

# Cyclic Shear Load Testing of Dowels in PCC Pavement Repairs

MARK B. SNYDER

There is a critical need to identify and develop reliable designs and construction techniques for full-depth repair load transfer systems. To address this need, a laboratory study was designed and performed to estimate the effects of several dowel load transfer system design and construction variables on dowel deflection and the development of dowel looseness. 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. One key finding of this study is that the dowel must be anchored firmly and supported uniformly to perform well. This can be accomplished by using thin, snug-fitting disks to retain the anchor material in the drilled hole during curing. This type of device should be used for all field installations to improve the performance of properly designed and constructed repairs.

The construction of full-depth repairs of Portland cement concrete (PCC) pavements has become a major part of pavement rehabilitation programs throughout the United States. Unfortunately, while many repairs have performed satisfactorily, many others have performed poorly. Many of these repair failures are directly related to the failure of the repair load transfer system. In 1985, the University of Illinois Department of Civil Engineering contracted with the Federal Highway Administration (FHWA) to conduct extensive field, laboratory, and analytical studies concerning the evaluation and rehabilitation of concrete pavements. This study included repeated shear load testing of dowels installed in concrete and surveys of more than 2,000 in-service, full-depth repairs with various load transfer system designs. This paper describes the design, conduct, results, and conclusions of the laboratory experiment.

## DESIGN OF THE LABORATORY EXPERIMENT

This study involved the application of repeated shear loads to dowels anchored in holes drilled in concrete specimens.

M. B. Snyder, Department of Civil and Environmental Engineering, Michigan State University, 347A Engineering Building, East Lansing, Mich. 48824-1226.

Data collection and analysis focused on the relationship between applied load and dowel deflection. The purpose of the laboratory study was to estimate the effects of several design and construction variables on the performance of dowels that are anchored into existing PCC slabs during the placement of full-depth repairs. Five design and construction variables were included in the main test matrix: dowel diameter, annular gap (the width of the void to be filled with anchor material when the dowel is placed in the exact center of the drilled hole), anchor material, embedment length, and drill type (varying drill impact energy). Two test levels, one "high" and one "low" (based on the current range of design and construction practice), were selected for each variable except for drill type, for which three types were selected. Table 1 summarizes the test values that were used for each variable.

Tests were also conducted on a number of "special" specimens, including two specimens with dowels cast in place in the lab (rather than drilled), two specimens with dowels turned on a lathe to provide a very tight friction fit, and one specimen with a large-diameter, hollow, stainless steel dowel. These tests were conducted for comparison purposes and to indicate future research needs. A replicated half-fraction, factorial experimental design was employed to provide a sound statistical basis for determining the main effects and interaction effects of the five variables under consideration. A detailed discussion of the experimental design is presented elsewhere (1, 2).

## PREPARATION OF TEST SPECIMENS

Portland cement concrete slabs were obtained from Interstate 70 near Effingham, Illinois, for the fabrication of test specimens. This pavement was constructed in 1962 using 10-in. (25-cm) reinforced PCC pavement with contraction joints at 100-ft (30.5-m) intervals. It had accommodated approximately 13.8 million, 18-kip (80-kN) ESALs in the design (outside) lane by the date of specimen removal.

In July 1985, 4-ft (1.2-m)-wide asphalt concrete pressure relief joints/repairs were placed near midslab at 1,000-ft (305-m) intervals (3). Four undamaged slabs (4 ft by 12 ft [1.2 m by 3.6 m]) were lifted out and transported to the University of Illinois, where they were cut into 18-in. by 12-in. (31-cm by 46-cm) test specimens. The specimen bases were capped with cement mortar to provide a stable base for testing.

A steel drilling frame was assembled to hold the specimens and drill rigs, ensuring that the holes were drilled perpendicular to and centered within one of the 12-in. (31-cm) faces of each test specimen.

TABLE 1 LABORATORY TEST PROGRAM

Variable	Low Value	Intermediate	High Value
Dowel diameter	1 in. (25 mm)		1.5 in. (38 mm)
Annular gap	1/32 in. (0.80 mm)		1/8 in. (3.2 mm)
Anchor material	Cement grout (Dayton Superior Sure-Grip—"flowable" mix)		Epoxy resin (Hilti HIT C-10)
Embedment length	7 in. (178 mm)		9 in. (229 mm)
Drill type; impact energy	Standard pneumatic; ~100 ft-lbs (~135 N-m)	Hydraulic percussion (TAMROCK); 25.2 ft-lbs (35.1 N-m)	Electropneumatic (Hilti, Inc.); 6.35 ft-lbs (8.6 N-m)

Anchor materials were prepared just prior to installation of the noncoated steel dowels. A two-cylinder caulking-gun arrangement provided by the manufacturer dispensed the epoxy mortar. This arrangement provided consistent "on-demand" proportioning and mixing of the mortar and hardener. The cement grout was mixed in accordance with the manufacturer's recommendations for achieving a "flowable" mix. Grout consistency was not measured quantitatively. Cement grout batches were sized to install three to five dowels in a 5- to 10-min period. A vinyl bag was filled with the grout and squeezed to force the grout through an attached nozzle into the drilled hole. This delivery system was recommended by Lippert (4). In each case, sufficient anchor material was injected to the backs of the drilled holes to produce some extrusion when the dowels were inserted.

A tight-fitting, hard nylon disk, 2 in. larger than the dowel diameter and approximately 3/32 in. (2.4 mm) thick (see Figure 1), was fixed on each dowel at a distance equal to the embedment length from one end of the dowel. These disks were used to prevent the anchor material from flowing out of the holes and creating voids around the dowels. They also

forced the anchor material to fill spalls near the dowel hole on the concrete face caused by the drill.

The dowels were inserted up to the nylon disks using a back-and-forth twisting action to ensure complete and uniform coverage of the dowel and filling of the annular gap with the anchor material. The dowels were allowed to settle or tip in the holes as the anchor material cured. A doweled test specimen (with grout retention disk intact) is shown in Figure 2. The nylon disks were removed after 24 hours.

Two specimens were prepared using 1-in. (25-mm)-diameter dowels cast in fresh concrete with 9 in. (229 mm) of embedment. The concrete mix was designed to produce a 3,000-psi (20.7-MPa) mix using Portland Cement Association procedures (5). These specimens were cured for 24 hours, subjected to 5,000 load cycles (to simulate early opening of the repair), cured for an additional 27 days, and subjected to an additional 595,000 load cycles. The purpose of these specimens was to set a standard of deflection performance against which to compare the anchored dowels, and to simulate the conditions imposed on the end of the dowel embedded in the repair.

