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DESIGN, FABRICATION, AND OPERATION OF THE PAVEMENT CRACK MONITOR GAUGE

FINAL REPORT

Prepared for
Pennsylvania Department of Transportation

By

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and
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May 7, 1990

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A mechanical gauge was developed to monitor the movement of crack or joint openings in portland cement concrete structures, in general, and portland cement concrete pavements in particular. Designed to be inexpensive and simple to operate, this gauge is capable of recording maximum, minimum, and instantaneous crack or joint openings. Specific recommendations were made for recording minimum and maximum pavement temperature over the monitoring period.

The report was written as a set of guidelines for design, fabrication, installation, and operation of the gauge as well as the temperature measuring device.

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1. INTRODUCTION

The major objective of cracking and seating of portland cement concrete (PCC) pavement slabs prior to overlay is to minimize the movement of the slab in terms of thermal contraction and expansion. The amount of contraction and expansion to which a given slab is subjected can be monitored by measuring the movement at the joints or cracks at each end of the slab. It is expected that the size of the slab will affect the amount of joint or crack movement. Since the crack-and-seat operation can be done with various sized pieces of the broken slab, it is critical to know how small the broken pieces must be to effectively disperse the movement of the slab.

The Federal Highway Administration (FHWA) has initiated a field project to evaluate the effect of the size of the broken slab on the total movement at the joint or crack. Several crack-and-seat test sections will be overlaid with different sized pieces of the broken slab and the horizontal movement at the cracks or joints will be monitored. Since a large number of sites will be monitored, it was desired that an inexpensive gauge be built to monitor the maximum and minimum crack or joint opening. The design, construction, installation, and other characteristics of the gauge, thermometer, and access box are discussed in the chapters that follow.

2. CRACK MONITOR GAUGE

A number of criteria were considered critical for the design of the crack monitor gauge. Specifically, the gauge must be accurate, inexpensive, easy to install, simple to operate, and durable. In addition, the gauge will have to be used in remote areas over long periods of time. This means that it should be able to operate without electrical power. These requirements rule out the use of any electronic instruments and make mechanical gauges virtually the only option.

One type of mechanical crack monitor gauge is available through Avongard and Soiltest. However, that gauge only measures the instantaneous crack or joint opening, with a resolution of 0.5 mm (0.020 in). There is currently no commercially available mechanical gauge that can register maximum, minimum, and instantaneous crack or joint openings.

DESIGN

Figure 1 shows the schematics of the mechanical gauge designed for this project. The gauge consists of two separate parts: a base plate and an overlapping plate. The base plate is firmly attached to the left side of the crack or joint (approach side). It contains a 2-in (50.8-mm) slot along which two pins can slide with some degree of friction. Each end of the slot has a keyhole to facilitate replacement of the pins, if necessary. There is also a fixed reference pin that is used to measure the relative position of the sliding pins.

The overlapping plate consists of a remote arm that is placed between the pins on the base plate, and a flat portion that is firmly attached to the right side of the crack or joint (leave side). As the crack or joint widens, the remote arm pulls the right pin toward the right until the crack or joint reaches its maximum opening. When the crack or joint opening starts to close, the remote arm moves toward the left pin. As the crack or joint resumes its initial opening and continues to narrow, the remote arm pushes the left pin toward the pin position corresponding to the minimum crack or joint opening.

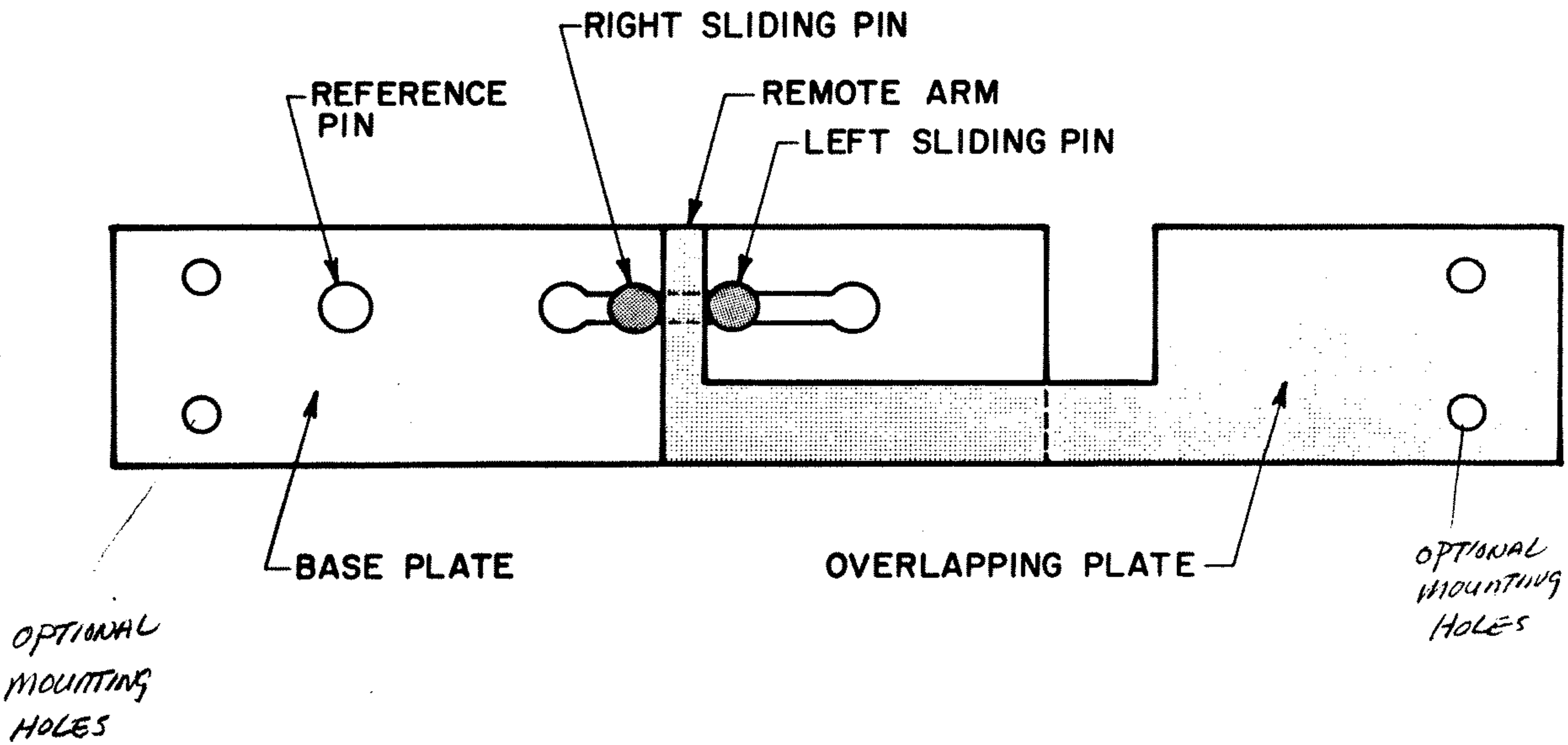


Figure 1. Schematics of the crack monitor gauge.

FABRICATION

Figures 2 and 3 illustrate engineering drawings of the designed gauge. The overall dimensions given in figures 2 and 3 are not critical. However, they have been selected to facilitate precise manufacturing and appropriate installation and operation of the gauge. The gauge is fabricated from 1/16-in- or 1/32-in-thick (1.6-mm- or 0.8-mm-thick) stainless steel plate.

