Inc. (CTL) staff were also added to the PCA database. Attempts were made to incorporate into the database a measure of subbase/subgrade erosion which could be used to modify the PCA erosion criteria. However, due to lack of an easy way to quantify pumping material, qualitative measure of pumping used in existing databases, and relatively small amount of slab corner break data, the erosion criteria was modified by analysis of transverse joint faulting data.

The collection of faulting and traffic data used in the analysis is summarized by region and state in Table 3. Survey data was collected in dry-freeze, dry non-freeze, wet-freeze, and wet non-freeze sections of the United States. Joint faulting data from a total of 509 projects was collected. Region classification criteria for wet or dry and non-freezing or freezing are summarized in Table 4. (11)

Faulting data from within each project consisted of both multiple survey sections and time periods. A detailed summary by pavement section is shown in Table 5. Data collected for each project included:

- State and county.
- Pavement classification and identification (interstate, state highway, rural route number, street, etc.).
- Survey section beginning and ending mile post.
- Year constructed.
- Number of traffic lanes (one direction), lane width, and direction.
- Pavement type (jointed plain - JPCP or jointed reinforced concrete pavement - JRCP).
- Concrete slab thickness.
- Average transverse joint spacing and type (right angle or skewed).
- Dowel bar diameter.
- Type of shoulder (tied concrete, asphalt, none).
- Longitudinal edge drains (new construction or retrofit).
- Base type (cement-treated, asphalt stabilized, lean concrete, or granular) and thickness.
- Subbase type and thickness.
- Subgrade soil type (AASHTO soil classification).
- Freezing index (degree days below 0 °C (32 °F)), annual precipitation, and pavement climatic region as defined in Table 4.
- Annual temperature range (July average daily maximum temperature minus January average daily minimum temperature).
- Average daily traffic (ADT), average daily truck traffic (ADTT), truck percentage, axle configuration, and equivalent single 80 KN (18-kip) axle loads (ESALs) over each survey period.
- Survey year, pavement age, faulting measurements (mm (in.)), presence of corner breaks, and qualitative measure of pumping at time of survey.

Since few states had corner break and pumping data, that data was not used in the analysis and was excluded from the database. To refine the PCA erosion criteria the accumulated percent erosion was correlated with degree of faulting for each pavement section. Modulus of subgrade reaction (k-value) and increases in support due to granular and stabilized subbases were calculated using the PCA thickness design guideline procedures. (1) One-way ADT was used to estimate the proportion of trucks in the right lane. (1) Erosion was calculated using load frequency, axle configurations, and weigh-in-motion (WIM) data when possible. When WIM data and truck load distributions were not available, standard W-4 tables based on roadway functional classification were used with load frequency and axle configuration to calculate erosion. When multiple pavement sections were surveyed the same year the faulting data was averaged.

As shown in Table 2 the environmental factors which were significant in prediction of joint faulting were the levels of moisture and temperature range. Temperature range and levels of moisture were categorized by the freezing index (degree-days below 0 °C (32 °F)), average annual precipitation (mm (in.)), soil drainability (AASHTO soil type), and presence of longitudinal edge drains.

The BMDP statistical analysis computer program was used to develop the relationships between accumulated erosion and joint faulting. (15) Nonlinear regression analysis techniques were used in the faulting prediction model development. An initial set of power parameters and variable coefficients was defined. A Taylor series expansion of the model was used near the initial set of parameters. Using partial derivatives with respect to each parameter and ignoring higher order terms, an approximation for the original function is derived which is linear in the power parameters and can then be solved with standard linear regression analysis techniques. This process is repeated until the sum of squared errors falls below a pre-selected minimum value. Linear regression techniques were then used to generate coefficients for the transformed variable (raised to an exponent). Statistically insignificant variables (t-statistic less than 2.0) were eliminated from the model. The nonlinear regression analysis to generate power coefficients and linear regression analysis to generate variable coefficients were repeated until all remaining variables were statistically significant in the prediction of joint faulting.

Since the faulting mechanisms and degree of faulting for doweled and undoweled joints may be different, two faulting predictive models were generated. For doweled pavements transverse joint faulting as a function of erosion and environmental variables is as follows:

$$\text{FAULT} = (\text{EROSION})^{0.25} * [0.0038332 * (\text{PRECIP} / 10)^{1.84121} + 0.0057763 * \text{JS}^{0.38274}] \quad (5)$$

where:

FAULT = faulting at doweled transverse pavement joints, in.
EROSION = calculated accumulated erosion (eqs.3 and 4), percent
PRECIP = annual precipitation, in.
JS = average joint spacing, ft

statistics: $R^2_{\text{adj}} = 0.703$
SEE (standard error of estimate) = 0.047 in.
n (no. of data points) = 281

For undoweled pavements transverse joint faulting as a function of erosion and environmental variables is as follows:

$$\text{FAULT} = (\text{EROSION})^{0.25} * [9.75873 \times 10^{-4} * (\text{PRECIP})^{0.91907} + 0.0060291 * \text{JS}^{0.54428} - 0.016799 * \text{DRAIN}] \quad (6)$$

where:

FAULT = faulting at undoweled transverse pavement joints, in.
EROSION = calculated accumulated erosion (eqs. 3 and 4), percent
PRECIP = annual precipitation, in.
JS = average joint spacing, ft
DRAIN = drainage dummy variable, 0 for none, 1 for edge drains

statistics: $R^2_{\text{adj}} = 0.743$
SEE (standard error of estimate) = 0.055 in.
n (no. of data points) = 582

The model predictive power, as measured by the coefficient of determination R^2 , is typical of other joint faulting models reviewed which had R^2 ranges from 0.53 to 0.81 and an average of 0.69. The standard errors of estimate for the both joint erosion model are also within the range of existing prediction models. The existing models have SEE ranges from 0.5 to 1.5 mm (0.02 to 0.06 in.) and averages 0.97 mm (0.038 in.). Summary statistics for the two faulting - erosion prediction models are presented in Table 6. Doweled and undoweled model prediction error distributions for wet regions (greater than 762 mm (30 in.) annual precipitation) and dry regions (less than 762 mm (30 in.) annual precipitation) are shown in Figures 1 through 4. Examination of prediction errors for both models indicates that they are symmetrically distributed around zero.

For the doweled joint model the freezing index, presence of shoulders, dowel diameter, base type, soil type, and drainage were not significant variables in predicting faulting. Variables such as slab thickness, dowel bearing stress, and subbase/subgrade support were inherently considered in the calculation of erosion. The calculation of erosion accounts for the benefits of using shoulders since the shoulder variable was statistically insignificant in prediction of doweled joint faulting.

For the undoweled model the freezing index and soil type were not significant variables in predicting joint faulting. Other variables such as slab thickness, subgrade/subbase support, base type, and shoulders were assumed to be inherently considered in the calculation of erosion.

SENSITIVITY ANALYSIS

A sensitivity analysis indicates that the change in faulting is consistent in direction with change in variables. Results of the sensitivity analysis is shown in Table 7.

Plots of faulting versus accumulated erosion are shown in Figures 5 through 8 for wet regions (annual precipitation of 1016 mm (40 in.)) and dry regions (annual precipitation of 381 mm (15 in.)). Figures 5 and 6 are for doweled joints and Figures 7 and 8 are for undoweled joints. The figures should not directly be used for comparing the effectiveness of dowel bars in reducing faulting since they are plotted as a function of erosion. The computed erosion factors take into account the benefits (higher amount of allowable loads) of dowel bars.

