Rehabilitation of Concrete Pavements

Volume IV: Appendixes

FOREWORD

This report is one volume of a four-volume set presenting the results of a
research study to develop improved evaluation procedures and rehabilitation
techniques for concrete pavements. Each report includes the Table of Contents
for all four volumes. Eight rehabilitation techniques were selected for
detailed investigation by field inspection and analytical study. These eight
techniques are diamond grinding, load transfer restoration, edge support,
full-depth repair, partial-depth repair, bonded concrete overlays, unbonded
concrete overlays, and crack-and-seat with AC overlay. Based on analysis of
the field data, a series of distress models were developed to predict the
performance of the various rehabilitation techniques under a variety of
conditions. These models and other information were then used to develop a
comprehensive prototype system for jointed plain, jointed reinforced, and
continuously reinforced pavement evaluation and rehabilitation.

This report will be of interest to engineers involved in planning, designing,
or performing rehabilitation of concrete pavements.

Sufficient copies of this report are being distributed by FHWA memorandum to
provide one copy to each FHWA Region and Division and two copies to each State
highway agency. Direct distribution is being made to the division offices.
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Research and Development

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16. Abstract

Extensive field, laboratory and analytical studies were conducted into the evaluation and rehabilitation of concrete pavements. Field studies included over 350 rehabilitated pavement sections throughout the U.S., and the construction of two field experiments. A laboratory study was conducted on anchoring dowels in full-depth repairs. Analyses of field and laboratory data identified performance characteristics, improved design and construction procedures, and provided deterioration models for rehabilitated pavements. A concrete pavement advisory system was developed to assist engineers in project level evaluation and rehabilitation.

This Volume IV contains a description of the data collection procedures, original pavement and rehabilitation design factors, extent of the database, description of database variables, and documentation of the laboratory dowel anchoring experiment.

This volume is the fourth in a series. The others in the series are:

FHWA NO.	Vol. No.	Title
RD-88-071	I	Repair Rehabilitation Techniques
RD-88-072	II	Overlay Rehabilitation Techniques
RD-88-073	III	Conc. Pvt. Eval. and Reh. System

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in²	square inches	645.2	millimetres squared	mm²
ft²	square feet	0.093	metres squared	m²
yd²	square yards	0.836	metres squared	m²
ac	acres	0.405	hectares	ha
mi²	square miles	2.59	kilometres squared	km²
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.028	metres cubed	m³
yd³	cubic yards	0.765	metres cubed	m³

NOTE: Volumes greater than 1000 L shall be shown in m³.

Symbol	When You Know	Multiply By	To Find	Symbol
	MASS			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
ha	hectares	2.47	acres	ac
km²	kilometres squared	0.386	square miles	mi²
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³
	MASS			
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
	TEMPERATURE (exact)			
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F
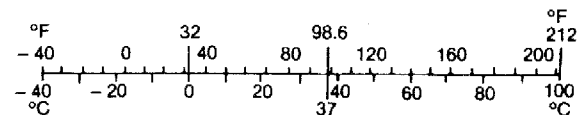
```
  °F            32           98.6                 212
 -40      0    |40    80    |120    160    200|
  |--|--|--|--|--|--|--|--|--|--|--|--|--|--|--|
 -40    -20    0     20    |40     60     80   100
  °C                       37                  °C
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(Revised April 1989)

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CHAPTER 1

INTRODUCTION

1.0 STUDY OBJECTIVE

The overall objective of this study was to develop improved evaluation procedures and rehabilitation techniques for concrete pavements. This objective was accomplished through extensive field, laboratory and analytical studies that have provided new knowledge and understanding of the performance of rehabilitated concrete pavements. New and unique evaluation and rehabilitation procedures and techniques were developed that will be very useful to practicing pavement engineers.

This final report, presented in four volumes, documents all of the results developed under the contract, "Determination of Rehabilitation Methods For Rigid Pavements", conducted for the Federal Highway Administration. This volume documents the data collection procedures and database description for the rehabilitation projects. Also included is a detailed chapter describing the laboratory shear testing of dowels anchored in concrete. A brief discussion of the laboratory dowel shear testing can be found in volume I, chapter 5.

1.1 FIELD STUDIES

The field studies involved a large and extensive field survey of 349 rehabilitation sections of jointed plain and reinforced concrete pavement. These sections were located in 24 States. Eight rehabilitation techniques were selected for detailed study:

- Diamond grinding.
- Load transfer restoration.
- Edge support.
- Full-depth repair.
- Partial-depth repair.
- Bonded concrete overlays.
- Unbonded concrete overlays.
- Crack and seat and AC overlay.

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CHAPTER 2

DATABASE DESCRIPTION

2.1 DATA COLLECTION PROCEDURES

The 349 uniform sections (from 267 different projects) included in the database represent many of the concrete pavement rehabilitation projects in existence today within the United States that have utilized at least one of the eight rehabilitation techniques of interest. These pavements were surveyed between June 1985 and August 1986.

There were five basic data types that were deemed necessary for the development of performance prediction models and the development and improvement of design and construction procedures. These include:

● Field condition data.

● Original pavement structural design, in situ conditions, and historical improvement data.

● Rehabilitation design data.

● Historical traffic volumes, vehicle classifications and accumulated 18-kip [80-kN] equivalent single-axle loadings.

● Environmental data.

The data sources and collection procedures used in this research study are described below.

2.1.1 Field Condition Surveys
A standard field condition survey was performed on each project or uniform section. The procedures used in the collection of condition data closely follow those described in NCHRP Project 1-19 (COPES) study for field data collection.(13) The distress identification manual developed for the COPES study was used as a standard for the identification and measurement of distresses and their severity levels.

The term "uniform section" was defined in the COPES study as a section of pavement with "uniform characteristics along its length including structural design, joint design and spacing, reinforcement, truck traffic, subgrade conditions, and distress".(14) To properly incorporate rehabilitation technique variation (e.g., different full-depth repair designs, different overlay thicknesses, etc.) into the uniform section concept, it was necessary to expand the definition of a uniform section to include uniformity of rehabilitation design.

Preliminary Work
The first step in project selection was to contact State department of transportation personnel to determine their interest in participating in the study. Project description forms were then sent to those States who were interested and willing to participate. The State personnel then selected representative rehabilitation projects that included one or more of the eight techniques, and filled out a project description form for each section.

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The project description forms from all over the country were reviewed by the Contractor, any inappropriate sections were excluded (where one or more of the eight rehabilitation techniques were not included for example), and detailed data collection forms were sent to the State personnel for the selected projects in their State. Upon completion of these data collection forms, data entry into the database was begun. If important data items were missing, an additional written request was sent to the State personnel for this information. In some cases, this information was retrieved in person through a trip to the State department of transportation office.

In preparation for the field work, the beginning and ending markers (stations, mileposts, landmarks) of the project were determined as best as possible in the office by verbal communication with state department of transportation personnel, prior to the commencement of surveying procedures. These steps ensured that any changes in uniform section pertaining to variations in the design of the original pavement or rehabilitation design would not be overlooked.

Field Work

After the preliminary identification of the uniform sections to be surveyed, the following procedures were used in the field data collection process.

- A two-person trained survey crew made at least one pass over the project areas at the posted speed. During the pass, changes in the pavement condition, in situ foundation conditions (cut/fill) and drainage were noted. This pass was used to determine whether one or more uniform sections were necessary on the basis of pavement distress, grade or drainage variation.

- The uniform sections were surveyed by representative sampling. Usually two 1000-ft [305 m] sample units were surveyed per uniform section. If the section was of considerable length (greater than 10 miles [16.1 km]), a third sample unit was taken to ensure reasonable coverage. The location of the sample units was selected randomly; however, sample units were selected such that grade conditions (cut/fill) along their lengths were as uniform as possible. Also, in consideration of the fact that a project or sample unit might require additional evaluation at some future date, many of the sample units were located at milepost markers for easier future identification.

- A very comprehensive distress survey was conducted along each sample unit. The condition of both lanes was measured where traffic or other conditions did not pose a serious safety hazard to the survey crew. The outer lane survey was conducted from the outer shoulder of the pavement and, likewise, the inner lane survey was conducted from the inner shoulder. Measurements of faulting and joint widths were taken 1 foot [0.3 m] from the PCC slab lane edge. Samples of the field data collection sheets are shown in figures 1 and 2. Figure 1 was used for the concrete-surfaced rehabilitation techniques, whereas the strip map shown in figure 2 was used for the asphalt-surfaced crack and seat projects. Also, photographs of the pavement, general topography and other distresses were recorded.

- The presence of subsurface drainage and the condition of subsurface drainage facilities were noted.

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stations

DISTRESS SURVEY FOR TRANSVERSE JOINT

	OUTER LANE						INNER LANE					
REGULAR JOINT / PATCH APPROACH JOINT / WITHIN APPROACH JOINT / WITHIN PATCH JOINT / PRESSURE RELIEF JOINT	STATION	STATION	STATION	STATION	STATION	STATION	STATION	STATION	STATION	STATION	STATION	STATION
	PATCH ID	PATCH ID	PATCH ID	PATCH ID	PATCH ID	PATCH ID	PATCH ID	PATCH ID	PATCH ID	PATCH ID	PATCH ID	PATCH ID
DISTRESSES												
SPALLING (TR. JOINT)												
(APPROACH SIDE 1)	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H
(LEAVE SIDE 2)	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H
SPALLING (CORNER)												
(APPROACH SIDE 1)	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H
(LEAVE SIDE 2)	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H
PUMPING	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H	L M H
FAULTING (in inches)												
JOINT WIDTH (in inches)												
CORNER BREAKS												
(APPROACH SIDE 1)	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N
(LEAVE SIDE 2)	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N
"D" CRACKING	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N
REACTIVE AGGREGATE	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N
SEALANT CONDITIONS												
ABSENCE	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N
COHESION FAILURE	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N
ADHESION FAILURE	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N
EXTRUSION	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N
OXIDATION (HARDENED)	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N
INCOMPRESSIBLES	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N	Y / N

DISTRESS SURVEY FOR REHABILITATION PATCH AREA

	OUTER LANE		INNER LANE	
TYPE OF MATERIAL / TYPE OF PATCH / PATCH LOCATION / PATCH LENGTH / PATCH WIDTH / SEALANT USED	PATCH ID	PATCH ID	PATCH ID	PATCH ID
	PCC __ AC __ OTHER___	PCC __ AC __ OTHER___	PCC __ AC __ OTHER___	PCC __ AC __ OTHER___
	FULL / __ PARTIAL DEPTH	FULL / __ PARTIAL DEPTH	FULL / __ PARTIAL DEPTH	FULL / __ PARTIAL DEPTH
	__ AT A JOINT __ BETWEEN JOINTS __ FULL SLAB REPLACEMENT	__ AT A JOINT __ BETWEEN JOINTS __ FULL SLAB REPLACEMENT	__ AT A JOINT __ BETWEEN JOINTS __ FULL SLAB REPLACEMENT	__ AT A JOINT __ BETWEEN JOINTS __ FULL SLAB REPLACEMENT
DISTRESSES	Y / N	Y / N	Y / N	Y / N
PCC or other material				
TRANSVERSE CRACKING	L M H	L M H	L M H	L M H
LONGITUDINAL CRACKING	L M H	L M H	L M H	L M H
SCALING	Y / N	Y / N	Y / N	Y / N
AC Patch material				
RUTTING	L M H	L M H	L M H	L M H
ALLIGATOR CRACKING	L M H	L M H	L M H	L M H
RAVELING	Y / N	Y / N	Y / N	Y / N
SHOVING	Y / N	Y / N	Y / N	Y / N
Partial depth patches				
LOSS OF PATCH MATERIAL				
(percent of patch area)				

Figure 1. Concrete pavement field data collection forms.

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Present Lane Width _____

Start Pt. Mile Mark _____   Start Pt. Station No. _____

80-   80-   80-

60-   60-   60-

40-   40-   40-

20-   20-   20-

Left Ln   Right Ln

Figure 2.   Asphalt concrete pavement field data collection forms.

2.1.2 Original Pavement and Rehabilitation Design Factors

For the collection of this data, the as-built original construction and rehabilitation construction plans, as well as special provisions for the rehabilitation projects, were obtained for each project. Much of the required data was obtained from these records; however, consultation with State department of transportation personnel was also necessary to collect additional information. Finally, data from other sources such as published reports was also used.

A detailed listing of the variables collected under this study pertaining to original pavement and rehabilitation design and rehabilitation field monitoring is included in section 2.6.

2.1.3 Traffic Data

Values for the average annual daily traffic and percent heavy commercial truck traffic were also collected from the State department of transportation records. Historical information was collected where the data was available; however, in some instances only current traffic levels were obtained. For the determination of the number of equivalent 18-kip [80 kN] single-axle loadings (ESALs) accumulated on each project, Federal Highway Administration W-4 truck axle load distribution data were utilized to compute the truck factors over the life of the pavements. The number of accumulated axle loads from the time of original pavement construction until the time each rehabilitation technique was applied, and from then until the time of survey, was calculated for each project.

2.1.4 Environmental Data

The average monthly precipitation and average daily minimum, maximum and mean temperatures were taken from National Oceanic and Atmospheric Administration data. The nearest weather station was assumed to be representative of the conditions at the project site. The mean Freezing Index was interpolated from the contour map developed by the Corps of Engineers for the continental United States.(14) The climatic zone as classified by Carpenter was also determined for each site.(14)

2.2 LABORATORY STUDIES

Laboratory studies included the first comprehensive testing of dowel anchoring procedures and designs. Full-scale repeated shear loading of dowels was conducted for up to one million load repetitions using slabs cut from I-70 in Illinois. Many different design, material and construction variables were considered in a factorial type experimental design.

2.3 ANALYTICAL STUDIES

Analytical studies were accomplished primarily to develop prediction models for rehabilitated pavement deterioration so that the service life of different rehabilitation techniques could be estimated. Twelve distress models were developed including reflective cracking, faulting, rutting, and serviceability for most of the above rehabilitation techniques. These models were incorporated into the evaluation and rehabilitation system.

2.4 EVALUATION AND REHABILITATION SYSTEM

A comprehensive concrete pavement evaluation and rehabilitation system was developed for jointed plain, jointed reinforced and continuously reinforced concrete

pavements. This system is intended to assist the design engineer in the following rehabilitation project design activities:

- Project data collection.
- Evaluation of present condition.
- Prediction of future condition without rehabilitation.
- Physical testing recommendations.
- Selection of feasible rehabilitation approaches.
- Development of detailed rehabilitation recommendations.
- Prediction of performance of the rehabilitation strategy.
- Cost analysis and selection of the preferred rehabilitation alternative.

The results of this research are published in four volumes:

- Volume I   Repair Rehabilitation Techniques

- Volume II   Overlay Rehabilitation Techniques

- Volume III   Concrete Pavement Evaluation/Rehabilitation System

- Volume IV   Appendixes

Each of these volumes are stand alone volumes that present the data, analyses and conclusions for each of the rehabilitation techniques and the evaluation and rehabilitation system.

2.5 EXTENT OF THE DATABASE

The database is comprehensive, containing as many projects as were available or that could be included within available resources. This was done to provide a wide range of data to facilitate regression analysis for the development of performance models.

An indication of the extent of this database is shown in tables 1 and 2. Table 1 represents the number of different project designs in the database by State and rehabilitation technique. In addition, there are typically two replicate sample units for each different design. Table 2 illustrates the climatic zone factorial for all of the rehabilitation sections defined in this study.

2.6 DESCRIPTION OF DATABASE VARIABLES

Tables 3 through 17 contain all of the variables collected for this rehabilitation study which pertain to the original pavement design, the design of each rehabilitation technique and the field monitoring of each rehabilitation technique. For each rehabilitation technique, the monitoring data collected applies to different sections of the rehabilitated pavement. For instance, edge support monitoring data was collected not only for the outer and inner traffic lanes, but also for the PCC tied shoulder, whereas the full-depth repair monitoring data applies to individual repairs and individual repair joints. The section headings for the database monitoring variables contain a description concerning the proper application of the field monitoring data to the various pavement sections.

The traffic database contains the annual average daily traffic, percent heavy commercial trucks, truck factor and accumulated 18-kip [80 kN] equivalent single-

Table 1. Breakdown of rehabilitation techniques by State.

STATE	FDR	PDR	DGD	LTR	CAS	UNBOL	BOL	ES	TOTAL
Arizona	1	1	3	0	0	0	0	0	5
Arkansas	1	0	1	0	1	0	0	1	4
California	3	0	7	0	6	0	0	0	16
Colorado	2	0	1	1	2	3	0	2	11
Florida	3	0	2	0	5	0	0	0	10
Georgia	5	6	16	2	0	2	0	0	31
Illinois	11	1	6	2	12	2	0	1	35
Iowa	5	0	2	0	0	0	25	0	32
Kentucky	0	0	0	0	9	0	0	0	9
Louisiana	1	1	1	1	0	0	1	0	5
Michigan	8	1	0	0	0	2	0	2	13
Minnesota	7	5	7	0	2	0	0	1	22
Nebraska	6	3	0	0	0	0	0	0	9
New York	1	1	2	2	10	0	2	0	18
Ohio	6	1	6	1	0	3	0	1	18
Oklahoma	1	0	2	2	0	0	0	0	5
Pennsylvania	5	2	3	1	2	2	0	2	17
South Carolina	2	1	2	0	0	0	0	1	6
South Dakota	0	3	3	0	3	0	1	0	10
Texas	6	3	0	0	0	0	0	0	9
Virginia	10	5	2	1	0	0	0	0	18
West Virginia	2	0	0	0	3	0	0	0	5
Wisconsin	8	1	5	0	15	0	0	0	29
Wyoming	2	1	5	0	0	0	2	2	12
Total	96	36	76	13	70	14	31	13	349

NOTE: FDR   = full-depth repair
      PDR   = partial-depth repair
      DGD   = diamond grinding
      LTR   = load transfer restoration
      CAS   = crack and seat and AC overlay
      UNBOL = unbonded concrete overlay
      BOL   = bonded concrete overlay
      ES   = edge support (tied PCC shoulder or edge beam)

* Represents the number of different uniform sections in
the database. In addition, there are typically two
replicate sample units for each different design.

Table 2. Climatic zone factorial for each rehabilitation technique.

DETERMINATION OF REHABILITATION METHODS FOR RIGID PAVEMENTS

FACTORIAL OF CLIMATIC ZONES FOR EACH REHABILITATION TECHNIQUE

	FDR	PDR	DGD	LTR	CAS	UNBOL	BOL	ES
WET-FREEZE	40	11	27	5	40	10	20	6
WET-FREEZE-THAW	11	6	22	2	12	0	1	1
WET-NO FREEZE	22	8	10	3	9	1	0	1
INTERMEDIATE-FREEZE	8	7	2	0	3	0	8	1
INTER. FREEZE-THAW	1	0	2	2	0	0	0	0
INTERMEDIATE-NO FREEZE	5	3	5	0	3	0	0	0
DRY-FREEZE	6	0	5	1	2	3	2	4
DRY-FREEZE-THAW	0	1	1	0	0	0	0	0
DRY-NO FREEZE	3	0	2	0	1	0	0	0
TOTAL UNIFORM SECTIONS	96	36	76	13	70	14	31	13

axle loads (ESALs) for the outer and inner lane. This information was calculated for each year since the project was rehabilitated with any of the eight techniques under consideration. The accumulated ESALs correspond to the loadings applied from the year of rehabilitation to the year of survey. An approximate value for the ESALs accumulated since original pavement construction was also determined.

The climatic database contains the average monthly temperature, the average daily maximum temperature, the average daily minimum temperature and the average monthly precipitation for each month of the year for each project site. These values correspond to the weather station nearest to the project site, which was assumed to represent the conditions at the project site. Also included in this database was an entry for the climatic zone and mean Freezing Index at the project site.

Table 3. Original pavement design variables for all projects.

Identification Number (State Code, Highway #, Milepost, Direction)

Beginning and Ending Mile Marker (station)

Number of Through Lanes in One Direction

Type of Original Pavement (JPCP, JRCP)

Layer Descriptions, Thicknesses, Material Types

Date of Original Pavement Construction

Dates and Description of Major Pavement Improvements

Average Contraction Joint Spacing

Skewness of Joints

Expansion Joint Spacing, if any

Transverse Contraction Joint Load Transfer System

Dowel Diameter, Spacing and Length

Type of Slab Reinforcement (welded-wire fabric, deformed rebar)

Longitudinal Bar/Wire Diameter, Spacing and Length

Type of Subgrade Soil (fine-grained, coarse-grained)

Outer Shoulder Surface Type

Original Subsurface Drainage Type

Original Subsurface Drainage Location

Table 4. Database design variables for diamond grinding.

Project Identification Number

Sample Unit

Primary Reason for Diamond Grinding

Extent of Diamond Grinding (entire pavement, at joints only)

Friction Number Before Grinding and Measurement Date

Friction Number After Grinding and Measurement Date

Equipment Used For Friction Testing

Roughness of Pavement Before Grinding and Measurement Date

Roughness of Pavement After Grinding and Measurement Date

Equipment Used For Roughness Measurement

Speed at Which Roughness Measurements Taken

Table 5. Database monitoring variables for diamond grinding.

GENERAL FIELD DATA:
        Sample Unit Length

        Foundation of Sample Unit (cut, fill or at grade)

        Condition of Drainage Ditches

        Subsurface Drainage Functional

        Number of Regular and Patch Joints

PAVEMENT DISTRESS DATA: (for outer lane and inner lane)
                               (low, medium and high severities)

        Centerline Joint Longitudinal "D" Cracking (Outer Lane Only)

        Transverse and Longitudinal Cracking

        Transverse and Longitudinal "D" Cracking

        Longitudinal Joint Spalling

        Scaling, Crazing, Map Cracking

        Mean Regular Joint Faulting over Sample Unit

        Mean Patch Joint Faulting over Sample Unit

        Mean Transverse Crack Faulting over Sample Unit

JOINT DISTRESS SUMMARY: (for outer lane and inner lane)
                               (low, medium and high severities)

        Transverse Joint Spalling (approach side, leave side)

        Transverse Joint Corner Spalling (approach side, leave side)

        Mean Pumping over Sample Unit

        Mean Joint Width over Sample Unit

        Corner Breaks (approach side, leave side)

        "D" Cracking along Joint and/or Reactive Aggregate in Slab

        Sealant Conditions (Cohesion Failure, Oxidized, etc.)

        Incompressibles in Joint

Table 6. Database design variables for load transfer restoration.

Project Identification Number

Sample Unit

Load Transfer Device Type (retrofit dowels, Double-vee shear devices)

Frequency of Installation (all joints, selected joints)

Lane in Which Load Transfer was Restored

Number of Devices Per Lane

Location of Load Transfer Devices Across the Lane

Diameter and Length of Retrofit Dowel Bars

Material Used to Backfill Slot/Core Hole

Bonding Agent Between Existing Slab and Backfill Material

Table 7. Database monitoring variables for load transfer restoration.

GENERAL FIELD DATA:
        Sample Unit Length

        Foundation of Sample Unit (cut, fill or at grade)

        Condition of Drainage Ditches

        Subsurface Drainage Functional

LOAD TRANSFER DEVICE DISTRESS DATA: (for individual restored joints
                                        and cracks)

        Load Transfer Device Type

        Station of Restored Joint or Crack

        Type of Joint

        Location of Joint (outer lane, inner lane)

        Number of Devices on Joint or Crack

        Device Performance (debonding of core, material failure, etc.)

JOINT DISTRESS SUMMARY: (for individual restored joints and cracks)

        Transverse Joint Spalling (approach side, leave side)

        Transverse Joint Corner Spalling (approach side, leave side)

        Mean Pumping at Restored Joint

        Mean Joint Faulting and Joint Width at Restored Joint

        Corner Breaks (approach side, leave side)

        "D" Cracking along Joint

        Reactive Aggregate

        Sealant Conditions (Cohesion Failure, Oxidized, etc.)

        Incompressibles in Joint

Table 8. Database design variables for edge support.

Project Identification Number

Sample Unit

Type of Edge Support System

Matching of Shoulder and Mainline Pavement Joints

Lane/Shoulder Tie System

Diameter of Tie Bars

Length of Tie Bars

Spacing of Tie Bars

Shoulder Width and Design Thickness

Shoulder Thickness Tapering, if any

Thickness of Undercut, if any

Type of Lane/Shoulder Joint

Lane/Shoulder Joint Forming Method

Table 9. Database monitoring variables for edge support.

GENERAL FIELD DATA:
        Sample Unit Length

        Foundation of Sample Unit (cut, fill or at grade)

        Condition of Drainage Ditches

        Subsurface Drainage Functional

        Number of Transverse Joints on the Mainline Pavement

        Number of Transverse Joints on the Shoulder

PAVEMENT DISTRESS DATA: (for outer lane, inner lane and shoulder)
                               (low, medium and high severities)

        Centerline Joint Longitudinal "D" Cracking (Outer Lane Only)

        Transverse Cracking

        Transverse "D" Cracking

        Longitudinal Cracking

        Longitudinal "D" Cracking

        Longitudinal Joint Spalling

        Scaling, Crazing, Map Cracking

        Lane/Shoulder Dropoff (Shoulder Only)

JOINT DISTRESS SUMMARY: (for outer lane, inner lane and shoulder)
                               (low, medium and high severities)

        Transverse Joint Spalling (approach side, leave side)

        Transverse Joint Corner Spalling (approach side, leave side)

        Mean Pumping over Sample Unit

        Mean Joint Faulting and Joint Width over Sample Unit

        Corner Breaks (approach side, leave side)

        "D" Cracking along Joint and/or Reactive Aggregate in Slab

        Sealant Conditions (Cohesion Failure, Oxidized, etc.)

