OKLAHOMA RESEARCH PROGRAM
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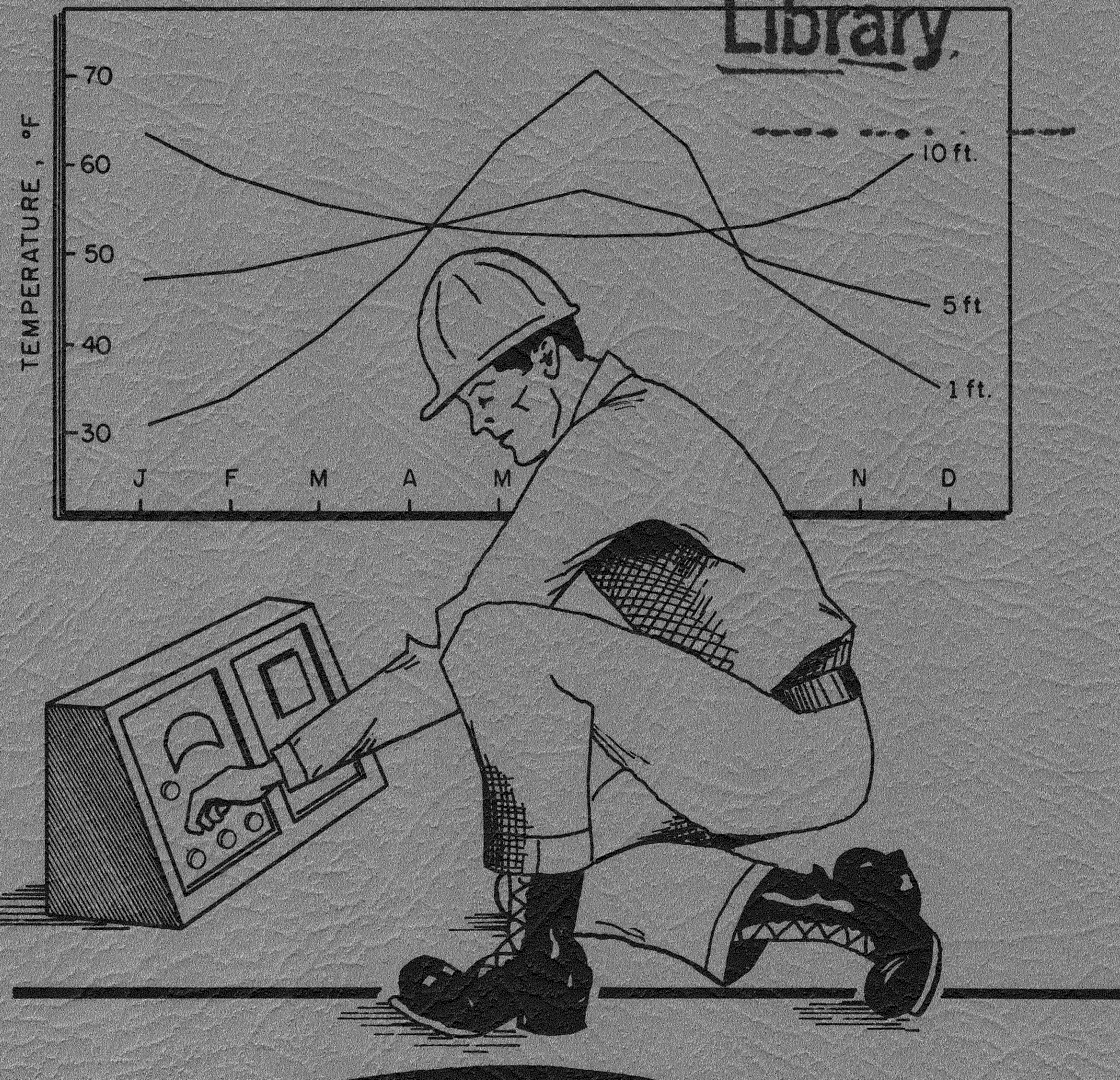


# SUBGRADE MOISTURE VARIATIONS

INTERIM REPORT VII

# SUBGRADE TEMPERATURE MEASUREMENT

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Stillwater, Oklahoma

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## INTERIM REPORT VII: SUBGRADE TEMPERATURE MEASUREMENT


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## PREFACE

In previous interim reports, data have been presented to show relations between measured subgrade moisture conditions, climatological factors, highway design characteristics, and pavement performance. Similar data are still being collected and evaluated to provide a background for the development of highway design recommendations to improve pavement performance.

Moisture conditions at several existing field research sites could not be related to measured precipitation, though subgrade moisture variations certainly occurred. At these sites, moisture conditions were thought to be temperature-dependent. The research described in this report was undertaken to develop instrumentation for measurement of subsurface temperature gradients beneath existing highways, relate them to measured subgrade moisture conditions, and determine the relative effect of subgrade temperature gradients on overall subgrade moisture variations in Oklahoma subgrades. Research objectives appear to have been satisfactorily accomplished.

This report is the seventh of an interim nature to be submitted by the Subgrade Moisture Variations research project, Oklahoma Research Program Number 64-01-3. Future interim reports will be concerned with evaluation of collected data and development of design recommendations for improving pavement performance on Oklahoma subgrades.

Support for this study is provided by the State of Oklahoma, Department of Highways, in cooperation with the U.S. Department of

Transportation, Federal Highway Administration, Bureau of Public Roads.
This support is gratefully acknowledged.

R.D.O.

T.A.H.

## LIST OF REPORTS

Interim Report I: "Preliminary Planning," by T. Allan Haliburton, June, 1966, reviews current utilization of nuclear equipment and presents a tentative plan for project operations.

Interim Report II: "Access Tube Installation," by Wayne L. Heiliger and T. Allan Haliburton, January, 1967, describes procedures used to install access tubing for nuclear depth moisture-density equipment beneath highway pavements.

Interim Report III: "A Preliminary Standardization and Calibration Procedure for Nuclear Depth Moisture/Density Gages," by E. W. LeFevre and Phillip G. Manke, May, 1967, describes an interim calibration procedure for project use of nuclear depth moisture and density gages.

Interim Report IV: "Suggested Nuclear Depth Gage Calibration Procedures," by Raymond K. Moore and T. Allan Haliburton, January, 1968, describes final procedures used in calibrating project nuclear depth moisture and density gages.

Interim Report V: "Data Summary 1966-1967," by T. Allan Haliburton, April, 1968, presents all data collected at the first 30 field test sites during the period June, 1966, to August, 1967.

Interim Report VI: "Evaluation of Collected Data 1966-1967," by B. D. Marks III and T. Allan Haliburton, May, 1968, presents an evaluation for all data collected at the first 30 field test sites during the period June, 1966, to August, 1967.

ABSTRACT

Measured moisture conditions at several existing field research sites could not be related to precipitation, and were thought to be temperature-dependent. Accordingly, subsurface thermistor probes were installed at six field research sites, to measure subgrade temperature gradients and relate them to measured subgrade moisture conditions. After a review of previous work in thermal moisture flow and subgrade temperature measurement by other agencies, instrumentation and procedures for measurement of subgrade temperatures under existing highway pavements are described, and procedures for data collection and evaluation are given.

Results of the research showed that temperature gradients caused measurable subgrade moisture migration, but, in Oklahoma subgrades, the magnitude of temperature-induced moisture variation appears to be of secondary nature, when compared to other factors causing subgrade moisture variations. It is possible, however, that temperature-induced moisture migration and resulting heave may be sufficient to cause initial pavement cracking. Once the pavement is cracked, large precipitation-dependent subgrade moisture variations occur, producing rapid pavement deterioration.

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# CHAPTER 1. INTRODUCTION

Subgrade moisture variations may cause changes in volume and strength of subgrade soils. These changes may contribute to premature highway pavement failure and result in high maintenance costs. Study of moisture variations and their effects on subgrade soil properties may result in revisions of current highway design methods and construction procedures, leading to improved pavement performance.

The School of Civil Engineering at Oklahoma State University began, in June, 1964, a six-year study of subgrade moisture variations under Oklahoma highway pavements. The study is conducted in cooperation with the State of Oklahoma, Department of Highways and the U.S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads.

## Statement of the Problem

Subgrade moisture variations beneath Oklahoma highways may be caused by infiltration of surface water or migration of moisture in the liquid phase from areas adjacent to the subgrade. Moisture variations beneath some highway pavements may also be temperature-dependent and occur in the vapor phase. Vapor phase moisture migration (thermal soil moisture flow) may occur if a temperature gradient is applied to the subgrade. Therefore, subgrade temperatures should be measured concurrently with subgrade soil moisture to determine what temperature gradients occur in highway subgrades, and whether these temperature gradients cause significant moisture migration.

## Scope of this Study

The scope of this study is 1) to develop methods and procedures for measuring subgrade temperatures, 2) to correlate measured subgrade temperatures and moisture conditions and 3) to present conclusions concerning the effects of subgrade temperature on subgrade moisture conditions.

# CHAPTER 2. THERMAL SOIL MOISTURE FLOW

## Theory of Thermal Soil Moisture Flow

A temperature gradient applied to a soil mass may cause soil moisture flow, mainly in vapor phase and caused by a decrease in vapor pressure along the temperature gradient. Vapor pressure is the pressure of water vapor when in equilibrium with its liquid phase (Ref 1). Equilibrium occurs when evaporation and condensation of water proceed at equal rates. For any given temperature there is only one pressure at which water vapor is in equilibrium with its liquid phase. Figure 2.1 shows that as temperature decreases vapor pressure decreases proportionally (Ref 1). A decrease in vapor pressure along the temperature gradient is the moving force of soil moisture flow. Soil moisture evaporates in the warm region of the soil mass, then follows the pressure gradient induced by the temperature gradient; therefore soil moisture moves in the direction of decreasing temperature.

The amount of thermal soil moisture flow is a function of soil type, density, and moisture content (Refs 2, 3, 4). Soils with large continuous voids such as sands and sandy silts experience greater amounts of thermal soil moisture flow than soils with small voids or tightly packed grains such as clays or very dense sand. Thermal soil moisture flow in saturated soils or soils with liquid moisture in their voids is negligible (Ref 5). Thermal soil moisture flow occurs in soils with low moisture contents. Maximum thermal soil moisture flow occurs

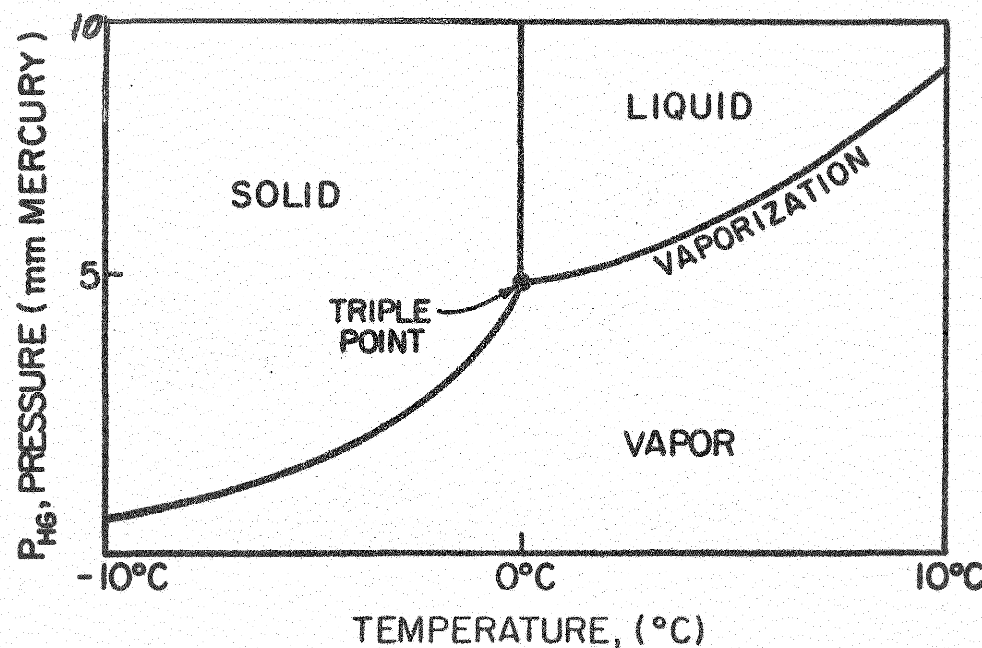


Figure 2.1. Triple Point Diagram for Water

when soil moisture content is near the soil's plastic limit (Ref 4).

Experimental Studies of Thermal Soil Moisture Flow

Within the last twenty years there have been many observations and investigations of soil moisture flow under influence of a thermal gradient. This flow occurs mainly in the vapor phase and, under specific conditions, may cause appreciable moisture movement.

Thermal soil moisture flow was investigated by Moore (Ref 6) and Smith (Ref 7). They found soil moisture flow increased with changing soil temperature conditions. Moore believed temperature changes caused transfer of soil moisture in liquid phase while Smith assumed that moisture moved in vapor phase.

In subsequent soil moisture studies, Gurr, Hutton, and Marshall (Ref 8) agreed with Smith's assumption of soil moisture transfer. They used soil samples sealed in plastic containers for their study. A sodium chloride solution was added to the soil, and one end of the plastic container was cooled to a temperature of $10^{\circ}C$ while the other end was maintained at a temperature of $25^{\circ}C$. They found soil moisture content increased at the cooled end while chlorides were deposited at the warm end. As a result, they believed soil moisture evaporated at the warm end and then moved to the cooled end as vapor. In a similar study, Hutcheon (Ref 9) used soil sealed in plastic containers. The containers had one end maintained at a temperature $10^{\circ}C$ to $20^{\circ}C$ cooler than the other end. He found soil moisture content increased near the cooler end while decreasing at the warmer end.

Taylor and Cavazza (Ref 10) modified Hutcheon's procedure. Their soil samples were prepared in five sections, separated by air gaps. The samples were sealed in containers, and a temperature gradient was applied to the soil. They found soil moisture content increased in the soil nearest the cooled section while decreasing near the warmer end. They believed that soil moisture moved in vapor phase, because moisture in liquid phase would not have passed across the air gaps. Philip and DeVries (Ref 5) were not satisfied with Taylor and Cavazza's idea of thermal soil moisture flow. DeVries believed thermal soil moisture flow occurred both in liquid and vapor phase. He believed soil moisture in liquid phase formed between soil grains at their points of contact. When a temperature gradient was applied to the soil, the liquid diffused to a vapor. After diffusion, the vapor flowed through the soil in the direction of decreasing temperature.

After Philip and DeVries' investigation, Moore (Ref 11) studied the possibility of soil moisture transfer in pavement subgrades. He measured moisture content and temperature of subgrade under a residential street in College Station, Texas, and found that a temperature gradient did exist in the subgrade but soil moisture content did not change. As a result, he believed the temperature gradient was insufficient to cause soil moisture flow.

Recently, Straub, Dudden, and Moorhead (Ref 12) studied soil moisture flow under pavement slabs. Thermistor probes were used to measure soil temperature, while nuclear depth gauges were used to measure soil moisture content. They found that soil temperatures and moisture contents changed, and believed changing soil moisture content was caused by varying soil temperatures. Richards (Ref 13) also studied thermal soil moisture flow under pavement slabs in Australia. Richards found temperature variations in soil under pavement slabs were of insufficient magnitude and duration to cause soil moisture flow. He believed the relatively constant air temperature of Australia caused temperature gradients under pavement slabs to be small.