Aluminum or hard plastic plates with 1/16-in (1.6-mm) thickness can also be used in certain applications. For most applications, stainless steel or aluminum is preferred over plastic since the overlapping plate remote arm can be easily adapted to accommodate any possible lateral misalignment of the sides of the crack or joint. Stainless steel is stronger and more resistant to environmental effects than aluminum. However, it is heavier and more expensive.

The sliding pins are made of 5/16-in-diameter (7.9-mm-diameter) Teflon rods. The sliding motion of the pins in the slot is frictional to prevent any accidental movement of the pins due to vibration. However, the friction between the pins and slot should not be so high as to prevent the sliding of the pins.

ACCURACY

Satisfactory performance of the crack monitor gauge depends on several factors, including proper manufacturing, installation, and measurement. The key point to be considered when installing the gauge is that each plate must be firmly connected to its appropriate side of the crack or joint such that the connections do not yield under the force caused by contraction or expansion of the slab. This can be minimized by using a stiff epoxy compound for the attachment of the gauge. Further, the gauge components must be properly aligned to each other and parallel to the top of the slab.

Accurate measurement of the positions of the sliding pins relative to the reference pin can be ensured by using a digital caliper with adjustable

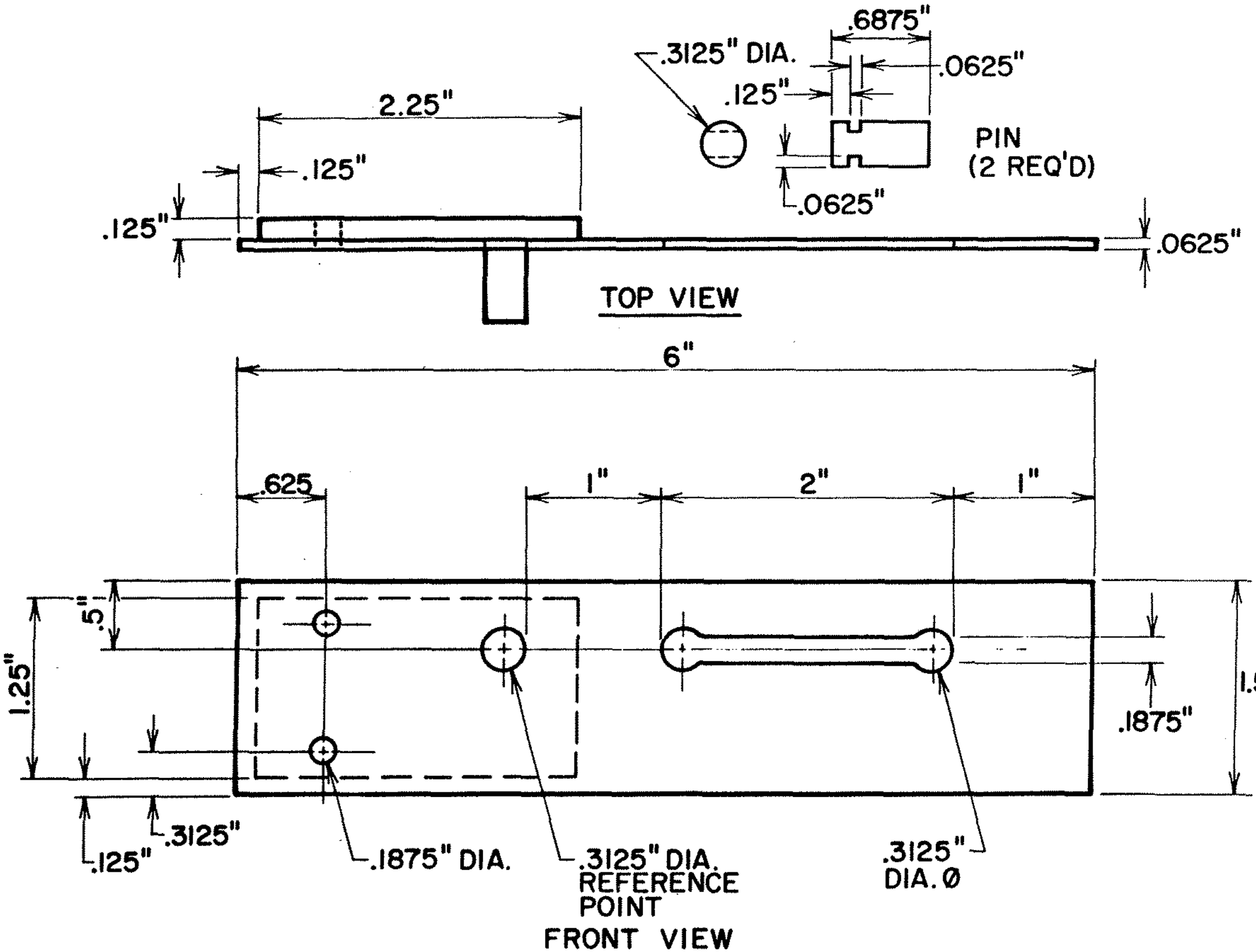


Figure 2. Engineering drawing of the base plate of the crack monitor gauge.