        Incompressibles in Joint

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Table 10.   Dataase design variables for full-depth repair.

Project Identification Number

Sample Unit

Number of Different Patch Designs in Sample Unit

Patch Type Design Number

Equipment Used for Cutting Boundaries

Depth of Typical Boundary Saw Cut

Concrete Breakup Method and Removal Method

Foundation Repair

Transverse Joint Design

Type of Transverse Joint at Repair Boundaries

Type of Transverse Joint Within Repair, if any

Type of Load Transverse System at Approach Joint

Type of Load Transverse System at Leave Joint

Type of Load Transverse System at Longitudinal Joint

Patch Joint Skew, if any

Transverse Boundary Joint Bar Diameter, Spacing and Length

Location of Transverse Bars

Load Transfer Bar Grouting Material

Reinforcement Steel Placed in Patch

Transverse Repair Sealing Method (at boundaries)

Type of Seal Forming (at the within joint)

Repair Curing Method

Typical Time Between Patch Placement and Opening to Traffic

Table 11. Database monitoring variables for full-depth repair.

PATCH DISTRESS DATA: (by individual patches)
           (low, medium and high severities)

  Patch Designation Number

  Patch Location by Lane (outer lane or inner lane)

  Type of Material (PCC, AC)

  Patch Location within Lane (at a joint, mid-slab)

  Patch Length and Width

  Subsealing of Patch Evident

  Transverse and Longitudinal Cracking

  Scaling

  Rutting

  Alligator Cracking

  Raveling of Patch Material (yes, no)

  Shoving of Patch Material (yes, no)

  Percent Loss of Patch Material

JOINT DISTRESS SUMMARY: (by individual patch joints)
           (patch approach, leave and within joints)
           (low, medium and high severities)

  Transverse Joint Spalling (approach side, leave side)

  Transverse Joint Corner Spalling (approach side, leave side)

  Mean Pumping at Joint

  Mean Joint Faulting and Joint Width at Joint

  Corner Breaks (approach side, leave side)

  "D" Cracking along Joint and/or Reactive Aggregate in Slab

  Sealant Conditions (Cohesion Failure, Oxidized, etc.)

  Incompressibles in Joint

Table 12. Database design variables for partial-depth repair.

Project Identification Number

Sample Unit

Patch Boundary Determination

Equipment for Cutting Boundaries

Depth of Typical Boundary Saw Cut

Deteriorated Concrete Breakup and Removal Method

Maximum Airhammer Size

Method Used to Clean Patch Area

Bonding Agent

Patch Material Used

Typical Air Temperature at Time of Placement

Joint Forming Method

Patch Curing Method

Time Between Patch Placement and Opening to Traffic

Table 13. Database monitoring variables for partial-depth repair.

PATCH DISTRESS DATA: (by individual patches)
                              (low, medium and high severities)

        Patch Designation Number

        Joint Station of Patched Joint or Crack

        Location of Joint (outer lane, inner lane)

        Type of Joint (regular joint, repair joint, transverse crack)

        Type of Patch Material and Number of Patches on the Joint

        Patch Location (approach side, leave side)

        Average Patch Length and Width

        Presence of Subsealing Holes near the Joint

        Transverse and Longitudinal Cracking

        Scaling

        Rutting

        Alligator Cracking

        Raveling and/or Shoving of Patch Material (yes, no)

        Percent Loss of Patch Material

JOINT DISTRESS SUMMARY: (by individual patch joints)
                              (low, medium and high severities)

        Transverse Joint Spalling (approach side, leave side)

        Transverse Joint Corner Spalling (approach side, leave side)

        Mean Pumping at Joint

        Mean Joint Faulting and Joint Width at Joint

        Corner Breaks (approach side, leave side)

        "D" Cracking along Joint and/or Reactive Aggregate in Slab

        Sealant Conditions (Cohesion Failure, Oxidized, etc.)

        Incompressibles in Joint

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Table 14. Database design variables for concrete overlays.

Project Identification Number

Sample Unit

Type of PCC Overlay (JPCP or JRCP)

Bonding Condition of Overlay (bonded, unbonded or partially bonded)

Initial Surface Preparation

Final Surface Preparation

Type of Grout Used For Bonding Overlays

Material Used to Prevent Bonding

Matching of Overlay and Existing Pavement Joints

Average Overlay Contraction Joint Spacing

Expansion Joint Spacing

Skewness of Joint

Contraction Joint Load Transfer System (dowels, aggregate interlock)

Dowel Diameter, Spacing and Length

Method used to Form Transverse Joints

Lane/Shoulder Joint Tie Bar Diameter, Spacing and Length

Type of Slab Reinforcement

Longitudinal Bar Diameter, Spacing and Length

Table 15. Database monitoring variables for concrete overlays.

GENERAL FIELD DATA:
   Sample Unit Length

   Foundation of Sample Unit (cut, fill or at grade)

   Condition of Drainage Ditches

   Subsurface Drainage Functional

   Number of Transverse Joints in the Sample Unit

PAVEMENT DISTRESS DATA: (for outer lane, inner lane and shoulder)
                            (low, medium and high severities)

   Centerline Joint Longitudinal "D" Cracking (Outer Lane Only)

   Transverse Cracking

   Transverse "D" Cracking

   Longitudinal Cracking

   Longitudinal "D" Cracking

   Longitudinal Joint Spalling

   Scaling, Crazing, Map Cracking

JOINT DISTRESS SUMMARY: (for outer lane, inner lane and shoulder)
                            (low, medium and high severities)

   Transverse Joint Spalling (approach side, leave side)

   Transverse Joint Corner Spalling (approach side, leave side)

   Mean Pumping over Sample Unit

   Mean Joint Faulting over Sample Unit

   Mean Joint Width over Sample Unit

   Corner Breaks (approach side, leave side)

   "D" Cracking along Joint and/or Reactive Aggregate in Slab

   Sealant Conditions (Cohesion Failure, Oxidized, etc.)

   Incompressibles in Joint

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Table 16. Database design variables for crack and seat.

Project Identification Number

Sample Unit

Presence of "D" cracking on Existing Pavement

Original Slab Repair

Pavement Breaker Type

Average PCC Breakage Size -- WIDTH

Average PCC Breakage Size -- LENGTH

Wire Mesh Cut or Broken

Seating Roller Type

Seating Roller Weight

Broken Pavement Exposure Time to Traffic

Table 17. Database monitoring variables for crack and seat.

GENERAL FIELD DATA:
        Sample Unit Length

        Foundation of Sample Unit (cut, fill or at grade)

        Condition of Drainage Ditches

        Subsurface Drainage Functional

PAVEMENT DISTRESS DATA: (for outer lane and inner lane)
                                (low, medium and high severities)

        Centerline Longitudinal Cracking (Outer Lane Only)

        Transverse Cracking

        Joint Reflective Cracking

        Longitudinal Cracking

        Lane Edge Cracking

        Mean Pumping over Sample Unit

        Alligator Cracking

        Block Cracking

        Raveling/Weathering

        Bleeding

        Potholes

        Rutting Inner Wheelpath (100-ft [30.5 m] intervals)

        Rutting Outer Wheelpath (100-ft [30.5 m] intervals)

CHAPTER 3

LABORATORY SHEAR TESTING OF DOWELS ANCHORED IN CONCRETE

3.1 EXPERIMENTAL DESIGN

The general concept of the study involved the application of repeated shear loads to dowels of various dimensions anchored in holes drilled in concrete specimens obtained from an inservice Interstate highway and the collection and analysis of dowel load and deflection data at several points during the load history of each dowel.

The effects of five design and construction variables -- 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) -- on the deflection response of dowels in full-depth repairs to repeated shear loads were investigated. 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 "levels" or types were selected. Table 18 summarizes the test values that were selected for each of the variables.

Tests were also conducted on a number of "special" specimens, including two specimens with dowels cast in place in the lab, 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 provide an indication of needs for future research.

Most test specimens were subjected to approximately 600,000 load cycles, although a few specimens received 2 million or more load cycles to more accurately document the development of dowel looseness.

A replicated half-fraction factorial experimental design was employed to provide a statistical basis for determining the main effects and interaction effects of the five variables under consideration. The use of a half-fraction factorial allows the estimation of main effects and two-way interaction effects while testing only half of the cells in the complete factorial matrix. Three-way and higher order interaction effects are considered negligible.(1)

The original replicated half-fraction factorial design was modified as testing progressed. Test cells and replicates were added to provide estimates of test result variability over various test factors. Specimen preparation and testing errors resulted in the deletion of some specimens from the testing program and adjustments were also made to the test matrix based on availability of specimens. Table 19 presents the matrix of specimens that were actually tested.

3.1.1 Preparation of the Test Specimens

Portland cement concrete slabs for fabricating test specimens were obtained from the outside eastbound lane of Interstate 70 near milepost 89, west of Effingham, Illinois. This pavement is a four-lane divided highway constructed of 10-in [25 cm] reinforced PCC pavement with contraction joints at 100-ft [30.5 m] intervals. The highway was constructed in 1962, and had accommodated approximately 13.8 million 18-kip [80-kN] single-axle loads in the design (outside) lane from the date of construction to the date of removal.

Table 18. Summary of test values used in dowel bar repeated
          shear tests.

VARIABLE	Low Value	Medium	High Value
Dowel Diameter	1" [2.5 cm]		1.5" [3.8 cm]
Annular Gap	1/32" [0.08 cm]		1/8" [0.3 cm]
Anchor Material	Cement Grout (Dayton Superior Sure-Grip -- "Flowable" Mix)		Epoxy Resin (Hilti HIT C-10)
Embedment Length	7" [17.8 cm]		9" [22.9 cm]
Drill Type	Standard Pneumatic	Hydraulic Percussion (TAMROCK)	Electro-Pneumatic (Hilti, Inc.)

Table 19. Experimental test matrix of specimens actually tested.

		1 in DOWEL BAR				1-1/2 in DOWEL BAR			
		1/32 in ANNULAR GAP		1/8 in ANNULAR GAP		1/32 in ANNULAR GAP		1/8 in ANNULAR GAP	
		CEMENT GROUT	EPOXY RESIN	CEMENT GROUT	EPOXY RESIN	CEMENT GROUT	EPOXY RESIN	CEMENT GROUT	EPOXY RESIN
TAMROCK HYDRAULIC DRILL	9 in EMBED		2 B2(CPR) D4	2	B1(CPR) C15(CPR) D7(CPR)	2 B5			3 C6(CPR) D16(TEST) A6(CPR)
	7 in EMBED	2 A16			2 A4 D2		2 B13 C10	2	
HILTI ELECTRIC DRILL	9 in EMBED		3 C19 D10 D10R	2 A8R D7R	3 B21 C15R D6	3 C21	3 A5 C19R	D13 3 B18 C6R C22	C3R 3 A6R B17
	7 in EMBED	2 A18 B4	A16R(cpr) A19R(cpr)	A12	2 A8 C3	C17	2 B11R(5in)	2 A10 D5	
SULLAIR PNEUMATIC DRILL	9 in EMBED	2 A1 B14			2 B7 D18		2 A2 D19	2 C12 D20	3 A13 B3 D22
	7 in EMBED		2 C2 D8	2 A20	C8	2 B20 C16			2 C7

Note: 1 in = 2.54 cm

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Four-in [10.2 cm] pressure relief joints were cut near mid-panel at 1000-ft [305 m] intervals in 1972. In July 1985 these relief joints were being replaced with 4-ft [1.2 m] bituminous concrete pressure relief joints/repairs. Using the existing relief joint as one transverse repair joint, the remaining transverse joint and the pavement centerline joint were cut with a diamond blade saw. The undamaged slabs were lifted out and loaded onto flat bed trucks for disposal.(2) Four of these slabs were transported and cut into 18 in by 12 in [31 cm by 46 cm] test specimens. Concrete located near the old relief joint, the lane/shoulder joint and the drilled lift-out holes was discarded. Eighteen usable test specimens were obtained from each slab. Eight 6-in [15.2 cm] diameter (nominal size) cores were also obtained from each slab for compression, split tensile, and elastic modulus testing in accordance with ASTM specifications C 39-72, C 496-71 and C 469-65. Test results are summarized in table 20.

Sand-cement mortar "caps" (generally less than 0.5 in [1.3 cm] thick) were cast on the bottom of each specimen to provide a level base for drilling and testing.

A steel drilling frame was assembled to hold the specimens and drill rigs in place during drilling and to ensure that the holes were drilled perpendicular and centered within one of the 12-in [31 cm] faces of the test specimens. Drilling dust and loose particles were removed from the holes using a large test tube brush and compressed air.

The uncoated steel dowels were washed with soap and water to remove dirt and oil buildups accumulated during shipping which might affect the curing and material properties of the anchor materials, dried with hand towels and allowed to air dry.

The dowels were installed horizontally in the test specimens by injecting sufficient anchor material into the backs of the drilled holes to cause material extrusion when the dowels were inserted. A tight-fitting nylon disk, 2 in larger than the dowel diameter and approximately 3/32 in [0.24 cm] thick was fixed on each dowel at a distance equal to the embedment length from one end of the dowel (see figures 3 and 4). These disks were used to prevent the anchor material from flowing out of the holes and creating voids around the dowels. They also force the anchor material to fill spalls near the dowel hole on the concrete face caused by the drill. One small "weep" hole was provided in each disk to allow excess anchor material to extrude.

The dowels were inserted up to the nylon disks with a back-and-forth twisting action (as recommended by Lippert) to ensure complete and uniform coverage of the dowel and filling of the annular gap with the anchor material.(3) The dowels were allowed to settle or tip in the holes as the anchor material cured.

The nylon disks were removed after 24 hours and the anchor material was inspected for surface voids or other visible faults that would affect test results.

An effort was made to test the cement grout specimens no sooner than 7 days and no later than 14 days after preparation. A similar effort was made to test the epoxy resin mortar specimens no sooner than 24 hours and no later than 7 days after preparation. Failures of the test equipment and other delays did result in exceptions, however. Analyses of replicate specimens of each type that were tested at different ages found that the effect of delaying testing beyond the time frames described above was insignificant.

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Table 20. Summary of results of material property tests performed on I-70 slabs.

	SLAB DESIGNATION			
	A	B	C	D
Compressive Strength (psi)				
n	3	3	3	3
mean	6283	5320	5819	7471
std. dev.	471	355	. 527	361
Split Tensile Strength (psi)				
n	3	3	3	3
mean	635	515	689	698
std. dev.	67	50	82	98
Elastic Modulus (psi x 10^6)				
n	1	1	1	1
result	4.8	4.4	4.6	5.2

Note: Multiply psi by 0.0068947 to get MPa.

$^3/_{32}$" R WEEP HOLE

1.0"(±)

D + 0.02"

NYLON OR PLASTIC
MATERIAL ($^1/_{16}$"MIN.
THICKNESS)
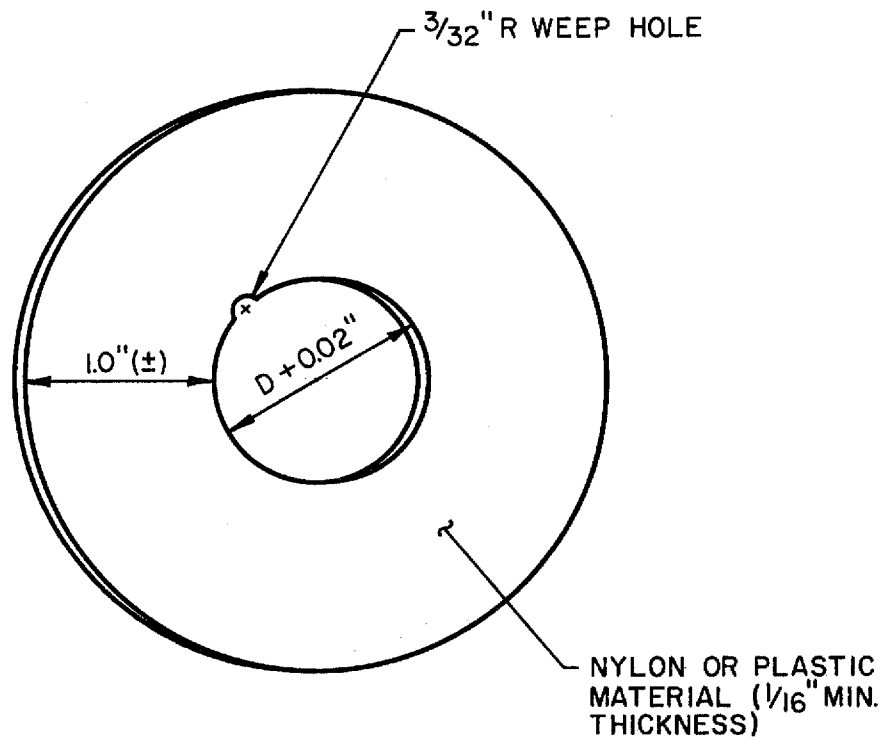
D = DOWEL DIAMETER
      (INCLUDING
       PROTECTIVE
       COATINGS, IF ANY)

Note: 1 in = 2.54 cm.

Figure 3.   Illustration of grout retention disk
              used in lab experiment.
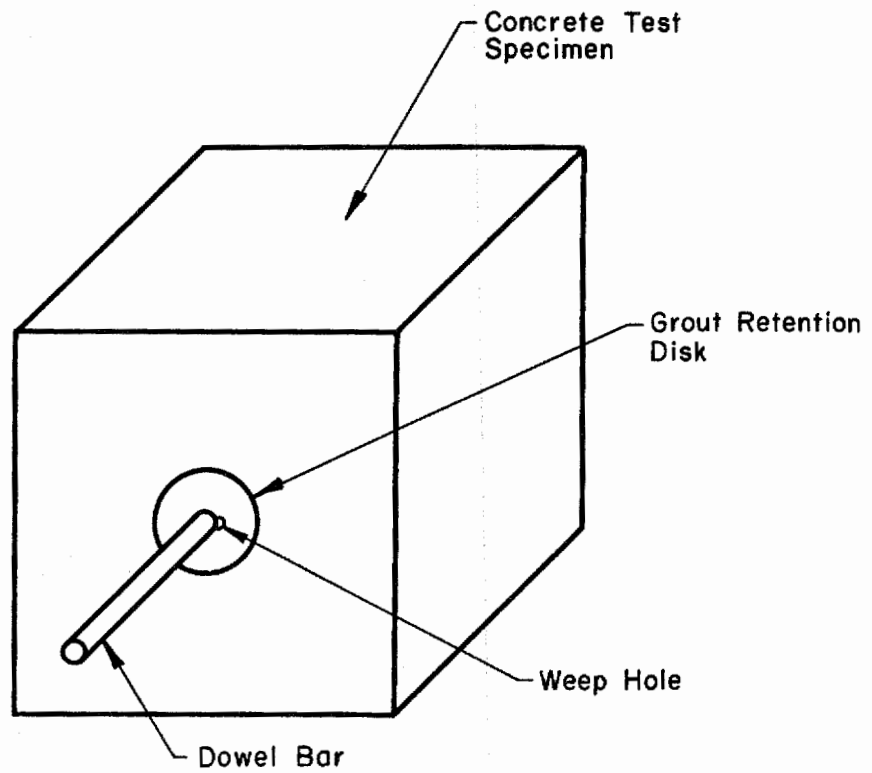
Figure 4. Illustration of dowel bar prepared for installation with grout retention disk in place.

Two specimens were prepared with 1-in [2.5 cm] diameter dowels cast-in-place with 9 in [22.9 cm] of embedment. The concrete mix was designed according to Portland Cement Association procedures for a 3000-psi [20.7 MPa] mix using 1.50-in [3.8 cm] top size crushed stone and sand from the contractor's concrete lab, a type I cement, and a water/cement ratio of 0.45.(4) These specimens were cured for 24 hours, subjected to 5000 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.

Specimens were also prepared to test the performance of dowels installed to an embedment length of 9 inches [22.9 cm] in very close-fitting holes. The inside diameter of holes drilled in two specimens using 1.0625-in [2.7 cm] nominal diameter drill steels mounted in the Hilti drill was measured and 1.25-in [3.2 cm] dowels were turned on a metal lathe to achieve dowel diameters 0.02 in [0.05 cm] less than the smallest diameter measured in each hole. The finished dowels were 1.06 and 1.10 inches [2.7 and 2.8 cm] in diameter. Insertion of the dowels showed that the smaller of the two was loose enough to be moved slightly in any direction. The larger could not be inserted to full-depth by hand. The larger dowel was forcibly inserted without anchor material using a large hammer. Before testing of the larger dowel, a vertical crack was noted through the center of the face of the specimen, although the crack did not deteriorate under test conditions.

3.1.2 Description of the Test and Related Equipment
Repeated bidirectional vertical shear loads were applied to the dowels installed in the test specimens. The magnitude and rise time of the loads were originally selected to simulate the response of the critical dowel installed in a transverse repair joint to the passage of a tandem-axle dual-wheel load with 18 kips [80-kN] per axle (AASHTO WB-50) at 55 miles per hour [90 km/h]. This simulation was accomplished using the finite-element slab analysis program ILLISLAB.(5) The load format was then modified to reflect the results of previous research efforts and test equipment limitations.(6,7) The load function finally utilized was a continuous sinusoidal form with a peak magnitude of ± 3000 pounds [13.4 kN] and a frequency of 6 Hz (see figure 5). Loads were thus applied at the rate of nearly 520,000 per day, allowing the application of about a years worth of heavy traffic loads to a single dowel installation each day.

The specimens were clamped to a thick steel plate using two sets of thick steel straps which were bolted to the plate and could be adjusted to accommodate specimens of varying width and height. The applied loads were generated hydraulically using an MTS Model 661 ram with an 11 kip [50 kN] capacity, which was controlled by a simple sine wave function generator. The load was applied to the dowel through a specially fabricated high-strength steel loading collar which was clamped to the dowel using large "set" screws. This collar allowed vertical deflection and associated angular movement of the dowel about a lateral axis. The collar contacted 2.5 in [6.5 cm] of the length of the dowel and was positioned 0.25 in [0.6 cm] from the concrete face.

A linearly varying deflection transducer (LVDT) was mounted on a bracket attached to the face of each specimen (using the HIT-C10 material) and connected to the load collar using a small nylon screw. This device was used to measure the movement of the dowel relative to the PCC specimen. The MTS load cell data was also collected for analysis and was used to assist in the computer control of the test. Figure 6 shows the load collar and LVDT attachment.

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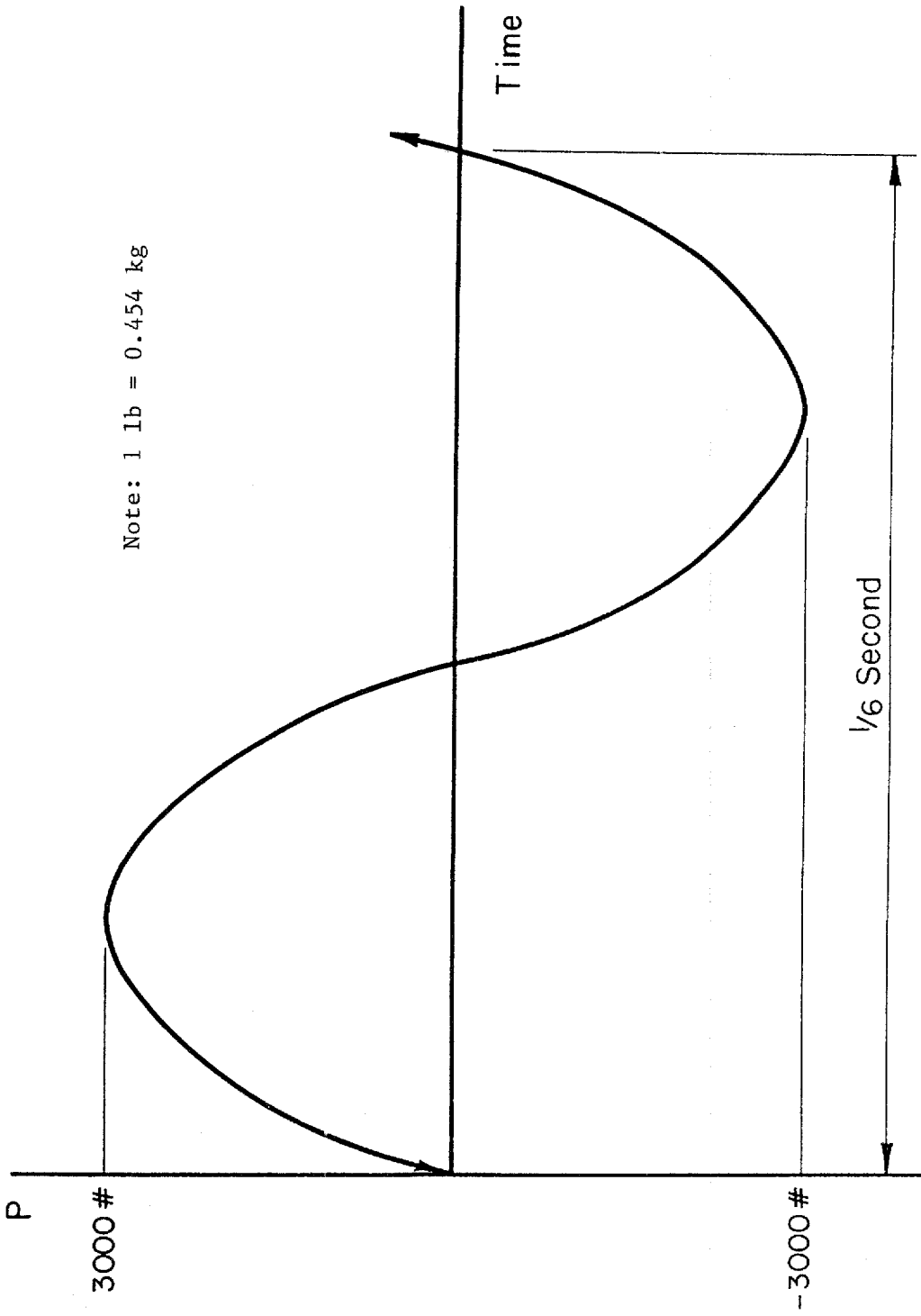
Figure 5. Illustration of load function used for lab testing.