The annual precipitation has a significant effect on joint faulting. For example, at 100 percent erosion for a 4.57 m (15 ft) long slab in a region with an annual precipitation of 1016 mm (40 in.) the predicted faulting for an undoweled joint as shown in Figure 8 is 4.3 mm (0.17 in.). For the same conditions but with a lower precipitation of 381mm (15 in.) the undoweled model shown in Figure 7 predicts faulting of 3.0 mm (0.12 in.) when no edge drains are present. A 63 percent reduction in precipitation results in a 29 percent reduction in faulting.

Joint spacing also has an effect on predicted faulting. For example, at 100 percent erosion for a 12.2 m (40 ft) long slab in a region with an annual precipitation of 381 mm (15 in.) the predicted faulting for doweled joint as shown in Figure 5 is 2.5 mm (0.10 in.). For the same conditions but with a smaller joint spacing of 4.57 m (15 ft) the doweled joint model shown in Figure 5 predicts faulting of 2.0 mm (0.08 in.). A 63 percent reduction in joint spacing results in a 20 percent reduction in faulting.

Longitudinal edge drains were also statistically significant in reducing undoweled joint faulting. For example, at 100 percent erosion for a 4.57 m (15 ft) long slab in a region with an annual precipitation of 1016 mm (40 in.) the predicted faulting for an undoweled joint without edge drains as shown in Figure 8 is 4.3 mm (0.17 in.). For the same conditions but using edge drains the undoweled model shown in Figure 8 predicts faulting of 3.0 mm (0.12 in.). A 29 percent reduction in joint faulting occurs when longitudinal edge drains are used.

A sensitivity analysis of the variables inherent to the erosion term indicates that the change in faulting is consistent in direction with change in the variable. Results of the sensitivity analysis is shown in Table 8.

A slab thickness-precipitation-shoulders sensitivity analysis of the modified erosion analysis for subbase support of 54.30 MPa/m (200 lb./in.³) and 135.75 MPa/m (500 lb./in.³) is shown in Figures 9 and 10 for doweled joints. A significant reduction in faulting for a given thickness occurs when tied-concrete shoulders are used in both the wet and dry climates. Less of

a reduction of faulting occurs with an increase of subbase support. At a thickness of 254 mm (10 in.), k of 54.30 MPa/m (200 lb./in.³), and an annual precipitation of 1016 mm (40 in.), the faulting decreases from 3.8 mm (0.15 in.) to 1.8 mm (0.07 in.) with the use of shoulders. For an annual precipitation of 381 mm (15 in.), faulting decreases from 1.3 mm (0.05 in.) to 0.5 mm (0.02 in.) with the use of shoulders. For a pavement with a thickness of 254 mm (10 in.) and tied-concrete shoulders, increasing the subbase support to 135.75 MPa/m (500 lb./in.³), decreases the faulting from 1.8 mm (0.07 in.) to 0.8 mm (0.03 in.). Overall, increasing subgrade support has less of an effect of faulting than does adding shoulders.

A slab thickness-precipitation-shoulders sensitivity analysis of the modified erosion analysis for subbase support of 54.30 MPa/m (200 lb./in.³) and 135.75 MPa/m (500 lb./in.³) for undoweled joints is shown in Figures 11 and 12. Again, a significant reduction in faulting for a given thickness occurs when tied-concrete shoulders are used in both the wet and dry climates. Faulting also decreases with an increase of subgrade support. At a thickness of 254 mm (10 in.), k of 54.30 MPa/m (200 lb./in.³), and an annual precipitation of 1016 mm (40 in.), the faulting decreases from 2.0 mm (0.08 in.) to 1.3 mm (0.05 in.) with the use of shoulders. For an annual precipitation of 381 mm (15 in.), faulting decreases from 1.0 mm (0.04 in.) to 0.8 mm (0.03 in.) with the use of shoulders. For a pavement with a thickness of 254 mm (10 in.) and tied-concrete shoulders, increasing the subbase support to 135.75 MPa/m (500 lb./in.³) decreases faulting from 1.3 mm (0.05 in.) to 0.8 mm (0.03 in.). If tied concrete shoulders are not used, an increase of subbase support to 135.75 MPa/m (500 lb./in.³) decrease faulting from 2.0 mm (0.08 in.) to 1.5 mm (0.06 in.).

To determine the reasonableness of the doweled and undoweled faulting models, predicted faulting was compared to the AASHO Road Test in Ottawa, Illinois for 6.1 m (20 ft) joint spacing and an annual precipitation of approximately 889 mm (35 in.). For slab thickness giving 100 percent erosion, the predicted faulting for doweled and undoweled joints is 2.546 mm (0.179 in.) and 4.521 mm (0.178 in.), respectively. The predicted faulting generated from models developed from two separate databases gives near equal terminal life faulting and indicates that the erosion and power criteria is effective in accounting for effects of shoulders, aggregate interlock, and use of dowel bars.

CONCLUSIONS

A method to incorporate climatic modifications to the 1984 PCA erosion criteria was developed. A survey of existing performance models identified numerous environmental variables that affect joint faulting, pumping, and roughness. A review of existing performance data indicated a lack of quantitative pumping (erosion) data which could be used to modify the erosion criteria. Therefore, a large joint faulting database was generated from available research studies and state pavement management systems to use in the modification development.

The erosion refinement consisted of adding variables used in existing faulting models to the erosion criteria and developing two faulting prediction models (doweled and undoweled joints) using nonlinear regression analysis techniques. The 1984 PCA erosion criteria was derived from doweled joint, no shoulder AASHO Road test data and related to studies on joint faulting to incorporate effects of concrete shoulders, undoweled joints, stabilized subbases, larger amounts of traffic, and increased service life. Significant variables added to the joint faulting prediction models included annual precipitation and joint spacing. For undoweled joints the use of edge drains was also a significant variable.

A sensitivity analysis of the variables in the faulting model and those inherent to the erosion term indicates that the change in faulting is consistent in direction with changes in the variables. The modified faulting models was also compared to the AASHO Road Test site at the Ottawa, Illinois and found to give reasonable results. This indicates that local annual precipitation, joint spacing, and use of edge drains (undoweled joints) along with the erosion and power criteria is effective in accounting for effects of shoulders, aggregate interlock, and use of dowel bars.

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TABLE 1 - Comparison of Thickness to Undoweled Pavement Performance

No. Semi-Trailers, per day	Design Thick., mm	Subbase Type	Drainage Rating	Slope Variance Factor, SVF	PSI	4.6 m Joint Spacing Fault, mm	6.1 m Joint Spacing Fault, mm
1600	279	Granular	Good	6	3.0	3.0	3.8
	279	Granular	Poor	26	2.3	4.0	5.3
	254	Cement Tr.	Good	-	-	3.7	3.8
	254	Cement Tr.	Poor	-	-	5.0	5.2
356	229	Granular	Good	4	3.0	3.2	4.0
	229	Granular	Poor	15	2.5	4.3	5.6
	211	Cement Tr.	Good	-	-	3.7	3.9
	211	Cement Tr.	Poor	-	-	5.1	5.4

