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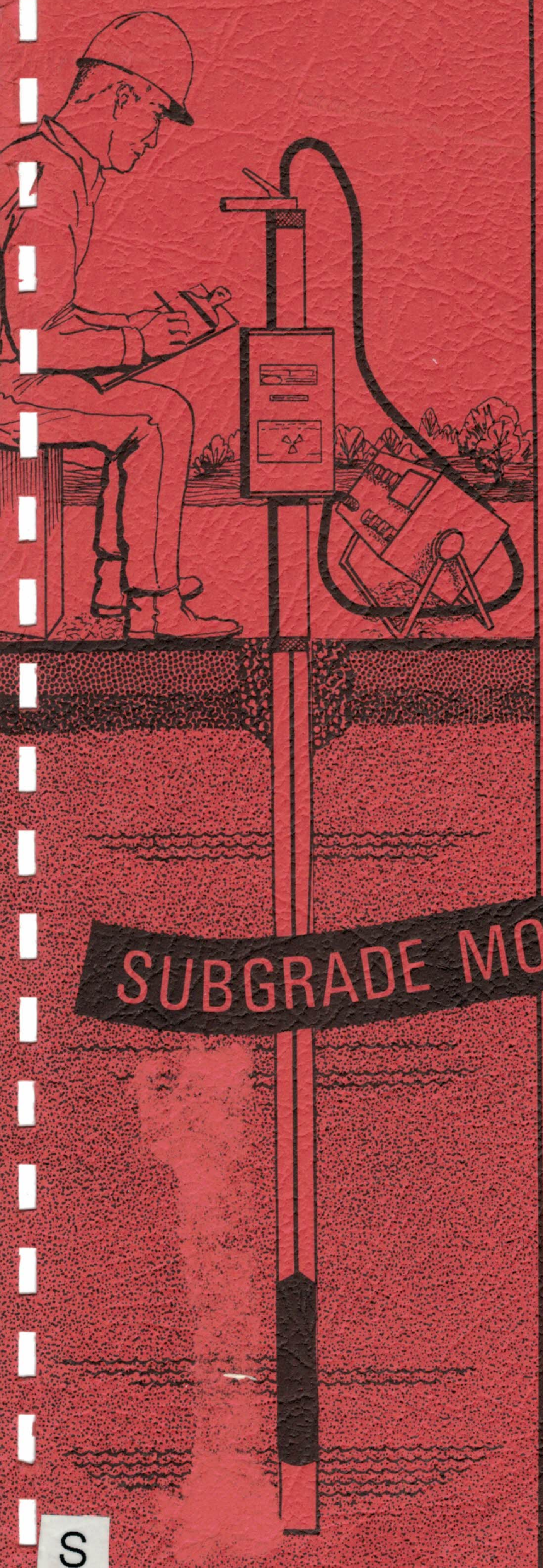

SUBGRADE MOISTURE VARIATIONS

FINAL REPORT

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By

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Project Director

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conducted for the

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Federal Highway Administration

by the

School of Civil Engineering
Office of Engineering Research
Oklahoma State University
Stillwater, Oklahoma

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PREFACE

As is obvious from the title page, this study was concerned with the effects of subgrade moisture conditions on Oklahoma highway performance. The final objective of the study was to develop design recommendations for improving Oklahoma highway performance. Before they could be made it was necessary to determine relations between subgrade moisture behavior and soil, climate, and pavement conditions. To accomplish this, it was necessary to develop instrumentation and procedures for collecting various data, some from beneath existing highway pavements.

Final results, conclusions, and recommendations of the study are contained herein. Documentation of findings, case histories, and collected data have been presented in previous interim reports. Those who expect radically new information concerning subgrade moisture behavior will be disappointed. The majority of collected data has confirmed ideas previously advanced and conclusions previously reached on a common sense basis. However, several suppositions concerning subgrade moisture behavior may be considered more nearly factual because of the study. Design and construction recommendations are also not particularly startling, though their implementation should result in definite improvement of pavement performance on expansive subgrades.

This is the final report submitted by the Subgrade Moisture Variations Research Project, Oklahoma Research Program Number 64-01-3. The author would like to acknowledge valuable contributions by Wayne L.

Heiliger, Raymond K. Moore, B. Dan Marks, III, Ronald D. Osterhout, Larry K. Shaw, and Donald R. Snethen. Without their excellent assistance the research would have been extremely difficult, if not impossible. Efficient traffic control services provided by Oklahoma Department of Highways maintenance forces should also be recognized, as well as the excellent cooperation received from the Research and Development Division, Oklahoma Department of Highways.

Support for this study was provided by the State of Oklahoma, Department of Highways, in cooperation with the U.S. Department of Transportation, Federal Highway Administration. This support is gratefully acknowledged.

T. A. H.

LIST OF REPORTS

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

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

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

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

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

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

Interim Report VII: "Subgrade Temperature Measurement," by Ronald D. Osterhout and T. Allan Haliburton, June, 1969, describes instrumentation and methods for subgrade temperature measurement, as well as results obtained from the measurements.

Interim Report VIII: "Evaluation of Collected Data 1966-1969," by Larry K. Shaw and T. Allan Haliburton, February, 1970, presents an evaluation of data collected at all 52 field test sites during the period 1966-1969, with emphasis on reasons for moisture behavior.

