FACTORS RELATING TO SUBGRADE MOISTURE VARIATIONS BENEATH OKLAHOMA HIGHWAYS

By

LARRY KEITH SHAW

Bachelor of Science

Oklahoma State University

Stillwater, Oklahoma

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Thesis Approved:

L. Allen Haliburton
Thesis Adviser

M. Abdel-Hady

James V. Parcher

D. Durham
Dean of the Graduate College

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TABLE OF CONTENTS

Chapter Page

V. (Cont'd)

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER I

INTRODUCTION

Premature failure of many highway pavements results from subgrade moisture variations and consequent changes in volume and strength of subgrade soils. Highway life and pavement performance may be improved by obtaining useful knowledge and understanding of subgrade moisture variations. Relationships between moisture variations, climatological conditions, pavement performance, soil types, and highway design may be found by long-term research.

The School of Civil Engineering at Oklahoma State University is presently engaged in a six-year Subgrade Moisture Variations research project, which began in June, 1964. The project is sponsored by the Oklahoma Department of Highways and the U. S. Department of Transportation, Federal Highway Administration, Bureau of Public Roads.

Fifty field research sites were installed throughout the central and north central/northeastern parts of Oklahoma. The sites were located on highways of various age, condition rating, cross-section, and pavement type. Three years of subgrade moisture and related data have been collected from Site Nos. 1-30 and two years from Site Nos. 31-50.

Statement of the Problem

Data collected during the first year of the research study has been previously evaluated and preliminary findings presented (Ref 1). However, before qualitative answers concerning the subgrade moisture problem in Oklahoma may be obtained and recommendations made for new highway design procedures, all data collected to date must be analyzed in careful detail. Preliminary conclusions must be updated or discarded and new conclusions and correlations developed to form a basis for highway design recommendations.

Scope of the Investigation

The scope of this investigation is threefold: 1) to review previous work on subgrade moisture behavior by this project and by other agencies, 2) to relate measured subsurface moisture conditions to soil, climate, and pavement conditions, and 3) to discuss obtained relationships as they apply to Oklahoma highway design.

CHAPTER II

THEORIES OF SOIL MOISTURE FLOW

Any force which upsets equilibrium of the soil-water system causes soil moisture flow. This flow may occur in the liquid phase, vapor phase, or a combination of the two, depending on the force or forces that act on the system. There are several hypotheses concerning the forces which cause moisture movements in soil. Among these, the ones most important in Oklahoma highway subgrades are: capillary pressure, osmotic pressure, hydrostatic pressure, chemical potential, temperature gradients, and hydrogenesis.

Marks and Haliburton (Ref 1) describe the effects of capillary pressure, osmotic pressure, hydrostatic pressure, and chemical potential. Height of capillary rise increases with decreasing pore size. Very small pores in clay soils restrict the flow rate, thus one finds that adverse moisture conditions due to capillarity occur more quickly in silts.

Compressive stresses in pore water due to surcharge and increasing temperature tend to reduce capillarity. Moisture migration by osmosis may eventually cause substantial moisture variations in subgrades, even through the rate and quantity is very small. Hydrostatic pressure will cause moisture flow in the liquid phase from a higher to a lower hydrostatic pressure. Chemical potentials due to soil mineralogical composition cause moisture flow from soil of lower ion exchange capacity to soil of high ion exchange capacity.

Moisture migration due to temperature gradients was investigated by Osterhout and Haliburton (Ref 2). This flow occurs mainly in the vapor phase because of a decrease in vapor pressure resulting from the temperature gradient. Low vapor pressure is associated with low temperatures, and high vapor pressure with high temperatures. For a given temperature, there is only one pressure at which water vapor is in equilibrium with its liquid phase. A temperature gradient causes a pressure gradient which results in vapor phase moisture movements. Saturated soils or soils with liquid moisture in their voids have negligible thermal moisture variations, while soils with moisture contents near their plastic limit experience maximum thermal moisture movements.

In order for moisture migration to occur in subgrades, there must be a source of free water. Marks and Haliburton (Ref 1) list six sources of moisture in subgrades: 1) seepage of water into the subgrade from higher ground, 2) fluctuation of the water table, 3) percolation of water through the pavement surface, 4) migration of water from shoulders, slopes, or verges, 5) migration of water from water-bearing layers below the subgrade, and 6) transfer of water vapor from any of the above sources.

Brakey (Ref 3) reports on hydrogenesis, which is a seventh source. Hydrogenesis is defined as generation of water. This phenomenon results at low temperatures when water is adsorbed on the surface of soil particles and held by surface tension. With a rise in temperature, the surface tension in the film of water decreases, forming a drop at the bottom of the particle. When the drop is of sufficient size it detaches itself from the soil particle to form capillary or free water, depending on the condition of the soil. It is protected from immediate evaporation by the particle above, and represents an actual moisture gain to the soil system. When the temperature decreases, the liberated drop is not available for thickening the adsorbed moisture layer of the original particle, as it has infiltrated deeper into the subgrade.

Winterkorn (Ref 4) says that a good water collection system must be composed of an open system through which large quantities of air can pass, yet be protected from undue losses by evaporation. The temperature of the collection system must vary considerably between the high and low extremes, and the soil mineral surfaces must have a great difference in their water-holding capacity at the two temperature extremes. It is further stated that open-graded, granular base material covered by black pavement has the qualifications of a good water collection system.

These theories of moisture movement were presented to provide a basic understanding of the modes by which moisture may migrate in highway subgrades. The fact that one or any combination of modes may act at once makes protection of subgrades a complex and baffling, if not frustrating, problem to highway engineers.

CHAPTER III

CONCLUSIONS FROM PREVIOUS SUBGRADE MOISTURE STUDIES

The highway engineer has long recognized that climatic conditions are responsible, to a great extent, for premature failure of highway pavements and bases. Increased pavement thickness and improved compaction and construction techniques are not complete solutions to the problem.

Over twenty years ago, Winterkorn (Ref 4) pointed out the mechanisms of climatic action on highways. The problem is not so much the amount of water in the subgrade, but fluctuations of the amount of water. This is evidenced by the number of cases where pavements on continuously saturated subgrades have yielded good performance and long life, while pavements in desert or arid climates have suffered a great deal of distress. The rainfall in these regions was negligible and the water table some distance below the surface.

Winterkorn (Ref 4) also noted that, while fluctuations in temperature and moisture levels in the highway structure are the main destructive forces, one cannot neglect average moisture and temperature values. These average values determine the rate at which fluctuations occur. For example, maximum moisture flow due to thermal gradients occurs when the soil moisture content is near the plastic limit.

Brakey (Ref 3) reports on the mechanism of hydrogeneses as an important contributor to the moisture problem in the highway structures of Colorado. The rainfall in the particular area was about seven inches per year and there was no evidence of a water table. The soil was an expansive shale. It was found that open-graded materials used for the base collected large quantities of water, which were fed into the expansive shale. Preventative measures were undertaken to reduce or stop infiltration of moisture into the subgrade. An asphalt membrane was applied over the impervious shale prior to laying the open graded granular base or backfill. The pavement was asphaltic concrete. Two years after completion, the sections where the membrane was used showed a substantial increase in moisture content in the sand above the membrane, while the shale immediately below the membrane underwent almost no change in moisture content.

In sections without a membrane, the moisture in the top one foot of the shale subgrade had doubled since construction. Most of the sites tested showed no visible exterior sources of free water such as poor drainage or aquifers. Thus, it was concluded that hydrogeneses was the culprit. Placing of asphaltic membranes has been employed under several new highways, and while the granular base increases substantially in moisture content above the membrane, no detrimental soil moisture changes have occurred beneath the membrane. Also, after several years the asphaltic membrane is still pliable and shows no signs of movement or cracking.

It is generally recognized that substantial increases in moisture content above optimum design levels cause some decrease in subgrade strength. Another detrimental effect of fluctuation in subgrade moisture is the volume change of cohesive soils. Kassiff, Livneh, and Wiseman (Ref 5) have listed four phenomena associated with variation of moisture content in clay subgrades:

1. shrinkage due to drying,
2. swelling due to wetting,
3. development of swelling pressures when confined from swelling, and,
4. decreasing strength and bearing capacity as a result of swelling.

Damage to pavement sections usually occurs in one or more major forms:

1. appearance of unevenness along a significant length of pavement without any cracking,
2. longitudinal cracking,
3. localized deformation, for example, near culverts, generally associated with lateral cracking, and
4. localized failure of the pavement, accompanied by surface disintegration.

Kassiff noted that correlation between Skempton's activity number and some normally active clays was poor. He found that the swelling potential of some normal clays showed them to be extremely expansive. His recommendations for better correlation were to supplement index property tests with free swell and shrinkage limit tests.

The relation between soil shrinkage and development of surface cracks in an experimental road in Kenya was investigated by Dagg and Russam (Ref 6). Long cracks running parallel to the edge of the pavement were a commonly observed feature on roads in tropical countries.

Horizontal and vertical movements of the soil surface resulting from moisture changes were measured. It was found that the cracks occurred between a zone of seasonal moisture content fluctuation, along the pavement edge, and a zone of more static conditions further under the pavement. The suggestion was made that lateral shrinkage of the soil under the shoulder and edge of the road caused systematic cracks to develop at the wet-dry interface in the subgrade. The interface generally occurred within two or three feet from the outside edge of the pavement.

Negligible vertical movements were noted on the centerline in the top 10 feet of soil, and graveled verges showed a similar pattern, drying to a depth of only three feet in time of severe drought. However, grassed verges experienced large moisture changes. Large vertical movements occurred in phase with the rainfall pattern. In times of drought, drying occurred to depths of ten feet, causing cracks to develop. These cracks usually closed during wet periods, but, in some cases, an appreciable amount of permanent deformation had developed from horizontal swelling of the subgrade soil. Under severe drought conditions, the shoulder experienced movements away from the center of the road. Overall movements of 0.75 in. or greater were observed.

The risk of cracking was minimized by decreasing the penetration of the wetting front under the edge of the pavement. This was effected by increasing shoulder slopes and improving shoulder surface. A well-prepared gravel shoulder was preferred to vegetative cover, with a well-graded and compacted lateritic gravel shoulder the best treatment. It behaved as an extension of the pavement; thus cracking occurred in the shoulder rather than in the road base. Komornik (Ref 7) investigated volume changes in clay soil as related to moisture variation in Israel. His work confirms the conclusions of Dagg and Russam. The wet-dry interface was very well illustrated by the fact that one road failed on the side adjacent to large trees, from excessive moisture losses to the vegetation.

Much has been reported on the subgrade moisture conditions in tropical countries, where rainfall generally occurs in one period of the year. The water table in these areas is usually very deep or non-existent. Russam (Ref 8) reports on subgrade moisture conditions in areas where there is some rain all year, and the water table is within 10 feet of the surface. It was concluded that flucturations in subgrade moisture content are influenced primarily by seasonal fluctuations in the water table. The magnitude of fluctuation was also of a smaller order than in arid regions.

This review of previous research indicates that more is being understood about subgrade moisture conditions. While some contradictions still exist, researchers are beginning to find some general trends. Regional and local conditions modify these trends such that long-term research is required to obtain sufficient data for proper highway design. These data must be collected, evaluated, and correlated. An approach to this problem is presented in the following chapters.

CHAPTER IV

DATA COLLECTION AND PRESENTATION

In order to obtain concise and valid conclusions from research, several criteria must be met. Accurate collection of data in connection with proper evaluation and correlation is necessary in reaching valid conclusions. This chapter describes procedures associated with collection and correlation of subgrade moisture and other related data.

Nuclear Equipment

The nuclear depth moisture and density probes used by the Subgrade Moisture Variations (SMV) project were manufactured by Troxler Electronic Laboratories, Inc., Raleigh, North Carolina. Soil properties were measured indirectly by the radiation backscatter phenomena in both the moisture and density gages. Calibration curves for the depth gages were obtained from soil type calibration procedures developed by Moore and Haliburton (Ref 6).

Site Selection and Installation

Research sites are presently located on existing highways in northeastern and north central Oklahoma. Thirty sites were installed during the summer of 1966 and 20 sites during the summer of 1967. Two additional sites were installed during the fall of 1967. Initial site locations were selected on the basis of three major criteria:

1. on Primary Federal Aid highways,
2. within ten miles of U.S. Weather Bureau climatological recording stations, and
3. within a reasonalbe driving radius of Oklahoma State University, Stillwater, Oklahoma.

Final selection of sites was made in the field. The general area of preliminary selection was visited to find an exact location possessing three qualities:

1. good sight distance in both directions,
2. adequate pavement width, and
3. a typical Oklahoma highway cross-section with desired soil conditions.

The majority of the test sites were located on grade sections, or on sections of slight cut or fill. Field test site locations are shown in Fig 4.1, and are listed in Appendix A.

Two essential requirements for nuclear probe access tube installation were that there be minimal air gap between the soil and access tube after placement, and that the installation be waterproof and protected from traffic.

Procedures for installation of access tubes were described by Heiliger and Haliburton (Ref 8). Depth of access tubes was 10 ft, and very straight, close tolerance holes were drilled to minimize air gap around the tubes after placement. A typical access tube installation is shown in Fig 4.2.

Site Instrumentation

Several different configurations of instrumentation are used at

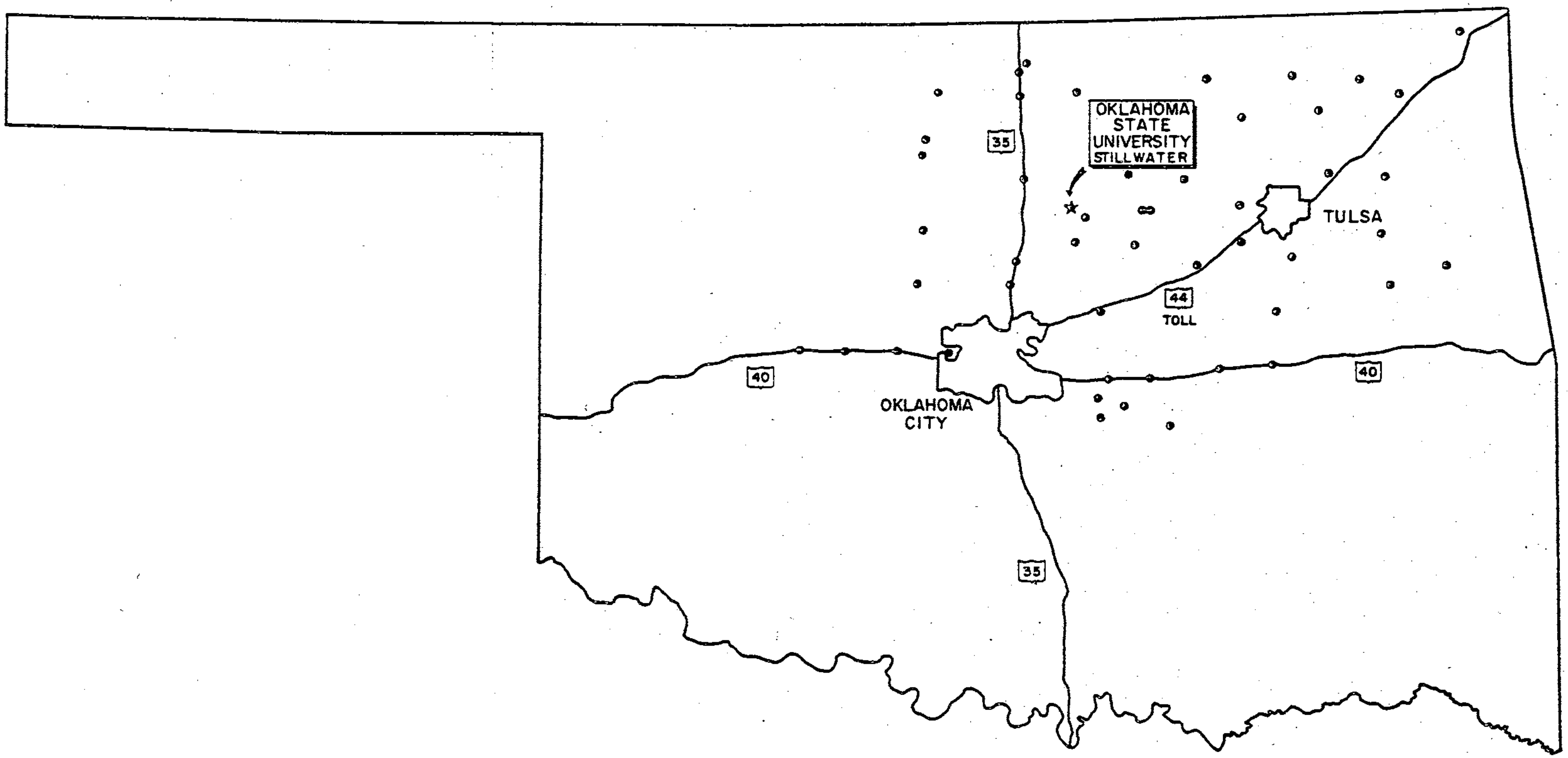


Figure 4.1. Field Test Site Locations of the SMV Project

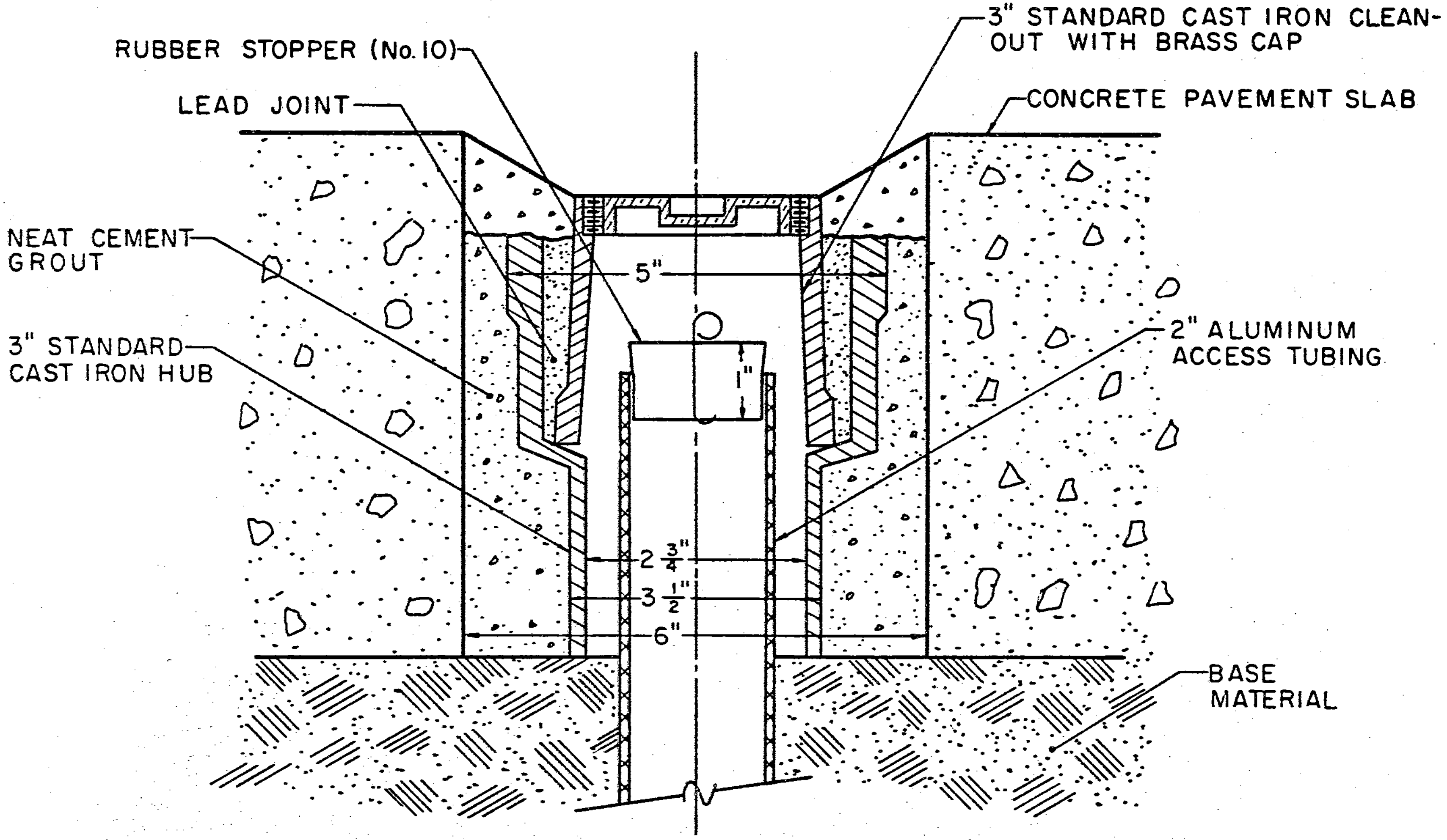


Figure 4.2. Nuclear Probe Access Tube in Pavement with Protective Covering

project field test sites. A research site may have up to five 10-ft nuclear probe access tubes, two subsurface bench marks, and two 10-ft subsurface thermistor probes, as shown in Fig 4.3. The instrumentation of each site is listed in Appendix A.

The original sites had only three nuclear probe access tubes, denoted as A, B, and C. Tubes D and E were added at some sites with wide sealed shoulders during the summer of 1968. Their purpose was to investigate the amount of infiltration between the pavement and shoulder, and to provide more information on moisture distribution across the subgrade.

Installation of the subsurface temperature probes was described by Osterhout and Haliburton (Ref 2). A subsurface thermistor probe consists of thermistors mounted at one-foot intervals on a 10-ft length of redwood. Two such probes were installed at each of six existing moisture research sites. One probe was placed beneath the centerline of the pavement and the other was placed just off the edge of the shoulder. The leads from the centerline probe were protected by a conduit layed in a trench cut across the pavement to the edge of the shoulder. The leads from both probes were placed in a waterproof box at the edge of the shouler. A temperature-calibrated galvanometer and recorder were connected to these leads to obtain subgrade temperature measurements. A typical subsurface temperature probe installation is shown in Fig 4.4. Readings were taken at approximate four-week intervals. A typical plot of subgrade temperature variations is shown in Fig 4.5.