1 in. = 25.4 mm

1 ft = .305 m

TABLE 2 - Identified Variables Which Affect Transverse Joint Distress

Category	Parameter	Influencing Variables	Effect on Faulting and Pumping
Traffic	No. of ESALs, semi-trailers	Single/tandem axle load, lane distribution	Increase with traffic and loads
Age	Years in service	Pavement design and construction	Increase with age
Pavement Design	Slab structural capacity	Slab thickness	Decrease with thickness
	Tied concrete shoulders	Corner deflection	Decrease if tied shoulders used
	Load transfer type	Aggregate interlock or dowel bars	Decrease if dowel bars used
	Load transfer efficiency	Dowel bar diameter and bearing stress	Decrease with diameter
	Subbase stabilization	Stabilization type and erodability	Decrease if stabilized subbase used
	Subgrade	AASHTO soil type, k- value, CBR	Decrease with support and drainability
	Joint spacing and opening	Subbase friction, temp. range, coef. of thermal exp., shrink.	Increase with joint spacing and opening
	Drainage	Edge drains	Decrease if edge drains used
	Concrete material	Strength and elastic modulus	Decrease with modulus and strength
Environmental	Precipitation	Annual precip., Thornthwaite Moisture Index	Increase with annual precipitation
	Freezing	Freezing index	Increase with freezing index
	Solar radiation	Temp. range, summer thermal efficiency, joint opening	Increase with solar radiation

TABLE 3 - Summary of States Surveyed

State	Climatic Region	No. of Projects	No. of Points	Data Source
Arizona	Dry Non-Freeze	7	7	ref. 15
California	Dry and Wet Non-Freeze	85	814	DOT, refs. 11 and 15
Connecticut	Wet-Freeze	7	9	DOT
Florida	Wet Non-Freeze	50	283	DOT, refs. 15 and 16
Georgia	Wet Non-Freeze	28	65	ref. 11
Iowa	Dry and Wet Freeze,	38	38	DOT
Illinois	Wet-Freeze, Wet Non-Freeze	8	15	DOT
Louisiana	Wet Non-Freeze	28	297	ref. 11
Michigan	Wet-Freeze	12	12	ref. 15
Minnesota	Dry-Freeze	105	921	DOT, refs. 11 and 15
North Carolina	Wet Non-Freeze	13	63	refs. 15 and 16
New York	Wet-Freeze	21	21	DOT, ref. 15
Ohio	Wet-Freeze	59	59	refs. 15 and 16
Pennsylvania	Wet-Freeze	5	5	ref. 15
Utah	Dry-Freeze	33	231	ref. 11
Wisconsin	Dry and Wet Freeze,	10	10	DOT
Total		509	2850	

TABLE 4 - Climatic Zone Classification

Climatic Zone	Annual Rainfall, mm	Freezing Index, Degree(°F)-Days
Wet Non-Freeze	Greater than 76	Less than 100
Wet-Freeze	Greater than 76	Greater than 100
Dry Non-Freeze	Less than 76	Less than 100
Dry-Freeze	Less than 76	Greater than 100

1 in. = 25.4 mm

TABLE 5 - Summary of Design Parameters of Pavement Sections Used in the Study

Region	State	Joint Type	Total No. of Section	No. of JPC Section	No. of JRC Section	Range in Pavement Age at Test, Years	Range in Slab Thickness, mm	Range in Joint Spacing, m	No. of Sec w/ Granular Base	No. of Sec w/ Stabilized Base	No. of Sec w/ Edge Drain	No. of Sec w/ Concrete Shoulder
Dry - Freeze	IA	Dow	18	18	0	3-11	254-292	6.1-9.1	9	9	5	8
	MN	Dow	82	6	76	3-51	178-254	4.6-12.1	75	7	8	4
		Plain	23	17	6	3-38	178-229	4.7-8.2	18	5	0	4
	UT	Plain	33	33	0	2-17	229-330	4.7	0	33	0	8
	WI	Dow	10	0	10	16-29	229	24.4	8	2	0	0
Dry - Non Freeze	AZ	Dow	1	1	0	4	254	4.6	0	1	0	1
		Plain	6	6	0	5-15	229-330	4.6	3	3	0	5
	CA	Plain	72	72	0	1-27	178-290	2.4-4.7	0	72	9	0
	CN	Dow	7	0		16-34	203-229	12.1	7	0	0	0
	IA	Dow	20	20	7	3-9	254-292	6.1	1	19	4	20
Wet - Freeze	IL	Dow	5	0	05	25-30	254	30.5	5	0	3	0
	MI	Dow	8	2	6	1-16	229-254	4.4-21.7	6	2	4	3
		Plain	4	4	0	12	229	4.7	0	4	3	1
	NY	Dow	19	5	14	12-22	229	6.1-19.4	17	2	0	3
		Plain	2	2	0	22	229	6.1	0	2	0	0
	OH	Dow	59	0	59	7-16	203-254	6.4-18.3	49	10	0	0
	PA	Dow	5	0	5	7	254	14.2	3	2	5	0
	CA	Plain	13	13	0	1-17	178-229	4.7	0	13	0	8
	FL	Dow	2	2	0	1-5	229-330	4.7-5.9	1	1	1	2
		Plain	48	48	0	2-28	203-229	6.1	20	28	33	0
Wet - Non Freeze	GA	Plain	28	28	0	5-19	229-254	6.1-9.1	2	26	25	0
	IL	Dow	3	0	3	24-27	254	30.5	3	0	2	0
	LA	Dow	28	5	23	9-22	229-254	6.1-17.8	8	20	9	0
		Dow	7	7	0	1-20	229-292	6.1-9.1	2	5	0	0
	NC	Plain	6	6	0	20	229	9.1	3	3	0	0

1 in. = 25.4 mm
1 ft = .305 m

TABLE 6 - Summary Statistics for PCA Faulting Prediction Models

Load Transfer Type and Equation No.	Coef. of Determin., R^2_{adj}	Std. Error of Est. SEE, in.	Variable (1)	Variable Coef.	T-Stat.
Doweled eq. 5	0.703	0.047	(PRECIP/10) 1.841211 JS 0.382/38	0.00383317 0.00577634	8.11 5.41
Undoweled. eq. 6	0.743	0.055	PRECIP 0.919069 JS 0.544277 DRAIN	0.000975873 0.00602913 -0.0167992	8.97 -10.86 -4.36

(1)NOTE: Independent variables multiplied by Erosion 0.25
 PRECIP = annual precipitation, in.
 JS = average joint spacing, ft
 DRAIN = drainage dummy variable, 0 for none, 1 for longitudinal edge drains

TABLE 7 - Sensitivity of Faulting to Variable Change

Independent Variable	Effect on Faulting	Sensitivity
Increase in erosion	increase	varies with erosion
Increase in precipitation	increase	high
Increase in joint spacing	increase	medium
Use of edge drains	decrease (undoweled)	medium

TABLE 8 - Sensitivity of Faulting to Variables Inherently Considered in Erosion

Independent Variable	Effect on Faulting	Sensitivity
Increase in slab thickness	decrease	varies with precipitation
Increase in foundation support	decrease	medium
Use of shoulders	decrease	medium