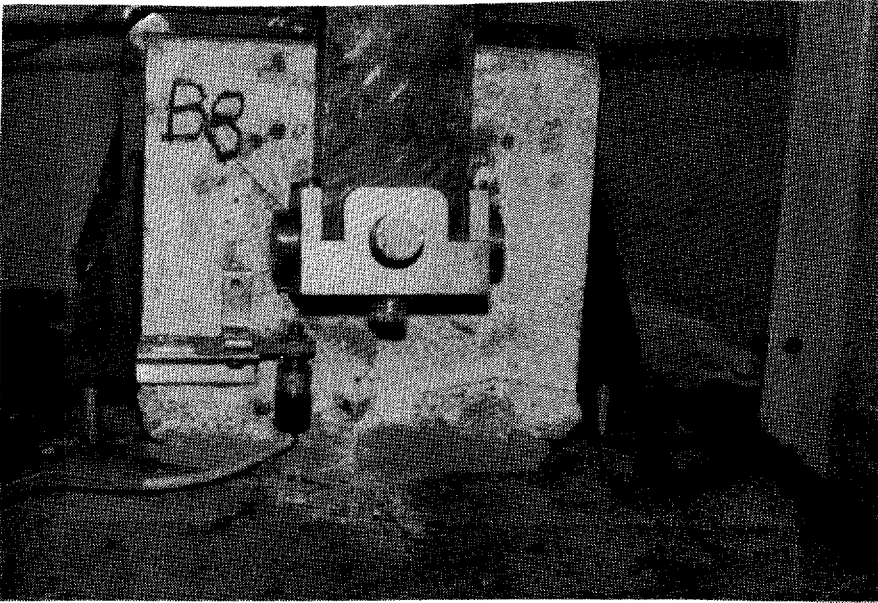
Figure 6. Photo of load collar and LVDT attachment.

The entire test operation was controlled by an IBM Personal Computer using a Data Translations DT-2801A Analog/Digital (A/D) board and a controlling program written in BASIC using the PCLAB library of A/D board control subroutines.(8) Figure 7 shows the entire test assembly arrangement.

The execution of the test control program produces a series of prompts requesting information concerning test specimen identification, design values, and test parameters, including magnitude and frequency of load, and timing, duration and frequency of data collection. Test initiation includes zeroing and calibrating the data collection channels and test operation allows the user to interrupt the test at any time, collect additional data at any time, and change certain test parameters, such as load cycle frequency.

Deflection and load data were typically collected during 10 load cycles immediately after the completion of 1, 2000, 5000, 20000, 100000, 300000 and 600000 load cycles. Extended test data was also collected after 1,200,000, 2,000,000 and 4,000,000 load cycles for certain specimens. Deflection and load data were collected 400 times per second (each) and stored on floppy disk with appropriate identification and test initiation data for later analysis. Data reduction programs were written and used to identify peak load, deflection, and dowel looseness conditions during each load cycle and average the results for each set of ten readings.

The reduced and summarized design and performance data was loaded into an SPSS database and a Lotus 1-2-3 spreadsheet for analysis, production of graphs, etc.(9,10)

3.2 LABORATORY STUDY RESULTS

3.2.1 Preliminary Results and Observations
Observations of the preparation and testing (and occasional failure) of the test specimens provided some insight into the performance of full-depth repairs.

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 will increase in the vicinity of the dowel, producing increased pavement and dowel deflections and increased bearing stresses. Since nylon dowel 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.

The electric-pneumatic drill was most acceptable in minimizing spalling, but the reduced impact energy resulted in a three to fourfold increase in the time required to drill each hole. The hydraulic drills provided a substantial reduction in spalling with no discernible increase in drilling time. The excessive spalling produced by the pneumatic drill was usually repaired easily by using the nylon dowel rings to retain the anchor material and the performance of these "repaired" specimens was equal to similar specimens prepared using other drills.

36
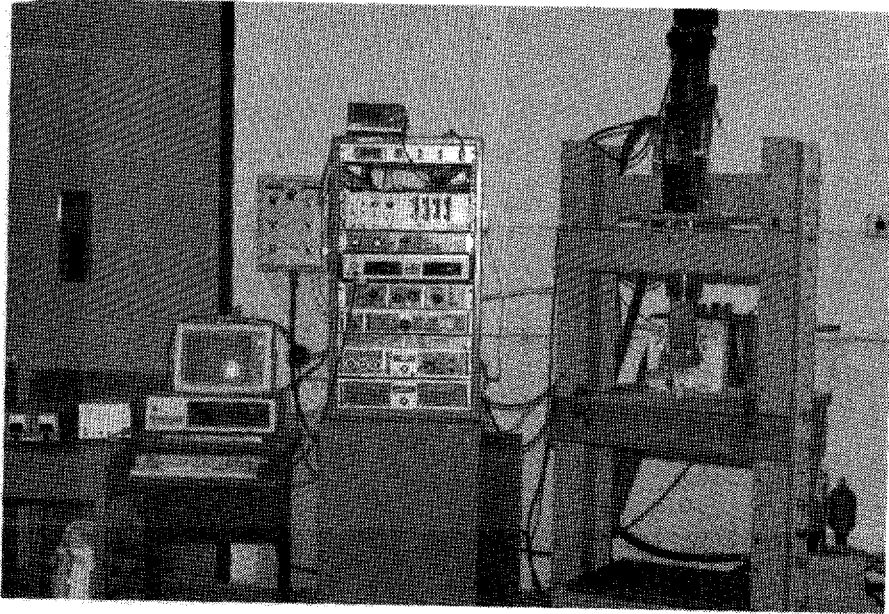
Figure 7. Repeated dowel load test assembly.

Consistency of Dowel Anchor Materials

The installation of dowels using cement grout was often difficult. Small batches of grout (sufficient for about four dowel installations) were carefully prepared in the lab to produce a "flowable" mix and appropriate quantities were delivered to the backs of the drilled holes. Specimens prepared immediately after mixing the grout received a grout that was almost "pourable," and retention of the grout was difficult, even using the nylon rings. Large voids were often observed around these dowels prior to testing (see figure 8) and their deflection profiles were often exaggerated. Specimens that were prepared around 5 minutes after the grout was mixed received a grout that was of the desired consistency, were found to have no voids (or only very small voids), and performed relatively well. Specimens that were prepared 10 minutes or more after mixing the grout received a very stiff grout that often compacted at the back of the hole, preventing proper installation of the dowels, rather than extruding out as the dowels were inserted. These specimens had to be cleaned out and grouted again using a more flowable grout.

The wide variation in grout consistency over a relatively short period of time in the highly controlled environment of the laboratory makes questionable the use of the same material in the field, where conditions can be much more harsh and quality control often takes a back seat to production. Field installations require a reliable, easy-to-use dowel installation material. Cement grout does not consistently meet these requirements.

The epoxy mortar used was almost always proportioned accurately and mixed thoroughly using a hand-held double-barrel caulking gun delivery system which produced a mortar that was the desired consistency. The mortar "set up" in about 5 minutes, which was more than enough time to install the dowel. 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.

The cost of the epoxy mortar is currently substantially higher than the cost of the cement grout, but the reliability and the uniform consistency of the epoxy should make it the preferred material.(3) Recently-developed epoxy delivery equipment using much larger cartridges and typical discounts for the purchase of large quantities should reduce the cost of the epoxy for field installations.

It should be noted that not all epoxy mortar materials perform like the one tested. Different "gel," "set" and cure times, and physical and chemical properties affect the suitability of a given material for pavement repair applications. Additional testing should be accomplished before using any unproven material.

Dowel Failures

Five of the 1-in [2.5 cm] diameter dowels tested experienced brittle fatigue failures at locations 0.75 to 1.5 in [1.9 to 3.8 cm] inside the face of the PCC specimens. This location corresponds approximately with the predicted point of maximum moment in the dowel (0.75 in [1.9 cm] inside the face), as presented by Friberg based on the work of Timoshenko.(11,12) Variations from the predicted location are probably due to nonuniform support of the dowel at the face due to spalling of the concrete during drilling and spalling of the cement grout mortar during testing due to high dowel bearing stress.

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.
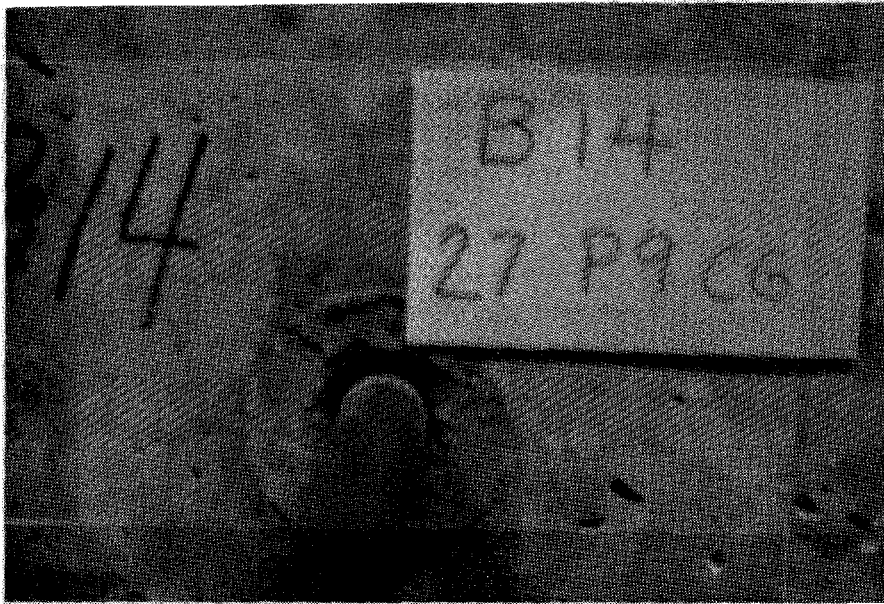
Figure 8. Photo of voids in cement grout anchor material.

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 Nylon Grout Retention Rings

The nylon 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" (e.g., using the cement grout about 5 minutes 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 resulted in these cases.

The use of the grout retention rings represented part of the effort to use the "best" repair preparation and construction techniques so that the maximum potential of each installation would be achieved. The use of these rings, therefore, also probably reduces the difference in performance that would have been observed between the two anchor materials and the three drill types if the rings hadn't been used. Based on initial observations, it would be expected that the elimination of the retention rings would result in much more variability of performance for the cement grout specimens. Higher deflections would be associated with more spalling around the drill hole, so better performance would be expected from holes drilled using low-impact energy drills.

3.2.2 Factors Affecting Dowel Deflection and Looseness

For the purposes of this study, dowel deflection refers to the dowel deflection (under an applied shear load of ±3000 pounds [13.4 kN]) measured using the LVDT attached to the load collar at a point approximately 1/2 in [1.3 cm] from the face of the specimen.

Dowel looseness was estimated by plotting measured dowel deflection vs. shear load and projecting the slopes of the loading and reverse loading portions of the load-deflection curve at ± 3000 pounds [13.4 kN] back to intercept the deflection axis. This technique was conceptualized by Teller and Cashell and is shown in figure 9.(6)

The half-fraction factorial experimental design employed in the lab tests allowed direct identification of significant effects through analysis of variance (ANOVA) techniques. Table 21 presents the analysis of variance computation sheet.

The six main variables of effects under consideration are number of load cycle repetitions, dowel bar diameter, annular gap, anchor material, embedment length, and drill type and these are referred to as effects 1 through 6, respectively. Interactions between effects are indicated by combinations of these numbers (e.g., the two-way interaction effect of load cycle applications, which is effect 1, and dowel diameter, which is effect 2, is called interaction effect 12). Since a half-fraction factorial experimental design was used, each computed main or interaction effect also represents a higher order interaction effect, or alias, which is listed below the primary effect being considered. As discussed previously,

40
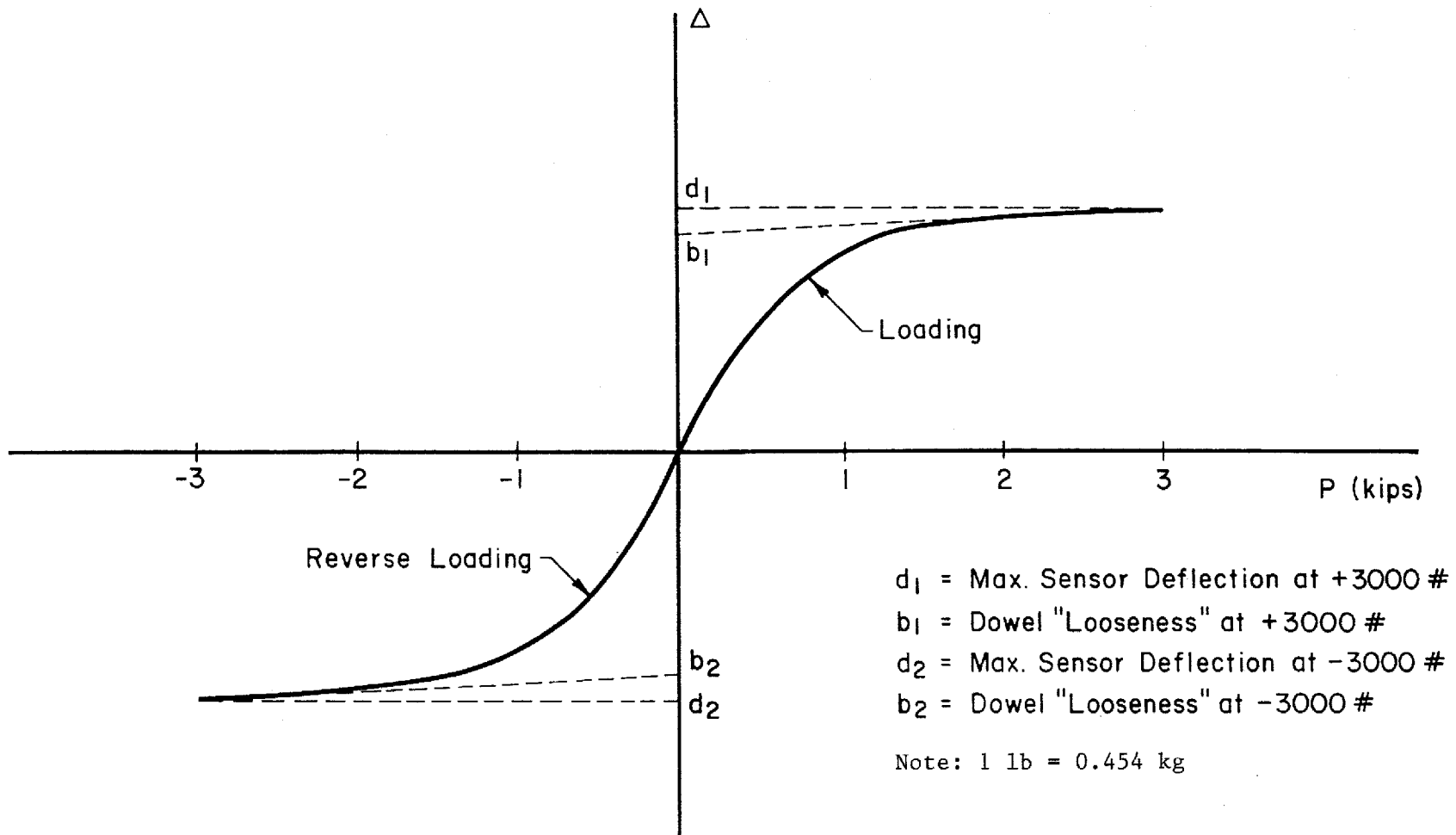
Figure 9. Illustration of estimation of dowel looseness from load-deflection curve. (47)

Table 21. Analysis of variance computation table.

Effect:	LOAD REPS 1 123456	DWLDIA 2 3456	ANNGAP 3 2456	ANKMATL 4 2356	EMBED 5 2346	DRLTYP 6=2345 2345	BMAXMIN	B-SE	DMAXMIN	D-SE
Level -1:	2000	1.0"	1/32"	OG	7"	Pneumatic				
Level +1:	100000	1.5"	1/8"	C10	9"	Electric				

Specimen

	LOAD REPS	DWLDIA	ANNGAP	ANKMATL	EMBED	DRLTYP	BMAXMIN	B-SE	DMAXMIN	D-SE
A18, B4	-1	-1	-1	-1	-1	1	14.45	3.08	20.04	1.73
	1	-1	-1	-1	-1	1	22.11	9.68	29.84	4.59
B20, C16	-1	1	-1	-1	-1	-1	1.64	0.49	5.88	1.38
	1	1	-1	-1	-1	-1	2.08	0.82	6.28	1.47
A20	-1	-1	1	-1	-1	-1	8.05		18.82	
	1	-1	1	-1	-1	-1	10.54		21.00	
A10, D5	-1	1	1	-1	-1	1	4.74	1.18	9.27	1.62
	1	1	1	-1	-1	1	5.88	0.87	10.10	1.75
C2, D8	-1	-1	-1	1	-1	-1	4.63	0.41	17.06	2.60
	1	-1	-1	1	-1	-1	8.76	1.15	17.38	1.38
B11R	-1	1	-1	1	-1	1	7.09		12.53	
	1	1	-1	1	-1	1	7.83		12.87	
A8	-1	-1	1	1	-1	1	15.61		26.80	
	1	-1	1	1	-1	1	19.63		31.12	
C7	-1	1	1	1	-1	-1	10.79		18.72	
	1	1	1	1	-1	-1	13.81		19.96	
A1	-1	-1	-1	-1	1	-1	7.80		15.00	
	1	-1	-1	-1	1	-1	9.06		16.39	
C21	-1	1	-1	-1	1	1	3.07		5.52	
	1	1	-1	-1	1	1	3.33		5.90	
A8R	-1	-1	1	-1	1	1	7.76		18.04	
	1	-1	1	-1	1	1	13.50		23.33	
C12, C20	-1	1	1	-1	1	-1	1.83	1.55	5.28	0.22
	1	1	1	-1	1	-1	3.01	4.95	5.47	0.52
C19, D10, D10R	-1	-1	-1	1	1	1	6.02	3.75	16.71	6.62
	1	-1	-1	1	1	1	8.96	4.70	17.13	6.53
A2, D19	-1	1	-1	1	1	-1	4.18	0.01	10.96	0.74
	1	1	-1	1	1	-1	4.95	0.12	11.07	0.86
B7, D18	-1	-1	1	1	1	-1	12.33	0.07	31.42	1.45
	1	-1	1	1	1	-1	17.43	2.41	32.53	1.04
A6R, B17 C3R	-1	1	1	1	1	1	6.56	0.51	19.79	4.32
	1	1	1	1	1	1	10.00	1.12	19.52	4.90

Effects:

	LOAD REPS	DWLDIA	ANNGAP	ANKMATL	EMBED	DRLTYP	BMAXMIN		DMAXMIN	
Bmaxmin:	2.77	-5.99	2.84	2.48	-2.37	2.23	8.67			
Dmaxmin:	1.75	-10.84	5.66	6.21	-1.48	1.58			16.62	

Table 21. Analysis of variance computation table (cont'd).

Effect:		12 13456	13 12456	14 12356	15 12346	16 12345	23 456	24 356	25 346	26 345	34 256

Level -1:
Level +1:

Specimen

		12 13456	13 12456	14 12356	15 12346	16 12345	23 456	24 356	25 346	26 345	34 256
A18, B4	73	1	1	1	1	-1	1	1	1	-1	1
	59	-1	-1	-1	-1	1	1	1	1	-1	1
B20, C16	38	-1	1	1	1	1	-1	-1	-1	-1	1
	47	1	-1	-1	-1	-1	-1	-1	-1	-1	1
A20		1	-1	1	1	1	-1	1	1	1	-1
		-1	1	-1	-1	-1	-1	1	1	1	-1
A10, D5	62	-1	-1	1	1	-1	1	-1	-1	1	-1
	75	1	1	-1	-1	1	1	-1	-1	1	-1
C2, D8	60	1	1	-1	1	1	1	-1	1	1	-1
	38	-1	-1	1	-1	-1	1	-1	1	1	-1
B11R		-1	1	-1	1	-1	-1	1	-1	1	-1
		1	-1	1	-1	1	-1	1	-1	1	-1
A8		1	-1	-1	1	-1	-1	-1	1	-1	1
		-1	1	1	-1	1	-1	-1	1	-1	1
C7		-1	-1	-1	1	1	1	1	-1	-1	1
		1	1	1	-1	-1	1	1	-1	-1	1
A1		1	1	1	-1	1	1	1	-1	1	1
		-1	-1	-1	1	-1	1	1	-1	1	1
C21		-1	1	1	-1	-1	-1	-1	1	1	1
		1	-1	-1	1	1	-1	-1	1	1	1
A8R		1	-1	1	-1	-1	-1	1	-1	-1	-1
		-1	1	-1	1	1	-1	1	-1	-1	-1
C12, C20	22	-1	-1	1	-1	1	1	-1	1	-1	-1
	52	1	1	-1	1	-1	1	-1	1	-1	-1
C19, D10,	62	1	1	-1	-1	-1	1	-1	-1	-1	-1
D10R	53	-1	-1	1	1	1	1	-1	-1	-1	-1
A2, D19	74	-1	1	-1	-1	1	-1	1	1	-1	-1
	86	1	-1	1	1	-1	-1	1	1	-1	-1
B7, D18	45	1	-1	-1	-1	1	-1	-1	-1	1	1
	04	-1	1	1	1	-1	-1	-1	-1	1	1
A6R, B17	32	-1	-1	-1	-1	-1	1	1	1	1	1
C3R	90	1	1	1	1	1	1	1	1	1	1

Effects:

	12	13	14	15	16	23	24	25	26	34
Bmaxmin:	-1.40	0.50	0.25	-0.18	0.47	-0.04	2.47	0.25	-1.45	3.87
Dmaxmin:	-1.35	0.11	-0.80	-0.68	0.89	-1.03	2.75	-0.04	-0.10	4.86

Table 21.   Analysis of variance computation table (cont'd).

Effect:	35 246	36 245	45 236	46 235	56 234	123 1456	124 1356	125 1346	126 1345	134 1256
Level -1:										
Level +1:										
Specimen										
A18, B4	1	-1	1	-1	-1	-1	-1	-1	1	-1
	1	-1	1	-1	-1	1	1	1	-1	1
B20, C16	1	1	1	1	1	1	1	1	1	-1
	1	1	1	1	1	-1	-1	-1	-1	1
A20	-1	-1	1	1	1	1	-1	-1	-1	1
	-1	-1	1	1	1	-1	1	1	1	-1
A10, D5	-1	1	1	-1	-1	-1	1	1	-1	1
	-1	1	1	-1	-1	1	-1	-1	1	-1
C2, D8	1	1	-1	-1	1	-1	1	-1	-1	1
	1	1	-1	-1	1	1	-1	1	1	-1
B11R	1	-1	-1	1	-1	1	-1	1	-1	1
	1	-1	-1	1	-1	-1	1	-1	1	-1
A8	-1	1	-1	1	-1	1	1	-1	1	-1
	-1	1	-1	1	-1	-1	-1	1	-1	1
C7	-1	-1	-1	-1	1	-1	-1	1	1	-1
	-1	-1	-1	-1	1	1	1	-1	-1	1
A1	-1	1	-1	1	-1	-1	-1	1	-1	-1
	-1	1	-1	1	-1	1	1	-1	1	1
C21	-1	-1	-1	-1	1	1	1	-1	-1	-1
	-1	-1	-1	-1	1	-1	-1	1	1	1
A8R	1	1	-1	-1	1	1	-1	1	1	1
	1	1	-1	-1	1	-1	1	-1	-1	-1
C12, C20	1	-1	-1	1	-1	-1	1	-1	1	1
	1	-1	-1	1	-1	1	-1	1	-1	-1
C19, D10	-1	-1	1	1	1	-1	1	1	1	1
D10R	-1	-1	1	1	1	1	-1	-1	-1	-1
A2, D19	-1	1	1	-1	-1	1	-1	-1	1	1
	-1	1	1	-1	-1	-1	1	1	-1	-1
B7, D18	1	-1	1	-1	-1	1	1	1	-1	-1
	1	-1	1	-1	-1	-1	-1	-1	1	1
A6R, B17	1	1	1	1	1	-1	-1	-1	-1	-1
C3R	1	1	1	1	1	1	1	1	1	1
Effects:										
Bmaxmin:	0.29	-1.49	0.15	-1.63	-2.40	0.33	0.37	0.22	-0.45	0.38
Dmaxmin:	1.42	-0.98	1.81	-1.91	-1.85	-0.01	0.76	0.38	-0.97	0.54

Table 21. Analysis of variance computation table (cont'd).