Interim Report IX: "Effectiveness of Existing Highway Designs," by Donald R. Snethen and T. Allan Haliburton, May, 1970, evaluates highway designs at existing test site locations with respect to their effectiveness in resisting effects of subgrade moisture changes.

Interim Report X: "Summary of Collected Data," by T. Allan Haliburton, August, 1970, presents all data collected at the 52 field test sites installed during the conduct of research. Because of its size, this report was published in limited quantity.

LIST OF FIGURES

ABSTRACT

This report presents the findings of a six-year study to relate subgrade moisture variations to soil, climate, and pavement conditions, and to suggest design recommendations for improving Oklahoma pavement performance. Only final conclusions and recommendations are presented, as documentation of findings, case histories, and collected data were presented in previous interim research reports.

After an analysis of research project effectiveness, general trends of Oklahoma subgrade moisture behavior are described, as are the effects of highway components on subgrade moisture behavior. Resistance of various highway components to subgrade moisture variations is also discussed, and specific recommendations for highway design and construction on expansive subgrades are made. Possible methods for implementation of research findings are also described.

Subgrade moisture contents were found to increase to an "equilibrium" value of approximately 1.1 to 1.3 times the subgrade plastic limit. Both seasonal and precipitation-dependent moisture variations were noted, and the primary criterion for maintaining stable moisture contents was found to be an impervious pavement system. Fill and transition sections did not usually perform as well as sections in cuts and on grade. The most apparent results of increased subgrade moisture contents and moisture variations were loss of subgrade support, excessive pavement deflections, and longitudinal cracking. Vertical subgrade heave was relatively insignificant, but lateral subgrade expansion, up to five inches in

magnitude, caused longitudinal pavement cracking, opened joints, and led to rapid pavement deterioration.

To minimize subgrade moisture conditions, the pavement design should include an impervious pavement, base, and/or subbase, continuous with eight-foot improved shoulders on each side of the pavement. Drainage conditions should be similiar for both sides of the highway.

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correct procedures for access tube installation and equipment calibration are followed. The educational and ability level of data collection personnel should be as high as practicable and they should definitely be aware of equipment operating characteristics and possible sources of equipment malfunction. The ability to recognize erroneous results was one of the most important factors leading to successful nuclear data collection.

Evaluation of Other Collected Data

The use of precipitation and air temperature data obtained from U.S. Weather Bureau Climatological Reporting Stations within ten miles of field test sites was found to provide adequate information for determining long-term trends, despite obvious local variations occurring at the sites. For studies where short-term effects are needed, or more precise correlations desired, precipitation and temperature records should be taken at the site itself, unless the cost of same appears prohibitive. For studies of at least twelve months duration, the use of available records from close-by sources appears reasonable.

Soils data at each site were obtained by augering during access tube installation and only routine tests were run on the material (Ref 2). The tests were adequate to classify the material for engineering purposes, but no testing on in-situ soils was done, primarily because of time limitations and available funds. Most troublesome cohesive Oklahoma soils have similar geologic and stress histories, thus the problem was not as great as it might have been. However, better relationships between subgrade moisture changes and pavement cracking, heave, and settlement would possibly have been obtained had swelling tests been run on "undisturbed" subgrade soils, and better data concerning apparent loss of subgrade support at several research sites would have been developed if strength tests had been run on "undisturbed" subgrade soil samples. It is definitely recommended that future studies concerned with subgrade moisture behavior include provisions for a more detailed soil exploration and testing program than was conducted by this project.

Data concerning typical highway cross-section, construction and maintenance history, traffic counts, and periodic performance ratings of pavement and shoulders at each site were furnished by the Research and Development Division, Oklahoma Department of Highways. Except in rare instances, no reasons were found to doubt the reliability of these data, and their use produced rational correlations. Greatest discrepancies were found between the indicated highway design (from construction blueprints) and the actual pavement system encountered during access tube installation. In most cases of discrepancy, base material had been destroyed or dispersed by subgrade intrusion or else design pavement thicknesses were not achieved.

With respect to future subgrade moisture research, detailed traffic counts appear to be of little use. Classification of traffic as either light, medium, or heavy appears sufficient for correlation of data. Small variations in pavement performance ratings also appear insignificant, and general classes of behavior such as excellent, good, etc., appear adequate for correlation purposes.

Written observations of site behavior by data collection personnel were found to be extremely useful in obtaining correlations between moisture changes and pavement performance. Of equal if not greater importance was the personal knowledge of each individual site obtained by periodic visitations for data collection and inspection purposes.

It is definitely recommended that, in research of this sort, supervisory personnel, particularly those concerned with evaluation of collected data, spend considerable time at the research sites, instead of merely looking at data in the office. Photographic records (at periodic intervals) were maintained for each research site, and photographs of any interesting phenomena were taken. These data also provided valuable information, particularly in determining long-term pavement performance trends, site drainage, etc. However, an inexpensive camera was used to obtain site photographs, and many pictures lacked clarity and were not suitable for either data correlation or report reproduction purposes. Future subgrade moisture research should include provision for periodic photographs with an excellent camera, as a detailed and reproducible photographic record of site behavior is both extremely useful in evaluation of obtained data and in presentation of data to interested parties. The time and expense involved in transporting photographers to various research sites to obtain pictures for report purposes would have paid for several excellent cameras.

