THERMAL SOIL MOISTURE FLOW BENEATH
OKLAHOMA HIGHWAYS

By

RONALD DEAN OSTERHOUT

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

1968

Submitted to the Faculty of the Graduate College
of the Oklahoma State University
in partial fulfillment of the requirements
for the Degree of
MASTER OF SCIENCE
August, 1969

THERMAL SOIL MOISTURE FLOW BENEATH
OKLAHOMA HIGHWAYS

Thesis Approved:

L. Allan Haliburton
Thesis Adviser

M. Lodell Hady

J. V. Parcher

D. D. Durham
Dean of the Graduate College

TO MY WIFE

for her sacrifice,

encouragement, and

understanding.

ACKNOWLEDGMENTS

The author wishes to express his appreciation to the following individuals.

To his major adviser, Professor T. Allan Haliburton, for his encouragement and counsel throughout this research.

To his committee members, Professor J. V. Parcher and Professor M. Abdel-Hady, for their interest and encouragement.

To his fellow graduate students, B. Dan Marks, Frank C. Townsend, Larry K. Shaw, and Donald R. Snethen for their assistance and fellowship.

To Mrs. Nancy Wolfe for typing the manuscript.

To Mr. Eldon Hardy for assistance in preparation of graphical portions of this thesis.

To Mr. Cecil K. Sharp for his assistance and suggestions in preparing temperature probes.

TABLE OF CONTENTS

LIST OF TABLES

CHAPTER I

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 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 variations and 3) to present conclusions concerning the effects of subgrade temperature on subgrade moisture variations.

CHAPTER II

THERMAL SOIL MOISTURE FLOW

Theory of Thermal Soil Moisture Flow

A temperature gradient applied to a soil mass may cause soil moisture flow. This flow occurs mainly in vapor phase and is 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 1, 2, 3). 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

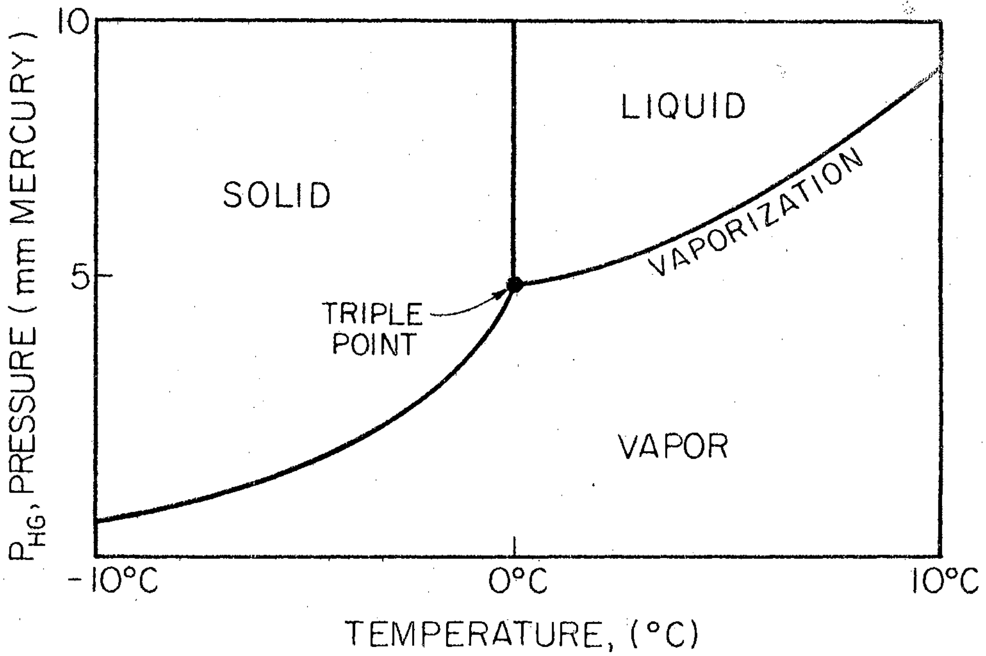


Figure 2.1. Triple Point Diagram for Water

voids is negligible (Ref 5). Thermal soil moisture flow occurs in soils with low moisture contents. Maximum thermal soil moisture flow occurs 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°C while the other end was maintained at a temperature of 25°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°C to 20°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 the 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 content 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 III

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 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 microcrystalline wax provided both 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°C to 150°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).

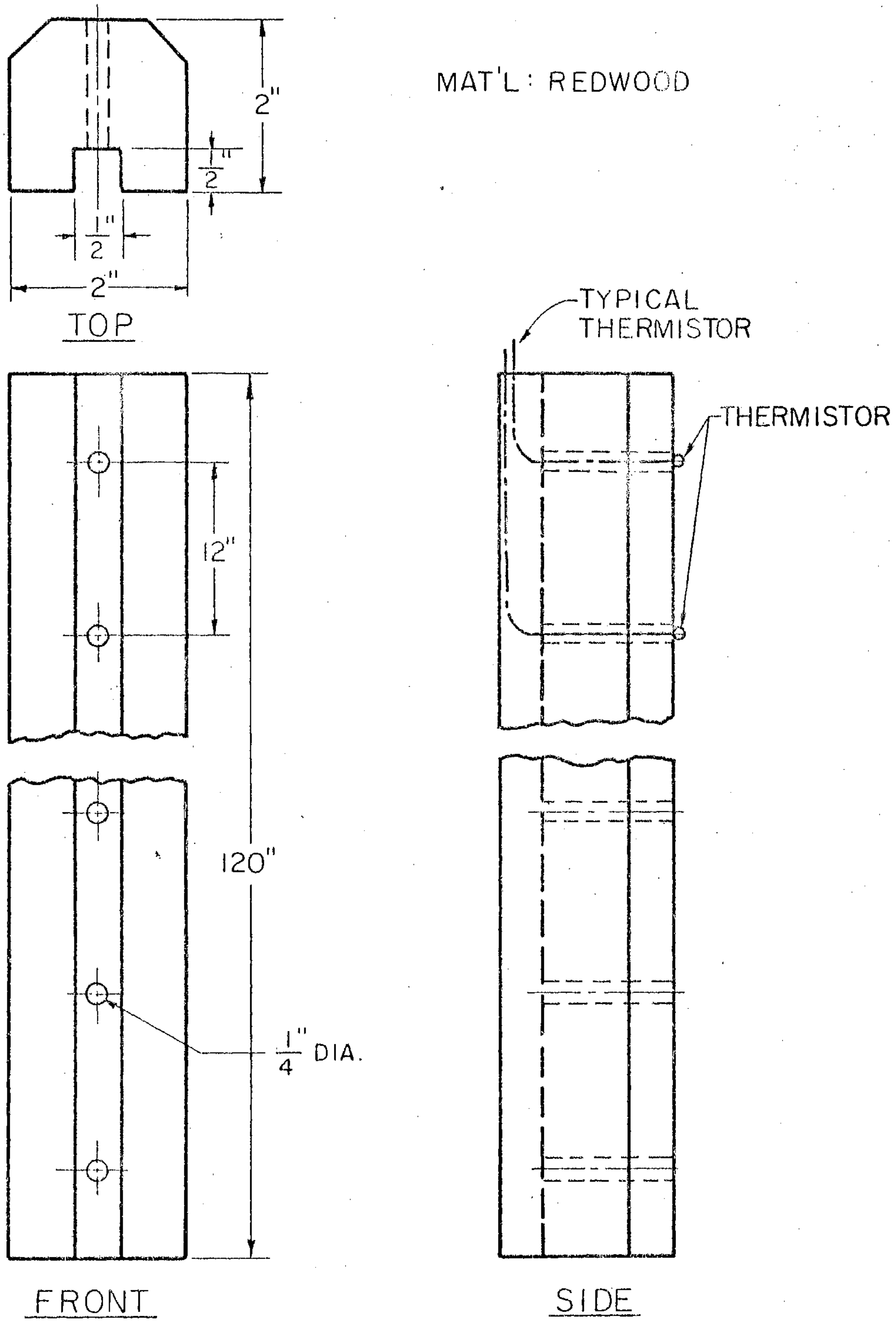


Figure 3.1. Temperature Probe

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°F to 105°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

There are forty-eight research sites with various soil and highway design characteristics 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

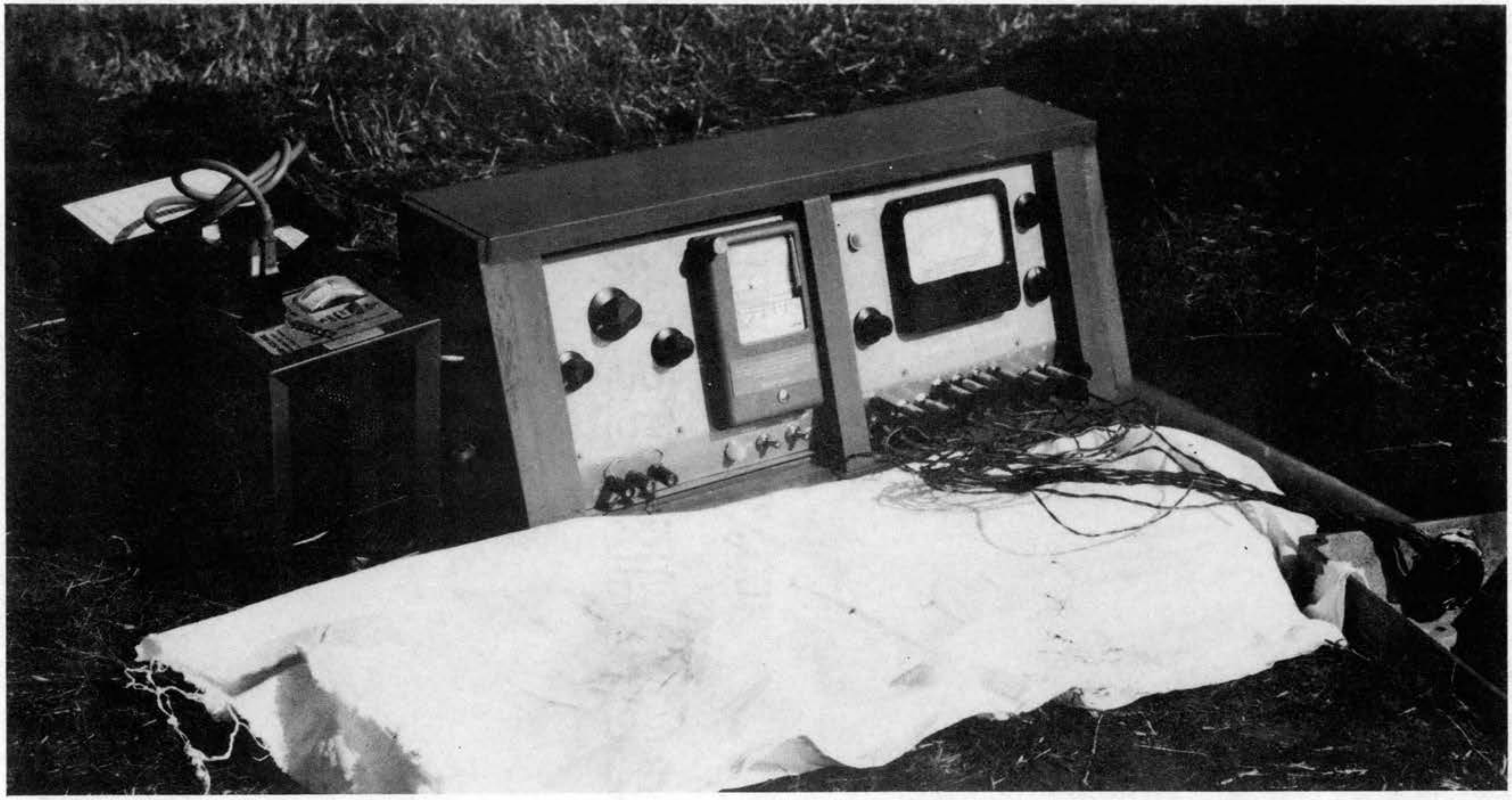


Figure 3.2. Power Inverter, Recorder and Telethermometer

moisture variations beneath pavements with high ratings were predominantly temperature dependent because moisture variations 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 improved shoulder, were installed in the subgrade at each temperature