The general conclusions of the investigations summarized in this chapter are that soil moisture flows when a temperature gradient is applied to the soil and this moisture flow occurs mainly in vapor phase. Many of these investigations were conducted in laboratories under ideal conditions, and did not duplicate actual conditions found under pavements and other covered areas. As a result, several field studies were made to determine if thermal soil moisture flow occurred in pavement subgrades. The field studies were inconclusive. Several researchers found that soil temperature and moisture content varied. Other researchers believed temperature gradients under pavements were of insufficient magnitude and duration to cause soil moisture flow.

# CHAPTER 3. EQUIPMENT AND PROCEDURES FOR MEASURING SUBGRADE TEMPERATURES

Highway subgrade temperatures were to be measured, to determine 1) what temperature gradient existed in the subgrade and 2) how the temperature gradient affected subgrade moisture conditions. This chapter describes equipment and procedures for measuring subgrade temperatures. Subgrade moisture measurements used in the study were collected by means of nuclear depth moisture and density probes. Detailed procedures for measuring subgrade moisture conditions are given by Marks and Haliburton (Ref 14).

## Construction of Temperature Probes

Subgrade temperatures were measured at one foot intervals to a depth of ten feet, to correspond with concurrent nuclear moisture measurements. Temperature probes were designed and constructed to obtain proper placement of temperature detectors. Thermocouples and thermistors were considered for use in subgrade temperature measurement. Thermocouples were rejected because of their tendency to require continuous recalibration; therefore thermistors (semiconductors which experience a large electrical resistance change with a slight change in temperature) were selected for use in the temperature probes. Recalibration was not necessary, and the particular thermistors selected were interchangeable.

As shown in Fig 3.1, a subgrade temperature probe consisted of one half of a redwood 2x4, ten ft in length, with thermistors inserted into 1/4 in. holes drilled at one foot intervals along the length of the redwood. Corners of the redwood were mitered so the probe could be inserted into a 2 in. OD hole augered in the subgrade. A 1/2 in. square channel cut along the length of the redwood provided a groove for lead wires that connected thermistors to standard 1/4 in. phone plugs. After thermistors and lead wires had been positioned in the redwood, melted microcrystalline wax was poured into the holes and square channel. The wax provided a means to waterproof and attach thermistors to the redwood.

Thermistors, lead wire, and phone plugs were purchased separately and assembled for use in the temperature probes at a considerable savings in cost. Individual components were purchased for approximately $4.00 while factory assembled components cost a minimum of $14.00. Total cost of a temperature probe constructed with individually purchased components was approximately $50.00. The thermistors selected for use in the temperature probes were Yellow Springs Instrument Company, Yellow Springs, Ohio, Model 44004 component thermistors which have a temperature measurement range of $-80^{\circ}C$ to $150^{\circ}C$. This model thermistor was selected because:

1. expected range of subgrade temperature occurrence was within the temperature detection range of the thermistor,
2. the Model 44004 thermistor was a general purpose component with a low unit cost, and
3. the thermistor was compatible with the selected readout instruments purchased from Yellow Springs Instrument Company (YSI).

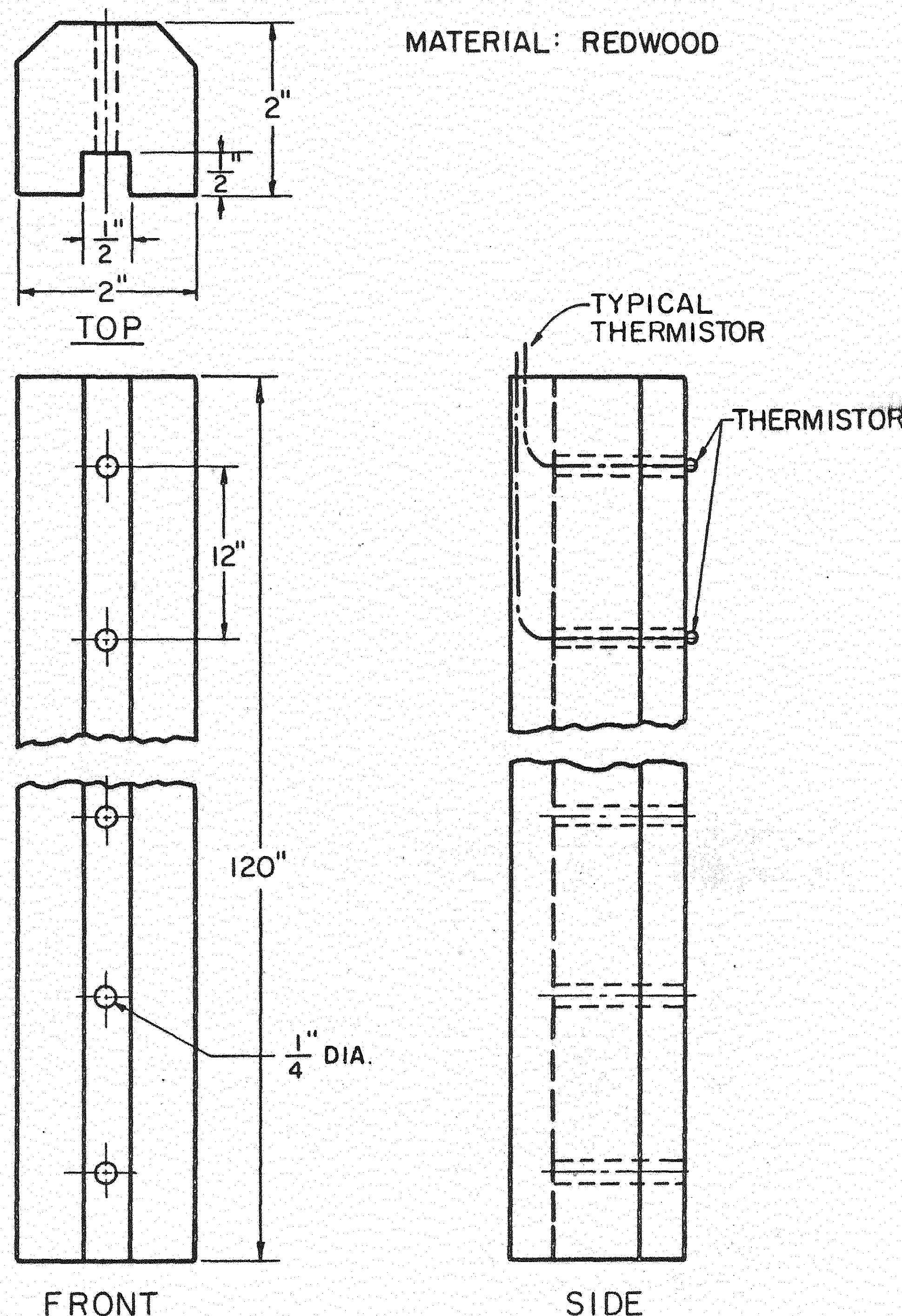


Figure 3.1. Temperature Probe

Any type of two conductor lead wire and standard 1/4 in. phone plug were suggested by the manufacturer for use with this model thermistor. However, the lead wire used was within size 18 to 22 gage, because ten pairs of lead wire within this particular range could be placed in the 1/2 in. square channel cut in the temperature probe.

## Instrumentation

Subgrade temperatures were measured indirectly by means of thermistors and specially designed electrical readout instruments. A thermistor, as noted previously, is a semiconductor in which a large change of electrical resistance is caused by a small change in temperature. Measurement of this resistance change will give the temperature at the point where the thermistor is located. If the thermistor is used as one arm of a Wheatstone bridge circuit, resistance of the thermistor may be determined by measuring current passing along that branch with a galvanometer. The galvanometer scale may be calibrated so that as current is measured temperature may be read directly from the scale. A galvanometer and Wheatstone bridge circuit designed specifically as a readout instrument for temperature measurement is manufactured by YSI, and called a YSI Thermistemp TeleThermometer. A Model 47TE TeleThermometer was purchased from YSI for this study. This telethermometer was selected because:

1. The Model 47TE TeleThermometer could measure temperature over the range $-10^{\circ}F$ to $105^{\circ}F$. Expected range of subgrade temperature occurrence was within this measurement range.
2. An automatic scanning feature of the telethermometer allowed one man to make subgrade moisture measurements while the telethermometer measured subgrade temperature. Data collection thus required a minimum of time.

To utilize the scanning feature of the telethermometer, it was necessary to purchase a YSI Model 80 Laboratory Recorder. This recorder was selected because it was designed as a companion instrument for the Model 47 TeleThermometer.

Both the recorder and telethermometer operated on 110 VAC power. To supply power in the field a portable DC-AC power inverter was purchased from Sears, Roebuck and Company. The portable power inverter was selected because of its ability to power the telethermometer and recorder for approximately eight hours. This allowed numerous subgrade temperature measurements without recharging the inverter. Figure 3.2 shows power inverter, recorder, and telethermometer connected for subgrade temperature measurement.

## Site Selection

Forty-eight research sites with various soil and highway design characteristics are currently located in north central and northeastern Oklahoma; six were selected to receive temperature probes. The number of sites was limited to six because the feasibility of such a study was to be determined before investing a larger sum of money, and the number of temperature probes that could be constructed and installed was limited because this initial study was to be completed within one year. Temperature site selection was based on several criteria to insure that sites with various soil and highway design characteristics would be selected. There were four basic criteria:

1. Only those SMV research sites with excellent pavement ratings were considered. Marks and Haliburton (Ref 14) hypothesized that moisture variations beneath pavements with high ratings might be predominatly temperature dependent because moisture varia-

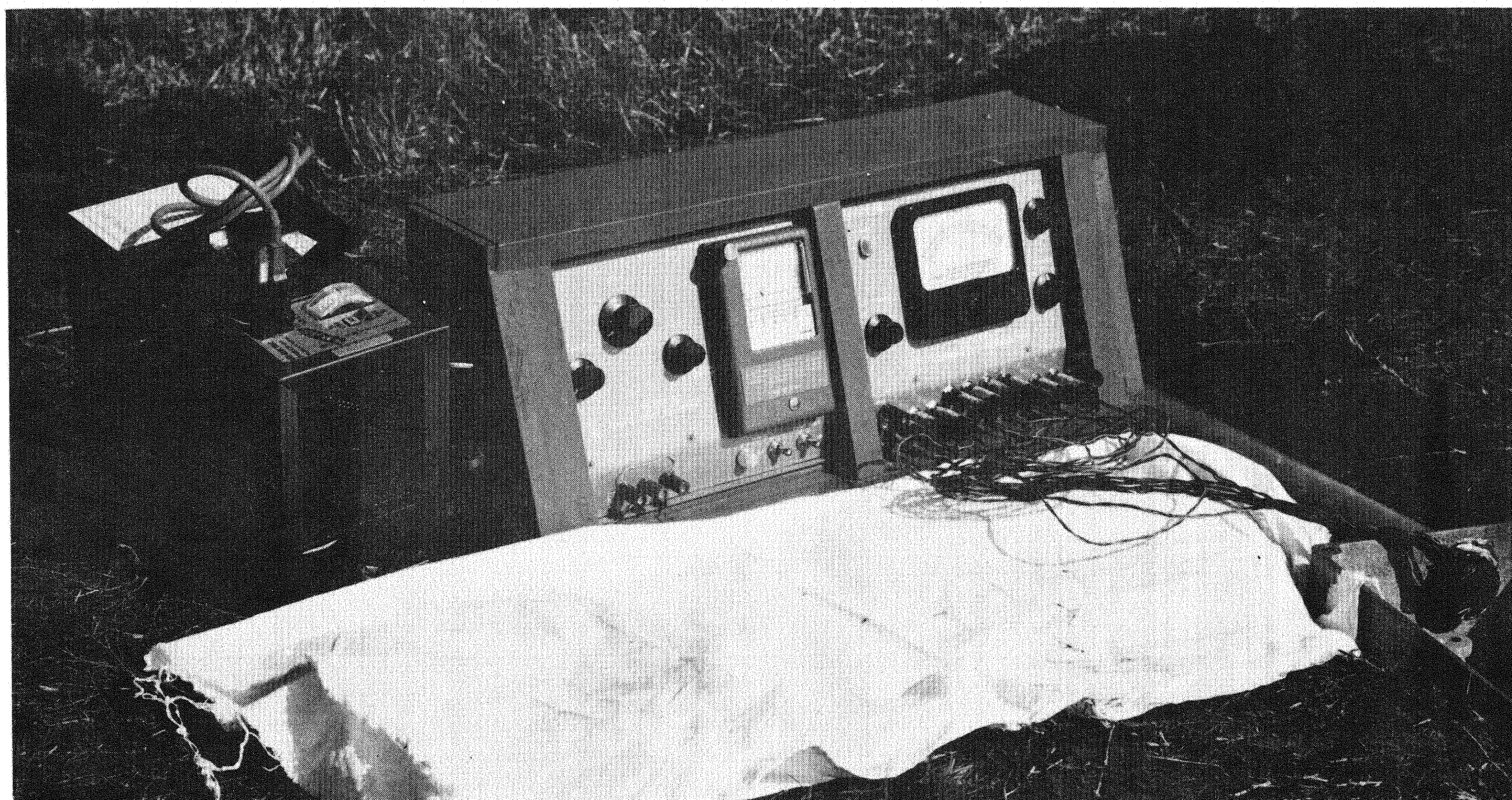

Figure 3.2. Power Inverter, Recorder and Telethermometer

tions could not be correlated with precipitation, and moisture content increased during winter months and decreased during summer months.

2. Subgrades in cut and fill sections were selected in order to determine if temperature gradients in cuts were different than temperature gradients in fills.
3. Subgrades with clayey, sandy, and silty soil were selected to study the possibility that appreciable thermal soil moisture flow occurred not only in coarse-grained soils but also in fine-grained soils.
4. Sites were also selected to study effects of pavement type. Sites with Portland cement concrete and asphaltic concrete pavement were chosen to determine if lighter colored PCC pavement affected subgrade temperature profiles differently than darker colored AC pavement.

Table 3.1 summarizes temperature site characteristics.

Before the six temperature sites were installed in highway subgrades, a demonstration temperature site was installed under a sidewalk near the Civil Engineering Annex at Oklahoma State University. The demonstration site was installed to test site installation procedures. Daily soil temperature measurements were made at the demonstration site to determine if daily soil temperature changes occurred and the amount of such changes.

## Temperature Site Installation

Two temperature probes, one near the highway pavement centerline and another approximately five feet from the edge of the pavement or

TABLE 3.1

TEMPERATURE SITE CHARACTERISTICS

| SMV Research Site No. | Location | | Soil Classification | | Subgrade Cross Section | Pavement Type | Shoulder Type |
|---|---|---|---|---|---|---|---|
| | County | Highway | Unified | AASHO | | | |
| 1 | Payne | US 177 | ML, SF | A4, A3 | Grade | PCC | Open |
| 12 | Creek | US 66 | CL | A6 | Grade | AC | Sealed |
| 21 | Garfield | US 81 | CL | A6 | Grade | PCC | Sealed |
| 26 | Pawnee | US 64 | CL | A6 | Fill | PCC | Sealed |
| 27 | Logan | I 35 | CH | A7 | Cut | PCC | Sealed |
| 29 | Tulsa | US 64 | CL | A7 | Fill | PCC | Sealed |

improved shoulder, were installed in the subgrade at each temperature site to determine if subgrade temperature gradients under pavements were different than temperature gradients in adjacent uncovered areas. Figures 3.3 and 3.4 illustrate placement of temperature probes at sites with improved and open shoulders.