Evaluation of Other Instrumentation and Procedures

In addition to subgrade moisture data, subgrade temperatures and pavement heave and/or settlement were measured at several research sites, as indicated from initial evaluation of research data (Ref 6). Thermistor temperature probes were installed in the subgrade with the drilling unit used for access tube installation, and lead wires were run through a channel cut in the pavement to a box adjacent to the shoulder (Ref 3). The thermistor probes and readout equipment worked quite well, but considerable difficulty was involved in maintaining a watertight box adjacent to the highway. Also, heavy truck traffic tended to crack the pea gravel concrete used to backfill the lead wire channel, thus perhaps cold mix patching should be considered for subsequent operations of this type. Useful data were obtained from the subgrade temperature measurements, and some sort of subgrade temperature measuring equipment is recommended for concurrent installation with moisture and density measuring equipment at any site where subgrade moisture conditions are to be measured.

Subsurface bench marks of capped 3/4 inch black iron pipe were installed inside open-ended nuclear probe access tubes at several sites (Ref 7). Pavement heave and/or settlement was determined by periodically measuring the distance between pavement surface and the top of the bench mark. No reasons were found to doubt reliability of bench mark data, and rational correlations between moisture conditions and measured pavement heave and/or settlement were obtained. Future subgrade moisture studies should definitely provide for some sort of subsurface bench marks, as data are obtained with a minimum of time and effort.

Evaluation of Data Collection Procedures

Subgrade moisture data was collected periodically on a six to eight week interval. This interval was a compromise between available funds and desire to obtain a maximum of useful information. The collection interval appears useful for prediction of long-term or even seasonal trends, but shorter collection intervals should be used if more detailed information is desired. The collection interval used appeared satisfactory for accomplishment of desired project objectives. Density data were collected at six-month intervals in winter and summer, as these

Effectiveness of Data Evaluation Techniques

As time and funds permitted, collected data were continuously evaluated, in an attempt to quickly locate erroneous information, evaluate the data collection process, and identify relevant trends at the earliest possible opportunity. Such a practice obviously increased the overall cost of research, but is credited with helping to obtain more reliable and useful data. It was found that an approximate 12 month period of data collection is required before significant trends can be observed or extrapolations made concerning future behavior. A comprehensive evaluation of this type was found to take approximately six months, as part-time research assistants were used in making the evaluation. It is therefore recommended that future subgrade moisture studies undertake periodic evaluations at approximate 18 month intervals, with the results of one evaluation used as the starting point for the next. In this manner, each evaluation should produce more detailed results, and an estimate of the time required to obtain satisfactory results may also be predicted. For this study, data collection was terminated as soon as it was obvious that additional data collection would not produce enough useful information to justify time and money involved. Such a decision was of necessity the result of continuous data evaluation during the life of the project.

Because of the volume and diversity of collected data, a mechanical sorting procedure was used to establish initial correlations (Refs 6, 7, 8). The technique produced a host of general correlations, which were then each investigated to determine if the correlation was factual or coincidental. This combination of mechanized correlation followed by application of engineering judgment appeared to produce a large number of rational correlations, and is thought to be an extremely efficient way to evaluate the volume of data involved. Again, personal knowledge of each research site and overall knowledge of the study by personnel making the evaluation were extremely helpful in obtaining rational correlations between relevant factors.

Summary

In this Chapter, the various procedures involved in conduct of research have been discussed from an effectiveness viewpoint. It is hoped that these observations will be of some use to other individuals and/or agencies contemplating similar subgrade moisture research.

CHAPTER 3. SUBGRADE MOISTURE BEHAVIOR IN OKLAHOMA

This Chapter presents research findings concerning subgrade moisture behavior under existing Oklahoma highways, i.e., the effect of soil, climate, and highway design on moisture behavior. Findings are presented in summary form, as detailed analyses and data from which conclusions were drawn are available elsewhere (Refs 3, 6, 7, 8, 10).

General Conditions Existing in Oklahoma

Several conditions existing in Oklahoma influence subgrade moisture behavior, and a review of these conditions is necessary to better understanding of results obtained by project research.

Climatological and Soil Conditions

As noted previously, all field research sites were located in the central and north central/northeastern part of the state. These areas are the most populus regions of the state, and thus where most highway mileage exists. Annual rainfall at the research sites varied between 10 and 40 inches, increasing from west to east. Monthly rainfall amounts are highly seasonal and more than 12 inches may fall during the spring in the eastern part of the state, with two inches or less during the winter at some western locations. Seasonal air temperatures range from an average monthly mean of over 80°F during July and August down to an average monthly mean of approximately 30°F in January and February. In many regions of the state, the water table is located close to the surface and exhibits seasonal movement, rising during winter months and falling during summer months. Higher rates of evaporation, evapotranspiration, and consumption during the summer are responsible for this behavior. From a climatological viewpoint, a period of drought in Oklahoma ended in 1965, just before installation of the first field research sites.

Clays and clay shales often utilized as subgrade material in this portion of the state may vary somewhat, but their origins and stress histories are similar. These soils are normally classified by the AASHO System as A-6 to A-7 and by the Unified System in the upper portion of the CL range or in the CH range. The majority of cohesive soils are preconsolidated (usually by dessication) and thus after remolding exhibit higher volume change potential than might be predicted from plasticity alone.