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

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 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 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

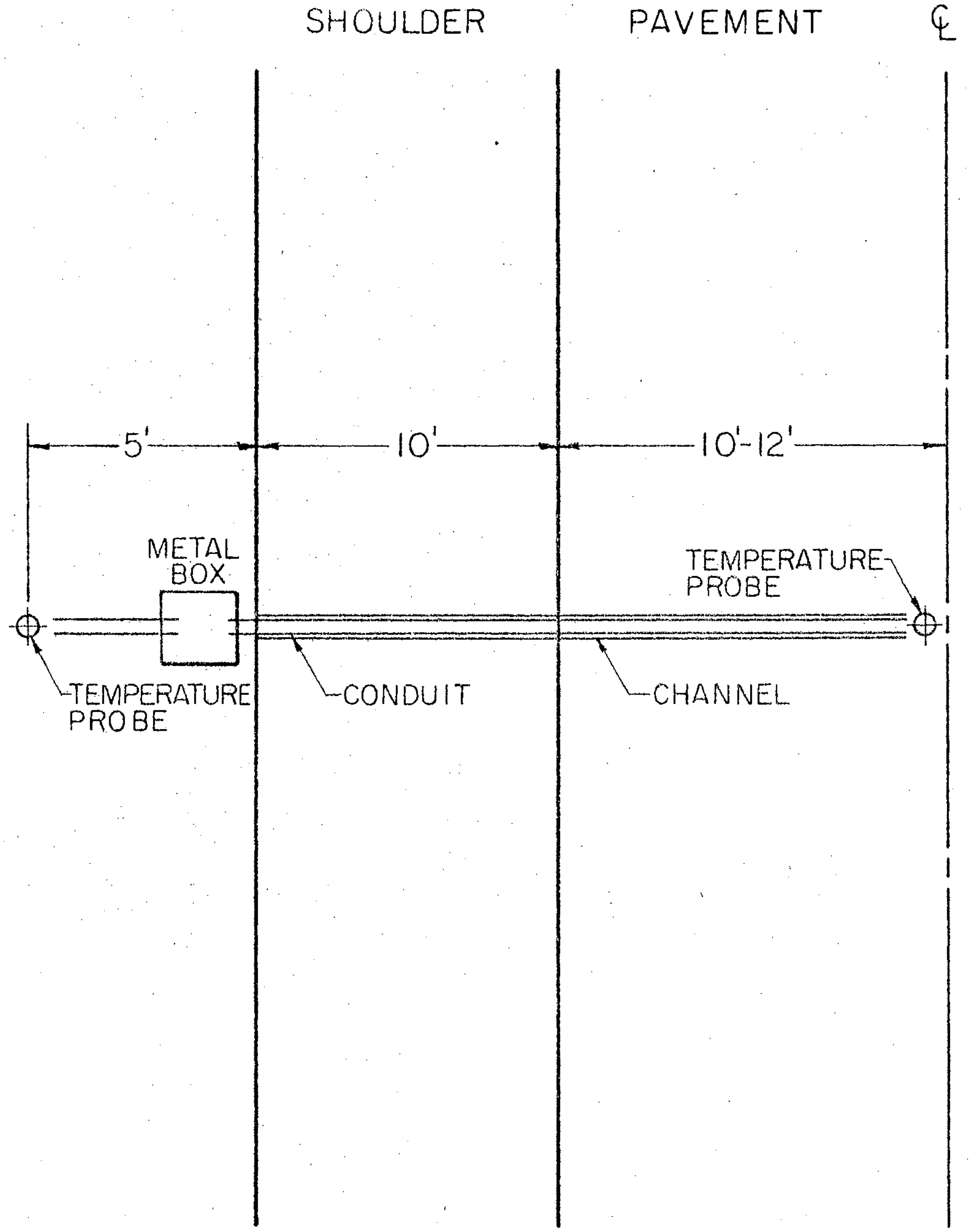


Figure 3.3. Temperature Site Plan for Sealed Shoulder

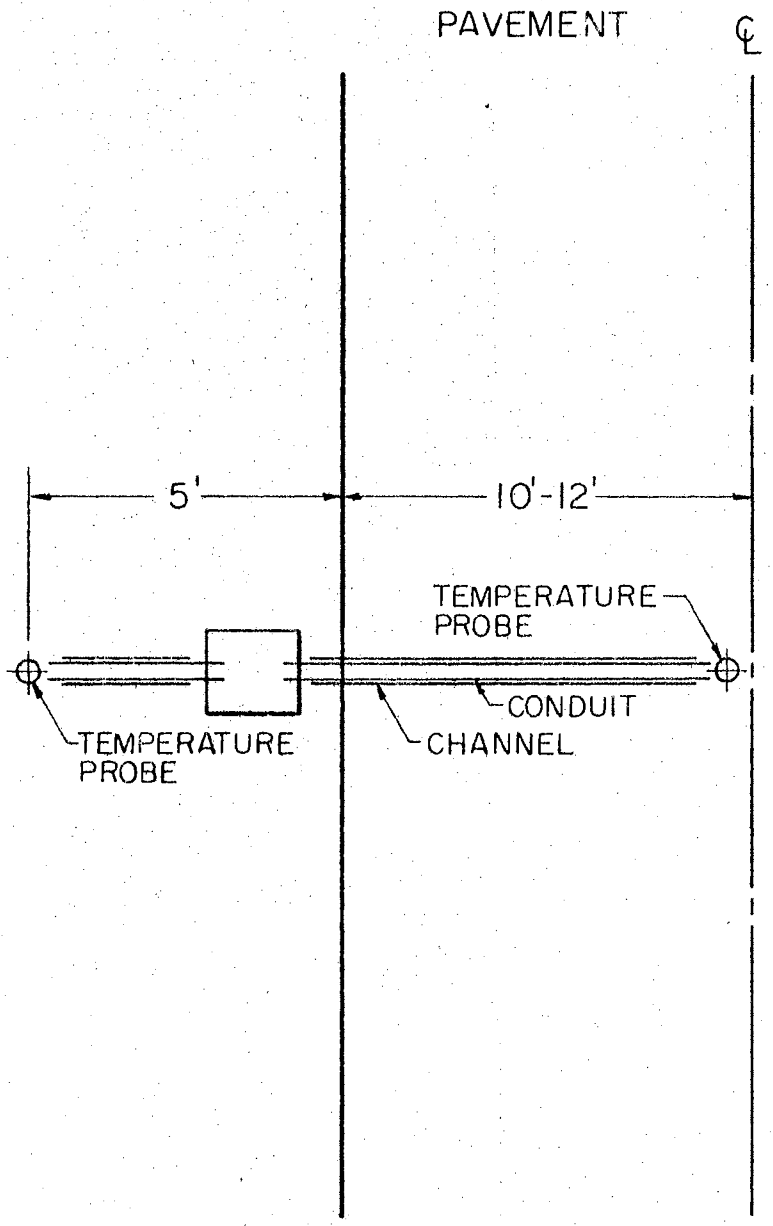


Figure 3.4. Temperature Site Plan for Open Shoulder

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

Figure 3.6. Workmen Removing Material from Channel

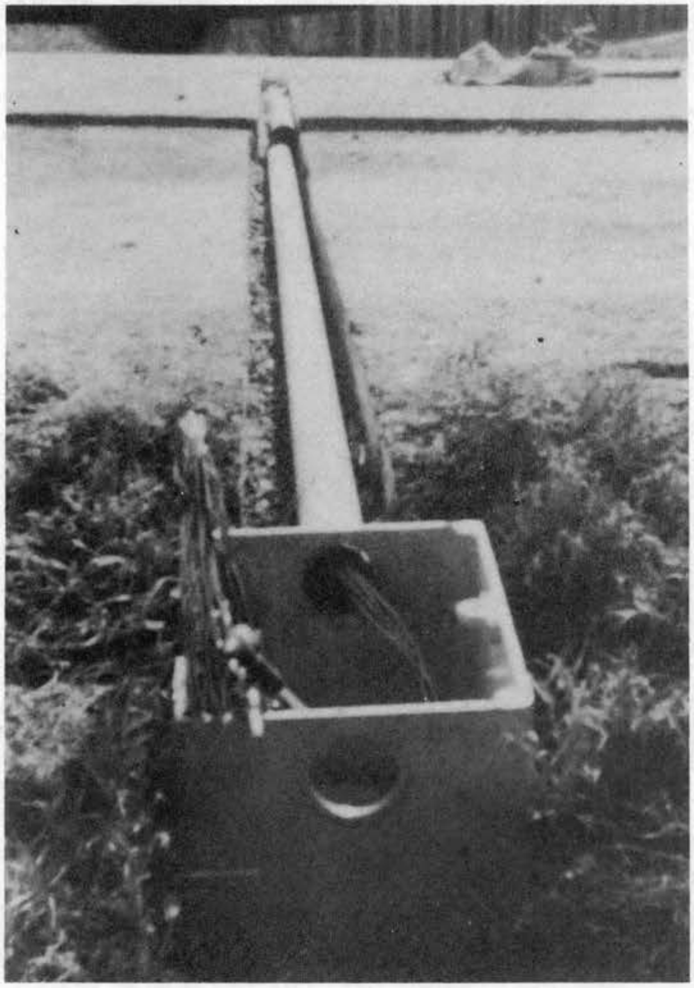


Figure 3.7. Channel and Conduit Prior to Patching

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 variations were affected by temperature. To correlate subgrade temperature and 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 approximately 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 temperature measurement cycle provided a better understanding of subgrade temperature variation.

