Design Procedure for Dowel Load-Transfer Systems for Full-Depth Repair Joints

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There is a critical need to develop more cost-effective and reliable design and construction procedures for the joint load-transfer systems for full-depth repairs of portland cement concrete pavements. A study conducted at the University of Illinois and funded by the FHWA was directed at the development of such a design procedure. This research work featured a laboratory study of the performance of dowel bars anchored in concrete slabs. This study produced models that predict the development of dowel bar looseness as a function of design and loading parameters. The research work also included a study of the long-term faulting and loss of load transfer across full-depth repair joints in experimental field installations in central Illinois. This study resulted in the development of a faulting model based on loss of load-transfer efficiency. These models were linked using a third model (relating dowel looseness and load-transfer efficiency) developed from data collected by other researchers conducting related studies. The three models were combined into a graphical procedure for easy use. Adjustments to the models for varying design reliability and site-specific field conditions are also discussed.

The construction of full-depth repairs of portland cement concrete (PCC) pavements has become a major part of pavement rehabilitation programs of transportation agencies throughout the United States. As such, it consumes a large portion of the rehabilitation budget for many projects. The high construction cost and inconsistent (but generally poor) field performance of full-depth repairs indicates that there is a critical need to identify and develop more cost-effective and reliable full-depth repair design and construction procedures.

In 1985 the University of Illinois (UI) Department of Civil Engineering was contacted by the Federal Highway Administration to conduct research under contract. Complete documentation of various portions of this research project has been presented previously (*1–3*). A portion of this research effort was devoted to advancing the state of the art of the design of doweled load-transfer systems for full-depth repairs of jointed concrete pavements. One focus of this work was the development of a new design procedure for full-depth repair load-transfer systems using models derived from data obtained from in-service repairs, laboratory studies, and theoretical analyses. This work is summarized in this paper.

Two of the most important sources of data for the development of this design procedure were a laboratory study of dowel bar performance and a study of the performance of field installations of full-depth repairs constructed using various load-transfer system designs.

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The laboratory study involved the application of 600,000 or more bidirectional 3,000-lb (13.4-kN) shear loads to single dowels anchored in holes drilled in concrete specimens. Test variables included dowel diameter, drill diameter and impact energy, anchor material, and dowel embedment. A thin nylon disk was placed around each of these dowels at the face of the concrete to retain the anchor material in the drilled hole until it could harden. Tests were also conducted using cast-in-place dowels, hollow stainless steel dowels, and dowels installed in very tight holes. Applied load and dowel deflection data were collected and analyzed to produce models for dowel deflection and looseness as functions of the test variables. This study has been documented in detail in previous papers (*1–3*).

The experimental field installations were constructed by the Illinois DOT (IDOT) on a portion of Interstate 70 in 1984. Design variables included dowel diameter, number of dowels per wheelpath, dowel anchor material, and the use of tie bars in lieu of dowels. IDOT and UI monitored the faulting performance and loss of load-transfer efficiency of these repairs through 1988, when the project was overlaid. This study is also documented in detail in previous papers (*1,2*).

DEVELOPMENT OF THE DESIGN PROCEDURE

The impact of dowel load-transfer system design (i.e., dowel diameter and length, drilled-hole diameter, anchor material, bearing stress) and load repetitions on the development of dowel looseness can be estimated using the following models, which were developed from the laboratory test data described previously.

For dowels anchored using the test epoxy mortar,

$$B_{\text{maxmin}} = [34{,}840(\text{AG}) + 1{,}167(\text{CT})^{1.058} - 9.899(\text{EB})^{1.160} + 1.079(\text{BS}) - 0.6912(\text{EN})^{1.831} + 8380]/1{,}000 \quad (1)$$

where $R^2 = 0.594$, C.O.V. = 36.9 percent, and $n = 178$.

For dowels anchored using the test cement group,

$$B_{\text{maxmin}} = \Big((\text{CT})\{-2347 + (\text{BS})[(0.762 + 2.604/\text{EN})]\} + 3883\Big)/1000 \quad (2)$$

where R^2 = 0.647, C.O.V. = 61.2 percent, and n = 109. In Equations 1 and 2,

B_{maxmin} = total dowel looseness (mils) (1 mil = 0.0254 mm),
AG = (nominal diameter of drilled hole − nominal dowel diameter) (in.),
CT = natural log of number of complete load cycle applications,
EB = dowel embedment (in.),
BS = Friberg's bearing stress (psi) (1 psi = 6.8947 kPa),
EN = estimated drill impact energy, ft-lb/blow (1 ft-lb = 6.5782 N-m).

A study of the field performance data collected from the IDOT experimental repair project in central Illinois yielded the following model for repair leave-joint faulting as a function of load deflection-based load transfer efficiency (*3*):

$$\text{FAULT} = 141900 * \text{LT}^{-3.807} - 0.1288 * \text{LT} + 23.37 \quad (3)$$

where

FAULT = repair leave-joint faulting (in. × 100),
LT = repair leave-joint deflection load transfer, as defined in Equation 2.1,
R^2 = 0.691,
n = 140 repair joints, and
SEE = 0.057 in. (1.5 mm).

The preceding models predict dowel looseness as a function of load-transfer system design and load parameters, and repair joint faulting as a function of load-transfer system efficiency. Thus, the prediction of repair faulting as a function of load-transfer system design and loading parameters based on variations in load-transfer system load and design parameters could be accomplished by "linking" these two types of models together through the use of a third model that predicts load-transfer efficiency as a function of dowel looseness. This type of model was developed by examining data collected under other studies.

Testing performed by Teller and Cashell on cast-in-place dowels resulted in the observation of a linear relationship between load-transfer efficiency and dowel looseness (*4*) (see Figure 1). This relationship was observed over a very small range of values because the cast-in-place specimens developed only small losses of load-transfer efficiency (compared with those observed for field installations of full-depth repairs).

Ciolko et al. (*5*) also monitored the development of looseness in load-transfer systems and compared this looseness with loss of load transfer. Their data for 9,000-lb (40.1-kN) load applications are also plotted in Figure 1. These data are for 1⅛-in. (28.6-mm) dowels and D-14L Starlugs (proprietary load-transfer devices) cast in concrete across joint widths of 0.25 and 0.75 in. (6.4 and 19 mm).

Teller and Cashell and Ciolko et al. used the following definition of load-transfer efficiency:

$$\text{Percent LTE} = [2 \times d_{UL}/(d_{UL} + d_L)] \times 100 \quad (4)$$

where

Percent LTE = deflection-based load transfer efficiency,
d_{UL} = measured deflection of the unloaded side of the joint or crack, and
d_L = measured deflection of the loaded side of the joint or crack.

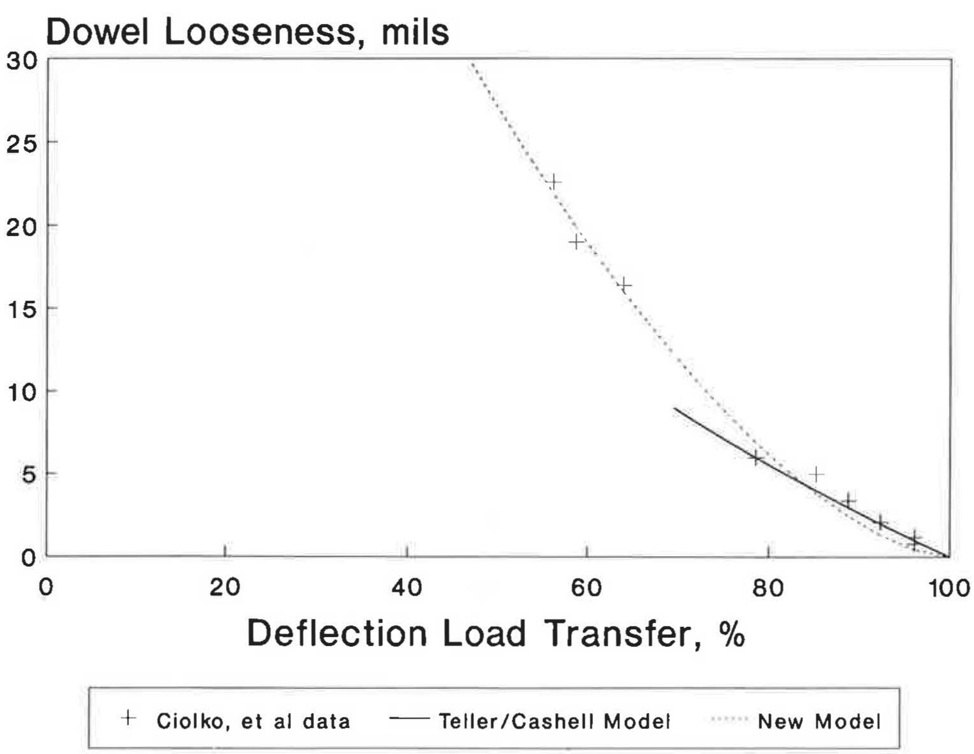

FIGURE 1 Data and models concerning the relationship between load-transfer capacity and dowel looseness.