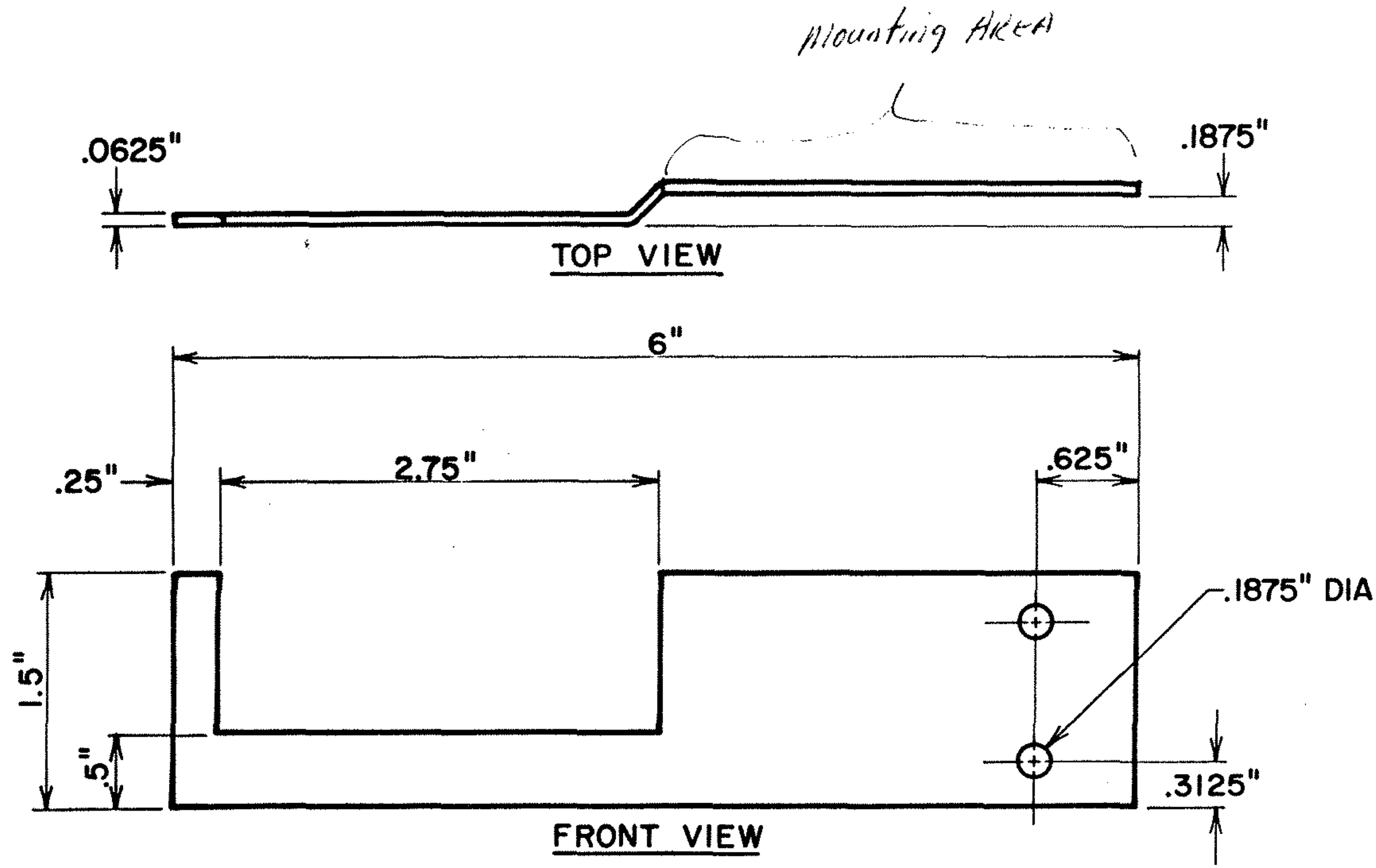


Figure 3. Engineering drawing of the overlapping plate of the crack monitor gauge.

friction at its thumbwheel. The friction of the thumbwheel should be set to its minimum value such that the measuring jaws of the caliper do not move the pins during the measurement. The overall dimension of the caliper must allow operation within the limited space of the access box after installation. Therefore, the use of 4-in (100 mm) calipers is suggested.

Digital calipers can usually resolve measurements to 0.0005 in (0.01 mm) and have an accuracy of +/- 0.001 in (0.025 mm). Considering the possible error of the operator, the expected accuracy of the readings from the crack monitor gauge is about +/- 0.01 in (0.25 mm).

FIELD INSTALLATION

The crack monitor gauge has been specifically designed to monitor crack or joint movement of PCC pavement slabs. However, the gauge can be used to monitor cracks in many other types of structures as well. The installation procedure described in this section pertains to its use on cracked and seated jointed concrete pavement slabs that are overlaid with asphalt concrete and have a paved shoulder. The gauge is designed to be installed on the edge of the slab at the outside lane-shoulder longitudinal joint.

After cracking and seating of the old concrete pavement slab, the station numbers of the cracks or joints selected for monitoring should be recorded and referenced. The candidate crack or joint should not exhibit a large lateral misalignment between both sides of the crack or joint, nor have badly broken edges. The minimum dimension of broken slab pieces required for installation is 1 ft (30 cm). When the break pattern specified is less than this dimension, breaking operations must be prohibited within 2 ft (60 cm) of the joint or crack to be instrumented. The crack monitor gauges will be retrofitted after the rehabilitation process is concluded including bringing the shoulder to grade. Since shoulder excavation for installation of gauges and access box may be a tedious operation, state highway agencies may want to consider inspecting candidate joints or cracks prior to paving the shoulder to ensure the crack or joint can accommodate the gauge.

Appendix A of this report lists the tools and equipment required for field installation. The following steps explain the installation process:

1. Identify the selected stations for installation and reference them so they can be located after the shoulder is paved.

2. After the shoulder has been paved and brought to grade, cut a 20-in-square (0.5-m-square) by 12-in-deep (0.3-m-deep) trench on the shoulder using a concrete saw. One side of the trench should be along the lane-shoulder joint.

3. Remove the shoulder material from the trench and clean the excavated area.

4. Use a 1/2-in-head (12.7-mm-head) cold chisel to expose the edge surface (side wall) of the overlaid concrete pavement slab, if necessary.

5. In order to examine the mounting surfaces, place the base plate of the crack monitor gauge to the left (approach side) of the designated crack or joint on the concrete side wall such that the top edge of the base plate is 1 in (2.5 cm) below the top of the old concrete pavement slab and the right edge of the base plate is adjacent to the crack or joint. Hold the base plate in place by hand. Check the clearance between the base plate and the slab so that the pins can move all the way along the slot and the key hole without touching the slab. If the pins touch the concrete, use a 3/16-in-head (4.7-mm-head) cold chisel to chip off a small groove on the concrete behind the slot.

6. Similarly, place the overlapping plate on the right side (leave side) of the crack or joint such that the top of the member is 1 in (2.5 cm) below the top of the old concrete slab and the remote arm is approximately at the middle of the slot and between the pins. Take care to insure that the edge of the mounting (attaching) portion of the overlapping plate does not extend into the joint or crack. This insures that the plates will not press against each other when the joint crack is fully closed.

7. While holding both parts of the gauge, check to see that they are parallel to the top of the slab. From directly above, look down at the top edge of the gauge and check that both parts of the gauge can slide parallel to each other with a slight clearance. If there is a misalignment, place the mounting portion of the overlapping plate in a vise and bend the remote arm to provide the necessary clearance. In some cases, it may be easier to correct the misalignment by chipping off some of the concrete at the point where the base or overlapping plate is being mounted.

8. If any corrective measure was taken, repeat steps 5 through 7 and recheck all the requirements. Once satisfied, use a pencil or marker to draw a template of the plates on the concrete slab, as

shown in figures 4 and 5, to guide installation. *Note: If a thermometer is installed at this location, refer to chapter 3 and proceed with the installation of the thermometer first, then continue the crack monitor gauge installation.*

9. Mix epoxy. Apply a thin coat (1/32-in-thick [0.8-mm-thick]) to the back of the spacer on the base plate, and fill the edge grooves around the spacer with epoxy as shown in figure 6. Apply a thin coat of epoxy to the mounting area on the concrete slab inside the previously drawn template. Align the base plate with the template on the concrete slab and apply pressure while gently twisting the base plate up and down a couple of times. Secure the gauge temporarily with duct tape while the epoxy cures. Avoid covering epoxied areas with duct tape, since this prolongs the curing time.

10. Apply thin coats of epoxy to the back of the flat mounting portion of the overlapping plate and to the concrete surface. Place the overlapping plate on the concrete slab with the remote arm between the pins and apply moderate pressure as in step 9 (see figure 7). If there is any epoxy in between the sliding components, wipe it off well. Temporarily secure the overlapping plate with duct tape as in step 9.

11. Protect the gauge from rain and cold weather during the curing of the epoxy. A heat lamp may be used to expedite the curing in cold weather.

12. In 70 °F (21 °C) temperature, allow 24 h for curing before using the gauge. In cooler temperatures, allow more time.

Figure 4. Drawing the template around the base plate.

Figure 5. Drawing the template around the overlapping plate.