Lead wires from the temperature probes were extended to the edge of the pavement or improved shoulder, where they terminated in phone plugs. The plugs were placed inside a "baggie" in a small waterproof metal box. Since the leads were extended from highway pavement centerline to the edge of the pavement or improved shoulder, it was necessary to cut a channel in the pavement and shoulder. The Oklahoma State Highway Department (OSHD) provided flagmen for traffic control and workmen and equipment to cut the pavement channel. A 2 1/2 in. square channel was cut in the pavement with a pavement saw. The channel was large enough to accommodate a 2 in. OD aluminum conduit, through which the leads were placed. The conduit was used because it was already available and phone plugs and leads were easily placed through the 1.90 ID in. hole. Figure 3.5 shows a workman using a pavement saw to cut a channel in PCC pavement. After a channel was cut, material in the channel was jackhammered loose and removed by hand, as shown in Fig 3.6. After placement of the aluminum conduit, the channel was patched. Channels in PCC pavement were patched with Type III pea gravel concrete, while channels in AC pavement and improved shoulders were patched with asphaltic cold mix. Figures 3.7 and 3.8 show views of a channel before and after patching.

Installation procedures were designed to minimize on-pavement working time. The shoulder hole was augered while the pavement channel was being cut. After completion of the shoulder hole, the drilling equipment was moved to the pavement centerline where pavement was cored

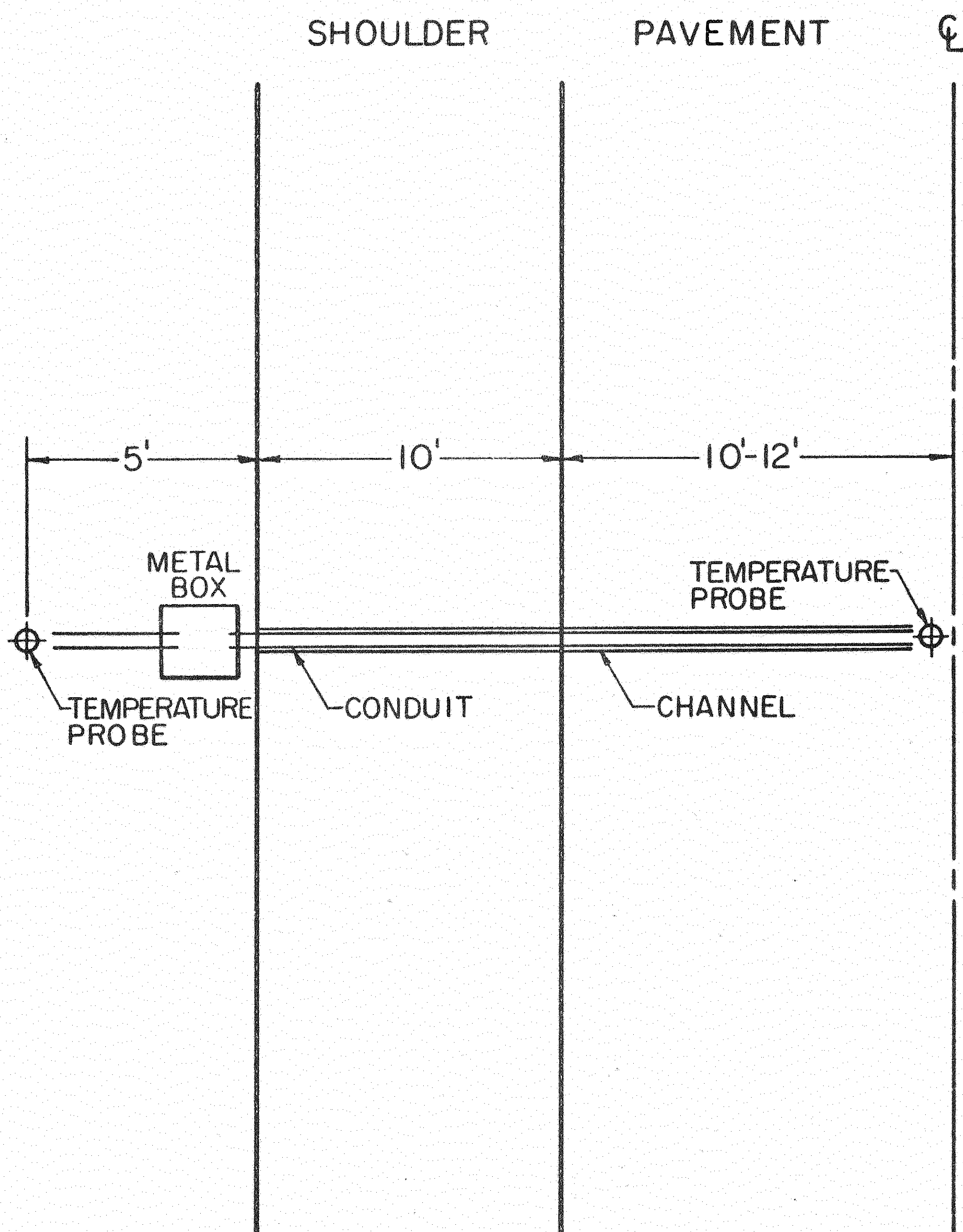


Figure 3.3. Temperature Site Plan for Sealed Shoulder

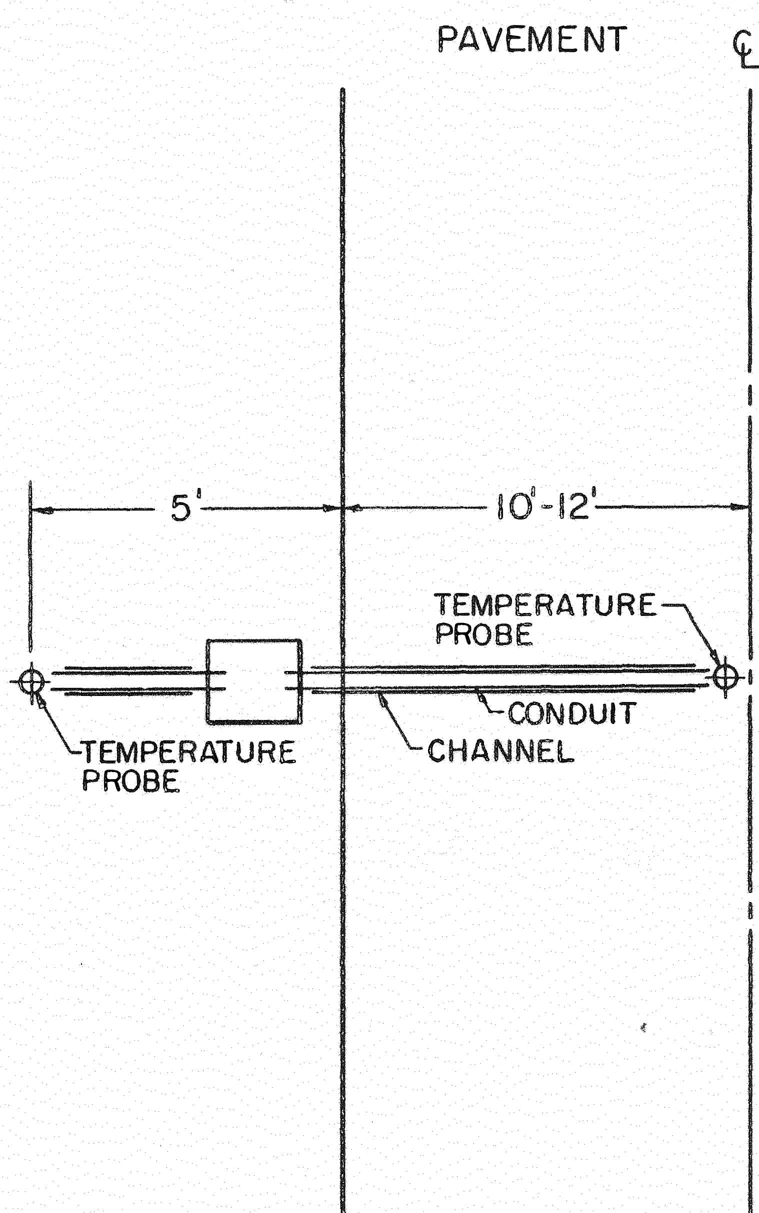


Figure 3.4. Temperature Site Plan for Open Shoulder

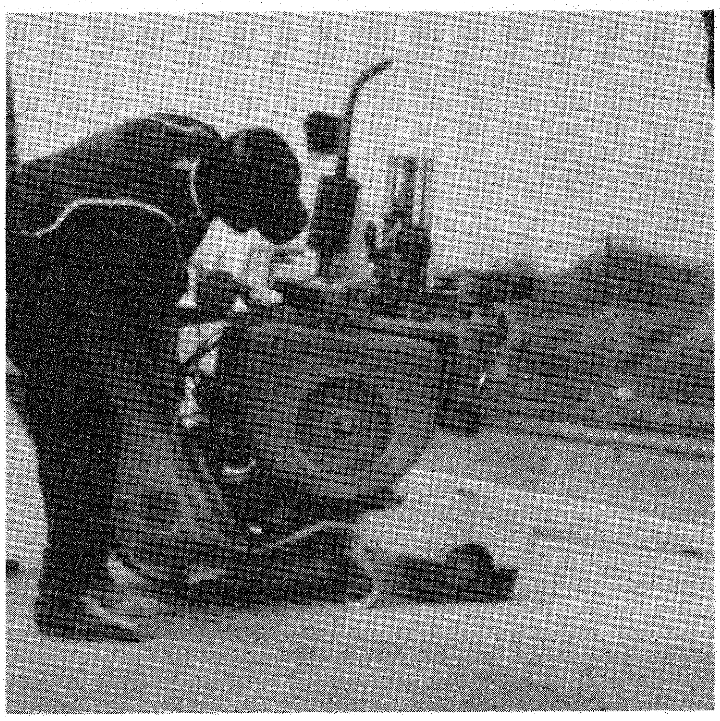

Figure 3.5. Workman Using Pavement Saw to Cut a Channel in PCC Pavement

Figure 3.6. Workmen Removing Material from Channel

Figure 3.7. Channel and Conduit Prior to Patching

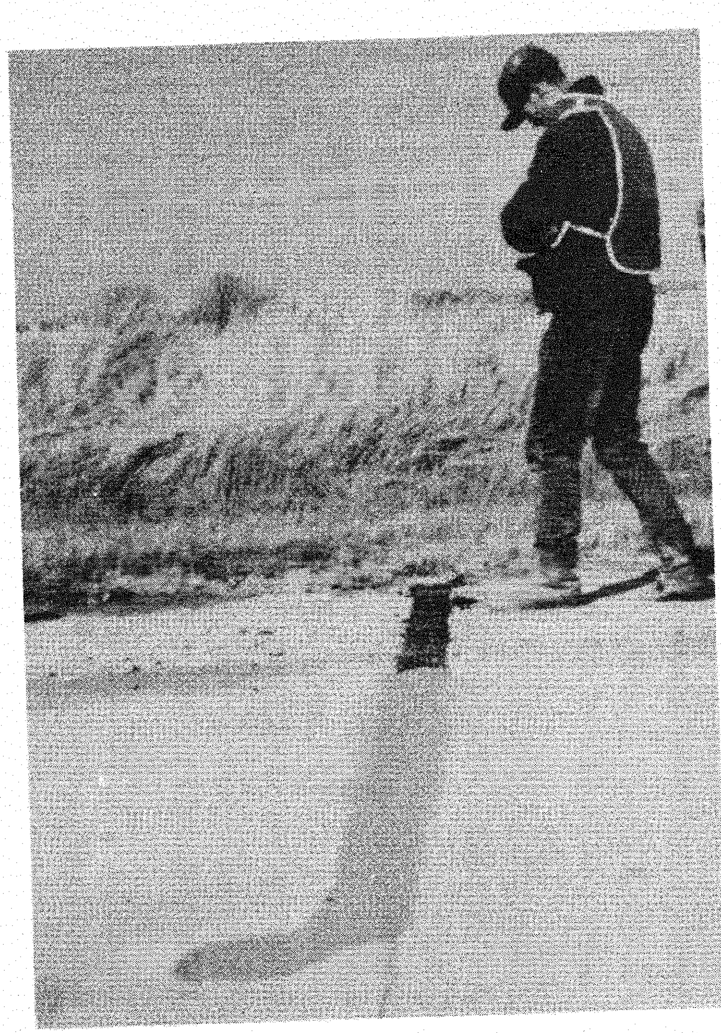

Figure 3.8. Channel After Patching

and the hole for the centerline temperature probe was augered. Temperature probes were inserted in the augered holes and leads placed into the aluminum conduit and extended into the metal box located at the edge of the pavement or improved shoulder. Figure 3.9 shows placement of temperature probes at a typical temperature site.

## Data Collection and Presentation

Subgrade temperatures were measured to determine if subgrade moisture conditions were affected by temperature. To correlate subgrade temperatures with moisture changes it was necessary to select a schedule for measuring subgrade temperatures that corresponded to an existing schedule for measuring subgrade moisture content. Subgrade moisture measurements were made on a six-to-eight week cycle as described by Marks and Haliburton (Ref 14). Subgrade temperature was measured on a three-to-four week cycle such that every second temperature measurement cycle occurred at exactly the same time moisture content was measured. The extra temperature measurement cycle was necessary because Moore (Ref 11) found that subgrade temperatures could increase or decrease appreciably within a four week period; the extra measurement cycle provided a better understanding of subgrade temperature variation. Furthermore, considering the relatively small voids in the clay subgrades prevalent at all but one research site, the authors doubted that appreciable moisture migration would occur over very short time intervals. Gradual changes under seasonally-existing gradients appeared more likely.

Climatological data (precipitation and monthly mean air temperatures) were collected in addition to subgrade temperature and moisture content data. Monthly mean high and low air temperature and monthly

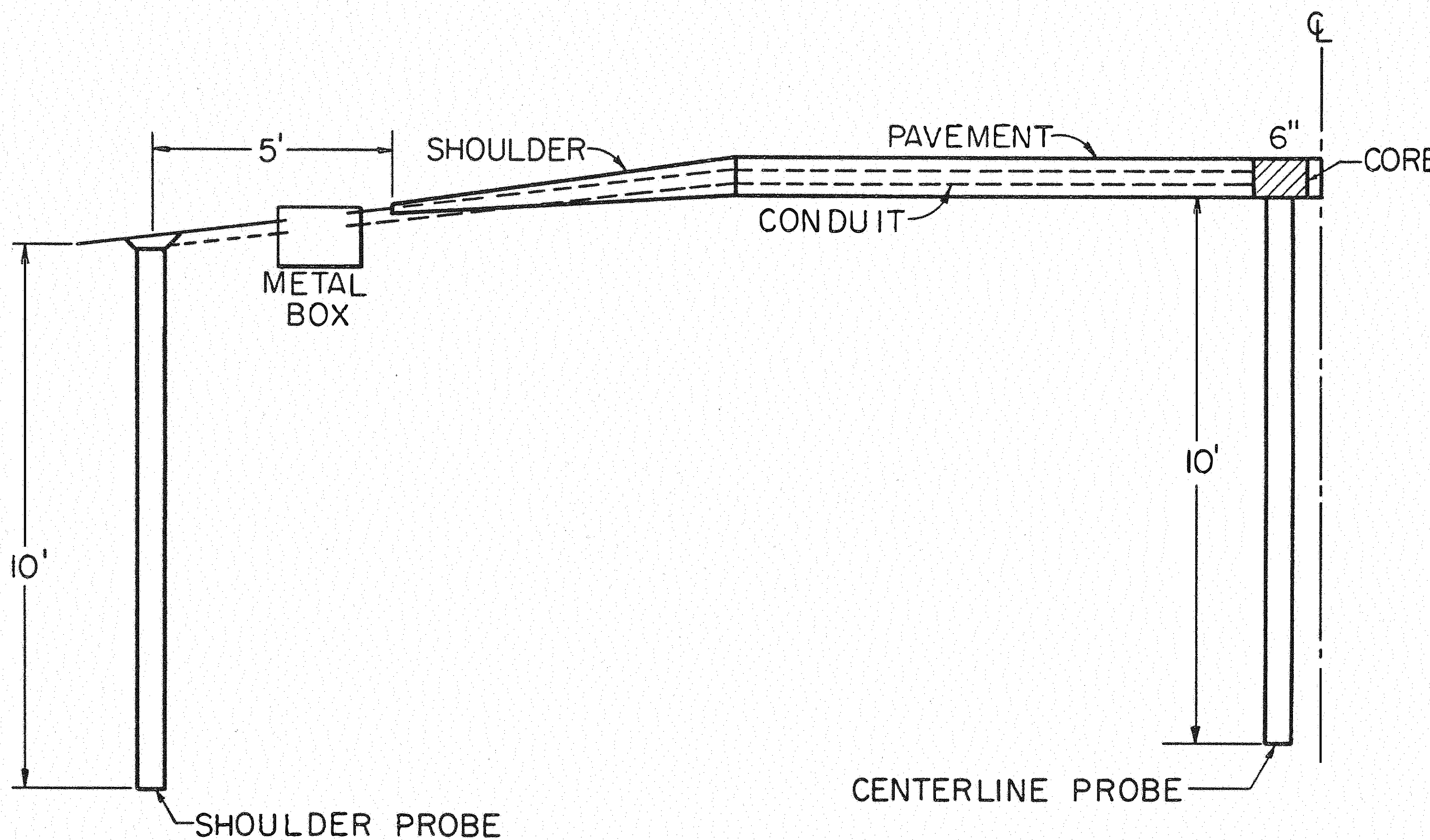


Figure 3.9. Temperature Site Installation

precipitation totals were gathered from Climatological Data - Oklahoma, a monthly bulletin supplied by the U.S. Department of Commerce. Monthly precipitation data were used to determine if subgrade moisture contents increased or decreased as precipitation increased or decreased, following the pattern found by Marks and Haliburton (Ref 14). They found that an increase in subgrade moisture content would occur approximately six to eight weeks after a period of large precipitation. Monthly air temperatures were studied to determine the extent that air temperature variations caused variations in subgrade temperatures.