The IDOT used a slightly different definition of load-transfer efficiency in their study of experimental repair installations:

$$\text{Percent LTE} = d_{UL}/d_L \times 100 \quad (5)$$

The Teller and Cashell and Ciolko et al. data load-transfer efficiency measurements were converted to the IDOT definition before they were plotted in Figure 1.

The following equation was developed to model load-transfer efficiency as a function of load-transfer system looseness using data from Ciolko et al.:

$$\text{Percent LTE} = 100 - (20.461 \times \text{LOOSE})^{0.619} \quad (6)$$

where

Percent LTE = computed percent deflection load transfer efficiency,
LOOSE = load transfer system looseness in one direction (mils) (1 mil = 0.0254 mm),
R^2 = 0.963,
n = 12 joints, and
C.O.V. = 3.5 percent.

This model is plotted through the data points in Figure 1. It should be noted that the looseness estimates obtained by Teller and Cashell and Ciolko et al. represent looseness in one direction (i.e., with the load being applied and released). The laboratory models presented in Equations 1 and 2 estimate the sum of looseness in both vertical directions (i.e., the load is applied, reversed, and then released).

Sequential use of the UI laboratory testing model, the Ciolko et al. model, and the IDOT field performance model allows the prediction of field performance of repairs constructed using various dowel load-transfer system designs. Graphical solutions can be prepared for each model and placed together to form a graphical procedure that allows direct estimation of performance from design inputs, as shown in Figures 2 and 3. Figure 2 assumes the use of epoxy mortar anchor materials, drill impact energy of 25 ft-lb/blow (35 N-m/blow), hole diameter equal to the dowel diameter plus 1/16 in. (1.6 mm), and 9 in. (23 cm) of embedment. Figure 3 assumes the use of cement grout anchor materials and drill impact energy of 25 ft-lb/blow.

In Figures 2 and 3, the dowel looseness predicted by Equations 1 and 2 has been reduced by 50 percent to match the definition of looseness used in the development of the load transfer–looseness model described above, and then increased by (1.64 × standard error of the model) to provide a 95 percent one-tailed estimate of dowel looseness. Thus, actual dowel looseness should be less than or equal to the predicted value in about 95 percent of all cases. Laboratory test load

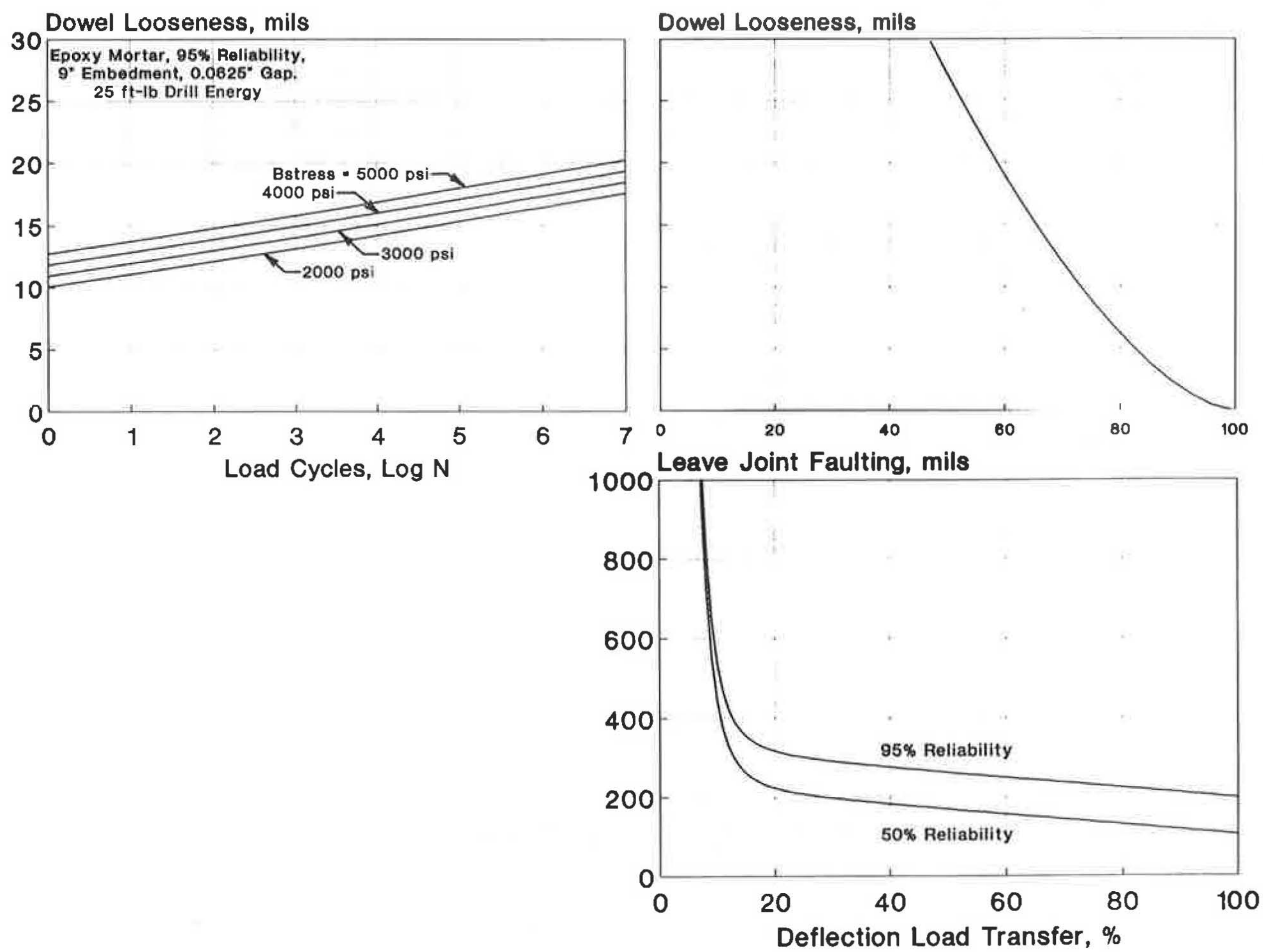

FIGURE 2 Proposed graphical procedure for the design of dowel load-transfer systems for full-depth repairs (epoxy mortar anchor material).

cycles must also be converted to 18-kip equivalent single-axle loads (ESALs) for field designs. The AASHTO Design Guide (*6*) suggests that a 36-kip (160-kN) tandem axle load (which was the load condition simulated in the laboratory study) on a 10-in. (25.4-cm) PCC slab has a load equivalency factor of approximately 2.5. Thus, each laboratory load cycle might be assumed to correspond to the passage of approximately 2.5 18-kip (80-kN) ESALs.

USING THE DESIGN PROCEDURE

Each model used in the development of this design procedure was derived empirically using laboratory or field performance data. The accuracy of each model is generally good, but some uncertainty is present in each case. Some of this uncertainty represents the variability that is inherent in the materials and factors being modeled; this uncertainty cannot be reduced and can be considered in the design only by incorporating statistical reliability concepts into the design procedure. However, some of the scatter in data points is due to differences in test specimen construction quality and the influence of environmental conditions on field measurements of load transfer.