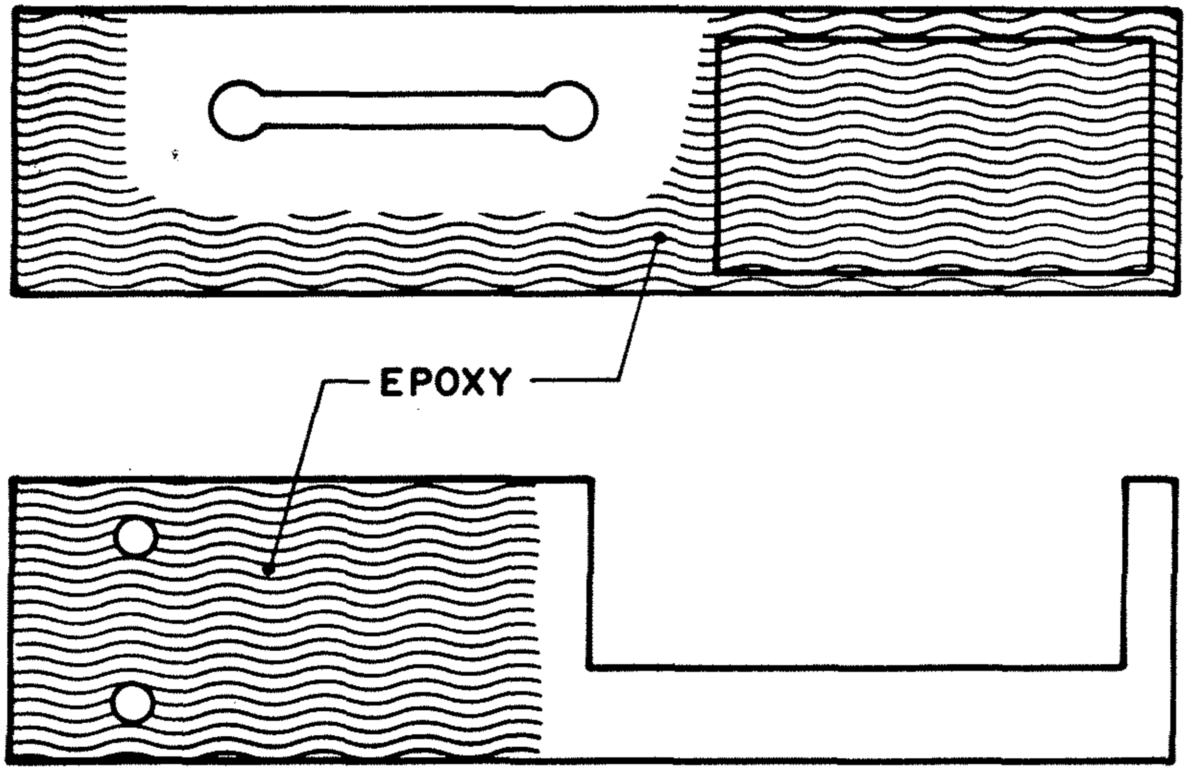


Figure 6. Application of epoxy to the mounting surfaces of the crack monitor gauge.

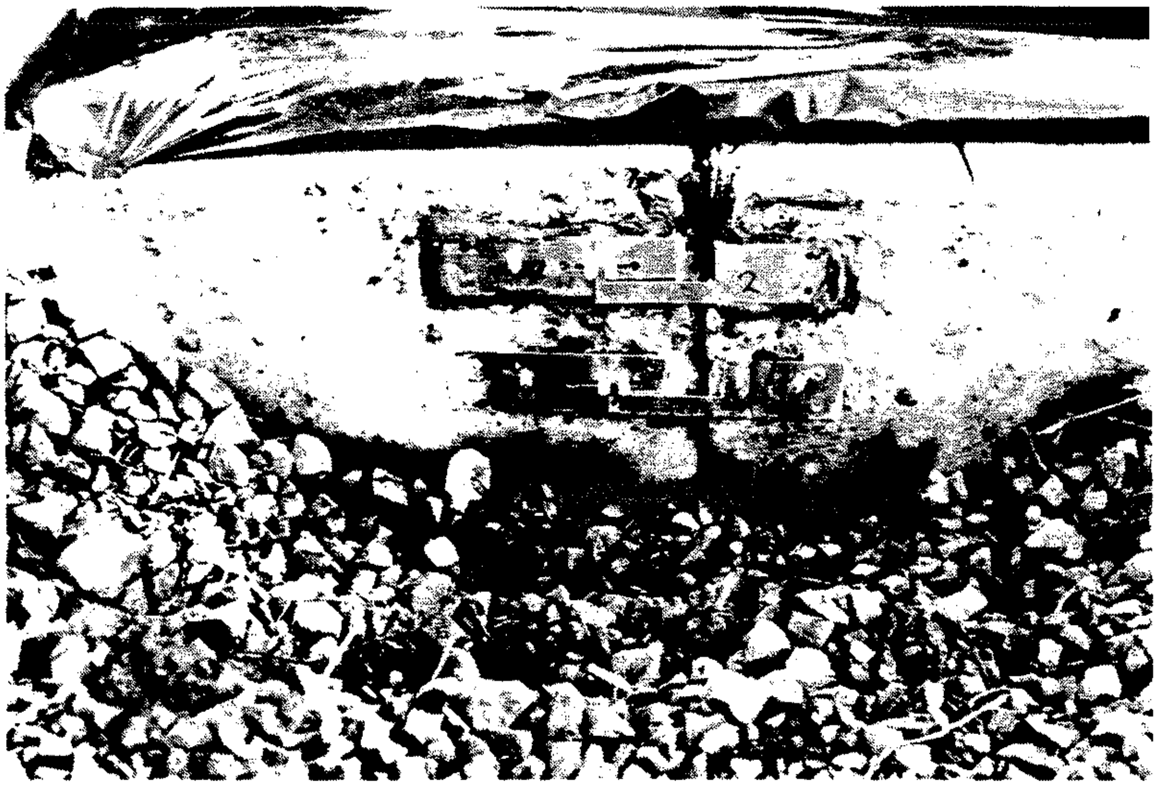


Figure 7. View of two crack monitor gauges installed at a joint.

3. TEMPERATURE SENSOR

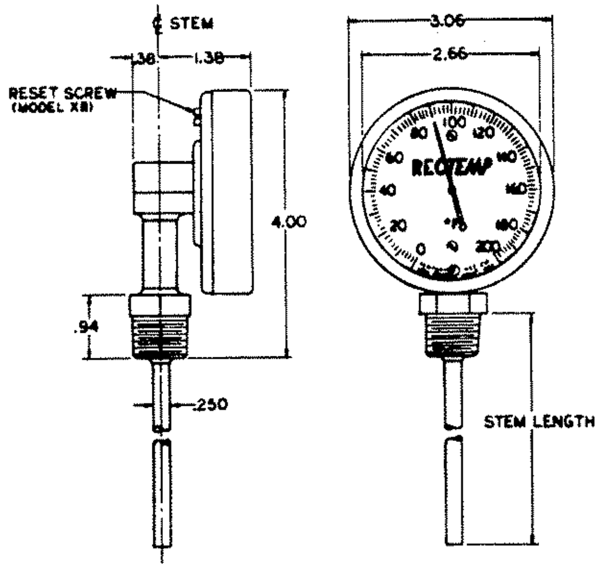
To monitor maximum and minimum crack or joint movement in PCC pavements, a continuous record of pavement temperature is essential. The most practical device that can provide a continuous temperature history for the pavement and that does not need electricity for monitoring and recording, is a chart recording stem thermometer. By installing two of these units, one at the top and one at the bottom of the pavement slab, a complete temperature history as well as gradient temperatures can be obtained for the pavement. However, these units come with a 24-h or 7-day recording chart and cost about $280 per unit. Therefore, their use is not recommended for this project.

Another alternative is to use a temperature measuring device that can record maximum and minimum temperatures in the pavement over a period of time. Two devices of this type are commercially available: gas- actuated and bi-metal thermometers. The former is more accurate and costs about $180 per unit. The latter type is more rugged and costs only about $55 per unit. The bi-metal thermometer is recommended for this project.

BI-METAL THERMOMETER

Figure 8 illustrates a typical bi-metal thermometer. The sensing element in this device is the bi-metal element, a single low-mass helix that fits inside the thermometer stem. Bi-metal elements are very responsive to temperature changes. To improve its accuracy, the element is usually heat treated and aged to relieve inherent stresses, and coated with a viscous silicon to reduce pointer oscillation and enhance temperature transmission.