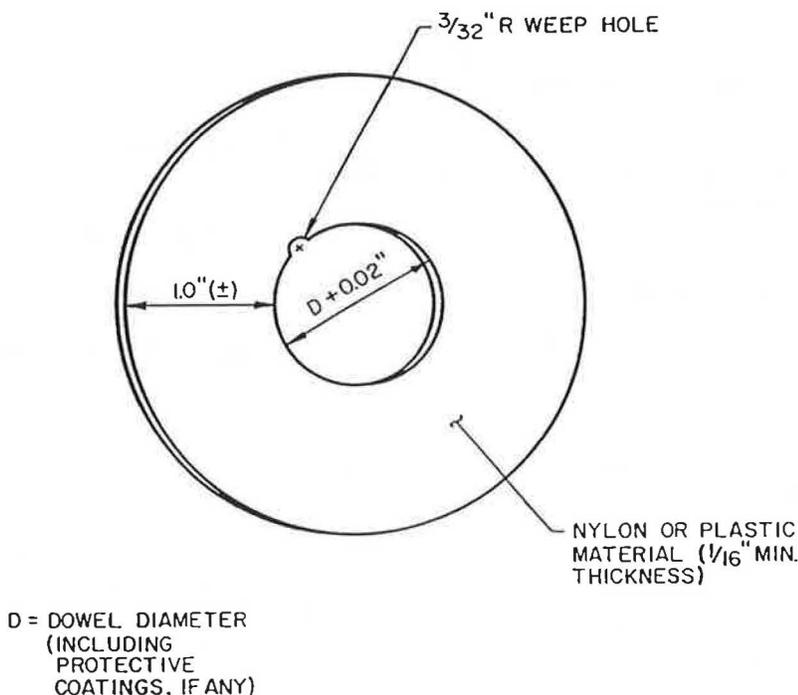


FIGURE 1 Illustration of grout retention disk used in laboratory study.



**FIGURE 2** Photo of grout retention disk installed on test specimen.

Two specimens were also prepared to test the performance of dowels installed in close-fitting holes. Dowels were turned on a metal lathe to achieve dowel diameters 0.02 in. (0.5 mm) less than the smallest diameter measured in each hole. The finished dowels were 1.06 and 1.10 in. (27 and 28 mm) in diameter. The dowels were inserted to a depth of 9 in. (229 mm) in holes drilled with  $1\frac{1}{16}$ -in. (27-mm) nominal diameter drill steels. The smaller of the two bars was loose enough to be moved slightly in any direction. Some epoxy mortar was placed around this dowel at the concrete face. The larger bar could not be inserted to full depth by hand. It was forcibly inserted without anchor material using a large hammer.

Specimens fabricated using cement grout were allowed to cure in the lab for 7 to 14 days prior to testing. Specimens prepared using epoxy mortar were cured for 24 hours to 7 days.

A more detailed discussion of test specimen preparation is included elsewhere (1, 2).

#### TEST EQUIPMENT, INSTRUMENTATION, AND RECORDING OF DATA

Repeated bidirectional vertical shear loads were applied to the dowels installed in the test specimens. Several load waveforms (simulating the passage of 36-kip [160-kN] tandem axles) were tried during preliminary tests. Specimen response was found to be relatively insensitive to the waveforms being considered. Thus, a continuous sinusoidal form with a peak magnitude of  $\pm 3,000$  lb (13.4 kN) and a frequency of 6 Hz was ultimately selected. This resulted in the application of nearly 520,000 load cycles per day, or about a year's worth of heavy traffic loads daily.

Loads were generated hydraulically using an MTS Model 661 ram with an 11-kip (50-kN) capacity. The load was applied to the dowel through a specially fabricated, high-strength steel loading collar that allowed vertical deflection and associated angular dowel movement about a lateral axis.

A linear variable differential transducer (LVDT) was mounted on an aluminum bracket attached to the face of each specimen and connected to the load collar using a small, threaded nylon rod. This device was used to measure electronically the movement of the load collar and dowel relative

to the PCC specimen. The MTS load cell data were also collected for analysis and to assist in computer control of the test program.

Deflection and load data were collected during ten load cycles immediately following completion of 1, 2,000, 5,000, 20,000, 100,000, 300,000, and 600,000 load cycles. Extended test data were also collected after 1,200,000, 2,000,000, and 4,000,000 load cycles for certain specimens.

Data collection was accomplished automatically using an IBM Personal Computer (PC) and a Data Translations DT-2801A Analog/Digital (A/D) board. Each data channel was sampled 400 times per second.

Further information concerning the test equipment, instrumentation, and data recording is presented elsewhere (1, 2).

#### TEST PROCEDURE

The entire test operation was controlled by the previously described PC and A/D board. The controlling program was written in BASIC using the PCLAB library of A/D board control subroutines (6). Execution of the test control program initiates a series of prompts requesting specimen information and test parameters. The program also includes provisions for (re-)zeroing and (re-)calibrating the data collection channels, test interruption, and test parameter modification.

A data reduction program was written and used to process the raw test data. This program identified average peak loads and computed average theoretical dowel looseness for each set of ten load cycles that comprised a data sample. The reduced and summarized data were loaded into an SPSS (7) database and a Lotus 1-2-3 (8) spreadsheet for analysis, production of graphs, and so forth.

Detailed descriptions of the test procedure, data reduction programs, summaries of the laboratory test data, load-deflection hysteresis loops, and dowel looseness envelopes are included elsewhere (1, 2).

#### PRELIMINARY RESULTS AND OBSERVATIONS

##### Effect of Drill Impact Energy on Spalling

Drills that impart high-impact energy produce more spalling on the concrete face near the drilled hole than drills using low-impact energy. The hydraulic drills produced significantly less spalling than the pneumatic drills, and the electric-pneumatic drills produced very little spalling at all.

Even relatively minor spalling around the drilled hole can result in a loss of dowel support. If the spall is not filled with dowel anchor material or PCC repair material, the effective joint width increases in the vicinity of the dowel, causing increased pavement and dowel deflections and increased bearing stresses. Since flat nylon rings were used to retain the anchor material in the drilled holes and spalled areas, the effect of spalling on dowel deflection could not be determined directly. However, increased deflections were recorded where the anchor material did not completely fill the dowel hole or the spalled area.

### Consistency of Dowel Anchor Materials

The installation of dowels using cement grout was often difficult. Specimens prepared immediately after the grout was mixed received a grout that was almost "pourable," and grout retention was difficult, even using the nylon rings. Large voids were often observed around these dowels prior to testing (see Figure 3), and they exhibited large deflections. Specimens prepared 5 min after the grout was mixed received a grout that was of the desired consistency, and were found to have no voids (or only very small voids); these specimens performed well. Specimens that were prepared 10 min or more after the grout was mixed often received a very stiff grout that compacted at the back of the hole, preventing proper installation of the dowels. These specimens had to be cleaned out and grouted again.

The wide variation in grout consistency over a relatively short period of time in a controlled laboratory environment brings into question the use of the same material in the field. It is possible that the larger batches typically used in field applications exhibit a different fresh-state behavior and may not be as sensitive to time as were the laboratory batches. Field conditions can be harsh, however, and quality control often takes a position secondary to that of production; a reliable, easy-to-use anchor material is needed for these situations. The cement grout did not consistently meet these requirements in the laboratory.