Effect:

	135 1246	136 1245	145 1236	146 1235	156 1234
Level -1:					
Level +1:					

Specimen

Specimen	135 1246	136 1245	145 1236	146 1235	156 1234
A18, B4	-1	1	-1	1	1
	1	-1	1	-1	-1
B20, C16	-1	-1	-1	-1	-1
	1	1	1	1	1
A20	1	1	-1	-1	-1
	-1	-1	1	1	1
A10, D5	1	-1	-1	1	1
	-1	1	1	-1	-1
C2, D8	-1	-1	1	1	-1
	1	1	-1	-1	1
B11R	-1	1	1	-1	1
	1	-1	-1	1	-1
A8	1	-1	1	-1	1
	-1	1	-1	1	-1
C7	1	1	1	1	-1
	-1	-1	-1	-1	1
A1	1	-1	1	-1	1
	-1	1	-1	1	-1
C21	1	1	1	1	-1
	-1	-1	-1	-1	1
A8R	-1	-1	1	1	-1
	1	1	-1	-1	1
C12, C20	-1	1	1	-1	1
	1	-1	-1	1	-1
C19, D10, D10R	1	1	-1	-1	-1
	-1	-1	1	1	1
A2, D19	1	-1	-1	1	1
	-1	1	1	-1	-1
B7, D18	-1	1	-1	1	1
	1	-1	1	-1	-1
A6R, B17 C3R	-1	-1	-1	-1	-1
	1	1	1	1	1

Effects:

	135 1246	136 1245	145 1236	146 1235	156 1234
Bmaxmin:	0.78	-0.15	0.23	-0.71	0.04
Dmaxmin:	0.39	-0.20	0.07	-0.63	-0.51

the higher order interaction effects are generally assumed to be insignificant, so the computed effect values are assumed to represent the primary effects being considered.

In each effect <u>column</u>, the presence of a 1 or a -1 indicates that the specimen being described in that <u>row</u> was tested at either a high level (1) or a low level (-1) for the given effect. The high and low levels selected for the main effects are described near the top of their respective columns. Thus, the test configuration of each specimen is described completely in the first seven columns of table 21. The next four columns contain the average computed total dowel looseness from 3000 lb [13.4 kN] loading to 3000 lb [13.4 kN] reverse loading (BMAXMIN), the standard deviation of that number (B-SE), the average measured total dowel deflection from 3000 lb [13.4 kN] loading to 3000 lb [13.4 kN] reverse loading (DMAXMIN), and the standard deviation of that number (D-SE) for each specimen configuration.

The computed values of each main or interaction effect on BMAXMIN and DMAXMIN is tabulated at the bottom of each column and is computed by summing the products of each 1 or -1 value with the value of BMAXMIN or DMAXMIN in the same row. A positive value suggests a positive relationship between the variable or variable combination and the predicted response. A negative value indicates an inverse relationship. A value of zero indicates that no relationship exists.

Nonzero effects that are due to random variation will be normally distributed and, when ranked according to relative magnitude, should plot on probability paper approximately as a straight line. Effects that do not lie on this line may be significant and should be investigated further. This approach is shown in table 22 and figure 10 for measured sensor deflection (DMAXMIN) and in table 23 and figure 11 for computed dowel looseness (BMAXMIN).

These tables and figures suggest that all of the main variables may significantly affect the development of dowel looseness and sensor deflection and sensor deflection as follows:

<u>Variable Changed</u>	<u>Effect on Deflection/Looseness</u>
Increasing Dowel Diameter	Decrease
Increasing Dowel Embedment	Decrease
Increasing Drill Impact Energy	Decrease
Epoxy Anchor Material (Instead of Cement Grout)	Increase
Increase Annular Gap	Increase
Increase Load Repetitions	Increase

These variables all affect dowel deflection and looseness as expected, with the exception of the effect of drill impact energy. As discussed previously, it is believed that the use of the nylon grout retention rings may have reduced (or eliminated) the effect of spalling caused by the use of high impact energy drills. Since the low impact energy drill was guided but hand-held, the apparent increase in dowel deflection could be due to slight increases in actual drilled hole diameter (which must be filled with a grout that is softer than the surrounding concrete).

Several significant two-factor interactions were also noted, including drill impact energy and dowel embedment length, anchor material and drill impact energy, anchor material and dowel diameter (bearing stress), and anchor material and annular

Table 22 Summary of ANOVA data for sensor deflection
(all specimens).

Rank	Plot	Dmaxmin	Effect		Alias
1	1.61	-10.84	DWLDIA	2	3456
2	4.84	-1.91		46	235
3	8.06	-1.85		56	234
4	11.29	-1.48	EMBED	5	2346
5	14.52	-1.03		23	456
6	17.74	-0.98		36	245
7	20.97	-0.97		126	1345
8	24.19	-0.80		14	12356
9	27.42	-0.68		15	12346
10	30.65	-0.63		146	1235
11	33.87	-0.51		156	1234
12	37.10	-0.20		136	1245
13	40.32	-0.10		26	345
14	43.55	-0.04		25	346
15	46.77	-0.01		123	1456
16	50.00	0.00		12	13456
17	53.23	0.07		145	1236
18	56.45	0.11		13	12456
19	59.68	0.38		125	1346
20	62.90	0.39		135	1246
21	66.13	0.54		134	1256
22	69.35	0.76		124	1356
23	72.58	0.89		16	12345
24	75.81	1.42		35	246
25	79.03	1.58	DRLTYP	6=2345	2345
26	82.26	1.75	LOAD REPS	1	123456
27	85.48	1.81		45	236
28	88.71	2.75		24	356
29	91.94	4.86		34	256
30	95.16	5.66	ANNGAP	3	2456
31	98.39	6.21	ANKMATL	4	2356

47
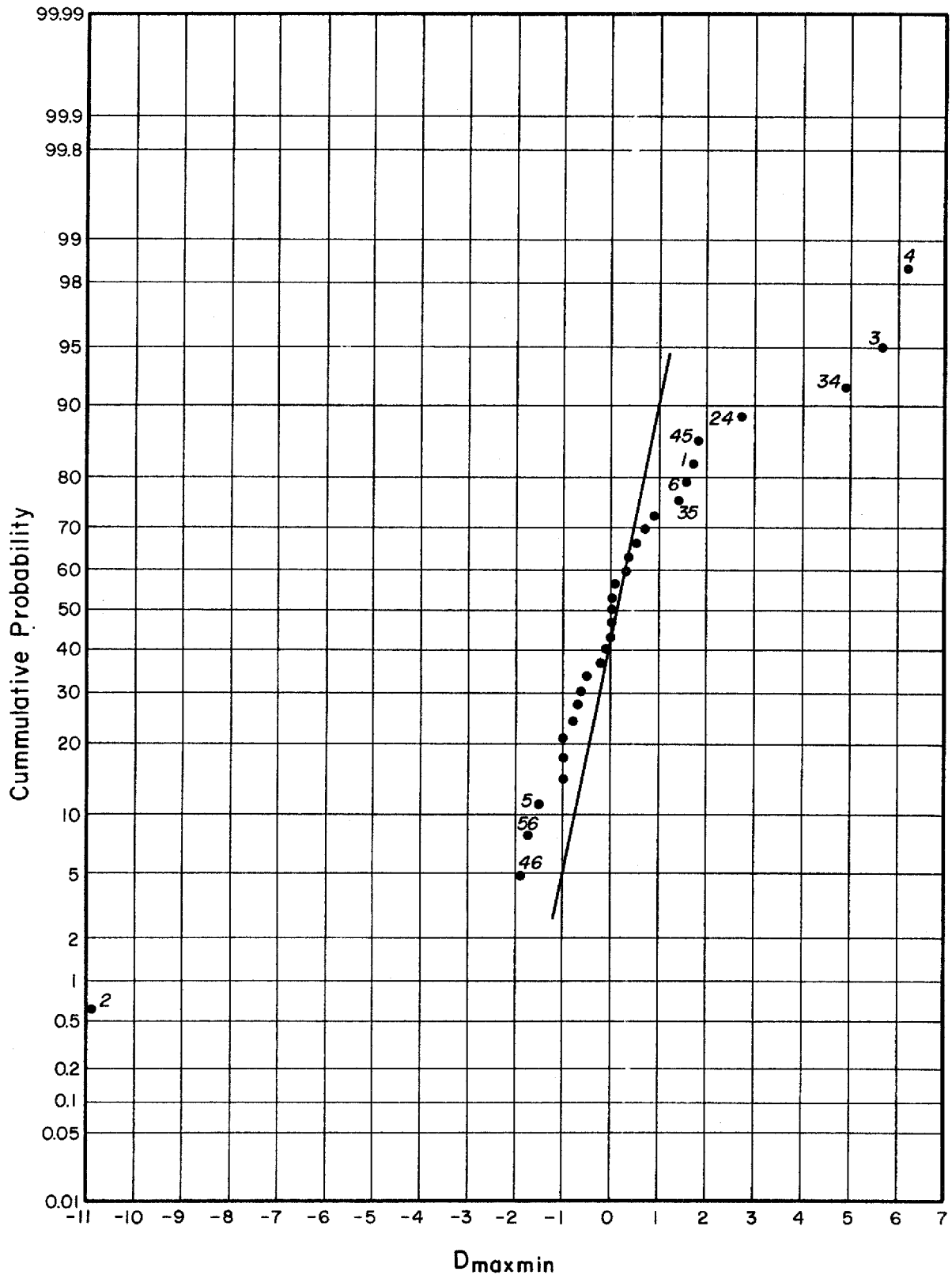
Figure 10. Plot of ANOVA data for sensor deflection (all specimens).

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Table 23 Summary of ANOVA data for dowel looseness
(all specimens).

Rank	Plot	Bmaxmin	Effect		Alias
1	1.61	-5.99	DWLDIA	2	3456
2	4.84	-2.40		56	234
3	8.06	-2.37	EMBED	5	2346
4	11.29	-1.63		46	235
5	14.52	-1.49		36	245
6	17.74	-1.45		26	345
7	20.97	-1.40		12	13456
8	24.19	-0.71		146	1235
9	27.42	-0.45		126	1345
10	30.65	-0.18		15	12346
11	33.87	-0.15		136	1245
12	37.10	-0.04		23	456
13	40.32	0.04		156	1234
14	43.55	0.15		45	236
15	46.77	0.22		125	1346
16	50.00	0.23		145	1236
17	53.23	0.25		25	346
18	56.45	0.25		14	12356
19	59.68	0.29		35	246
20	62.90	0.33		123	1456
21	66.13	0.37		124	1356
22	69.35	0.38		134	1256
23	72.58	0.47		16	12345
24	75.81	0.50		13	12456
25	79.03	0.78		135	1246
26	82.26	2.23	DRLTYP	6=2345	2345
27	85.48	2.47		24	356
28	88.71	2.48	ANKMATL	4	2356
29	91.94	2.77	LOAD REPS	1	123456
30	95.16	2.84	ANNGAP	3	2456
31	98.39	3.87		34	256

49
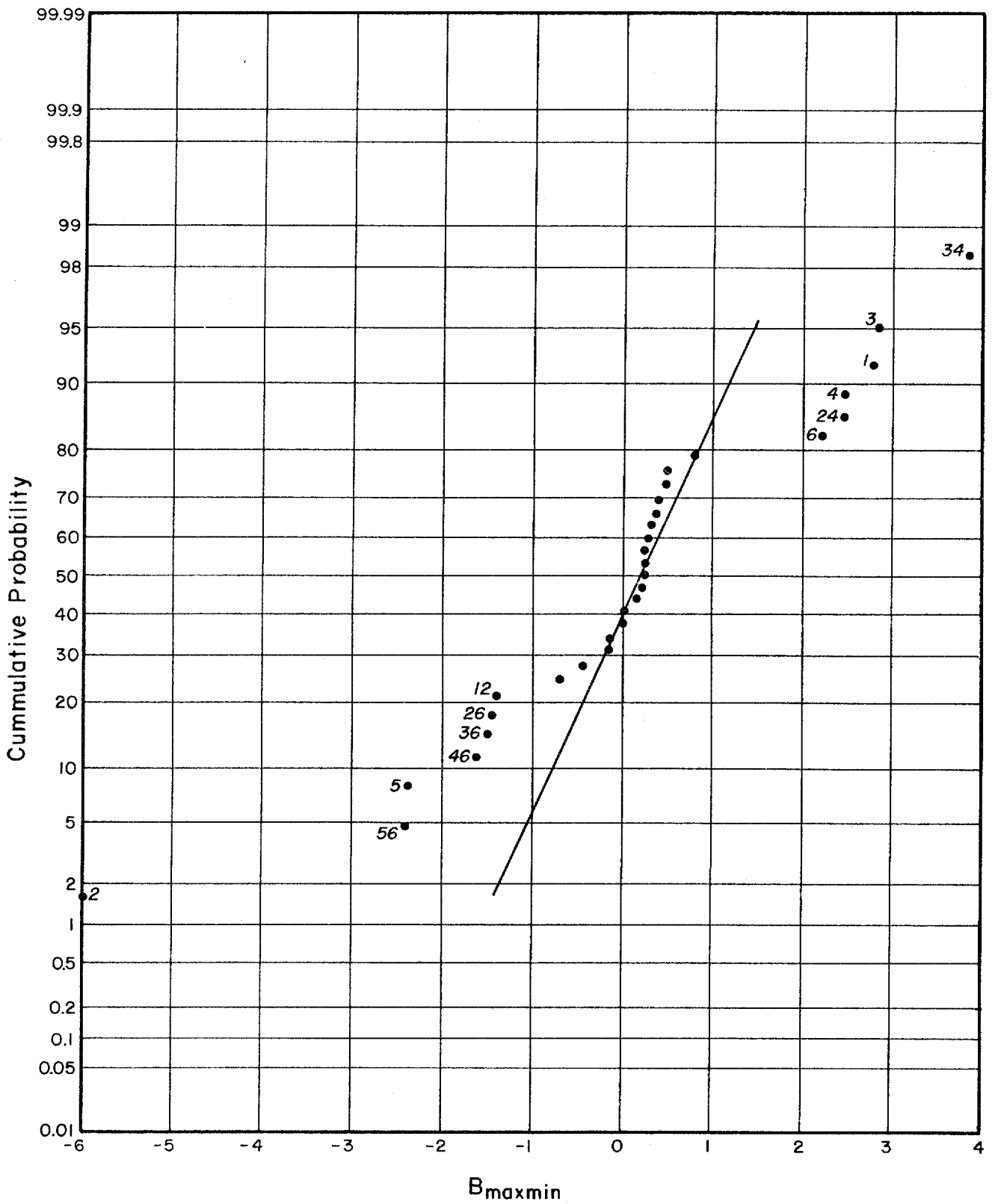
Figure 11. Plot of ANOVA data for dowel looseness (all specimens).

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gap. Since many of these two-factor interactions indicated a strong relationship between anchor material and some other variable, the database was subdivided according to anchor material and an analysis of variance was conducted for each of the new data sets. Tables 24 through 27 present the ranked ANOVA results for each anchor material set as they affect DMAXMIN and BMAXMIN. Clearly, the main effects are still among the most significant in each of the anchor material database subsets. Performance models were developed for each of these data sets.

The strength of the main effects and the significance of several two-factor interaction effects point to additional conclusions concerning the stiffness of the anchor materials. Since the cement grout is more rigid than the epoxy mortar, the effects (and interaction effects) of dowel diameter (bearing stress) 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 it becomes easier to install the bar in a stiffer grout, which provides more uniform dowel support.

Since the epoxy mortar is a softer material than either the cement grout or the concrete specimen, the deflections of bars embedded in this material are more sensitive to dowel diameter (bearing stress) and embedment, with increases in either resulting in decreased deflections. As annular gap increased, deflections generally increased as well due to the use of larger volumes of softer material. Since the epoxy mortar was always delivered at a uniform consistency that allowed easy insertion of the dowels, there is no apparent need (for installation purposes) for a large annular gap, as with the cement grout. It may be appropriate to use epoxy mortar with the smallest annular gap that will allow dowel installation without excessive force. This would allow the mortar to fill voids and spalls using a minimum thickness of the softer material and allowing the bar to be supported directly by the concrete in many places. Additional research should be conducted to verify this.

3.2.3 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 the accuracy of the models. 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:

$$B_{maxmin} = 34840\,(AG) + 1167\,(CT)^{1.058} - 9.899\,(EB)^{1.160}$$
$$+ 1.079\,(BS) - 0.6912\,(EN)^{1.831} + 8380$$

Statistics:
$$R^2 = 0.594$$
$$COV = 36.9\%$$
$$n = 178$$

$$D_{maxmin} = 54210\,(AG) + 643.3\,(CT) - 2117\,(EB)$$
$$+ 2.031\,(BS) - 8.822\,(EB)(EN) + 21210$$

Table 24   Summary of ANOVA data for sensor deflection
(cement grout specimens).

Rank	Plot	Dmaxmin	Effect		Alias
1	1.61	-27.02	ANKMATL	4	2356
2	4.84	-13.60	DWLDIA	2	3456
3	8.06	-3.49		46	235
4	11.29	-3.29	EMBED	5	2346
5	14.52	-2.56		14	12356
6	17.74	-1.52		26	345
7	20.97	-1.52		146	1235
8	24.19	-1.36		126	1345
9	27.42	-0.95		36	245
10	30.65	-0.83		56	234
11	33.87	-0.81		34	256
12	37.10	-0.75		15	12346
13	40.32	-0.58		136	1245
14	43.55	-0.50		156	1234
15	46.77	-0.44		13	12456
16	50.00	0.00		12	13456
17	53.23	0.44		134	1256
18	56.45	0.50		123	1456
19	59.68	0.58		125	1346
20	62.90	0.75		145	1236
21	66.13	0.81	ANNGAP	3	2456
22	69.35	0.83		23	456
23	72.58	0.95		25	346
24	75.81	1.36		135	1246
25	79.03	1.52		16	12345
26	82.26	1.52		35	246
27	85.48	2.11		124	1356
28	88.71	2.56	LOAD REPS	1	123456
29	91.94	3.29		45	236
30	95.16	3.49	DRLTYP	6=2345	2345
31	98.39	13.60		24	356

Table 25 Summary of ANOVA data for dowel looseness
(cement grout specimens).

Rank	Plot	Bmaxmin	Effect		Alias
1	1.61	-14.86	ANKMATL	4	2356
2	4.84	-8.46	DWLDIA	2	3456
3	8.06	-3.85		46	235
4	11.29	-2.52		14	12356
5	14.52	-2.52	EMBED	5	2346
6	17.74	-2.36		56	234
7	20.97	-1.77		12	13456
8	24.19	-1.74		36	245
9	27.42	-1.74		26	345
10	30.65	-1.23		126	1345
11	33.87	-1.18		146	1235
12	37.10	-1.03	ANNGAP	3	2456
13	40.32	-0.41		15	12346
14	43.55	-0.38		136	1245
15	46.77	-0.29		156	1234
16	50.00	-0.12		134	1256
17	53.23	0.12		13	12456
18	56.45	0.29		123	1456
19	59.68	0.38		125	1346
20	62.90	0.41		145	1236
21	66.13	1.03		34	256
22	69.35	1.18		16	12345
23	72.58	1.23		135	1246
24	75.81	1.74		35	246
25	79.03	1.74		25	346
26	82.26	1.77		124	1356
27	85.48	2.36		23	456
28	88.71	2.52		45	236
29	91.94	2.52	LOAD REPS	1	123456
30	95.16	3.85	DRLTYP	6=2345	2345
31	98.39	8.46		24	356

Table 26   Summary of ANOVA data for sensor deflection
(epoxy mortar specimens).

Rank	Plot	Dmaxmin	Effect		Alias
1	1.61	-8.09		24	356
2	4.84	-8.09	DWLDIA	2	3456
3	8.06	-2.88		56	234
4	11.29	-2.88		23	456
5	14.52	-1.02		25	346
6	17.74	-1.02		36	245
7	20.97	-0.61		15	12346
8	24.19	-0.61		145	1236
9	27.42	-0.59		124	1356
10	30.65	-0.57		135	1246
11	33.87	-0.57		126	1345
12	37.10	-0.52		156	1234
13	40.32	-0.52		123	1456
14	43.55	-0.33	DRLTYP	6=2345	2345
15	46.77	-0.33		46	235
16	50.00	0.00		12	13456
17	53.23	0.17		136	1245
18	56.45	0.17		125	1346
19	59.68	0.25		16	12345
20	62.90	0.25		146	1235
21	66.13	0.34	EMBED	5	2346
22	69.35	0.34		45	236
23	72.58	0.65		134	1256
24	75.81	0.65		13	12456
25	79.03	0.95		14	12356
26	82.26	0.95	LOAD REPS	1	123456
27	85.48	1.33		26	345
28	88.71	1.33		35	246
29	91.94	10.52		34	256
30	95.16	10.52	ANNGAP	3	2456
31	98.39	39.45	ANKMATL	4	2356

Table 27 Summary of ANOVA data for dowel looseness
          (epoxy mortar specimens).

Rank	Plot	Bmaxmin	Effect		Alias
1	1.61	-3.52		24	356
2	4.84	-3.52	DWLDIA	2	3456
3	8.06	-2.44		56	234
4	11.29	-2.44		23	456
5	14.52	-2.22	EMBED	5	2346
6	17.74	-2.22		45	236
7	20.97	-1.24		36	245
8	24.19	-1.24		25	346
9	27.42	-1.17		26	345
10	30.65	-1.17		35	246
11	33.87	-1.03		124	1356
12	37.10	-1.03		12	13456
13	40.32	-0.24		16	12345
14	43.55	-0.24		146	1235
15	46.77	0.04		145	1236
16	50.00	0.04		15	12346
17	53.23	0.07		125	1346
18	56.45	0.07		136	1245
19	59.68	0.33		126	1345
20	62.90	0.33		135	1246
21	66.13	0.36		156	1234
22	69.35	0.36		123	1456
23	72.58	0.60		46	235
24	75.81	0.60	DRLTYP	6=2345	2345
25	79.03	0.87		13	12456
26	82.26	0.87		134	1256
27	85.48	3.02	LOAD REPS	1	123456
28	88.71	3.02		14	12356
29	91.94	6.72		34	256
30	95.16	6.72	ANNGAP	3	2456
31	98.39	19.82	ANKMATL	4	2356

Statistics: R^2 = 0.584
                    COV = 28.7%
                    n   = 178

where:

B_{maxmin} = Total dowel looseness (as defined previously), mils

D_{maxmin} = Total sensor deflection (as defined previously), mils

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

EN   = Estimated drill impact energy, ft-lbs/blow

Figures 12 through 15 illustrate the sensitivity of the deflection model to the input parameters. The sensitivity of the "looseness" model is similar, although it is subject to some interpretation since it is a computed (rather than measured) response.

Figure 12 illustrates the relatively large effect of annular gap and the comparatively small effect of number of load applications on dowel deflection when the epoxy mortar was used. 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 13 further defines the response of the epoxy mortar to applied loads by showing the expected total vertical dowel movement for several values of dowel bearing stress for each of the annular gap values tested. The predicted behavior is linear because of the form of the equation, which in turn reflects the fact that only two levels of bearing stress were examined. Additional data may produce a nonlinear relationship, but the overall indicated effect of increased bearing stress is likely to be similar. This model predicts dowel deflection increases of 60-100 percent or bearing stress increases from 1000 psi to 5000 psi [6.9 to 34.5 MPa].

Figure 14 shows that the flexibility of the epoxy mortar results in increased sensitivity to dowel embedment length because the mortar allows the dowel to deflect slightly inside of the drilled hole, whereas the cement grout has the potential to hold the bar rigidly. The increased deflection that results from decreasing embedment length from 9 to 7 in [23 cm to 18 cm] is approximately 10 percent and is probably not critical. It should be emphasized that the deflection of the bar within the drilled hole is probably due to the flexibility of the material; there is no reason to believe that the epoxy deteriorates within the drilled hole when no deterioration was observed at the joint face where stresses are highest.