Data presentation was in graphical form. Subgrade moisture content, subgrade temperature, monthly precipitation, and monthly air temperature were plotted versus time as shown in Figs 3.10, 3.11, and 3.12. This method of data presentation was selected because it was quite simple and permitted easy correlation of all data collected during comparable time periods. Correlation and evaluation of research data are discussed in the following chapter.

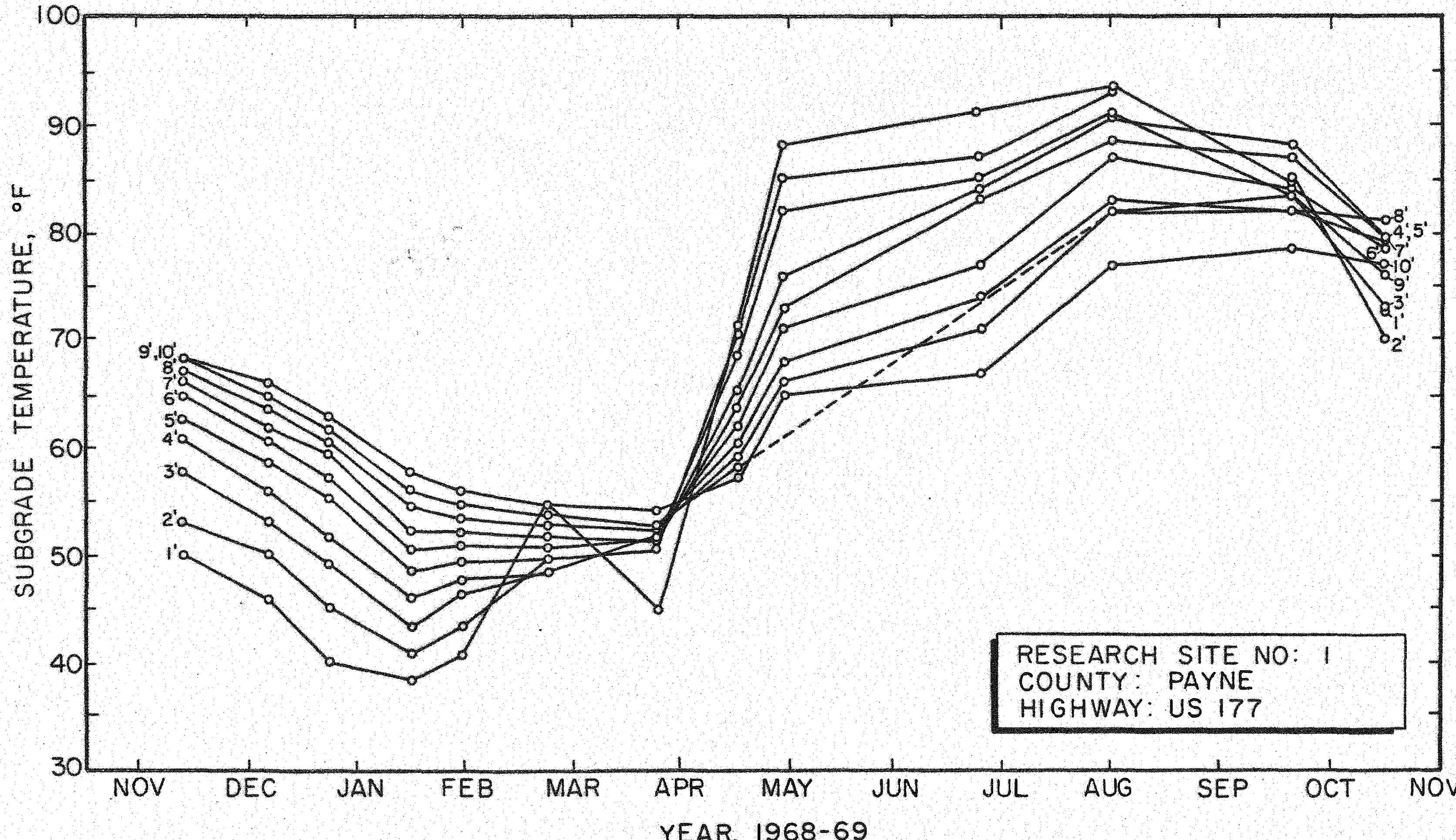


Figure 3.10. Subgrade Temperature Variations at Site No. 1

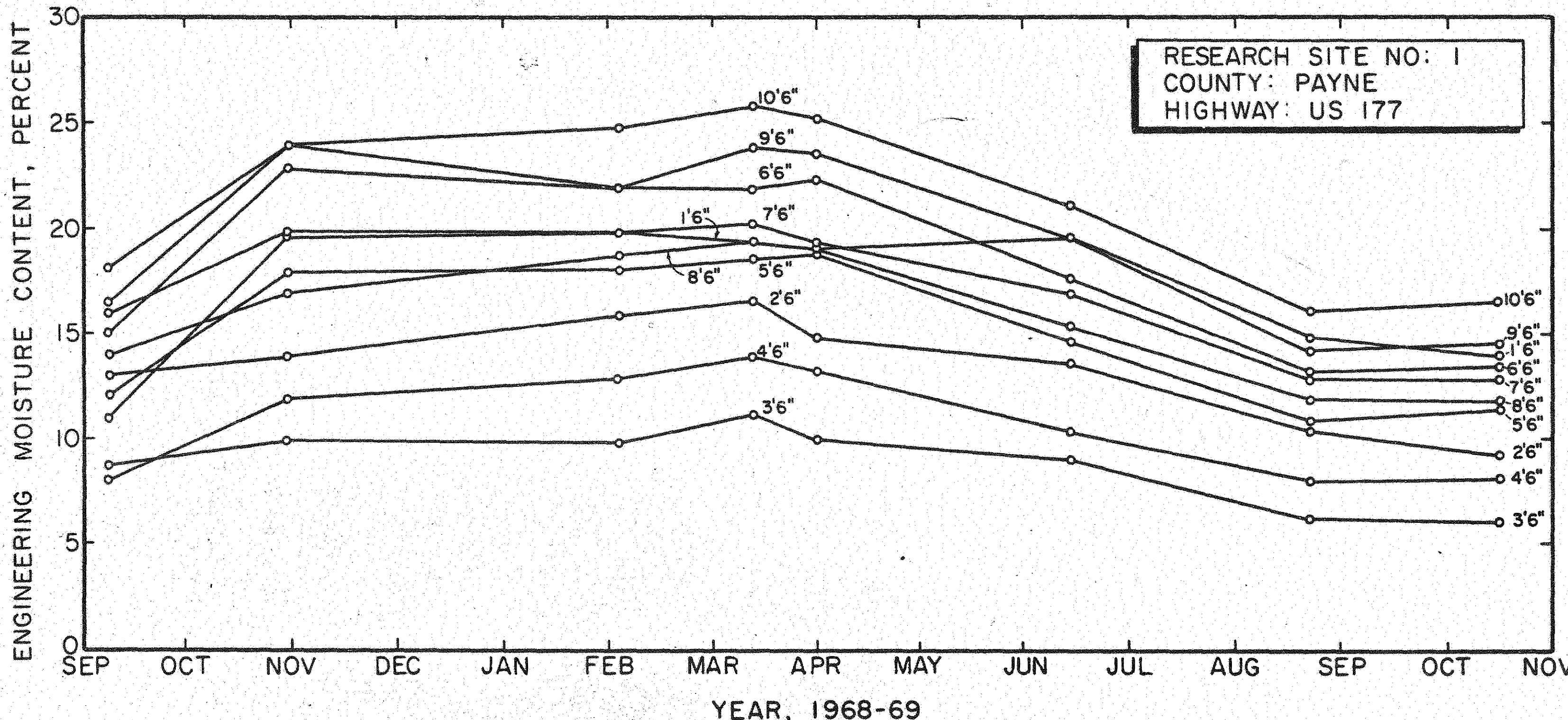


Figure 3.11. Moisture Variations Beneath Pavement Centerline at Site No. 1

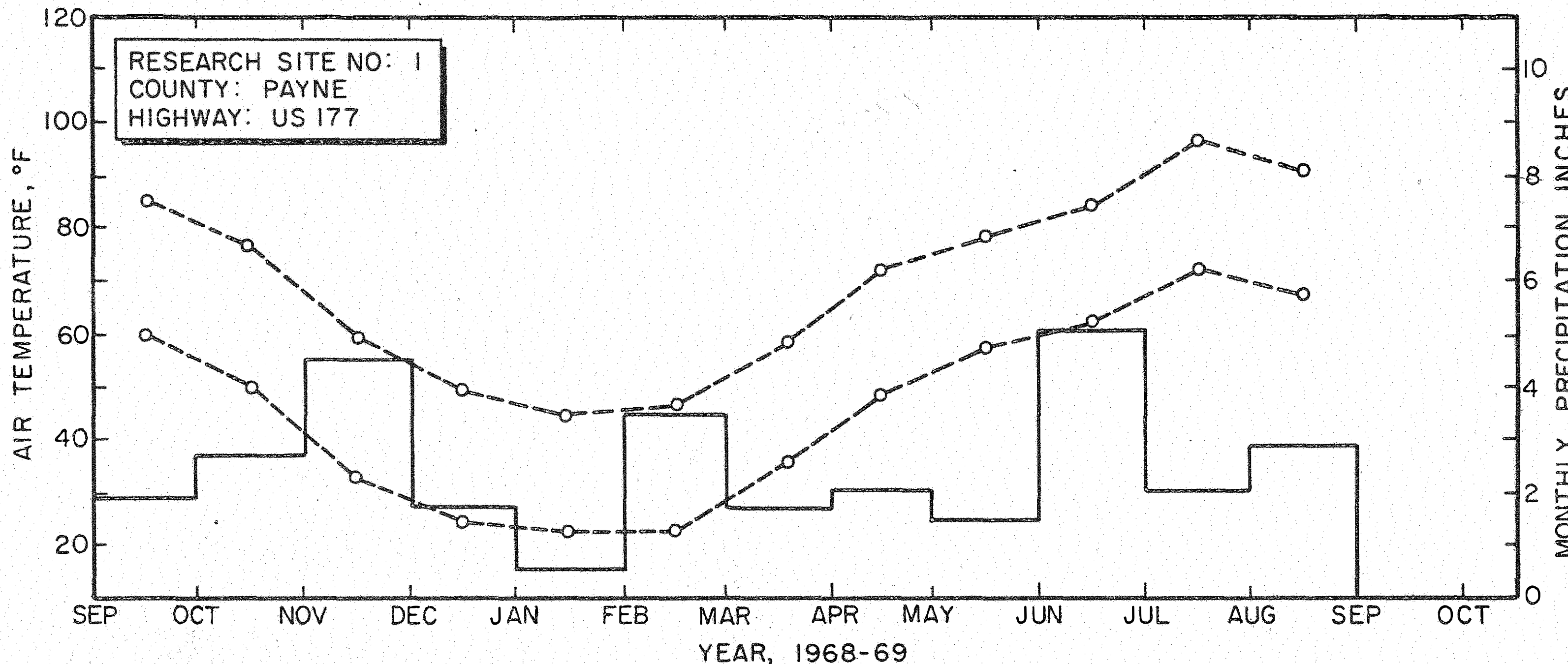


Figure 3.12. Climatological Data from Site No. 1

# CHAPTER 4. PRESENTATION AND CORRELATION OF SUBGRADE TEMPERATURE AND MOISTURE DATA

Subgrade temperature variations, trends detected from collected temperature data, and the possible influence of temperature on subgrade moisture migration are discussed in this chapter.

Subgrade temperature measurements were begun November 19, 1968, when temperature probes were installed at SMV Research Site No. 1. Temperature probes were installed and measurements started at Site No. 26 on December 17, 1968, Site Nos. 21 and 27 on January 21, 1969, Site No. 29 on January 22, 1969, and Site No. 12 on March 4, 1969. Temperature data discussed in this chapter were measured at each site between its installation date and October, 1969. As discussed in the previous chapter, subgrade temperatures were measured at one foot intervals to a depth of ten feet, and Fig 4.1 shows the selected method of plotting temperatures at each level versus time. This method of data presentation permitted detection of temperature variation trends occurring during the data collection period.