After the sites had been installed, research personnel observed that, during certain times of the year, access tubes used for depth moisture and density measurements at some sites became loose in their

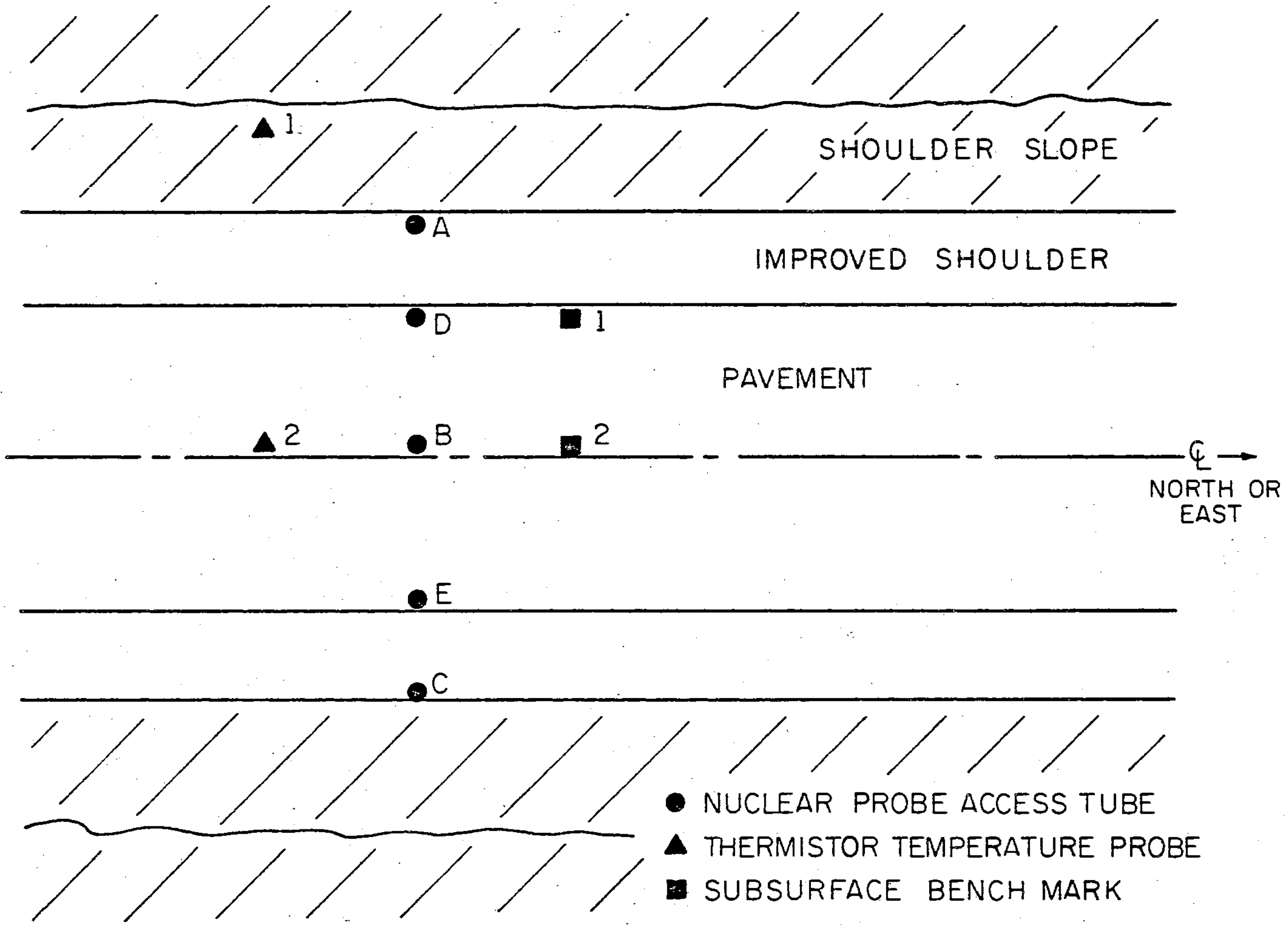


Figure 4.3. Instrumentation Layout for a Typical Field Research Site

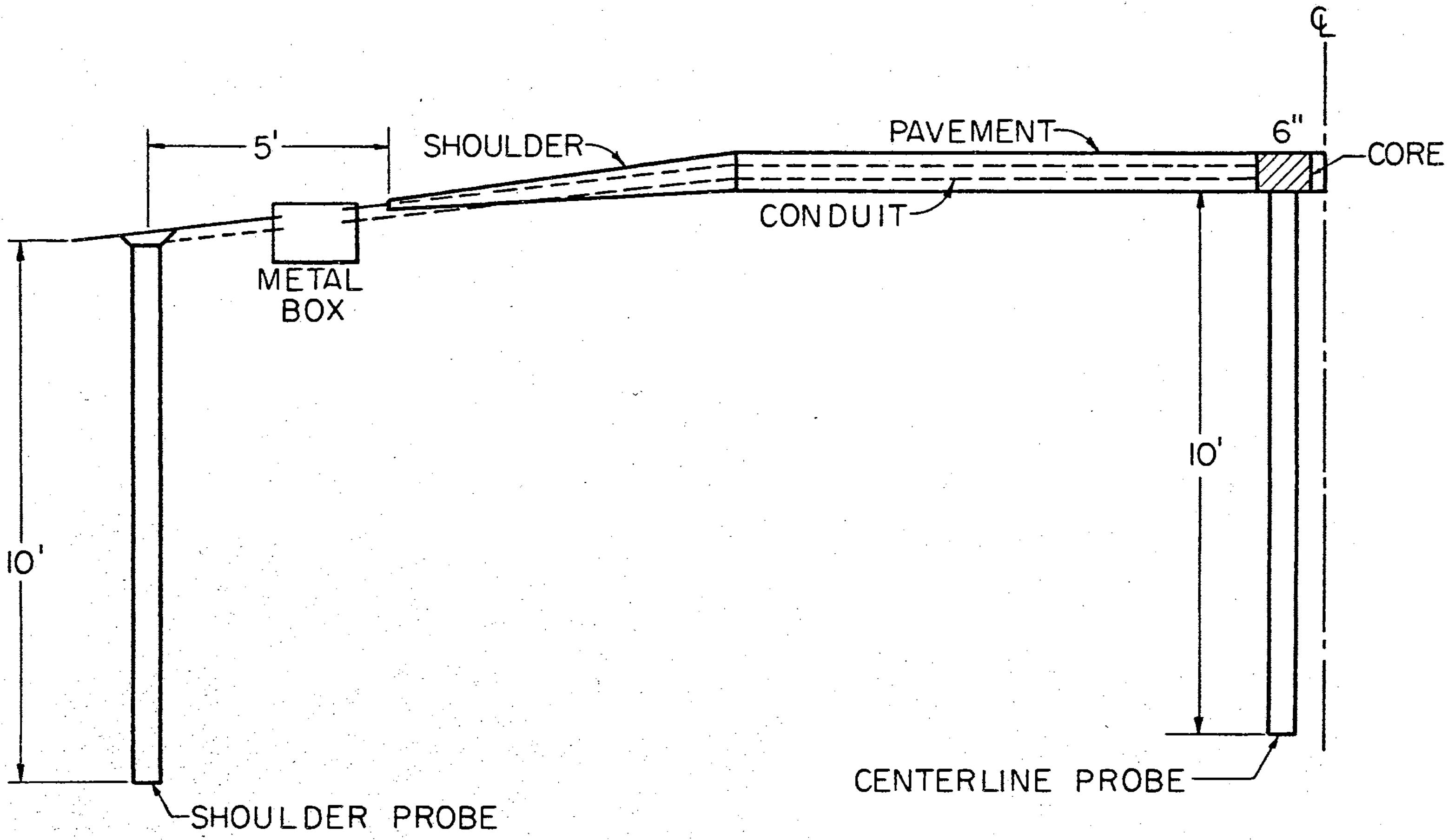


Figure 4.4. Thermistor Subgrade Temperature Probe Installation Detail

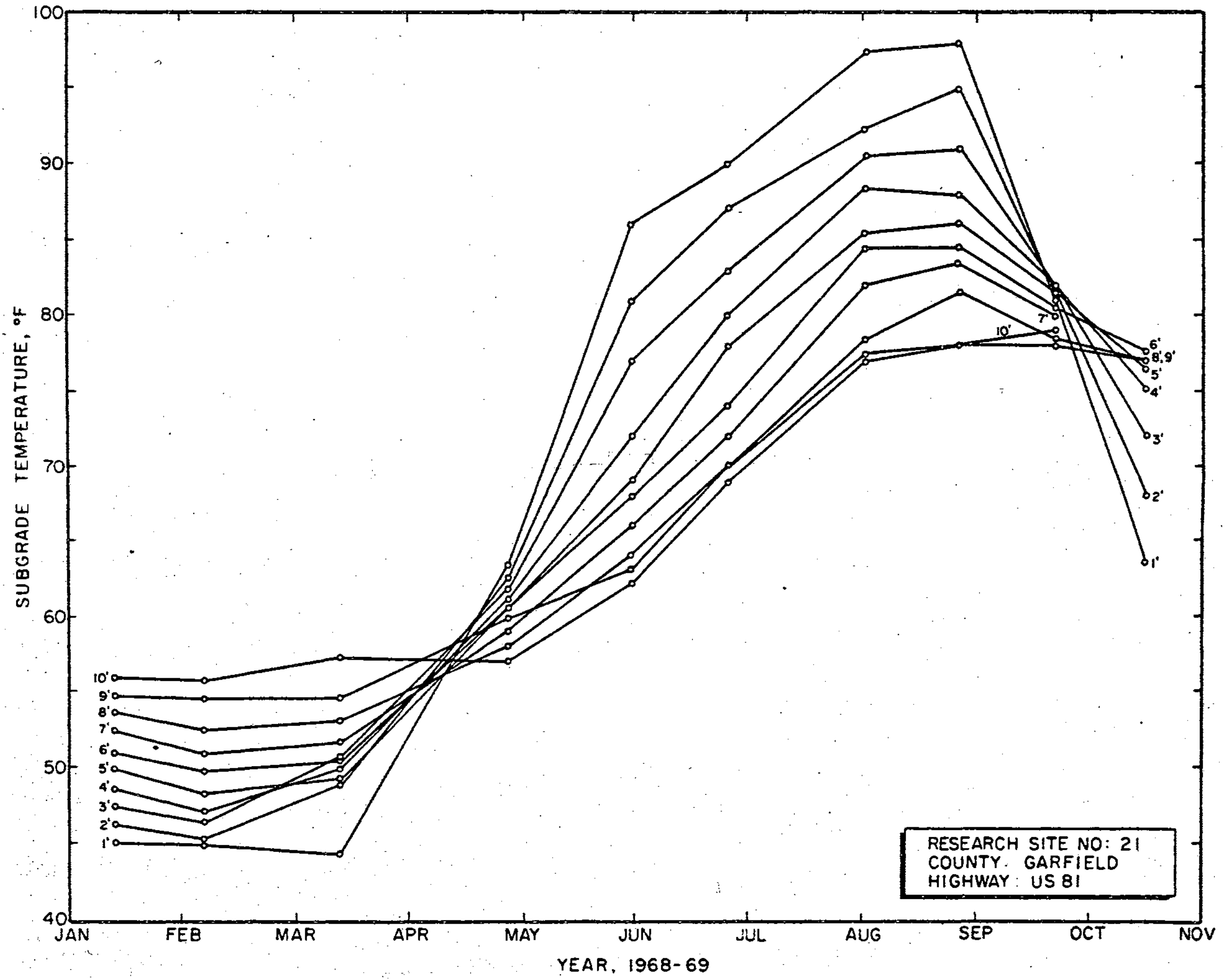


Figure 4.5. Subgrade Temperature Beneath Pavement at Site No. 21

holes, even though tubes had previously fit tightly. Data at these sites indicated a reduction in subgrade moisture content, so it was suspected that the subgrade was shrinking away from the tubes. At other sites, the access tubes were warped so that the probes would not enter the tube, which was still tight in the subgrade. This behavior occurred at times when data indicated an increase in subgrade moisture content. Marks and Haliburton (Ref 1) recommended that subsurface bench marks be installed to determine the relation between pavement movements and subgrade moisture conditions. They also noted that these data might help clarify the effects of soil type on pavement performance.

Subsurface bench marks were installed during the summer of 1968. To prevent bench mark movement with subgrade volume change, a 12 ft length of 3/4 in. black pipe was installed through the pavement inside a 10 ft, open-ended access tube. The end of the pipe was driven into the subgrade at the 10 ft depth. Since moisture conditions below 10 ft appeared to be relatively constant at the great majority of field test sites, the bench mark length was justified. One such bench mark was installed at the centerline of the pavement and one near the edge. On Portland cement concrete pavements, both bench marks were installed in the same slab.

Bench mark readings were obtained by using a steel ruler and a straight edge. An initial reading was taken when the bench mark was installed. Thereafter, readings were taken at approximate six week intervals when moisture data were collected at the site. The amount of pavement heave and/or settlement was based on the initial bench mark readings and was correlated with the respective subgrade moisture contents. Subsurface bench mark details are shown in Fig 4.6, and a typical plot of pavement movement is shown in Fig 4.7 for both the centerline and edge of the section. The access tube installation procedure, described by Heiliger and Haliburton (Ref 8), was adapted to install the subsurface thermistor probes and subsurface bench marks.

Data Collection Procedures

Marks and Haliburton (Ref 1) describe, in detail, the procedure for collection of nuclear moisture and density data. Moisture data were collected on a six to eight-week interval and wet density data were collected on a six month interval. Raw data was reduced by computer to volumetric and engineering moisture content and wet-dry density values. Nuclear probe calibration curves and weight-volume relationships were programmed to facilitate conversion of volumetric to engineering moisture content. The engineering moisture contents were then plotted against time for a three year period by another computer routine. It was found to be efficient and economical to plot results in this way, considering the quantity of data to be plotted.

A typical plot of moisture variations is shown in Fig 4.8. Dry density values were tablulated, since there were only two values per year and little variation was noted.

Subgrade temperature measurements were conducted on a four-week interval. The actual procedure is described elsewhere (Ref 2). At sites where subgrade temperature probes were installed, nuclear moisture measurements were made concurrently.

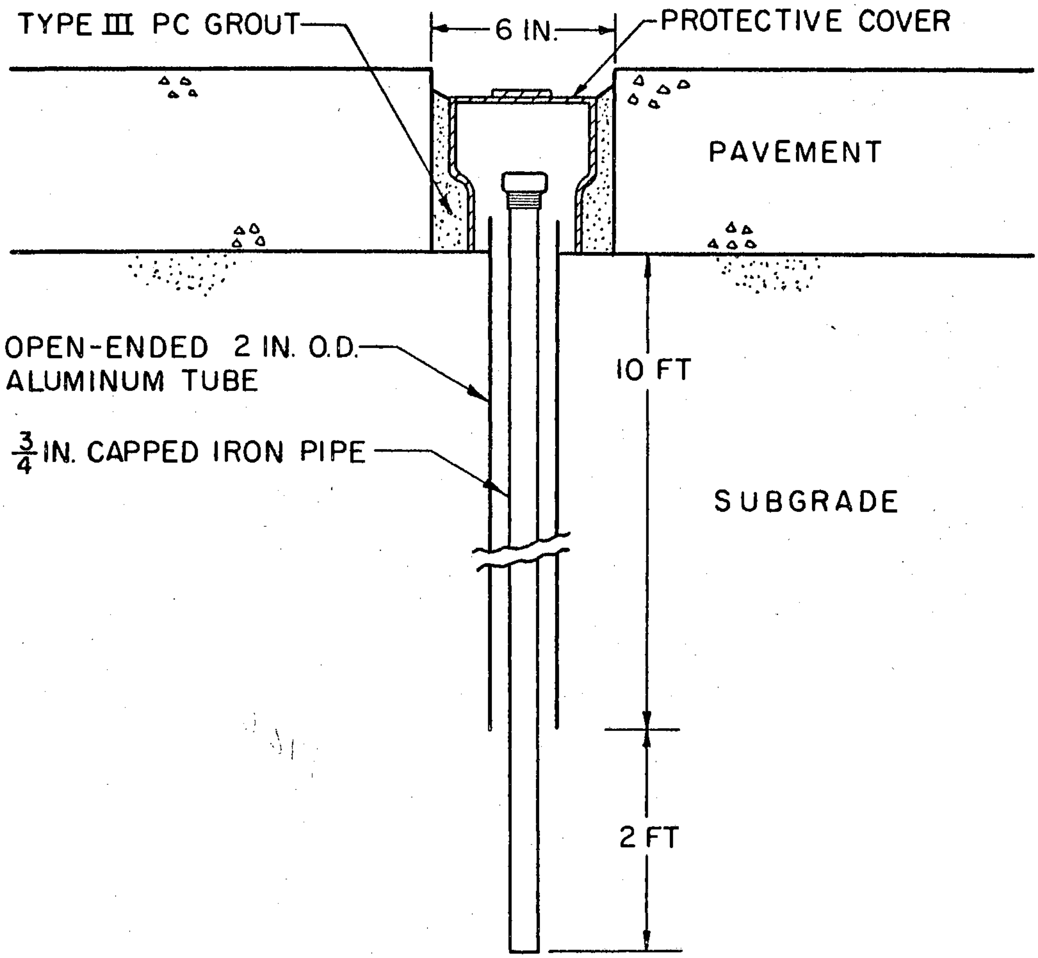
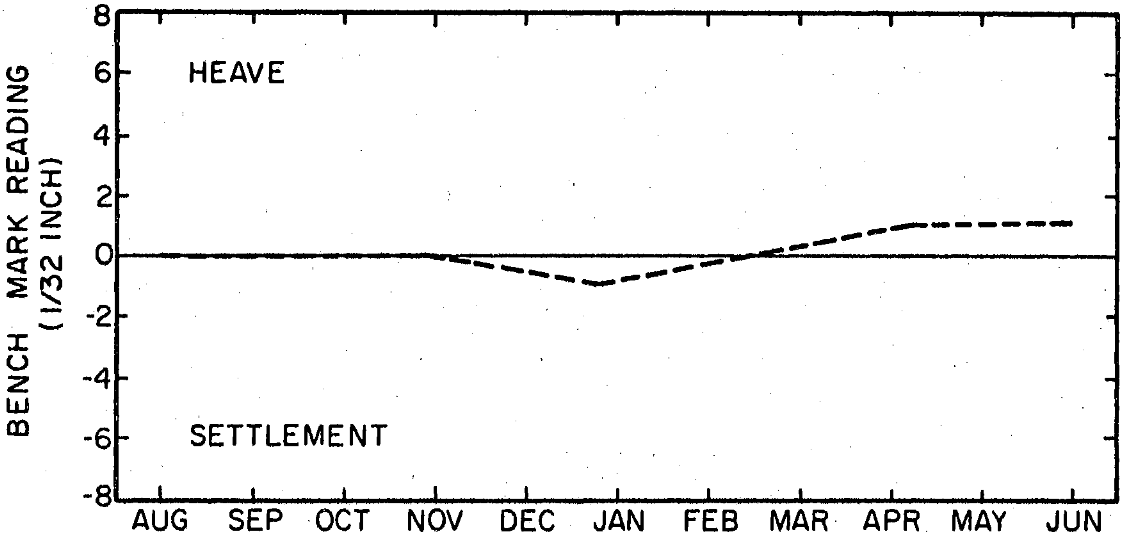
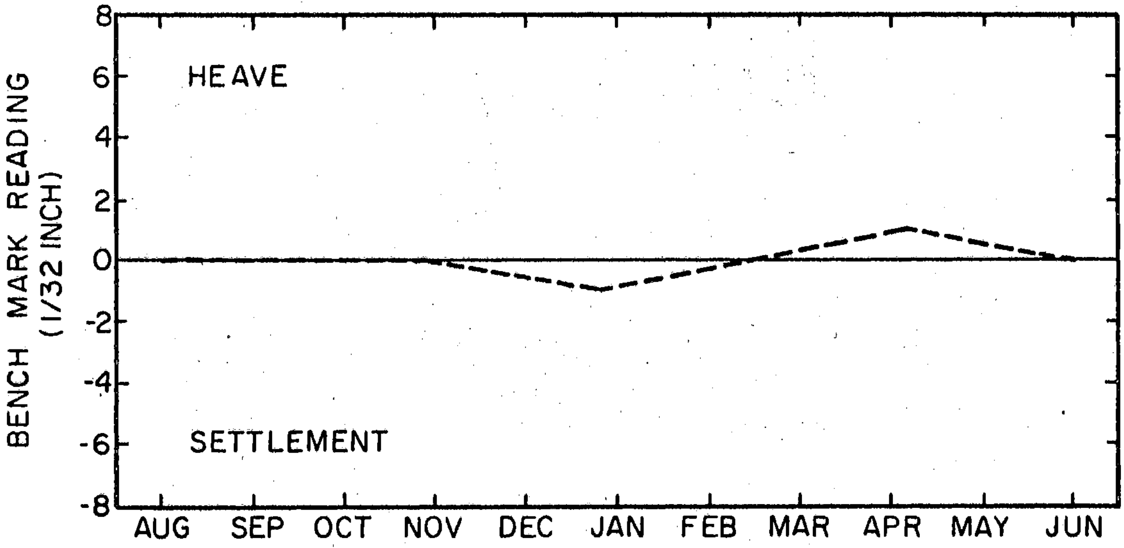


Figure 4.6. Subsurface Bench Mark Detail



(a) PAVEMENT CENTERLINE



(b) PAVEMENT EDGE

Figure 4.7. Typical Bench Mark Readings from Site No. 2

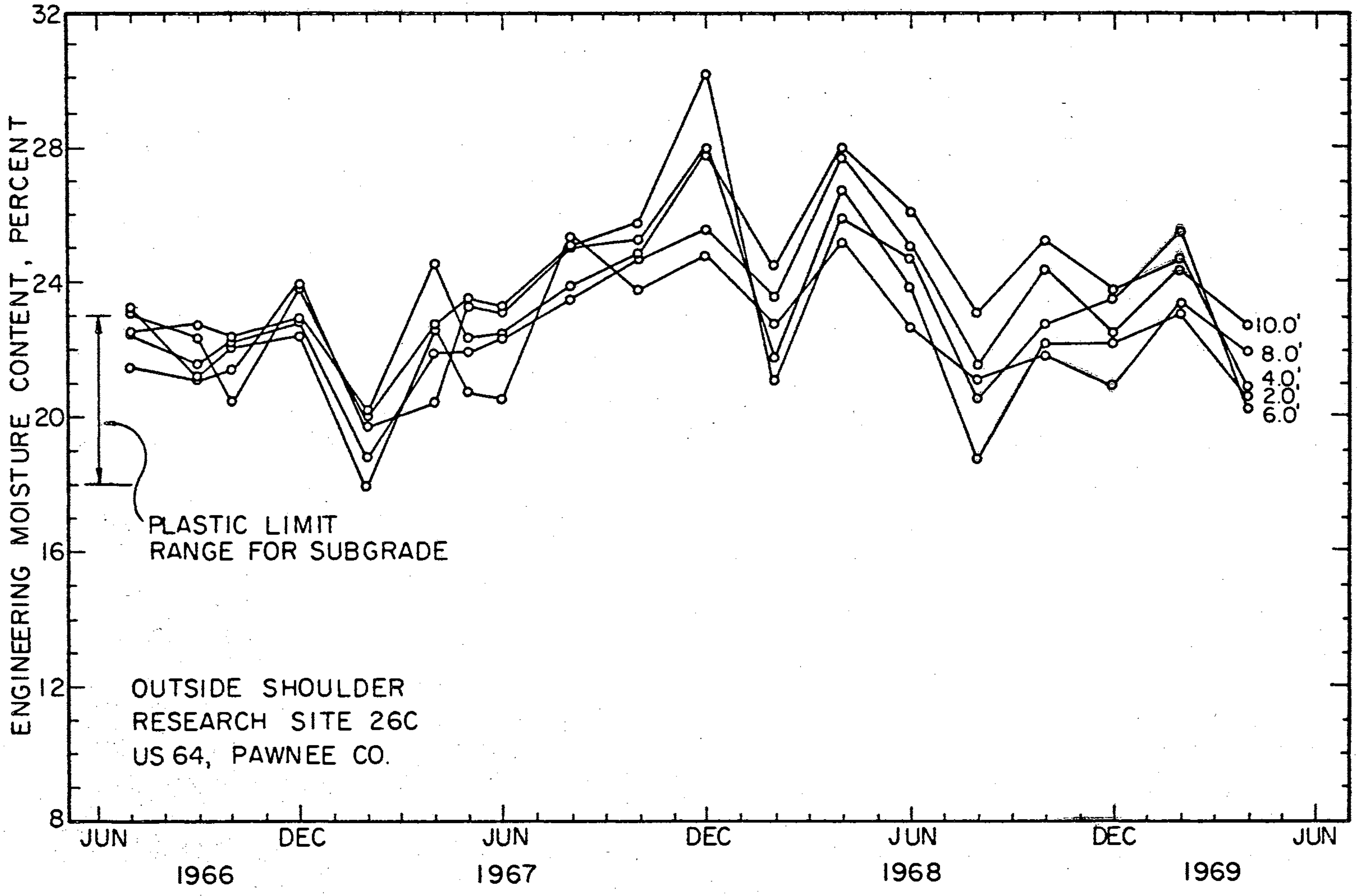


Figure 4.8. Subgrade Moisture Variations at Selected Levels from Research Site No. 26

As previously mentioned, bench mark elevations were measured when subgrade moisture measurements were taken. Relative movement of the pavement was also plotted versus time.

Subgrade Soils Data

Soil samples were obtained from subgrades at each site during installation of nuclear moisture and density access tubes. Samples were obtained at one foot intervals in the augered holes. While this may not be the most effective method of soil sampling, it was adequate for classification of the subgrade soil. Subgrade soils were classified by the Unified and AASHO classification systems. Soil tests for classification included specific gravity, Atterberg limits, and linear shrinkage (Ref 8). Subgrade soils data was presented as shown in Fig 4.9.

Climatological Data

All research sites were located near U. S. Weather Bureau climatological recording stations. Monthly mean high and low air temperatures, as well as precipitation quantities, were extracted directly from Climatological Data, Oklahoma. Mean high and low air temperatures were plotted with monthly precipitation, indicated by bar graphs, superimposed on the same sheet. The time scale was that used for other experimental data. A typical plot is shown in Fig 4.10.

Plotting subgrade moisture variations, subgrade temperature variations, pavement heave and/or settlement, and precipitation and air temperature on the same time scale greatly facilitated comparison of these data.