The following sections provide guidance for considering the factors described above, as well as example uses of the proposed design procedure.

Applications Requiring No Adjustments

Suppose that the repairs at a particular site are to be designed so that the average repair leave-joint faulting after 10 million 18-kip ESALs is no more than 0.15 in. (3.8 mm). Figure 4 shows the use of Figure 3 to solve this problem, assuming that cement grout anchor materials are to be used together with grout retention rings.

The lower graph is entered at 15 on the *y*-axis, and a horizontal line is drawn to intersect the 50 percent (mean) curve for faulting versus deflection-based load transfer. The deflection-based load transfer at this point (about 64 percent) is that which must remain (on the average) after the application of the design loads.

A vertical line is drawn upward to intersect the curve modeling deflection-based load transfer as a function of dowel looseness. Sixty-four percent deflection-based load transfer corresponds to the development of approximately 16 mils (0.41 mm) of dowel looseness after the application of the design loadings.

A horizontal line is now drawn back to the upper left graph to intersect a vertical line drawn from the design traffic level. Ten million 18-kip ESALs is approximated by 4 million laboratory load cycles (log 4 million = 6.6). In this case, 4 million load cycles and 16 mils of dowel looseness correspond to a maximum allowable bearing stress of about 5,200 psi (35.9 MPa).

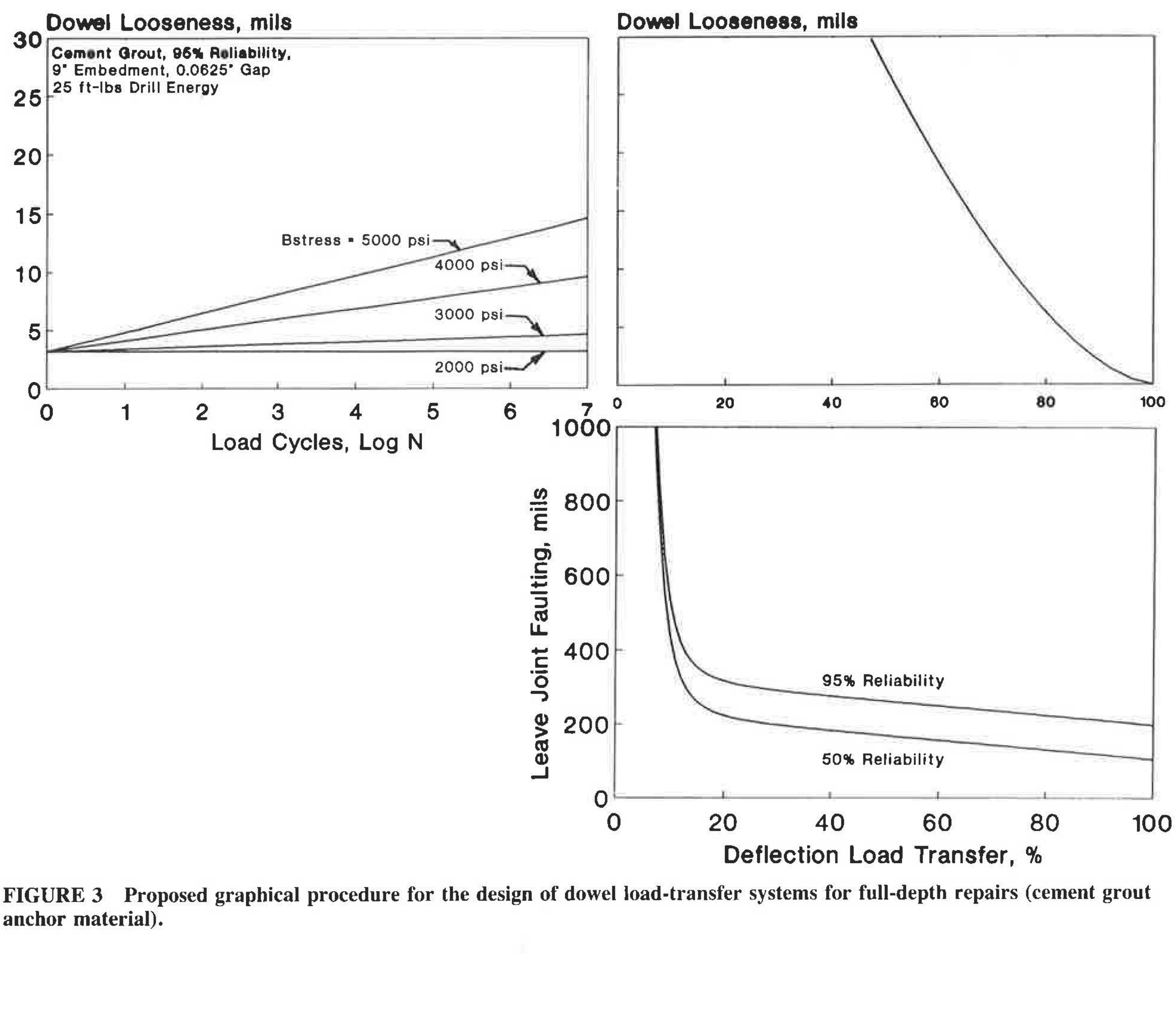

FIGURE 3 Proposed graphical procedure for the design of dowel load-transfer systems for full-depth repairs (cement grout anchor material).

Figures 5 and 6 present graphical solutions for Friberg's bearing stress [modified to allow consideration of the effects of dowels within 1.0*(PCC radius of relative stiffness) of the applied load]. According to these charts, two or more dowels of 1.0 in. (25.4-mm) diameter or more placed on 12- to 18-in. (31- to 46-cm) centers in each wheelpath will perform as required for the conditions assumed.

Although the design procedure does not specifically express a preference for one "acceptable" design over another, the selection of designs that further reduce bearing stress through the use of more dowels, larger dowels, and closer dowel spacings will generally produce better and more reliable results. For example, if the selected design exactly produces the design bearing stress of 4,800 psi (33.1 MPa) and the resulting dowel looseness is modeled with 95 percent reliability (as in Figures 2, 3, and 4), and the average joint faulting (50 percent reliability) is predicted to be 0.15 in. (3.8 mm), the overall reliability of the design is approximately (0.95)(0.5) = 0.475 or 47.5 percent. If the selected joint design produces a lower bearing stress, the predicted dowel looseness (95 percent level) will also decrease, producing an increase in load-transfer capacity and a corresponding increase in the level of reliability associated with achieving 0.15 in. of faulting. For example, 3,000 psi (27.6 MPa) of bearing pressure corresponds to about 6 mils (0.15 mm) of dowel looseness, which suggests about 80 percent load transfer and 0.15 in. of faulting with 65 percent reliability for an overall design reliability (0.95)(0.65) = 0.6175 or 62 percent. The first design will probably come close to achieving the stated design objective; the second should easily exceed the objective.

Adjustments for Increased Design Reliability

The IDOT I-70 field experiment produced the load-transfer and faulting data that were used to develop Equation 3. However, there was significant scatter of the data points about this model, particularly for higher levels of measured load transfer. For example, the model predicts about 0.10 in. (2.5 mm) of faulting for 100 percent load-transfer conditions, whereas the observations ranged from no faulting to about 0.25 in. (6.4 mm). Nearly all of the data points lie within two standard deviations of the model, as shown in Figure 7. This variability is probably due to many factors, including environmental conditions at the time the deflection measurements were taken and slight variances in deflection testing procedures. For example, load-transfer efficiency based on deflection measurements might approach 100 percent during periods of slab thermal expansion, whereas faulting develops during periods of lesser load-transfer efficiency.