After reviewing the preliminary copies of this report, the FHWA requested that a definition of the term "expansive soils" be placed in the report. It is the author's opinion that this report will be of little use to anyone who does not already know how to recognize "expansive soils" when they are encountered. Nevertheless, as used in this report, expansive soils are defined as those which, when used as subgrade in their natural and/or compacted state, exhibit changes in volume and strength with changes in water content; these changes being of such magnitude that special design/construction techniques are required to maintain relatively constant soil moisture contents, thus minimizing volume and strength changes and insuring adequate highway performance. Considering the wide variation in specific test procedures, classification systems, and design methods currently used by highway-oriented agencies in the

U. S. and abroad, a more specific definition appears irrelevant.

Highway Construction Methods

Because of economic and/or political considerations, many older highways in Oklahoma were built by stage construction methods. Currently, all major highway construction in Oklahoma is conducted under a long-range planning and construction program, also resulting in stage construction. Contracts for grading and drainage structures are let and completed with a one to three-year delay before contracts are let for base and surfacing. Base and surfacing construction is usually begun during the warm spring and hot summer months. As a consequence, the subgrade may dry to a considerable depth before surfacing is applied.

In any case, because of erosion and unauthorized traffic, the top portion of the previously compacted subgrade is usually no longer suitable and is scarified and recompacted just prior to application of base and surfacing. The preconsolidated clays found in Oklahoma are extremely susceptible to moisture accumulation and resulting swelling when artifically compacted, particularly if compaction is dry of optimum. Most compaction of cohesive Oklahoma subgrades is performed dry of optimum, as the optimum compaction moisture content is usually only slightly less than the subgrade plastic limit, and in some cases is equal to this value. Even when diligent attempts are made to compact at higher moisture contents, the combination of high temperature, low humidity, and high wind speed prevalent during Oklahoma construction seasons tends to dry the soil as fast as the contractor can wet it.

Observed Trends in Subgrade Moisture Behavior

Data obtained from the study indicate two basic types of moisture behavior, subgrade moisture accumulation and subgrade moisture variation, exist in expansive Oklahoma subgrades. Combinations of these conditions were also noted to occur. Factors responsible for each type of behavior are discussed in the following sections.

Subgrade Moisture Accumulation

Subgrade moisture accumulation was found to occur in expansive Oklahoma subgrades at many research sites. Moisture contents under new and relatively new construction and older existing pavements with wide improved shoulders and excellent pavement ratings tended, after a short initial period at construction moisture contents, to increase without significant variation until an "equilibrium" moisture content of approximately 1.1 to 1.3 times the subgrade plastic limit was achieved. The word "equilibrium" is actually a misnomer, as, in most cases, after reaching the "equilibrium" point, variations in moisture content begin to occur around this value. The prime criterion for subgrade moisture accumulation without significant variation was found to be an impervious pavement system.

On the average, between 18 months and two years were required for moisture to accumulate from initial conditions (usually below optimum compaction moisture) up to the "equilibrium" value of 1.1 to 1.3 times the subgrade plastic limit. Effects of this moisture accumulation on subgrade volume change will be discussed later. For these impervious pavements, moisture accumulation is thought to occur primarily from capillary sources, i.e., prevention of evaporation, with some sites obtaining moisture by infiltration from outside paved shoulders. Subgrade temperature gradients were found to cause only small moisture changes.

Typical cases of observed moisture accumulation may be seen in Figs 3.1 and 3.2. Fig 3.1 shows rainfall and centerline moisture variations at Site No. 12, a two-lane AC pavement with improved shoulders over asphaltic black base and no subbase. The base is continuous under pavement and shoulders, and the section is located in a slight cut with only fair drainage and a water table close to the surface. In this case moisture content increased at all levels to an approximate "equilibrium" value and then remained roughly constant. This type of "uniform" moisture accumulation results from capillary sources.

It should be noted that, despite the increase in subgrade moisture content the pavement section remains in excellent condition. The moisture contents under the shoulders have increased in similar magnitude, but with more variation, as they are affected by the "fair" drainage conditions; and some shoulder movement and cracking was observed in late 1969. The impervious shoulder-to-shoulder base effectively stopped rapid variations under the centerline and allowed a relatively uniform vertical movement of the entire section; lateral subgrade expansion effects were minimized by the flexibility of the asphaltic base.

Figure 3.2 shows moisture accumulation typical of new construction accumulation from surface infiltration. Site 50 is a two-lane PCC pavement over sand-asphalt with sealed shoulders over soil cement. After an initial "stable" period moisture levels increased toward "equilibrium" conditions, starting at the upper levels and progressing downward. Moisture conditions under the soil-cement shoulder (Fig 3.3) showed more variation.