The epoxy mortar and delivery system used in the lab almost always proportioned, mixed, and delivered a mortar that was of the desired consistency. The mortar "set up" in about 5 min, which was more than enough time for dowel installation. Curing was complete in about 24 hours (according to the manufacturer), although the dowels could not be moved or removed by any means after about an hour of curing.

Although the cost of the epoxy mortar is currently substantially higher than the cost of the cement grout (4), the reliability and the uniform consistency of the epoxy should make it the preferred material.

It should be noted that not all epoxy mortar materials are suitable for pavement repair applications. Additional testing should be accomplished before using any unproven material.



FIGURE 3 Photo of void above dowel anchored using fluid cement grout.

### Dowel Failures

Five of the specimens with 1-in. (25-mm)-diameter dowels experienced brittle fatigue failures at locations 0.75 to 1.5 in. (19 to 38 mm) inside the face of the PCC specimens. This location corresponds approximately to the predicted point of maximum moment in the dowel (0.75 in. [19 mm] inside the face), as presented by Friberg (9) based on the work of Timoshenko and Lessels (10). Some of these failures occurred after as few as 40,000 load cycles, while others occurred after nearly 600,000 load cycles.

Four of the failed dowels were anchored using cement grout, while one was anchored using epoxy mortar. Large voids were visible above three of the four grouted dowels prior to testing. These observations indicate the variability of quality of the cement grout anchor material (in spite of the use of the nylon grout retaining rings) and demonstrate the importance of providing void-free, uniform dowel support in pavement joints.

### Effectiveness of Grout Retention Rings

The grout retention rings were clearly very effective in reducing the outflow of anchor materials from the drilled holes and ensuring more uniform dowel support. They also forced excess anchor material into the spalled area created by drilling, effectively repairing the spall and reducing dowel deflections.

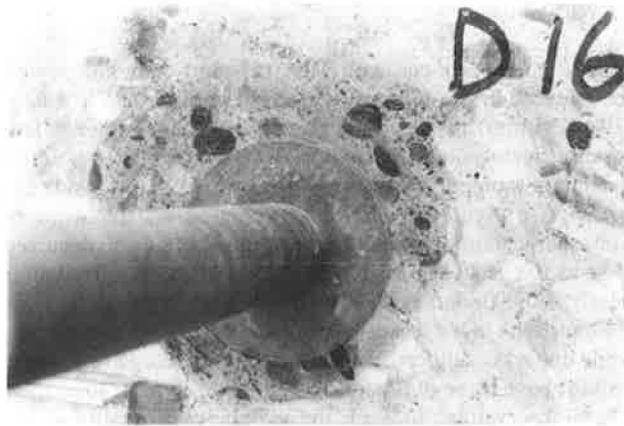
The effectiveness of the rings was highly dependent on the fluidity of the anchor material being used. Very fluid cement grouts were difficult to work with and were not retained well, even with the rings. Excellent results were obtained using materials that were "flowable" (i.e., the cement grout about 5 min after mixing or the epoxy mortar, as delivered), because they were fluid enough to be moved into the voids, yet viscous enough not to flow appreciably under gravity alone. A smooth, void-free face was produced when material of this consistency was used with the grout retention rings (see Figure 4).

### FACTORS AFFECTING DOWEL DEFLECTION AND LOOSENESS

In this paper, "dowel deflection" refers to the deflection (under an applied shear load of  $\pm 3,000$  lb [13.4 kN]) measured using the LVDT attached to the load collar at a point approximately  $\frac{1}{2}$  in. (13 mm) from the face of the specimen. Dowel looseness was estimated by plotting measured dowel deflection versus shear load and projecting the slopes of the loading and reverse loading portions of the load-deflection curve at  $\pm 3,000$  lb (13.4 kN) back to intercept the deflection axis. This technique was conceptualized by Teller and Cashell (11) and is shown in Figure 5.

The half-fraction, factorial experimental design employed in the lab tests allowed direct identification of significant effects through analysis of variance (ANOVA) techniques. The details of this analysis are presented elsewhere (1, 2), but the results are summarized herein.

Most of the main variables were found to affect significantly sensor deflection and the development of dowel looseness. These effects are summarized below:



**FIGURE 4** Photo of dowel anchored using epoxy mortar and grout retention disk.

<i>Variable Changed</i>	<i>Effect on Deflection/Looseness</i>
Increasing dowel diameter	Large decrease
Increasing dowel embedment	Very small decrease
Epoxy anchor material (instead of cement grout)	Small increase
Increase load repetitions	Increase (magnitude varies with other design parameters)

Several significant two-factor interactions were also noted, including anchor material and annular gap, anchor material and dowel diameter (bearing stress), and anchor material and drill impact energy. Additional analyses clarified these relationships, as described below.

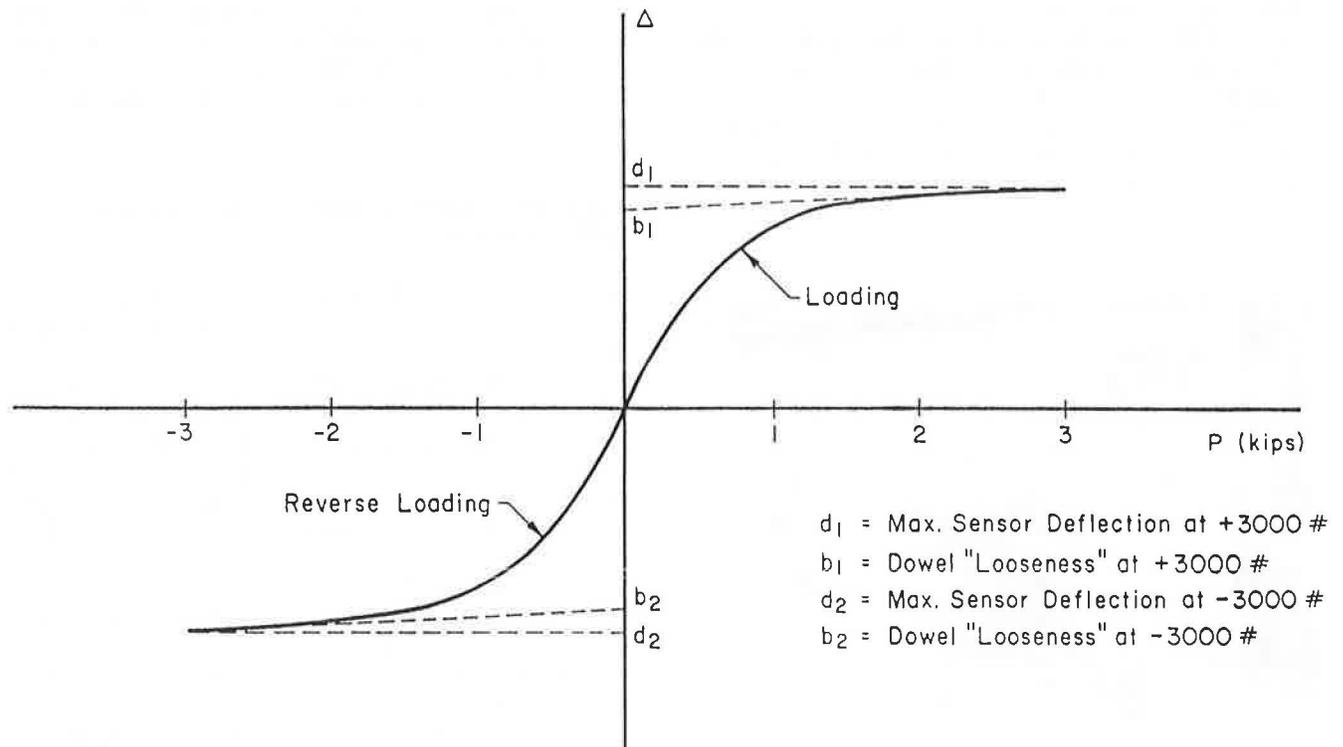
Because the epoxy mortar was a softer material than either the cement grout or the concrete specimen, the deflections