Figure 15 shows the unexpected prediction of higher deflections with lower drill impact energy. As discussed before, it is believed that the grout retention rings masked the true effect of drill impact energy by filling the joint face spalls with

Predicted Deflection Range
9" Embed, 1" Dowel, Med Energy Drill

Dmax – Dmin (0.001 in)

[1 in = 2.54 cm]

Load Cycles (millions)

—■— 1/32" Annular Gap   —+— 1/8" Annular Gap
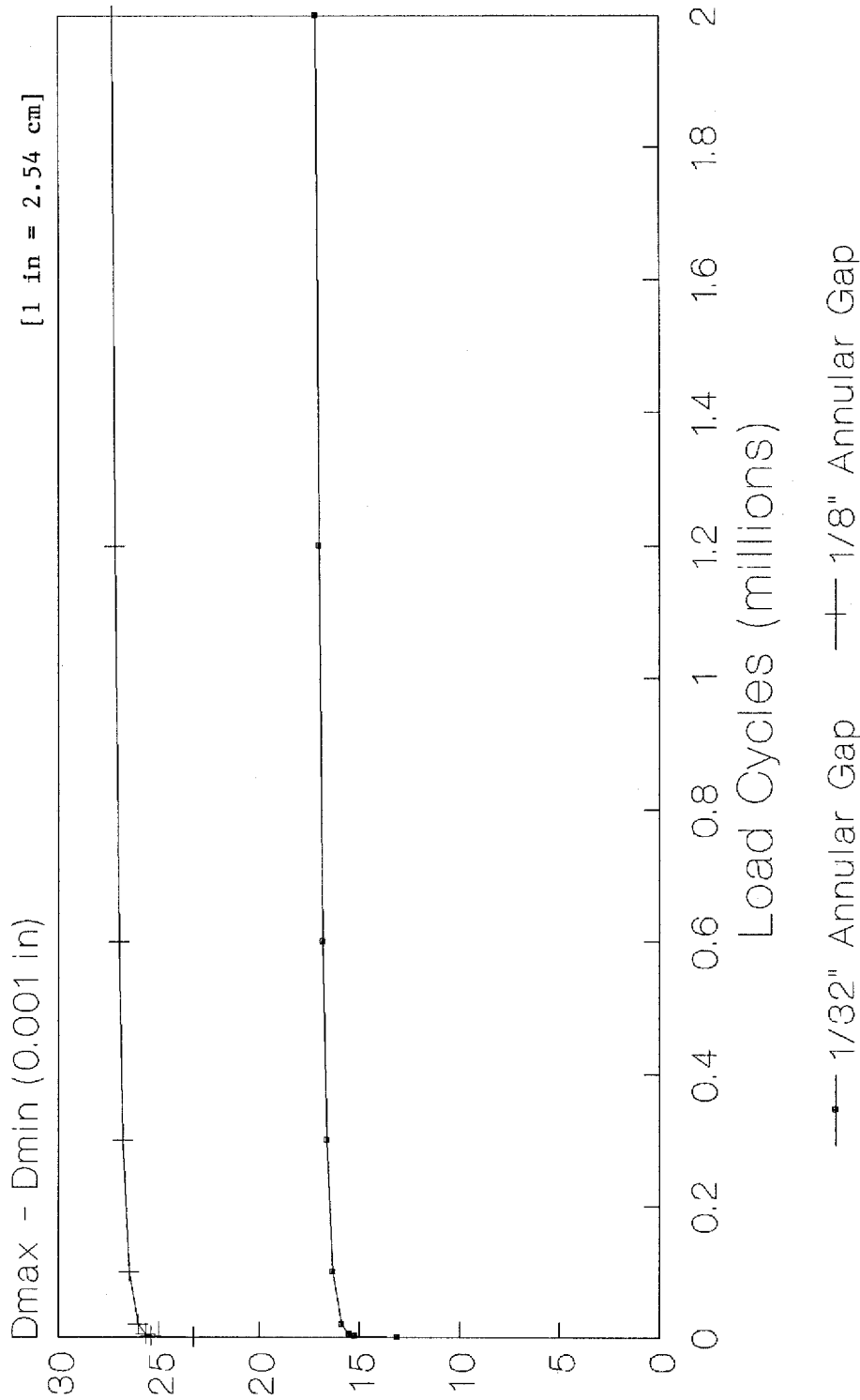
Figure 12.   Predicted effect of annual gap and load cycles on sensor deflection of epoxy mortar specimens with 1-in [2.5-cm] dowels and 9 in [23 cm] of embedment.

Pedicted Deflection Range
N=600000, 9" Embed, Med Energy Drill

Dmax – Dmin (0.001 in)

[1 in = 2.54 cm, 1 psi = 0.0069 MPa]

Bearing Stress (psi)

── 1/32" Annular Gap   ─┼─ 1/8" Annular Gap
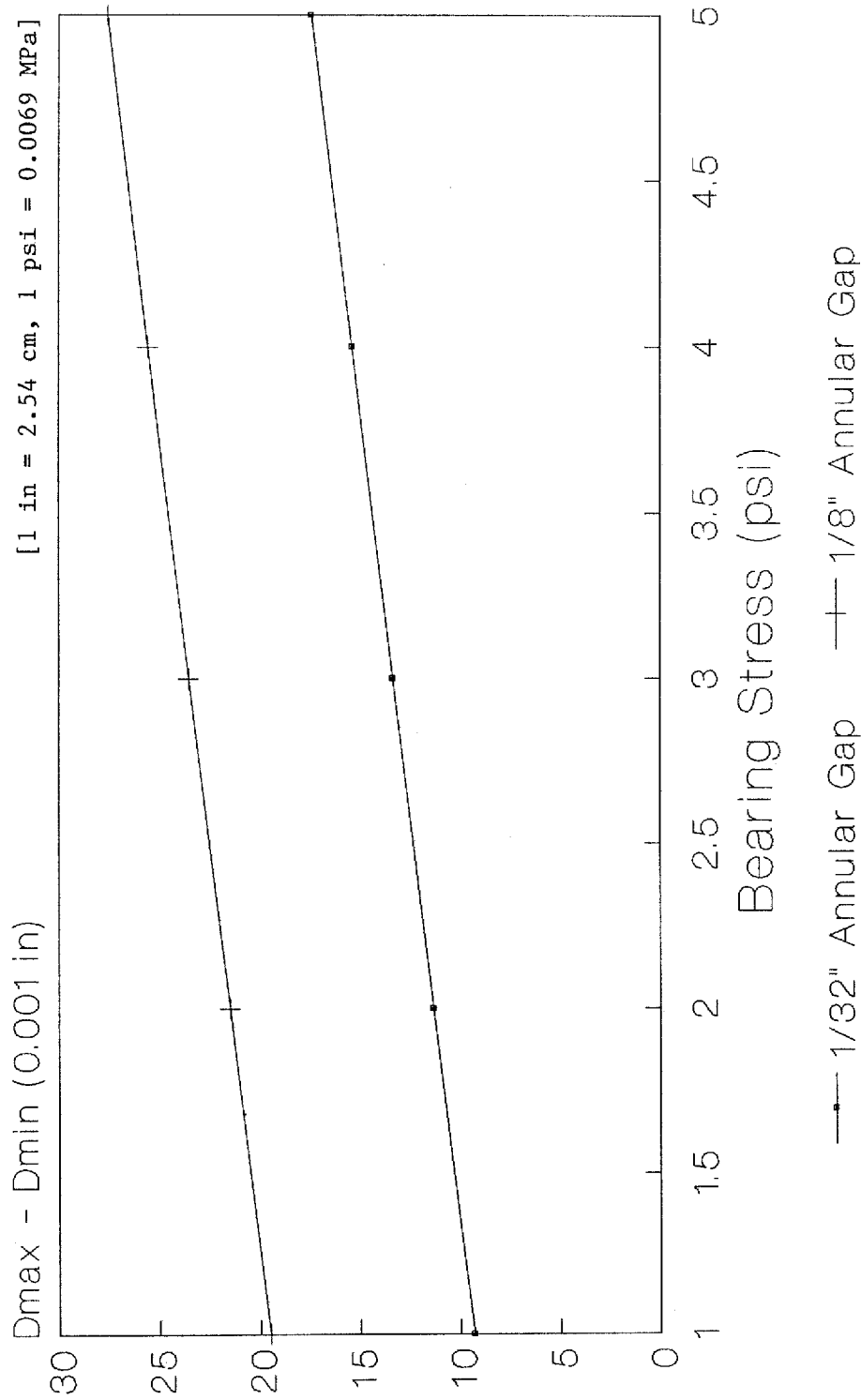
Figure 13. Predicted effect of annual gap and bearing stress on sensor deflection of epoxy mortar specimens with 9 in [23 cm] of embedment after 600,000 load cycles.

Predicted Deflection Range
N=600000, 1" Dowel, Med Energy Drill

Dmax - Dmin (0.001 in)

Dowel Embedment, in [1 in = 2.54 cm]

—■— 1/32" Annular Gap   —+— 1/8" Annular Gap
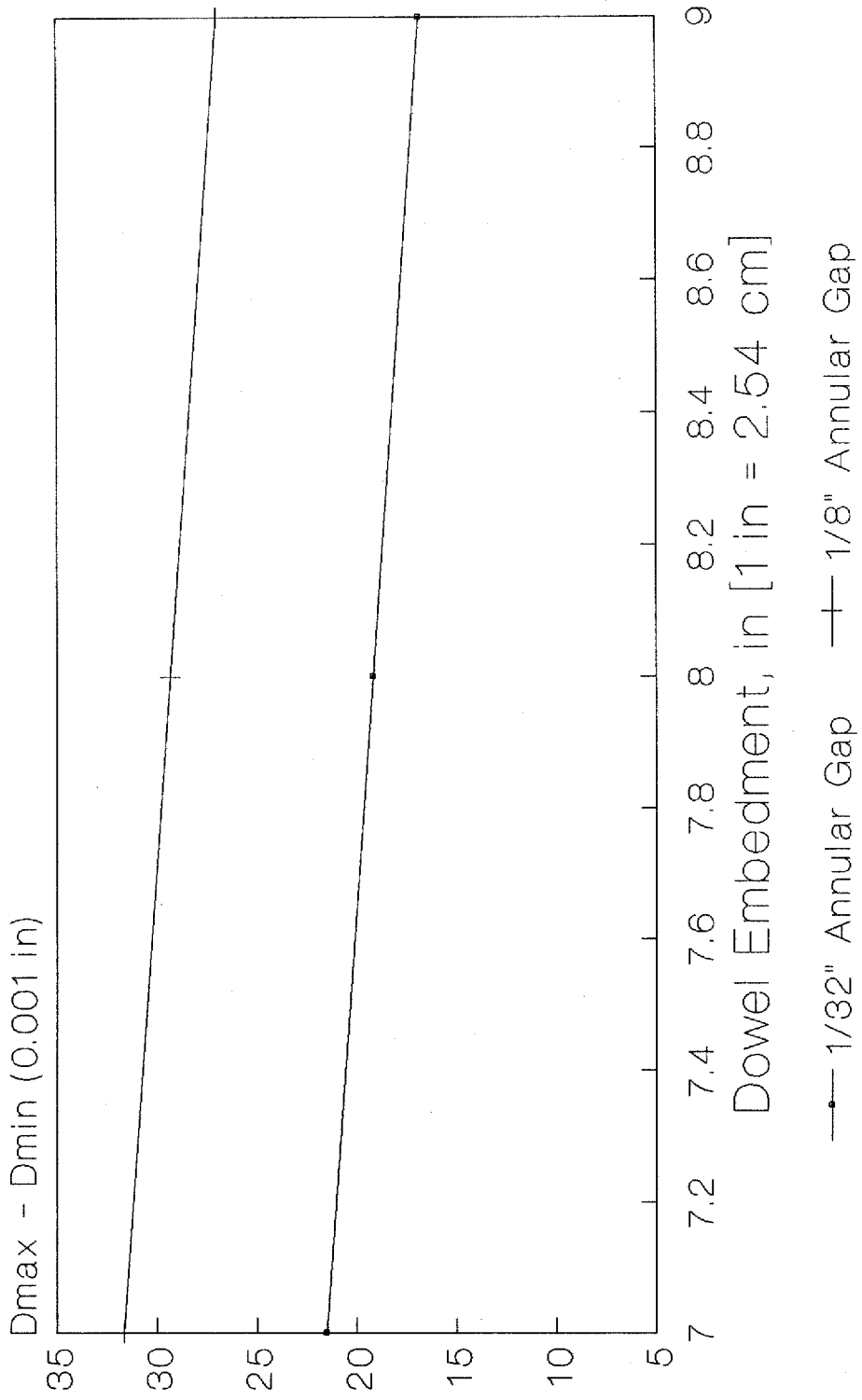
Figure 14.   Predicted effect of annual gap and embedment length on sensor deflection for epoxy mortar specimens.

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Predicted Deflection Range
N=600000, 1 in Dowel, 9 in Embed

Dmax – Dmin (0.001 in)

[1 in = 2.54 cm, 1 ft-lb = 1.357 N-m]

Drill Energy (ft-lbs/blow)
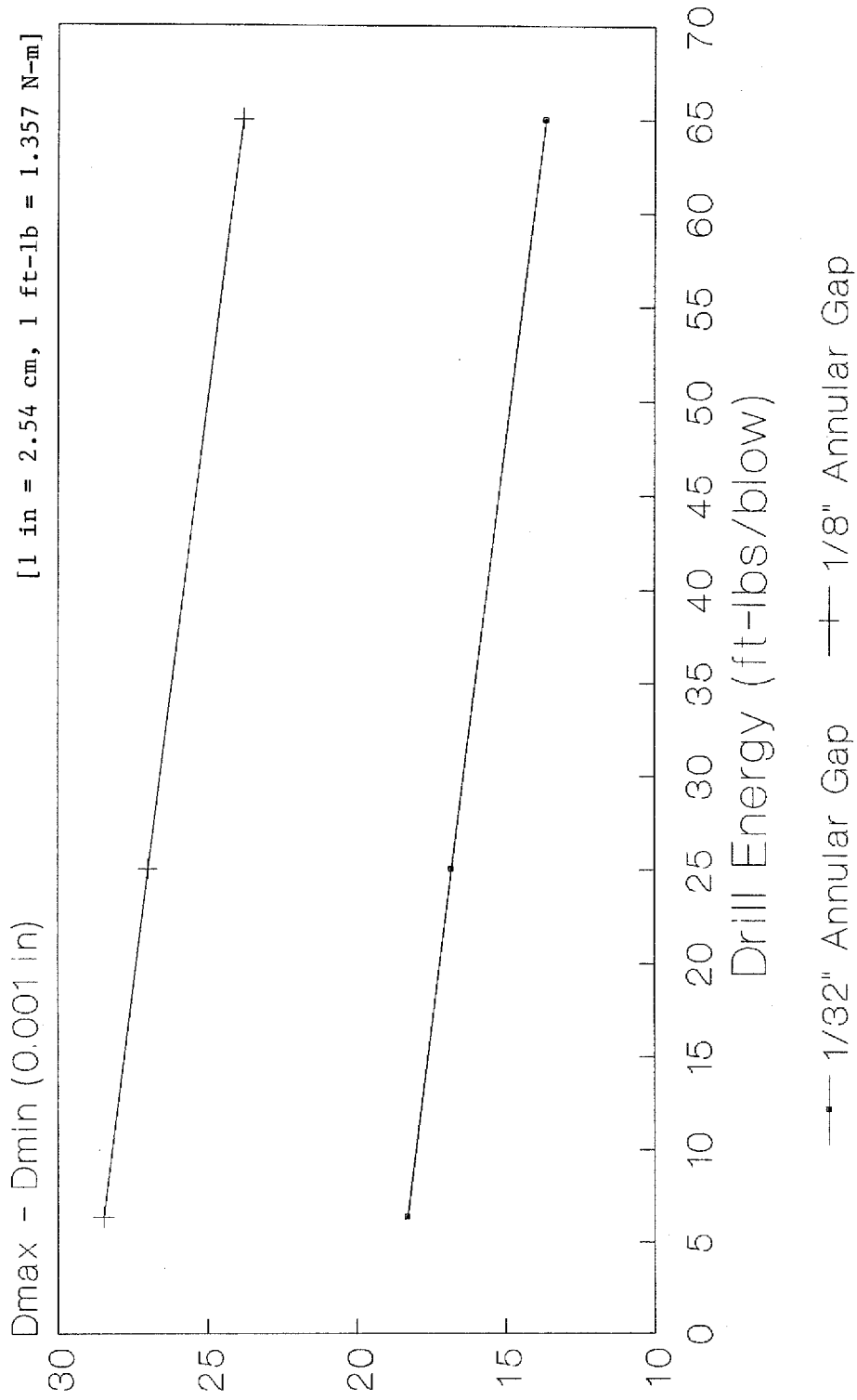
—■— 1/32" Annular Gap   —+— 1/8" Annular Gap

Figure 15. Predicted effect of annual gap and drill energy on sensor deflection for epoxy mortar specimens.

anchor material and reducing all deflections significantly. The effect presented in figure 15 may be due to the use of different drill guide systems for each drill, resulting in more variable drilled hole diameters and shapes.

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

$$B_{maxmin} = [\; CT \; (\; -2347 + BS \; (\; 0.762 + 2.604 / EN) \;)$$

$$+ 3883 \;] \; / \; 1000$$

Statistics: R^2 = 0.647
COV = 61.2%
n = 109

$$D_{maxmin} = [\; 6.072 \; (BS) - 66.96 \; (EN) + 13900 \; (AG)$$

$$+ 572.7 \; (CT) - 8946] \; / \; 1000$$

Statistics: R^2 = 0.663
COV = 43.3%
n = 110

where:

B_{maxmin} =   Total dowel looseness (as defined previously), mils

D_{maxmin} =   Total sensor deflection (as defined previously), mils

AG   = (Nominal diameter of drilled hole - Nominal dowel diameter), in

CT   = Natural log of number of complete load cycle applications

BS   = Friberg's bearing stress, psi

EN   = Estimated drill impact energy, ft-lbs/blow

Figures 16 through 18 illustrate the sensitivity of the deflection model to the input parameters. The sensitivity of the "looseness" model is similar, although it is subject to some interpretation since it is a computed (rather than measured) response. It should be noted that these models were developed using only data from specimens that did not fail prematurely and therefore they tend to represent "potential" performance rather than average observed performance. The failed specimens were eliminated because their deflections prior to failure (often from the very beginning) exceeded the capacity of the deflection sensor.

Figure 16 shows the sensitivity of the deflection model to annular gap and suggests that increasing the annular gap increases dowel deflection slightly, which is contrary to the conclusion previously drawn for cement grout installations. This is because the model is based primarily on specimens that performed well (i.e., many of the small annular gap/1 inch [2.5 cm] dowel specimens that failed were not included in the development) and the effect of annular gap is actually smaller than the variability between measurements for the large dowel diameters.

Predicted Dowel Deflection Range
Bstress=3000 psi, Energy = 25 ft-lbs

Dmax - Dmin (0.001 in)   [1 in = 2.54 cm, 1 ft-lb = 1.357 N-m]

Load Cycles (Millions)

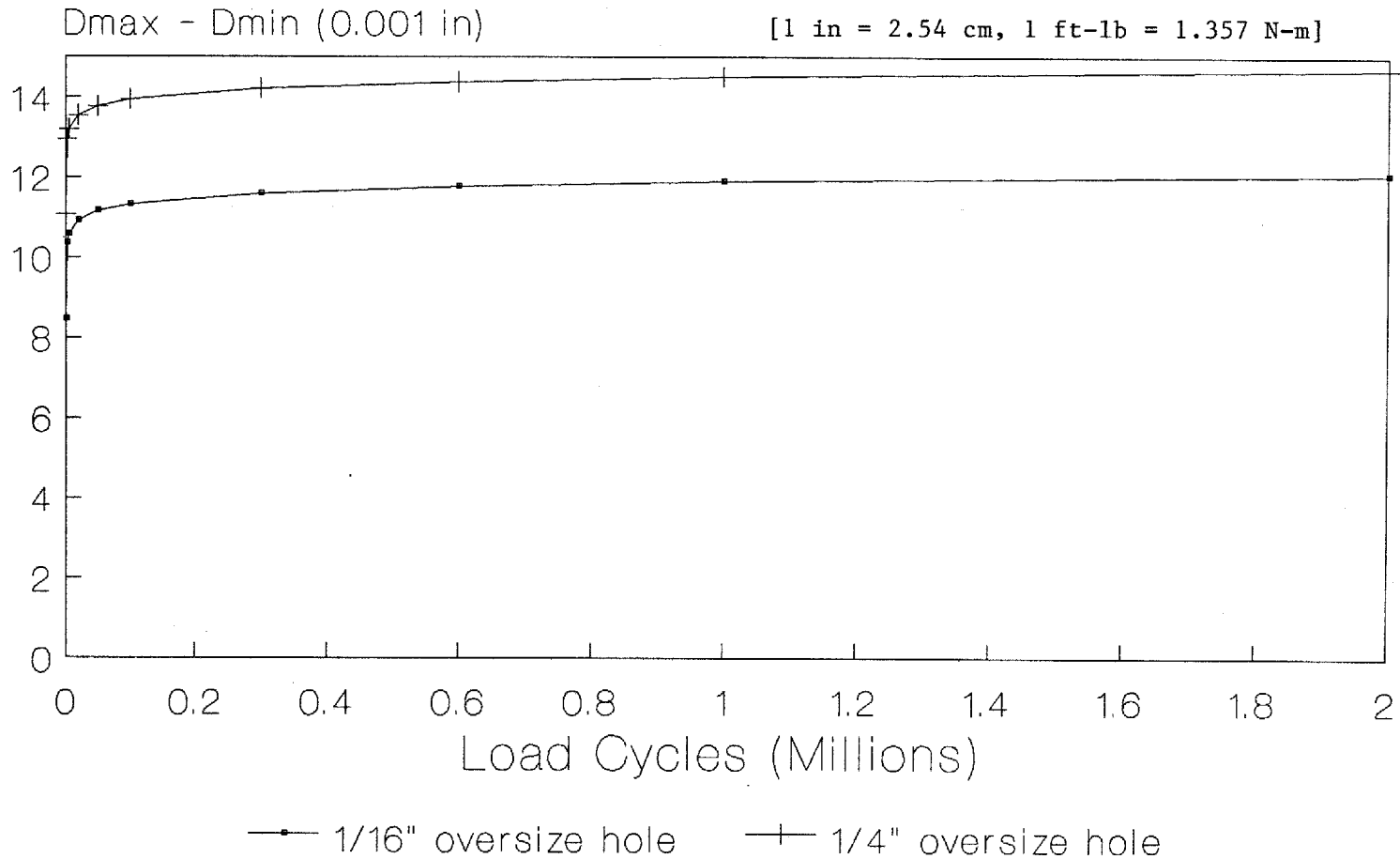—■— 1/16" oversize hole   —+— 1/4" oversize hole

Figure 16. Predicted effect of annual gap and load cycles on sensor deflection for cement grout specimens.

Figure 17 illustrates the sensitivity of the model to both annular gap and drill impact energy. The reversed effect of the annular gap was discussed above and the masking effect of the grout retention ring on the drill energy (spalling) was discussed previously.

Figure 18 shows the sensitivity of the model to bearing stress and annular gap. The large effect of bearing stress on performance is clear and suggests that the bearing stresses that result from the use of 1-in [2.5 cm] dowels result in deterioration of the anchor material at the joint face. The 1.5-in [3.8 cm] dowels are represented by the lowest curves, which suggest acceptable performance.

The effect of increased heavy load repetitions is presented in all three figures. When good installations are achieved, rapid increases in deflection typically occur at first as the dowel becomes "seated" and subsequent increases are generally small. Poor installations were observed to have excessive deflections at the start which increased as the dowel impacted the supporting material, causing it to deteriorate. As stated earlier, these models were developed using only specimens that performed adequately and are not representative of the general lab experience with the use of cement grout anchor material.

The results of the lab study can be further illustrated by looking at the deflection profiles and "looseness" envelopes for various specimens. Figures 19 through 24 are measured deflection profiles for representative specimens after they had been subjected to 300,000 load cycles. Each deflection profile consists of four response curves -- loading (lower curve, right side), load relaxation (upper curve, right side), reverse loading (upper curve, left side) and reverse load relaxation (lower curve, left side). The graph titles include pertinent test information in the form xx ay bbb, where xx is the nominal diameter of the drilled hole in millimeters (27 = 1.0625 in, 32 = 1.25 in, 40 = 1.5625 in, and 44 = 1.75 in), ay is the drill type (E = electric, H = hydraulic, P = pneumatic) and embedment length in inches [1 in = 2.54 cm], and bbb is the type of anchor material used (C10 = epoxy mortar, CG = cement grout).

Figures 25 through 30 are dowel "looseness" envelopes for the same specimens, illustrating the development of looseness over time for each specimen. 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 "total looseness" (plotted as squares) is the distance between the other two curves and corresponds to B_{maxmin} in the regression models.

A comparison of figures 19 and 20 illustrates the increase in dowel deflection that was observed to accompany increases in annular gap when the epoxy anchor material was used. Figures 25 and 26 show that the larger annular gap consistently produced larger deflections throughout the testing period. These figures also illustrate that the reverse loading mode typically produced higher deflections that 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 and a thicker layer on top. Since the deformations are somewhat dependent on the deformation of the supporting layer, the thicker layer on top allows more deflection in reverse loading.