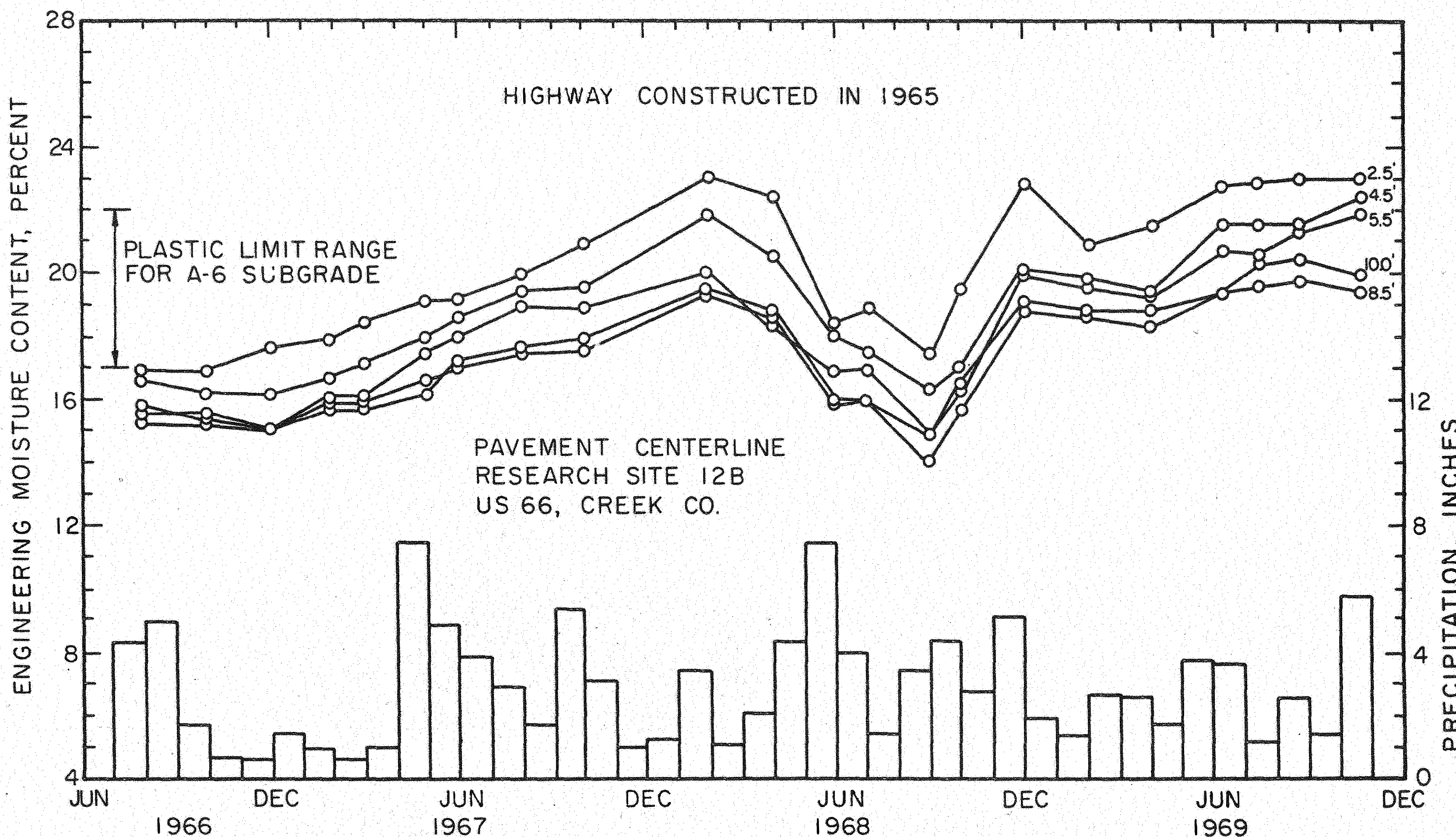


Figure 3.1 Moisture Variations at Selected Levels Beneath Pavement at Site No. 12