of bars embedded in this material were more sensitive to dowel diameter (bearing stress) and embedment. Increases in either lead to decreased deflections. As annular gap increased, deflections generally increased owing to the use of larger volumes of softer material. Because the epoxy mortar was always delivered at a uniform consistency that allowed easy insertion of the dowels, there was no apparent need (for installation purposes) for a large annular gap. Therefore, it may be appropriate to use epoxy mortar with the smallest annular gap that will allow dowel installation without excessive force. Voids and spalls would then be filled with a minimum thickness of the softer mortar, allowing the bar to be supported directly by the concrete in many other places.

Since the cement grout was more rigid than the epoxy mortar that was used, the effects (and interaction effects) of dowel diameter and embedment on dowel deflection are reduced for this material. Furthermore, it appears that a larger annular gap generally produces better results for cement grout, presumably because this facilitates dowel installation in a stiffer grout, resulting in more uniform dowel support.

**LOAD-DEFLECTION PROFILES AND DOWEL LOOSENESS ENVELOPES**

Some of the lab study results are illustrated in Figures 6 through 11, which present dowel “looseness” envelopes (illustrating the development of looseness over time) for several representative specimens. In these figures the “upstroke looseness” (data plotted as × signs) is the component of total looseness computed from the reverse loading curve, “downstroke looseness” (data plotted as diamonds) is the component of total looseness computed from the normal loading curve, and the



**FIGURE 5** Graphic estimation of dowel “looseness.”

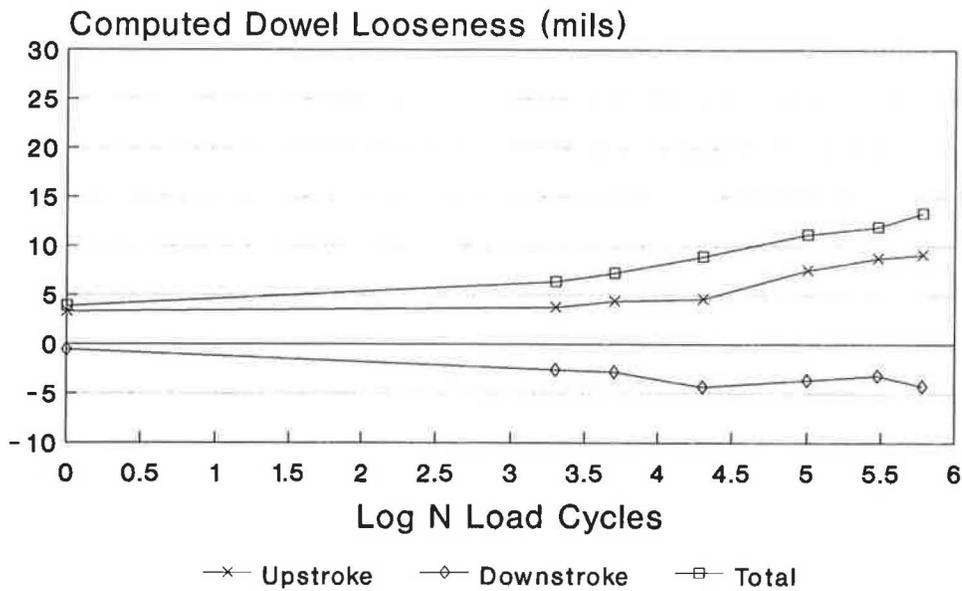


FIGURE 6 Dowel looseness envelope: 1-in. dowel diameter, 1/16-in. hole, 9-in. embedment, electric drill, epoxy mortar (Specimen D10R).

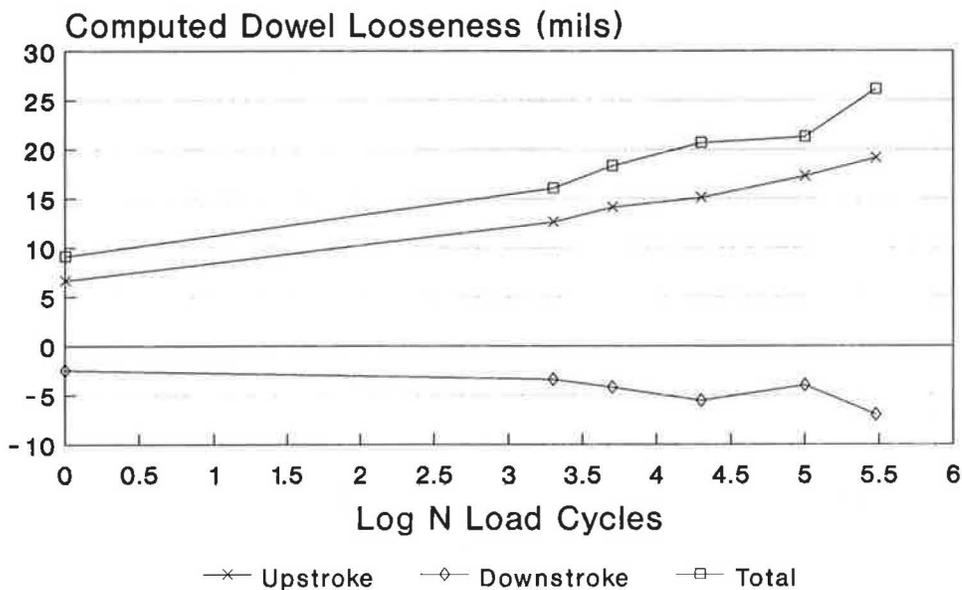


FIGURE 7 Dowel looseness envelope: 1-in. dowel diameter, 1/4-in. hole, 9-in. embedment, electric drill, epoxy mortar (Specimen D6).

“total looseness” (plotted as squares) is the distance between the other two curves.

A comparison of Figures 6 and 7 illustrates the increase in dowel deflection/looseness that accompanied increases in annular gap when the epoxy anchor material was used. These figures also illustrate that the reverse loading mode typically produced higher deflections than normal loading. This is presumably due to settlement of the dowel during curing, which results in the dowel bearing on a very thin layer of anchor material on the bottom with a thicker layer on top. Since deflections are partially dependent on the deformation of the

supporting layer, the thicker layer of softer material on top allows more deflection in reverse loading.