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

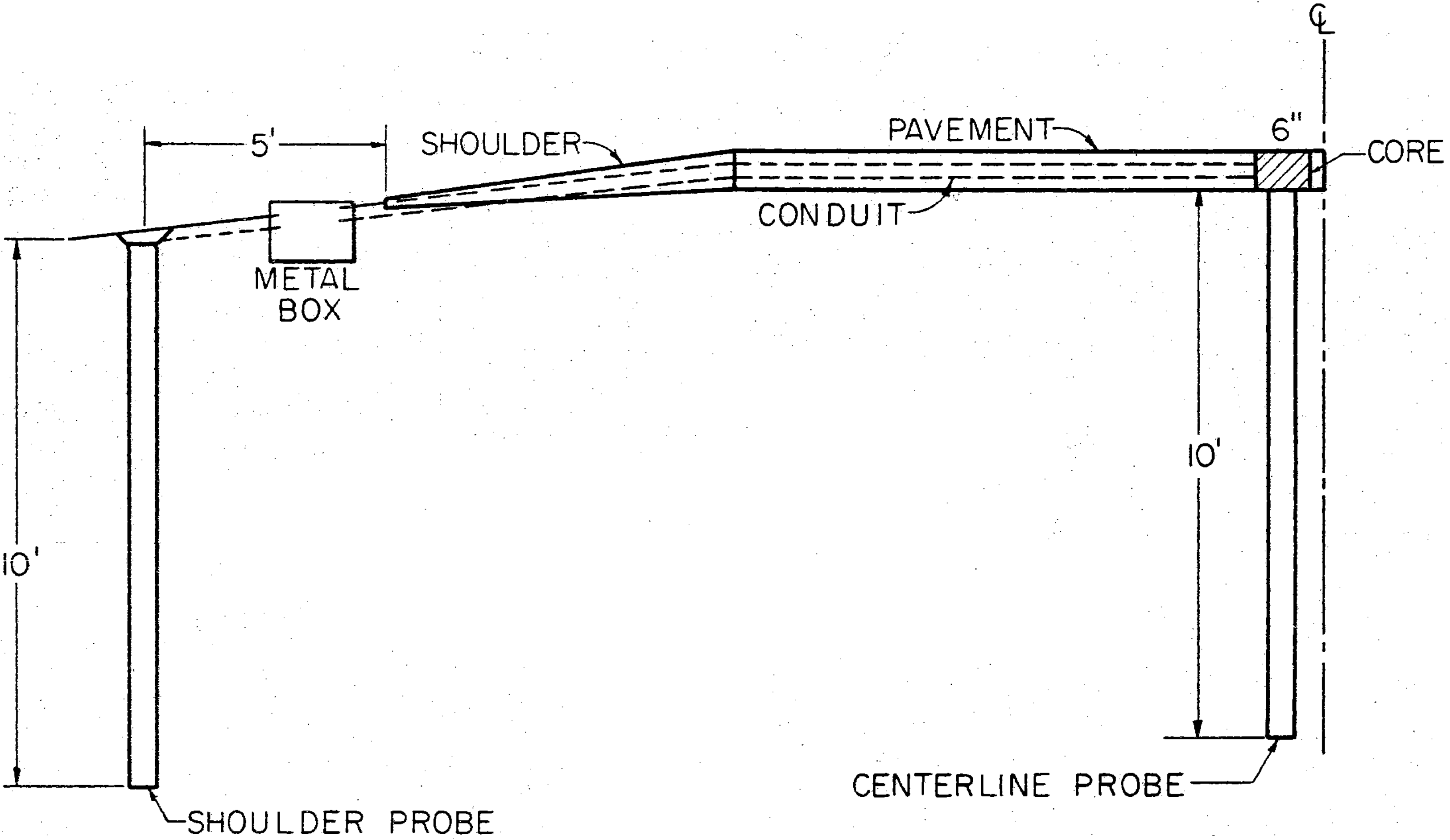
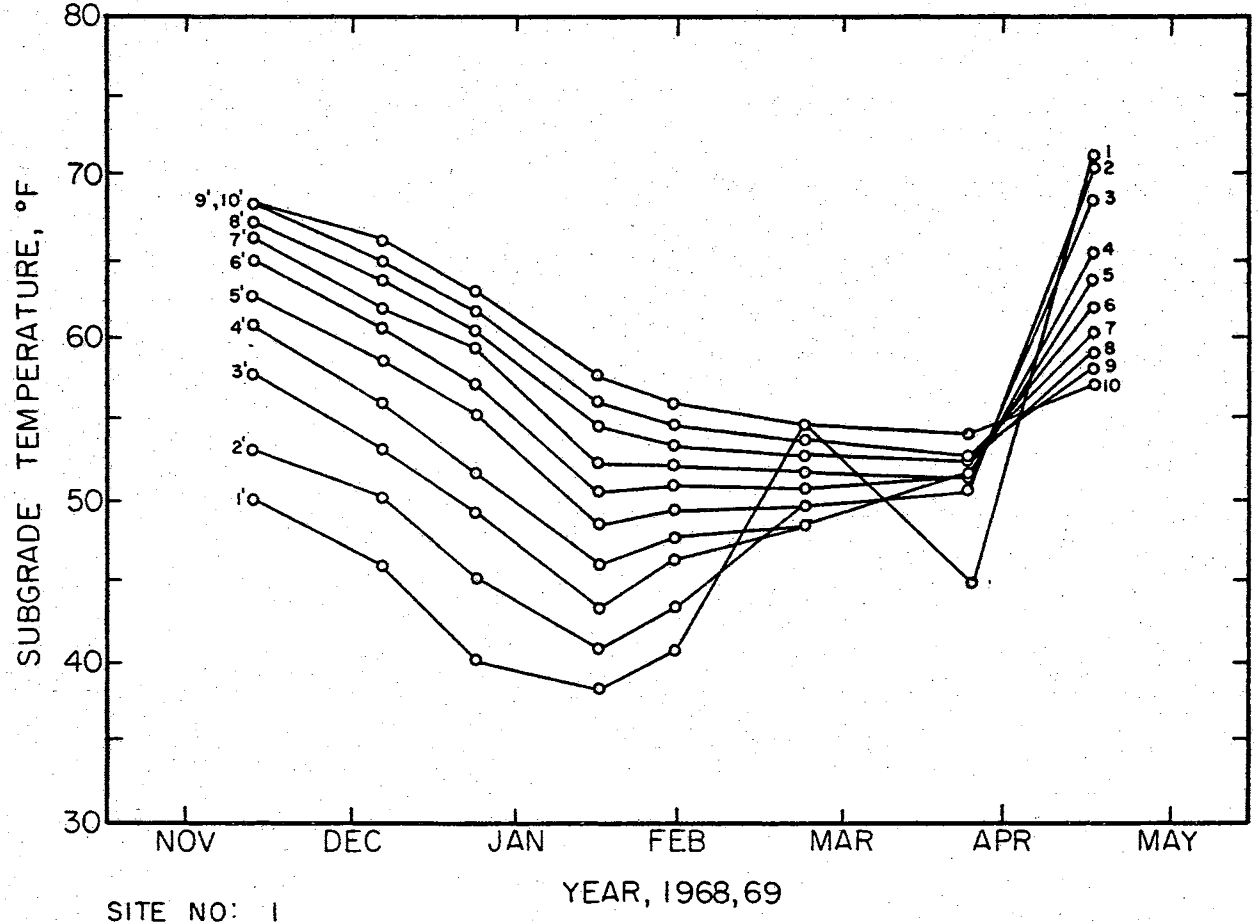


Figure 3.9. Temperature Site Installation

variations 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.