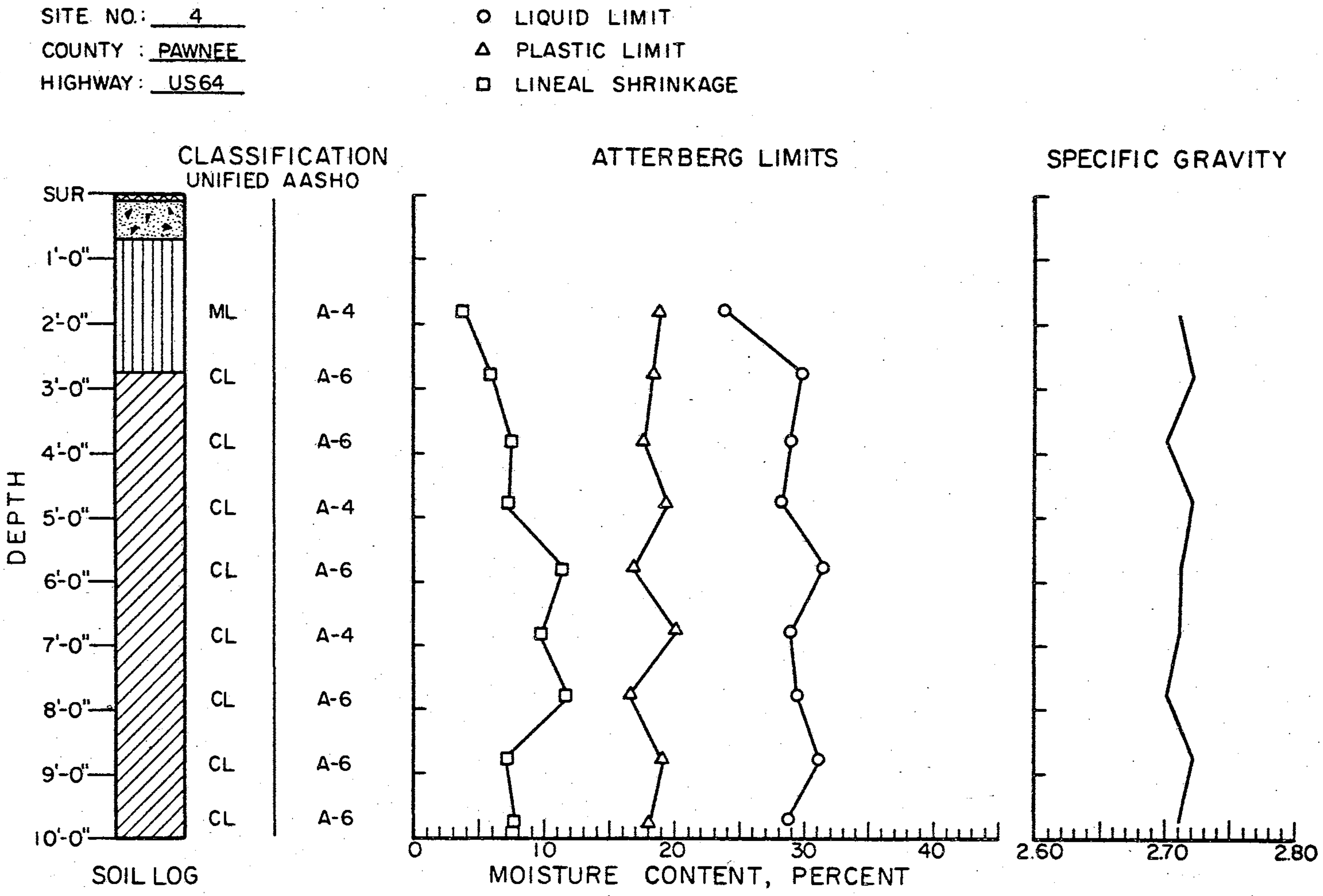


Figure 4.9. Typical Soil Profile from Research Site No. 4

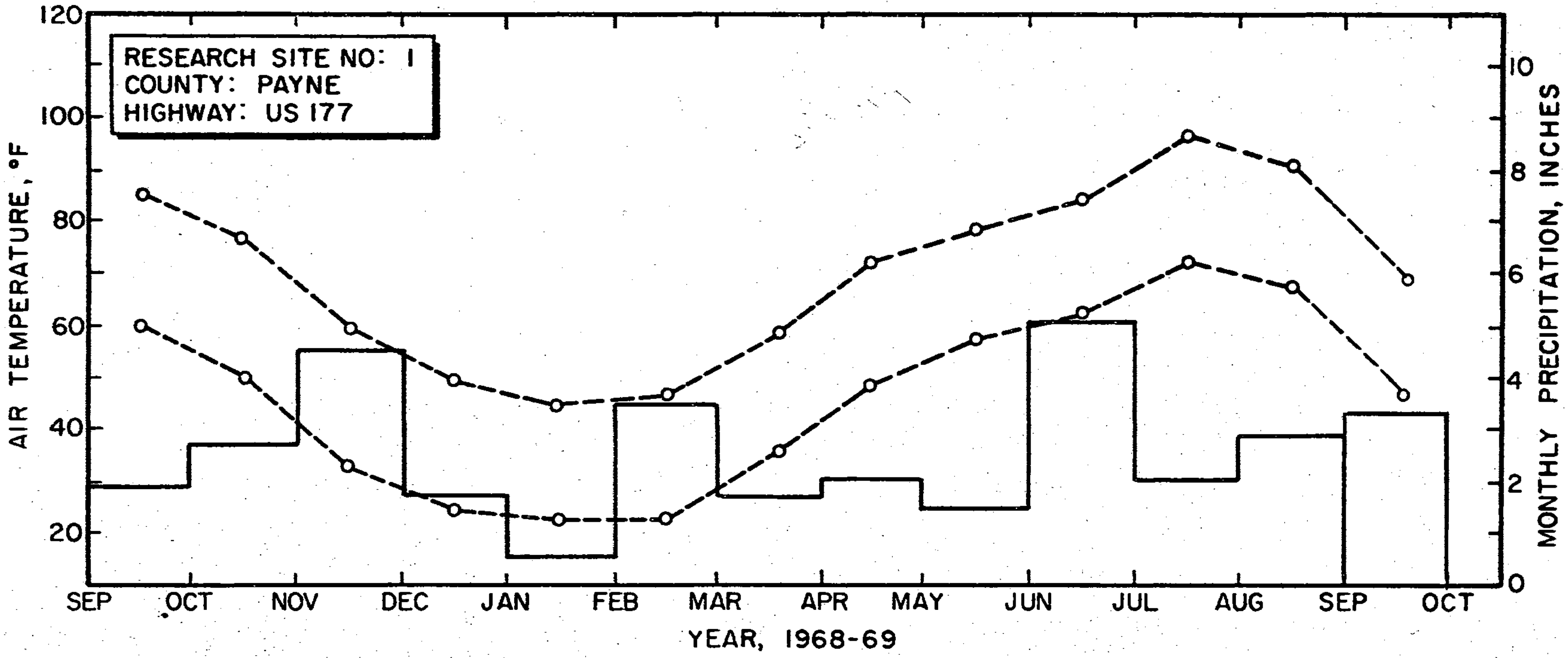


Figure 4.10. Climatological Data from Site No. 1

Miscellaneous Data

Highway pavement and shoulder performance data were obtained from the Oklahoma Department of Highways, Research and Development Division. The Research and Development Division also provided typical design cross-section details at each site, as well as traffic volumes and a construction and maintenance history of each site. Pavement ratings for all sites are shown in Table 4.1.

Pavement and shoulder ratings for this research study were obtained by conventional procedures, consisting of a visual inspection and evaluation of pavement and shoulder surfaces, based on the number and extent of defects. Profilometer and Benkleman beam data were not collected. Hartronft (Ref 9) described the conventional methods used in this study as well as new procedures that have been proposed. Descriptive terms used in conventional method are summarized in Table 4.2 and Table 4.3.

Observation sheets were completed every time nuclear moisture data was collected. These sheets provided information about sites that were repaired, gave a continuous record of how the highway was maintained, and have also served to explain and supplement photographs taken every six months at each site. A typical observation sheet is shown in Fig 4.11.

The data collection procedures discussed in this chapter were devised by SMV personnel. Evaluation and correlation of all field data collected through June, 1969 is discussed in the next chapter.

TABLE 4.1

CONDITION RATINGS FOR SMV SITES

	CONDITION RATING					
SITE NUMBER	SURFACE			SHOULDER		
	1967	1968	1969	1967	1968	1969
1	91	87	90	•	•	•
2	81	77	82	94	90	90
3	93	88	90	96	95	90
4	50	89	85	•	•	•
5	64	63	78	65	65	75
6	85	83	87	•	•	•
7	85	84	85	91	94	85
8	60	60	98	85	82	98
9	95	94	94	92	90	65
10	87	85	100	79	89	94
11	90	89	91	91	90	86
12	97	97	95	95	97	92
13	79	79	84	•	•	•
15	91	90	90	94	94	94
16	90	90	90	90	89	84
17	75	79	80	80	80	81
19	82	87	90	93	94	97
20	96	95	97	93	95	93
21	95	92	93	92	92	90
22	89	87	93	95	95	89
23	92	92	89	90	80	77
24	90	90	89	85	83	83
26	97	95	96	94	92	90
27	88	90	85	92	92	86
29	93	91	92	91	89	87
30	97	96	94	90	90	80
31	97	96	98	91	90	95
32	82	90	92	90	93	90
33	95	92	98	97	94	90
34	96	94	97	92	88	92
35	90	90	91	90	95	93
36	97	95	96	98	95	92
37	97	96	95	96	90	95
38	97	96	94	96	94	87
39	94	94	94	88	80	82
40	95	93	95	82	79	90
41	92	93	90	91	92	89
42	96	96	97	80	84	85
43	94	96	94	95	93	92
44	98	96	95	98	94	84
45	95	92	97	80	75	71
46	82	80	89	•	•	•
47	95	94	95	95	94	93
48	96	95	96	97	94	88
49	95	94	98	93	94	95
50	100	98	97	98	94	88
••51			98			98
••52			97			98

• Shoulder is unimproved

•• Sites #51 and #52 newly constructed. Opened to traffic September, 1969.

TABLE 4.2

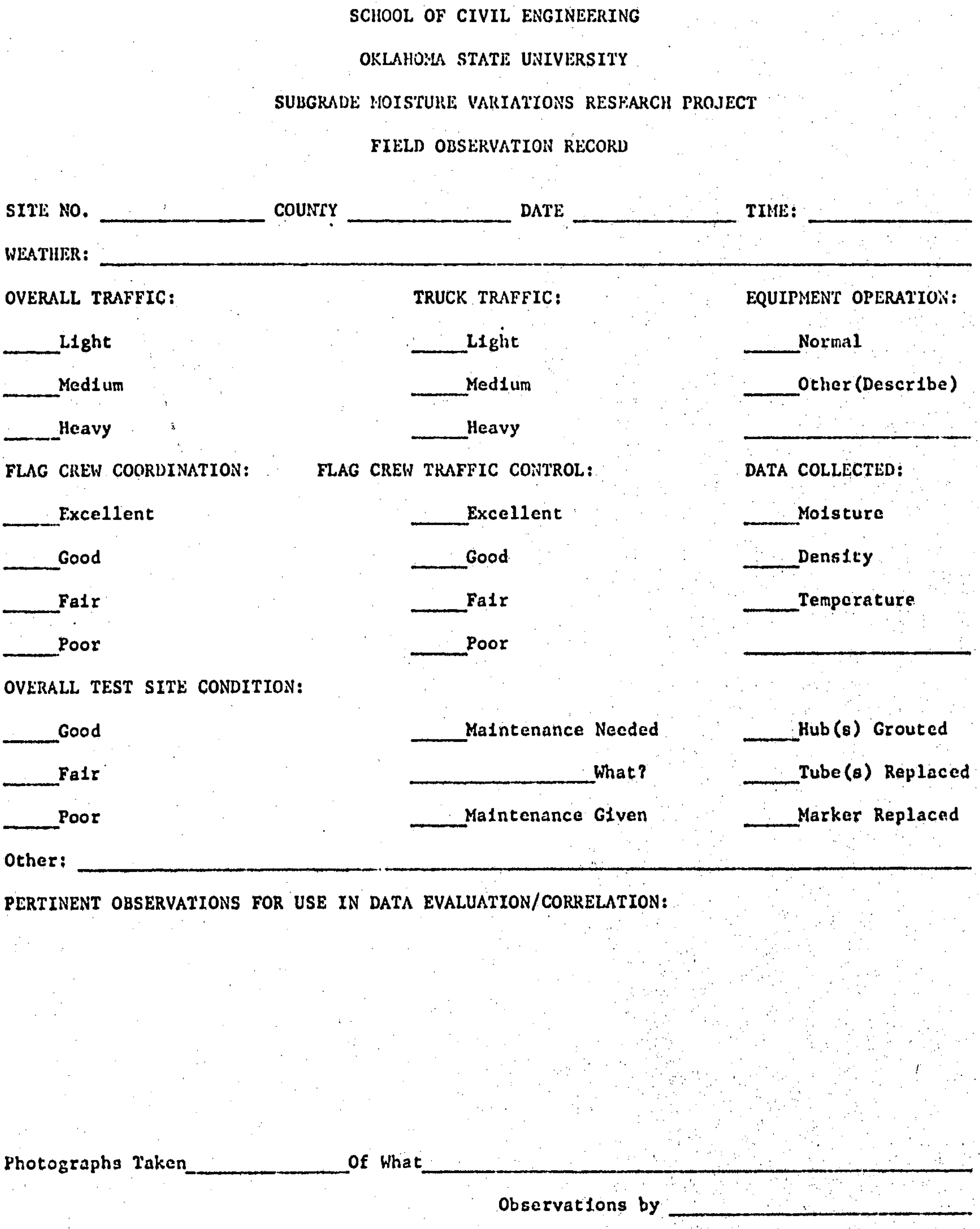
VISUAL CONDITION SURVEY-TERMS

Terms	Percent of Surface Area Affected
Few, slight	5
Some	5 to 15
Considerable	15 to 30
Extensive	30

TABLE 4.3

VISUAL CONDITION SURVEY-CLASSES AND RATING

Classes	Rating (%)	Remarks
Superior	98-100	No apparent major or minor defects. No maintenance performed.
Excellent	90-97	No base failures or other major defects and no structural maintenance has been necessary. Any one or all of the following characteristics may be present within a 0.2 mi. extent; slight surface roughness, or cracking, riding quality impaired but very slightly.
Good	80-89	No base failures. Any one or all of the following characteristics may be present within a 0.2 mi. extent; some surface roughness or cracking, slight raveling, or distortion.
Average	65-79	Few localized base failures, considerable surface roughness, or cracking, some raveling (especially in the outer wheel lanes and along the edges), some distortion.
Poor	50-64	Considerable base failures, extensive surface roughness, or cracking, surface raveled extensively throughout its width or considerable distortion.
Failure	50	Numerous and extensive base failures, extensive distortion, extensive traffic hazards due to failures and distortion or routine and special maintenance repairs have not been effective.



SCHOOL OF CIVIL ENGINEERING

OKLAHOMA STATE UNIVERSITY

SUBGRADE MOISTURE VARIATIONS RESEARCH PROJECT

FIELD OBSERVATION RECORD

SITE NO. ____________ COUNTY ____________ DATE ____________ TIME: ____________

WEATHER: ____

OVERALL TRAFFIC:	TRUCK TRAFFIC:	EQUIPMENT OPERATION:
_____Light	_____Light	_____Normal
_____Medium	_____Medium	_____Other(Describe)
_____Heavy	_____Heavy	______________
FLAG CREW COORDINATION:	FLAG CREW TRAFFIC CONTROL:	DATA COLLECTED:
_____Excellent	_____Excellent	_____Moisture
_____Good	_____Good	_____Density
_____Fair	_____Fair	_____Temperature
_____Poor	_____Poor	______________
OVERALL TEST SITE CONDITION:		
_____Good	_____Maintenance Needed	_____Hub(s) Grouted
_____Fair	____________What?	_____Tube(s) Replaced
_____Poor	_____Maintenance Given	_____Marker Replaced

Other: ____

PERTINENT OBSERVATIONS FOR USE IN DATA EVALUATION/CORRELATION:

Photographs Taken ____________ Of What ______________________________

Observations by ____________________

Figure 4.11. SMV Observation Sheet

CHAPTER V

DATA CORRELATION AND EVALUATION

This chapter discusses methods used in correlation of compiled data, relationships between subgrade moisture variations and contributing factors as obtained from data correlation, and evaluation of data collected to date by the Subgrade Moisture Variations research project.

General Conditions Existing in Oklahoma

Several conditions exist in Oklahoma that influence subgrade moisture behavior, and a review of same is necessary to better understanding of results obtained from data correlation and evaluation.

Climatological Conditions

As noted previously, all field research sites were located in the central and north central/northeastern parts of Oklahoma. Annual rainfall in this region averages between 10 and 35 inches, increasing from west to east. The monthly rainfall amounts are highly seasonal and average between five to 12 inches during the spring and two inches or less during the winter. Seasonal air temperatures range from an average monthly mean of over 80°F in July and August down to an average monthly mean of 30°F in January and February. The water table is located close to the surface in many regions of the state and often exhibits seasonal movements, generally higher during the winter months and lower during the summer. Higher rates of evaporation, evapotranspiration, and consumption during the summer, tapering off considerably in the winter, are responsible for this behavior. It should be noted that a period of drought in Oklahoma ended in 1965, just before installation of the first field research sites.

Soil Conditions

The clays found in Oklahoma may vary somewhat, but their origins and stress histories are similar. Deposited during the Permian period of the Paleozoic era, these soils are normally classified by the AASHO system as A-4 to A-7, and are heavily overconsolidated by dessication.

Highway Construction Methods

Many Oklahoma highways are built by stage construction methods. Grading and drainage contracts are let and completed one to three years prior to letting the base and surfacing contracts. Surfacing is usually begun during the warm spring and hot summer months. Consequently the subgrade may dry out to a considerable depth before surfacing is applied. For expansive Oklahoma subgrades, the optimum moisture content is usually 1 to 2 percent less than plastic limit. These soils are extremely susceptible to moisture accumulation and subsequent swelling, particularly when compacted dry of optimum.

Correlation Procedures

Three years of moisture, density, and climatological data from Site Nos. 1-30 and two years of data from Site Nos. 31-50, plus data from subsurface bench marks and temperature probes were to be evaluated. A mechanical sorting procedure, similar to that developed by Marks and Haliburton (Ref 1), was used to establish general trends. Features such as pavement type, base material, condition rating of pavement and shoulders, moisture variations, rainfall/temperature data, and construction dates for each site were coded on IBM cards. Conditions at each of the sites are summarized and a detailed explanation of coding criteria and sorting schemes is presented in Appendix B.

Trends in subgrade moisture behavior and relations to pavement performance suggested in previous literature (Refs 1, 2, 3, 5, 6) were investigated first (by sorting) to test their validity with respect to conditions in Oklahoma. Investigation of why a trend was valid or invalid was accomplished by visual inspection of data from individual sites. Hints of new trends were followed until firm relationships were established or clues were found to be misleading.

Trends in Subgrade Moisture Behavior and Related Factors

Data obtained from the study to date indicate several general trends of subgrade moisture behavior exist in expansive Oklahoma subgrades. Soon after construction or following long periods of drought, subgrade moisture contents under impervious pavement increase toward an "equilibrium" value near the soil's plastic limit. At sites where pavement was not impervious or poor drainage existed, seasonal precipitation caused cyclic/seasonal moisture variations. Temperature gradients acted only as a secondary influence on moisture migration.

Subgrade Moisture Accumulation - New Construction

Subgrade moisture accumulation was found in expansive Oklahoma subgrades at many sites. Under newly constructed pavements and pavements with wide shoulders and excellent pavement ratings the subgrade moisture content tended to increase toward an "equilibrium" value near the soil's plastic limit. Data indicated capillary moisture was usually the primary cause. Previously mentioned methods used in most Oklahoma highway construction probably influence subgrade moisture accumulation.

For example, Site No. 50 is located in Payne County on SH 51. This two-lane highway with improved shoulders was constructed in 1967. Sand-asphalt base was used under the Portland cement concrete pavement with sealed shoulders over soil-cement base. The subgrade is composed of A-6 to A-7 clay with a plastic limit range of 20-24% and an average lineal shrinkage of 15%. The research site was installed in July, 1967 in a slight cut, with good drainage, and the highway sloping downhill to the east. At the time of site installation the initial moisture contents were at least four percent below the plastic limit to a depth of ten feet. This is shown by the moisture variations beneath the pavement at Site No. 50, plotted in Fig 5.1. The reason for the marked difference between moisture contents at the upper and lower levels is that the A-7 clay extends from three to six feet below the pavement, bounded on top and bottom by the A-6 soil. This "tighter" or less permeable layer tends to smooth out any effects of surface runoff infiltration, and the magnitude of increase in moisture content at the upper levels is greater than at the lower levels. No significant increases in moisture content occurred until the following year

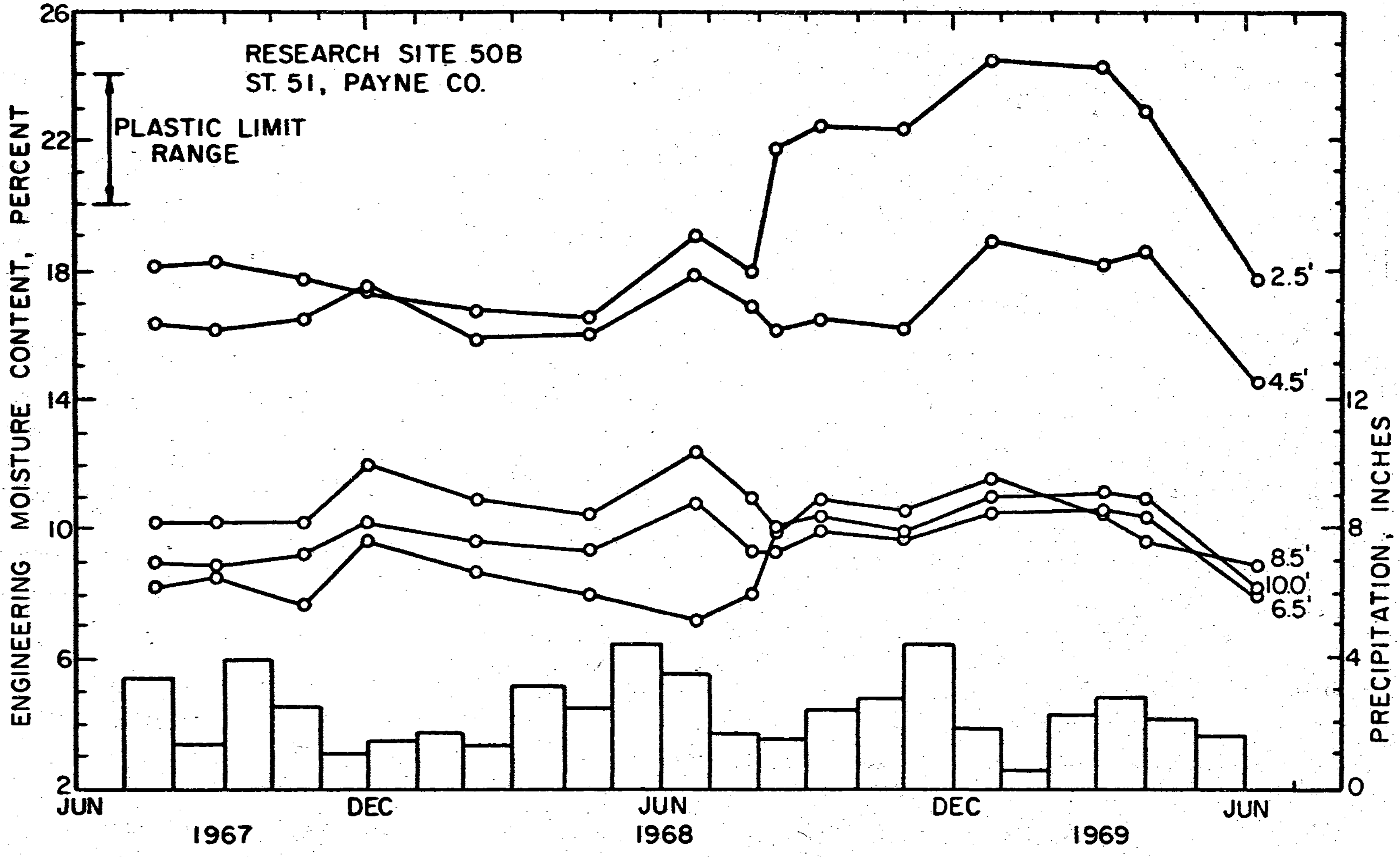


Figure 5.1. Moisture Variations at Selected Levels Beneath Pavement Centerline and Rainfall at Site No. 50

when rainfall increased substantially at this site. Data from additional nuclear access tubes at the pavement edge, installed in August, 1968, indicate moisture increases were occurring at approximately the same rate as under the centerline, as shown by the plot in Fig 5.2. Moisture variations under the shoulder at Site No. 50 are shown in Fig 5.3. Accumulation occurred at a faster rate under the shoulders at all levels. Fluctuation in moisture content at the 2.5 ft level preceeded those at lower levels.

Subgrade Moisture Accumulation - Old Construction

Moisture accumulation was also observed in subgrades of pavement that were not new but had wide shoulders and excellent pavement ratings, and even at sites where pavement distress was visible. Long periods of drought, which, with resulting lower water tables can dry Oklahoma highway subgrades to at least a 10 ft depth. As previously mentioned, a period of drought ended in Oklahoma in 1965. The first research sites were installed in the summer of 1966, and accumulation from greater availability of moisture and rising water tables is certainly to be expected.

Generally, variations are insignificant prior to reaching the equilibrium value, unless the pavement is pervious, without improved shoulders, or poor drainage conditions exist. In the later case, precipitation dependent variations are usually superimposed on the general increase in subgrade moisture content.