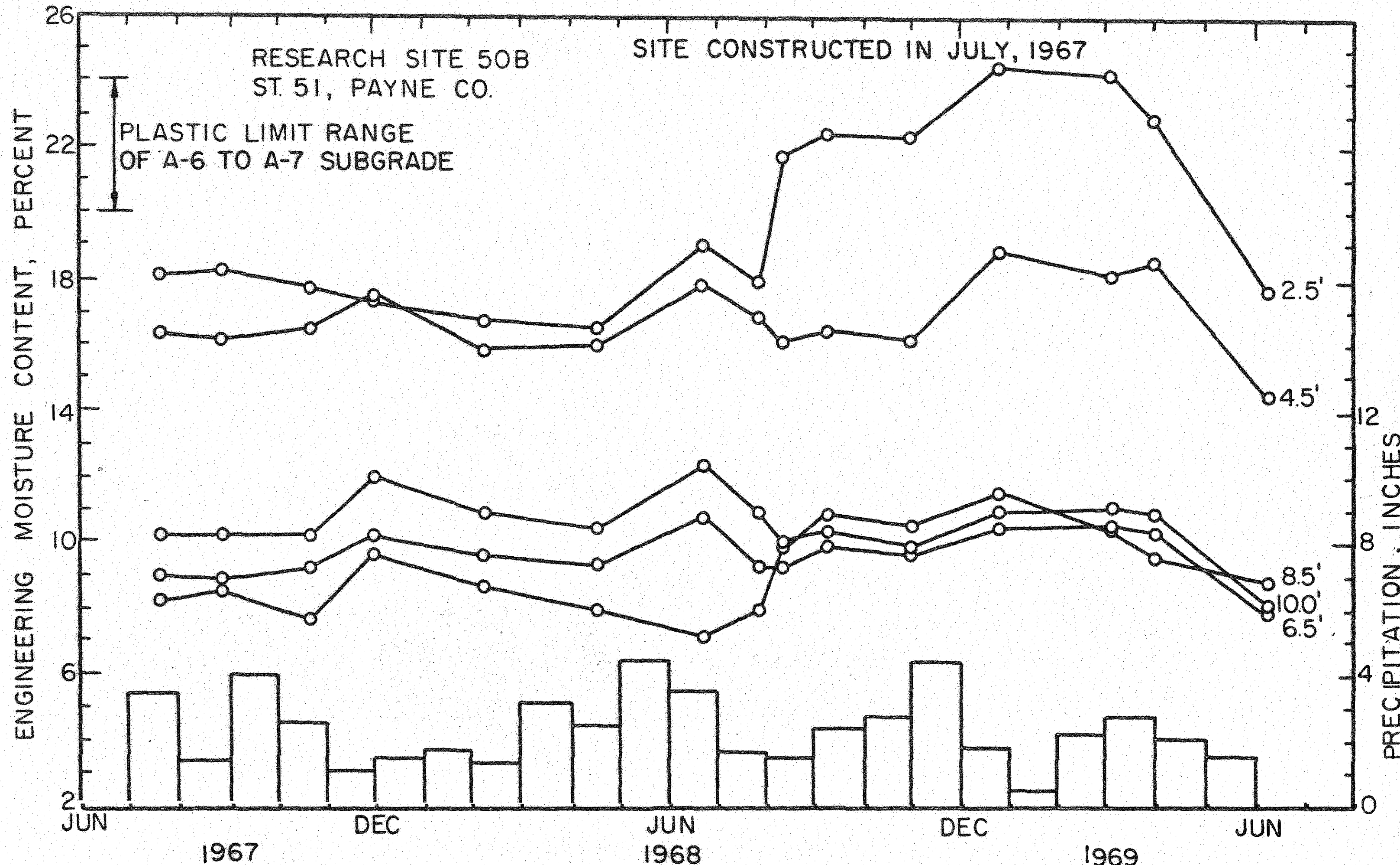


Figure 3.2 Moisture Variations at Selected Levels Beneath Pavement Centerline and Rainfall at Site No. 50