If 100 percent deflection load transfer is provided continuously by the dowels alone (with no significant contributions from slab compression, aggregate interlock, and contributing factors), one would not expect faulting to develop. Thus, the

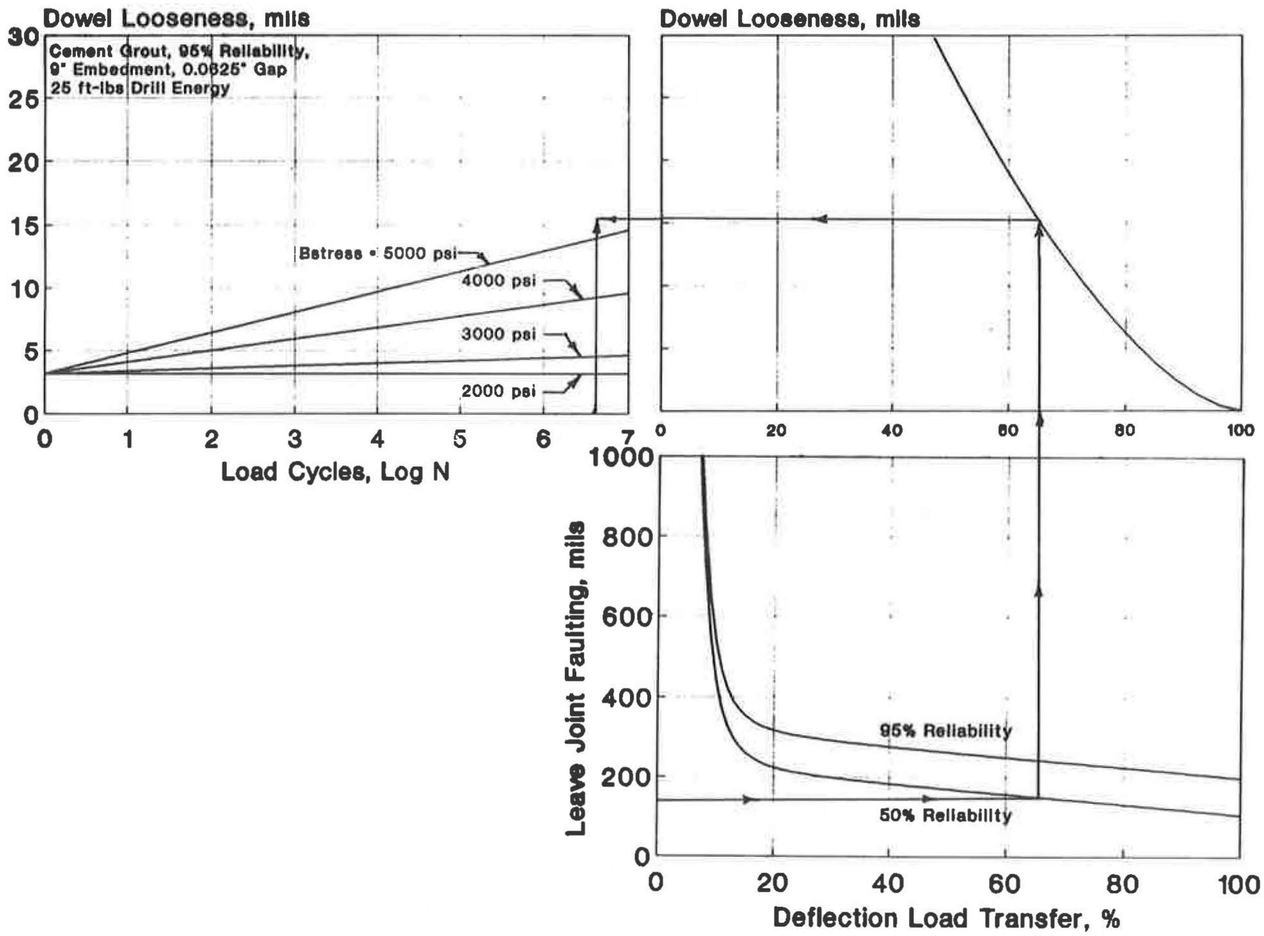

FIGURE 4 Graphical solution for design example in section on Applications Requiring No Adjustments.

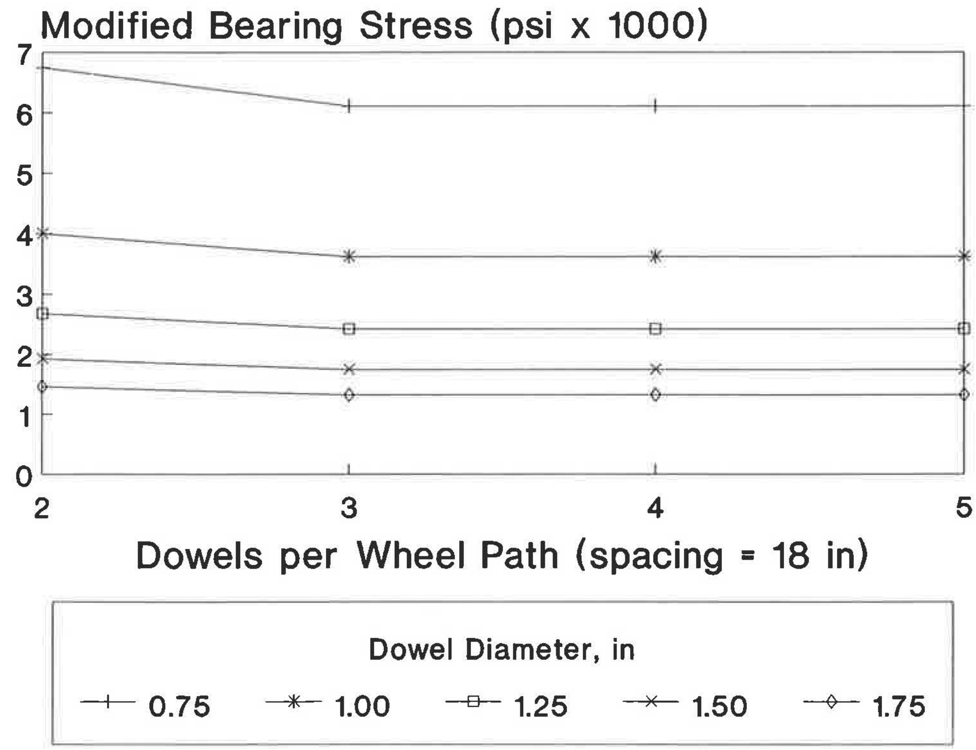

FIGURE 5 Graphical solution for Friberg's bearing stress [dowel spacing = 18 in. (45 cm)].

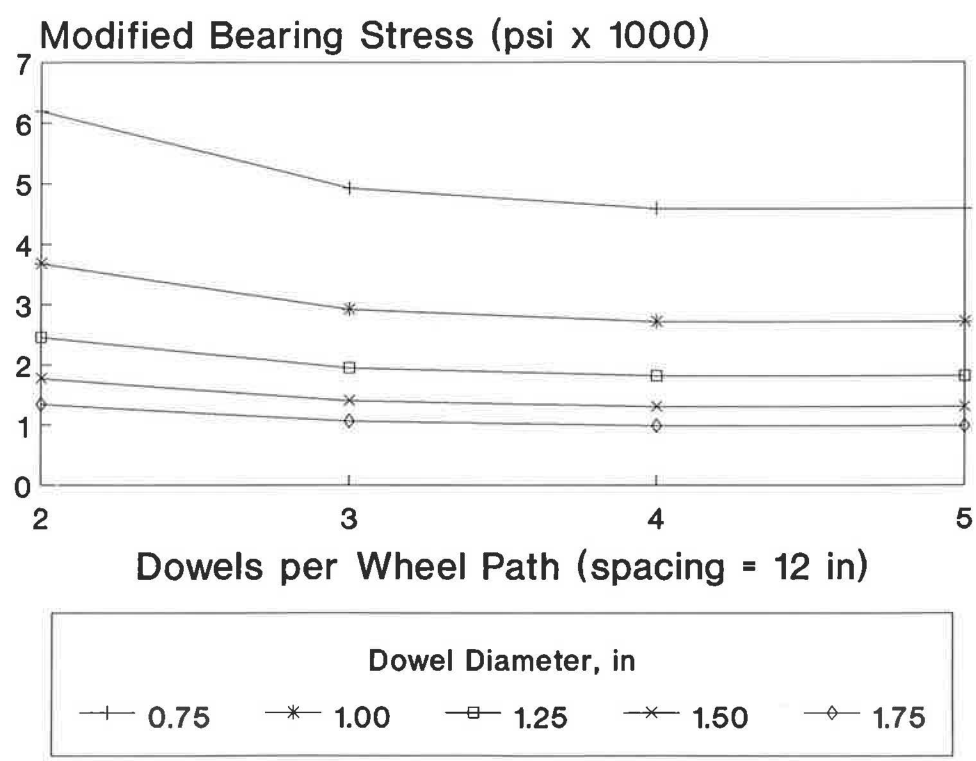

FIGURE 6 Graphical solution for Friberg's bearing stress [dowel spacing = 12 in. (30 cm)].

lowest curve in Figure 7 (mean minus two standard deviations) could be considered to represent perfect dowel installations and could be used when excellent dowel anchoring is guaranteed (i.e., when using good materials, construction techniques, and some device to retain the grout in the dowel hole during curing). The higher curves could be used for more conservative designs where uniformly good dowel support is not assumed and load transfer will be derived from dowel contributions as well as seasonal factors such as aggregate interlock, base support, and slab compression.