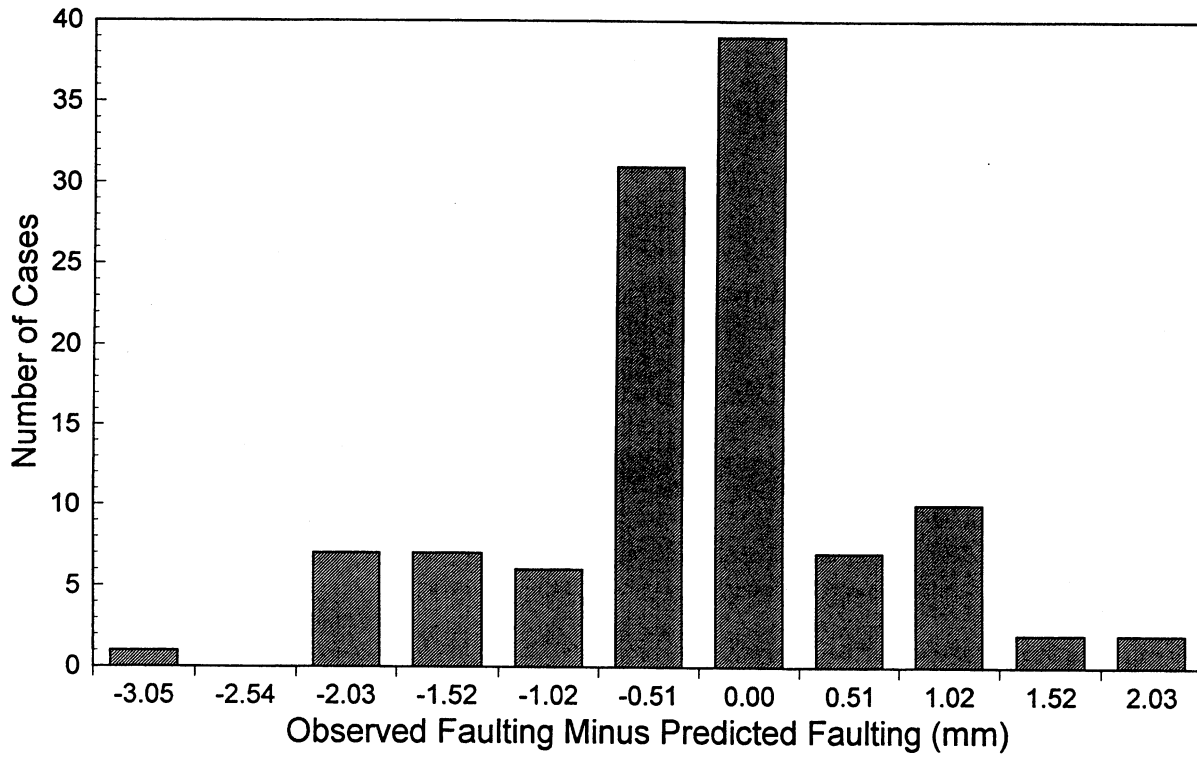


Figure 1 - Faulting Prediction Error for Doweled Joints in a Dry Region

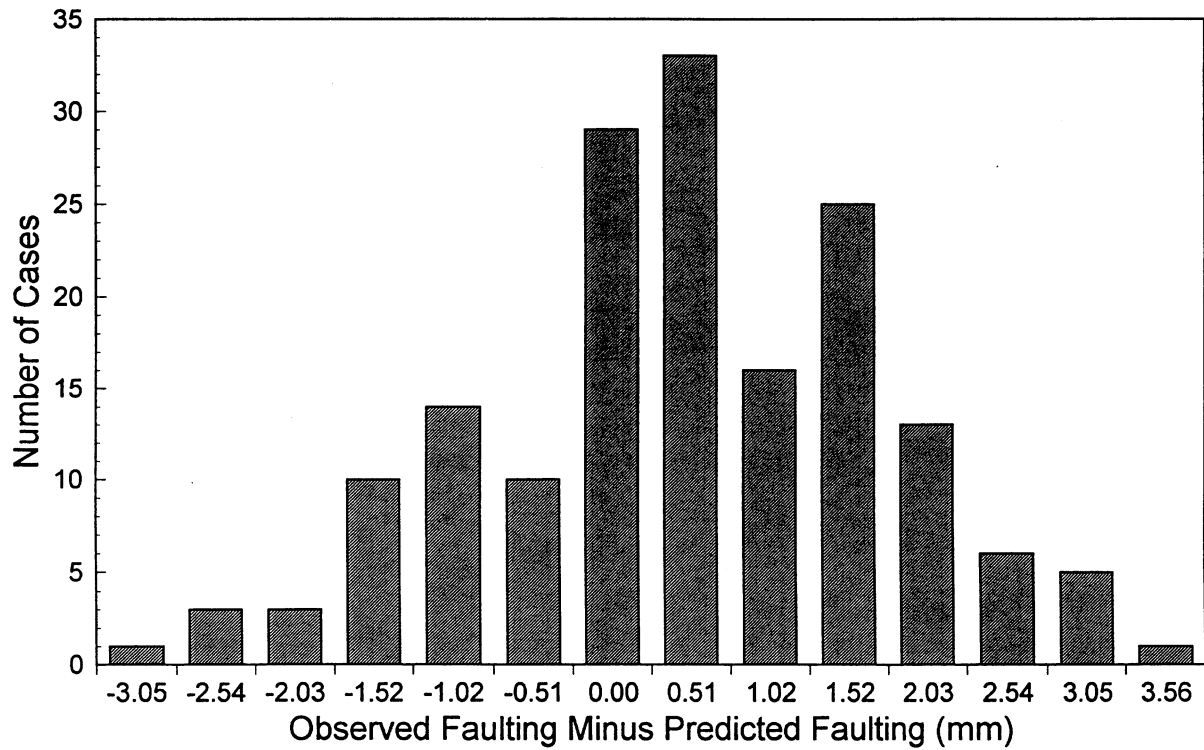


Figure 2 - Faulting Prediction Error for Doweled Joints in a Wet Region

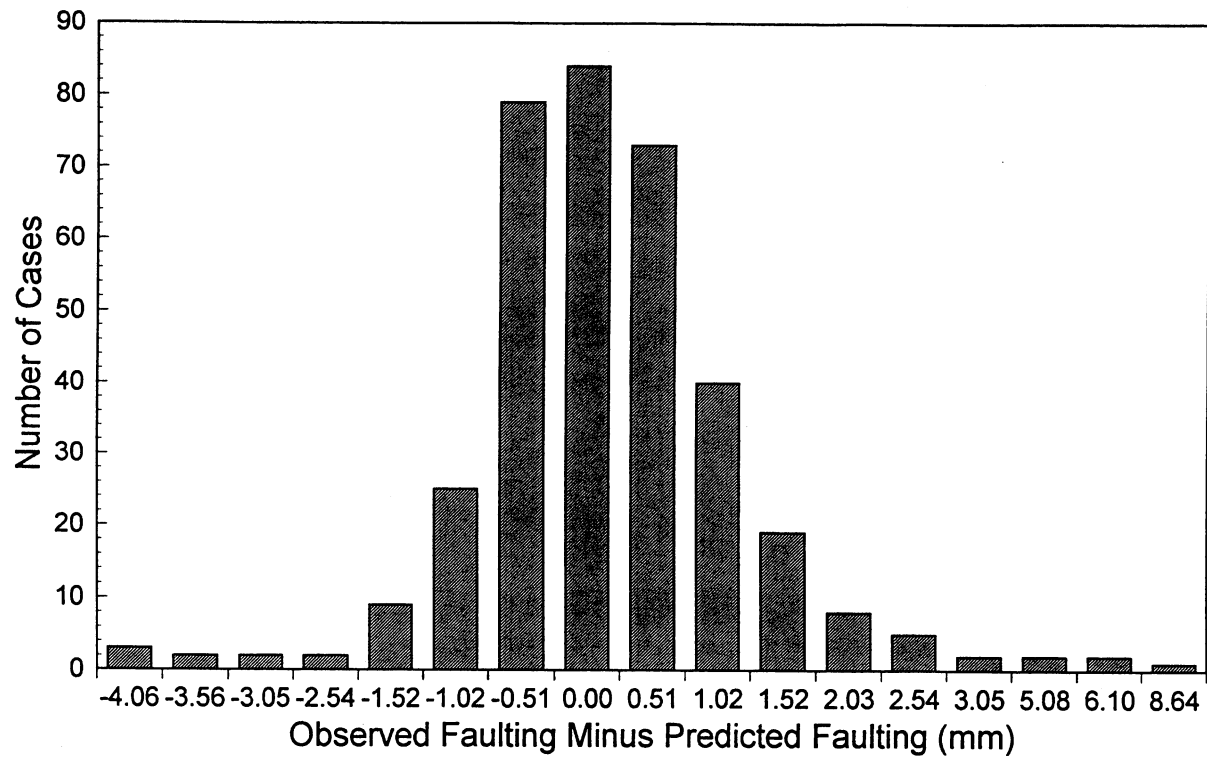