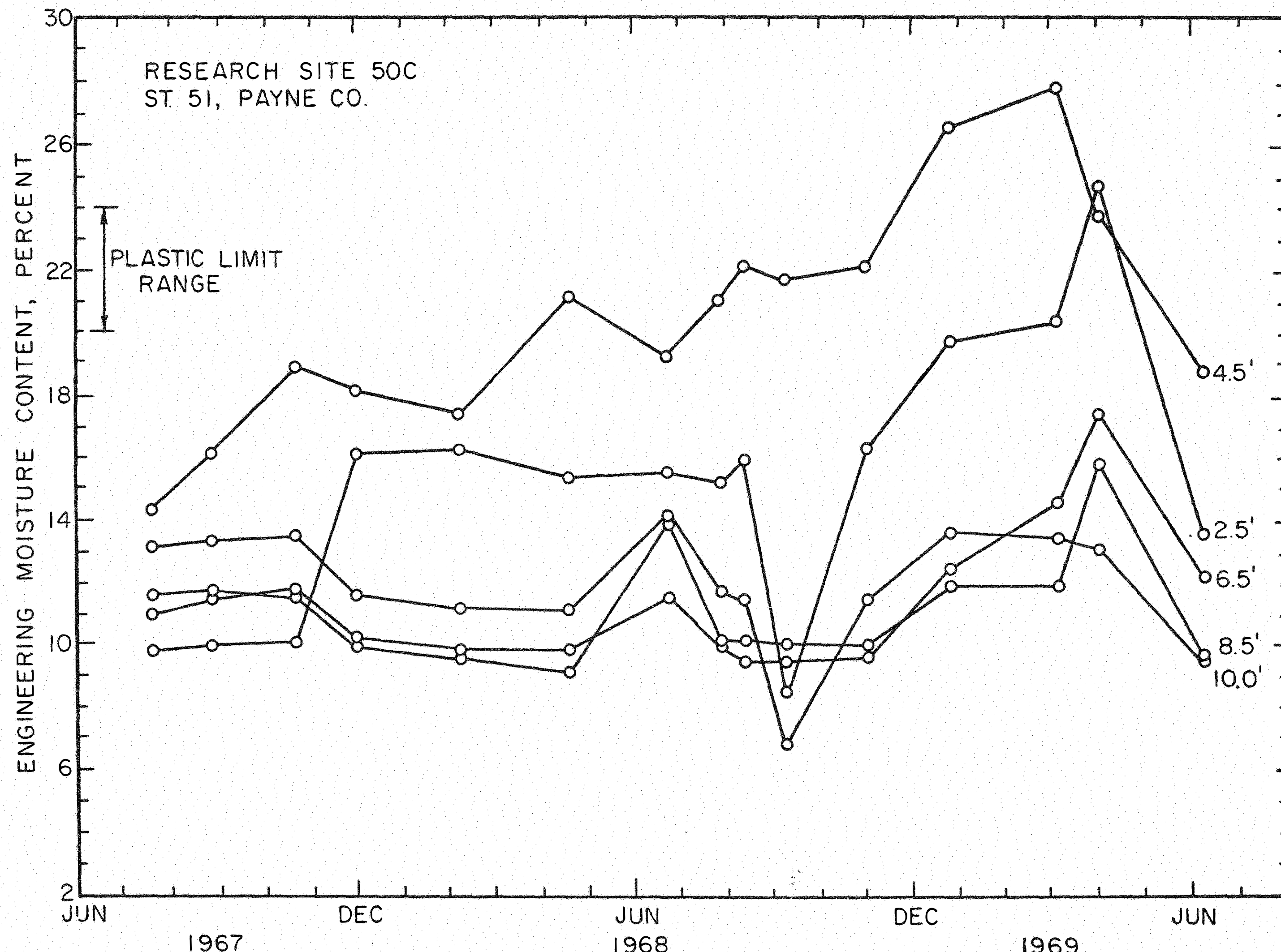


Figure 3.3. Moisture Variations at Selected Levels Beneath Shoulder at Site No. 50

Bench mark data at this site indicated small vertical movements during this period, as only the upper five to seven feet exhibited any noticeable moisture increase, but lateral subgrade expansion in the upper levels opened the center longitudinal pavement joint and hairline longitudinal cracks appeared in the rigid pavement. Extensive shoulder cracking and separation at the pavement/shoulder joint was also observed, less than two years after construction. A few miles further along this section a three-mile length of pavement on similar subgrade exhibited two-inch wide longitudinal cracking within a year after construction. The cracking produced by this moisture accumulation has rendered the pavement system pervious and future subgrade moisture variations may be expected to increase in frequency and magnitude.

Accumulation noted under older construction in excellent condition porbably resulted from the end of a drought cycle in 1965, just before the first research sites were installed. Increased availability of moisture from rainfall and rising water tables probably caused this behavior. At these older sites, moisture measurements made since 1967 have indicated a decline in moisture accumulation, compared with the initial rate, as subgrade moisture contents beneath these sections approached the plastic limit of the subgrade material.

At sites with less than excellent pavement ratings (usually indicative of pervious pavement or open joints), open shoulders, or fair to poor drainage, subgrade moisture variations were found to occur superimposed on the overall accumulation trend. The majority of these moisture variations were caused by rainfall infiltration/evaporation, usually from outside the shoulders or through the pavement surface, but they did not appear to halt the rate of moisture accumulation, which continued in most cases until subgrade moisture contents were above the plastic limit. After reaching this "equilibrium" value, moisture contents at the first two types of sites were subject to large variations. Initial accumulation behavior noted at these sites is thought to result from general drying of subgrade caused by the previously mentioned drought.

An example of both subgrade moisture accumulation and variation is shown in Fig 3.4. Site No. 21 is on half of a four-lane divided highway, constructed in 1959 of PCC pavement over sand cushion on A-6 subgrade and having improved shoulders over a mechanically stabilized aggregate base. Drainage is rated fair because of gently sloping shoulders and flat on-grade terrain. Pavement at the site has remained in excellent condition, even though some transverse and longitudinal pavement joints are open. Shoulder separation and settlement begin to occur in late 1969, as subgrade moisture contents passed the plastic limit.

Moisture conditions at this site consist of accumulation, caused by capillarity and occuring more or less uniformly at all levels, plus variations from infiltration into the sand base course. It should be noted that variations decrease in magnitude with depth, and that large moisture variations in the sand cushion (2.0 ft. level measurement) precede variations in the subgrade. A reasonable lag relationship between rainfall and moisture content variations in the sand cushion and later in the subgrade may also be observed.

Subgrade Moisture Variation

At most research sites where moisture accumulation was not in progress, moisture variations were found to occur either seasonally in annual cycles or to be precipitation/evaporation dependent. Seasonal moisture