For example, Site No. 21 is located in Garfield County on US 81. The four-lane divided highway was constructed in 1959 with PCC pavement and improved shoulders. The subgrade is classified as A-6 with

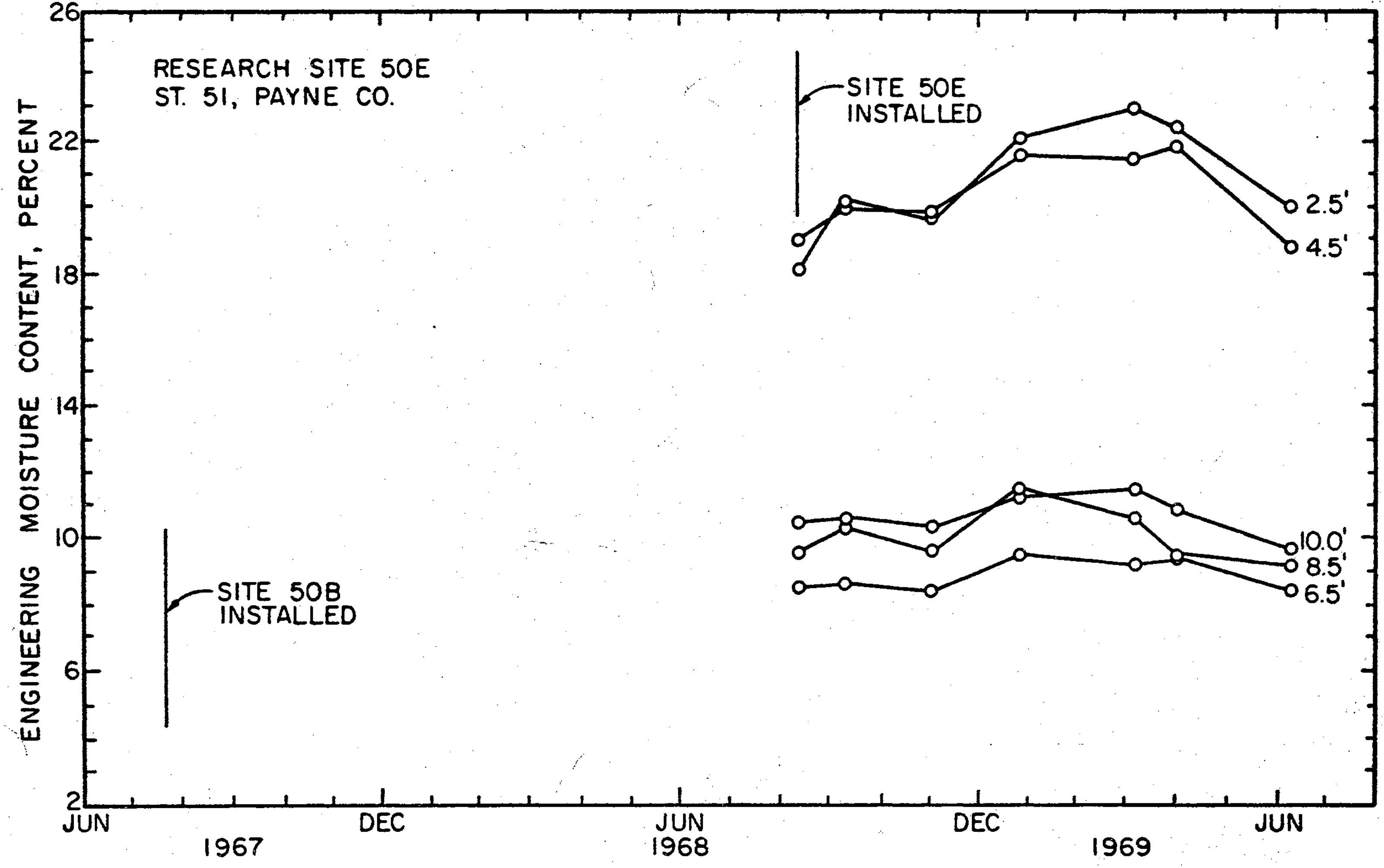


Figure 5.2. Moisture Variation at Selected Levels Beneath Pavement Edge at Site No. 50

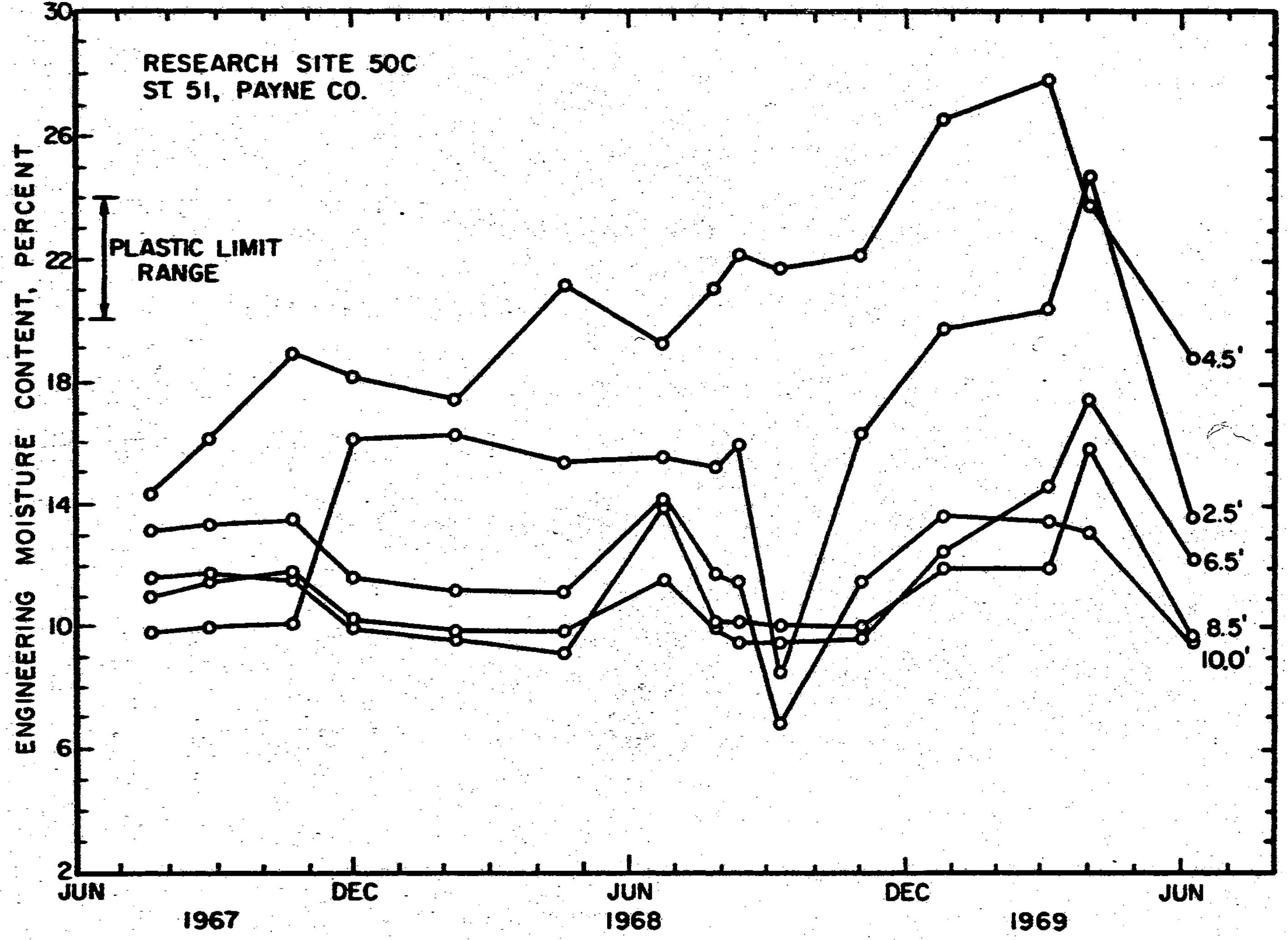


Figure 5.3. Moisture Variations at Selected Levels Beneath Shoulder at Site No. 50

a plastic limit of 18-22 percent, lineal shrinkage averages about 10 percent, and the base material is a fine sand cushion. Drainage is rated fair because water stands in the median after rains and shoulder slopes are very gentle. Even though pavement and shoulder ratings are excellent, some shoulder settlement has been noted. The research site was installed in August, 1966, just after the period of drought mentioned previously.

Moisture accumulation is the more predominant mode of subgrade moisture behavior with "cyclic" variations superimposed on the accumulation, as shown in Fig 5.4, a plot of moisture variations under pavement at the site. Monthly rainfall is also shown in Fig 5.4, and the time lag between rainfall is generally six to eight weeks, as noted in previous literature (Ref 1). Moisture contents decrease with depth, except for the 2.0 foot level shown in Fig 5.4. This is indicative of precipitation dependent moisture variation. Because of the geometry of the nuclear probe, the 2.0 foot level means 2.0 feet from the pavement surface to the bottom of the probe, consequently the 2.0 foot level reflects moisture content of the sand cushion. Moisture content fluctuates more in the sand cushion than any other level and moisture variations in the subgrade are generally preceeded by a corresponding variation in the sand cushion, which probably acts as a moisture reservoir feeding moisture to the subgrade. Moisture conditions under the shoulders varied at a faster rate, but the general trend was the same as under the pavement, because of the pervious stabilized aggregate base material used under the shoulders.

The water content/plastic limit ratio of most expansive subgrades under impervious pavements at the "equilibrium" value was between 1.1

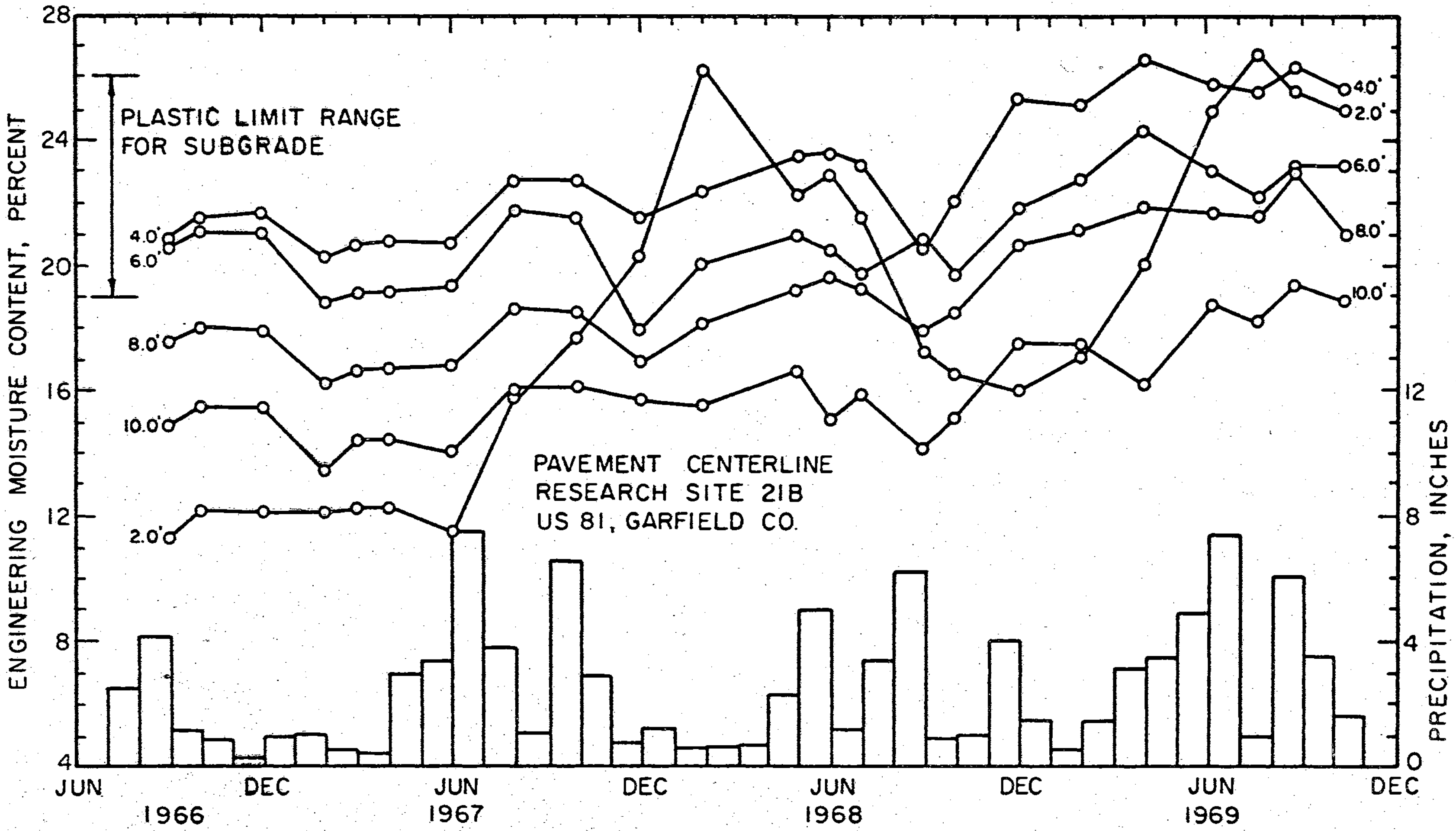


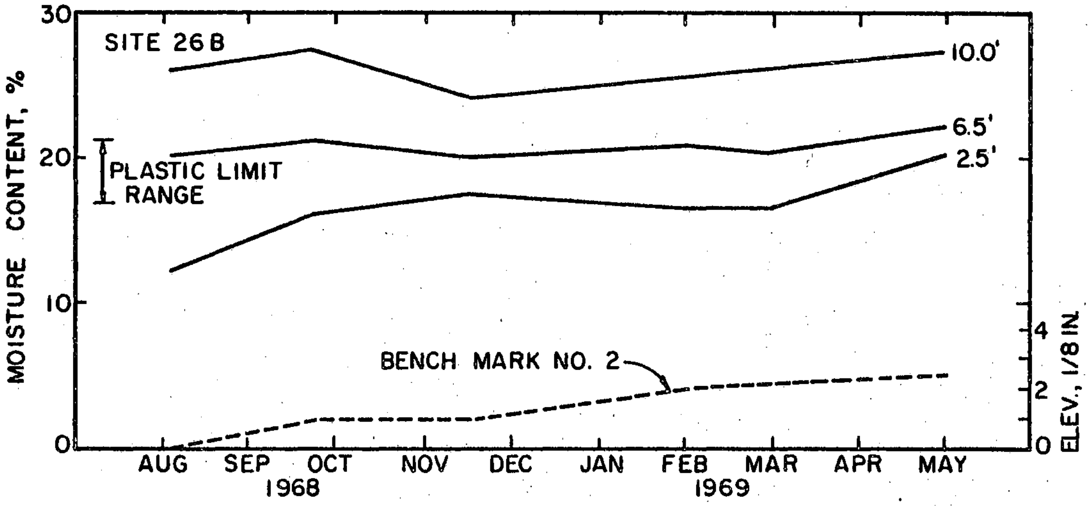
Figure 5.4. Moisture Variations at Selected Levels Beneath Pavement and Rainfall at Site No. 21

and 1.3. This would indicate the soil moisture content was near "wet of optimum" moisture content and tension in the capillary water was near zero.

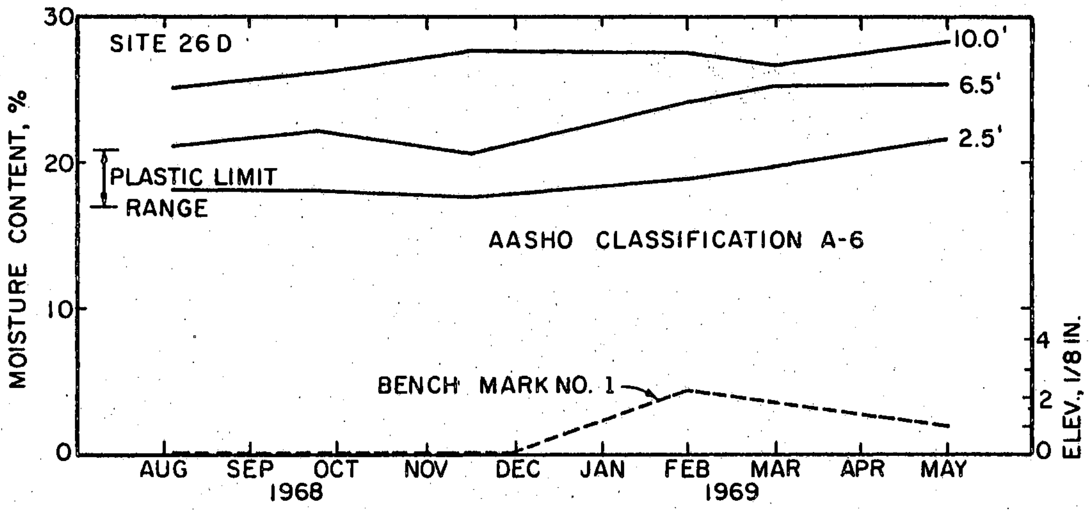
Soil Volume Change - Old Construction

Subgrade moisture accumulation and resulting volume change can cause poor pavement performance. As mentioned previously, Oklahoma clays are very expansive and swelling occurs both laterally and vertically. Bench marks, described in a previous Chapter, were installed in 1968 at selected sites to monitor vertical settlement and/or heave. It was also hoped that the relations between soil type and subgrade moisture behavior, if any existed, might be clarified.

Site No. 26 is located in Cleveland County on US 64. The two-lane highway was constructed in 1963 with PCC pavement on a sand base course and improved shoulders over stabilized aggregate base material. A rather uniform A-6 subgrade material exists at the site, and it has a plastic limit range of 18-22% and lineal shrinkage of 10-16%. The research site is located at the beginning of a shallow transition subgrade cross-section. The bench mark in the pavement edge is located to the cut side of the section. Pavement and shoulder ratings have steadily decreased at this site since 1966. Presently, the pavement rating is excellent, but the shoulder rating has dropped to good because of settlement and slight cracking in the shoulder. Figure 5.5 shows a plot of moisture behavior and bench mark readings at Site No. 26. A water table below this site probably exerts the greatest influence on moisture behavior, because moisture content increases with depth and the zone of capillary rise appears to be holding moisture



(a) PAVEMENT CENTERLINE



(b) PAVEMENT EDGE

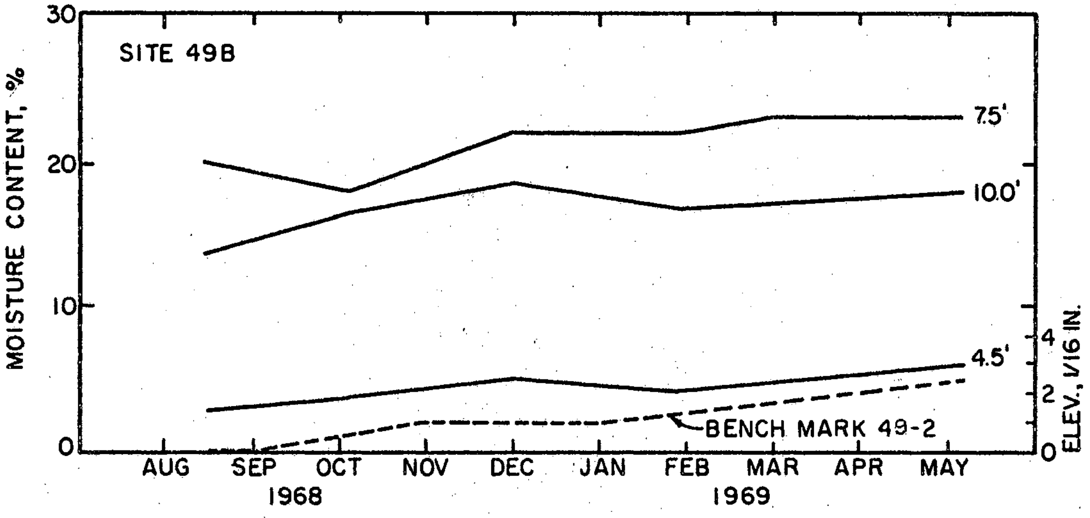
Figure 5.5. Moisture Variations at Selected Levels and Bench Mark Elevations at Site No. 26

contents in the lower levels well above the plastic limit. Increases in moisture content at the lower levels do not appear to effect vertical movements as much as do those within six feet below the pavement.

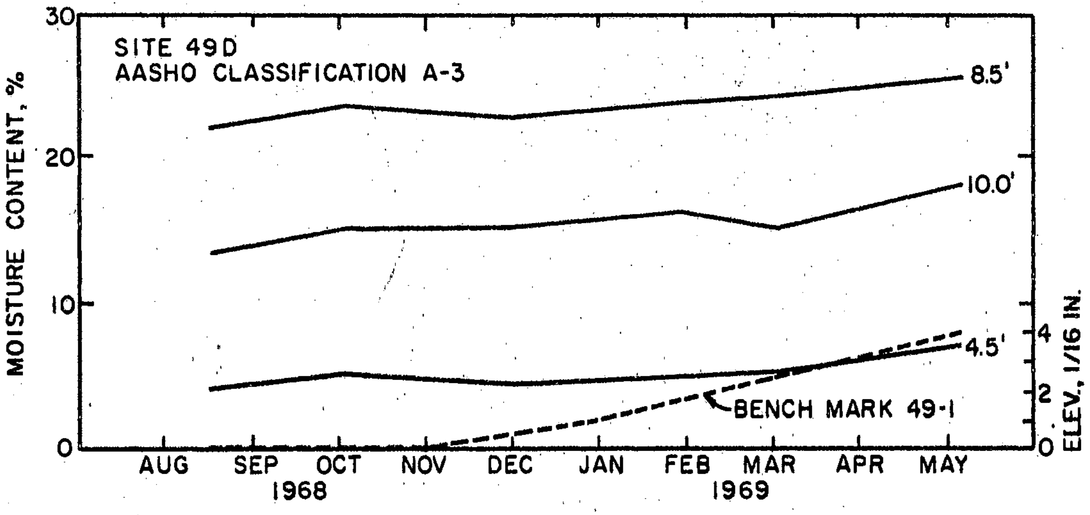
A five percent increase in subgrade moisture content caused almost 3/8 in. heave at the pavement centerline while 1/4 in. heave resulted from a two or three percent increase in moisture content under the pavement edge. Greater heave of the pavement centerline was caused by the 2.5 ft level under the centerline being considerably "wetter" than the corresponding depth at the pavement edge. A greater increase in moisture at the centerline therefore resulted in greater heaving. In a transition section, subgrade moisture contents are higher on the "cut" side than on the "fill" side and this explains the higher initial moisture contents at the pavement edge.

Soil Volume Change - New Construction

The swelling potential of even "good" Oklahoma subgrade soils is illustrated by conditions observed at Site No. 49, located in Payne County on SH 51. The two-lane highway was completed in 1967 and has asphaltic concrete (AC) pavement with improved shoulders on a sand-asphalt base. The research site was installed in 1967, just after surfacing, on a slight cut with downhill grade. The drainage is rated as good. Classification of the subgrade soil by the AASHO system is A-3, a red, clayey sand that exhibits no obtainable Atterberg limits. However, the pavement centerline and edge did heave with increasing moisture content, but to a lesser degree than more plastic subgrades. Moisture behavior and corresponding pavement movements for Site No. 49 are shown in Fig 5.6. Heave at Site No. 49 was the result of an



(a) PAVEMENT CENTERLINE



(b) PAVEMENT EDGE

Figure 5.6. Moisture Variations at Selected Levels and Bench Mark Elevations at Site No. 49

increase in moisture content at all levels, not just a few, as was common where subgrades exhibited more plastic behavior. Most of the sites on grade or cut sections heaved more at the pavement edge than at centerline, because there was less moisture content fluctuation at centerline on new construction or pavements with excellent ratings and improved shoulders.

The results of lateral swelling are illustrated in Fig 5.7, a photograph of the outside shoulder of I-40 adjacent to Site No. 42 in Seminole County. This four-lane divided highway was constructed in 1965 and has PCC pavement with improved shoulders extending four feet inside and 10 ft outside the pavement, on a uniform A-7 clay subgrade with a plastic limit range of 18-20 percent and lineal shrinkage of 18 percent. The base material is sand-asphalt under the pavement and soil-cement under the shoulders. The outside shoulder has moved laterally away from the pavement, opening the joint between shoulder and pavement approximately one inch. The shoulder surface has also cracked extensively, in both transverse and longitudinal directions. The longitudinal cracks are within three to five feet of the shoulder edge and are probably caused by the wet-dry interface described by Dagg and Russam (Ref 6). A plot of moisture conditions under the highway at Site No. 42 for the wet and dry seasons of the year is shown in Fig 5.8, and seasonal fluctuations under the outside shoulder are more severe than under the inside shoulder or pavement centerline. Divided highways generally exhibit this type of moisture behavior because the median does not drain as well as the outside shoulder, thus most four-lane divided highways have only fair to good drainage.