Figure 3 - Faulting Prediction Error for Undoweled Joints in a Dry Region

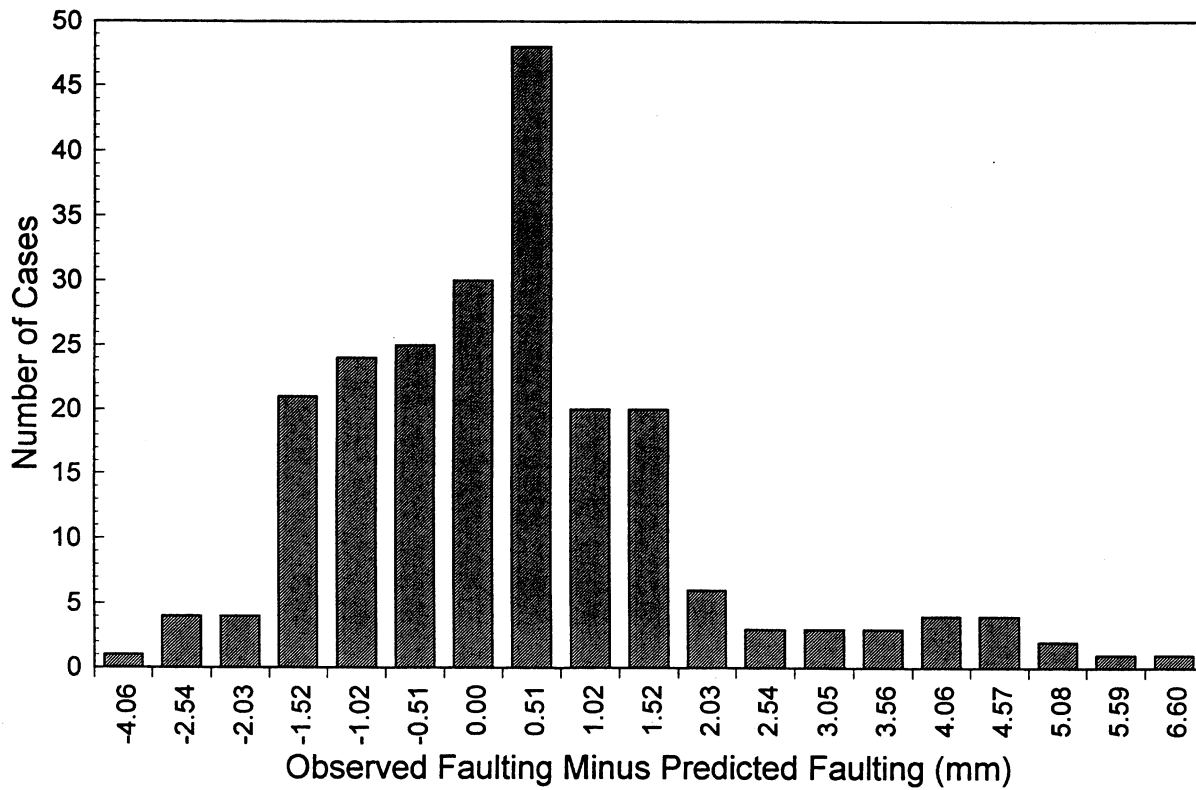


Figure 4 - Faulting Prediction Error for Undoweled Joints in a Wet Region

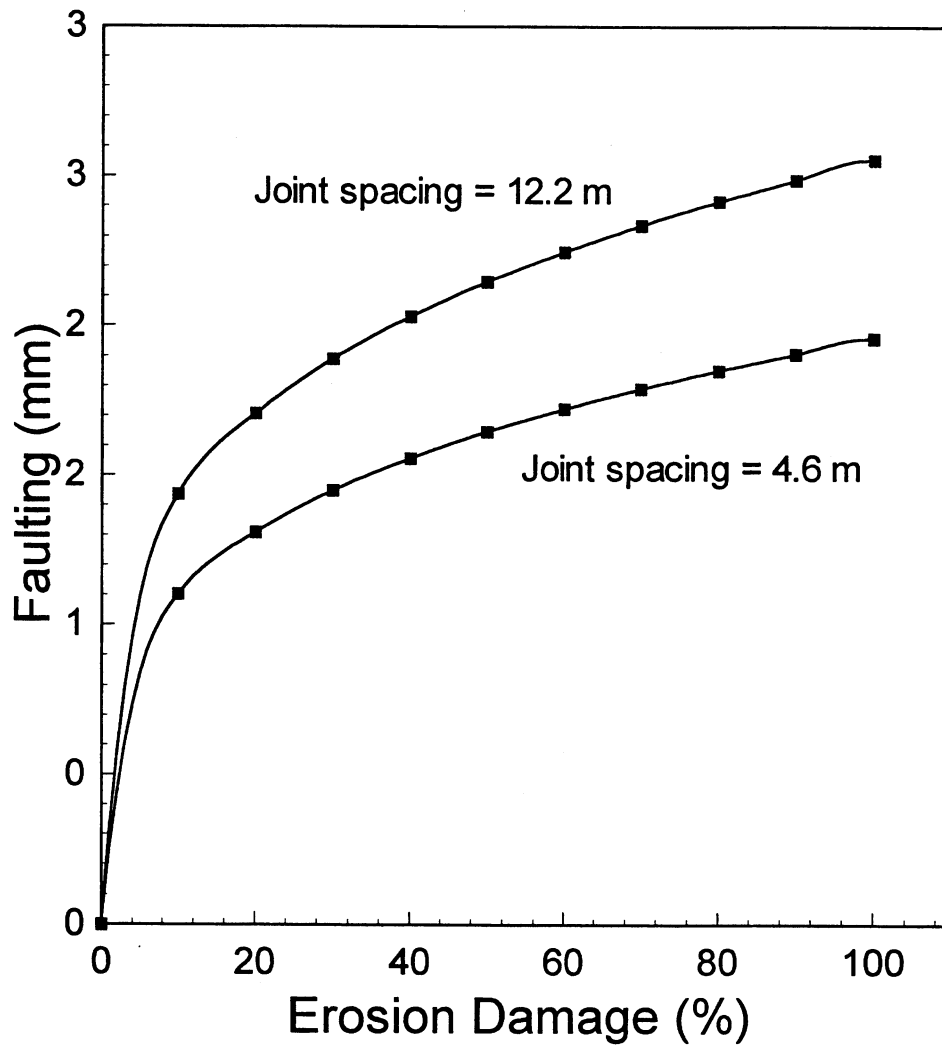


Figure 5 - Faulting versus Accumulated Erosion for Doweled Joints in a Dry Region