For example, suppose that the design problem from the section on Applications Requiring No Adjustments is repeated, except that it is now desired that the stated level of repair leave-joint faulting [0.15 in. (3.8 mm)] be the maximum allowable (rather than the average) at any repair, with a high degree of reliability. As described above, one approach would be to use the more conservative 95 percent reliability curve in the lower graph rather than the 50 percent reliability curve.

Unfortunately, the curves are very flat in the region of interest for the above problem, and the 95 percent reliability curve cannot be intersected at any realistic deflection-based load-transfer value for 0.15 in. (3.8 mm) of faulting. Thus, the design reliability will be less than 95 percent. Figure 3 predicts no significant increase in dowel looseness or joint faulting when bearing stress is less than or equal to 2,000 psi (13.8 MPa). This value should be selected for design, although some unacceptable faults will probably still develop. Two thousand psi is predicted to produce 4 mils (0.1 mm) of dowel looseness with 95 percent reliability; this looseness is predicted to produce 0.15 in. of faulting with about 70 percent reliability. Thus, the overall design reliability is approximately (0.95)(0.70) = 0.665 or 66.5 percent.

Adjustments for Variable Construction Quality

Another approach to achieving improved design reliability is to reduce the design dowel looseness value to account for the poor installation of some dowels. Reducing the design dowel looseness will result in a lower allowable bearing stress and therefore more or larger dowels, or both. Selection of appropriate dowel looseness reduction factors and the use of this approach are described below.

The laboratory study of dowel performance described earlier (*1–3*) included the use of grout retention disks to help ensure that the annular gap was completely filled with anchor material and that the dowels were uniformly supported. In most cases, this goal was accomplished. However, in some cases the cement grout was sufficiently fluid to flow out of the drilled hole in spite of the use of the grout retention disk, leaving a void over or around the dowel, or in both. Thus, some of the specimens tested probably resembled typical field installations, where the use of grout retention disks has been rare.

The effect of these voids on the development of dowel looseness (and the subsequent development of faulting) is tremendous. Figures 8 through 10 show laboratory test specimens (after testing) that were fabricated using the same design

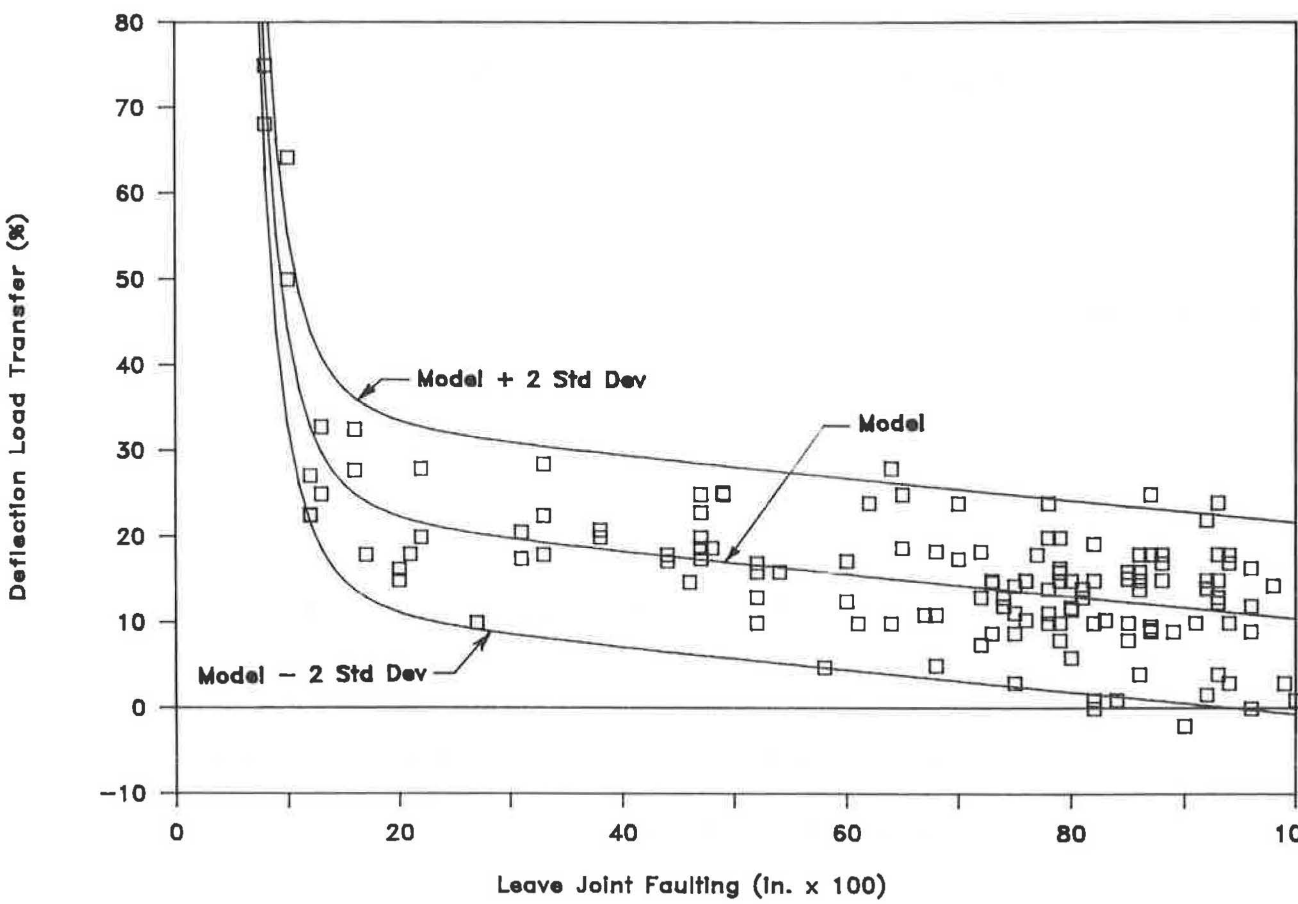

FIGURE 7 Distribution band (mean ± two standard deviations) for I-70 load transfer versus faulting data.

parameters [cement grout anchor material, 1.5-in. (38-mm) dowel, 1.75-in. (44-mm) hole drilled with the electric drill, 9-in. (23-cm) embedment]. Specimen C6R was constructed well (see Figure 8), B18 had a small void over the dowel (see Figure 9), and C22 had a large void over and around the dowel (see Figure 10). Figures 11, 12, and 13 present the dowel looseness envelopes for these three specimens and show increases in looseness of approximately 70 and 200 percent for specimens B18 and C22, respectively, over that of specimen C6R. Figures 14 through 16 present load-deflection traces for the three specimens that were taken after only 2,000 load cycles. These figures show that the looseness was present in the flawed installations from the beginning of the test program and only worsened with time. Further documentation of the effect of construction quality on dowel looseness are presented in previous papers (*2,3*). Typical increases in laboratory specimen dowel looseness ranged from 60 to 300 percent, depending upon the anchor material used and the sizes of the void, dowel bar, and annular gap. However, increases of up to 1100 percent were observed in some cases.