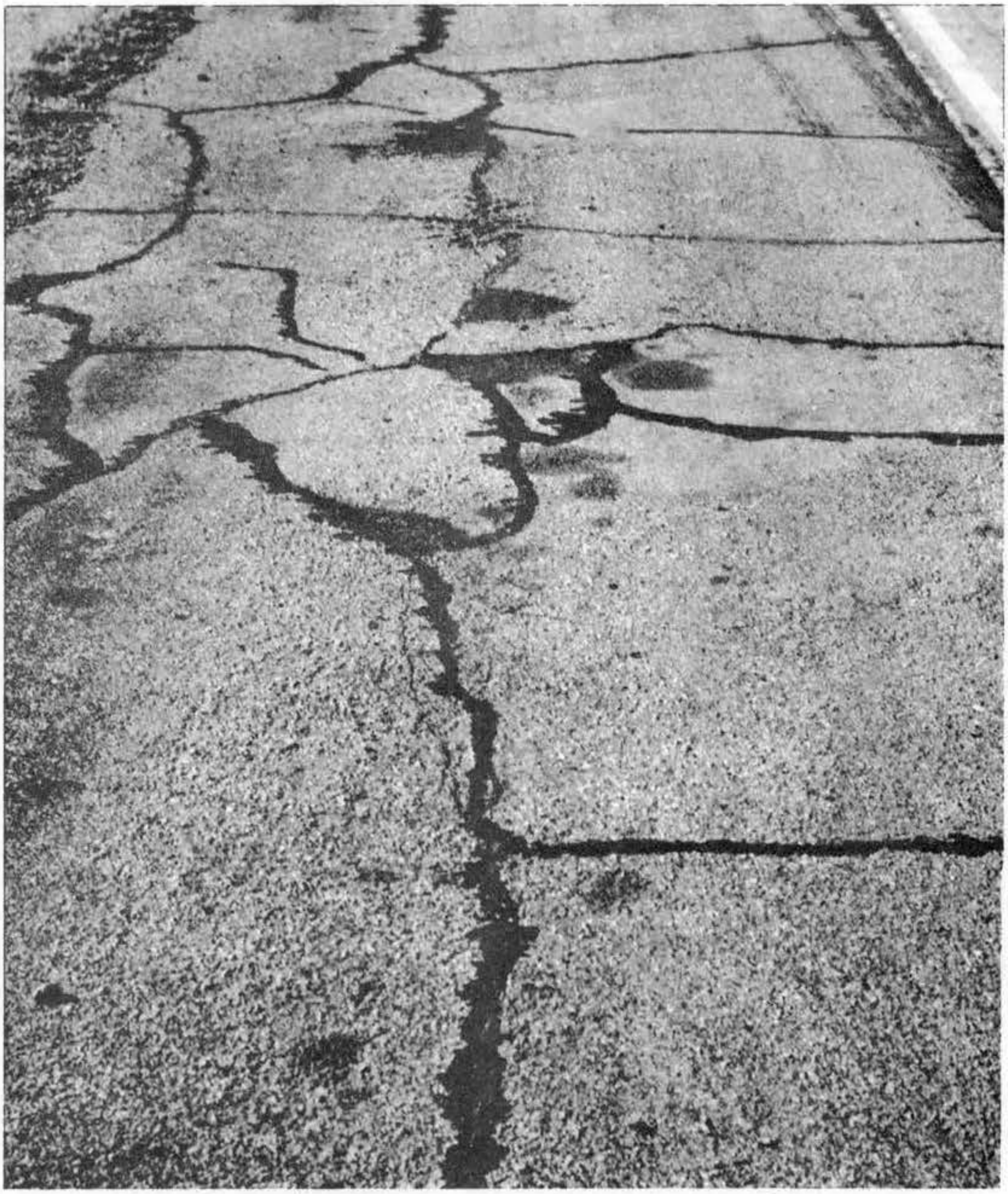


Figure 5.7. Transverse and Longitudinal Cracks in Outside Shoulder at Site No. 42

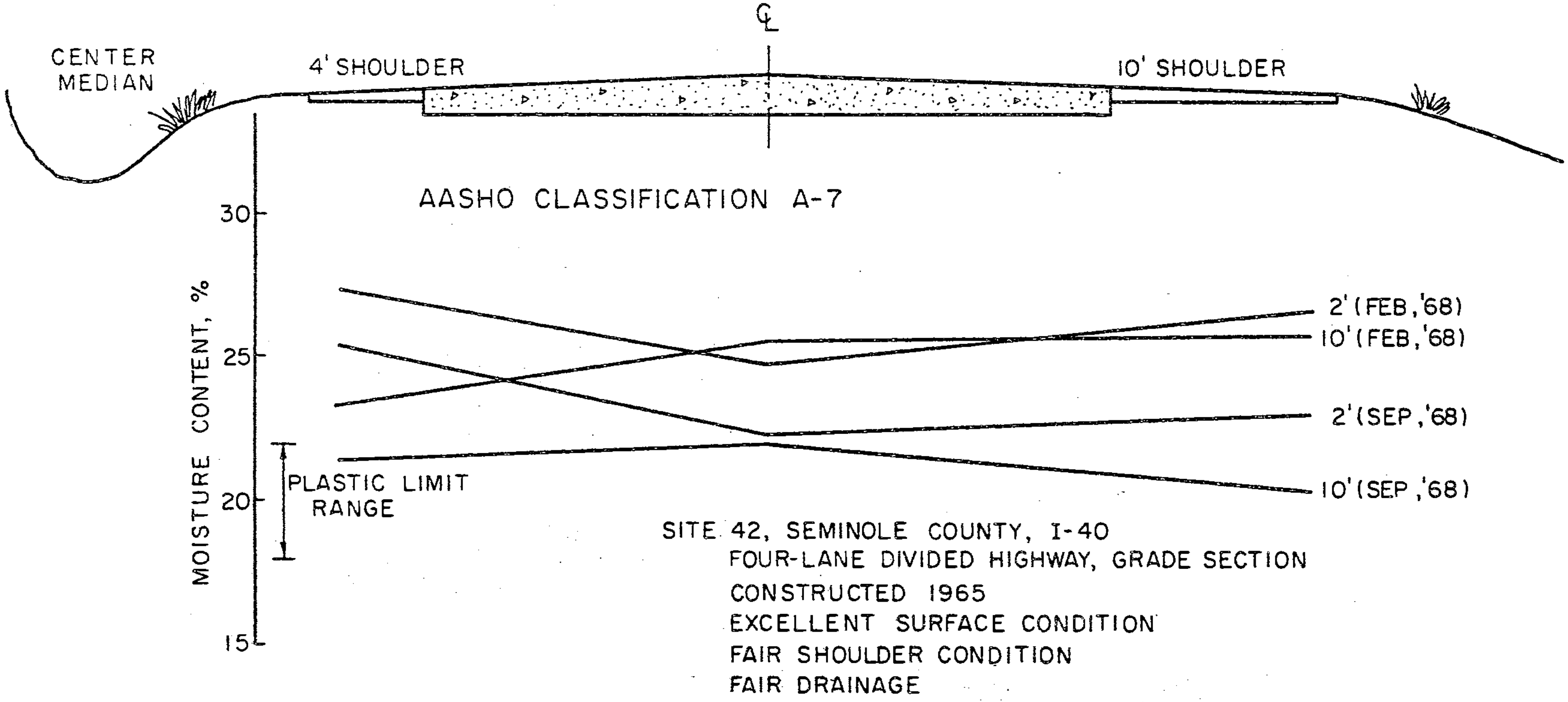


Figure 5.8. Subgrade Moisture Distribution at Site No. 42

Tensile stresses in the soil-cement base material, as a result of swelling caused by increased moisture content, probably caused the shoulder cracking shown in Fig 5.7. Observation records and photographs of Site No. 42 indicate the cracks have doubled in extent and number since the summer of 1967, when first observations were made. The new cracks probably caused fluctuations before they were sealed, as shown in Fig 5.9, a plot of moisture variations under the outside shoulder at Site No. 42. It can also be seen in Fig 5.9 that, prior to sealing the cracks in the summer of 1968, moisture content had increased to well above the plastic limit range. After sealing, moisture contents were reduced to an equilibrium valve with the moisture content/plastic limit ratio between 1.1 and 1.2. As previously mentioned, greater fluctuations in subgrade moisture content occur under the outside shoulder and this probably resulted in differential movements between the pavement and outside shoulder, causing the new, unsealed cracks shown in Fig 5.7.

All sites instrumented with bench marks showed signs of vertical pavement heave with increasing moisture content, even though the sites had wide shoulders and excellent pavement ratings. In grade and cut sections, pavement edges heave more than at the centerline, from greater magnitude of moisture content variation. In fills and transitions, greatest heave was observed at the pavement centerline, from generally higher moisture contents there.

Seasonal Subgrade Moisture Variation

Subgrade moisture variation was another predominant mode of behavior observed at research sites. Generally subgrade moisture

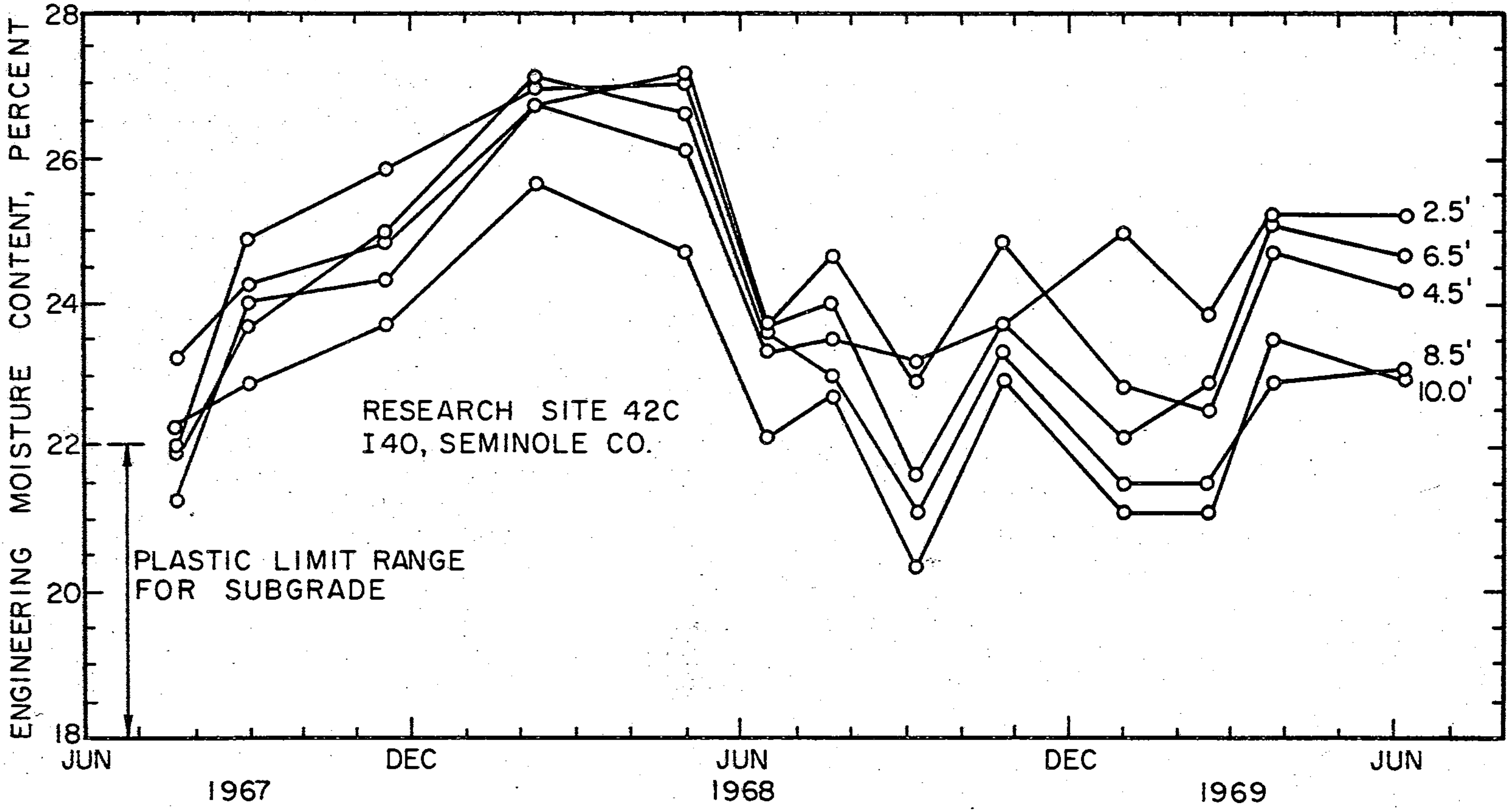


Figure 5.9. Moisture Variations at Selected Levels Beneath Outside Shoulder at Site No. 42

variations were found to be either seasonal or precipitation-dependent. Seasonal subgrade moisture variations were first thought to be temperature-induced, but further investigation revealed seasonal movements of the water table, as previously mentioned, were probably responsible. While the water table is generally at ten feet or more below the surface in Oklahoma, the zone of capillary rise often extends very close to the surface, and it is this zone of capillary water which influences seasonal variations, illustrated by conditions at Site No. 12, located in Creek County on US 66. The two-lane AC pavement with improved shoulders was constructed in 1965 over a uniform A-6 subgrade. Drainage at this site is rated fair because of gently sloping shoulders and verges, and research personnel have observed the ditches remaining wet for several days after a rain. Pavement and shoulders are rated excellent and show no signs of distress. Subgrade moisture variations under the pavement at Site No. 12 are shown in Fig 5.10, with monthly rainfall. The research site was installed in 1966 just after construction and Fig 5.10 indicates a general increase in moisture content that is not related to precipitation in 1966 and 1967. Moisture contents increased until an "equilibrium" value was reached in 1968, then variations occurred on a seasonal cycle, higher moisture contents during the winter and lower moisture contents during the summer. Approximately the same rate of moisture content increase/decrease was noted at all levels. Thus temperature-induced moisture migration did not occur, since in the winter, moisture contents at the upper levels and vice-versa during the summer, and this is not apparent in Fig 5.10.

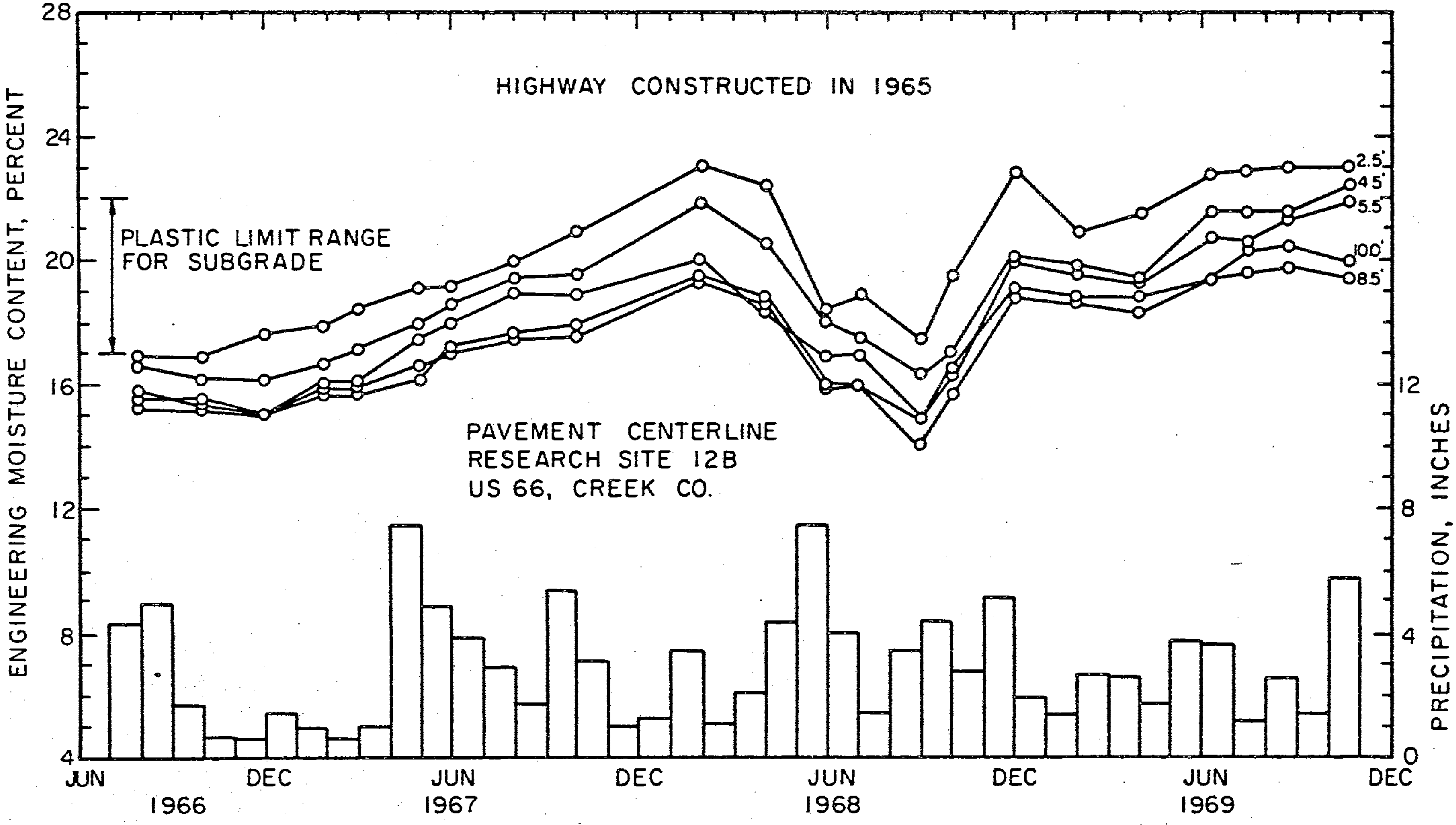


Figure 5.10. Moisture Variations at Selected Levels Beneath Pavement at Site No. 12

Precipitation-Dependent Subgrade Moisture Variation

Precipitation-dependent subgrade moisture variations usually occurred in subgrades of pavements with poor ratings and/or without sealed shoulders, and moisture variations generally lagged rainfall by a period of six to eight weeks. Asphaltic concrete overlay pavements also generally exhibited this behavior.

Infiltration occurred through cracks in the overlay, as is shown by moisture variations and rainfall at Site No. 4. This two-lane PCC pavement with open shoulders was constructed in 1930, directly on the subgrade, and has been continuously overlayed with AC by Oklahoma Highway Department maintenance forces. No records are available to show when the first overlay was completed. The highway is on grade in a creek-bottom area. The pavement rating increased from poor to good because of a second overlay in 1967, but has decreased steadily since that time. Drainage is rated fair because of gently sloping shoulders.

Figure 5.11 shows moisture variations and rainfall at Site No. 4, installed in July 1966. Moisture contents decrease with depth and some levels are above the subgrade liquid limit. Moisture contents had decreased when the second overlay was applied and heavy precipitation in the winter of 1967-68 caused a sharp increase in moisture contents, particularly at the 2.5 foot level. The bearing capacity was greatly reduced and in the early spring of 1968 the new overlay cracked. Since the old overlay was already cracked, infiltration occurred. Research personnel reported a "thumping" noise whenever traffic crossed the transverse joints before and after the second overlay. Much of the subgrade support was evidently lost long before 1966 when first observations were made. Figure 5.12 shows a photograph of the

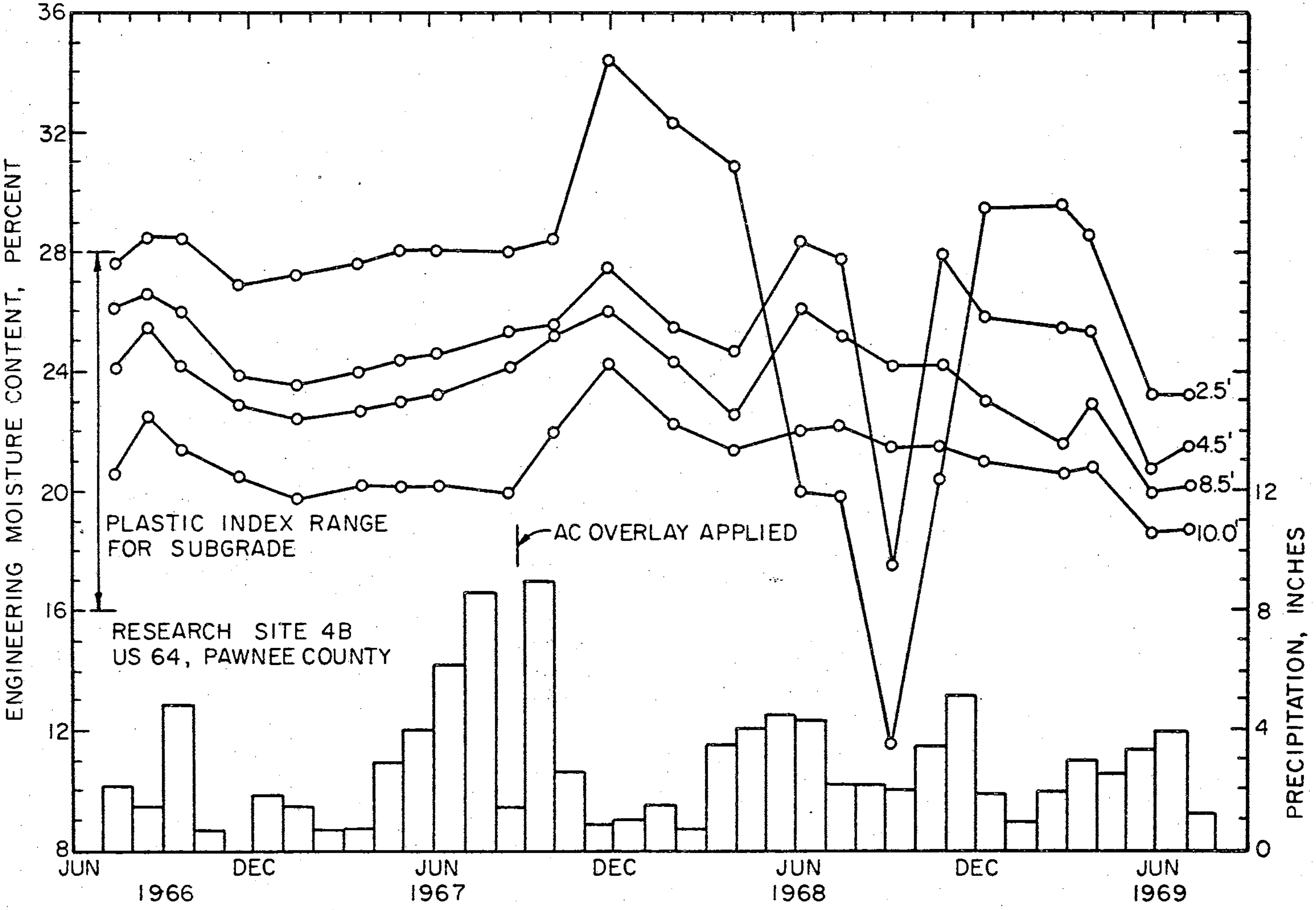


Figure 5.11. Moisture Variations at Selected Levels Beneath Pavement and Rainfall at Site No. 4

Figure 5.12. Transverse and Longitudinal Cracks in Overlay at Site No. 4

reappearance of centerline and transverse joints adjacent to Site No. 4. Details of the cracking are shown by a photograph in Fig 5.13, where the size of the transverse joint in the underlying PCC pavement is indicated by the size of the AC chunks from the new overlay. Also evident is longitudinal cracking between the pavement and the widened portion. Figure 5.14 shows the subgrade soil profile at Site No. 4. The silty layer under the pavement probably acts as a "holding basin" for infiltration into the subgrade below.

Seasonal subgrade moisture variations generally occurred at sites on pavements with sealed shoulders and excellent pavement ratings. Variation was effected by a seasonal variation in the water table elevation and thus the zone of capillary rise. The maximum moisture content/plastic limit ratio was generally less than 1.3.

Precipitation-dependent subgrade moisture variations generally occurred in subgrades of pavements with poor ratings and/or without sealed shoulders or base material. Infiltration through joints and cracks in the pavement resulted in moisture contents well above the plastic limit and sometimes above the liquid limit, causing loss of subgrade support for the pavement.