## Subgrade Temperature Variations and Trends

Temperature gradients were found to occur in highway subgrades and to vary with seasonal air temperature. Fig 4.1 shows typically encountered subgrade temperature variations. Temperatures at all levels decreased during the period from November to January. During February and March the temperatures at all upper levels (1 ft, 2 ft, and 3 ft)

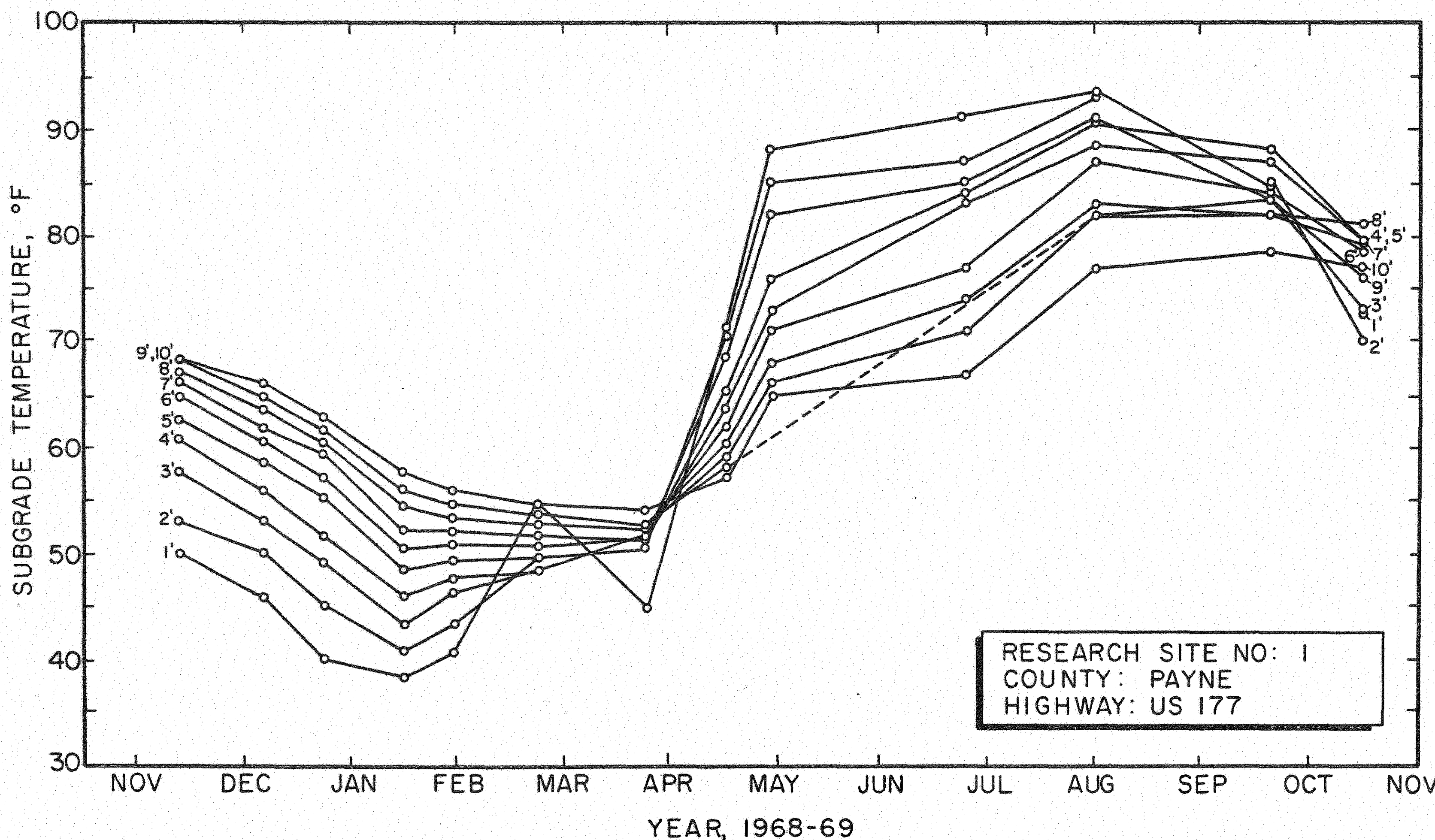


Figure 4.1. Subgrade Temperature Variations at Site No. 1

began to increase. Figure 4.2 indicates that air temperature decreased and increased during the same period. Fluker (Ref 15) found that soil temperature changed on annual cycles and changes in soil temperature followed changes in seasonal air temperature. During winter months the cooler soil temperatures occurred near the surface while during summer months soil temperature was relatively cooler at depths below three feet. He also found that soil temperatures differed less than 4°F at all levels above 10 ft during two periods each year. The first period occurred during April and the second during October when soil temperature gradients reversed. For example, before April the 2 ft and 3 ft levels of the soil were cooler than the 9 ft and 10 ft levels. After April the lower levels were relatively cooler than the upper levels. This reversal occurred again during October but in the opposite direction. Fig 4.1 shows that subgrade temperature for all levels at Site No. 1 differed less than 8°F during March. This trend indicates the temperature gradient was experiencing the reversal described by Fluker, which occurred in April, 1969. Temperatures plotted in Fig 4.1 increased at all levels during the summer months and then cooled at all levels as fall began, with another gradient reversal occurring toward the end of September, 1969, once again following the trend of air temperature.

Subgrade temperatures beneath PCC pavement were found to be a few degrees cooler than temperatures beneath darker-colored AC pavement. This may have been caused by the ability of darker-colored AC pavement to adsorb solar radiation. Straub, Dudden, and Moorhead (Ref 12) found that darker colored pavements adsorbed solar radiation more readily than lighter colored pavements, and that subgrade temperatures were affected by the amount of solar radiation adsorbed. They found that

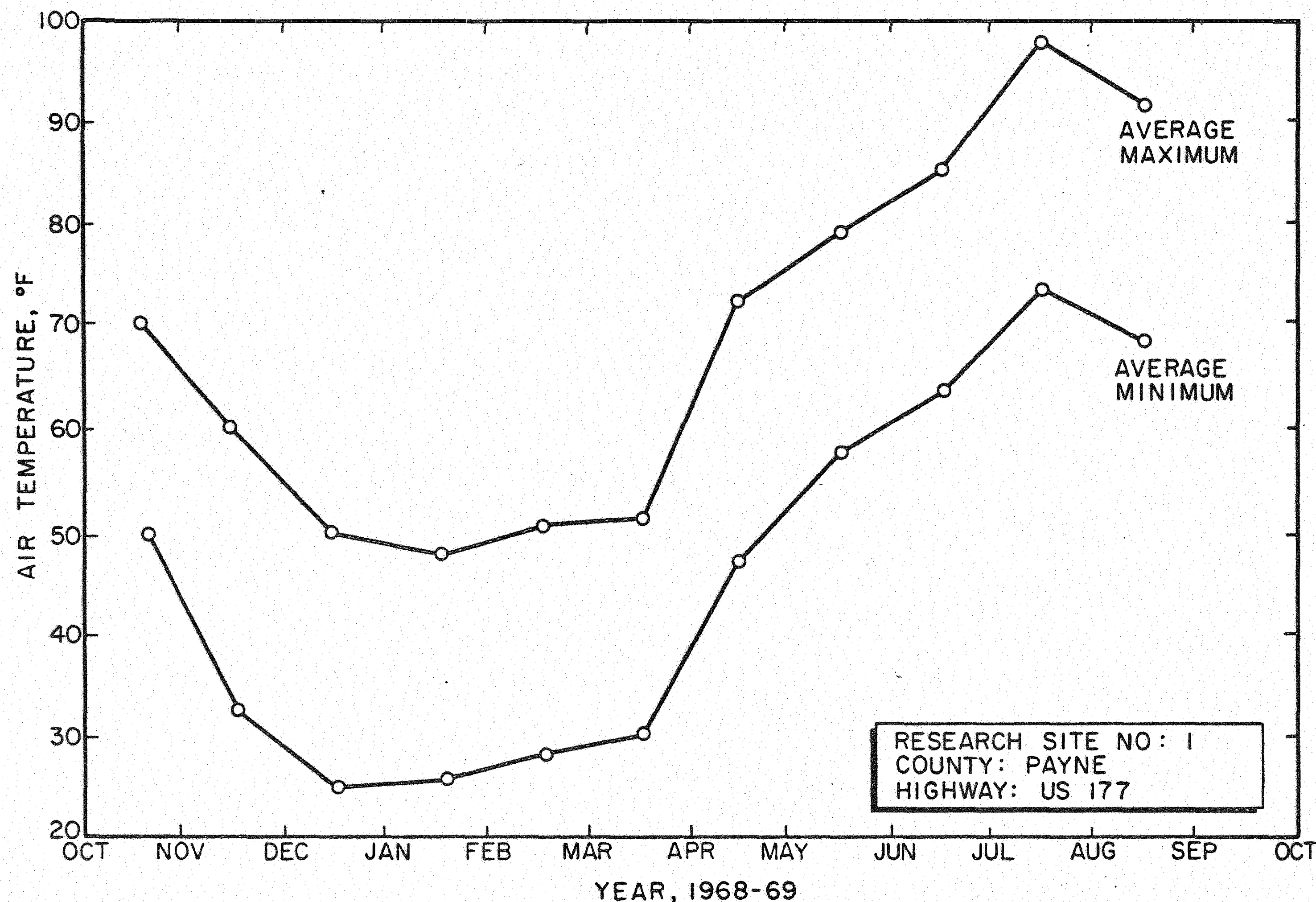


Figure 4.2. Mean Monthly Maximum and Minimum Air Temperature at Site No. 1

subgrades beneath black pavements were as much as 30°F warmer than subgrade beneath white pavements. As shown in Fig 4.3, temperatures beneath AC pavement at Site No. 12 were approximately 3°F warmer than temperatures beneath PCC pavement at Site No. 29.

No appreciable differences were found between temperature gradients measured in cuts and fills. Heat transfer may occur in soil when different regions of the soil are at different temperatures. This transfer will be in the direction from warmer to cooler regions (Ref 1). Therefore, heat transfer may occur in subgrades if there are regions of different temperature in the subgrade soil. If the surface of the subgrade is cooler than the soil at depths below the surface of the subgrade, heat may be transferred toward the surface (Ref 1). Because of the greater amount of subgrade surface area in fills, compared to surface area in cuts, there could possibly be a greater amount of heat transfer in fills. For example, heat may be transferred vertically toward the pavement or horizontally toward the sides of fills, while heat transfer toward a surface in cuts may occur only in the vertical direction. The possibility that more heat may be transferred from the subgrade in fills than from cuts may cause temperatures in fills to be less than temperatures in cuts, however, as shown in Fig 4.4, there was very little difference in temperature gradients measured at the two particular research sites during the data collection period chosen.

At each site, temperatures at all levels beneath the pavement were warmer than the temperatures at corresponding levels in adjacent uncovered subgrade at the edge of the pavement or improved shoulder. For example, Figs 4.5 and 4.6 show that temperatures measured beneath pavement at Site No. 21 were 3° to 5°F warmer during winter months than