SITE NO: 1
COUNTY: PAYNE
HIGHWAY: US 177

Figure 3.10. Subgrade Temperatures at Site No. 1

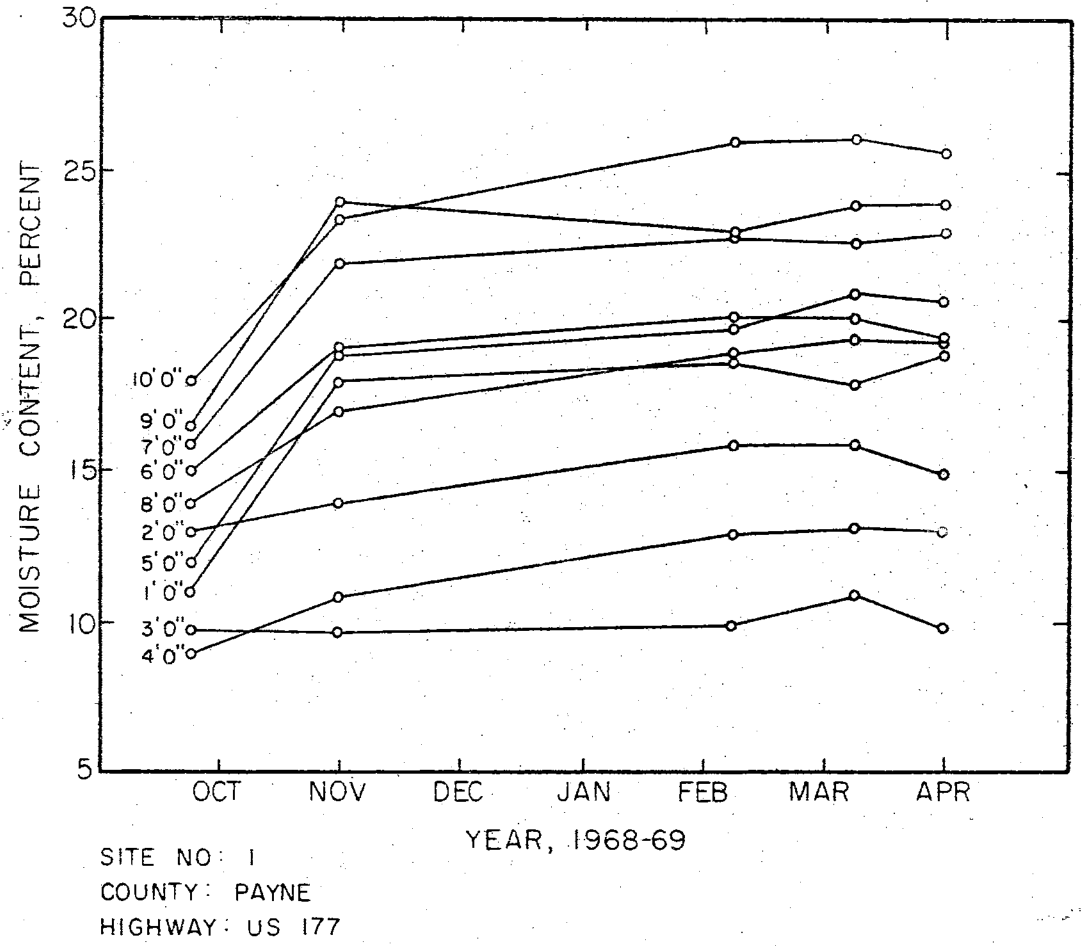


Figure 3.11. Moisture Variations Beneath Pavement at Site No. 1

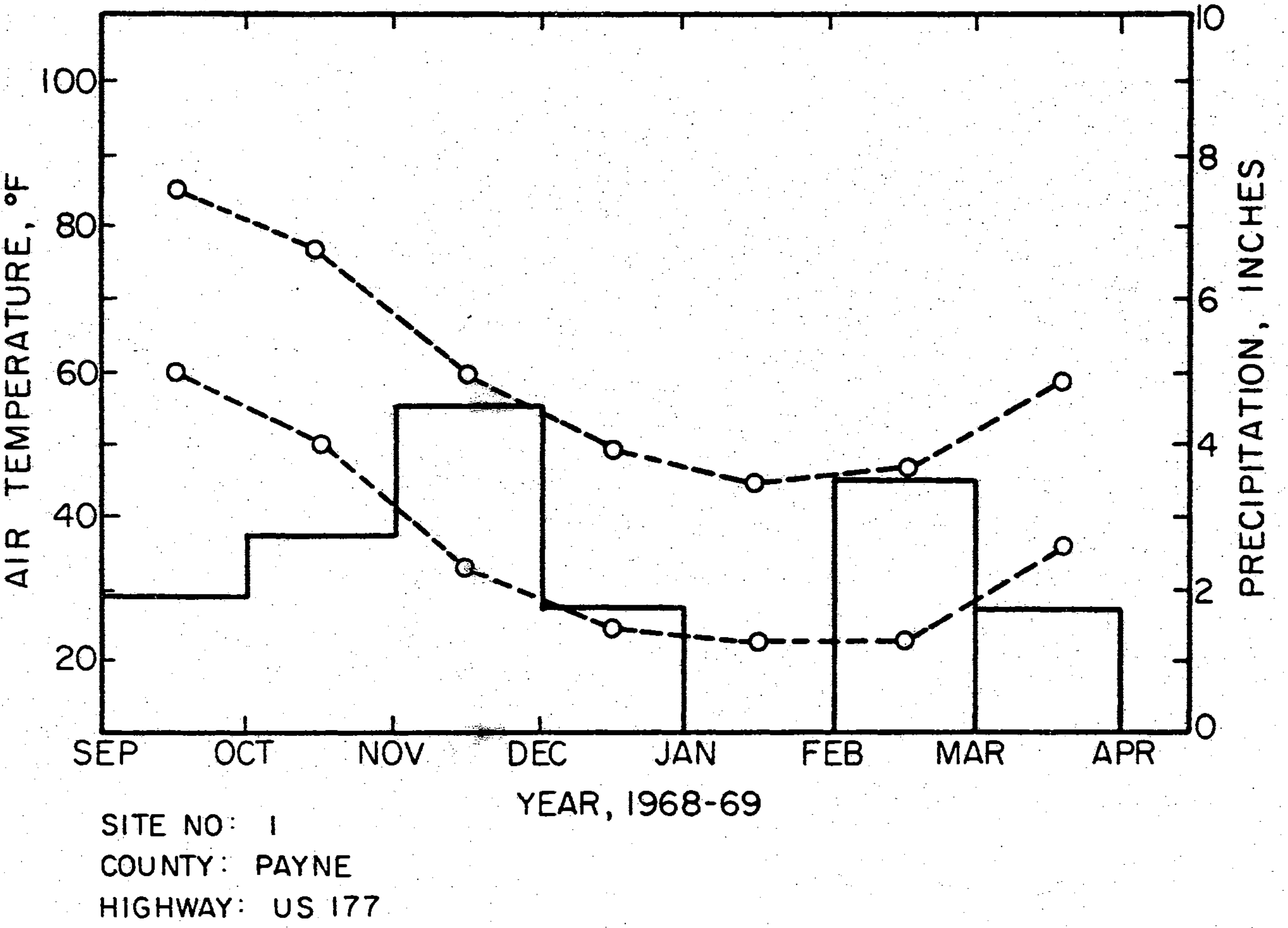


Figure 3.12. Climatological Data from Site No. 1

CHAPTER IV

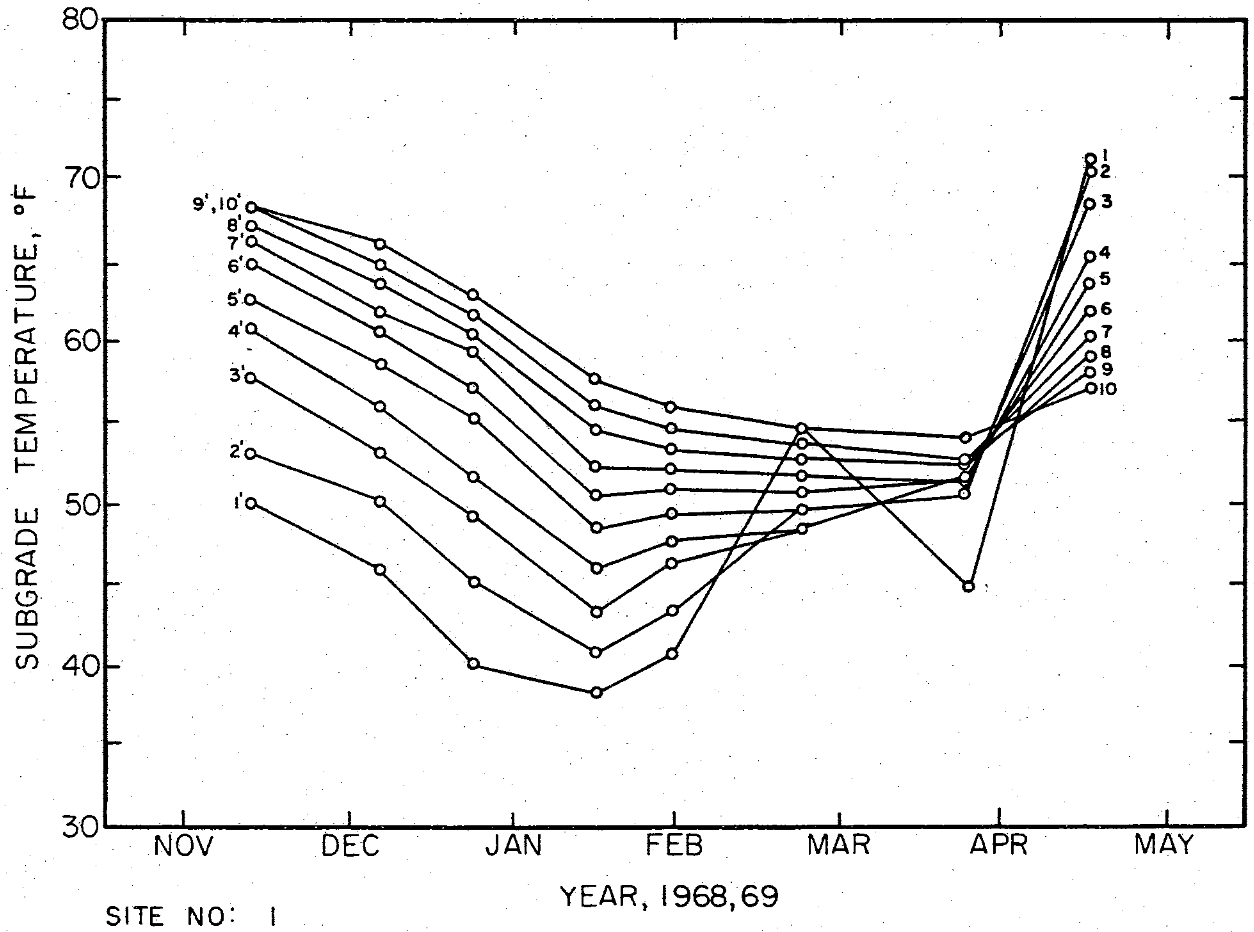
PRESENTATION AND CORRELATION OF SUBGRADE TEMPERATURE AND MOISTURE DATA

Subgrade temperature variations, related trends detected from collected temperature data, and the possible influence of temperature on subgrade moisture variations 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 April 28, 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 temperatures for each level plotted 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 subgrade and vary with seasonal air temperature. Figure 4.1 shows typically encountered subgrade temperature variations. Temperature for all levels



SITE NO: 1
COUNTY: PAYNE
HIGHWAY: US 177

Figure 4.1. Subgrade Temperature at Site No. 1

decreased during the period from November to January. During February and March the temperature for all upper levels (1 ft, 2 ft, 3 ft) 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 during an annual cycle and the 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. Figure 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.

Subgrade temperatures beneath PCC pavements were found to be a few degrees cooler than the temperature beneath darker colored AC pavement. This may have been caused by the ability of darker colored AC pavement to absorb solar radiation. Straub, Dudden, and Moorhead (Ref 12) found that darker colored pavements absorbed solar radiation more readily than lighter colored pavements, and the subgrade temperatures were affected by the amount of solar radiation absorbed. They found that subgrades beneath black pavements were as much as 30°F warmer than subgrade beneath white pavements. As shown in Fig 4.3, temperatures