Comparing Figures 7 and 8 illustrates that dowels properly installed using cement grout typically exhibited lower deflections than those installed in the same size holes using the epoxy mortar. It must be emphasized, however, that it was often difficult to obtain good anchoring using cement grout due to the extreme variability of grout consistency over short periods of time.

A comparison of Figures 8 and 9 shows the tremendous reduction in deflection (~75 percent) that typically accom-

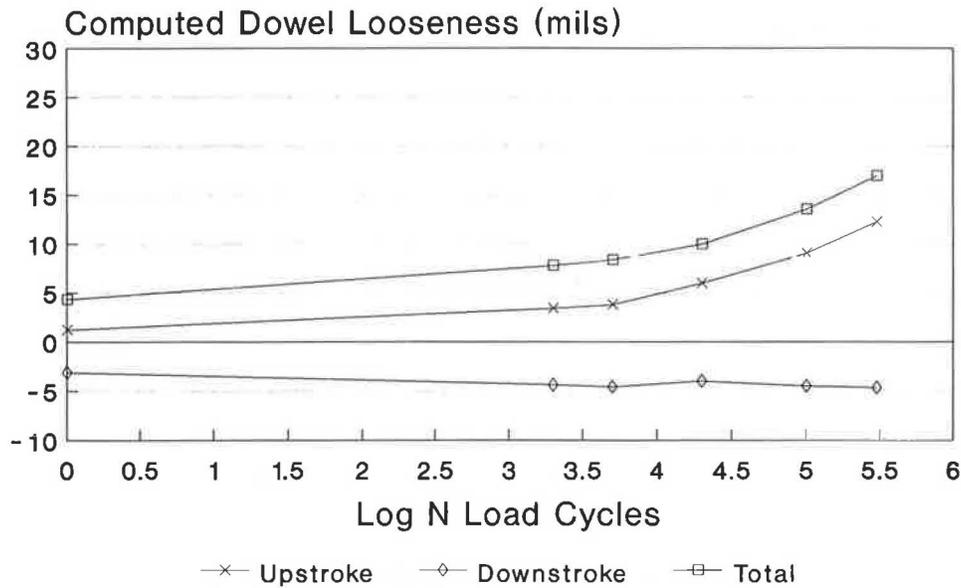


FIGURE 8 Dowel looseness envelope: 1-in. dowel diameter, 1¼-in. hole, 9-in. embedment, electric drill, cement grout (Specimen A8R).

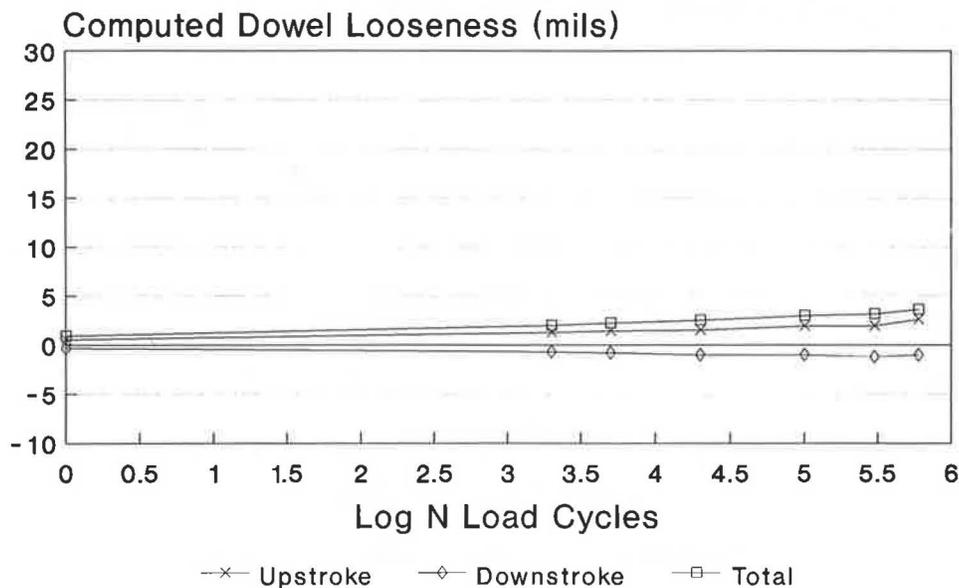


FIGURE 9 Dowel looseness envelope: 1.5-in. dowel diameter, 1¼-in. hole, 9-in. embedment, electric drill, cement grout (Specimen B18).

panied an increase in dowel diameter from 1 in. to 1.5 in. (25 mm to 38 mm).

Figures 10 and 11 illustrate that the effect of dowel embedment on dowel deflection was typically very small for the range of embedments tested (7 to 9 in. [18 to 23 cm]). This confirms other studies that have suggested that embedment lengths of 6–7 in. are adequate for the dowel sizes currently used in highway applications. The effect of embedment on dowel deflection would probably have been larger if grout retention rings had not been used to ensure uniform dowel support.

Figure 12 presents the deflection profile obtained from one of the specimens that was prepared by casting a 1-in. (25-mm)-diameter dowel (embedded 9 in. [23 cm]) in a block of concrete, curing it 24 hours, applying 5,000 load cycles, curing an additional 27 days, and applying an additional 295,000 load cycles. It was believed that a properly prepared, cast-in-place specimen would represent the best possible support that could be provided a dowel and would be a “yardstick” against which to compare the performance of similar specimens. The relatively flat deflection profile indicates that no real looseness existed at the time of testing and confirms the use of such

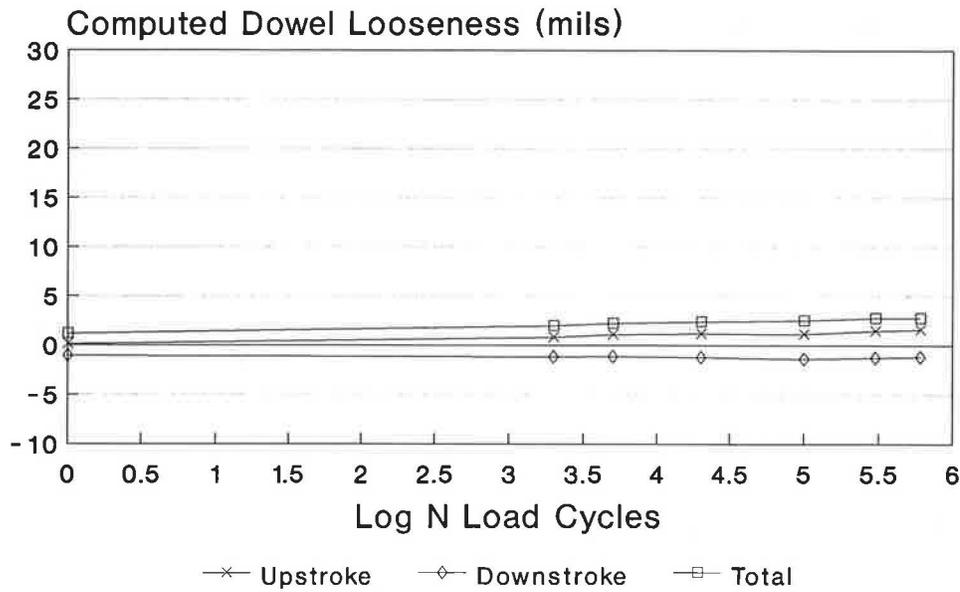


FIGURE 10 Dowel looseness envelope: 1.5-in. dowel diameter, 1¼-in. hole, 9-in. embedment, pneumatic drill, cement grout (Specimen D20).