Temperature-Induced Subgrade Moisture Migration

As previously mentioned, moisture variations not related to precipitation were initially thought to be temperature induced, but additional research (Ref 2) indicated that subgrade moisture migration caused by temperature gradients is of relatively low magnitude, when compared to the effects of water-table fluctuations. Since the

Figure 5.13. Close-up of Transverse and Longitudinal Crack Along Pavement Edge at Site No. 4

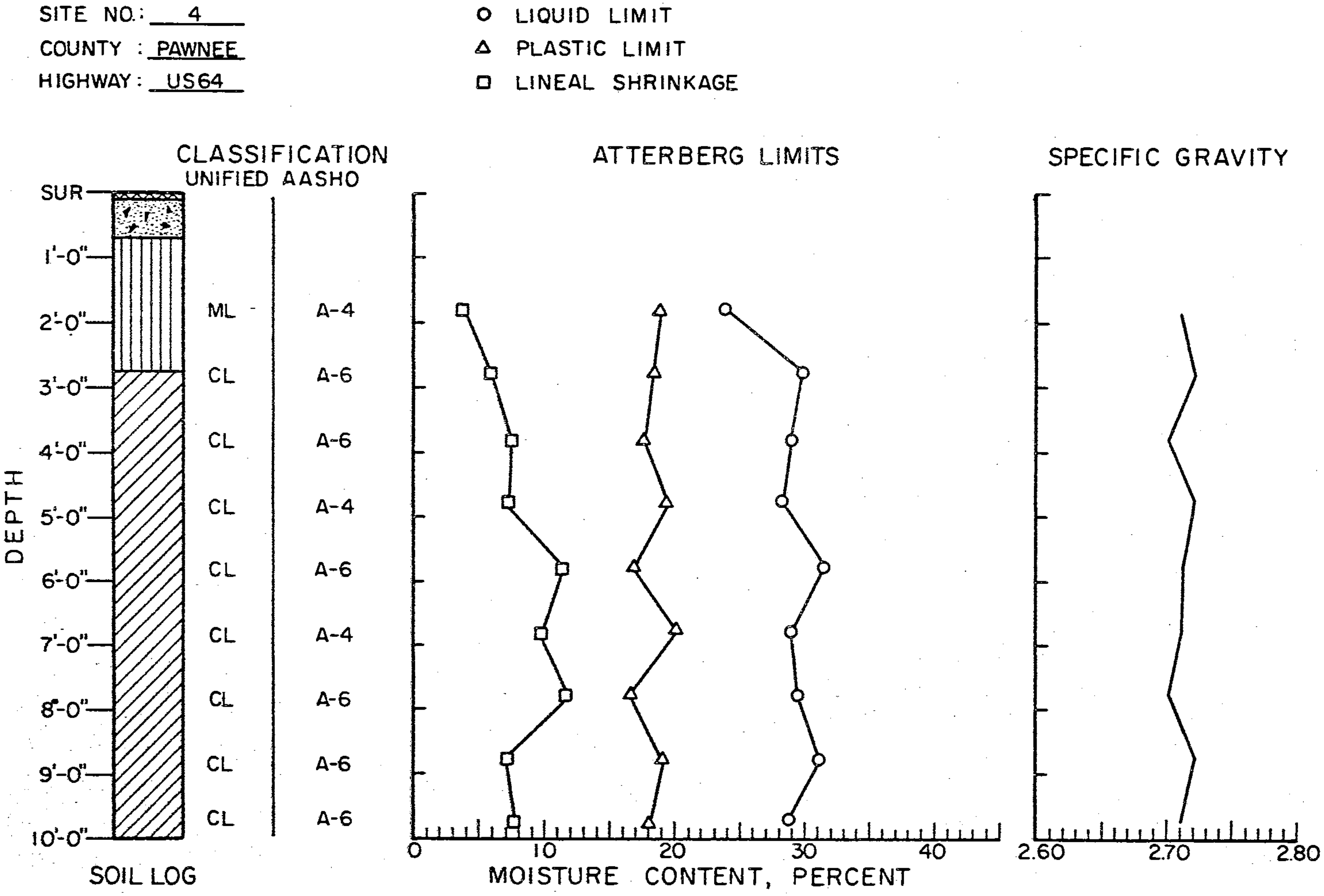


Figure 5.14. Soil Log from Site No. 4

subgrades in Oklahoma do not freeze (Ref 2), heaving problems are the result of expansive subgrade soils.

Correlations Between Highway Design and Subgrade Moisture Behavior

Subgrade moisture behavior is definitely affected by highway design. The effects of shoulder width, drainage, highway cross-section, soil type, and base material are discussed in this section.

Shoulder Width

Installation of nuclear access tubes recommended in previous research (Ref 1) has clarified the relation between shoulder widths and subgrade moisture behavior. Increasing shoulder widths reduced the effects of runoff infiltration. This is shown by Figs 5.15 and 5.16, which illustrate typical moisture profiles under pavement grade sections with and without wide improved shoulders. In both cases, greatest fluctuations in moisture content occur near the outer edges of the section. However, more severe fluctuations occur in the section with open shoulders. Less severe differential movements from more nearly uniform moisture content are common in pavements with wide shoulders. Sealed shoulders also produced more nearly constant and uniform rates of subgrade moisture increase/decrease under both pavement centerlines and edges.

Drainage Conditions

Drainage conditions and infiltration tendencies are closely related to shoulder and verge slope. Generally, steeper verge and

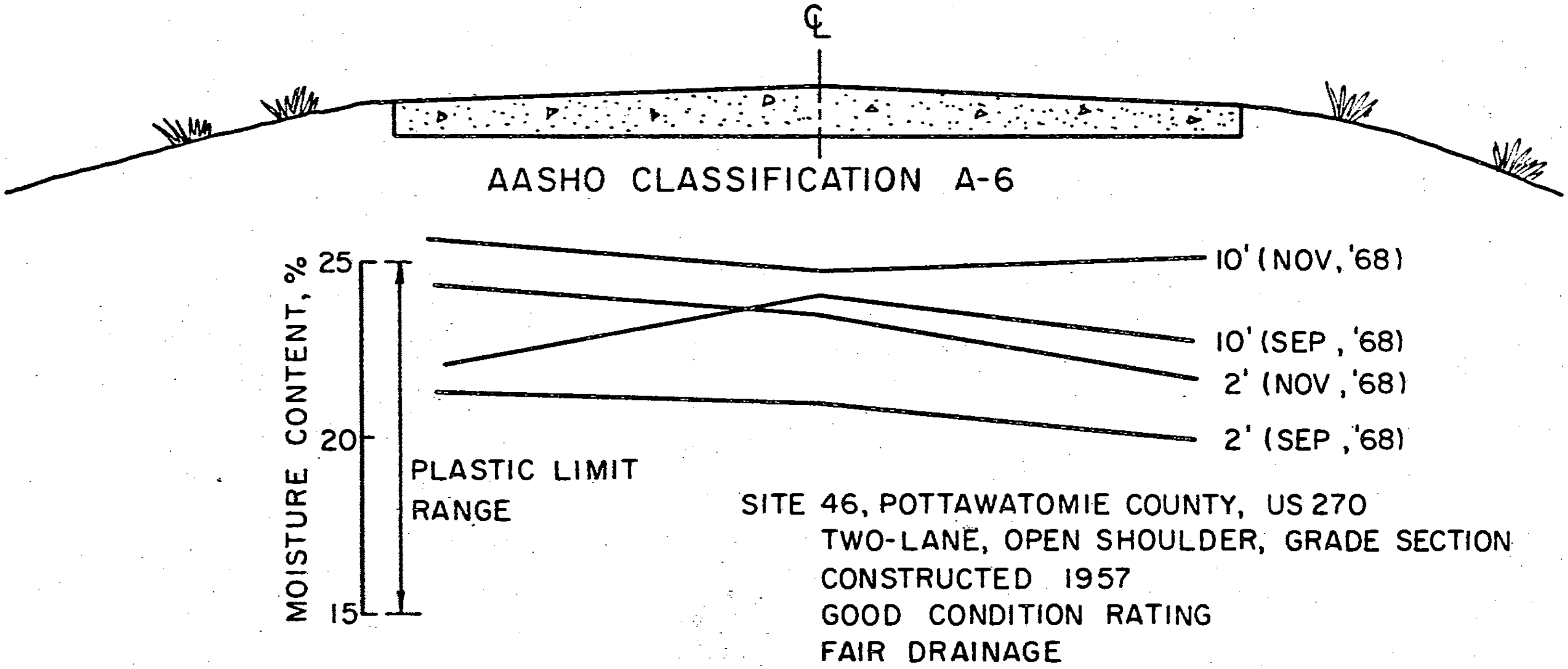
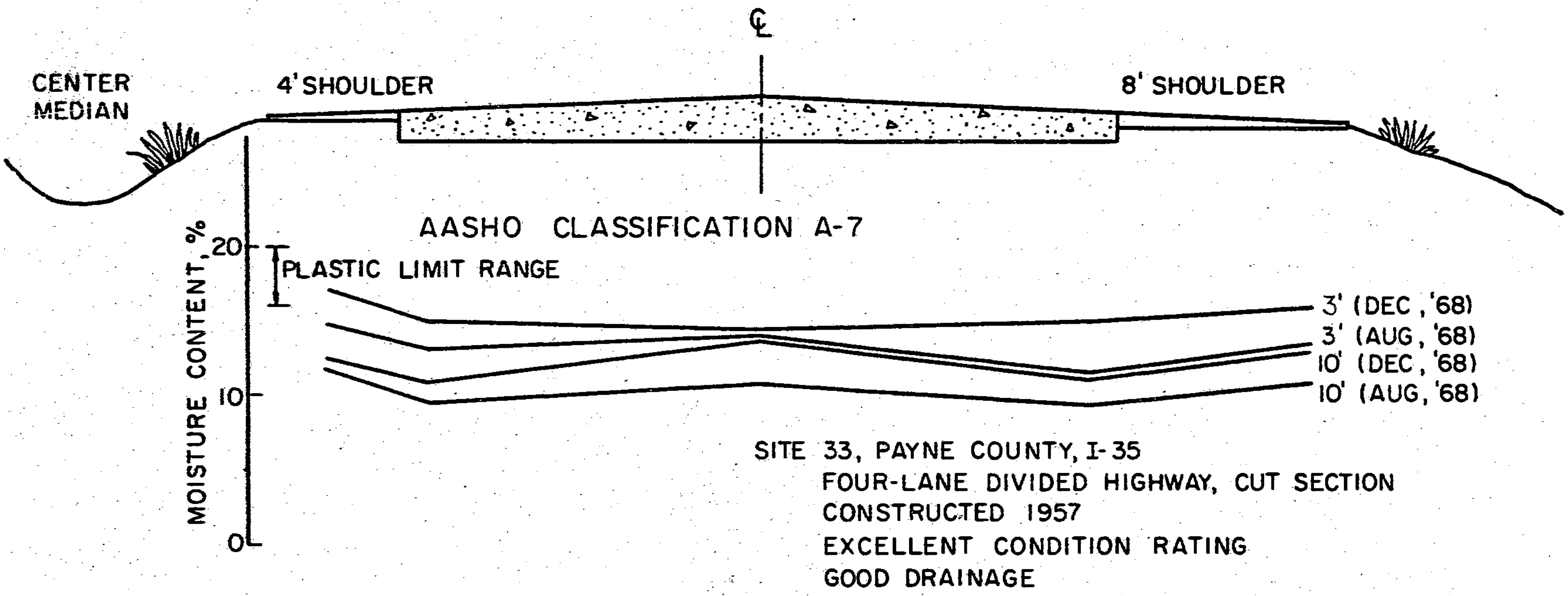


Figure 5.15. Subgrade Moisture Distribution at Site No. 46



SITE 33, PAYNE COUNTY, I-35
FOUR-LANE DIVIDED HIGHWAY, CUT SECTION
CONSTRUCTED 1957
EXCELLENT CONDITION RATING
GOOD DRAINAGE

Figure 5.16. Subgrade Moisture Distribution at Site No. 33

shoulder slopes reduce infiltration into the subgrade. Quick removal of surface runoff from ditches, i.e., no ponding of water, was found to further reduce infiltration at most of the research sites -- particularly in cut, grade, and the uphill side of transition sections.

Drainage conditions at Site No. 22, on US 81 in Kingfisher County, illustrate the relation of infiltration and verge/shoulder slopes. The two lane AC highway was constructed in 1924 and was overlayed and widened with improved shoulders in 1957 to increase traffic capacity. Stabilized aggregate base material was used under the pavement and shoulders, while the subgrade consists of sandy, A-3 material that has a layer of A-6 clay between the four and five ft levels. Drainage is rated fair because the east verge has a gentle slope and has been noted to remain wet for several days after a rain, while the west verge is on a somewhat steeper slope. The pavement is on grade and is rated excellent. A moisture profile under the pavement is shown in Fig 5.17, where left is to the west. Greater fluctuations under the east or right hand shoulder between the wet and dry seasons of the year were caused by poorer drainage, resulting in more infiltration on the east verge. The steeper verge on the west, or left hand side, provided better drainage and less infiltration. At the shallower 2.0 foot depth, moisture contents under the pavement centerline are between the moisture contents at the shoulder, while at the 10.0 ft depth the centerline moisture content remains almost constant during the wet and dry periods of the year. The previously mentioned clay layer between four and five feet probably acts as a moisture "barrier" and reduces the effects of infiltration from the shoulders, and it

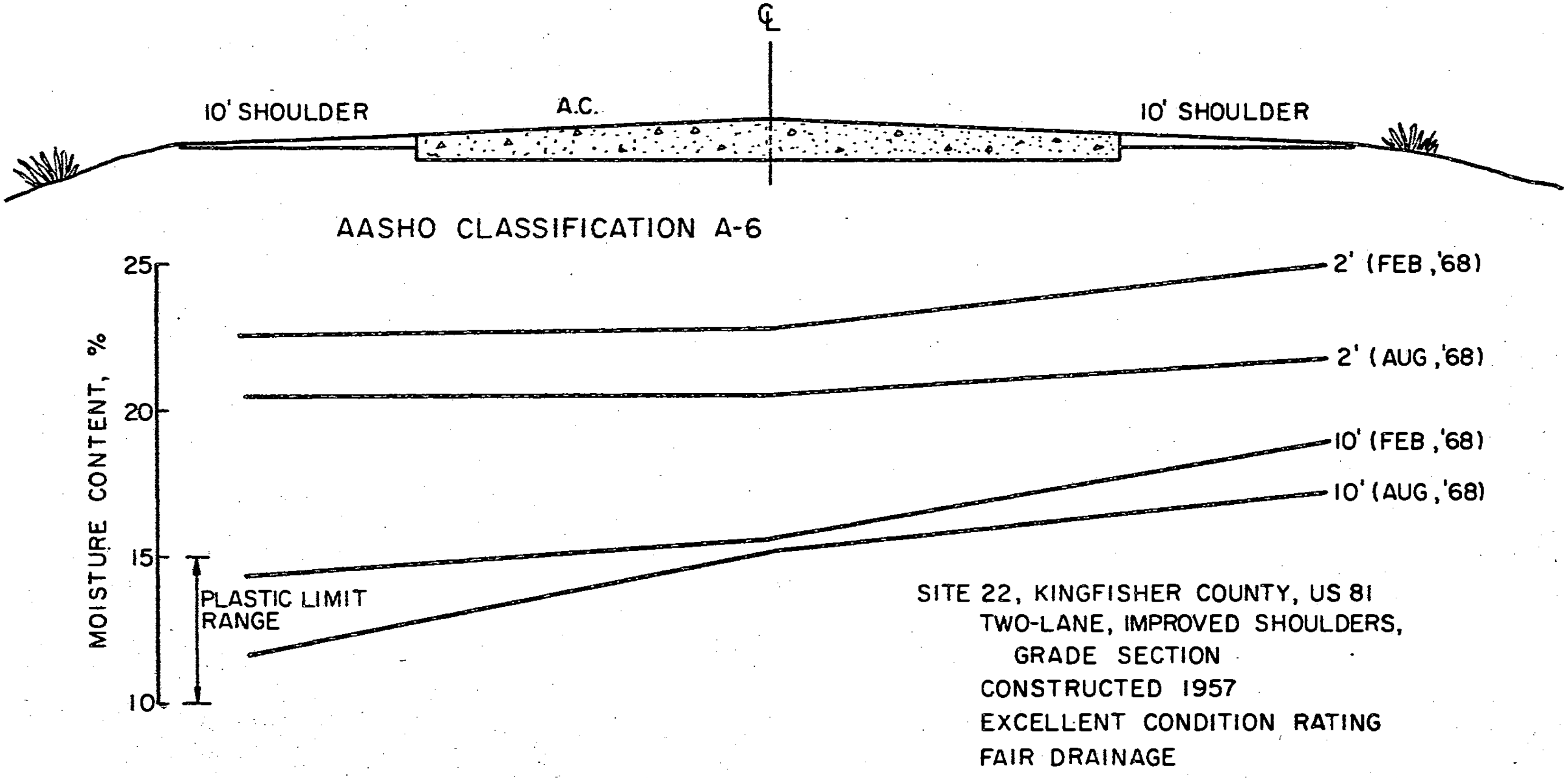


Figure 5.17. Subgrade Moisture Distribution at Site No. 22

maintains a higher moisture content in the upper levels than in the lower levels.

At most research sites, gently sloping verge/shoulder slopes caused greater infiltration of runoff than did steeper sloping verges. Ditches which remain wet or soggy for several days after a rain also cause greater infiltration.

Highway Cross-Section

Type of highway cross-section affected subgrade moisture conditions, with pavements on grade or in slight cuts usually exhibiting higher pavement ratings, probably from more nearly uniform moisture conditions in the subgrade.

Fill and transition sections usually exhibited fair to good pavement and shoulder ratings, but suffered shoulder settlements because of dryer subgrade moisture conditions under the shoulders.

Site No. 29 is a relatively high fill section on US 64 in Tulsa County. The two-lane highway has PCC pavement with improved shoulders and was constructed in 1960 on a uniform A-7 clay subgrade with a plastic limit range of 20-28% and an average lineal shrinkage of 20%. Capillary water accumulates under the pavement centerline, but probably evaporates near the edge of the shoulders because of greater surface area on the embankment sides. A photograph of one shoulder at Site No. 29 is shown in Fig 5.18. This shoulder has settled 2 to 3 inches, as has the other shoulder, because of generally dryer conditions under the shoulders. Figure 5.19 is a photograph of the pavement edge at Site No. 29. The ripples in the pavement edge are probably joints, since a transverse joint usually coincides with

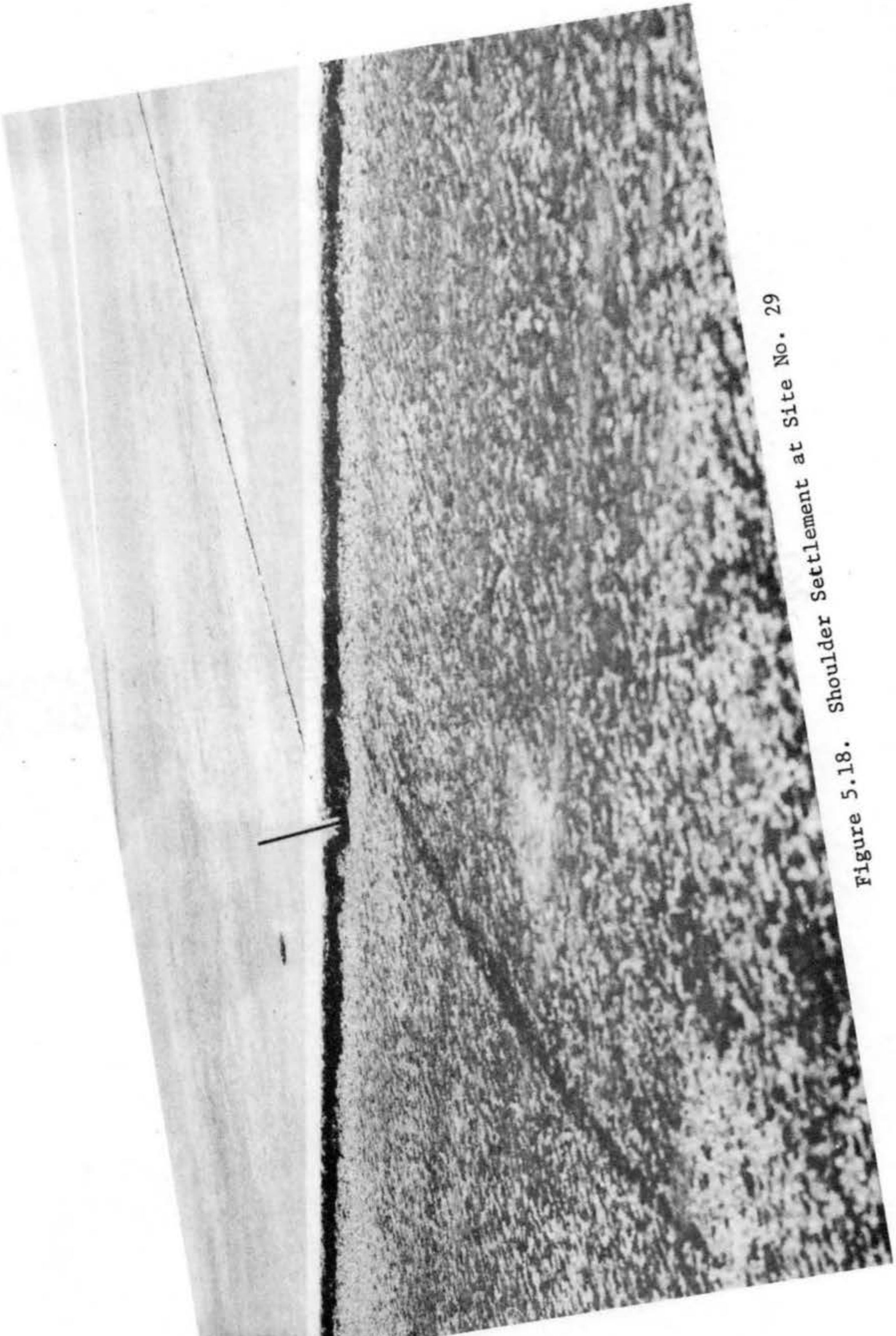


Figure 5.18. Shoulder Settlement at Site No. 29

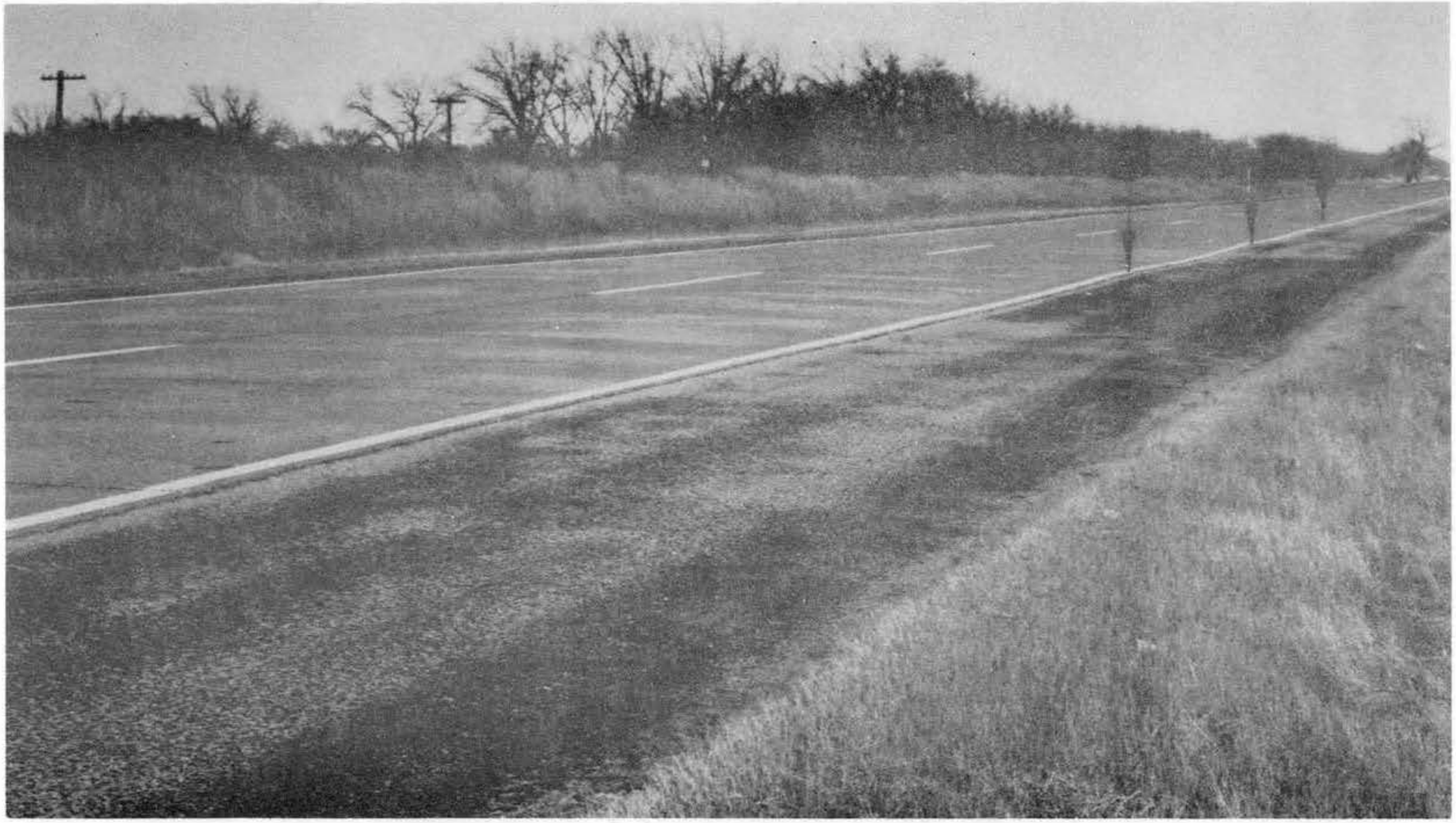


Figure 5.19. Ripples in Pavement Edge at Site No. 29

the peak of a ripple. Pavement and shoulder ratings at Site No. 29 are good.