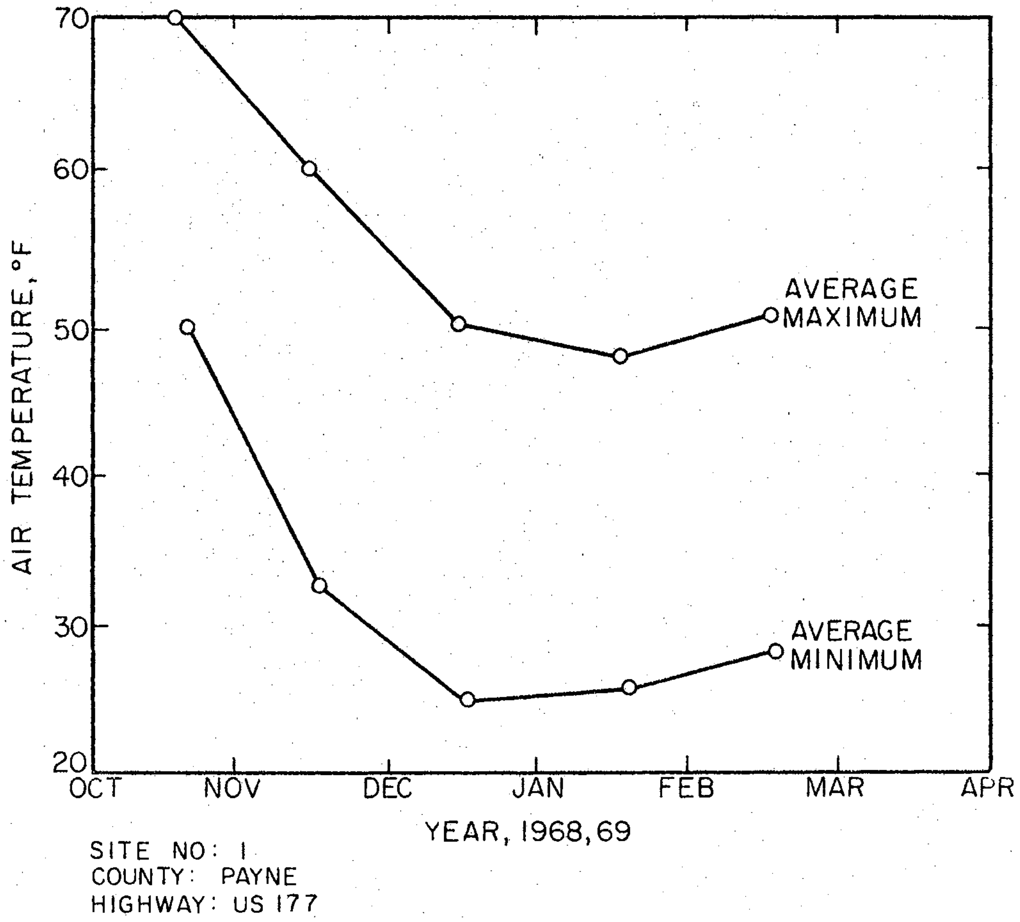


Figure 4.2. Mean Monthly Maximum and Minimum Air Temperature at Site No. 1

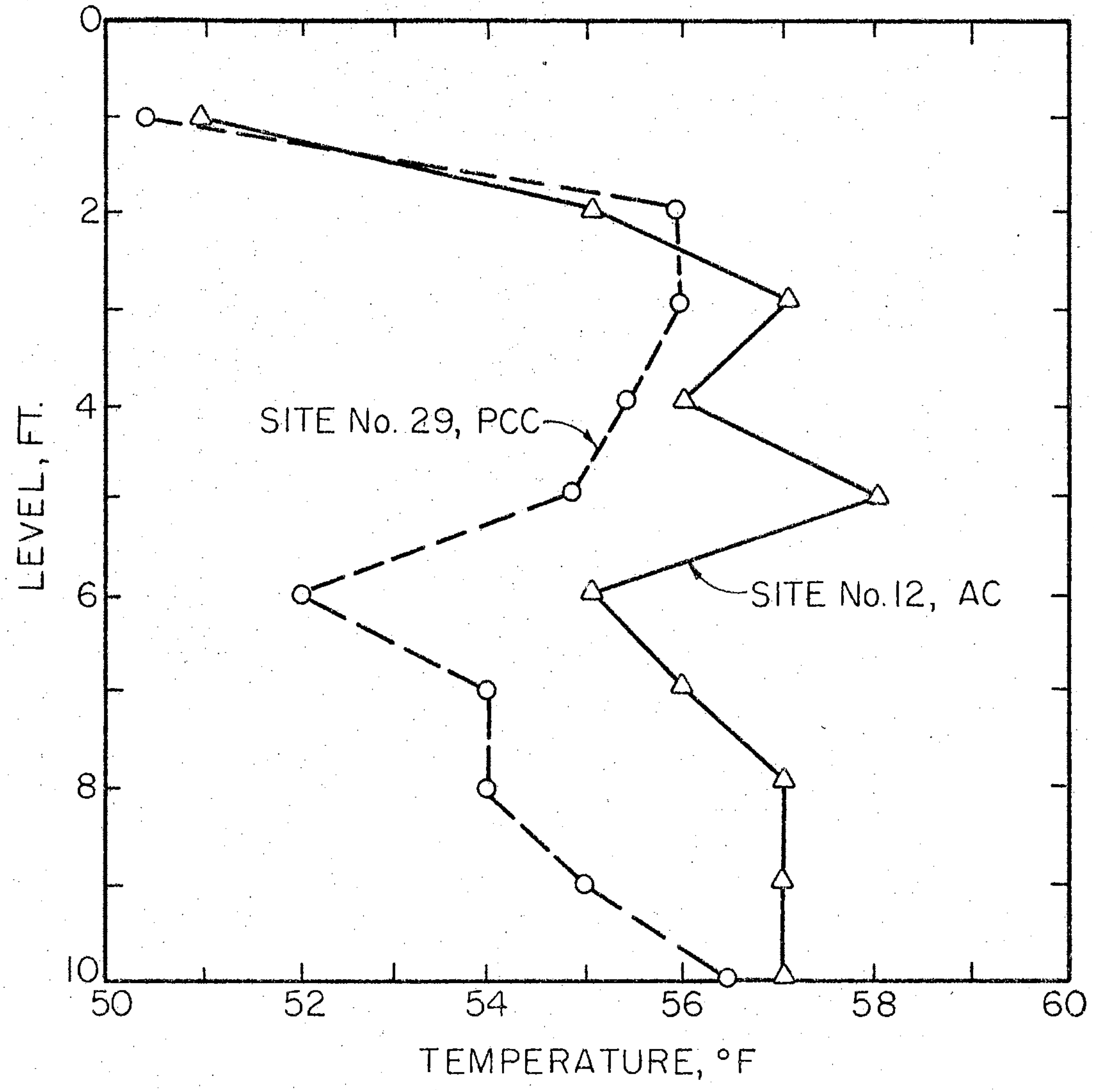


Figure 4.3. Temperature Gradients in Subgrades of AC and PCC Pavements

beneath AC pavement at Site No. 12 were approximately 3°F warmer than temperatures beneath PCC pavement at Site No. 29.

There were no appreciable differences in 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 a 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, 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 the surface in cuts may occur only in a vertical direction. The possibility that more heat may be transferred from the subgrade in fills than from cuts may cause tempeatures 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.

Temperature at all levels beneath the pavement at each site was warmer than the temperature 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 than temperatures measured in uncovered subgrade. This is in agreement with Moore (Ref 11) who found that soil temperatures beneath pavements were warmer than temperatures