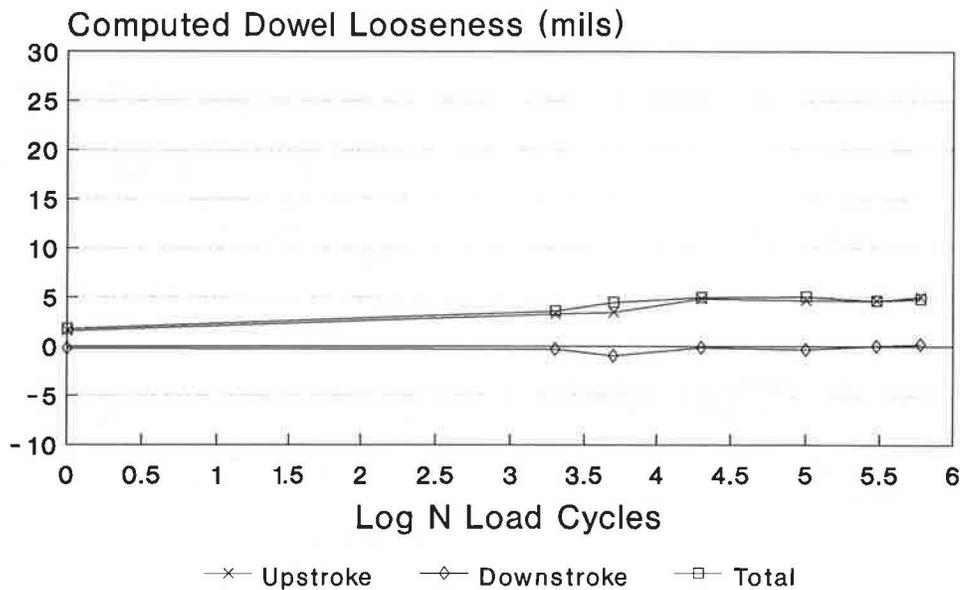


FIGURE 11 Dowel looseness envelope: 1.5-in. dowel diameter, 1¼-in. hole, 7-in. embedment, electric drill, cement grout (Specimen A10).

specimens as idealized dowel installations. A comparison of this profile to those of other 1-in. (25-mm) doweled specimens suggested that the cement grout specimens have the potential to approach this level of dowel support most closely, particularly when longer embedment lengths and good grout installations are present. By comparison, the epoxy mortar specimens performed well when the annular gap was small and the embedment length was 9 in. (23 cm). The “looseness” history of the cast-in-place specimen also suggested excellent performance.

The 1⅝-in. (41-mm) O.D. hollow stainless steel dowel was installed using the epoxy mortar to a depth of 7 in. (18 cm)

in a 1¾-in. (44-mm) nominal diameter hole. Its performance was similar to that of a 1-in. (25-mm)-diameter solid dowel with a slightly thicker supporting layer of epoxy mortar. A solid bar (or a tube with thicker walls) would probably have provided better performance. In addition, the stainless steel did not bond to the epoxy mortar, allowing the bar to be twisted freely after testing, although the bar was not necessarily loose.

The two specimens that were prepared using “close-fitting holes” rapidly developed deflections that were beyond the capability of the sensor to measure (>0.05 in. [1.27 mm] in either direction). Neither could be tested to the full 600,000

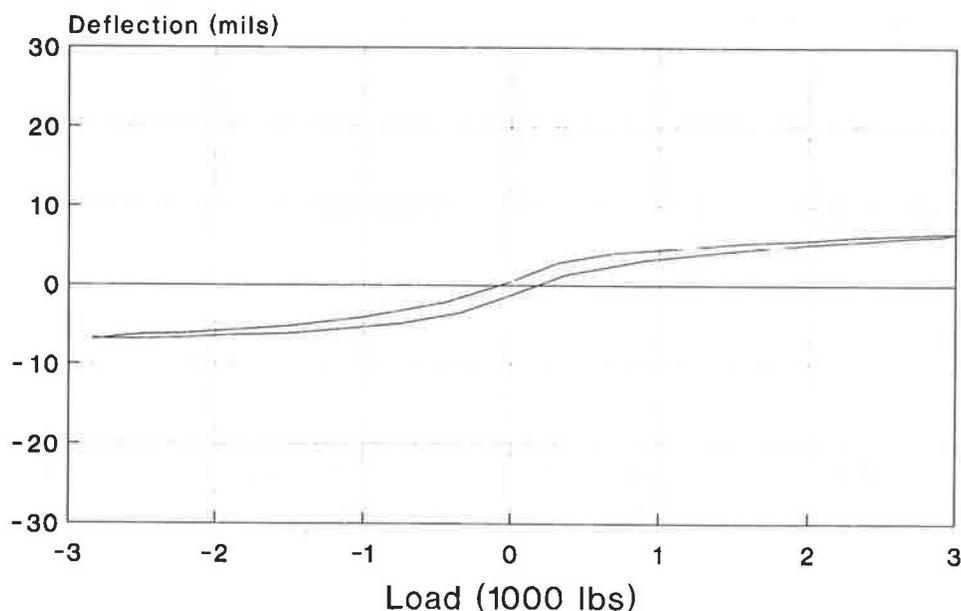


FIGURE 12 Load-deflection profile for cast-in-place specimen after 300,000 load cycles (1-in. dowel).

load repetitions because of possible damage to the test equipment. One of the specimens failed after fewer than 60,000 load cycles.

#### DOWEL DEFLECTION AND LOOSENESS MODELS

The data sets for each anchor material type were used to develop predictive models for sensor deflection and dowel looseness. Although many factors and interactions appear to affect these performance measures, their inclusion often made the models much more complex without significantly improving their accuracy. Satisfactory models were often obtained using nonlinear regression techniques and including only main effects.

The models developed for the epoxy mortar anchor material are presented below:

$$B_{\max\min} = [34840(AG) + 1167(CT)^{1.058} - 9.899(EB)^{1.160} + 1.079(BS) - 0.6912(EN)^{1.831} + 8380]/1000$$

$$R^2 = 0.594 \quad \text{C.O.V.} = 36.9\text{percent} \quad n = 178$$

$$D_{\max\min} = [54210(AG) + 643.3(CT) - 2117(EB) + 2.031(BS) - 8.822(EB)(EN) + 21210]/1000$$

$$R^2 = 0.584 \quad \text{C.O.V.} = 28.7\text{percent} \quad n = 178$$

where

- $B_{\max\min}$  = total dowel looseness (as defined previously) (mils) (1 mil = 0.0254 mm);  
 $D_{\max\min}$  = total sensor deflection (as defined previously) (mils);

AG = annular gap = (nominal diameter of drilled hole - nominal dowel diameter)(in.) (1 in. = 25.4 mm);

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); and

EN = estimated drill impact energy, ft-lb/blow (1 ft-lb = 6.5782 N-m).