These thermometers are constructed from stainless steel. They are available in 3-in (7.6-cm) and 5-in (12.7-cm) diameter display faces (dials) and come in various stem lengths and temperature ranges and models. The location of the stem relative to the display dial varies among available models.



NOTE: Measurements in inches.

Figure 8. Typical upright bi-metal thermometer.

For this project, an upright model manufactured by Reotemp Instrument Corporation with a 4-in (10-cm) stem, 3-in (7.6 cm) display dial, and working range of -40 °F to 160 °F (-40 °C to 71 °C) is recommended. A special order is required to customize this model with minimum and maximum pointers.

INSTALLATION

The bi-metal thermometers should be installed in close proximity to the crack monitor gauges and housed in the same access box. The following steps describe the installation procedure for this device:

1. Locate a point to the right (leave side) of the crack or joint at mid-depth of the concrete slab and approximately 5 in (12.7 cm) to the left.
2. Use a 3/16-in-head (4.7-mm-head) cold chisel and hammer to create an indentation on the side of the concrete slab for guiding the drill bit.
3. Using a powerful hammer drill with a 1/4-in (6.3-mm) bit, drill a hole horizontally and 4.5-in-deep (11.4-cm-deep).
4. Insert the stem of the thermometer loosely into the hole to verify that the hole has sufficient depth and width.
5. Remove the thermometer and fill the hole with a viscous silicon.

Note: To avoid damage to the thermometer, do not insert the thermometer before the crack monitor gauge and the access box are installed.

4. ACCESS BOX

The crack monitor gauge and the thermometer are installed along public highways. To avoid any potential hazard for motorists, the excavated area should be completely covered. An access box is needed to house the crack monitor gauge and the thermometer. The access box must be able to sustain the weight of a fully loaded truck wheel. The box should also protect the gauge and thermometer from environmental factors and provide easy access to these instruments.

DESIGN

Figure 9 depicts the rectangular access box with overall dimensions of 20 x 10 x 12 in (51 x 25 x 31 cm). It consists of three side walls and a top. One 20-in side of the box is open and placed by the concrete slab. The bottom of the box is left open to allow for drainage and easy installation. The top is hinged on the narrow side and is screwed to the other side wall. When properly installed, the top should be flush with the road/shoulder surface with the hinged side on the approach slab side of the crack or joint.

FABRICATION

The box is made of steel in order to withstand a loaded truck tire. The three side walls are fabricated from a single 1/8-in-thick (3.2-mm-thick) sheet of steel with bent corners; the top of the box is fabricated from a 1/4-in-thick (6.3-mm-thick) steel plate. The box should be painted black to make it less noticeable.

INSTALLATION

After installation of the crack monitor gauge and the thermometer, the access box can be installed. It is recommended that the thermometer be removed during installation of the box to avoid any possible damage. The following steps describe the installation procedure:

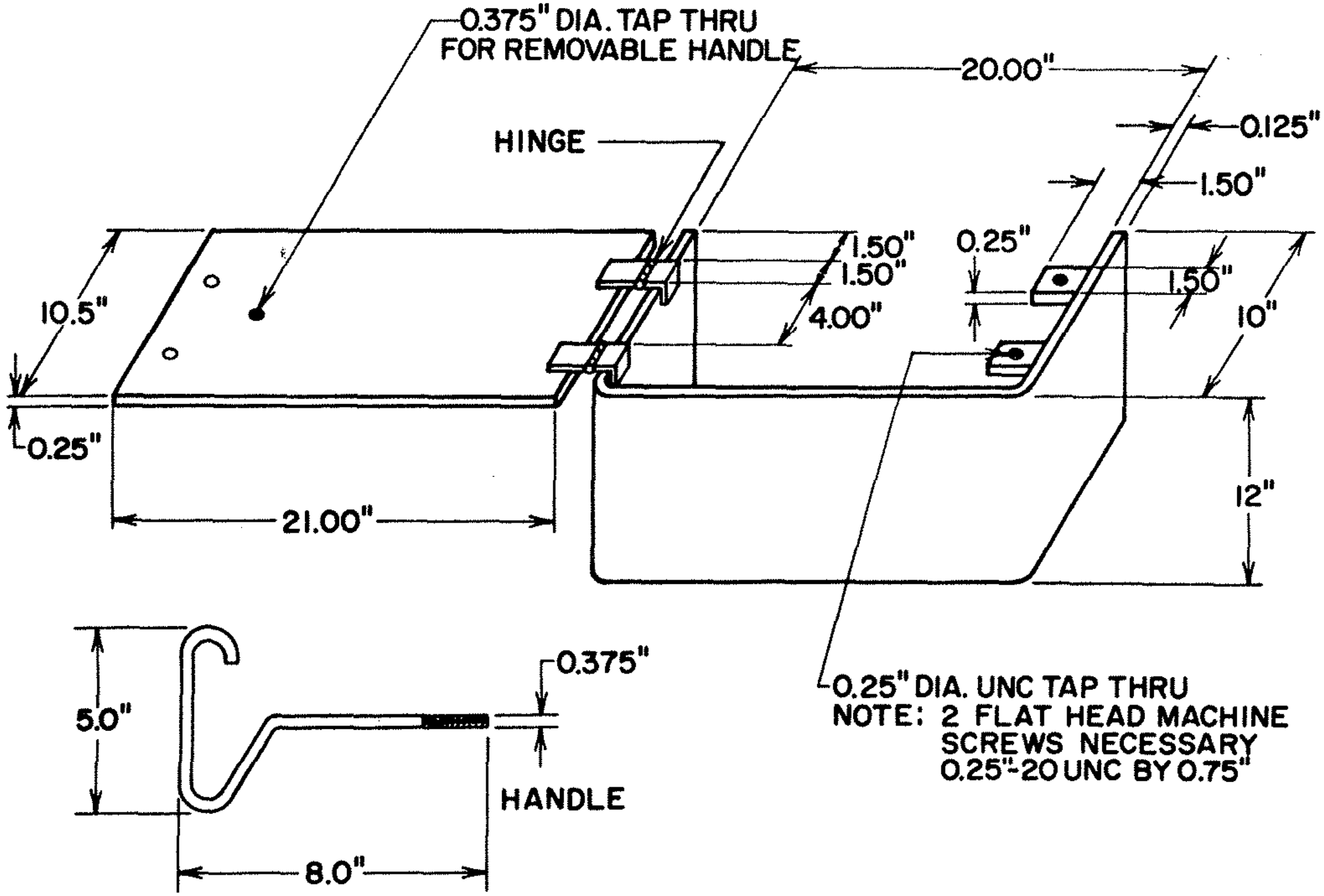


Figure 9. Schematics and dimensions of the crack monitor gauge access box.

1. Place the box in the cut trench with the open side toward the concrete slab (see figure 10). The top of the box should be flush with the shoulder. If the top of the box is more than 1/2 in (1.3 cm) above the shoulder, and cannot be forced down by pounding on the top edge of the side walls (avoid pounding on the hinges), remove the box and use chisel and hammer to lower the support.

2. If the support is too deep or too soft, place large pieces of rock or scrap steel plate under the side walls to raise and/or strengthen the support.

3. Once satisfied with the support condition and overall box placement and functioning, try inserting the thermometer. Also, use the caliper on the gauge to make certain there is enough clearance for operation of the caliper in the extreme pin positions. Make any adjustments deemed necessary.

4. Use cold-mix or hot-mix asphalt concrete to fill the remainder of the excavated shoulder and compact. Take care that the access box doesn't move along the edge of the slab.