Shoulder settlement also occurred in relatively slight fill sections. Site No. 42, described previously, is located on a slight fill. Figure 5.20 is a photograph of the outside shoulder near Site No. 42. Dryer conditions under this shoulder have caused the shoulder to settle over one inch.

Subgrade Soil Type

Subgrade soil type was found to be related to subgrade moisture behavior. Data from sites with bench marks indicates plastic and non-plastic subgrade soils swelled with increasing moisture content, although the plastic subgrade soils swelled more. Most plastic subgrade soils exhibited an average heave/moisture content increase ratio of 1/12 in./% as compared to less than 1/16 in./% for "good" non-plastic subgrade soils. Figure 5.21 is a picture of the shoulder adjacent to Sites No. 49 and 50. As mentioned previously, Site No. 49 is AC pavement with a sand-asphalt base under the shoulders, while Site No. 50 has PCC pavement and soil-cement base under the shoulders. The sites are within 50 yds of each other, though they have different subgrades. The plastic subgrade soil at Site No. 50 heaved four times as much as the "good" subgrade at Site No. 49. It is readily apparent that the soil-cement base has been cracked as a result of this swelling while the sand-asphalt base did not crack. Before the cracks were sealed moisture content increased considerably under the shoulder at Site No. 50. Close scrutiny of Fig 5.21 will show longitudinal cracking near the shoulder edge of the section with soil-cement base, which

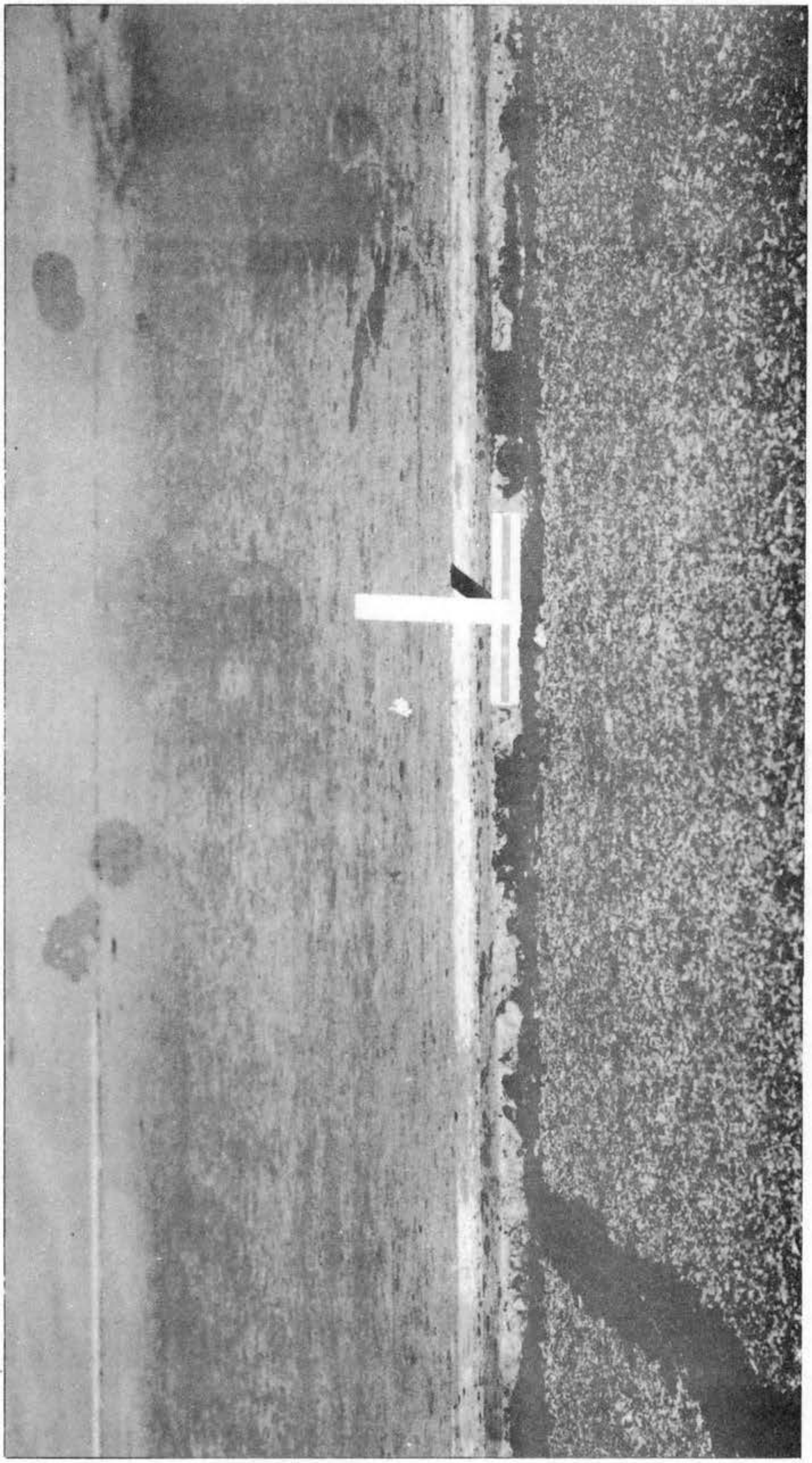


Figure 5.20. Shoulder Settlement at Site No. 42

Figure 5.21. Shoulder Cracks Adjacent to Site Nos. 49 and 50

was probably caused by development of a wet-dry interface.

Layers of plastic subgrade soil within a non-plastic material acted as a moisture barrier that reduced the effects of infiltration. In subgrades of pervious pavements, silty or sandy base material acted as a holding basin to feed infiltration directly into the subgrade below, while under impervious pavements the coarser grained base material acted as a reservoir/distribution system to spread the subgrade moisture rather evenly.

Under pavements with excellent ratings and wide shoulders, moisture in clay subgrades increased to an equilibrium value near a moisture content/plastic limit ratio of 1.1 to 1.3, while subgrades under pervious pavements sometimes had moisture contents above the liquid limit. Clay subgrades also tended to develop a wet-dry interface under the edge of shoulders, fill sections and where good drainage conditions existed.

Site No. 2 is located on SH 51 in Payne County. The two-lane highway was originally constructed in 1930 with open shoulders and PCC pavement on a uniform A-3 sandy soil. In 1955 an overlay was applied and wide shoulders were added to allow for increased traffic. The subgrade has a liquid limit of 20% but no plastic limit or lineal shrinkage. A water table was encountered during site installation in 1966, at a depth of 8 to 10 feet. Moisture variations beneath the pavement are shown in Fig 5.22, along with rainfall for the three-year period of study. Subgrade moisture conditions appear to be influenced by both precipitation and the fluctuating water table. Bench mark data from Site No. 2 indicate heaving with increasing moisture content, but, as at Site No. 49, heaving is generally less than 1/8 inch.

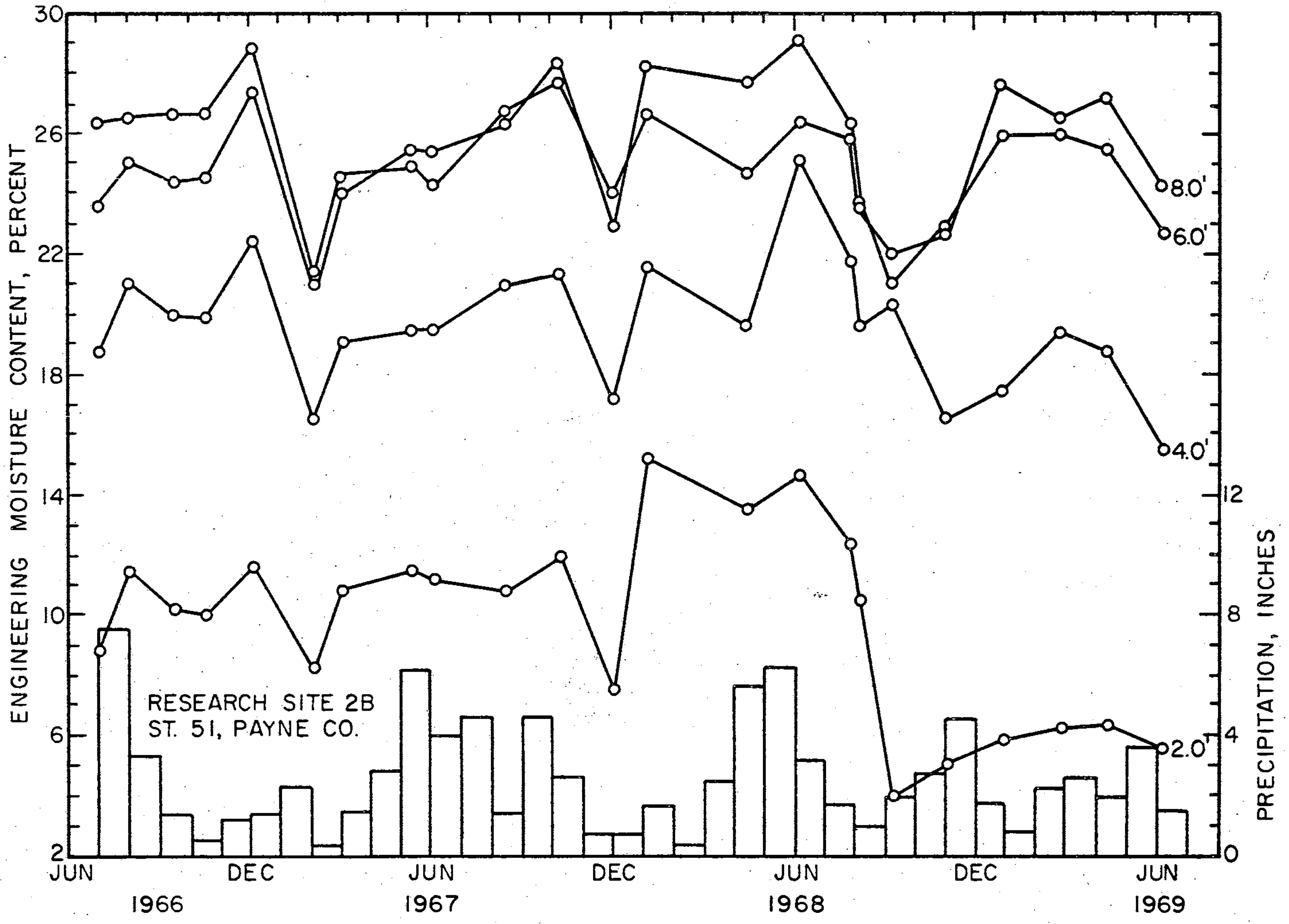


Figure 5.22. Moisture Variations Beneath Pavement at Site No. 2

Hair-line cracks in the overlay denote location of transverse and longitudinal joints in the original PCC pavement, and probably allow some infiltration into the subgrade. The reason for good behavior of the overlay at Site No. 2 is the soil type.

Base Material

Base and subbase materials used on expansive Oklahoma subgrades must serve these purposes:

1. provide support for pavement,
2. minimize infiltration, and
3. protect pavements from tensile stresses associated with swelling soils.

Sand cushion, stabilized aggregate (SABC), and sand asphalt (SACC) are base course types commonly used in Oklahoma highway construction. SACC or lime-modified subgrade material are commonly used as subbase.

Previous research (Ref 1) noted that sand cushions under concrete pavements acted as reservoirs that hold large amounts of moisture and cause moisture contents to approach the liquid limit of subgrade soils. Hydrogenesis was not thought to be the cause of high moisture contents under open-graded bases, since poor pavement ratings or fair drainage conditions usually existed.

Soil-cement base in contact with expansive compacted subgrades tends to crack easily as a result of lateral volume changes associated with increasing subgrade moisture contents, particularly when used as base material in shoulders. No pavement cracking resulting from use of soil-cement base was observed at research sites, probably because of the use of a subbase between the expansive subgrade and soil-cement base. Use of subbase under soil-cement evidently provides protection from the tensile stresses and uneven heaving of expansive subgrade soils.

SACC and SABC have been used very successfully as the only base material under pavements. Both are less pervious than the sand cushion and seem to be more "flexible" than soil-cement.

Miscellaneous Factors Related To Subgrade Moisture Behavior

Several miscellaneous factors were found to be related to subgrade moisture behavior during the three years of data collection. The more interesting phenomena included shoulder cracking under heavy traffic loads, "creep" of concrete pavements during summer months, and poor joint maintenance.

Shoulder Cracking Under Traffic Loads

Wide shoulders on pavements at uphill grades are often used by slower traffic, i.e., heavily loaded trucks, to allow faster traffic to pass. Cracking of shoulder surface and base material is sometimes the result of heavy traffic loads, as shown in Fig 5.23. Infiltration through these cracks in the shoulder affects subgrade moisture behavior. As noted before, pervious pavements and shoulders exhibit lower surface condition ratings and have more maintenance problems. Passing lanes on uphill grades would eliminate this problem.

Creep of Concrete Pavements

One of the most unusual phenomena noted has been "creep" of

Figure 5.23. Shoulder Failure Because of Heavy Traffic

concrete pavements during late summer months. Creep is most noticeable near bridge abutments and where PCC and AC pavements meet "end to end" in the same highway. During late summer months the PCC pavement "grows" or "creeps" because of thermal expansion. Research sites installed in the last concrete slab adjacent to AC pavement have been damaged as a result of pavement creep, by the hubs being pushed against the access tubes and deforming them so the nuclear depth probes would not fit. The hubs at Site No. 28 moved one or two inches, rendering the site useless without installation of new access tubes. Consequently, it was abandoned. Movements at other sites have been less than 3/4 inch.

Poor Joint Maintenance

As noted previously, concrete pavements grow because of thermal expansion. Upon contraction, joints are wider since only each slab contracts. If the widened joint is not sealed, solid material fills the joint. Upon the next expansion/contraction cycle, the total "growth" is greater because the joints have been filled. As the joints become wider, greater amounts of infiltration occur, causing the subgrade soil to swell and this swelling opens the joints still further. When subgrade moisture contents are high enough, pumping may occur, and the pavement fails because of reduced bearing capacity and loss of subgrade support. Figure 5.24 shows a pavement which has failed completely because of swelling soils and improper maintenance of the joints. Figures 5.25 and 5.26 show details of wide joints, differential movement along the pavement centerline, and pavement cracking. Nearby is the subgrade for the new replacement highway, which has

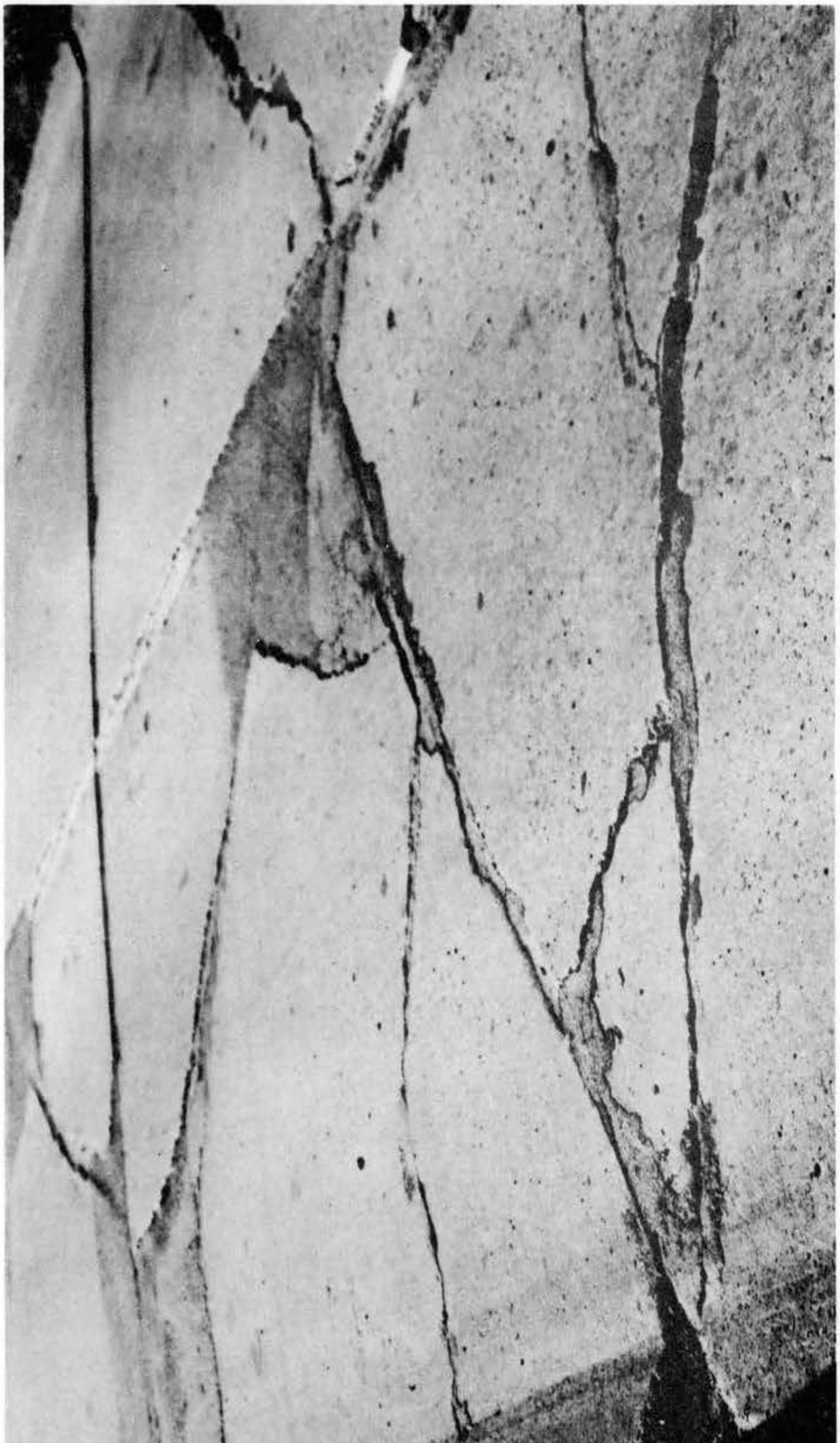


Figure 5.24. Overall View of Complete Pavement Failure

Figure 5.25. Close-up of Cracks and Joints in Figure 5.24

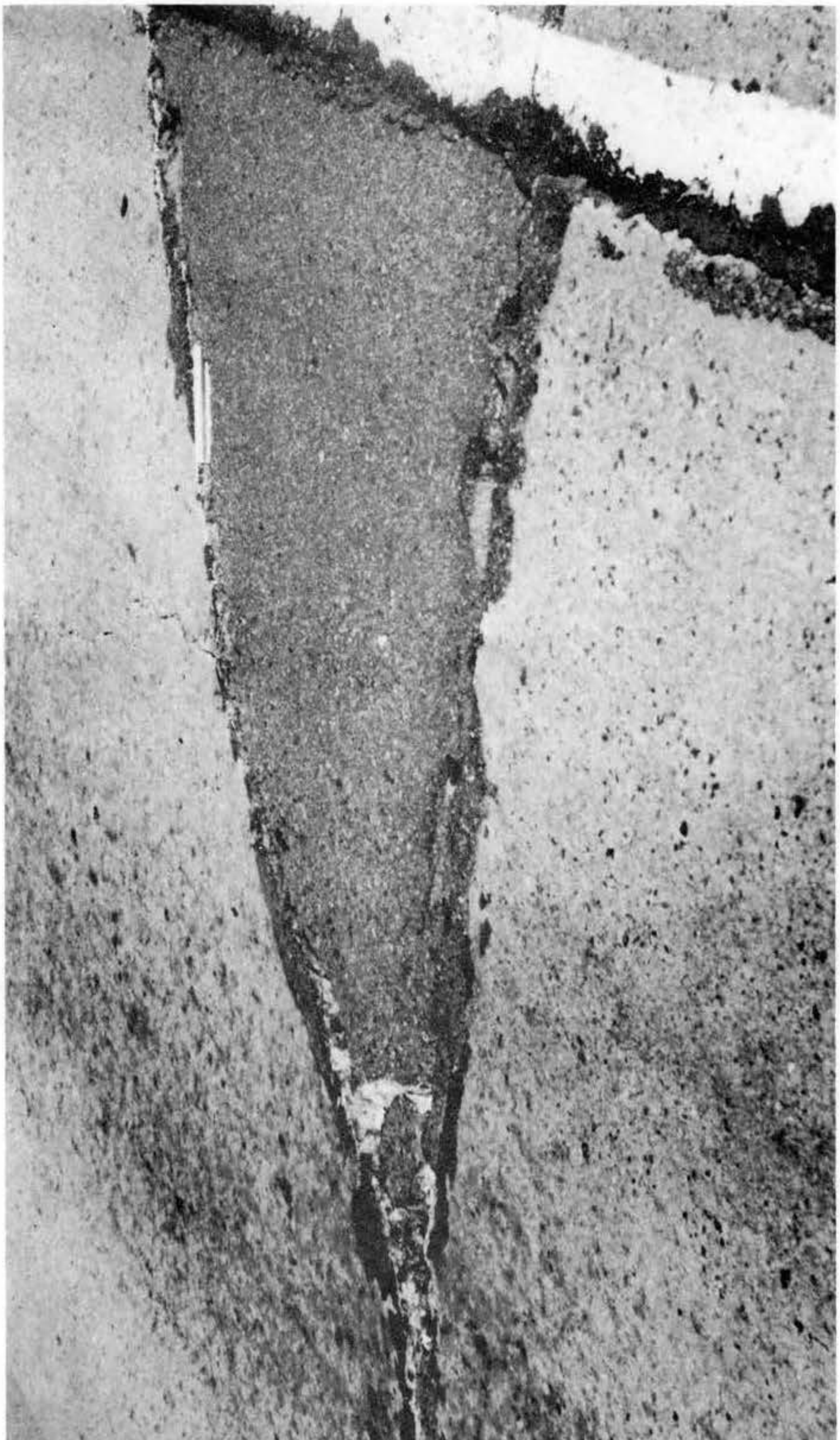


Figure 5.26. Open Centerline Joint and Corner Crack

been open to the climate for two years. The surface is quite dry and loose, and one wonders how long it will be before the new highway, once surfaced, resembles the one it replaced.

Summary

Subgrade moisture behavior and related trends were discussed in this Chapter. Subgrade moisture accumulation and variation were found to be the most predominant modes of behavior. Relationships between the modes of subgrade moisture behavior and highway performance were discussed, as were the factors that affected the modes of subgrade moisture behavior. Conclusions from this evaluation and recommendations concerning future study of relationships between subgrade moisture behavior and highway performance are listed in the following Chapter.

CHAPTER VI

CONCLUSIONS AND RECOMMENDATIONS

Data from three years of study was evaluated and discussed in Chapter V. Correlation of trends in subgrade moisture behavior and related factors has produced the following conclusions:

1. Two modes of subgrade moisture behavior occur in Oklahoma subgrades: subgrade moisture accumulation and subgrade moisture variation.
2. Subgrade moisture accumulation occurred after highway construction and/or long periods of drought (which caused drying of subgrades to depths of ten feet or more). Accumulation continues until subgrade moisture content reaches an "equilibrium" value, near a moisture content/plastic limit ratio of 1.1 to 1.3.
3. Subgrade moisture variations are either precipitation or water table-dependent. Precipitation-dependent moisture variations occur in subgrades of pavements with poor ratings and/or an open graded, coarse grained base material. Water table dependent moisture variations occur in subgrades where the moisture content is a result of the zone of capillary rise from a water table, and pavement ratings are higher.
4. Higher pavement ratings were evident in impervious pavements with wide shoulders, impervious and flexible base material,

and grade or cut sections.

5. Highways with wide shoulders exhibited more nearly constant moisture conditions and reduced moisture content increase/decrease beneath the pavement, while moisture conditions beneath shoulders varied somewhat more.
6. Subgrade moisture contents were found to fluctuate severely beneath shoulders in fill and transition sections, but fluctuate less in grade or cut sections.
7. Wet-dry interface behavior seems to be the cause of longitudinal cracking in shoulders.
8. Subgrade soils encountered in this study were found to be expansive, even though classification systems sometimes indicated otherwise.
9. Lateral and vertical swelling of expansive Oklahoma subgrades were found to cause most damage to soil-cement base material and to pavements without base material.
10. Flexible, impervious base materials, such as stabilized aggregate base courses or sand-asphalt base courses, reduced infiltration and resisted cracking better than sand cushion or soil-cement base materials.