FIGURE 8 Laboratory test specimen C6R after testing.

FIGURE 9 Laboratory test specimen B18 after testing.

If it is assumed that poor construction quality will produce voids that allow the development of dowel looseness values that exceed the design value by, say, 300 percent, the design value must be reduced by 75 percent. Thus, the design looseness used in the section on Applications Requiring No Adjustments must be reduced to 16 mils × 0.25 = 4 mils (0.0838 mm). This new design value corresponds to a bearing stress of about 2,000 psi. Figures 5 and 6 suggest that two or more dowels of 1.5 in. diameter or more placed on 12- to 18-in. (31- to 46-cm) centers in each wheelpath will perform as required for these conditions. Three or more 1.25-in. (32-mm) dowels on 12-in. (31-cm) centers should also be acceptable.

As discussed previously, the selection of designs that reduce bearing stresses to levels that are even lower than those determined to be "acceptable" will generally improve repair performance and reliability.

FIGURE 10 Laboratory test specimen C22 after testing.

Adjustments for Site-Specific Factors

The design procedure described in this paper was developed using a single source of field data, the IDOT experimental repair test data from I-70 in central Illinois. Because the repairs included in this data base are all located at a single site, it is impossible to directly incorporate the effects of various climates on full depth repair faulting. However, other faulting models are available that are based on more broad-based data sources. These models can be used to estimate the effects of site-specific factors for both the I-70 location and any other location. The value of faulting selected for use in the design procedure can then be adjusted by the difference between these two values to "correct" for these factors. The use of such models to adjust the proposed design procedure is described below.

It should be noted that the effects of site-specific factors estimated by any models may be confounded with other variables in the same models. Furthermore, these models will likely be based on data from repairs that were constructed without grout retention rings and will probably predict larger effects for each independent variable than would be expected with the use of the construction techniques used in the laboratory study and assumed by the proposed design procedure. They may also be subject to many other limitations. Thus, their use in the manner described below may or may not be appropriate. Any adjustments of the nature described herein must be tempered with sound engineering judgment.

Adjustment for Improved Repair Support

Suppose that the repairs described in the section on Applications Requiring No Adjustments are to be constructed on a stabilized base. A reduction in faulting might be expected over similar repairs constructed on a granular base, such as was used at the I-70 test site.

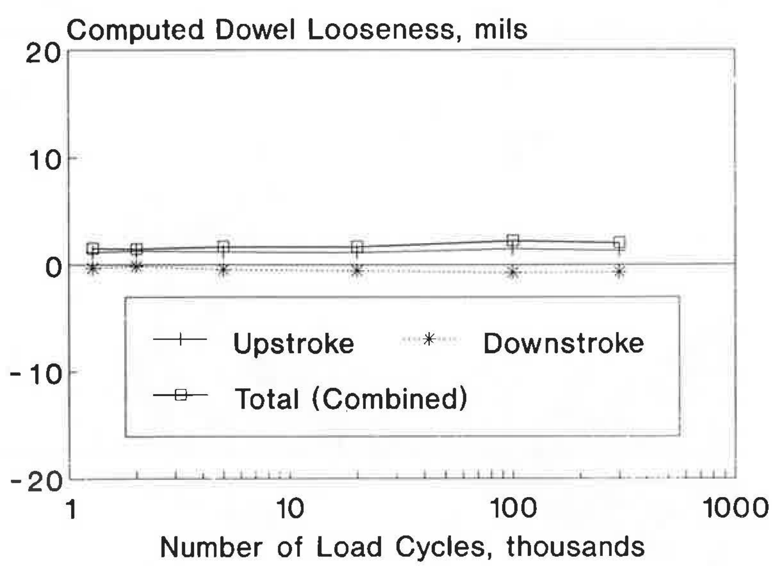

FIGURE 11 Dowel looseness envelope for laboratory specimen C6R.

The following is one model that has been developed to predict the development of faulting for joints as a function of base type and other variables (*1*):

$$\text{FAULT} = \text{ESAL}^{0.7419}\,(0.03641 - 0.02921\,\text{BASE}) + 0.2754\,[(\text{AGE})(\text{FI})]^{0.01889} - 0.2834 \quad (7)$$

where

FAULT = doweled repair leave-joint faulting (in.),
ESAL = cumulative 18-kip (80-kN) ESALs applied since repair construction (millions);
BASE = 1 for stabilized material (e.g., CAM or BAM) used anywhere in the pavement structure, 0 otherwise;
AGE = repair age (years);
FI = U.S. Army Corps of Engineers freezing index (Fahrenheit degree-days);
R^2 = 0.406,
n = 113 repair joints,
SEE = 0.048 in. (1.2 mm).

Figure 17 presents the sensitivity analysis of the decrease in joint faulting predicted by this model for the I-70 site conditions in which a stabilized base is used rather than a granular base. This figure indicates that a reduction of approximately 0.16 in. (4.1 mm) of faulting can be expected after 10 million 18-kip ESALs. Because the field performance model used in the proposed design procedure was derived using data from repairs constructed on granular bases, it might be appropriate to adjust the acceptable or design level of faulting upward from 0.15 in. (3.8 mm) by 0.16 in. (4.1 mm) to 0.31 in. (7.9

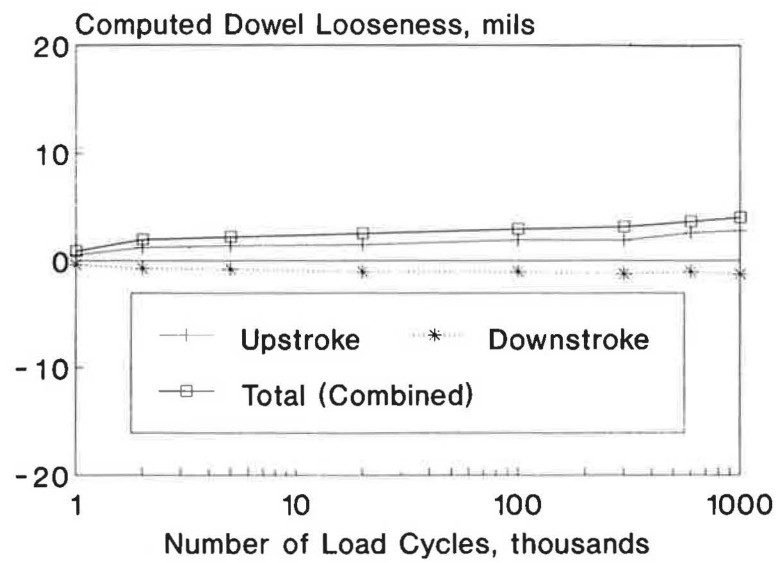

FIGURE 12 Dowel looseness envelope for laboratory specimen B18.

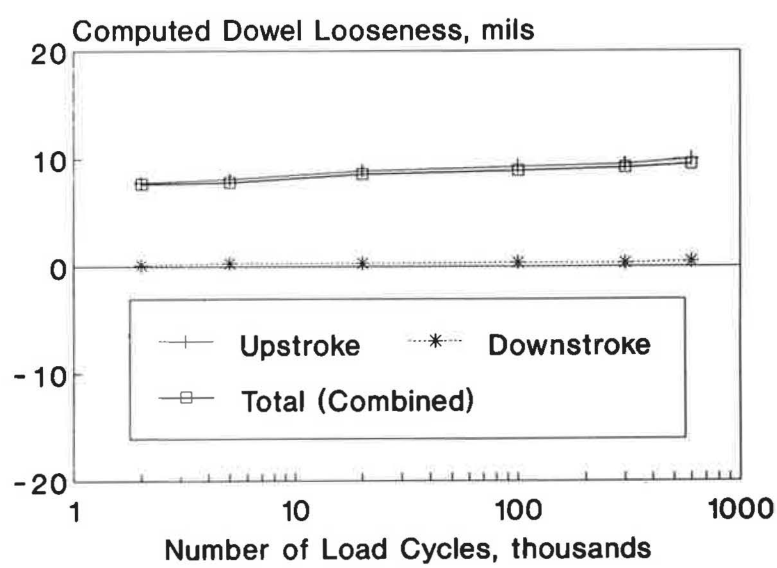

FIGURE 13 Dowel looseness envelope for laboratory specimen C22.

mm), thereby relying on the stabilized base to reduce the bearing stresses and actual faulting that develops.