5. Make sure that the top of the box can be opened and is nearly flush with the shoulder surface.

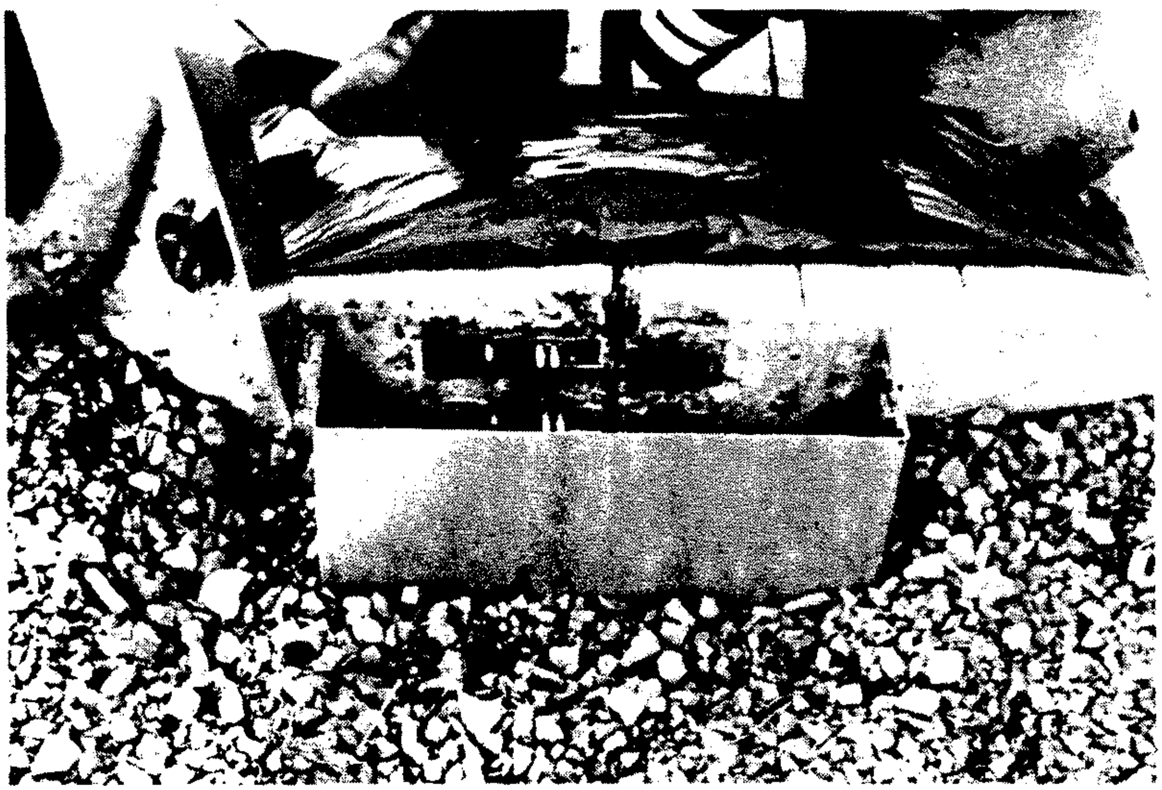


Figure 10. Placement of the access box.

5. OPERATION AND MEASUREMENT

PRINCIPLE OF OPERATION

At the beginning of the gauge monitoring period, the crack or joint opening (W_i) should be accurately measured and recorded on the data sheet (figure 11). Then the sliding pins should be pushed against both sides of the remote arm (see figure 12), and the distance between the fixed reference pin and the left sliding pin (R_i) should be measured and recorded with an inside caliper (see figure 13). This reading will also be used as the reference distance for calculation of the maximum and minimum crack or joint openings of the first period. At the end of each monitoring period, the distances between the reference pin and the new positions of the sliding pins are measured using an inside caliper and recorded on the data sheet (SD and LD). The sliding pins are then manually pushed against both sides of the remote arm, and the distance between the reference pin and the left sliding pin (R_n) is measured as shown in figures 12 and 13 and recorded on the next line of the data sheet (to be used as the reference distance for the next monitoring period). Once these parameters have been measured for a given period, the maximum, minimum, and instantaneous crack or joint openings may be calculated.

If the crack or joint opening changes by an amount equal to Δ in one direction, the remote arm moves by the same amount in the same direction (see figure 14). Therefore:

$$W_i = W_n + \Delta \qquad (1)$$

and

$$R_n + \Delta = R_i \qquad (2)$$

where

W_i = initial joint opening

W_n = instantaneous joint opening

R_i = initial reference distance

R_n = instantaneous reference distance

CRACK MONITOR DATA SHEET

Location:	Mid-depth Gauge
Date of Installation:	1/16/90
System of Units (mm or inch):	mm
Initial Joint Opening (Wi):	5.42
Initial Reference Distance (Ri):	44.08

Date	Time	Measured Parameters: Reference Distance Rn	Measured Parameters: Short Dist. SD	Measured Parameters: Long Dist. LD	Calculated Parameters: Joint Opening Instant Wn	Calculated Parameters: Joint Opening Minimum Wmin	Calculated Parameters: Joint Opening Maximum Wmax
1/19/90	2:05 PM	44.08	44.08	58.50	5.42	5.42	6.58
1/22/90	2:25 PM	44.87	44.82	58.45	6.21	6.16	6.53
1/23/90	1:35 PM	44.89	44.77	58.57	6.23	6.11	6.65
1/24/90	1:45 PM	44.79	44.19	58.18	6.13	5.53	6.26
1/25/90	2:20 PM	44.19	44.18	57.82	5.53	5.52	5.90
1/26/90	2:00 PM	44.48	44.32	58.09	5.82	5.66	6.17
1/30/90	4:45 PM	44.80	44.63	58.72	6.14	5.97	6.80
1/31/90	2:00 PM	45.18	45.18	58.45	6.52	6.52	6.53
2/ 1/90	3:00 PM	45.27	44.94	58.65	6.61	6.28	6.73
2/16/90	2:00 PM	45.06	43.97	58.54	6.40	5.31	6.62
2/23/90	11:30 AM	43.97	43.81	58.78	5.31	5.15	6.86

Footnote:

Wn = Rn + Wi - Ri
Wmin = Wn - (Rn - SD)
Wmax = Wn + LD - (Rn + b + d)
b = Width of the remote arm = 6.83 mm
d = diameter of the left sliding pin = 6.43 mm

Figure 11. Data sheet for a rigid pavement joint at the Pennsylvania State University Pavement Durability Facility.

Figure 12. Pushing the sliding pins against the remote arm.