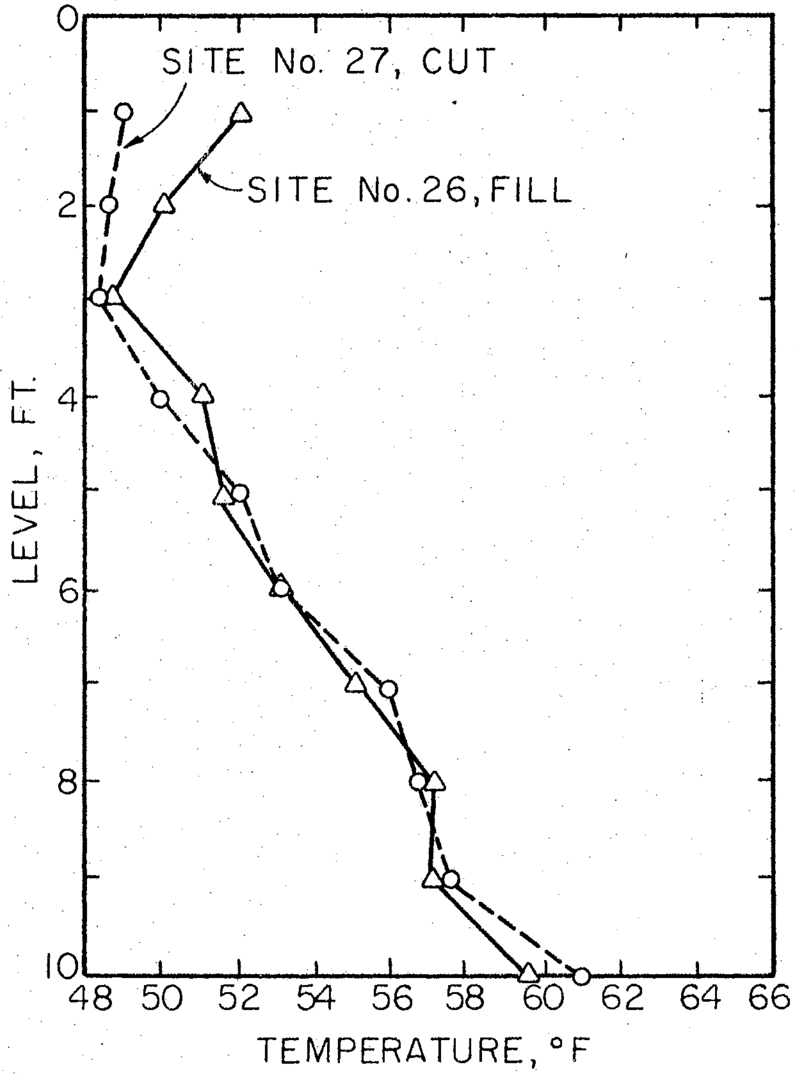


Figure 4.4. Temperature Gradients in Cut and Fill Sections

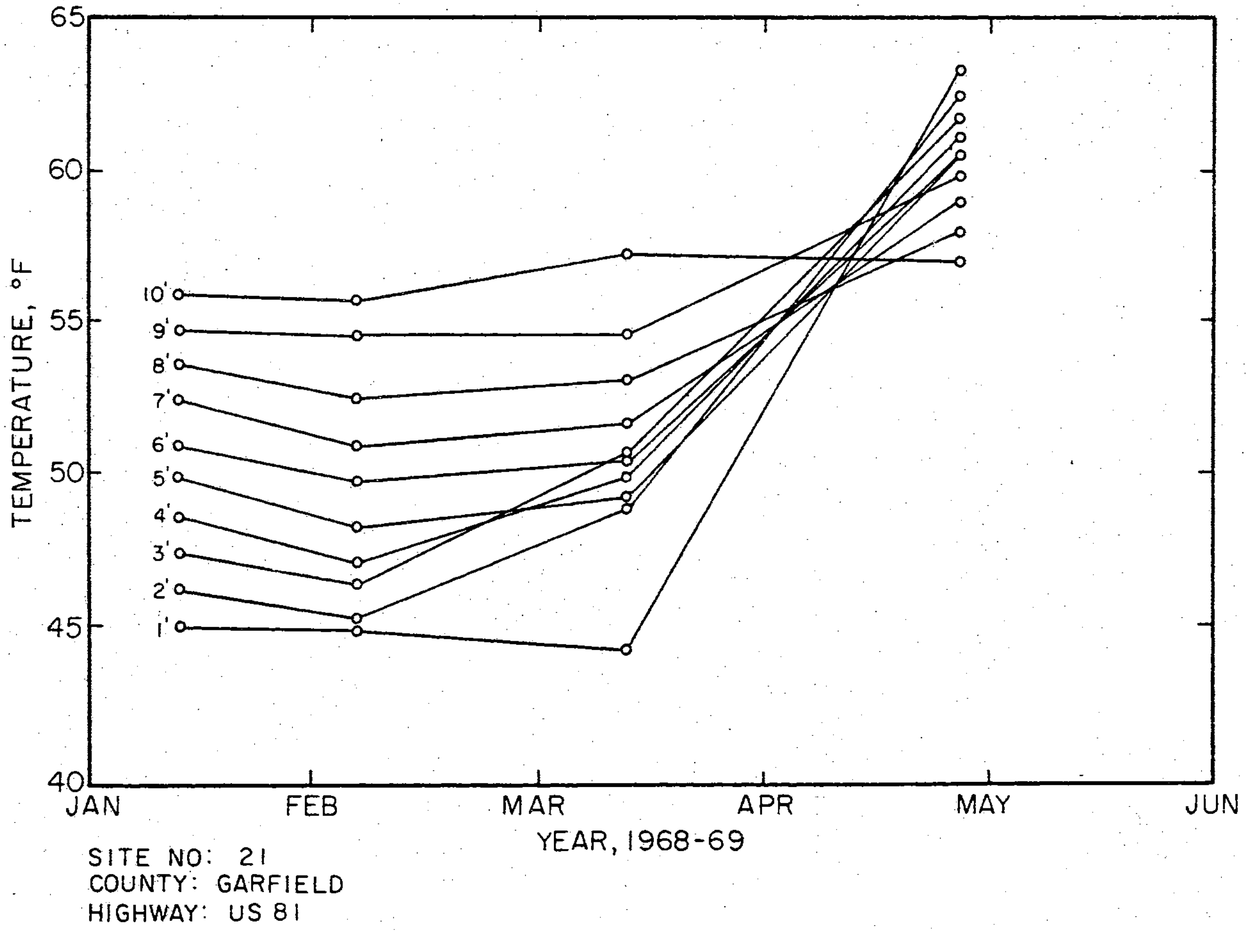


Figure 4.5. Subgrade Temperatures Beneath Pavement at Site No. 21

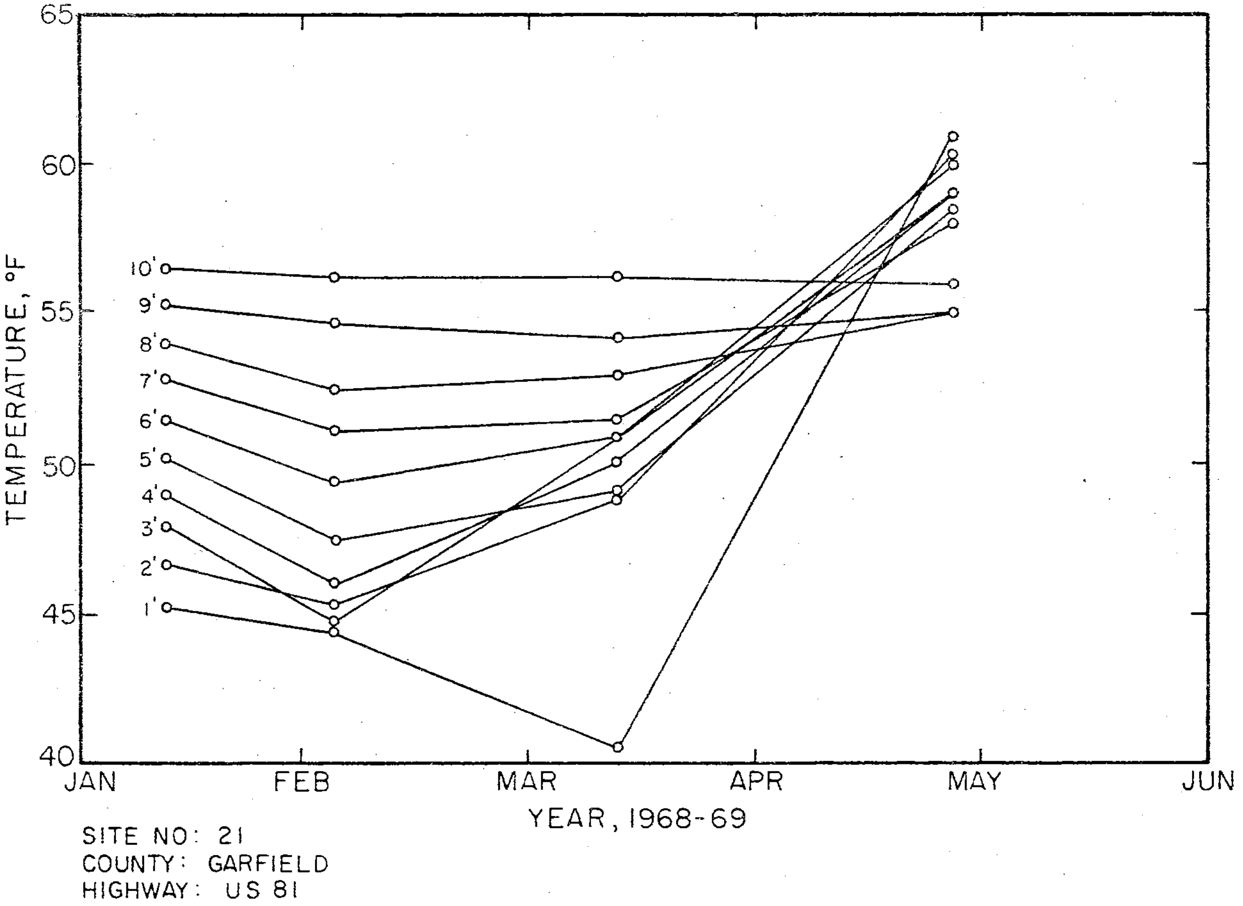


Figure 4.6. Subgrade Temperatures in Uncovered Area Adjacent to Pavement at Site No. 21

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 Temperature and Moisture Variation

As discussed in Chapter II, 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 a 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.

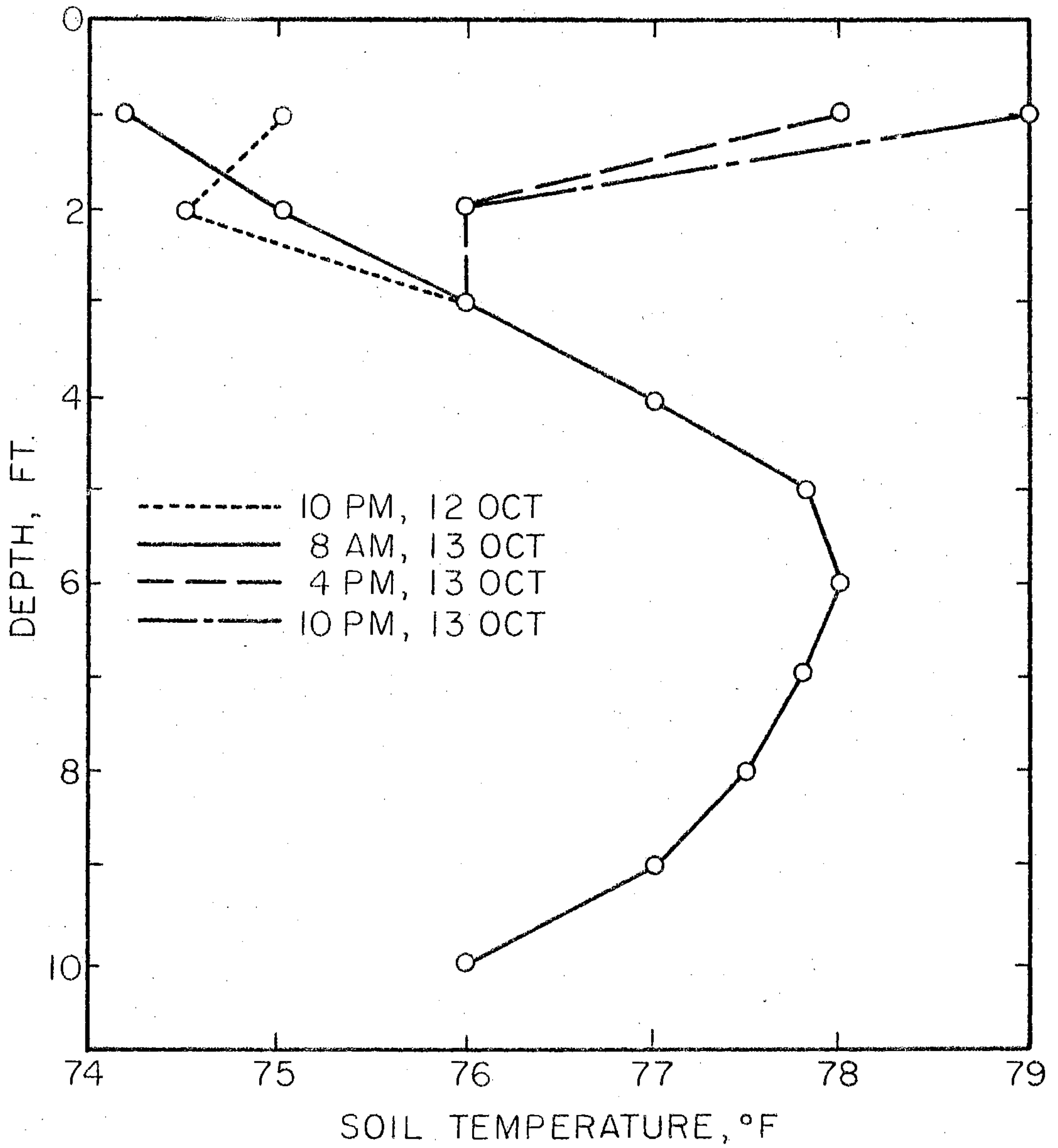


Figure 4.7. Variation of Temperature Gradient at Demonstration Site During 24 Hour Period, 12-13 Oct 1968

The subgrade moisture content beneath the 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. Figure 4.8 shows the moisture content of levels 2 ft and 3 ft decreased during the period from May through October and then increased during the period from November to April. 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.