Because only very low levels of deflection load transfer are required to achieve this level of performance, any reasonable load-transfer system will probably provide acceptable performance. Acceptable performance may even result without the use of dowels of any kind (provided the base is sufficiently stiff and resistant to erosion). These results are based on the assumption that good materials and construction techniques (including grout retention disks) are used. Such designs have not proven adequate for typical field installations (7,8).

Adjustment for Site-Specific Environment

Faulting models have been developed that consider environmental factors, such as freezing index, annual precipitation, etc. The following model, developed by Ortiz et al. (9), is one such model:

$$\begin{aligned}\text{FAULT} = {} & \text{TOTRAF}^{0.4782} * (-0.3679 \\ & + 0.0078 * \text{LENGTH}^{1.5368} - 2.3885 * \text{DOWEL} \\ & - 2.9277 * \text{UCUT} + 0.2847 * \text{PRECIP}^{0.970} \\ & + 1.40\text{E-}7 * \text{FREEZIN}^{2.256})\end{aligned} \quad (8)$$

where

FAULT = predicted repair joint faulting (mils);
TOTRAF = total number of truck loads crossing the joint;
LENGTH = length of repair (ft);
DOWEL = 0 if no dowel bars, otherwise 1;
UCUT = 0 if not an undercut repair, otherwise 1;

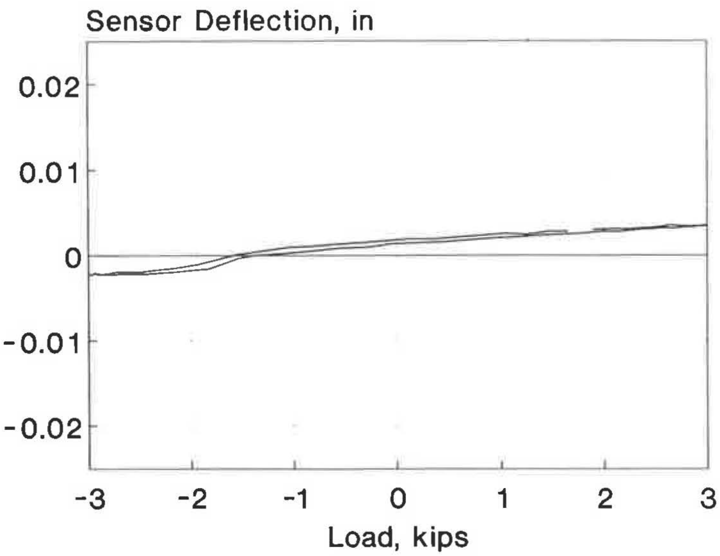

FIGURE 14 Load-deflection profile for laboratory test specimen C6R after 2,000 load cycles.

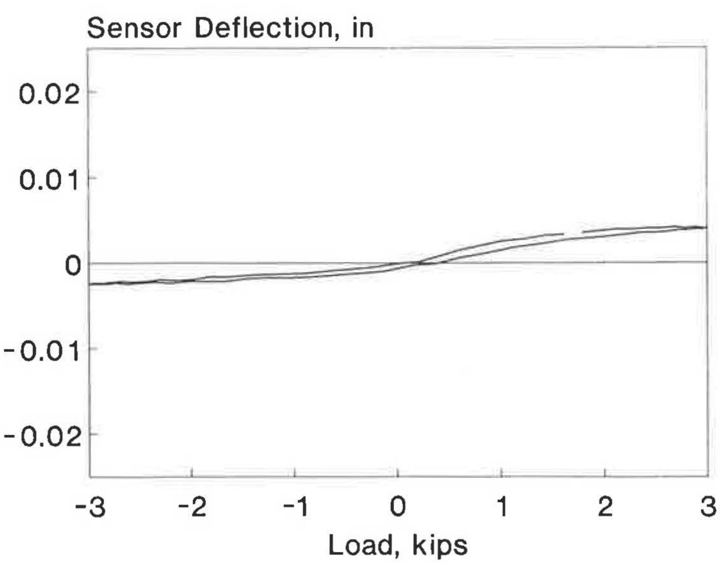

FIGURE 15 Load-deflection profile for laboratory test specimen B18 after 2,000 load cycles.

PRECIP = average annual precipitation (in.);
FREEZIN = U.S. Army Corps of Engineers mean freezing index (Fahrenheit degree-days);
R^2 = 0.48,
n = 678,
SEE = 0.115 in. (2.92 mm).

The sensitivity of predicted joint faulting to annual precipitation (all other variables held constant at I-70 test site values) is shown in Figure 18.

Suppose that the repairs described in the section on Applications Requiring No Adjustments are to be constructed at a site that receives 30 in. (76 cm) of precipitation per year rather than the 37 in. (94 cm) per year received at the I-70 test site. Figure 18 indicates that the new site could expect a component of faulting due to precipitation of about 32 mils (0.81 mm) after the application of 10 million 18-kip ESALs, whereas the comparable value for the I-70 site would be about 38 mils (0.97 mm). Thus the "design" faulting used to enter the proposed design chart could be increased from 0.15 in. (3.8 mm) to about 0.156 in. (4.0 mm) to account for the reduction in faulting that might be anticipated due to the decreased precipitation. In this case, the final load-transfer system design would not change significantly.

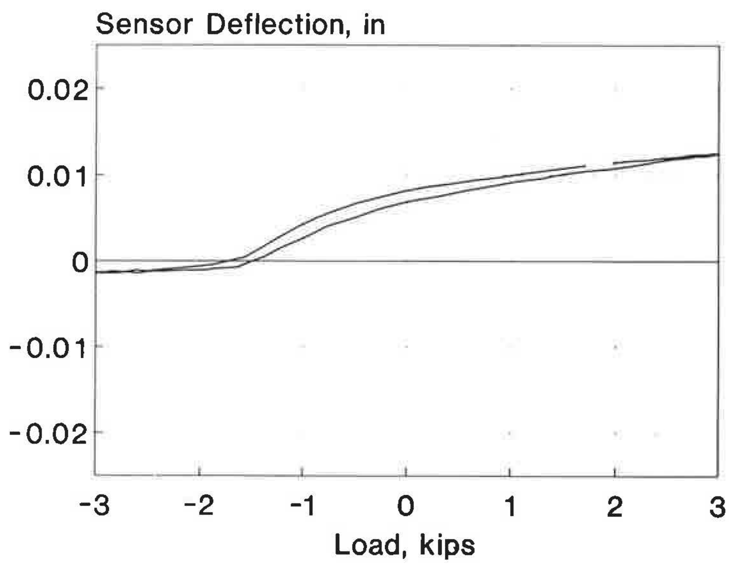

FIGURE 16 Load-deflection profile for laboratory test specimen C22 after 2,000 load cycles.

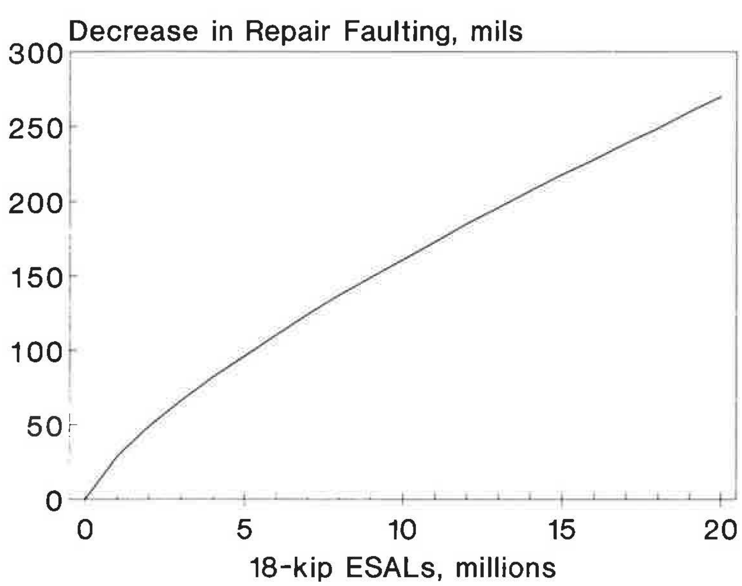

FIGURE 17 Predicted reduction in repair joint faulting where stabilized base materials are used.