For future study of moisture behavior in Oklahoma subgrades, the following are recommended:

1. Data collection at sites which have special instrumentation should be continued until just before project termination.
2. Data should be evaluated again, to develop highway design and construction criteria that reduce the undesirable effects of subgrade moisture behavior.

3. If time and funds can be made available, highway test sections should be constructed to test recommended highway design and construction criteria.

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APPENDIX A

RESEARCH SITE LOCATIONS AND INSTRUMENTATION

SMV FIELD TEST SITE LOCATIONS, SITES NO. 1 - 52

Site No. 1

In Payne Co. northwest of Perkins, 0.3 mile north on US 177 from wye jct. of US 177 and S 33, adjacent to mileage sign indicating 10 miles from Stillwater. Marker on west fence row. Site on level upland terrain.

Site No. 2

In Payne Co. east of Stillwater, approximately 300 yds east on S 51 from GRDA sub-station. Site in rolling upland area. Marker on south fence row. GRDA sub-station is approximately 1.5 miles east of Stillwater on S 51.

Site No. 3

In Noble Co. northwest of Perry, 1.8 miles north on I 35 from jct. of I 35 and US 64. Site in east lane, approximately 100 yds south of "Tonkawa 31, Wichita 101" mileage sign. Marker on east fence row. Site on open, gently rolling upland terrain.

Site No. 4

In Pawnee Co. southeast of Pawnee, 4.8 miles east on US 64 from Oklahoma Highway Department division yard on outskirts of Pawnee, 1/4 mile east of bridge over Bear Creek, 1/4 mile west of Santa Fe railroad bridge overpass. Marker on south fence row. Site in creek-bottom area.

Site No. 5

In Osage Co. northeast of Pawhuska, 1.5 miles southwest on US 60 from jct. of US 60 and S 99, approximately 100 ft southwest of US 60 - S 99 route marker facing southwest. Marker on northwest fence row. Site on open upland terrain.

Site No. 6

In Washington Co. east of Bartlesville, 6.2 miles east on US 60 from jct. of US 60 and US 75, approximately 200 yds west on US 60 from Hog Shooter Creek. Site on fill section in creek-bottom area. Marker on south fence row.

Site No. 7

In Craig Co. west of Vinita, 0.6 mile east on US 66-60 from wye jct. of US 66 and US 60. In south lane of divided highway, approximately 30 ft west of entrance to Martin ranch. Marker on south fence row. Site on open, gently rolling upland terrain.

Site No. 8

In Mayes Co. south of Pryor, 0.2 mile north on US 69 from jct. of US 69 and US 69A. Approximately adjacent to billboard facing north on west side of highway. Marker on east fence row. Site on open, fairly level upland terrain.

Site No. 9

In Muskogee Co. northwest of Muskogee, in west-bound lane of US 64 0.7 miles west from Arkansas River bridge. Marker on north fence row. Site in rolling upland area.

Site No. 10

In Okmulgee Co. north of Okmulgee, 2.0 miles north on US 75 from railroad crossing, end of divided highway, and Okmulgee north city limit. Site in west lane of divided highway, marker on west fence row. Site on upland terrain in slight cut.

Site No. 11

In Creek Co. west of Sapulpa, 1.3 miles east on US 66 from jct. of US 66 and S 33, adjacent to an "Animal Clinic". Marker on south fence row. Site in creek-bottom area.

Site No. 12

In Creek Co. north of Bristow, 2.6 miles north on US 66 from jct. of US 66, S 48, and S 16, 0.3 miles north of bridge over Sand Creek. Marker on west fence row. Site on upland terrain in slight cut.

Site No. 13

In Lincoln Co. west of Chandler, 0.8 miles west on US 66 from jct. of US 66 and S 18, 200 ft west of Champlin service station. Marker on south fence row. Site in rolling hilly terrain.

Site No. 14

This site has been abandoned.

Site No. 15

In Osage Co. east of Ponca City, 1.6 miles east of US 60 from jct. of US 60, S 11, and US 177. Marker on north fence row. Site on level upland terrain.

Site No. 16

In Nowata Co. east of Nowata, 0.3 mile south on S 28 from jct. of US 60 and S 28. Marker on west fence row. Site on upland terrain.

Site No. 17

In Ottawa Co. north of Miami, 2.5 miles north on US 69 from jct. of US 66, US 69, and S 10, adjacent to Sacred Heart Catholic Church. Site on four-lane undivided highway, marker on east fence row. Site on level upland terrain.

Site No. 18

This site has been abandoned.

Site No. 19

In Wagoner Co. north of Wagoner, 3.9 miles north on US 69 from jct. of US 69 and S 51, 100 yds south of east-west powerline crossing. Marker on east fence row. Site on upland terrain.

Site No. 20

In Tulsa Co. northwest of Broken Arrow, 0.5 mile northwest on S 51 (Broken Arrow Expressway) from Lynn Lane overpass and exit. Site in north lane of divided highway, north of unusual church. Marker on north fence row. Site on rolling upland terrain.

Site No. 21

In Garfield Co. on the northwest edge of Enid, 100 yds north of Atwood's Farm and Home Supply store on US 81. Marker on west fence row. Site in upland area.

Site No. 22

In Kingfisher Co. south of Hennessey, 3.9 miles south on US 81 from jct. US 81 and S 51. Marker on west fence row. Site in slight cut on rolling upland terrain.

Site No. 23

In Rogers Co. north of Talala, 1.6 miles north of Talala city limit on US 169. Approximately 100 yds north of beginning of portland cement concrete pavement with improved shoulders. Marker on west fence row. Site on level upland terrain.

Site No. 24

In Rogers Co. southwest of Claremore, 1.5 miles southwest on US 66 from jct. of US 66 and US 66 truck route. Site in southeast lane of divided highway, marker on southeast fence row. Site on upland terrain.

Site No. 25

This site has been abandoned.

Site No. 26

In Pawnee Co. southeast of Cleveland, 2.5 miles southeast on US 64 from jct. of US 64 and S 99, 0.5 mile southeast of Cleveland drive-in theater. Marker on southwest fence row. Site on hilly upland terrain.

Site No. 27

In Logan Co. northeast of Guthrie, 6.0 miles north on I 35 from jct. of I 35 and S 33. Approximately 100 yds south of overpass. Site in west lane of divided highway. Marker on west fence row. Site in slight cut on rolling, upland terrain.

Site No. 28

This site has been abandoned.

Site No. 29

In Tulsa Co. southeast of Bixby, 5.5 miles south and east on US 64 from jct. of US 64 and S 67, 0.8 mile east of bridge over Snake Creek. Marker on south fence row. Site on slight fill in creek-bottom area.

Site No. 30

In Tulsa Co. east of Sand Springs, 0.5 mile east on US 64 from US 64 - S 151 overpass, 100 ft east of "Keystone Dam - ST 51" exit sign. Site in north lane of divided highway 1/2 mile north of Arkansas River, marker on north fence row. Site on slight fill in Arkansas River bottom.

Site No. 31

In Kay Co. southwest of Tonkawa, 74 yds south on I 35 from "Tonkawa" exit sign, 0.3 mile south of I 35 - US 60 junction. Portland cement concrete pavement with improved shoulders on upland terrain. Site in east lane of divided highway and marker on east fence row. South of OSHD maintenance yard.

Site No. 32

In Kay Co. west of Blackwell, 0.7 mile south on I 35 from I 35 - SH 11 junction (Blackwell exit). Portland cement concrete pavement with improved shoulders in slight cut. Site in east lane of divided highway and marker on east fence row.

Site No. 33

In Payne Co. west of Stillwater, 0.8 mile south on I 35 from I 35 - SH 11 junction. 0.5 mile north of "Stillwater 1 Mile" exit sign. Asphaltic concrete pavement with improved shoulders in slight cut. Marker on west fence row, site in east lane of divided highway.

Site No. 34

In Garfield Co. north of Enid, 6.5 miles north on US 81 from US 81 - SH 15, 3.7 miles north on US 81 from SMV Site No. 21. Portland cement concrete with improved shoulders in slight cut. Site in east lane of divided highway, marker on east fence row.

Site No. 35

In Kingfisher Co. south of Kingfisher, 2.7 miles south on US 81 from US 81 - SH 33 junction. Portland cement concrete with improved shoulders on level upland terrain. Site in west lane of divided highway, marker on west fence row.

Site No. 36

In Caddo Co. west of Hydro, 0.3 mile west on I 40 from OSHD maintenance yard on south side of highway. Asphaltic concrete pavement with improved shoulders in rolling upland terrain. Site in south lane of divided highway, marker on south fence row.

Site No. 37

In Caddo Co. north of Hinton, 0.9 mile east on I 40 from I 40 - US 281 junction. Asphaltic concrete pavement with improved shoulders on hilly terrain. Site in south lane of divided highway, marker on south fence row.

Site No. 38

In Canadian Co. west of El Reno, 1.1 miles west on I 40 from I 40-US 66 junction. Asphaltic concrete pavement with improved shoulders on gently rolling terrain. Site in north lane, marker on north fence row.

Site No. 39

In Canadian Co. west of Bethany, 1.5 miles west on US 66 - US 270 from bridge over North Canadian River on west Bethany city limit. Portland cement concrete pavement in creek-bottom area. Site in south lane of divided highway, marker on south chain-link fence row.

Site No. 40

In Pottawatomie Co. southwest of Shawnee, 50 yds north on US 270 (Gordon Cooper Expressway) from US 270 - Hardesty Road junction, 1.1 miles south on US 270 to US 270 - SH 18 junction, adjacent to "Shawnee --Next Three Exits" sign facing south. Portland cement concrete pavement with improved shoulders on level upland terrain. Site in east lane of divided highway, marker on east fence row.

Site No. 41

In Pottawatomie Co. north of Shawnee, 0.5 mile east on I 40 from I 40 - SH 18 junction (Shawnee exit). Asphaltic concrete pavement with improved shoulders on rolling upland terrain. Site in south lane of divided highway, marker on south fence row.

Site No. 42

In Seminole Co. north of Seminole, 0.75 miles east on I 40 from I 40 - SH 99 junction. Portland cement concrete pavement with improved shoulders on slight fill in creek-bottom area. Site in south lane of divided highway, marker on south fence row. (OSHD yard N.W. of exit).

Site No. 43

In Okfuskee Co. east of Okemah, 0.6 mile east on I 40 from SH 27 - I 40 junction. Asphaltic concrete pavement with improved shoulders on upland terrain. Site in south lane of divided highway, marker on south fence row. (OSHD yard S.W. of Okemah exit.)

Site No. 44

In Okmulgee Co. northeast of Henryetta, 0.8 mile north on US 75 from US 75 - US 62 junction. Portland cement concrete pavement with improved shoulders in a slight cut section in hilly terrain. Site in east lane, marker on east fence row.

Site No. 45

In Seminole Co. west of Wewoka, 200 yds west of US 270 of US 270 - US 270(City) wye, 30 yds east of creek. Portland cement concrete with improved shoulders on fill in creek-bottom area. Marker on north fence row.

Site No. 46

In Pottawatomie Co. west of Seminole, 0.7 mile west on US 270 from US 270 - SH 9A junction (east) and 0.7 mile east on US 270 from US 270 - SH 9A junction (west). Portland cement concrete pavement with open shoulders in creek-bottom area. Marker on south fence row just east of creek.

Site No. 47

In Pottawatomie Co. southeast of Tecumseh, 4.7 miles south on US 177 from the junction of US 270 - US 177. Site located 50 yards from south end of asphaltic asbestos concrete test section with improved shoulders. Marker on south fence row just east of creek.

Site No. 48

In Logan Co. southwest of Guthrie, 1.4 miles south in I 35 from I 35 - SH 33 junction. Portland cement concrete pavement with improved shoulders on slight fill in creek-bottom area. Site in east lane of divided highway, marker on east fence row.

Site No. 49

In Payne Co. west of Yale, 0.5 mile east on SH 51 from SH 51 - SH 18 junction. Asphaltic concrete pavement with improved shoulders in slight cut section. Marker on south fence row.

Site No. 50

In Payne Co. west of Yale, 0.5 mile east on SH 51 from SH 51 - SH 18. 50 feet east of SMV Site No. 49. Portland cement concrete pavement with improved shoulders in a slight cut section. Marker on south fence row.

Site No. 51

In Canadian Co. southwest of El Reno, 0.9 mile west on I 40 from I 40 - Country Club Road junction. Portland cement concrete pavement with improved shoulders on slight cut. Site in north lane of divided highway, marker on north fence row.

Site No. 52

In Canadian Co. southwest of El Reno, 0.9 mile west on I 40 from I 40 - Country Club Road junction. 100 feet west of SMV Site No. 51. Portland cement concrete pavement with improved shoulders on slight cut. Site in north lane of divided highway, marker on north fence row.

TABLE A.1

Instrumentation, Reading Levels, and Depths for SMV Sites

Site No.	Tube Length (ft)		
	Hole		
	A	B	C
1(T)	10.0	10.0	10.0
2(B)	10.0	9.5	10.0
2	D 9.7	E10.0	F10.0
3	10.0	10.0	10.0
4	8.5	10.0	6.5
5	4.8	4.8	4.2
6	9.9	10.0	10.0
7	9.5	9.5	10.0
8	8.1	10.0	6.5
9	10.0	10.0	10.0
10	10.0	10.0	10.0
11	9.9	10.0	10.0
12(T)	9.9	9.9	10.0
13	9.8	9.0	10.0
15	9.7	10.0	10.0
16	5.8	7.2	6.7
17	9.7	10.0	10.0
19	10.0	10.0	9.8
20	10.0	9.9	10.0
21(T)	10.0	9.5	10.0
22	10.0	9.6	10.0
23	9.1	9.9	10.0
24	9.4	10.0	10.0
26(TB)	9.5	9.9	10.0
26	D10.0	E10.0	
27(T)	7.3	9.5	9.7
29(TB)	9.6	9.6	9.9
29	D10.0	E10.0	
30	10.0	10.0	10.0
31	10.0	10.0	10.0
32	10.0	9.6	10.0
33(B)	9.9	9.9	10.0
33	D10.0	E10.0	
34	10.0	10.0	9.8
35	10.0	10.0	9.8
36	10.0	9.8	9.9
37	10.0	9.4	9.9
38	9.6	9.4	9.5
39	9.9	10.0	10.0
40	9.9	10.0	9.9
41	9.9	9.9	9.4
42	9.9	9.9	9.9
43	10.0	10.0	9.9
44	9.7	9.7	9.9
45	9.9	10.0	10.0
46	9.9	9.9	9.9
47	9.8	9.9	9.6
48	10.0	10.0	10.0
49(B)	10.0	9.8	9.8
49	D10.0	E10.0	
50(B)	10.0	10.0	10.0
50	D10.0	E10.0	
51(B)	10.0	10.0	10.0
51	D10.0	E10.0	
52(B)	10.0	10.0	10.0
52	D10.0	E10.0	

If the tube is an exact foot in length (±0.25' or ±3") pull probe up 6" for first level, then continue up in one foot increments.

If the tube is an exact half foot in length (±0.25' or ±3") then pull probe up in one foot increments.

(T) - Designates temperature probe.
(B) - Designates bench marks.
(TB)- Designates temperature probe and bench marks.

APPENDIX B

CODING CRITERIA AND SORTING SCHEMES

DATA CODING SYSTEM

I. Type of Pavement

    1. Portland cement concrete
    2. Asphaltic concrete
    3. Asphaltic concrete overlay on Portland cement concrete

II. Type of Shoulders

    1. Improved
    2. Open

III. Base Material

    1. Stabilized aggregate base course
    2. Sand base course
    3. Sand asphalt base course

IV. Typical Cross-section

    1. Out
    2. Fill
    3. Grade
    4. Transition

V. Unified Subgrade Soil Classification

    1. CL - clay, low plasticity
    2. CH - clay, high plasticity
    3. SF - sand with some fines
    4. ML - inorganic silts, low plasticity
    5. SP - sand, poorly graded, fairly clean

VI. AASHO Subgrade Soil Classification

1. A-1
2. A-2
3. A-3
4. A-4
5. A-5
6. A-6
7. A-7

VII. Pavement Rating: 1967, 1968, and 1969

1. Superior
2. Excellent
3. Good
4. Fair
5. Poor

VIII. Shoulder Rating: 1967, 1968, 1969

1. Superior
2. Excellent
3. Good
4. Fair
5. Poor

IX. Drainage

1. Good
2. Fair
3. Poor

X. Time Lag Between Maximum Rainfall Occurrence and Maximum Moisture Occurrence (no. of four-week periods)

   A. Hole A; 1966, 1967, 1968

   B. Hole B; 1966, 1967, 1968

   C. Hole C; 1966, 1967, 1968

XI. Plastic Limit

   1. Below 10%

   2. 10% to 20%

   3. Above 20%

XII. Liquid Limit

   1. Below 20%

   2. 20% to 30%

   3. 30% to 40%

   4. Above 40%

XIII. Average Daily Traffic: 1967, 1968

   1. Over 8000

   2. 5000-8000

   3. 3000-5000

   4. 1000-3000

   5. Less than 1000

XIV. Construction Date

   1. 1930-1939

   2. 1940-1949

   3. 1950-1959

   4. 1960 to present

XV. Year of Maximum Rainfall, Spring 1967 to Spring 1968

0. No

1. Yes

XVI. Moisture Variations Abruptly Change Order of Magnitude

0. No

1. Yes

XVII. Heavy Precipitation, Winter 1967-1968 (more than 2 inches per month)

0. No

1. Yes

TABLE B.1

Input Data for Each Research Site

Site Number	Pavement Type	Shoulder Type	Base Type	Highway Cross-section	Unified Soil Classification	AASHO Soil Classification	Pavement Rating			Shoulder Rating			Drainage	TIME LAG Between Maximum Rainfall Occurrence and Maximum Sub-grade Moisture Occurrence									Plastic Limit	Liquid Limit	Average Daily Traffic		Construction Date
														A			B			C							
							67	68	69	67	68	69		66	67	68	66	67	68	66	67	68			67	68	
1	1	2	2	3	4	4	2	2	2	5	5	5	2	0	1	2	1	1	1	1	1	1	2	3	4	4	1
2	3	1	2	4	3	3	3	3	3	1	2	2	1	1	3	7	5	5	1	5	3	8	3	4	3	2	3
3	2	1	1	3	2	4	1	2	2	1	1	2	1	8	0	1	8	0	1	1	1	1	2	2	2	2	4
4	3	2	2	3	1	6	5	2	3	5	5	5	2	2	3	3	0	3	3	0	3	3	2	2	4	4	1
5	3	2	1	2	1	6	5	5	3	5	5	4	1	2	0	0	2	0	0	2	0	0	2	2	4	4	4
6	1	2	2	2	1	6	3	3	2	5	5	5	2	2	2	6	2	2	1	2	2	1	2	2	3	2	1
7	3	1	1	1	1	6	3	3	3	2	1	3	1	4	2	0	3	3	1	3	2	1	1	1	2	3	4
8	3	1	1	3	1	7	5	5	1	3	3	1	1	2	3	3	0	3	3	1	3	2	1	1	2	2	4
9	1	1	2	1	2	7	1	1	1	2	2	5	1	0	3	0	0	4	2	3	3	0	2	1	1	2	3
10	2	1	2	1	1	6	2	3	1	3	2	1	1	0	4	1	0	2	1	0	7	1	2	3	2	2	4
11	2	1	2	3	5	3	2	2	2	2	2	2	2	0	3	1	0	3	2	0	3	1	3	4	2	2	3
12	2	1	2	3	1	6	1	1	1	1	1	2	2	2	3	3	0	3	2	4	3	3	2	2	3	3	4
13	3	2	2	2	5	3	3	3	3	5	5	5	2	3	1	1	2	2	1	2	1	1	3	4	4	4	3
15	1	1	2	1	3	4	2	2	2	1	1	1	1	0	2	1	0	2	1	3	2	1	2	3	3	2	3
16	2	1	1	2	1	6	2	2	2	2	2	3	1	3	2	1	3	0	1	3	2	1	1	2	5	5	2
17	2	2	1	3	1	6	4	3	3	3	3	2	2	2	2	1	2	1	1	2	1	2	2	1	1	3	1
19	3	1	2	3	1	4	3	2	2	1	1	1	1	0	3	3	0	3	3	0	3	3	1	3	2	2	4
20	2	1	2	1	1	6	1	1	1	1	1	1	1	1	3	3	4	5	5	1	3	3	2	2	1	1	4
21	1	1	2	3	1	6	1	2	1	2	2	2	1	2	2	1	3	2	3	3	2	1	2	2	4	3	3
22	2	1	1	3	5	3	2	2	1	1	1	2	2	2	1	1	0	0	3	2	0	2	3	4	3	2	3
23	1	1	1	3	1	7	2	2	2	2	3	3	1	0	2	2	0	3	2	2	0	2	1	1	4	4	4
24	1	1	2	3	1	7	2	2	2	3	3	3	1	1	2	1	0	2	2	1	1	2	1	2	1	1	3
26	1	1	2	4	5	6	1	1	1	1	2	2	1	2	1	2	0	2	2	2	2	2	2	2	4	3	4
27	1	1	1	1	2	7	2	2	3	2	2	2	1	0	2	1	3	3	1	3	2	2	1	1	2	2	4
29	1	1	2	2	1	6	1	2	2	2	2	2	1	2	2	2	3	3	3	1	2	2	1	2	3	3	4
30	1	1	2	2	3	4	1	1	1	2	2	3	1	2	2	1	3	3	4	2	1	1	3	4	4	4	4
31	1	1	2	3	5	1	1	1	1	2	2	1	1		3	2		0	3		1	3	3	4	2	2	4
32	1	1	2	1	1	7	3	2	2	2	1	2	1		1	1		0	1		0	1	1	1	2	2	4
33	2	1	1	1	1	7	1	2	1	1	1	2	1		2	1		2	1		2	2	2	1	2	2	4
34	1	1	2	1	1	4	1	1	1	2	2	2	1		1	1		2	2		0	1	1	2	4	4	4
35	1	1	2	3	4	6	2	2	2	2	1	1	1		2	0		3	3		0	0	1	2	3	3	3
36	2	1	1	2	5	1	1	1	1	1	1	2	1		0	1		0	1		2	1	3	4	2	2	3
37	2	1	2	1	1	4	1	1	1	1	2	1	1		2	2		2	3		2	2	3	3	2	2	4
38	2	1	1	3	1	4	1	1	1	1	1	2	1		2	2		2	2		2	2	1	2	1	1	4
39	1	1	2	3	1	6	1	1	1	2	3	3	2		2	1		2	2		2	2	1	3	1	1	3
40	1	1	2	3	1	6	1	1	1	3	3	2	2		2	1		2	2		2	2	1	2	2	2	4
41	2	1	2	2	1	7	2	1	2	2	2	2	1		0	1		2	1		2	1	1	1	2	2	4
42	1	1	3	2	1	7	1	1	1	3	3	3	1		2	2		2	2		2	2	1	1	2	2	4
43	2	1	3	2	1	6	1	1	1	1	1	2	1		0	1		2	1		1	1	3	2	2	2	4
44	1	1	3	2	2	7	1	1	1	1	1	3	1		2	1		1	0		1	0	1	1	2	2	4
45	1	1	2	2	1	6	1	2	1	3	4	4	1		1	1		1	1		1	1	1	2	3	3	3
46	1	2	2	3	1	6	3	3	2	5	5	5	2		1	1		1	1		1	1	1	2	3	3	3
47	2	1	3	4	5	1	1	1	1	1	1	1	1		2	2		2	2		2	2	3	4	4	4	4
48	1	1	2	2	5	1	1	1	1	1	1	2	1		2	2		2	1		2	1	3	4	2	1	4
49	2	1	2	1	5	1	1	1	1	1	1	1	1		0	3		0	0		0	3	3	4	4	4	4
50	2	1	3	1	2	7	1	1	1	1	1	2	1		3	3		1	1		0	1	1	1	4	4	4

VITA

Larry Keith Shaw

Candidate for the Degree of

Master of Science

Thesis: FACTORS RELATING TO SUBGRADE MOISTURE VARIATIONS BENEATH OKLAHOMA HIGHWAYS

Major Field: Civil Engineering

Biographical:

Personal Data: Born in Altus, Jackson County, Oklahoma, March 2, 1944, the son of E. W. and Juanita Shaw.

Education: Attended elementary school in Altus, Oklahoma; graduated from Altus High School, Altus, Oklahoma, on May 25, 1962; received an Associate of Arts Degree from Altus Junior College on May 21, 1965; received a Bachelor of Science Degree in Civil Engineering from Oklahoma State University of Applied Sciences and Agriculture on May 28, 1969; completed requirements for the Master of Science Degree in Civil Engineering in May, 1970.

Professional Experience: Employed as an Instrument man on survey party for Russ-Mitchell Construction Co., during the summer of 1962; Party Chief on survey party for Western Contracting Corp. during the summer and fall of 1963; Research Assistant, Subgrade Moisture Variations Research Project, Oklahoma State University, Stillwater, Oklahoma, 1966-1970.