Comparing figures 20 and 21 illustrates that dowels properly installed using cement grout typically exhibited lower deflections than those installed using the epoxy mortar. Figures 26 and 27 show that similar results were obtained at other

Predicted Dowel Deflection Range
Bstress=3000, Drill Energy/Ann Gap

Dmax - Dmin (0.001 in)

[1 in = 2.54 cm]

Load Cycles (millions)

6.4/0.063   6.4/0.25   25/0.063
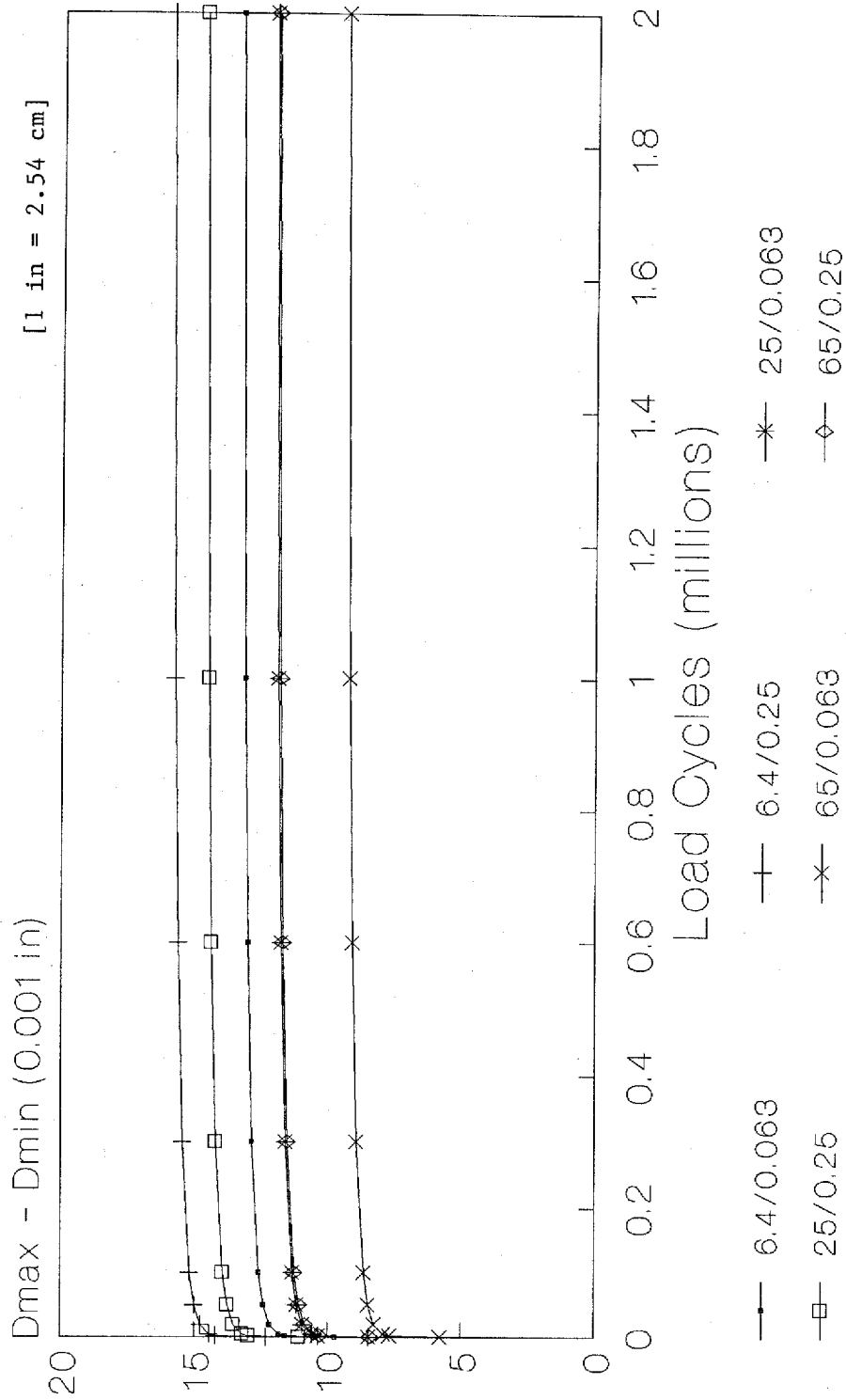
25/0.25   65/0.063   65/0.25

Figure 17.   Predicted effect of annual gap and drill impact energy on sensor deflection for cement grout specimens.

Predicted Dowel Deflection Range
Energy=25, Bstress/Ann Gap

[1 in = 2.54 cm]

Dmax − Dmin (0.001 in)

Load Cycles (millions)

- 2000/0.063
- 3000/0.063
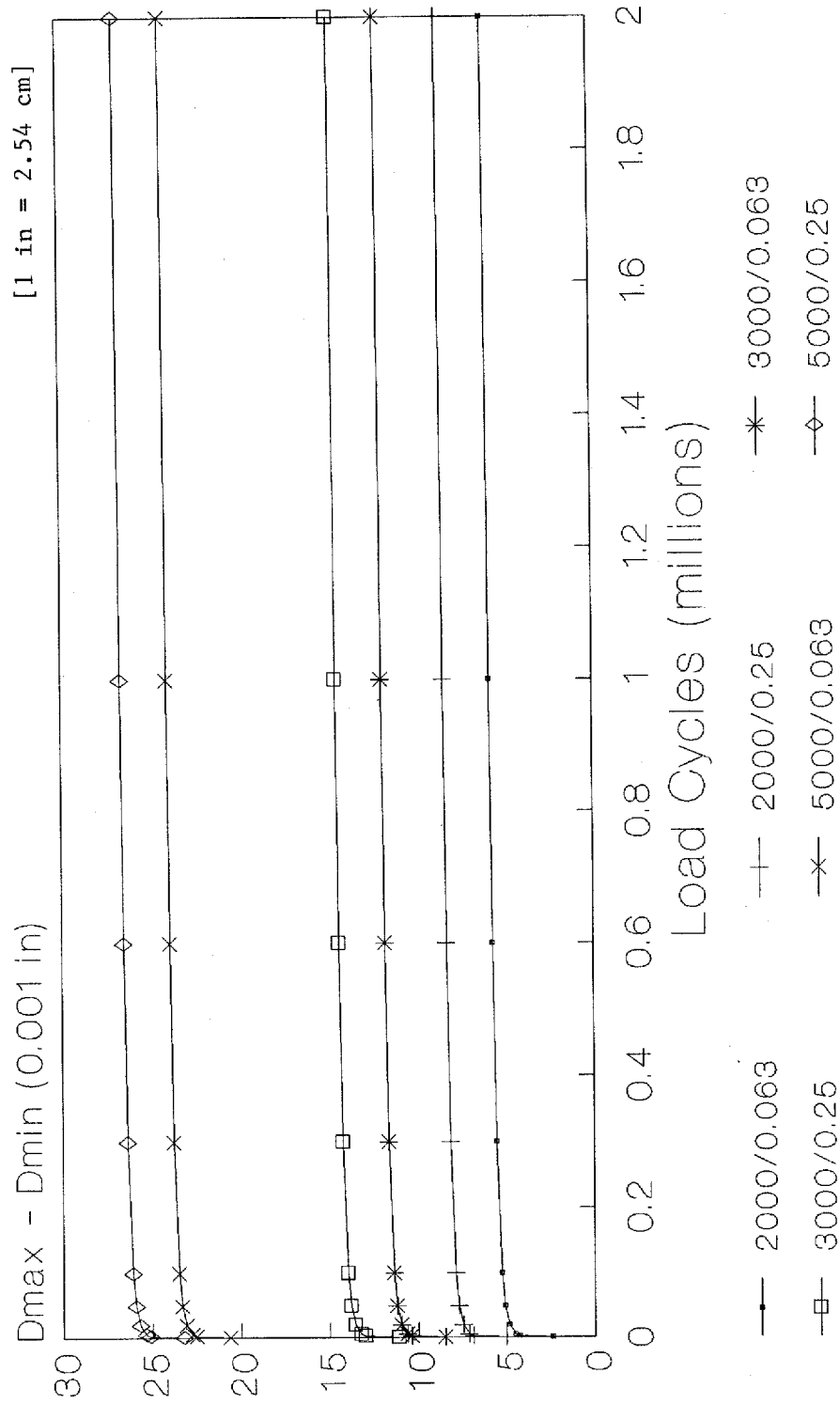- 2000/0.25
- 5000/0.063
- 3000/0.25
- 5000/0.25

Figure 18. Predicted effect of annual gap and bearing stress on sensor deflection for cement grout specimens.

points in the loading history. 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 21 and 22 shows the tremendous reduction in deflection that typically accompanied an increase in dowel diameter from 1 in to 1.5 in [2.5 to 3.8 cm]. Figures 27 and 28 compare the load history performance of the same two specimens and show that the 1.5-in [3.8 cm] dowel exhibited a total computed "looseness" of less than 6 mils [0.015 cm] after 600,000 load cycles.

Figures 22 and 23, and figures 28 and 29 show that the difference in deflection profiles actually varied very little for different drill types. A slight improvement is noted for the high-energy drill, but it is suspected that this improvement is due to the difference in drill guidance systems rather than impact energy. The use of the grout retention ring is believed to have eliminated the effects of increased impact energy, which resulted in more spalling around the drilled hole and would reduce dowel support if unrepaired.

Figures 23 and 24, and figures 29 and 30 illustrate that the effect of dowel embedment on dowel deflection was typically very small for the range of embedments tested. This confirms other studies which have suggested that embedment lengths of 6 - 7 in are adequate for the size dowels currently used in highway applications.

Figure 31 presents the deflection profile obtained from one of the specimens that was prepared by casting a 1-in [2.5 cm] diameter dowel (embedded 9 inches [23 cm]) in a block of concrete, curing it 24 hours, applying 5000 load cycles, curing an additional 27 days, and finally applying an additional 595,000 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 specimens as an idealized dowel installation. A comparison of this profile to other 1-in [2.5 cm] dowelled specimens suggests that the cement grout specimens have the potential to most closely approach this level of dowel support, 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 epoxy mortar specimens performed much more consistently than the cement grout specimens. Figure 32 presents the history of "looseness" for the cast-in-place specimen. Although it is apparent that the deflection sensor slipped somewhat near the end of the test, the total looseness trend is relatively uniform and suggests good overall performance, and can be compared to similar looseness curves for the other specimens.

Figure 33 presents the deflection curve for the 1.625-in [4.1 cm] O.D. hollow stainless steel dowel that was installed using the epoxy mortar to a depth of 7 inches [18 cm] in a 1.75-in [4.4 cm] diameter hole. The profile is similar to that illustrated in figure 20, which was produced using a 1-in [2.5 cm] diameter dowel with a slightly thicker supporting layer of epoxy mortar. A solid bar (or a tube with thicker walls) would probably have provided a more acceptable deflection

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profile. 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. Figure 34 shows the computed "looseness" history for this specimen.

The two specimens that were prepared using "close-fitting holes" and no grout of any type were very loose (compared to the other specimens) and rapidly developed deflections that were beyond the capability of the sensor to measure (>0.05 inches [0.13 cm] in either direction). Neither could be tested to the full 600,000 load repetitions because of possible damage to the test equipment. One of the specimens failed after less than 60,000 load cycles.

3.2.4 Conclusions
Conclusions drawn from the laboratory study are summarized with the field study conclusions in volume I, chapter 5.

Specimen D10R, 27 E9 C10, 300000 Cycles
Sensor Deflection vs. Load

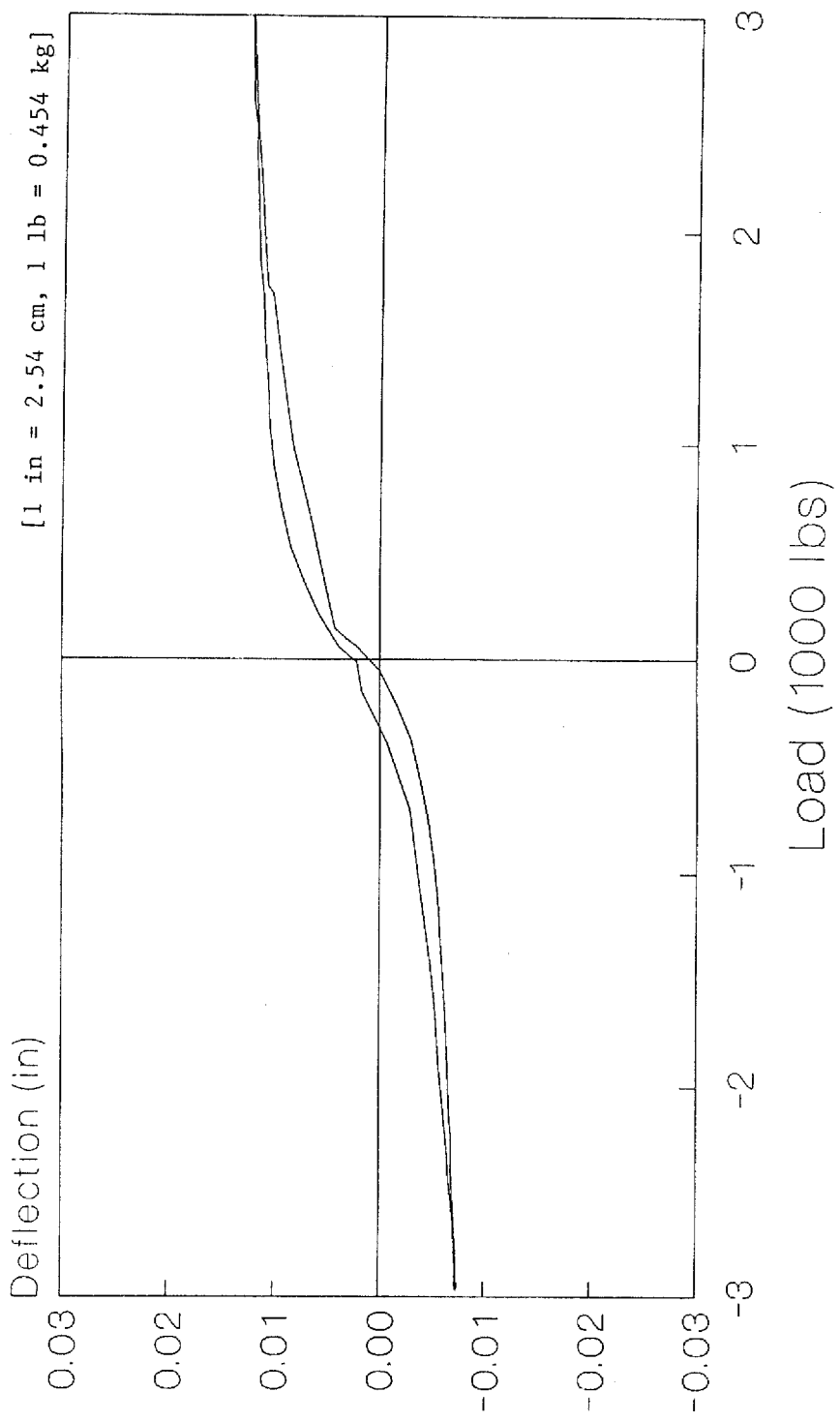[1 in = 2.54 cm, 1 lb = 0.454 kg]

Deflection (in)

Load (1000 lbs)

Figure 19. Measured load-deflection profile after 300,000 load cycles for specimen D10R (1-in [2.5-cm] dowel, 1/32-in [0.08-cm] annual gap, 9-in [23-cm] embedment, low-energy drill, epoxy mortar).

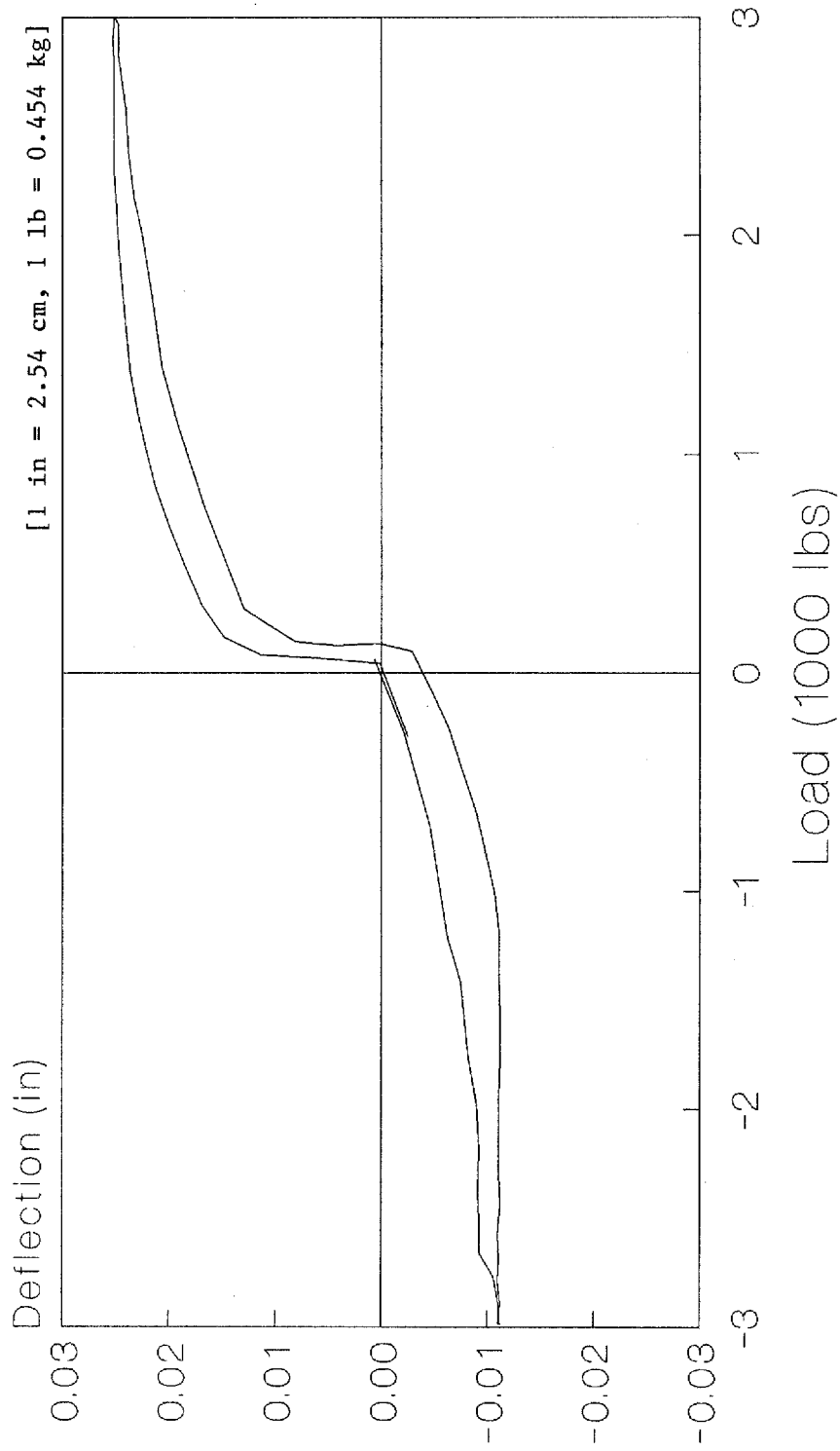## Specimen D6, 32 E9 C10, 300000 Cycles
Sensor Deflection vs. Load

[1 in = 2.54 cm, 1 lb = 0.454 kg]

Deflection (in)

Load (1000 lbs)

Figure 20. Measured load-deflection profile after 300,000 load cycles for specimen D6 (1-in [2.5-cm] dowel, 1/8-in [0.3-cm] annual gap, 9-in [23-cm] embedment, low-energy drill, epoxy mortar).

Specimen A8R, 32 E9 CG, 300000 Cycles
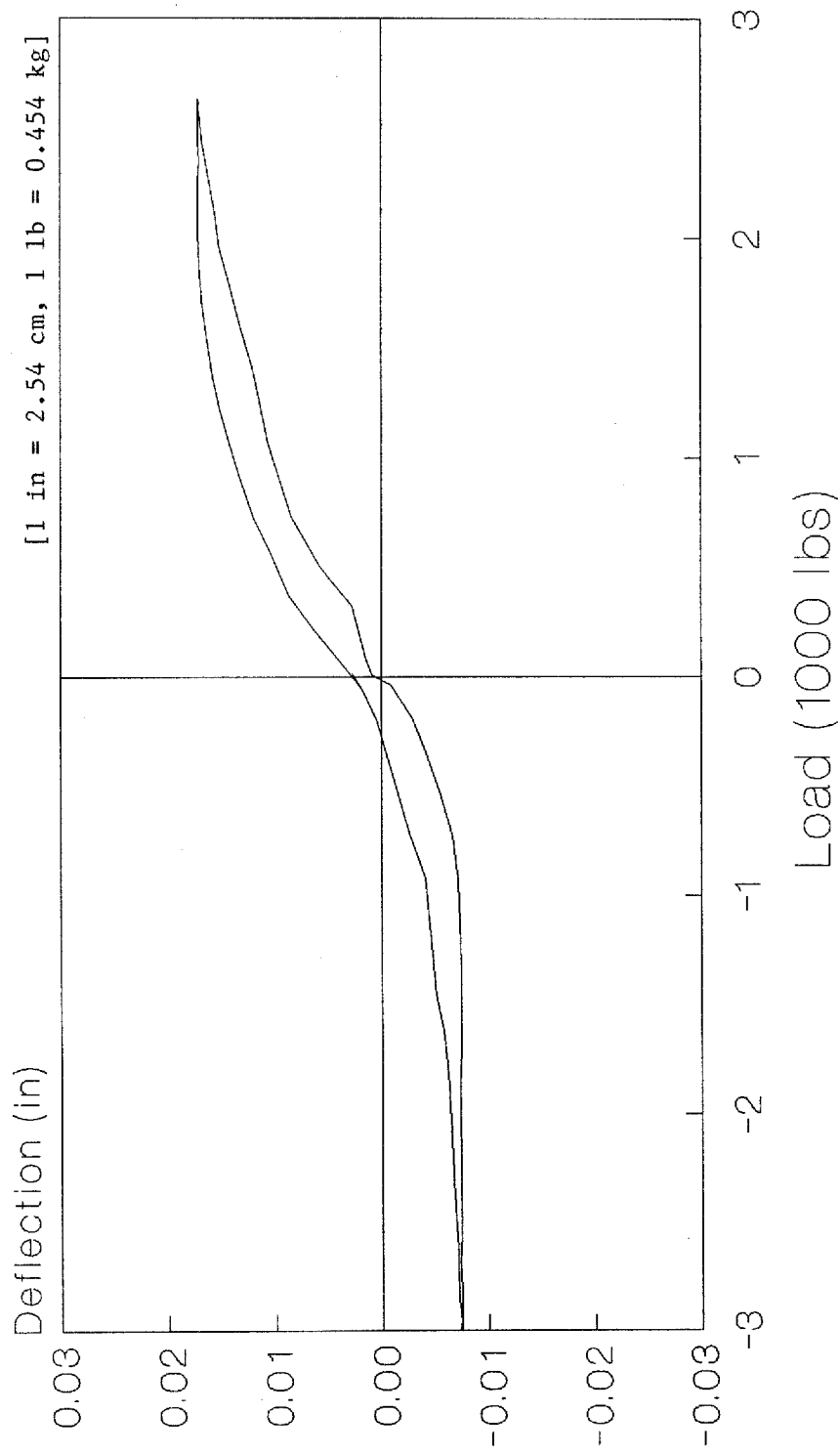## Sensor Deflection vs. Load

Figure 21. Measured load-deflection profile after 300,000 load cycles for specimen A8R (1-in [2.5-cm] dowel, 1/8-in [0.3-cm] annual gap, 9-in [23-cm] embedment, low-energy drill, cement grout).