VERIFICATION OF THE DESIGN PROCEDURE

The design procedure set forth in this paper was developed using laboratory data based on the use of grout retention disks, which were found to affect performance tremendously. The use of these disks in field applications is just beginning to take place; long-term monitoring data from such projects are not yet available. Thus direct verification of the design procedure with field performance data is not possible at this time.

The proposed design procedure can be checked for "reasonableness." Figure 19 presents a summary of the average dowel looseness, deflection load-transfer efficiency, and faulting that are predicted for a small factorial combination of bearing stresses (2,000 versus 5,000 psi) (13.8 versus 34.5 MPa) and traffic [10,000 18-kip (80-kN) ESALs versus 10,000,000 18-kip ESALs]. The results appear to be quite reasonable: increases in bearing stress or traffic or both have the expected effects on predicted dowel looseness, deflection load-transfer efficiency, and faulting. Dowel looseness and deflection load-transfer efficiency are most sensitive to the design inputs. The range of predicted average faulting, however, is small. The models used to demonstrate this procedure will not generally predict large faults because the I-70 performance data (upon which portions of the procedure are based) did not exhibit large faults except where the deflection-based load-transfer efficiency dropped below about 30 percent, which occurs only when the dowels are quite loose. Large faults are predicted only when the design inputs are adjusted by large amounts for construction or environmental reasons. For example, increasing the dowel looseness by several hundred percent to account for poor construction and the presence of voids around the dowel will produce predictions of large faults. Otherwise, excellent construction is assumed and only small faults are predicted.

Another measure of reasonableness is comparison with accepted guidelines. For example, the American Concrete Institute (ACI) recommends that concrete bearing stresses be limited to

$$r_{ba} = f'c(4 - b)/3 \qquad (9)$$

where

r_{ba} = allowable bearing stress (psi),
b = dowel diameter (in.),
$f'c$ = ultimate concrete compressive strength (psi) (*10*).

The design procedure for cement grout anchor materials predicts little change in faulting for bearing stresses less than a few thousand pounds per square inch. Equation 9 suggests that, for concrete with a compressive strength of 3,000 psi (20 700 kPa), bearing pressures of up to 2,000 psi (13 800 kPa) are allowable for dowels up to 2 in. (5 cm) in diameter. Bearing pressures up to 3,000 psi are allowable for dowels up to 1 in. (2.54 cm) in diameter. Thus, the proposed design procedure appears to agree with these recommendations.

Design procedure results can also be compared with the I-70 experimental field study data. Although grout retention disks were not used along this project, the construction of these repairs was carefully monitored. As a result, they might have been expected to perform at or near the levels predicted by the proposed design procedure.

All of the repair load-transfer systems produced small bearing stresses (generally 2,000 psi or less, assuming uniform support conditions) and all had been subjected to about 5 million 18-kip ESALs by the summer of 1988. Figure 3 predicts faulting of less than 0.23 (5.8 mm) and deflection load transfer of about 90 percent or more. Most of the repairs exhibited faults in the predicted range, but did not have such high load-transfer efficiencies (*1,2*). Possible reasons for the apparent discrepancies in performance include the following:

1. Traffic loads may have actually been heavier than believed. Traffic load data for this project were obtained from the State

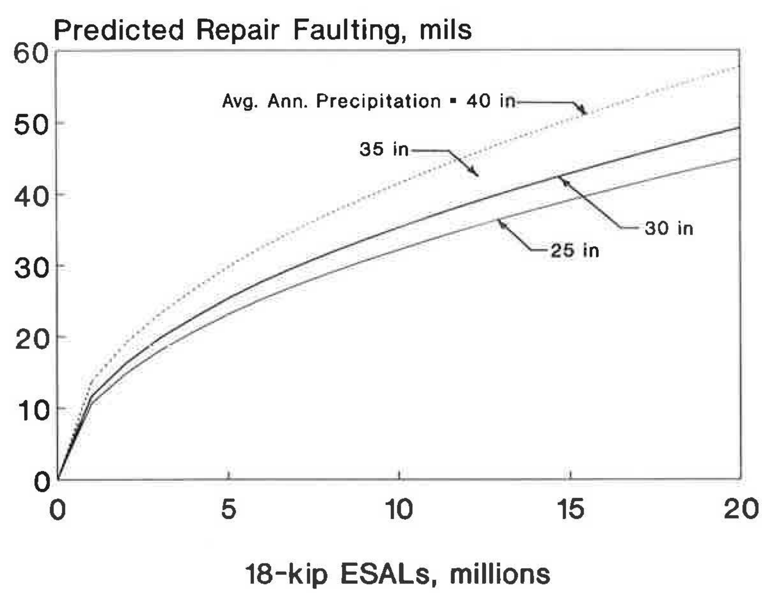

FIGURE 18 Predicted effect of variations in annual precipitation on repair joint faulting. (Illinois I-70 site conditions assumed.)

of Illinois Highway Design Manual, which is based on the results of static weight tests along the Illinois Interstate system. However, recent unpublished studies sponsored by the FHA concerning the use of Weigh-In-Motion (WIM) devices indicate that static weigh-station data may underestimate truck load factors by a factor of 1.2 or more, and that Interstate truck load factors may be underestimated by factors as great as 1.45. Underestimated traffic loads result in the overprediction of load-transfer efficiency and the underprediction of faulting.

2. The load equivalency factors used by the IDOT (and other highway agencies) in the estimation of cumulative 18-kip ESALs are based on the results of the AASHO Road Test. These factors were developed to relate the effects of various truck loads and axle configurations on observed pavement performance (e.g., roughness and distress). The effects of axle loads and configurations may be very different for the development of dowel looseness and loss of load-transfer efficiency. Thus, the computed accumulation of traffic at the I-70 test site may not accurately represent the effects of traffic on dowel looseness and load-transfer efficiency, which were used to predict joint faulting.

3. Construction quality may not have been as good as hoped. It was noted in the laboratory that the use of the cement grout was highly sensitive to both time and environmental conditions. It is easy to imagine the inclusion of voids in the repair anchor materials, in spite of the stringent quality control that was present during construction. The use of grout retention rings would probably have produced results that agreed more closely with the predicted results.

CONCLUSIONS

The design procedure concept presented in this paper appears to be reasonable for repairs that are constructed using good construction techniques, including the use of grout retention rings. Accurate validation cannot be accomplished because few in-service repairs have been constructed using the laboratory construction techniques.

Cumulative 18-kip [80-kN] Load Applications

Bearing Stress (psi)	10,000	10,000,000
2000	4	4
5000	11	17

Dowel Looseness (mils) [1 mil = 0.0254 mm]

Cumulative 18-kip [80-kN] Load Applications

Bearing Stress (psi)	10,000	10,000,000
2000	84	84
5000	72	63

Deflection Load Transfer Efficiency (%)

Cumulative 18-kip [80-kN] Load Applications

Bearing Stress (psi)	10,000	10,000,000
2000	0.11	0.11
5000	0.14	0.16

Joint Faulting (in) [1 in. = 25.4 mm]

FIGURE 19 Sensitivity of the proposed design procedure to variations in bearing stress and load repetitions.

If the demonstrated design procedure is valid, it suggests that most repair load-transfer designs in use today would be quite adequate if they were properly constructed. The use of the grout retention ring to help ensure uniform support of the dowel by the anchor material without the development of voids must be considered essential in all future full-depth repair installations.

It must be emphasized that the procedure presented in this paper is primarily intended to demonstrate an approach to designing dowel load-transfer systems for full-depth repairs of PCC pavements. Although the specific models that were used for this demonstration are considered good over the data bases from which they were derived, they are not intended to be used universally. More broadly based models will certainly improve the validity and usefulness of the procedure presented herein.

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