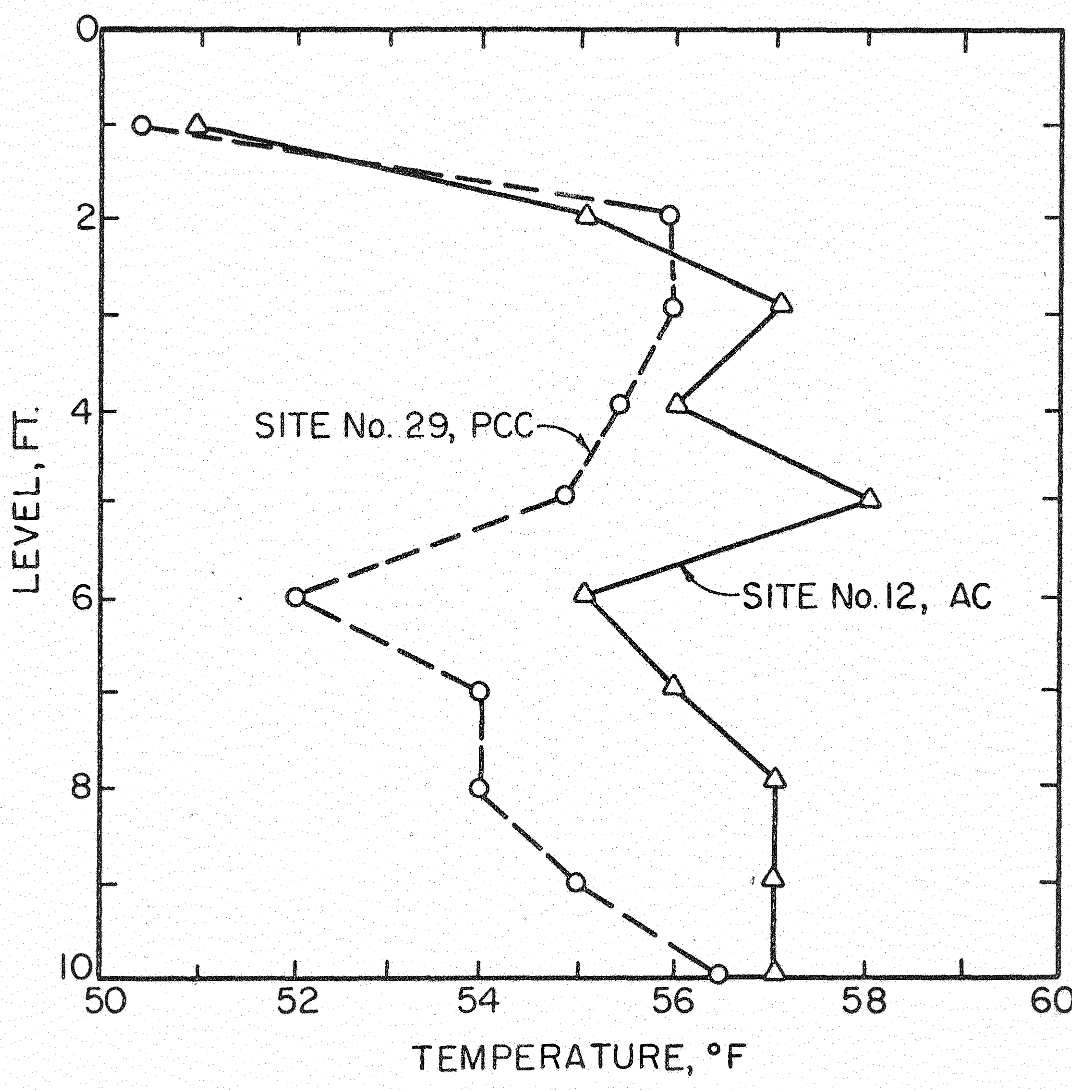


Figure 4.3. Temperature Gradients in Subgrades of AC and PCC Pavements

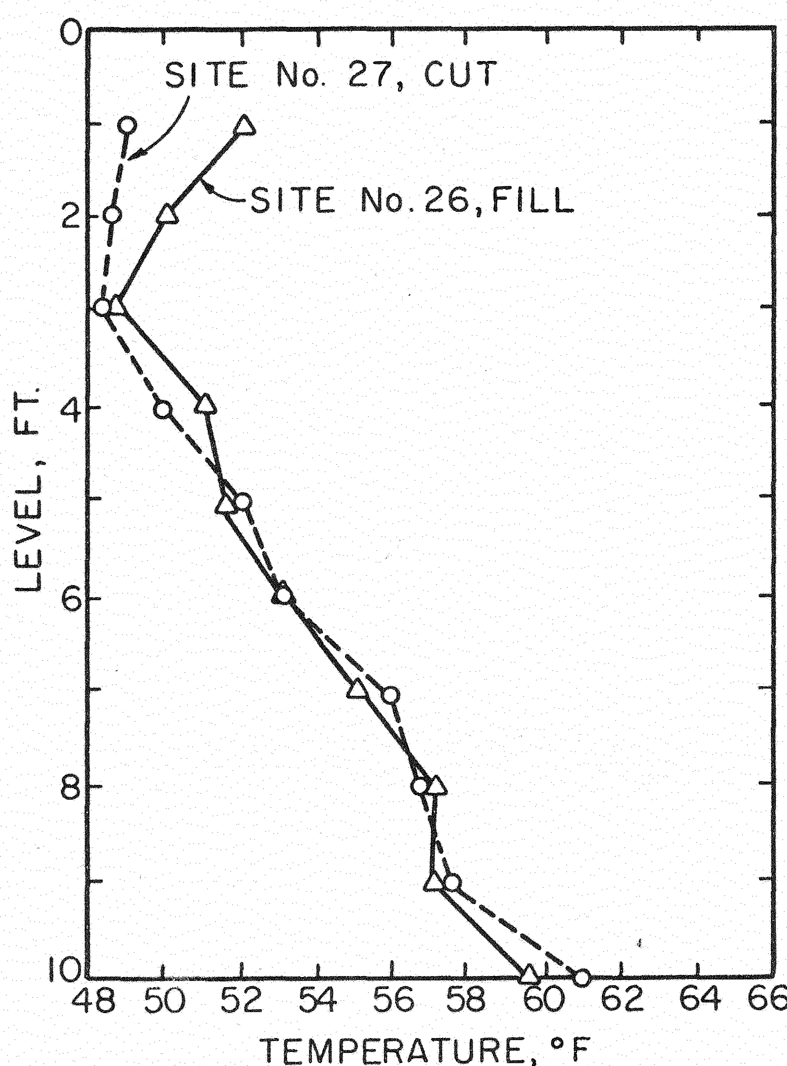


Figure 4.4. Temperature Gradients in Cut and Fill Sections

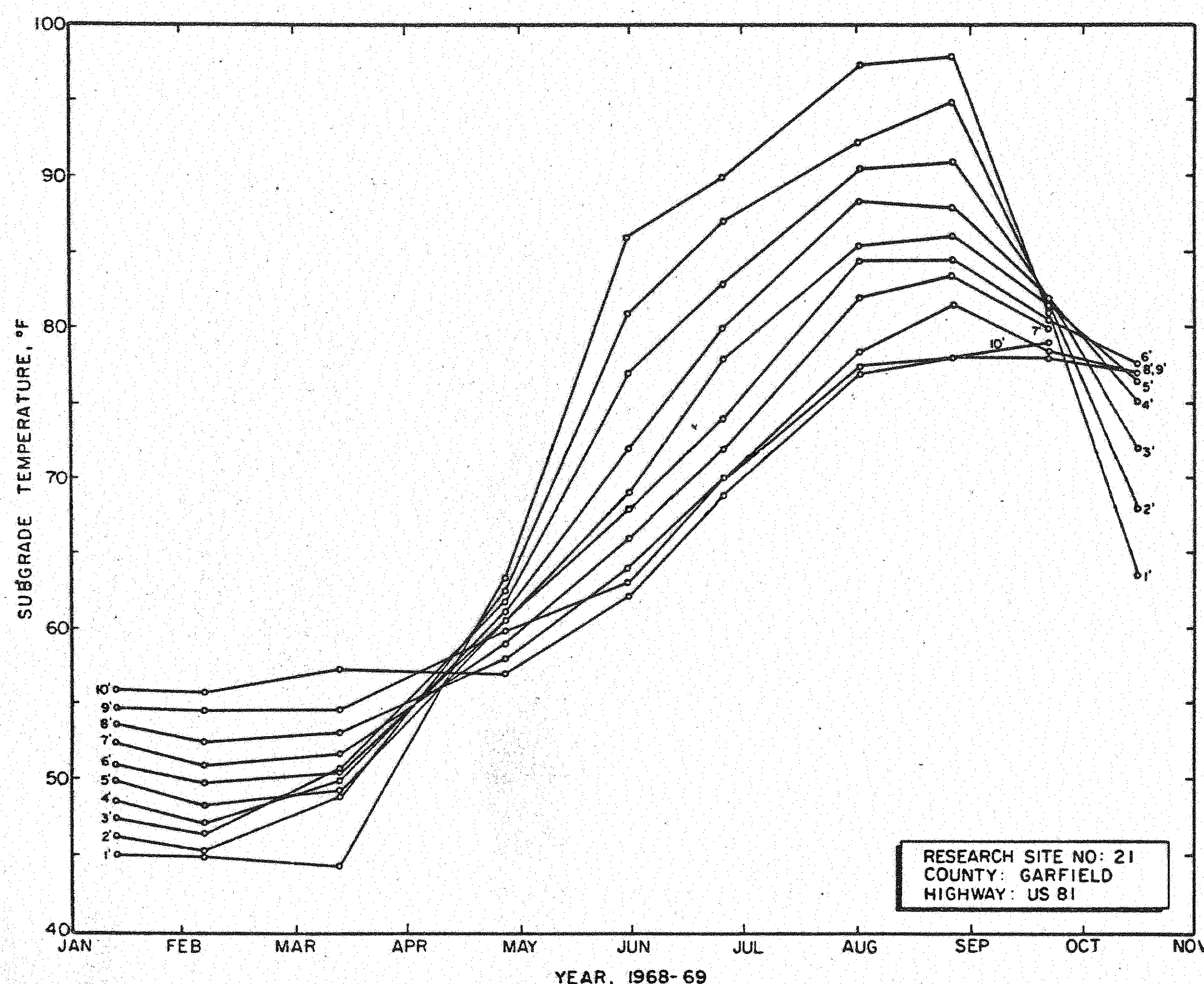


Figure 4.5. Subgrade Temperatures Beneath Pavement Centerline at Site No. 21

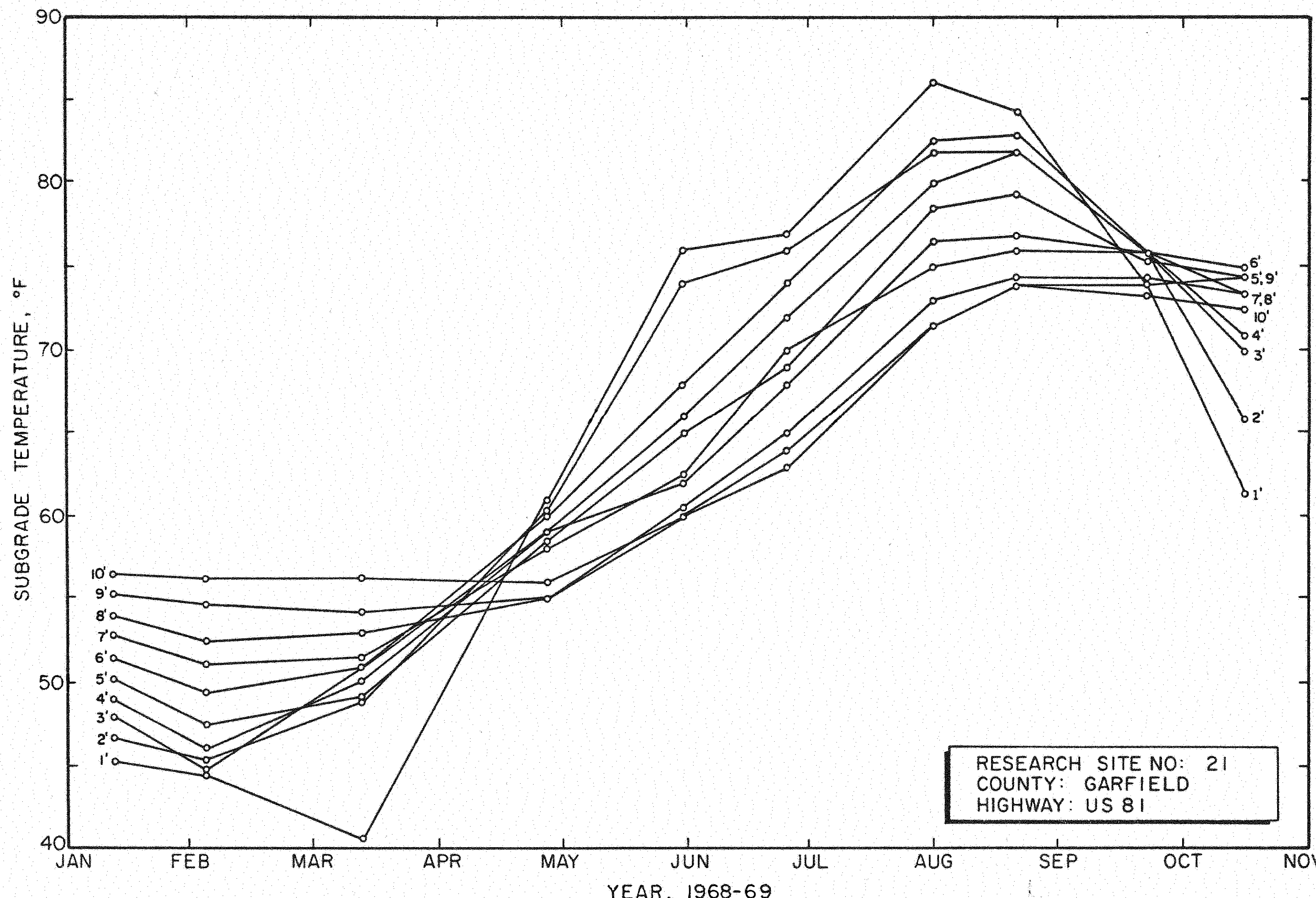


Figure 4.6. Subgrade Temperatures in Uncovered Area Adjacent to Pavement at Site No. 21

temperatures measured in uncovered subgrade, and up to 10°F warmer during summer months. This is in agreement with Moore (Ref 11) who found that soil temperatures beneath pavements were warmer than temperatures in surrounding uncovered soil. He attributed the difference in temperature to the ability of the pavement to absorb heat.

Daily soil temperatures measured at the demonstration site indicated daily temperature variations extended to a depth of 2 ft to 3 ft below the surface of the sidewalk. As shown in Fig 4.7, daily changes in soil temperature decreased as depth increased. The 1 ft level varied as much as 5°F while the 2 ft level varied less than 2°F, and the temperature below the 3 ft level did not vary during this particular 24 hour period.

## Correlation of Subgrade Temperatures with Measured Moisture Variations

As discussed in Chapter 2, thermal soil moisture flow may occur in a soil mass if a temperature gradient is applied to the soil. This moisture flow occurs mainly in vapor phase and moves in the direction of decreasing temperature.

Temperature gradients measured at each temperature site during the period from December through March showed increasing temperature as depth increased. Any thermal moisture flow that occurred in the subgrade during this period would have moved up, in the direction of decreasing temperature, therefore subgrade moisture content data were studied to determine if the 1 ft, 2 ft or 3 ft levels experienced an increase in moisture content during the period from December through March. An increase of moisture content at the cooler upper levels of subgrade while moisture content decreased at the lower warmer levels would indicate that the increase of moisture content was the result of thermal soil moisture flow.

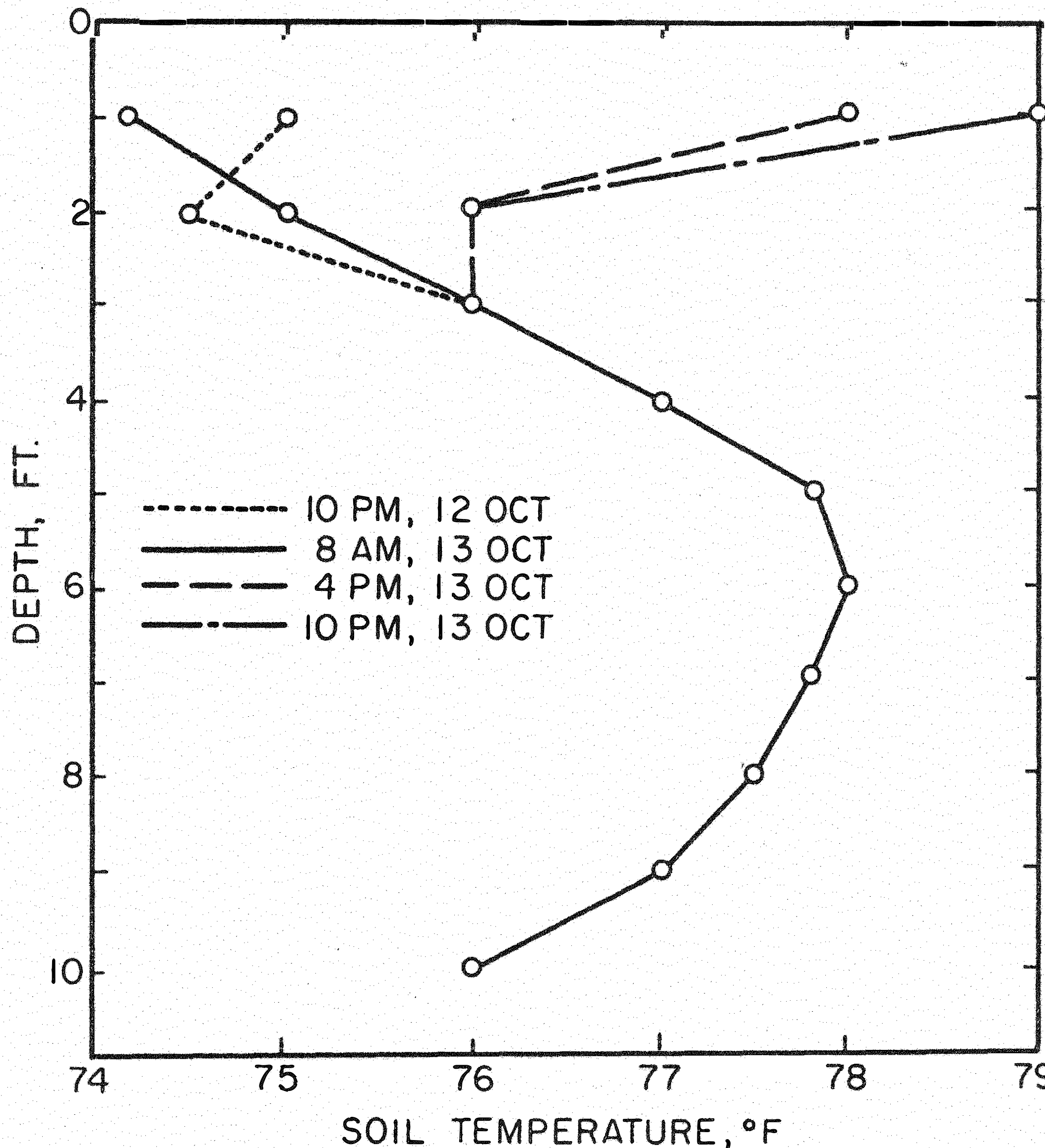


Figure 4.7. Variation of Temperature Gradient at Demonstration Site During 24 Hour Period, 12-13 Oct 1968

The same approach was followed in evaluating data for the summer months, when, if temperature gradients affected moisture migration, moisture in the upper levels should decrease while increasing at lower levels of the subgrade. During the gradient reversals in April and September, moisture should migrate toward and away from the intermediate levels.

Subgrade moisture contents beneath pavement at Site Nos. 26, 27, and 29 appeared to be influenced by temperature gradients. During December the moisture content at the 1 ft and 2 ft levels increased while decreasing at all lower levels. During March, when temperatures at the 1 ft, 2 ft and 3 ft levels and bottom 10 ft level were the warmest in the subgrade, the moisture content decreased in the upper and lower levels while increasing at the 5 ft and 6 ft levels. Fig 4.8 shows the moisture content at the 2 ft and 3 ft levels of Site No. 26 decreased during the period from May through October, 1968, and then increased during the period from November, 1968, to April, 1969. During the spring and summer of 1969, moisture contents again decreased at the upper levels while increasing slightly at the lower levels. Moisture contents in the upper levels also increased during the fall of 1969, but so did moisture in the lower levels. This indicates that moisture content of the two upper levels increased during the periods when they were the coolest levels and decreased during the periods when they were the warmest levels in the subgrade. Similarly, moisture content at the 8 ft and 9 ft levels increased during the spring and summer months when they were the coolest levels and decreased during the fall and winter months when they were the warmest levels.