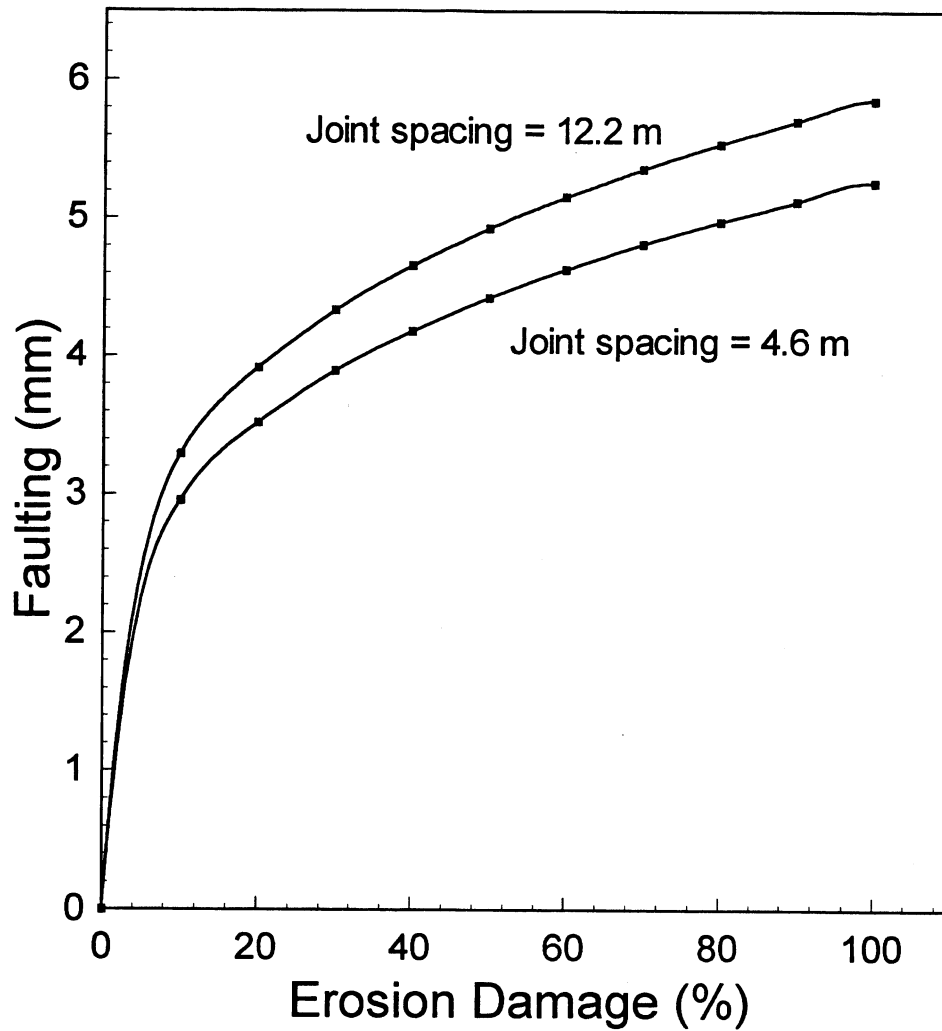


Figure 6 - Faulting versus Accumulated Erosion for Doweled Joints in a Wet Region

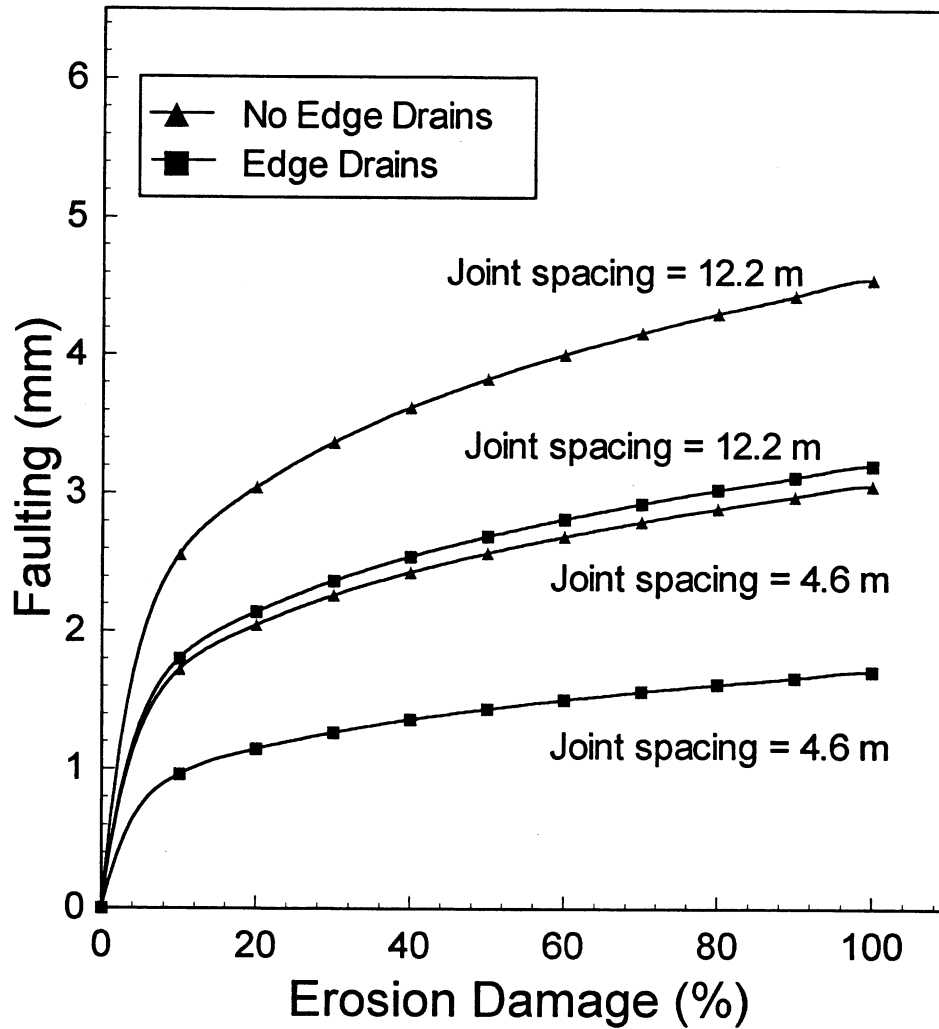


Figure 7 - Faulting versus Accumulated Erosion for Undoweled Joints in a Dry Region