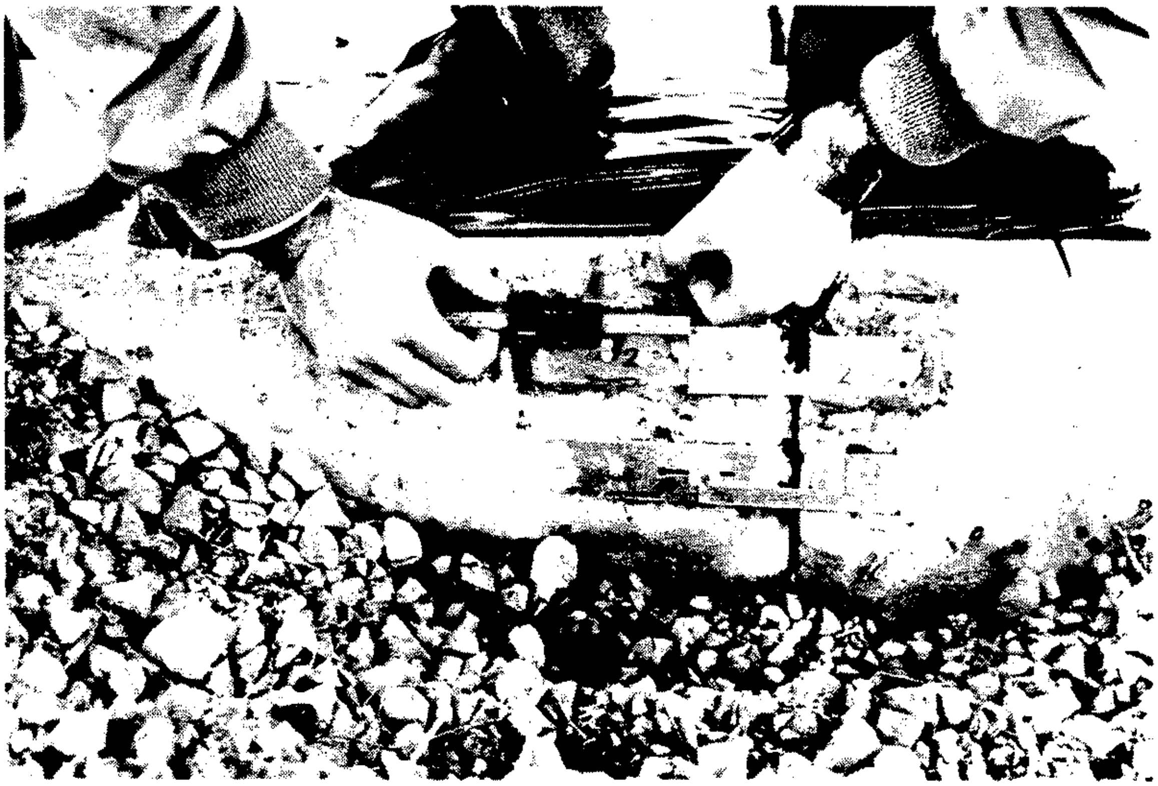


Figure 13. Measuring the distance between the reference pin and the left sliding pin.

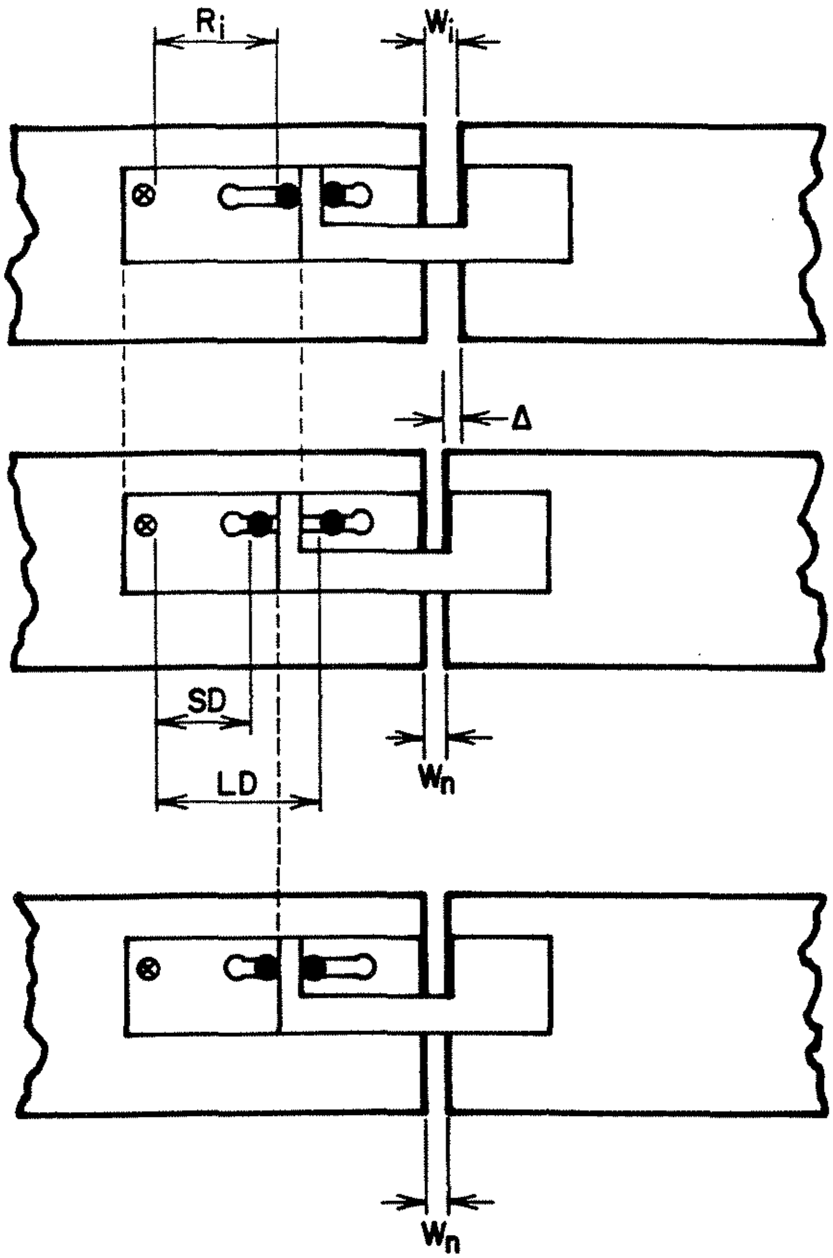


Figure 14. Schematics of operation of crack monitor gauge.

The elimination of Δ between equations 1 and 2 by adding both sides and rearranging, gives:

$$W_n = R_n + W_i - R_i \qquad (3)$$

When the concrete slabs expand, the crack or joint opening becomes smaller. From the above discussion with reference to figure 14, it can be seen that this reduction in the joint opening is equivalent to the distance that the left pin is pushed to the left by the remote arm.

$$\text{Crack or Joint Opening Reduction During the Period} = (\text{Initial Short Distance}) - (\text{Current Short Distances}) = R_n - SD \qquad (4)$$

where

SD = short distance, the distance between the reference pin and left sliding pin

Subtracting the joint opening reduction (equation 4) from the instantaneous joint opening results in the minimum joint opening during the period:

$$W_{min} = W_n - (R_n - SD) \qquad (5)$$

As the concrete slabs contract, the joint opening increases and the remote arm pulls the right pin to the right. This increase in crack or joint opening is equivalent to the distance that the right pin has moved.

$$\text{Original Position of Right Pin} = R_n + b + d \qquad (6)$$

$$\text{Crack or Joint Opening Increase During the Period} = LD - (R_n + b + d) \qquad (7)$$

where

b = width of the remote arm

d = diameter of the left pin

LD = long distance, the distance between the reference pin and right sliding pin

Adding the joint opening increase (equation 7) to the instantaneous joint opening yields the maximum crack or joint opening:

$$W_{max} = W_n + LD - (R_n + b + d) \quad (8)$$

The above equations are valid for any consistent units of measurement. Figure 11 illustrates a completed data sheet for a pavement joint monitored at the Pennsylvania State University Pavement Durability Facility. All the measurements in figure 11 are in millimeters. Appendix B includes a blank data sheet with the equations required to perform the calculations. Figure 15 depicts instantaneous, minimum, and maximum joint openings for that joint.

INSTRUCTIONS ON CONDUCTING MEASUREMENTS

The following steps describe the procedure for performing periodic measurement of crack or joint movement:

1. Fill out the top portion of the data sheet by recording the location of the installed gauge (i.e., road number and station), date of installation of the gauge, and the system of units that will be used for performing measurements. Consistent units should be used for the entire data sheet.

2. Measure the crack or joint opening near the point of installation of the gauge using the inside caliper or any other means as accurately as possible. Record this measurement under W_i at the top of the data sheet.