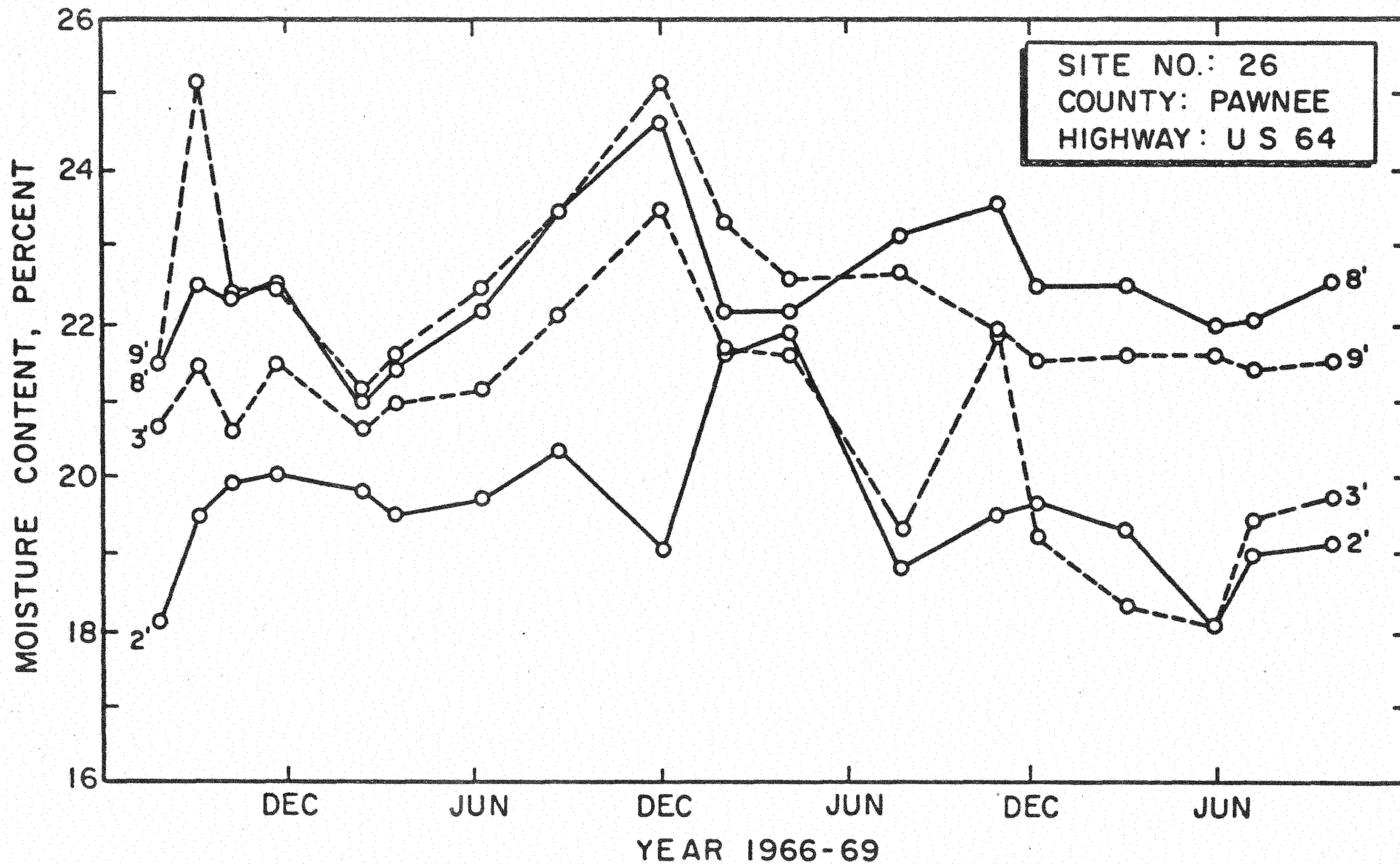


Figure 4.8. Subgrade Moisture Variations Under Pavement Centerline at Research Site No. 26

Site No. 26 is located on U.S. 64 in Pawnee County, on PCC pavement resting on a fine sand cushion placed over a CL subgrade with a plastic limit of about 20. The highway section, constructed in 1963, has improved shoulders and is located on a hilly upland terrain. The pavement is higher than surrounding ground; one side of the shoulder has a profile similar to that found on a slight fill. Drainage is away from the site and there is little chance of water collecting near the pavement or shoulders on the east side and only a slightly better chance for ponding near the west shoulder. The water table is thought to be at a depth of about 100 ft, though, under prolonged heavy rainfall conditions it is possible that water seeping down the hilly terrain could create a temporary perched water table in the subgrade. This behavior was observed to occur in April, 1968.

Pavement and shoulders at this site have been and are rated excellent, though shoulder settlement and separation of the east shoulder were observed to begin in July, 1969. Moisture variations at this site cannot be related to precipitation, and the absence of a permanent water table tends to eliminate capillarity as a source of seasonal variation. However, except for a general increase/decrease in moisture during the winter of 1967, moisture contents at the site (since installation in 1966) have remained relatively constant around the plastic limit value for the subgrade.

It is possible that at some time between construction in 1963 and site installation in 1966 a temporary water table may have formed at the site, and supplied enough moisture to allow the subgrade to reach its plastic limit "equilibrium" moisture content. At later times this moisture may have been induced to migrate thermally up and down in the subgrade, but the magnitude of variation has been small, and the maximum changes that can be attributed to temperature are on the order of 1 - 2% engineering moisture content.

The moisture content at the 8 ft and 9 ft levels at Site No. 26 did not vary as much as the moisture content at the 2 ft and 3 ft levels. This may have been the result of soil type. The soil in the top three feet of the subgrade is sand while the soil in the lower levels is clay. Hutcheon (Ref 9) and Hanks (Ref 2) found that appreciable thermal soil moisture flow occurred mainly in soils with large open voids, as are found in sandy soils. Therefore, the flow in the top two feet may have been greater than the flow at the 8 ft and 9 ft levels because the sandy soil had larger voids than the clay in the lower part of the subgrade.

Subgrade moisture variations at Site Nos. 1, 12, and 21 could not be correlated with temperature variations: the moisture variations appeared to be caused primarily by precipitation and water table movement. Water tables in central Oklahoma are usually close to the surface, and tend to move closer to the surface during the winter, retreating in the summer months. The fine-grained subgrades prevalent in Oklahoma have high capillary rise potential, and some seasonal subgrade moisture variations may be caused by movement of the zone of capillary rise. Sites Nos. 1, 12, and 21 have excellent pavement ratings, and thus should have relatively impervious pavement, however, moisture movement appears to be affected by factors other than temperature gradients. For example, the moisture variations at Site No. 1, shown in Fig 4.9, when compared to a plot of monthly total precipitation (Fig 4.10), show that an increase in moisture content at all levels occurred in November

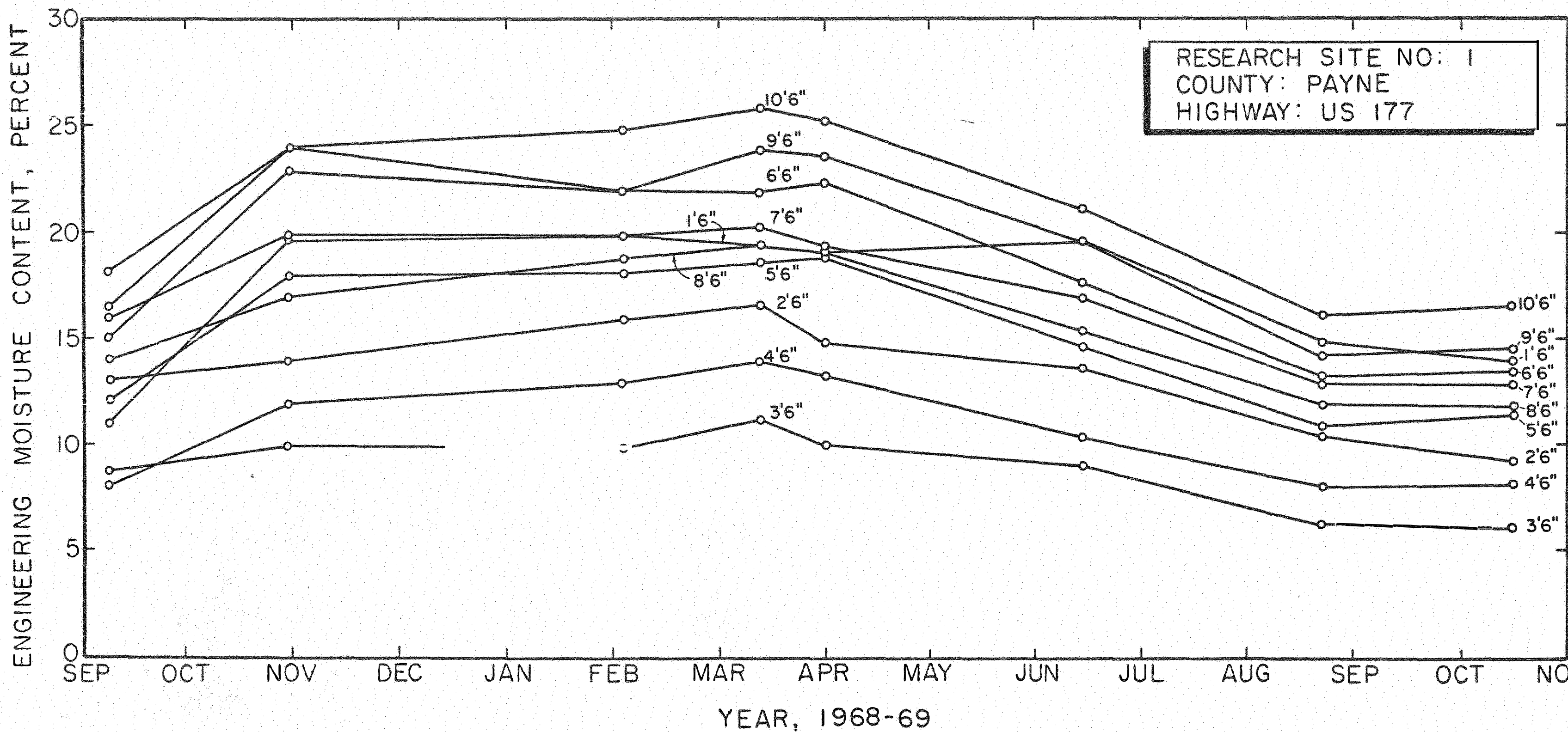


Figure 4.9. Subgrade Moisture Variations Under Pavement Centerline at Research Site No. 1

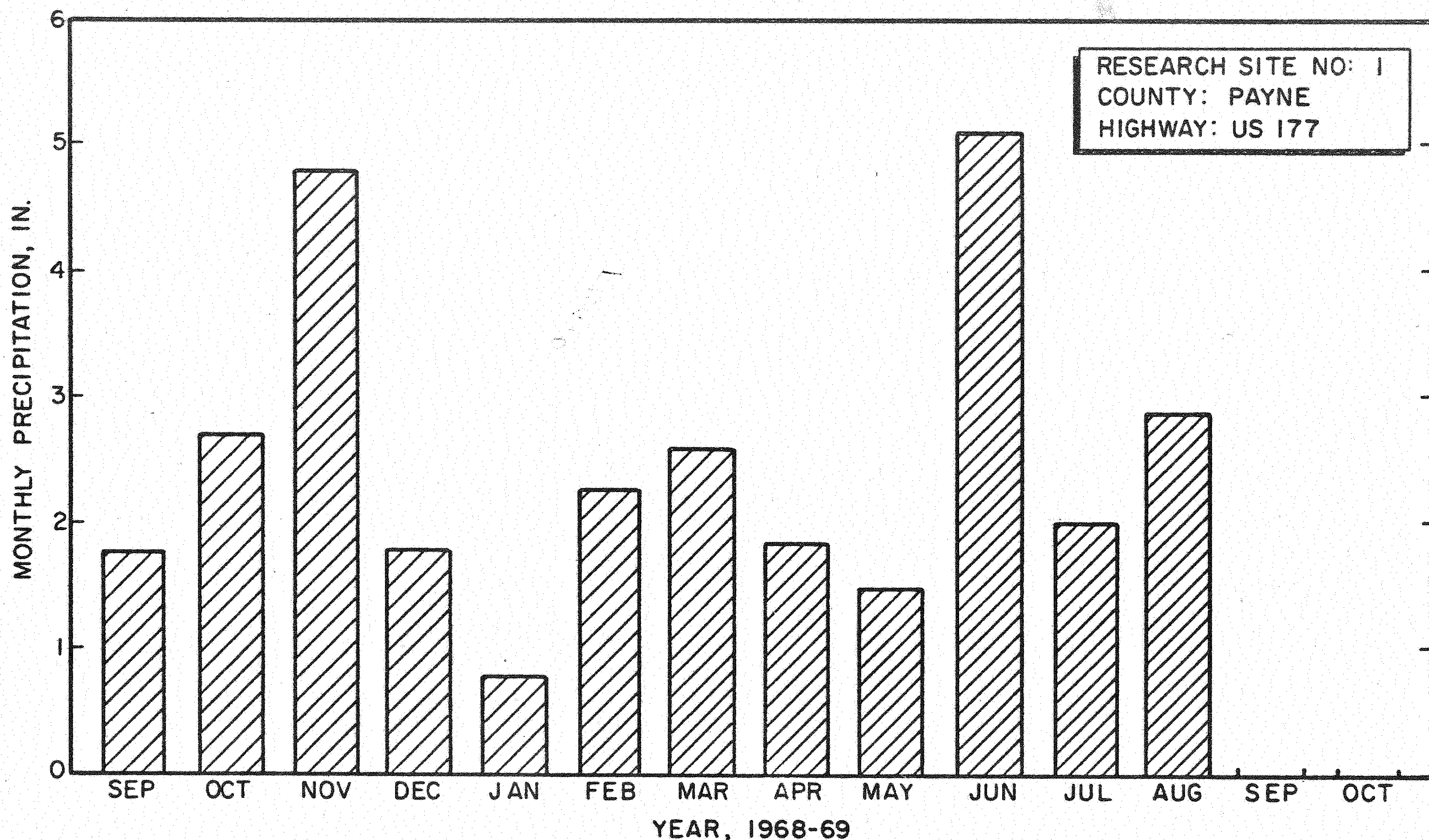


Figure 4.10. Total Monthly Precipitation at Site No. 1

and again in March, and these increases in moisture occurred within four weeks after the occurrence of a large amount of precipitation, both in November and March. However, large rainfall in June produced a noticeable increase in moisture only at the 1.5 ft level and a slight increase at the 2.5 ft and 3.5 ft levels, all counter to a general downward trend in moisture content for the subgrade. Furthermore, the rate of moisture content increase and decrease during the period shown appears nearly the same for all levels. The subgrade at this site is a fine-grained sandy soil with relatively low plasticity, and should be more susceptable to temperature-induced moisture movement than some other sites on more cohesive material. However, the behavior noted at Site Nos. 26, 27, and 29 did not occur.

The relatively impervious pavement condition is responsible for the smooth increases noted after rainfall periods, as rapid infiltration and evaporation through cracked or porous sections produce a much more jagged and sawtooth-shaped curve of moisture variation. Considering the relative amounts of change produced by precipitation, particularly in June, it appears that a factor other than precipitation or subgrade temperature is affecting moisture migration at this site.

As the water table is relatively close to the surface at this site, even rising to the 10 ft level during the winter, it is possible that main variations at this site are caused by rise and fall of capillary moisture, following seasonal water table movements. A farmhouse and well are located approximately 100 ft from Site No. 1, and higher summer pumping rates from this well may accentuate normal water table variation. Additional evidence for this hypothesis was obtained by noting that summer subgrade moisture contents are higher in upper levels under the shoulder away from the well, despite similar drainage conditions for each shoulder.

During the periods of gradient reversal, April and September-October, moisture conditions might have been affected by temperature gradients. In April, moisture decreased at the warmer upper and lower levels while increasing at the cooler intermediate levels. The reverse was true in September, as moisture contents increased at upper and lower levels while decreaseing at intermediate levels. However, the relative magnitude of these changes was only 1 - 2 percent engineering moisture content.