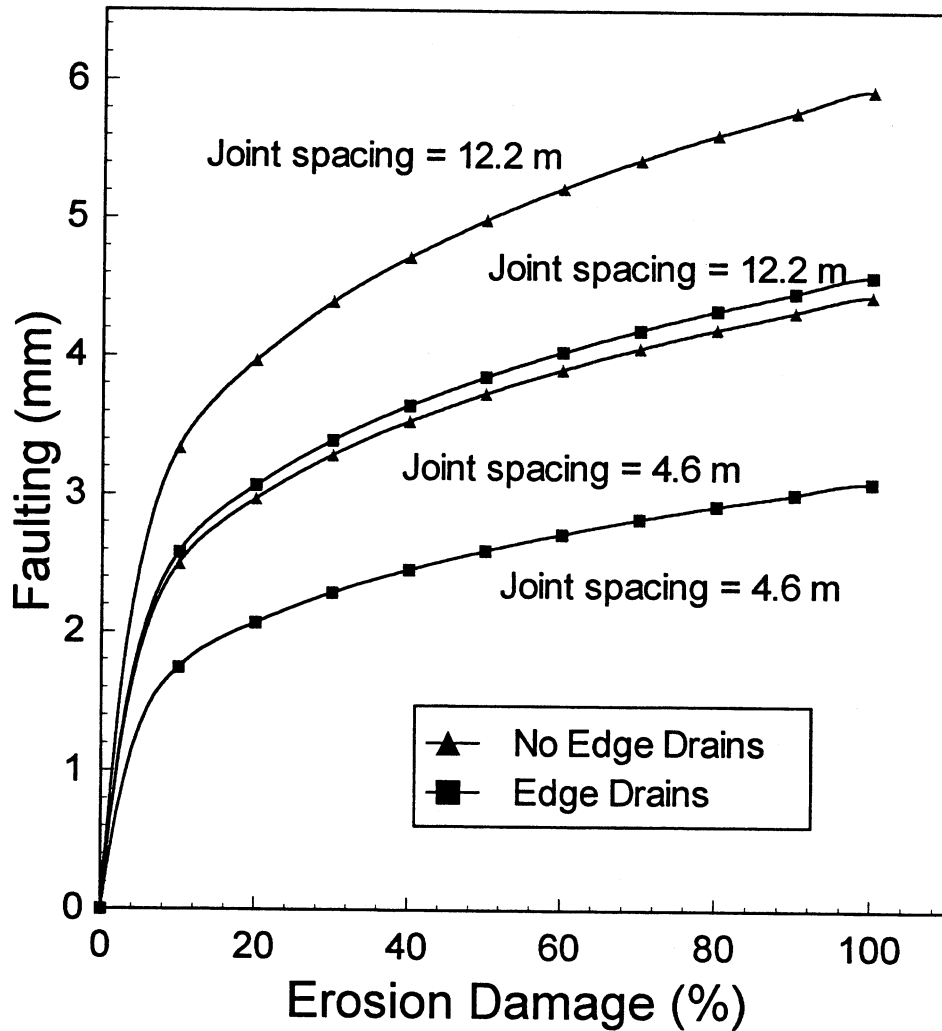


Figure 8 - Faulting versus Accumulated Erosion for Undoweled Joints in a Wet Region

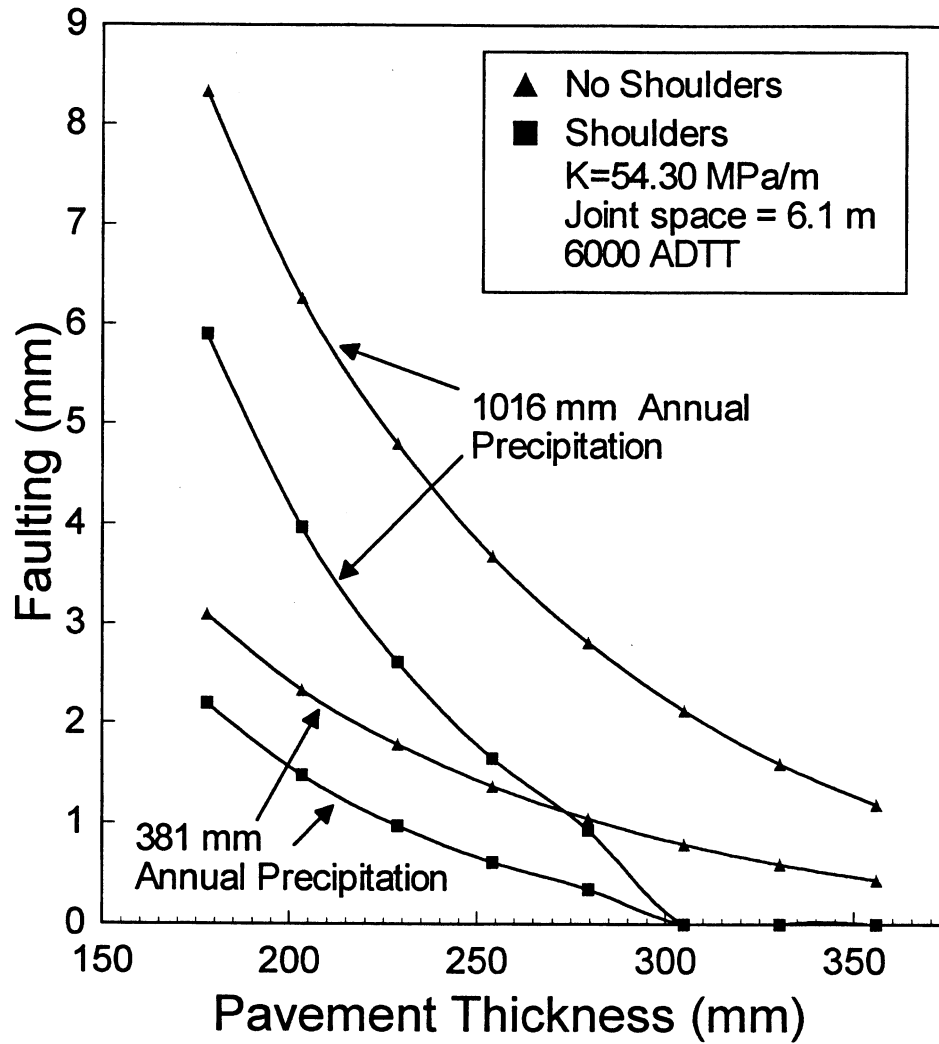


Figure 9 - Slab Thickness - Precipitation Analysis of the Modified Erosion Analysis for a Doweled Joint

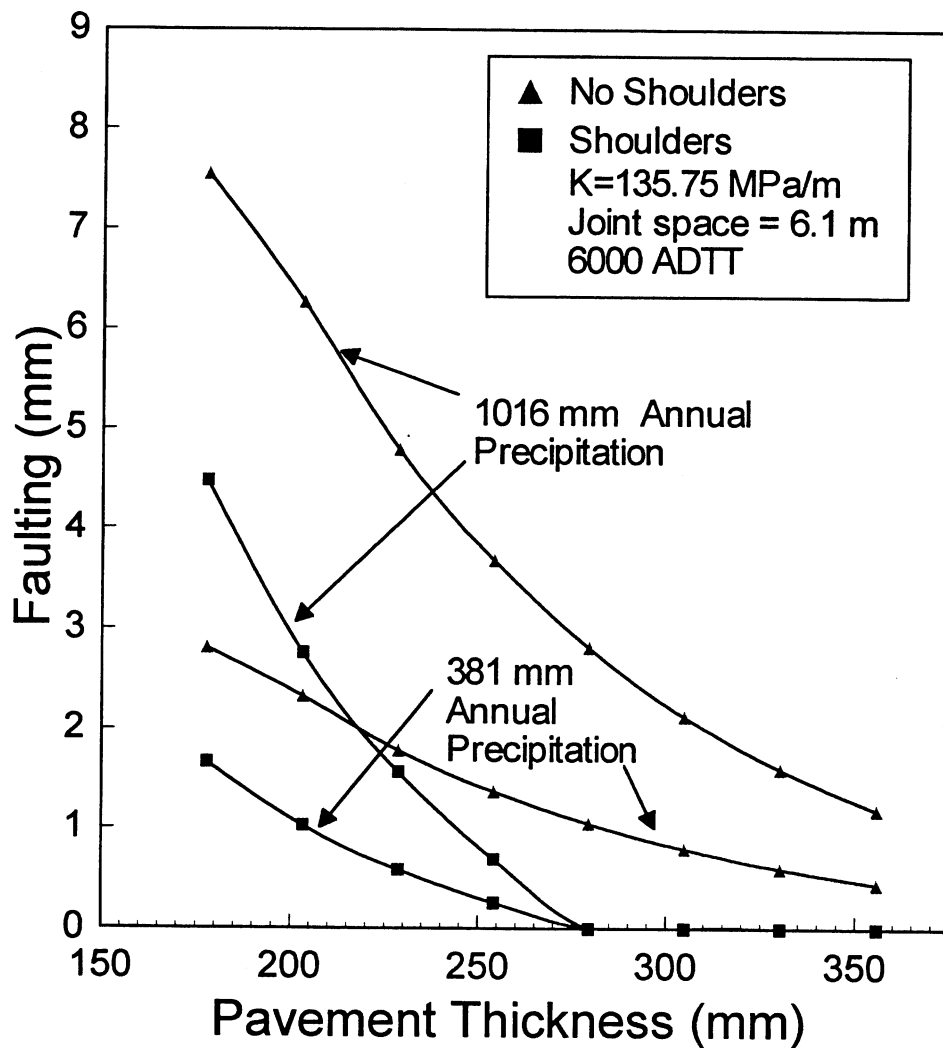


Figure 10 - Slab Thickness - Precipitation Analysis of the Modified Erosion Analysis for a Doweled Joint