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

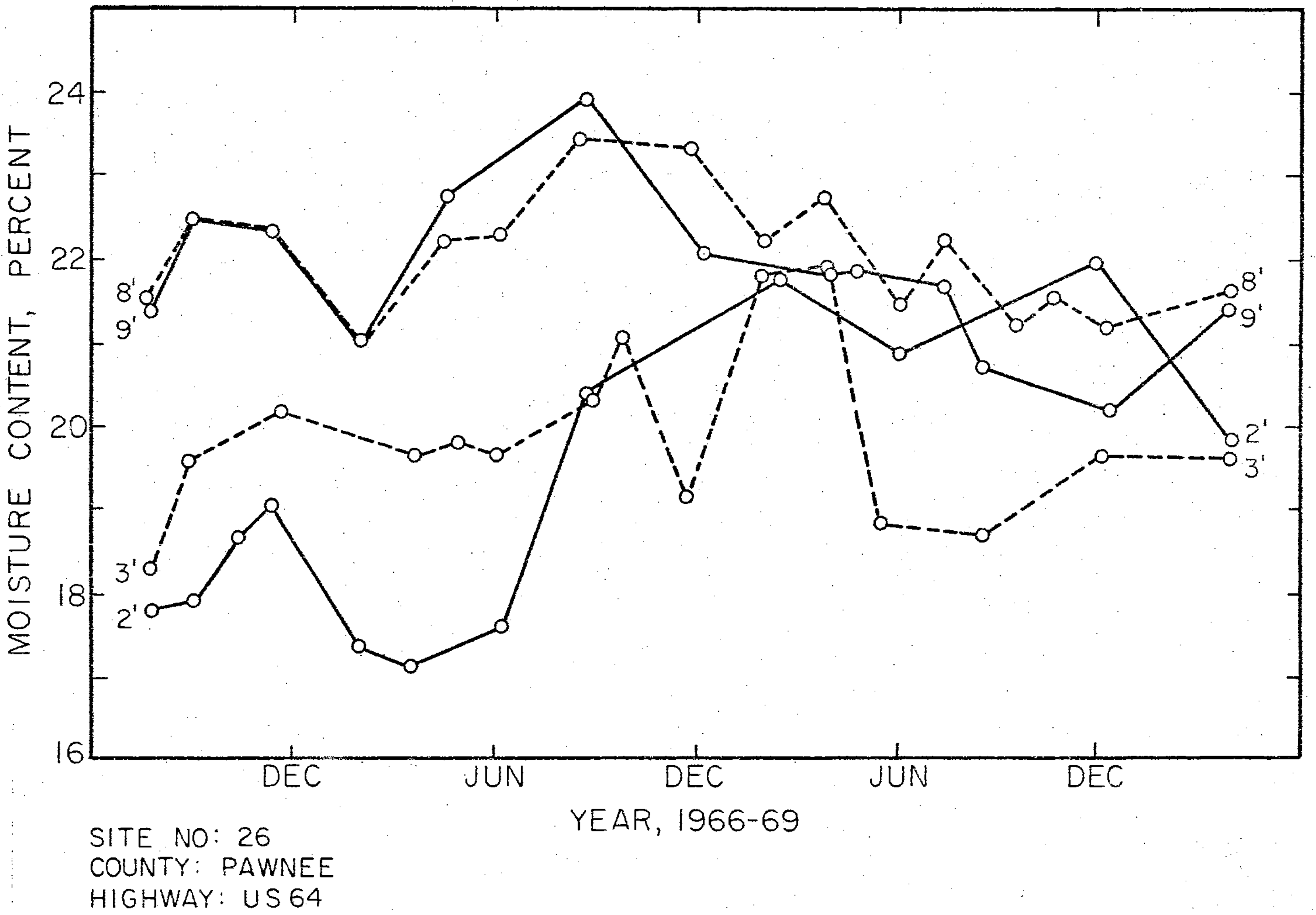


Figure 4.8. Subgrade Moisture Variation Beneath Pavement at Site No. 26

be correlated with temperature variations: the moisture variations appeared to be caused primarily by precipitation. An increase in subgrade moisture content at each of these three sites occurred four to six weeks after occurrence of a large amount of rainfall. Marks and Haliburton (Ref 14) found that moisture variations in subgrades beneath pavements with poor ratings resulted from infiltration of runoff, and increases in subgrade moisture content lagged rainfall occurrence by four to six weeks. Although Site Nos. 1, 12, and 21 have excellent pavement ratings, the moisture variations appeared to be affected by precipitation. 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 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. The moisture variations at Site No. 12 also appeared to be affected by precipitation as described by Marks and Haliburton. Figures 4.11 and 4.12 show moisture variations and precipitation that occurred at Site No. 12. An increase in moisture content occurred in November and December approximately four weeks after the occurrence of a large amount of precipitation in October and November.

Thermal soil moisture slow may occur in highway subgrades in addition to precipitation-dependent moisture flow. However, it may be difficult to determine the amount of moisture variation caused by thermal moisture flow. Figures 4.8 and 4.9 show that thermal soil moisture flow may cause subgrade moisture content to vary less than 2% while precipitation may cause moisture content to vary as much as 6-8%. Therefore,