At these particular periods of the year, the water table in Oklahoma has usually been at its rather stable seasonal level for some time and is getting ready to move upward or downward, depending on the season. Water table ( and thus capillary) stability may allow measurement of small changes produced by temperature gradients, but the larger effects on subgrade moisture from varying water tables may obscure measurement of temperature-induced moisture flow, and may also upset equilibrium conditions for same.

The moisture variations at Site No. 12 also did not appear to be temperature-dependent. Site No. 12 was constructed in late 1965 and has PCC pavement and improved shoulders on a rather uniform CL clay subgrade with a plastic limit of 18-20. The site was installed in July, 1966, and, shortly after installation, a constant rate of moisture increase began at the site which continued until November, 1968. The rate of moisture content increase was not affected by seasonal precipitation (which was rather low until September, 1968) or air temperature. A total increase of about 5 percent engineering moisture content was observed during the 28 month period from site installation to November,

1968. Figures 4.11 and 4.12 show moisture variations and precipitation that occurred at Site No. 12 during the period subgrade temperatures were measured.

The water table at this site is also close to the surface, though below the 10 ft level. Drainage at the site is rated only fair, and the ditches adjacent to the highway were noted to remain wet and soggy for long periods after the heavy rains occurring in the fall of 1968. Pavement and shoulders at this site are rated excellent; this is confirmed by the rather smooth moisture variations noted at the site, indicating a lack of rapid infiltration/evaporation through the pavement.

Moisture accumulation at this site from July, 1966 to November 1968 is thought to occur from capillary sources, fed by a relatively constant water table. The heavy rains of September-November, 1968, collected in ditches adjacent to the pavement, and reduced evapotranspiration associated with cooler fall temperatures allowed the standing water to slowly migrate downward, causing either an increased moisture content in passing, or perhaps a general rise in the water table, thus bringing the capillary moisture source nearer the surface. The former hypothesis seems more logical, as capillary moisture accumulation should continue to only approximately the plastic limit of a cohesive soil; after that time the high degree of saturation and relatively complete double water layers of the subgrade tend to inhibit further accumulation from capillary sources and a more or less "equilibrium" condition is reached.

At this site, the above hypothesis is reinforced by noting that the increased moisture contents were maintained only until the spring of 1969, despite a large (for Oklahoma) amount of regular precipitation during the spring and summer. Higher spring and summer air temperatures caused

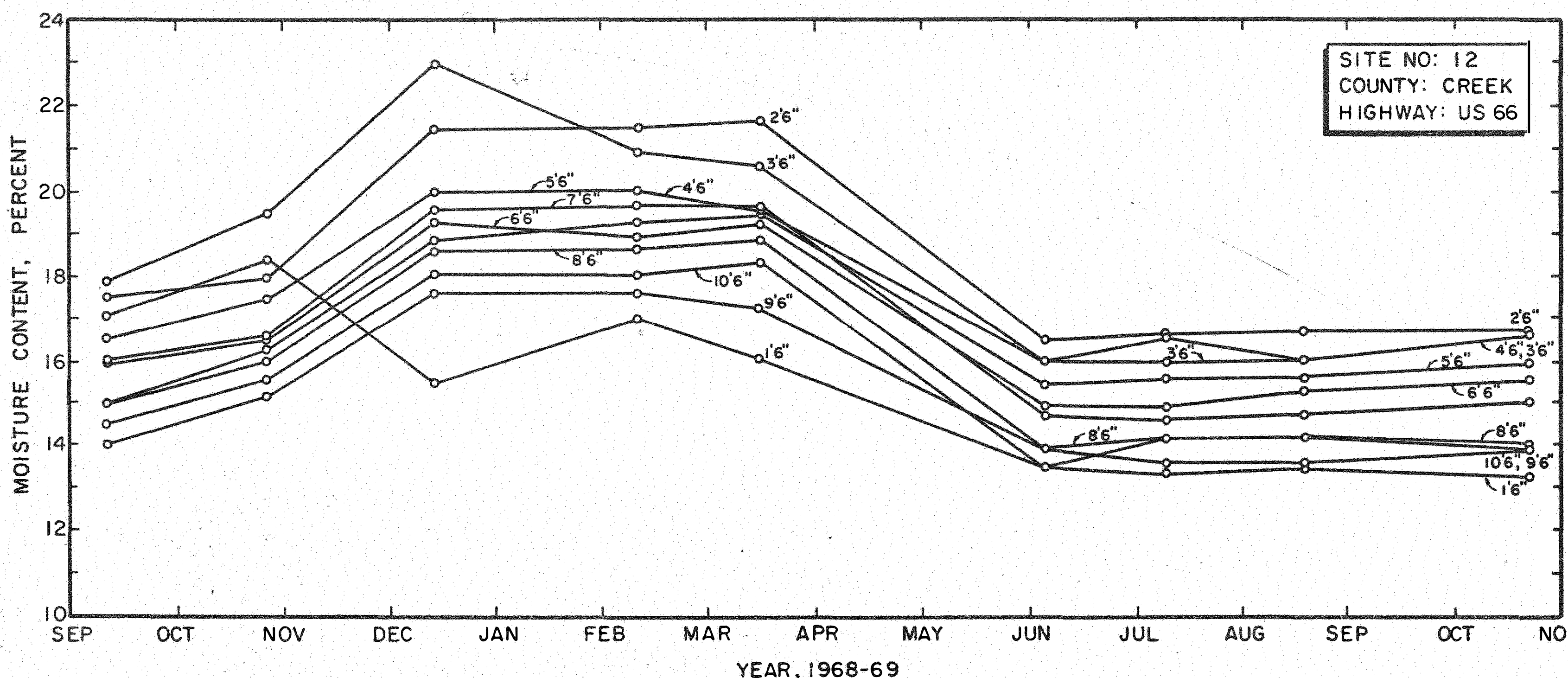


Figure 4.11. Subgrade Moisture Variation Beneath Pavement Centerline at Site No. 12

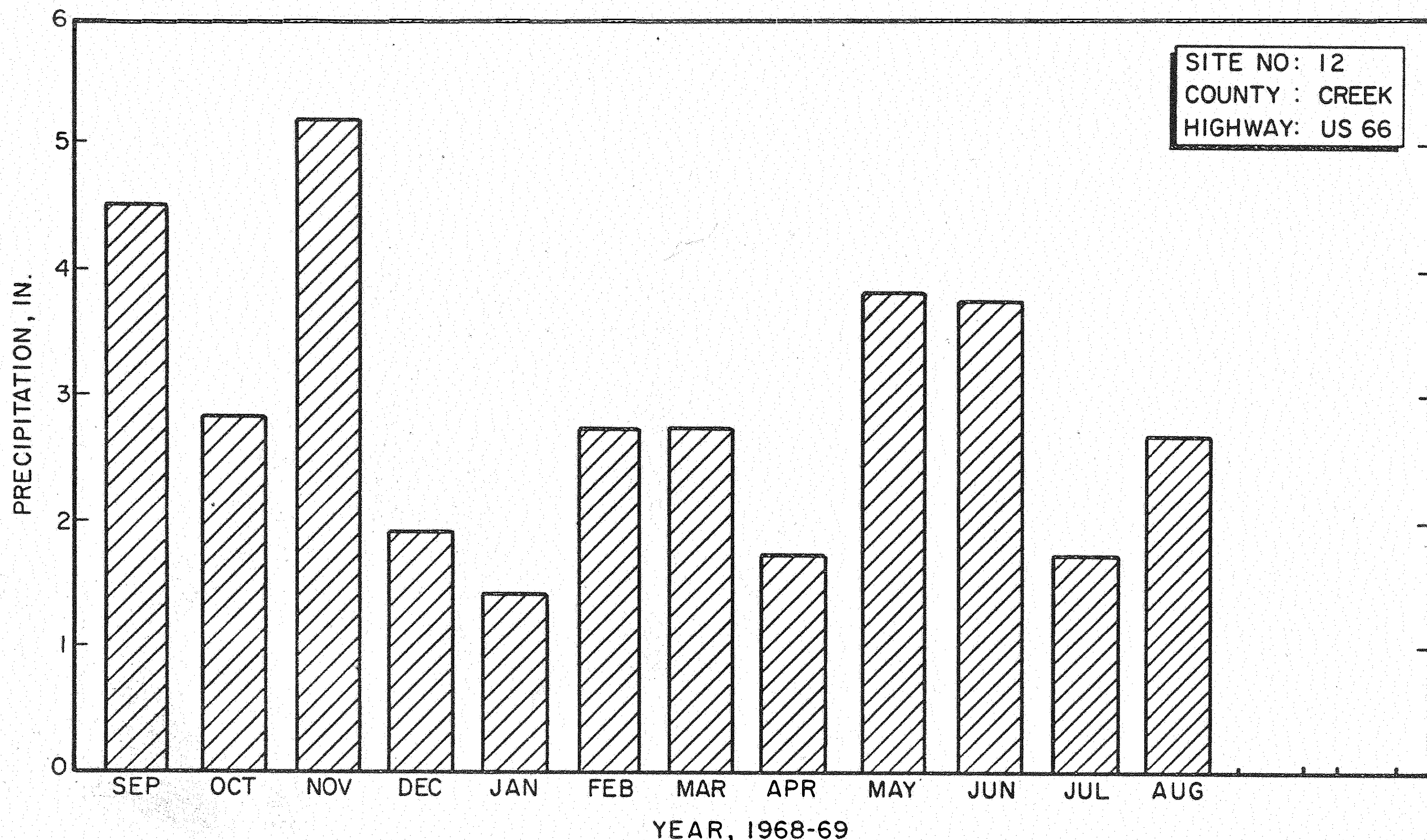


Figure 4.12. Total Monthly Precipitation at Site No. 12

evaporation of rainfall from the ditches before the water could migrate. The excess moisture accumulated in the subgrade during the winter, being "free" as the subgrade double layers were, for all practical purposes, complete, continued its slow downward migration to the water table. Evidence of this behavior may be seen by inspection of measured moisture contents in March, 1969, where moisture contents at the upper levels are decreasing while increasing at intermediate and lower levels. This type of behavior might be attributed to temperature effects, but the temperature gradient during this period was very small, and thermal moisture migration is thought to be negligible in cohesive soils at moisture contents near and above the plastic limit.

After June, 1969, subgrade moisture contents returned to their "equilibrium" near the plastic limit of the subgrade, and as this section has survived heave resulting from an approximate 5 percent moisture increase in the subgrade, without pavement cracking or shoulder deterioration, it should provide many years of future service. It is worthy of note that moisture contents under the shoulders increased at the same rate, or perhaps slightly faster than under the pavement centerline, which is not the usual behavior for pavements on expansive subgrades. However, the "only fair" drainage at the site and tendency for water to stand in the ditches may have helped to supply water to the subgrade at the pavement/shoulder edges, and produce relatively uniform swelling with a minimum of differential movement. In the opinion of the authors, if this site had been constructed with the drainage conditions usually specified in current "good" highway design procedures, severe pavement cracking and resulting rapid infiltration/evaporation of moisture through the pavement would not be occurring.

Thermal soil moisture flow may occur in highway subgrades in addition to precipitation-dependent or capillary moisture flow. However, it may be difficult to determine the amount of moisture variation caused by thermal effects. Figures 4.8 and 4.9 show that thermal soil moisture flow may cause subgrade moisture content to vary less than 2% while precipitation and/or capillary effects may cause moisture content to vary as much as 6-8%. Therefore, any thermal soil moisture flow that occurs may not appear to affect subgrade moisture content, because, even if the pavement and shoulders are impervious, precipitation and capillary effects will predominate.

## Summary

Subgrade temperature variations and other related trends detected from temperature measurements were discussed in this chapter. Temperature gradients were found to occur in highway subgrade, and the gradients beneath pavements differed from the gradients in uncovered subgrade. The possible influence of temperature gradients on subgrade moisture variations was also discussed. Moisture variations at several research sites appear to be influenced by temperature while moisture variations at other research sites appear to be influenced by other factors. Conclusions from this study and recommendations concerning future study of temperature effects on subgrade moisture variations are listed in the following chapter.

# CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

Subgrade temperatures were measured at six research sites during the period from November, 1968, through October, 1969. Equipment and procedures for measuring subgrade temperature and effects of temperature on subgrade moisture conditions are described in Chapters 3 and 4. The following conclusions may be made concerning subgrade temperature, temperature measurements, and influence of temperature on subgrade moisture migration:

1. Temperature gradients occurred in highway subgrades and were related to air temperature variations. The maximum winter gradient was approximately 2°F/ft and occurred during January, while the maximum summer gradient was approximately 2.5°F/ft and occurred during July and August.

2. Subgrade temperatures were dependent on pavement color. Subgrade temperatures beneath asphaltic concrete pavements were a few degrees warmer than temperatures beneath Portland cement concrete pavement.

3. Subgrade temperatures in cuts were similar to temperatures in fills in magnitude and variation.

4. Temperatures beneath pavement were warmer than temperatures in uncovered subgrade.

5. Equipment and procedures for measuring subgrade temperatures were both economical and effective.

6. Subgrade thermal soil moisture flow appeared to occur at some of the research sites. Subgrade moisture contents increased at cooler levels while decreasing at warmer levels.

7. Thermal soil moisture flow in sandy soil was greater than thermal soil moisture flow in clayey soil.

8. Subgrade moisture variations at several of the temperature measurement research sites were primarily affected by factors other than temperature gradients. Even though pavement at the sites was relatively impervious, precipitation appeared to have a noticeable influence on subgrade moisture contents, particularly at upper levels. Moisture variations at some of the sites also appeared to be caused by seasonal movement of the water table, and thus the height to which capillary moisture would rise in the subgrade.

9. Moisture variations caused by thermal soil moisture flow were quite small compared to variations caused by precipitation and capillarity. It is therefore concluded that temperature-induced subgrade moisture migration is a secondary effect, compared (in magnitude) to those produced by precipitation and capillarity, in Oklahoma subgrades. However, it is possible that the relatively small migration produced by temperature gradients, when coupled with the "dry of optimum" subgrades usually existing under new construction in Oklahoma, may, in time, cause enough moisture transfer to the upper levels of the subgrade for resultant heave to crack the pavement and open the way for large precipitation/evaporation-induced moisture variations.

Under the above conditions, moisture would migrate thermally to the upper levels during cooler months, but would be attracted and held in the cohesive subgrade's double layers during the warmer months and not migrate downward. The next cooler period would allow additional upward migration, etc., until upper subgrade moisture contents reached the vicinity of the material's plastic limit. Unfortunately, no temperature probes were installed in new construction to test this hypothesis.

For further study of temperature effects on Oklahoma subgrade moisture variations, the following are recommended:

1. Temperature measurements should be continued. Subgrade temperatures should be measured at the six research sites until shortly before project termination to determine size and variation of temperature gradients and their relation to moisture movement during approximately one and one-half annual cycles.

2. While available time and funds do not permit the installation of temperature and moisture measuring equipment at a site(s) to test the previously stated hypothesis concerning accumulation of appreciable moisture by thermal migration, this is suggested as a worthwhile future project. In addition to the field study, a laboratory study might be conducted to determine the amount of thermal soil moisture flow caused by temperature gradients found to occur in typical Oklahoma cohesive highway subgrades, and to determine if the flow is, in fact, reversible at low soil moisture contents.

3. In future installations to measure subgrade temperature, probes should be installed in both shoulders at each research site. Temperature probes installed at the pavement centerline and five feet from the edge of pavement or improved shoulder provide subgrade temperature variations for only half the subgrade cross-section, while temperature probes installed at both shoulders and centerline would provide temperature variations for the entire subgrade cross-section. In some cases, the assumption a symmetrical temperature profile may not be justified.

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