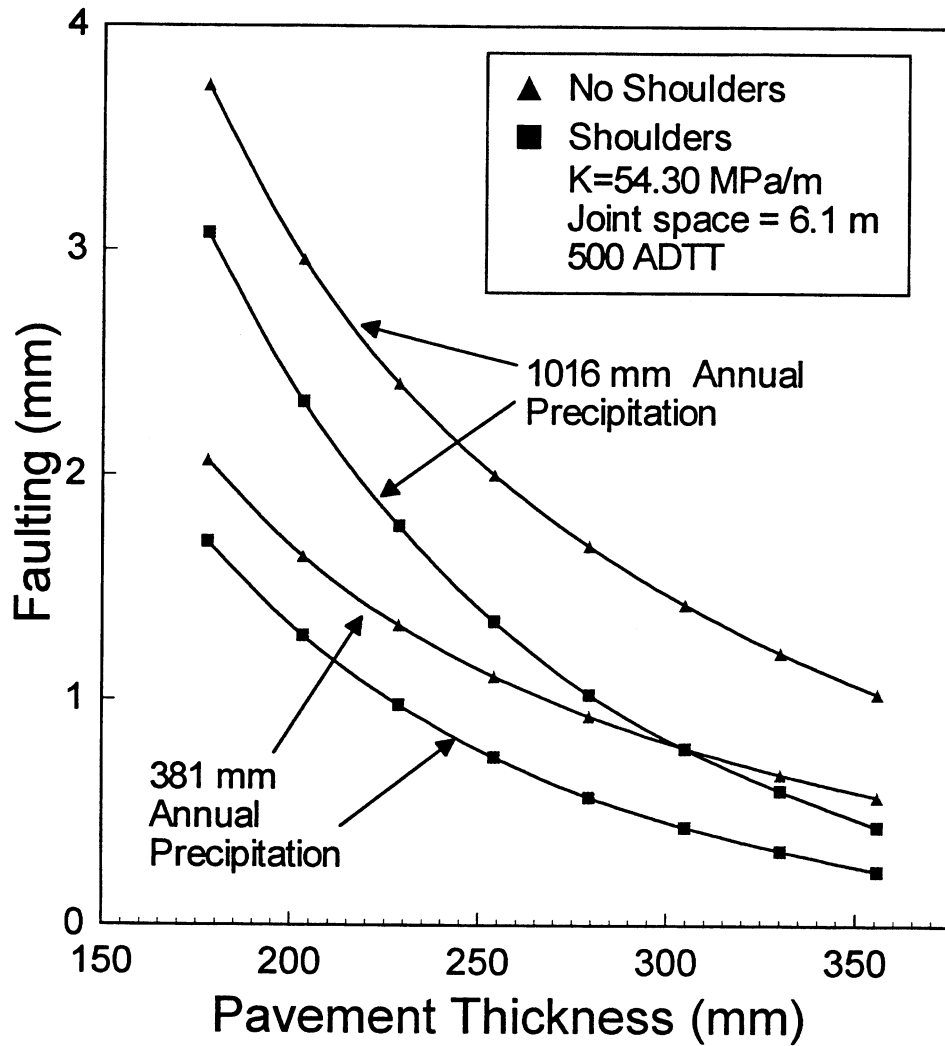


Figure 11 - Slab Thickness - Precipitation Analysis of the Modified Erosion Analysis for a Undoweled Joint

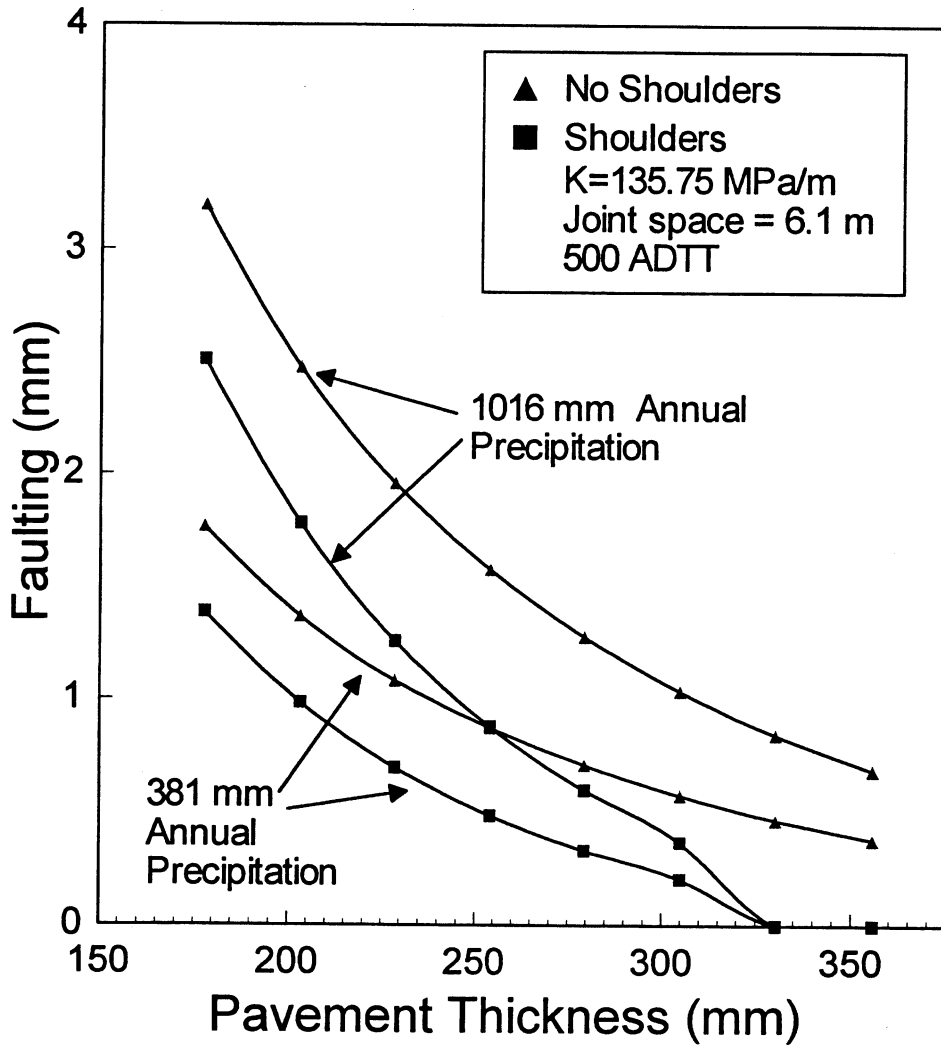


Figure 12 - Slab Thickness - Precipitation Analysis of the Modified Erosion Analysis for a Undoweled Joint