Figures 13 through 15 illustrate the sensitivity of the deflection model to the input parameters. The sensitivity of the "looseness" model is similar.

Figure 13 illustrates the relatively large effect of annular gap and the comparatively small effect of the number of load applications on dowel deflection for epoxy mortar installations. This confirms that the epoxy mortar is flexible (when compared to the surrounding concrete) and that thin supporting layers (sufficient to fill drilling voids) are best. It also shows that the material is very resistant to fatigue and undergoes very little permanent deformation or deterioration after many repeated load applications.

Figure 14 further defines the response of the epoxy mortar to applied loads by showing the expected total vertical dowel movement for combinations of bearing stress and annular gap values tested. The predicted behavior is linear because only two levels of bearing stress were examined. Additional data may produce a nonlinear relationship, but the overall effect is likely to be similar. This model predicts dowel deflection increases of 60 to 100 percent for bearing stress increases from 1,000 psi to 5,000 psi (6,900 to 34,000 kPa).

Figure 15 shows that the flexibility of the epoxy mortar makes it sensitive to dowel embedment length. The increase

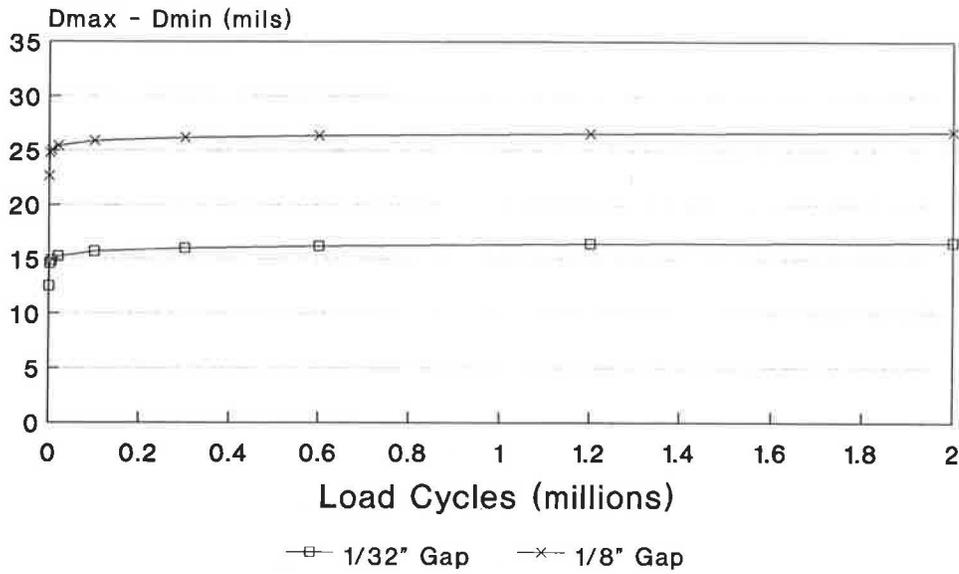


FIGURE 13 Predicted effect of annular gap and load cycles on deflection for epoxy mortar specimens (9-in. embed, 1-in. dowel, medium-energy drill).

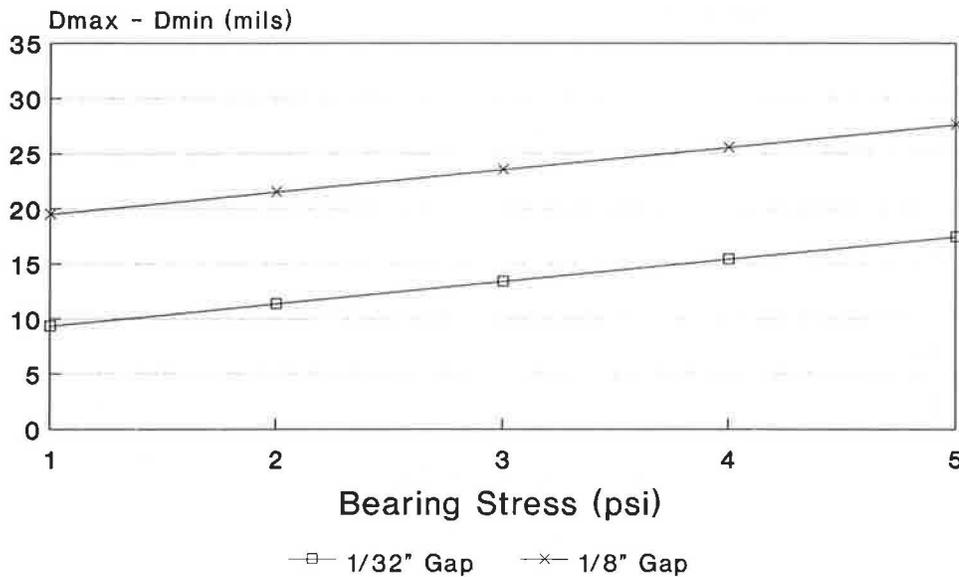


FIGURE 14 Predicted effect of annular gap and bearing stress on deflection of epoxy mortar specimens (N = 600,000, 9-in. embed, medium-energy drill).

in deflection that results from decreasing embedment length from 9 in. to 7 in. (23 cm to 18 cm) is approximately 10 percent and is not considered significant.

The models developed for the cement grout anchor system are presented below:

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

$R^2 = 0.647 \quad \text{C.O.V.} = 61.2 \text{ percent} \quad n = 109$

$$D_{\text{maxmin}} = (6.072(BS) - 66.96(EN) + 13900(AG) + 572.7(CT) - 8946)/1000$$

$R^2 = 0.663 \quad \text{C.O.V.} = 43.3 \text{ percent} \quad n = 110$

where all variables are defined as described previously.

It should be noted that these models were developed using only those data that were obtained before deflections exceeded the capability of the measuring device. Some cement grout specimens exhibited excessive deflections after relatively few load applications, and data could be collected only for low numbers of load applications. Thus, the cement grout models may tend to underestimate dowel deflection and looseness after many load applications.