3. Measure the width of the remote arm and the diameter of the left sliding pin and record these measurements at the bottom of the data sheet.

4. Push the sliding pins against both sides of the remote arm as shown in figure 12.

5. Measure the distance between the fixed reference pin and the left sliding pin using an inside caliper as shown in figure 13.

6. Record the measured distance in step 5 under R_i at the top of the data sheet.

7. Record the measured distance in step 5 as the first entry under the R_n column. Record the date and time of measurement as the first entries under the appropriate columns, and reset the maximum and minimum pointers of the thermometer.

8. At the end of the first monitoring period (beginning of the next period), perform the following steps:

   a. Record the date and time under the appropriate columns on the data sheet.

   b. Read the maximum and minimum pavement temperatures over the monitoring period from the thermometer and record them under the appropriate columns on the data sheet.

   c. Measure the distances between the reference pin and the new positions of the sliding pins and record them under the SD and LD columns.

   d. Repeat steps 4 and 5 and record the measurement under the appropriate column for the next monitoring period.

9. Repeat steps 8 a, b, and c for every monitoring period.

PERFORMING CALCULATIONS

After completion of every monitoring period (every line in the data sheet), instantaneous minimum and maximum crack or joint opening can be calculated using equations 3, 5, and 8 respectively. These equations also appear at the bottom of the data sheet. Therefore, in order to complete all the calculations, equations 3, 5, and 8 must be used for each line in the data sheet, and the resulting parameters must be recorded under the appropriate columns in the data sheet.

The entire data sheet with all the pertinent equations can be entered into a spread sheet on a personal computer, and the results can be plotted as shown in figure 15.

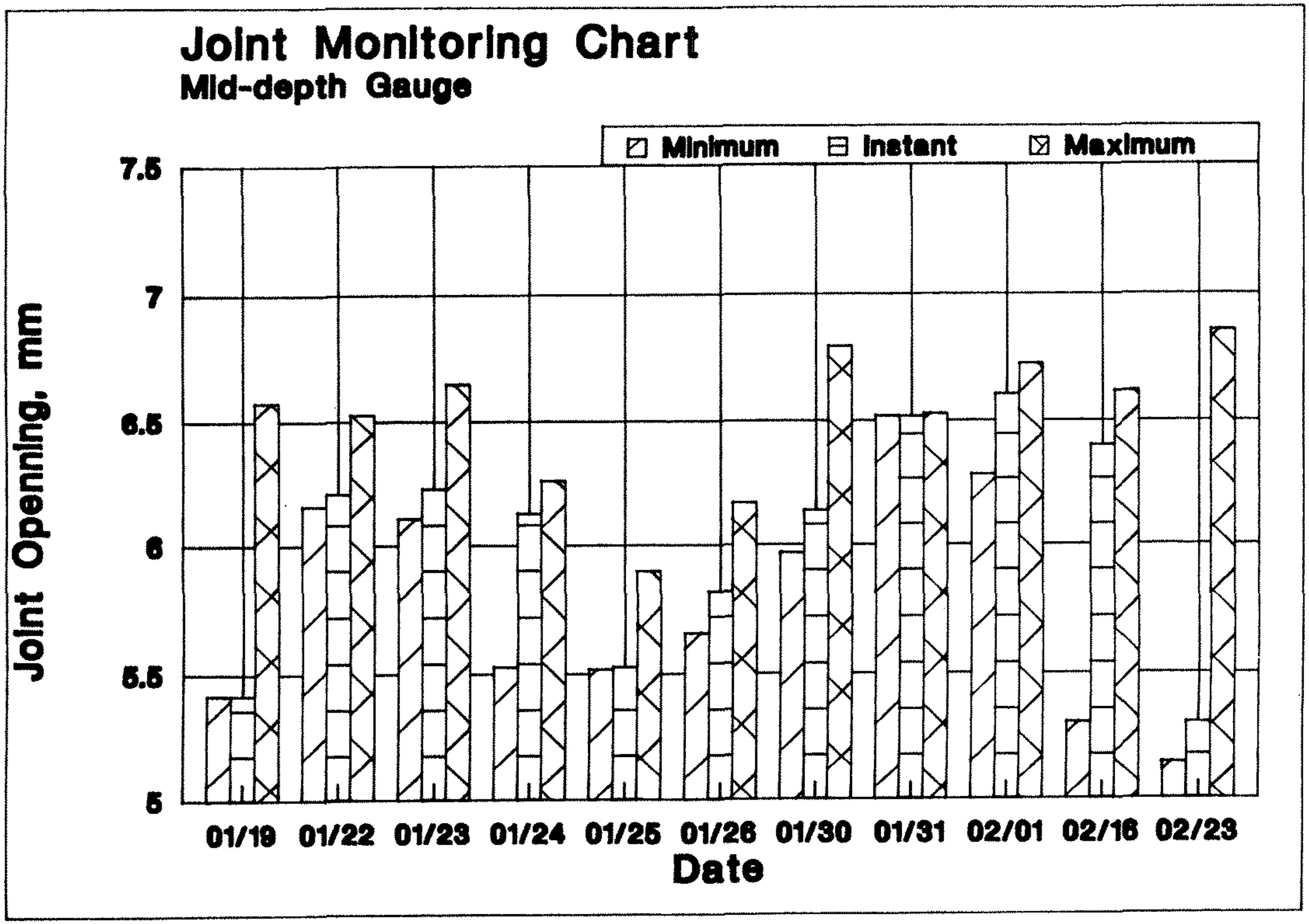


Figure 15. Rigid pavement joint monitored at the Pennsylvania State University Pavement Durability Facility.

6. SUMMARY

A mechanical gauge was developed to monitor the movement of crack or joint openings in portland cement concrete pavements. Although it was designed specifically for monitoring crack or joint movement in rigid pavements, the gauge can be used for other types of concrete structures as well. Measurements of maximum, minimum, and instantaneous crack or joint openings can be obtained from this gauge. Low cost, high accuracy, and ease of installation and operation are some of the characteristics of this mechanical gauge.

The report includes guidelines for the design, fabrication, installation, and operation of the crack monitor gauge as well as the thermometer and access box.

APPENDIX A: REQUIRED TOOLS AND EQUIPMENT FOR FIELD INSTALLATION

GENERAL TOOLS

Cold chisels (3/16-in, 1/2-in, 3/4-in head [4.7-mm, 1.3-cm, 1.9-cm head])
Hammer
Pick axe
Pry bar
Scoops
Shovels
Measuring tape
Plastic sheets
Duct tape
Epoxy (paste form)
Silicon rubber
Disposable mixing plate for epoxy or paint mixing can
Putty knife for mixing and applying epoxy
Marking pens

EQUIPMENT

Concrete saw
Drill hammer (minimum of 1.5 hp)
Drill bits (3/16-in, 1/4-in [4.7-mm, 0.63-mm])
Power generator (minimum of 15 A and 2000 W)

APPENDIX B: CRACK MONITOR DATA SHEET

Location:
Date of Installation:
System of Units (mm or inch):
Initial Joint Opening (Wi):
Initial Reference Distance (Ri):

Date	Time	Pavement Temperature		Measured Parameters			Calculated Parameters		
							Crack or Joint Opening		
		Min. (F)	Max. (F)	Reference Distance Rn	Short Dist. SD	Long Dist. LD	Instant Wn	Minimum Wmin	Maximum Wmax

Footnotes:

Wn = Rn + Wi - Ri
Wmin = Wn - (Rn - SD)
Wmax = Wn + LD - (Rn + b + d)
b = Width of the remote arm =
d = diameter of the left sliding pin =