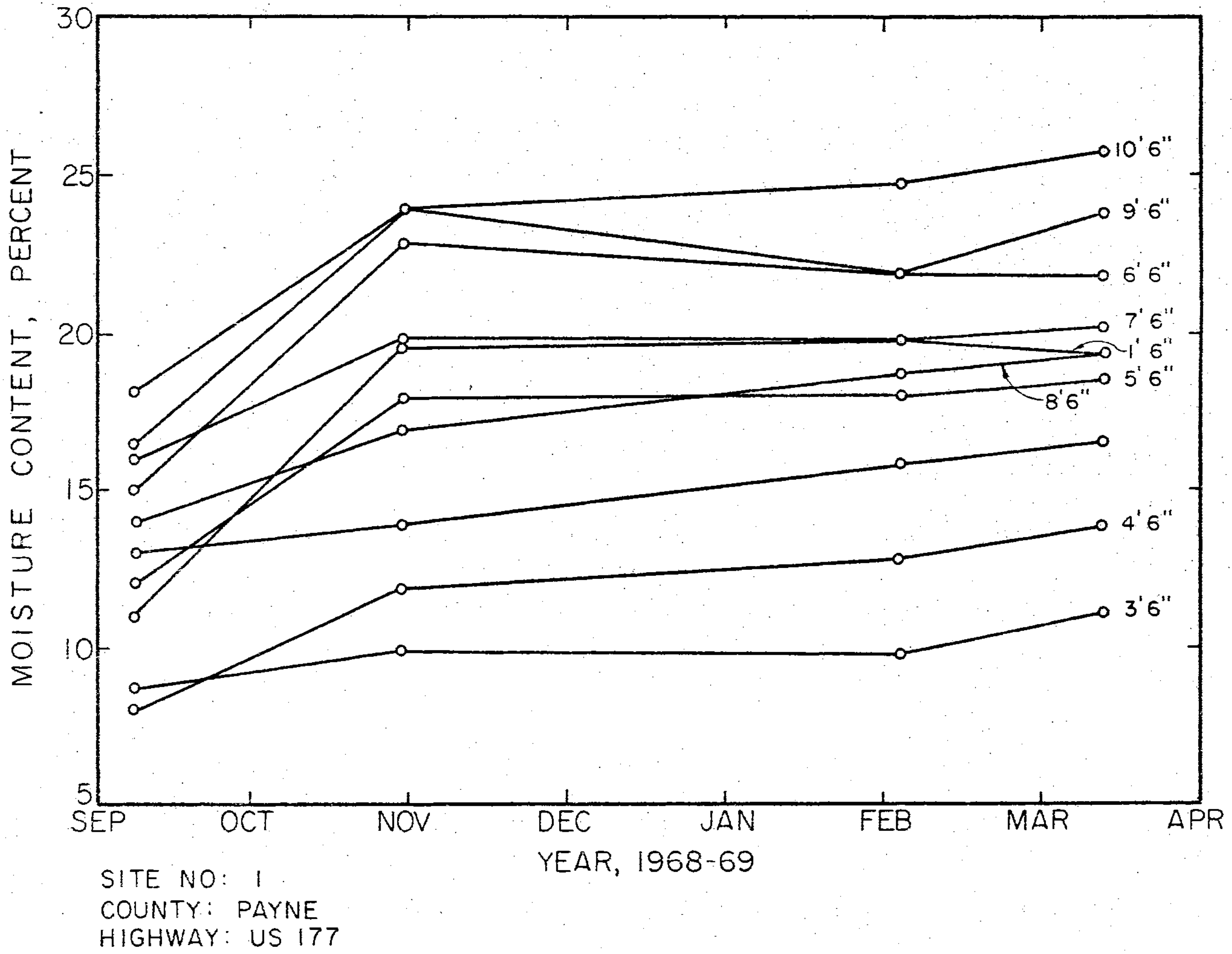


Figure 4.9. Subgrade Moisture Variation Beneath Pavement at Site No. 1

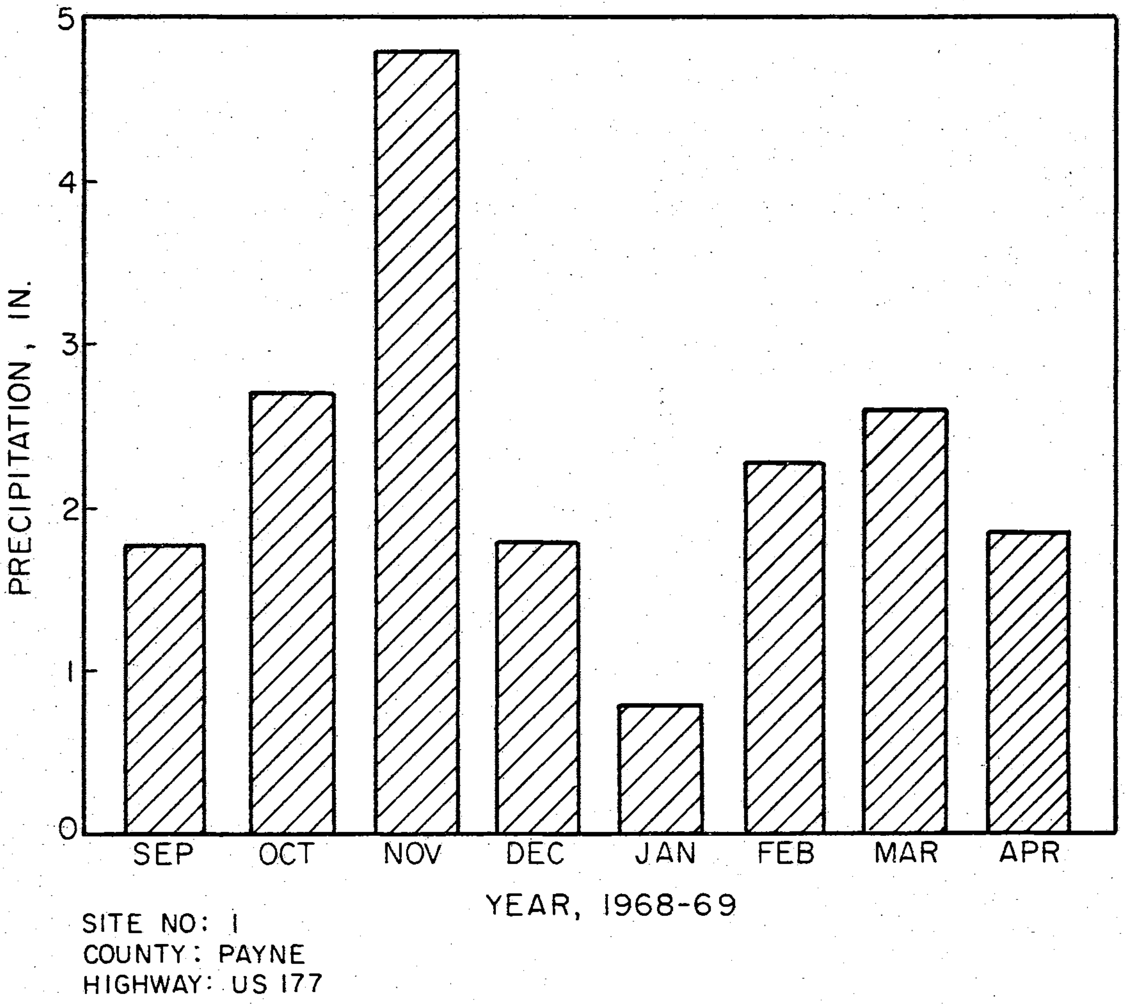


Figure 4.10. Total Monthly Precipitation at Site No. 1

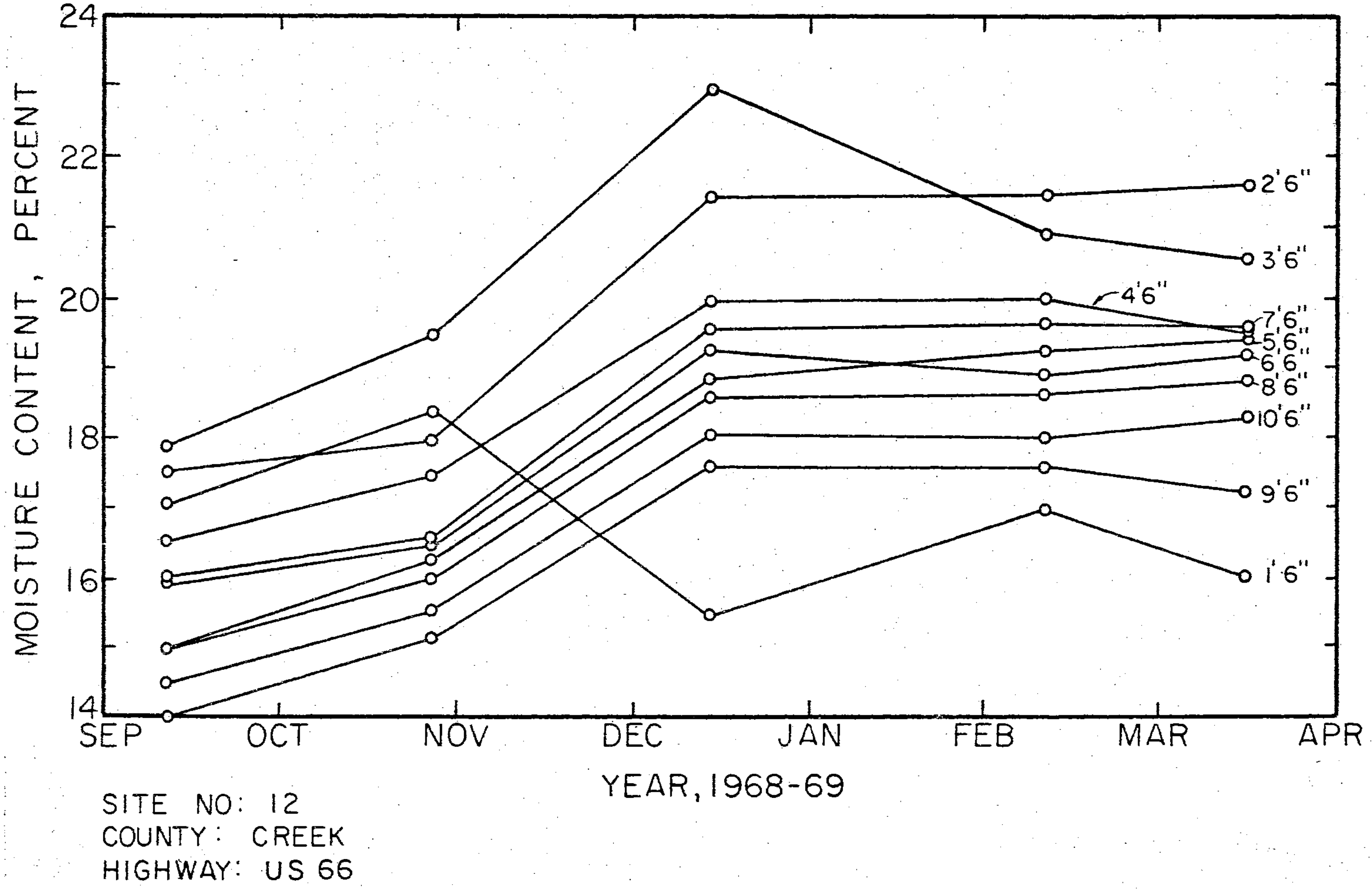


Figure 4.11. Subgrade Moisture Variation Beneath Pavement at Site No. 12

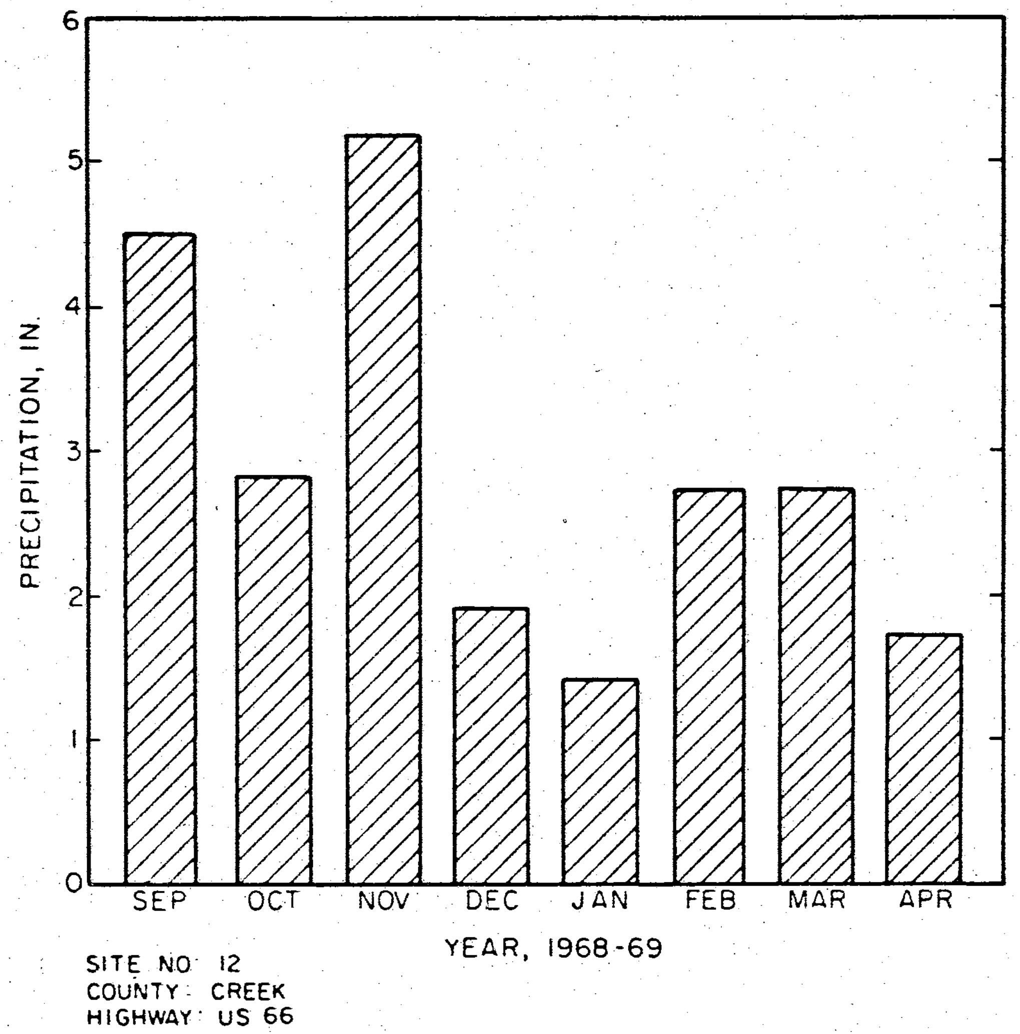


Figure 4.12. Total Monthly Precipitation at Site No. 12

thermal soil moisture flow that occurs may not appear to affect subgrade moisture content, because the larger precipitation-dependent moisture variations 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 precipitation. Conclusions from this study and recommendations concerning future study of temperature effects on subgrade moisture variations are listed in the following chapter.

CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

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

1) Temperature gradients occurred in highway subgrades and were related to air temperature variations. The maximum gradient was approximately 2°F/ft and occurred during January.

2) Subgrade temperatures were dependent on pavement color. Subgrade temperatures beneath asphaltic concrete pavement 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 the

research sites. Subgrade moisture content 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 precipitation-dependent. Subgrade moisture contents increased significantly within four weeks after the occurrence of rainfall.

9) Moisture variations caused by thermal soil moisture flow were quite small compared to variations caused by precipitation. It is therefore concluded that temperature-induced subgrade moisture variations are a secondary effect, compared to those produced by precipitation, in Oklahoma subgrades.

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

1) Temperature measurements should be continued. Subgrade temperatures should be measured at the six research sites for a minimum period of twelve months to determine size and variation of temperature gradients during an annual cycle.

2) A laboratory study should be conducted to determine amount of thermal soil moisture flow that may be caused by the temperature gradients found to occur in highway subgrades.

3) Temperature probes should be installed in both shoulders at each temperature 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.

REFERENCES

1. Jumikis, A. R. Thermal Soil Mechanics. Rutgers University Press. New Brunswick, New Jersey, 1966.

2. Hanks, R. J. "Water Vapor Transfer in Dry Soils." Soil Science Society Proceedings, Vol. 22, 1958.

3. Hayden, F., P. L. Brown and D. D. Dickey. "Water Movement and Loss Under Frozen Soil Conditions." Soils Science Society Proceedings, Vol. 28, 1964.

4. Cary, J. W. "Soil Moisture Transport Due to Thermal Gradients." Soil Science Society of America, Vol. 30, No. 4, 1966.

5. Philip, J. R. and D. A. DeVries. "Moisture Movement in Porous Materials Under Temperature Gradients." Transactions, American Geophysical Union, Vol. 38, No. 2, April, 1957.

6. Moore, R. E. "The Relation of Soil Temperature to Soil Moisture." Soil Science Proceedings, Vol. 5, 1940.

7. Smith, W. O. "Thermal Transfer of Moisture in Soils." Transactions, American Geophysical Union, Hydrology Section, 1944.

8. Gurr, C. G., T. J. Marshall and J. T. Hutton. "Movement of Water in Soil Due to a Temperature Gradient." Soil Science, Vol. 74, No. 5, 1952.

9. Hutcheon, W. L. "Moisture Flow Induced by Thermal Gradients Within Unsaturated Soils." Highway Research Board, Special Report No. 40, 1958.

10. Taylor, S. A. and L. Cavazza. "The Movement of Soil Moisture in Response to Temperature Gradients." Soil Science Society of America, Vol. 18, No. 4, 1954.

11. Moore, W. M. "Exploratory Study of Moisture Migration in Naturally Occurring Swelling Clays Related to Vertical Movements of Pavements." Submitted to the faculty of the graduate college of the Texas A&M University in partial fulfillment for the Degree of Doctor of Philosophy, College Station, Texas, May, 1965.

12. Straub, A. L., P. F. Dudden and F. T. Moorhead. "Frost Penetration and Moisture Changes Related to Highway Pavement Shoulder Color." Presented at Highway Research Board 48th Annual Meeting, Washington, D. C., January, 1969.

13. Richards, B. G. "Pavement Temperatures and Their Engineering Significance in Australia." Highway Research Board, Special Report No. 103, 1969.

14. Marks, B. D. and T. Allan Haliburton. "Interim Report VI: Evaluation of Collected Data." Subgrade Moisture Variations Research Project, School of Civil Engineering, Oklahoma State University, Stillwater, Oklahoma, May, 1968.

15. Fluker, B. J. "Soil Temperatures." Soil Science, Vol. 86, 1958.

VITA 2

Ronald Dean Osterhout

Candidate for the Degree of

Master of Science

Thesis: THERMAL SOIL MOISTURE FLOW BENEATH OKLAHOMA HIGHWAYS

Major Field: Civil Engineering

Biographical:

Personal Data: Born in Stockton, California, January 2, 1945, the son of Emery G. and Gladys Osterhout.

Education: Attended elementary school in Beggs and Bristow, Oklahoma; graduated from Bristow High School, Bristow, Oklahoma, May 25, 1963; received Bachelor of Science Degree in Civil Engineering from Oklahoma State University of Agriculture and Applied Science on August 1, 1968; completed requirements for the Master of Science Degree in Civil Engineering in August, 1969.

Professional Experience: Employed with Sinclair Oil and Gas Company during the summers of 1964 and 1965; Engineer Trainee with Pan American Petroleum Corporation during the summers of 1966 and 1967; Research Assistant, Subgrade Moisture Variations Research Project, Oklahoma State University, Stillwater, Oklahoma, 1968-1969.