Figure 16 shows the sensitivity of the dowel deflection model to bearing stress and annular gap. The sensitivity of the "looseness" model is similar. The large effect of bearing stress on performance is clear and suggests that the bearing stresses that result from the use of 1-in. (25-mm) dowels (2,500–4,000

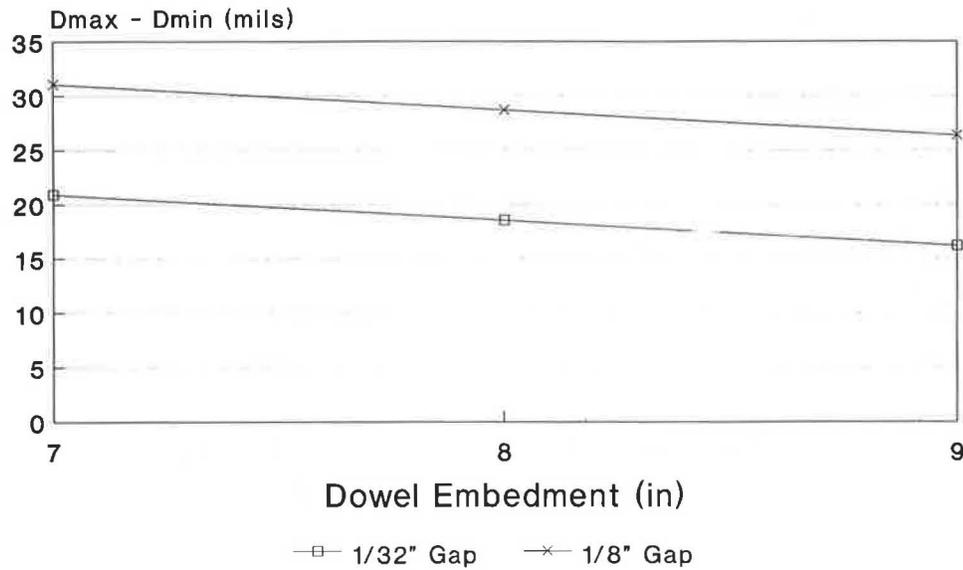


FIGURE 15 Predicted effect of annular gap and embedment length on deflection for epoxy mortar specimens ( $N = 600,000$ , 1-in. dowel, medium-energy drill).

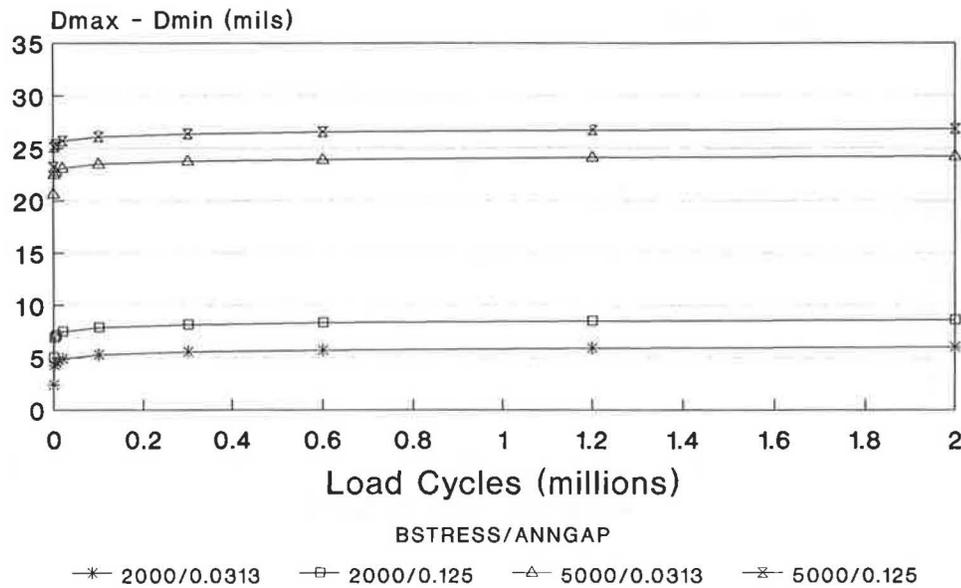


FIGURE 16 Predicted effect of annular gap and bearing stress on deflection for cement grout specimens (medium-energy drill).

psi [17,500–28,000 kPa]) result in deterioration of the anchor material at the joint face. The 1.5-in. (38-mm) dowels (1,000–2,000 psi [7,000–14,000 kPa]) are represented by the lowest curves, which suggest acceptable performance.

The effect of increased heavy load repetitions is also presented in this figure. When good installations are achieved, rapid initial increases in deflection occur as the dowel becomes “seated”; subsequent increases are generally small. Poor installations (characterized by large voids at the joint face) were observed to have excessive deflections from the start; these deflections increased as the dowel repeatedly contacted the supporting material, causing it to deteriorate.

### CONCLUSIONS AND RECOMMENDATIONS

The following conclusions and observations were drawn from the analysis of the laboratory experiment results:

1. The use of grout retention disks is essential to achieve the potential performance of any anchored dowel installation. The disks should fit the dowels snugly and have “weep holes” to allow excess anchor material to escape. Excess anchor material should be used to fill spalls surrounding the drilled hole. These disks should be specified for all doweled, full-depth repair construction projects to ensure good bearing support around the dowel.

2. The epoxy mortar anchoring material was easier to use and produced more consistent results than the cement grout. Dowel deflections and computed "looseness" were lower when cement grout was properly installed (i.e., when no voids were present and uniform support was provided). The potential of the cement grout was difficult to achieve, however, because the consistency of the grout typically changed rapidly over very short periods of time.

3. The use of larger diameter dowels significantly reduces concrete bearing stresses, dowel deflections, and dowel "looseness" when all other factors are held constant.

4. Increasing the size of the annular gap (drilled hole radius minus dowel radius) from  $\frac{1}{32}$  in. to  $\frac{1}{8}$  in. (0.8 mm to 3.2 mm) improved the performance of dowels anchored in cement grout, apparently because better distribution of stiff grout could be achieved. Very fluid grouts performed poorly, regardless of the annular gap.

5. Small annular gaps improved the performance of dowels anchored in epoxy mortar because thinner supporting layers of epoxy mortar, which was softer than the concrete specimens, deformed less than thick layers. The consistency of the material was such that good support and filling of the voids were achieved regardless of the annular gap.

6. Reducing dowel embedment resulted in very small increases in dowel deflection and "looseness" when epoxy mortar was used. Even smaller increases resulted when good cement grout specimens were tested.

7. Close-fitting holes probably offer promise when used with good anchor materials, quality control, and grout retention disks. Cement grout and "no-grout" applications may experience poor performance due to nonuniform support of the dowel and drill-induced spalling at the joint face.

8. The hollow stainless steel dowel performed adequately, although it did not bond with the epoxy mortar that was used. Concurrent testing by the FHWA has demonstrated the need to fill hollow dowels with concrete or some other stiff material to reduce deformation of the dowel at the joint face (12).

9. It appears that the following design and construction parameters would provide excellent field performance on primary and Interstate installations:

- $1\frac{1}{2}$ -in.-diameter (nominal), corrosion-resistant solid steel dowels;
- $1\frac{1}{16}$ -in.-diameter (nominal), guided drills for epoxy mortar anchor materials;  $1\frac{3}{4}$ -in.-diameter (nominal), guided drills for cement grout anchor materials;
- 7-in. or greater dowel embedment;
- Use of rapid-curing, consistent, easy-to-use anchor material (reduction of the emphasis on using the cheapest materials when they are difficult to install adequately); and
- Use of grout retention disks during curing of the anchor materials. Field testing of these recommendations should be accomplished prior to widespread installation.

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