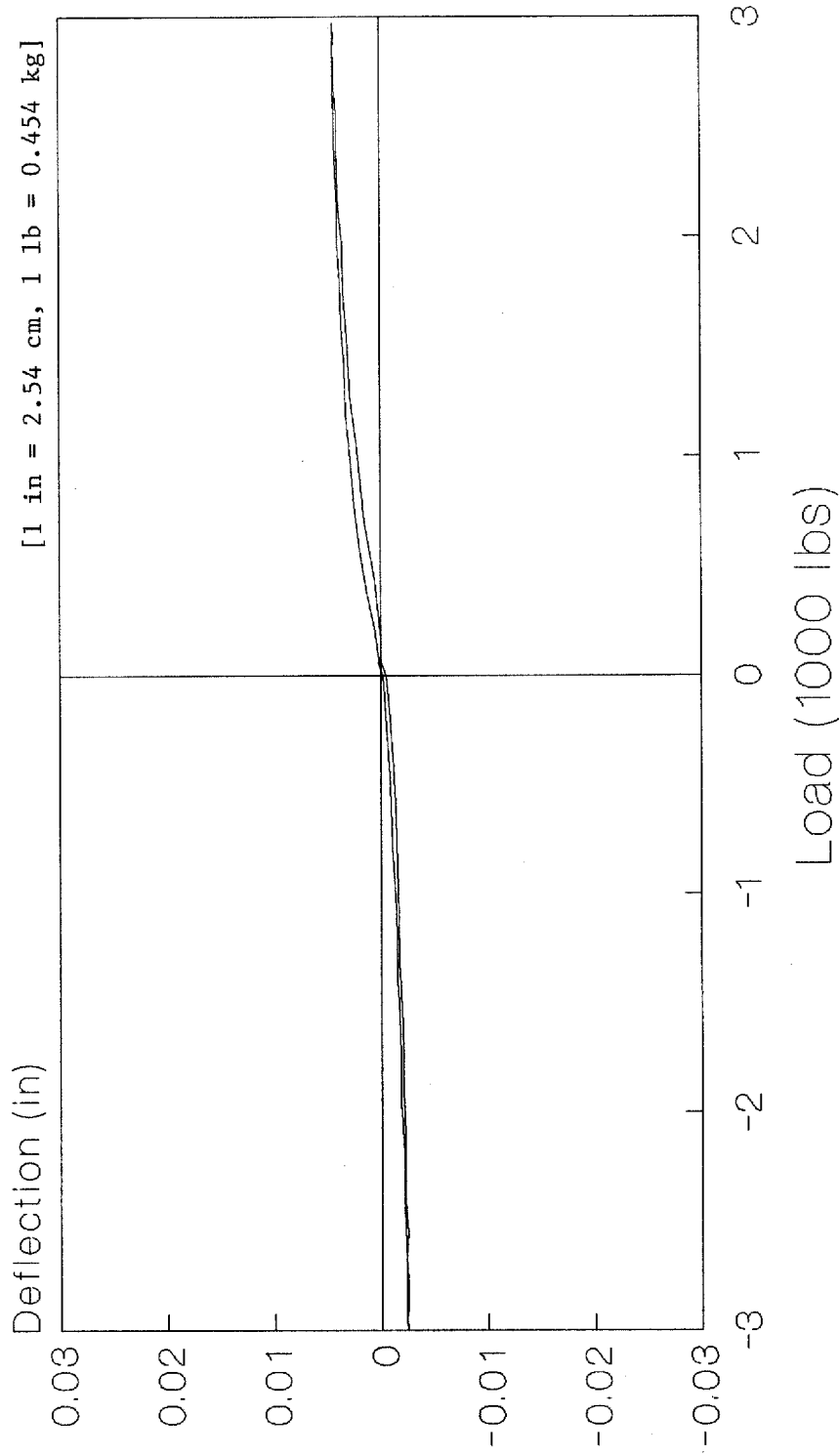# Specimen B18, 44 E9 CG, 3000000 Cycles
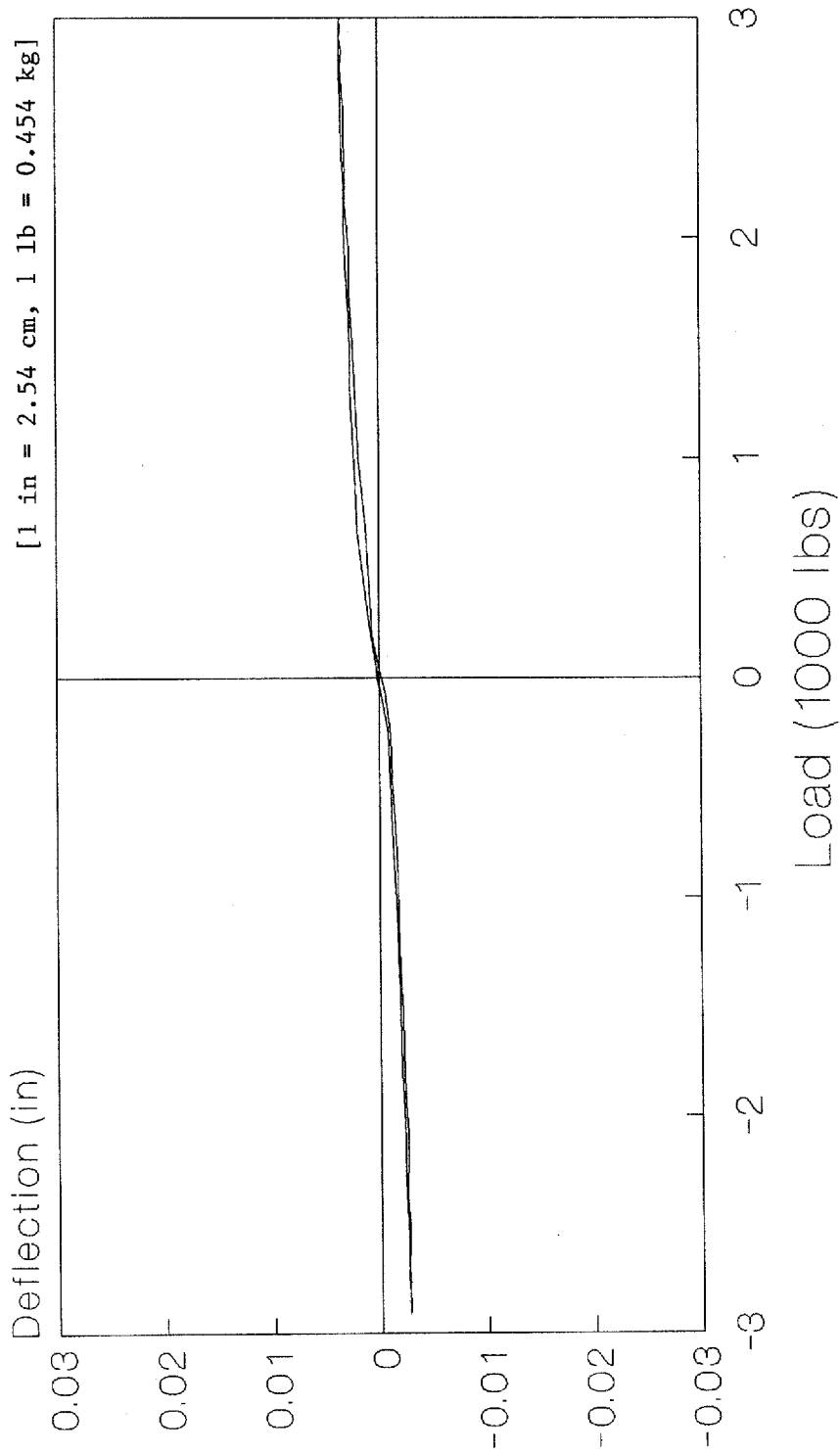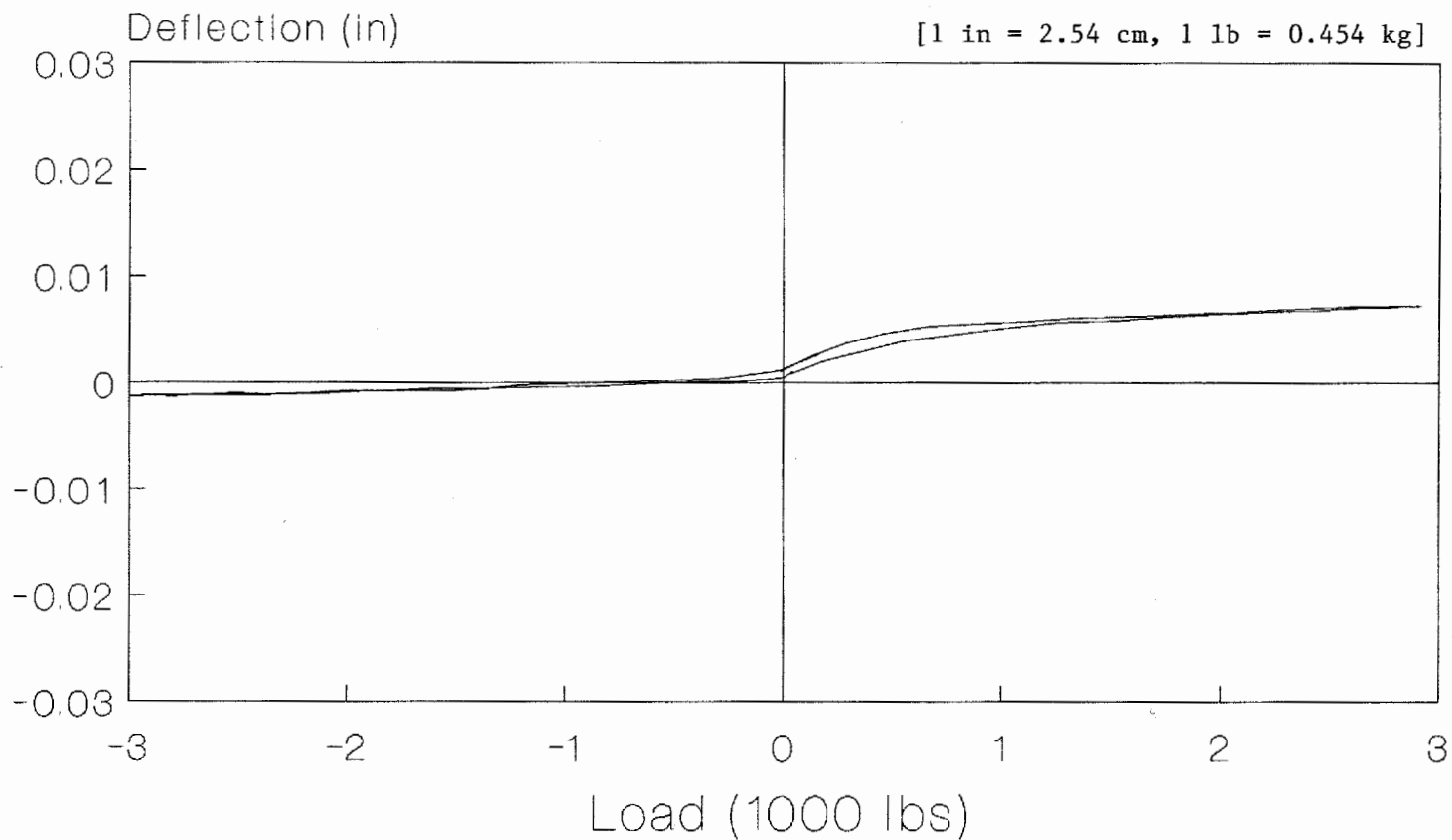## Sensor Deflection vs. Load

[1 in = 2.54 cm, 1 lb = 0.454 kg]

Figure 22. Measured load-deflection profile after 300,000 load cycles for specimen B18 (1.5-in [3.8-cm] dowel, 1/8-in [0.3-cm] annual gap, 9-in [23-cm] embedment, low-energy drill, cement grout).

Specimen D20, 44 P9 CG, 3000 Cycles
Sensor Deflection vs. Load

[1 in = 2.54 cm, 1 lb = 0.454 kg]

Figure 23. Measured load-deflection profile after 300,000 load cycles for specimen D20 (1.5-in [3.8-cm] dowel, 1/8-in [0.3-cm] annual gap, 9-in [23-cm] embedment, high-energy drill, cement grout).

Specimen A10, 44 E7 CG, 300000 Cycles
Sensor Deflection vs. Load

Figure 24. Measured load-deflection profile after 300,000 load cycles for specimen A10
            (1.5-in [3.8-cm] dowel, 1/8-in [0.3-cm] annual gap, 7-in [18-cm] embedment,
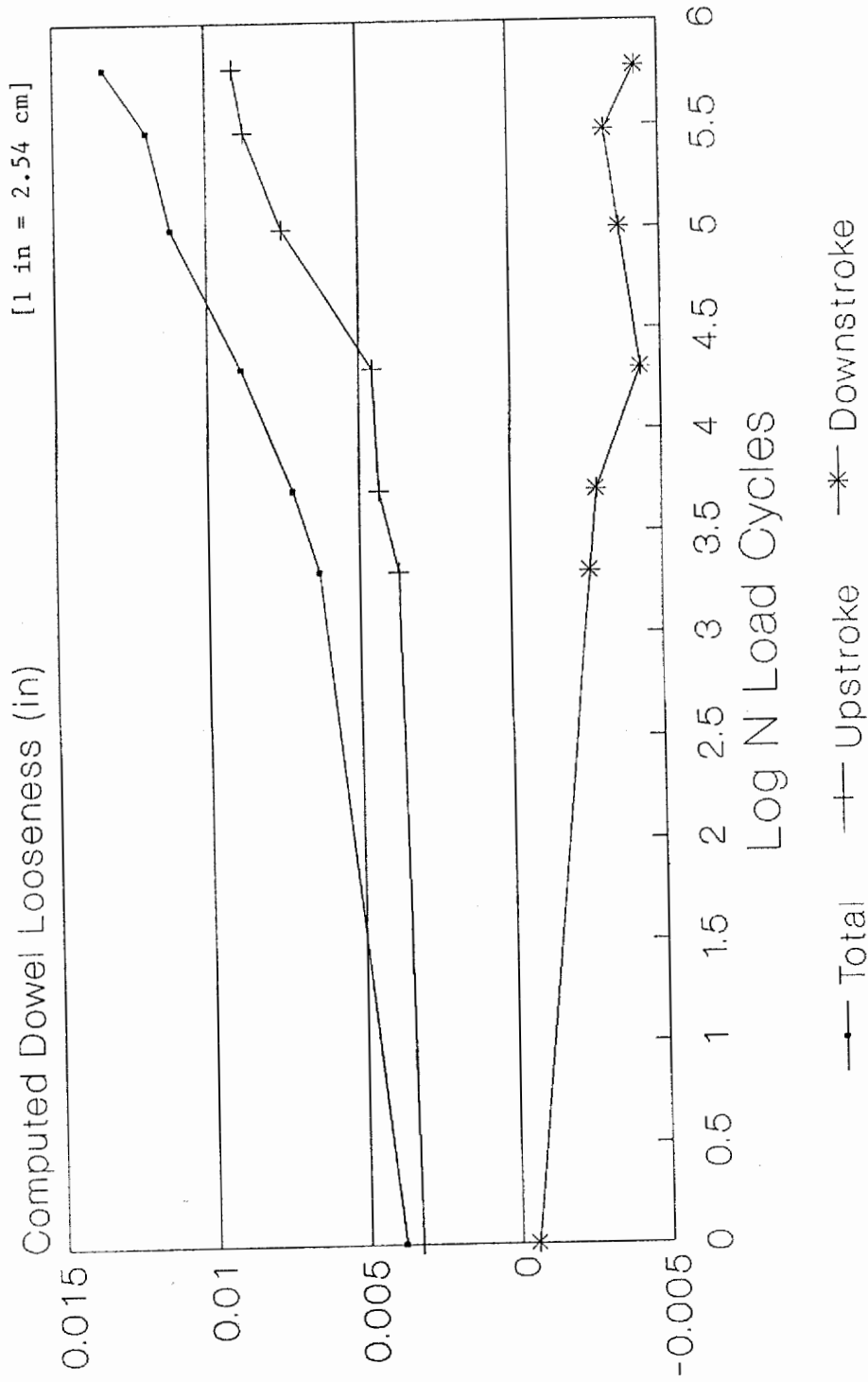   low-energy drill, cement grout).

Figure 25. Computed dowel looseness vs. log load cycles for specimen D10R (1-in [2.5-cm] dowel, 1/32-in [0.08-cm] annual gap, 9-in [23-cm] embedment, low-energy drill, epoxy mortar).
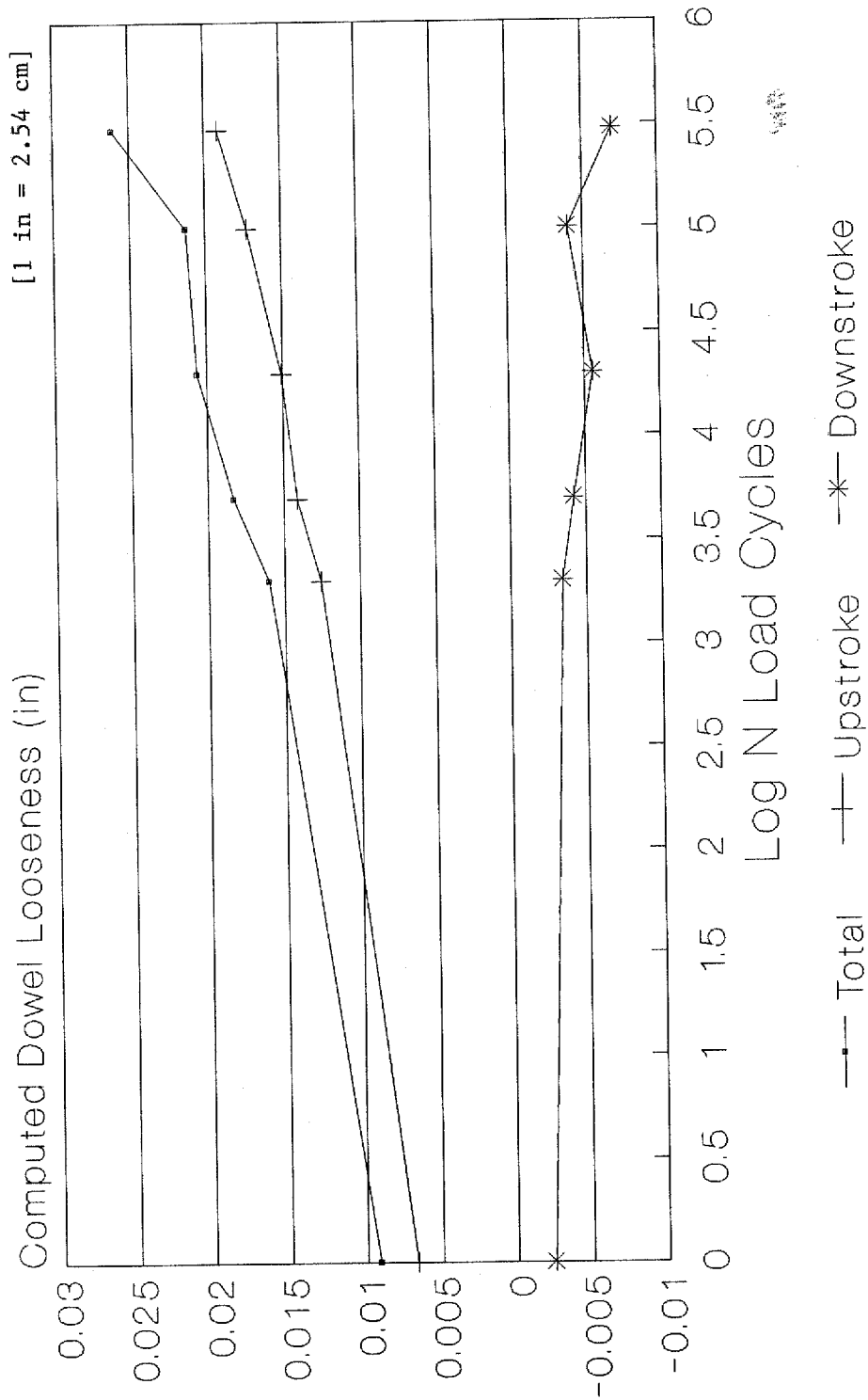
Figure 26.   Computed dowel looseness vs. log load cycles for specimen D6 (1-in [2.5-cm] dowel, 1/8-in [0.3-cm] annual gap, 9-in [23-cm] embedment, low-energy drill, epoxy mortar).
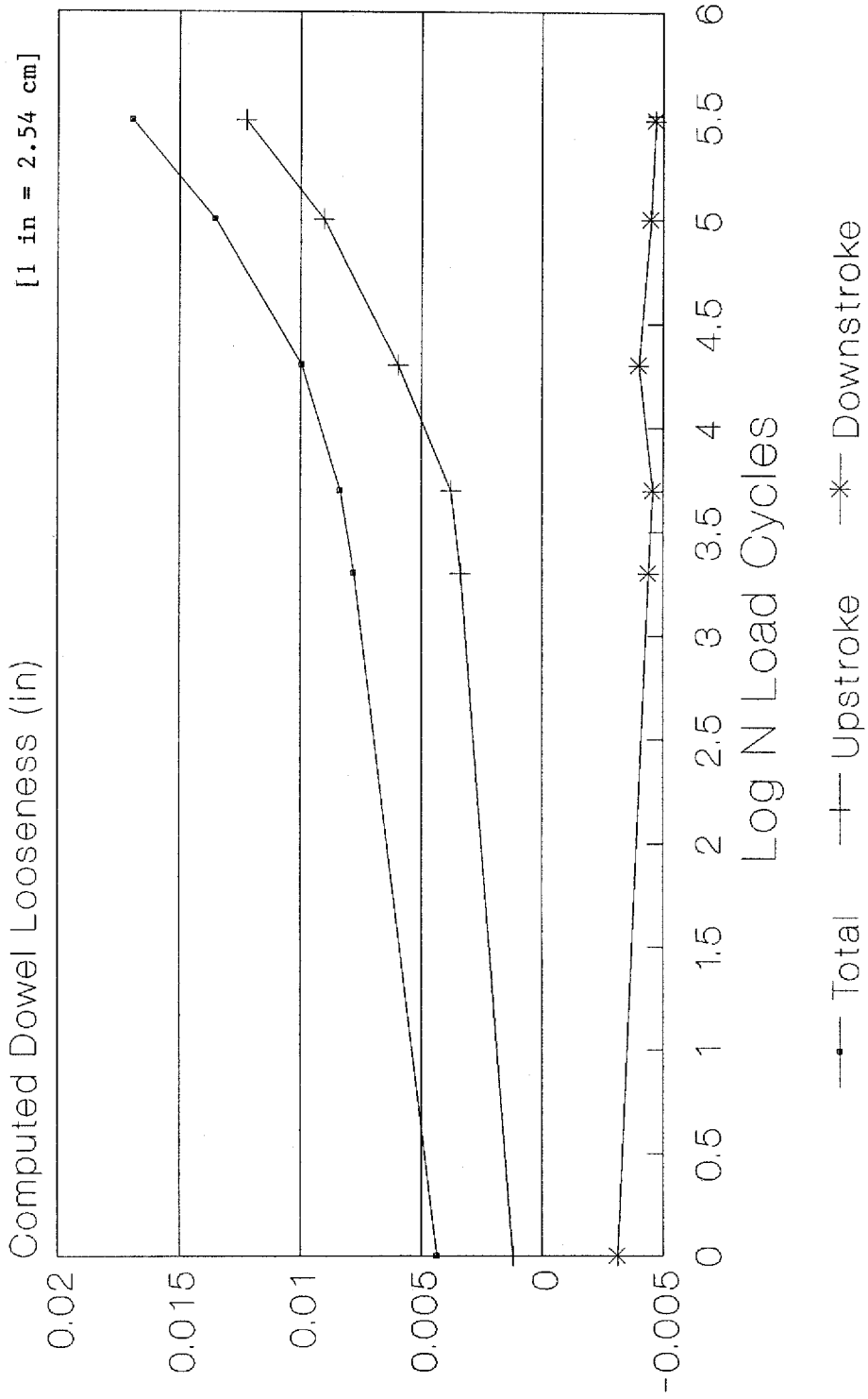
Figure 27. Computed dowel looseness vs. log load cycles for specimen A8R (1-in [2.5-cm] dowel, 1/8-in [0.3-cm] annual gap, 9-in [23-cm] embedment, low-energy drill, cement grout).

Dowel Looseness vs. Log N
Specimen B18, 44, E9, Cement Grout

Figure 28. Computed dowel looseness vs. log load cycles for specimen B18 (1.5-in [3.8-cm] dowel, 1/8-in [0.3-cm] annual gap, 9-in [23-cm] embedment, low-energy drill, cement grout).
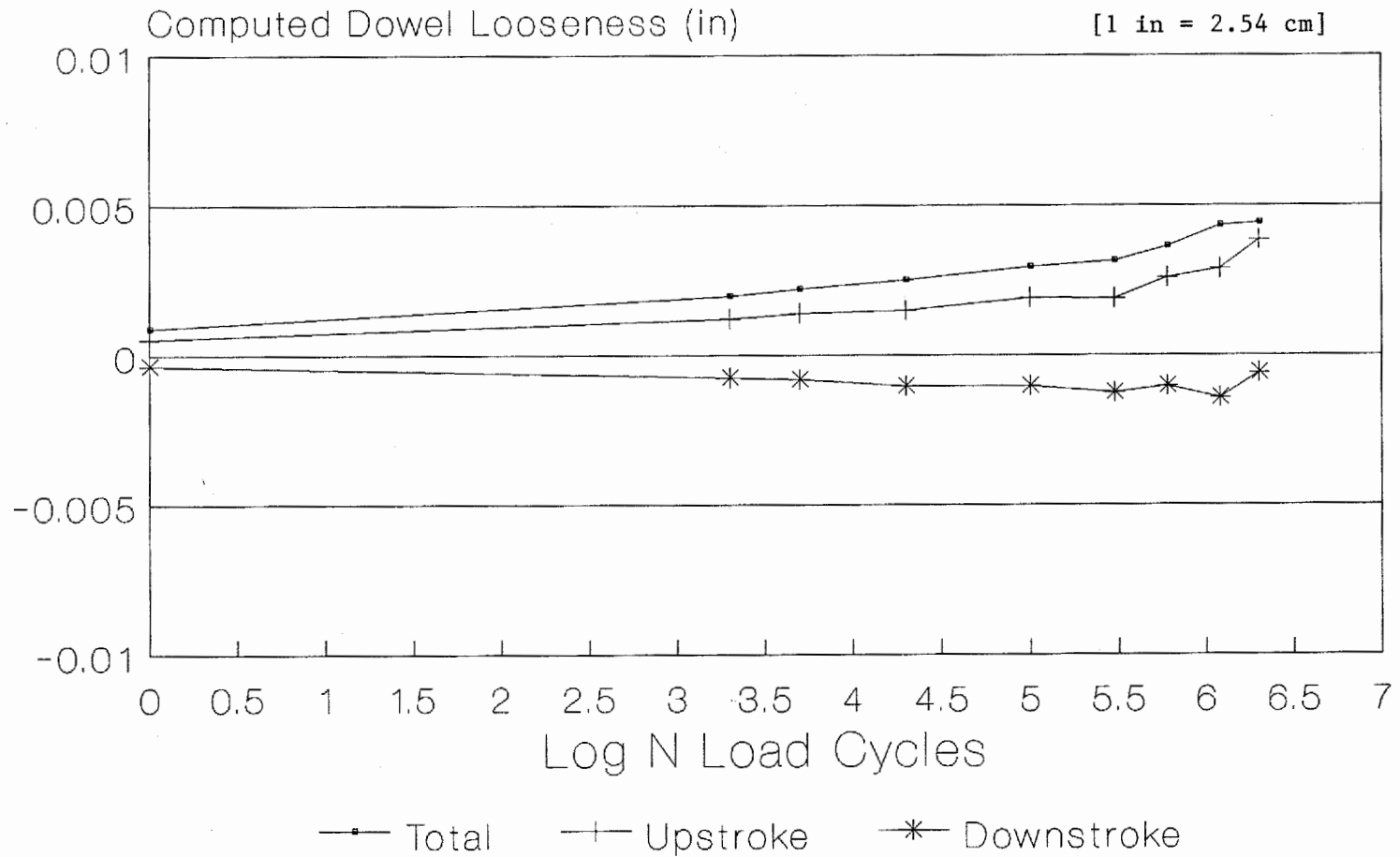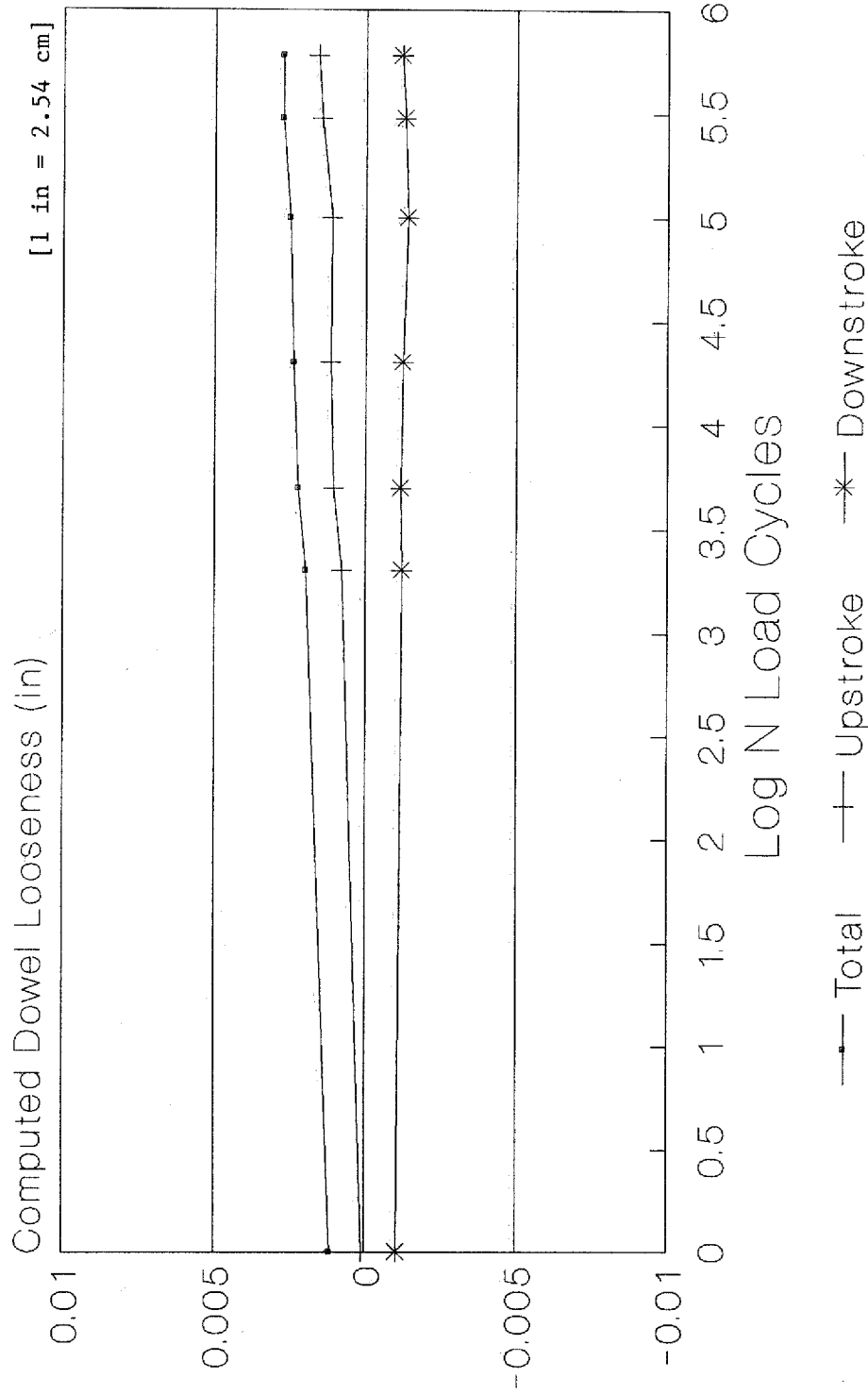
Figure 29.   Computed dowel looseness vs. log load cycles for specimen D20 (1.5-in [3.8-cm] dowel, 1/8-in [0.3-cm] annual gap, 9-in [23-cm] embedment, high-energy drill, cement grout).

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Dowel Looseness vs. Log N
Specimen A10, 44, E7, Cement Grout

[1 in = 2.54 cm]

Computed Dowel Looseness (in)

— Total   —+— Upstroke   —*— Downstroke
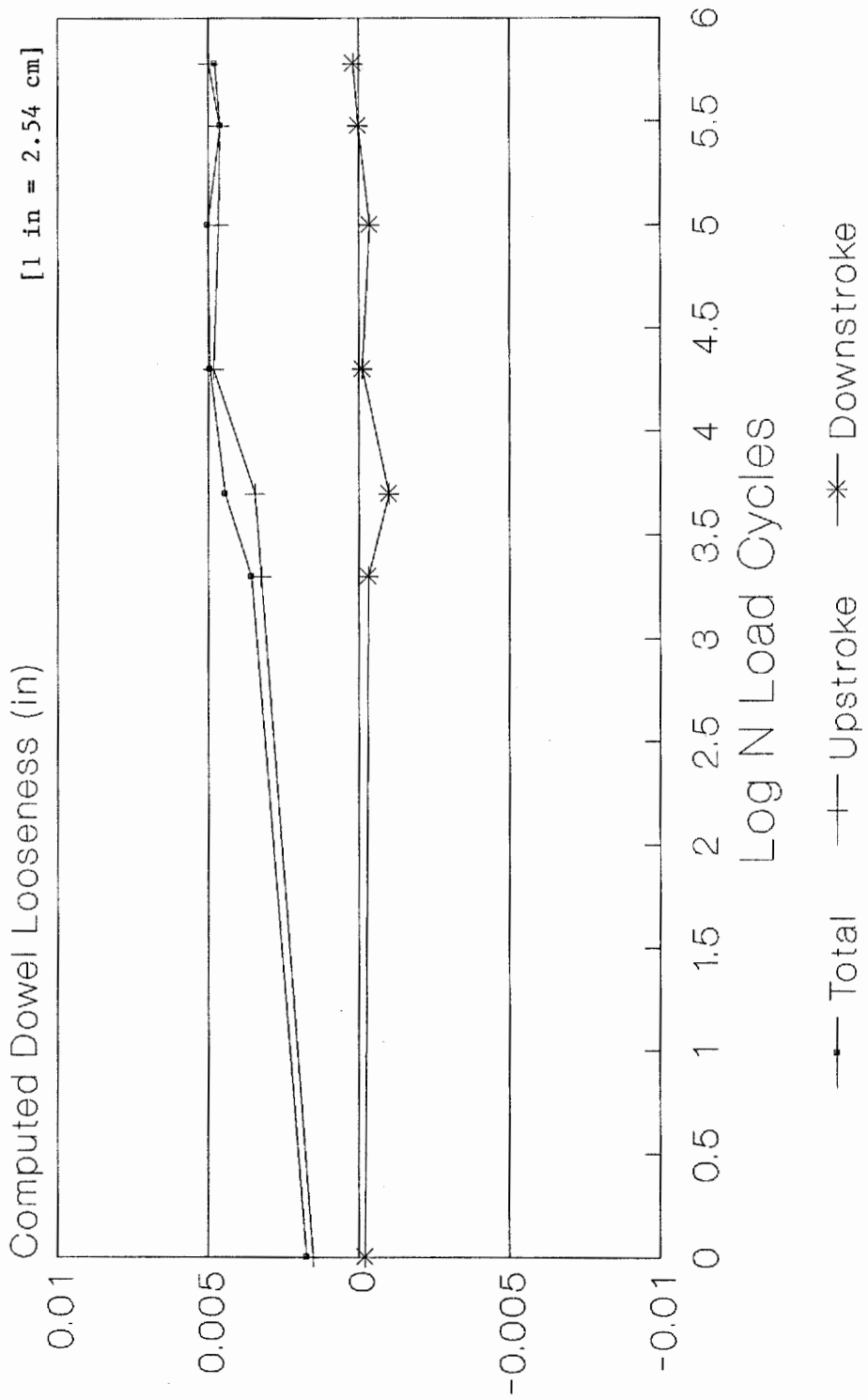
Log N Load Cycles

Figure 30.   Computed dowel looseness vs. log load cycles for specimen A10 (1.5-in [3.8-cm] dowel, 1/8-in [0.3-cm] annual gap, 7-in [18-cm] embedment, low-energy drill, cement grout).

Specimen Lab1, 28 Days, 300000 Cycles
Sensor Deflection vs. Load

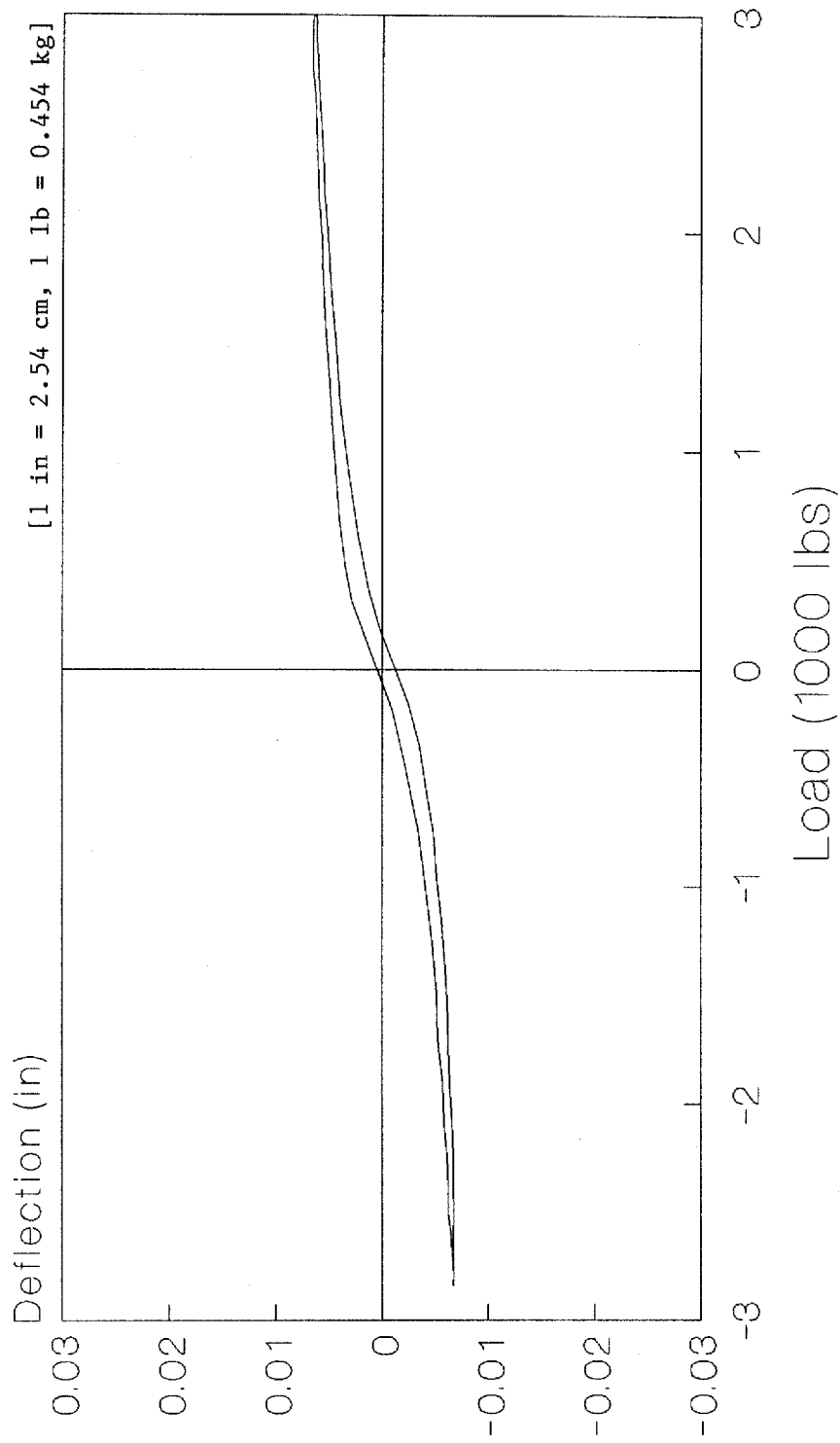[1 in = 2.54 cm, 1 lb = 0.454 kg]

Deflection (in)

Load (1000 lbs)

Figure 31. Measured load-deflection profile after 300,000 load cycles for cast-in-place specimen (1-in [2.5-cm] dowel, 9-in [23-cm] embedment).
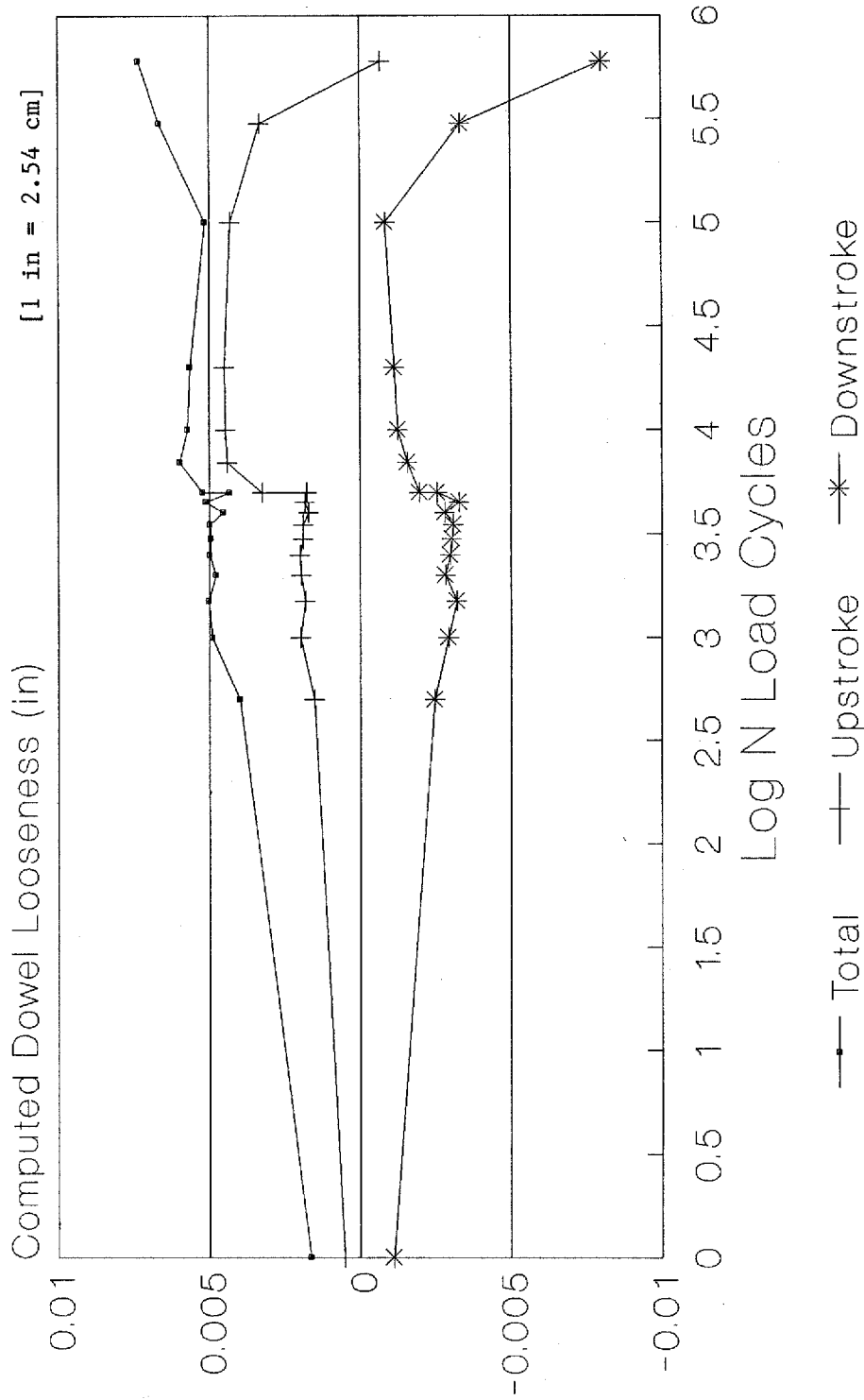
Figure 32. Computed dowel looseness vs. log load cycles for cast-in-place specimen (1-in [2.5-cm] dowel, 9-in [23-cm] embedment).

Specimen C9, 44 H7 C10, 300000 Cycles
Sensor Deflection vs. Load

[1 in = 2.54 cm, 1 lb = 0.454 kg]

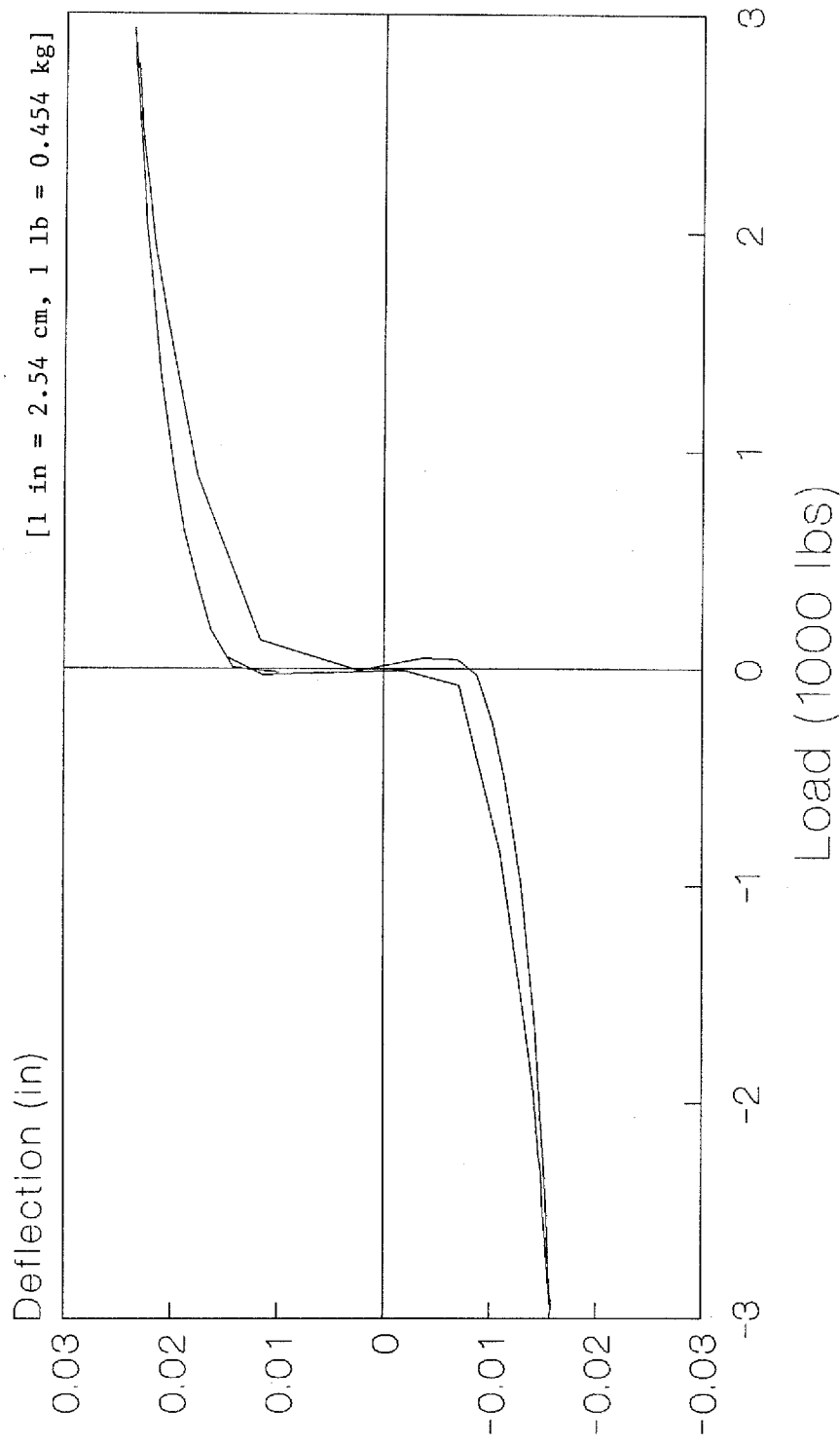Deflection (in)

Load (1000 lbs)

Figure 33.   Measured load-deflection profile after 300,000 load cycles for stainless steel
pipe (1.625-in [4.1-cm] by 1/8-in [0.3-cm] wall thickness pipe, 7-in [18-cm]
embedment, medium-energy drill, epoxy mortar).

Dowel Looseness vs. Log N
Specimen C9, 44 H7 Epoxy, Hollow SS Bar

Computed Dowel Looseness (in)

[1 in = 2.54 cm]

Log N Load Cycles
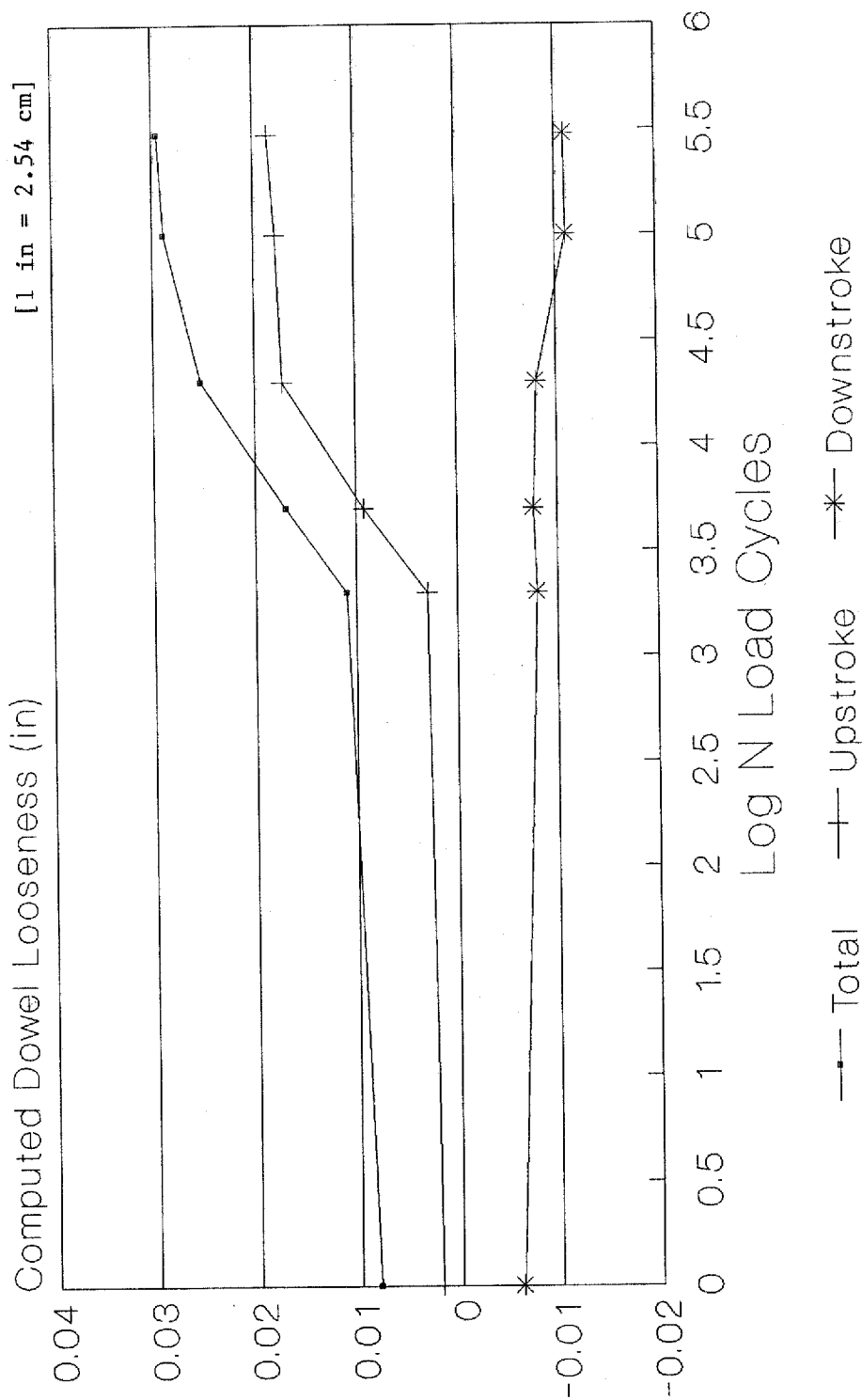
— Total   — Upstroke   — Downstroke

Figure 34.   Computed dowel looseness vs. log load cycles for stainless steel pipe (1.625-in [4.1-cm] by 1/8-in [0.3-cm] wall thickness pipe, 7-in [18-cm] embedment, medium-energy drill, epoxy mortar).

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