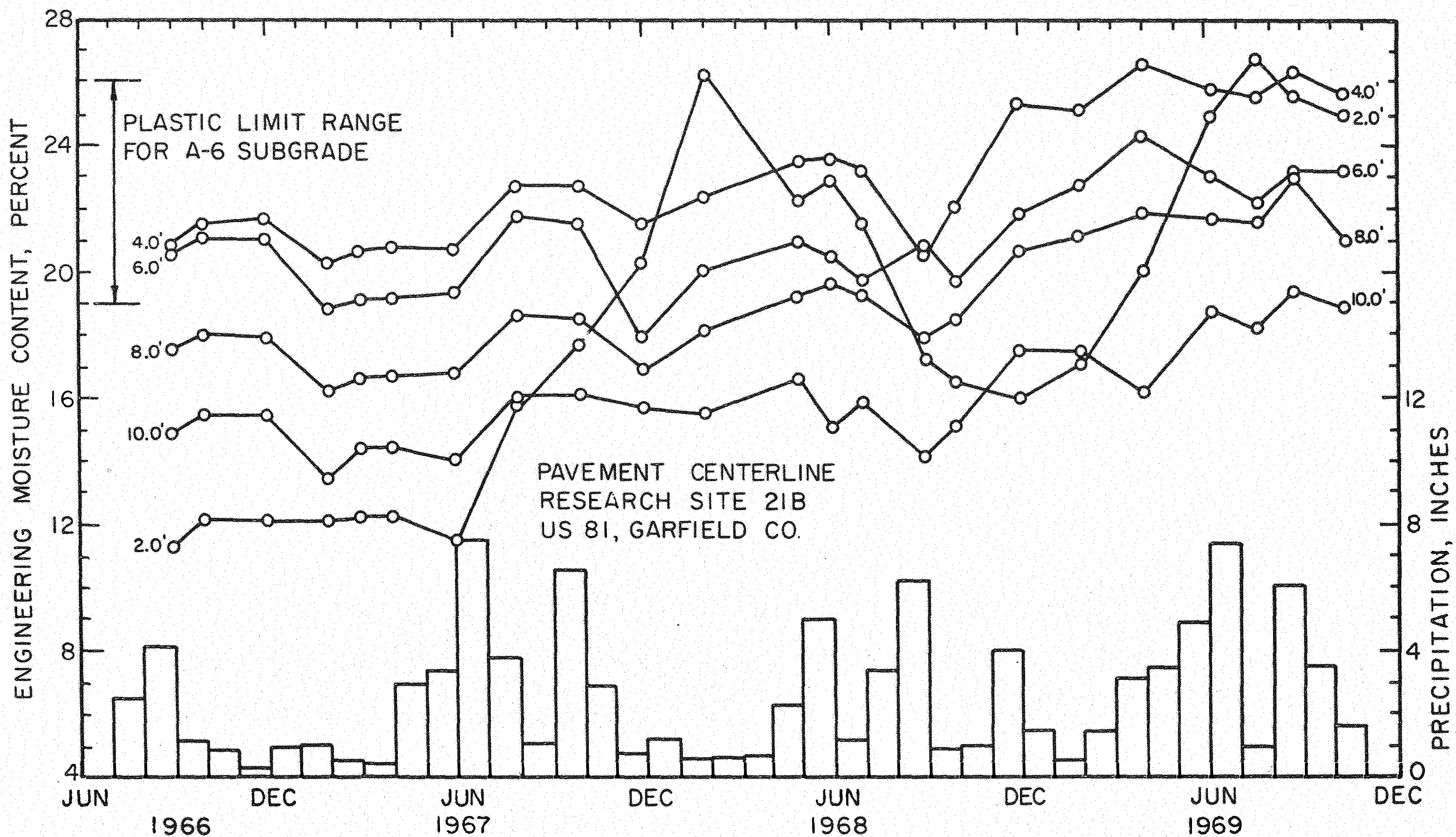


Figure 3.4 Moisture Variations at Selected Levels Beneath Pavement and Rainfall at Site No. 21

variations were found to occur in annual cycles with maximum moisture contents occurring during winter months. Most research sites where purely seasonal moisture variations occurred were on excellent rated and impervious pavement, and moisture variations had little relation to measured precipitation, particularly under pavement centerlines. Initially, it was thought that these variations were temperature-induced, but additional research (Ref 3) indicated that, while temperature-induced migration does occur in Oklahoma subgrades, it is of relatively low magnitude, causing only a one or two percent engineering moisture content variation annually. In almost all cases for sites where moisture variations were seasonal and could not be related to rainfall, the greater majority of moisture variation was found to be caused by seasonal water table movement, moving the zone of capillary rise, or else by delayed infiltration from areas adjacent to the pavement, caused by particular highway drainage conditions. Because of the diverse conditions existing at field test sites, the author is hesitant to estimate the average variation produced by seasonal changes, but most seasonal variations did not exceed five percent engineering moisture content, and many were half this value.

Seasonal trends were also noted to occur at sites located on pervious pavements, but cyclic variations were affected considerably by precipitation/evaporation, usually occurring through the pavement surface. Precipitation-dependent variations were also noted to occur at most sites with open shoulders, despite pavement condition. Many sites where precipitation/evaporation affected subgrade soil moisture were located on rigid pavement sections modified by asphaltic concrete overlay. At several sites where asphaltic concrete overlay was applied during the course of moisture measurement, the overlay reduced moisture variations for only a four to six month period, and in some cases, increased moisture variations resulted immediately after the overlay was applied.

For example, subgrade moisture variations at Site No. 4, shown in Fig 3.5, are typical of those caused by direct rainfall infiltration through the pavement. The two-lane pavement with open shoulders was originally PCC placed directly on the subgrade in 1930. It has received several AC overlays since that time. The site is in a creek-bottom area, and infiltration occurs both through cracks in the pavement and from outside the pavement edges. Evaporation occurs through cracks in the pavement.

Pavement at the site received AC overlay and was widened approximately 3 feet in 1967, as noted in Fig 3.5. This overlay was placed during a period of high (for Oklahoma) precipitation and sealed the pavement surface, minimizing subgrade moisture evaporation through cracks in the previous overlay. As a result, moisture contents in the upper subgrade increased greatly and the resulting vertical and lateral subgrade expansion plus loss of subgrade support caused severe cracking of the new AC overlay in a short period. Moisture loss through the new cracks soon occurred and the section subgrade was soon back on a precipitation/evaporation moisture cycle. In this case the AC overlay improved performance for less than a year. The proper use of asphaltic concrete overlays to reduce subgrade moisture variations is discussed in Chapter 5.

As a general rule, subgrade moisture variations generally lagged rainfall by a period of six to eight weeks, with longer times being required for variations to occur at deeper depths. Magnitude of variations was highly dependent upon overall pavement condition, whether or

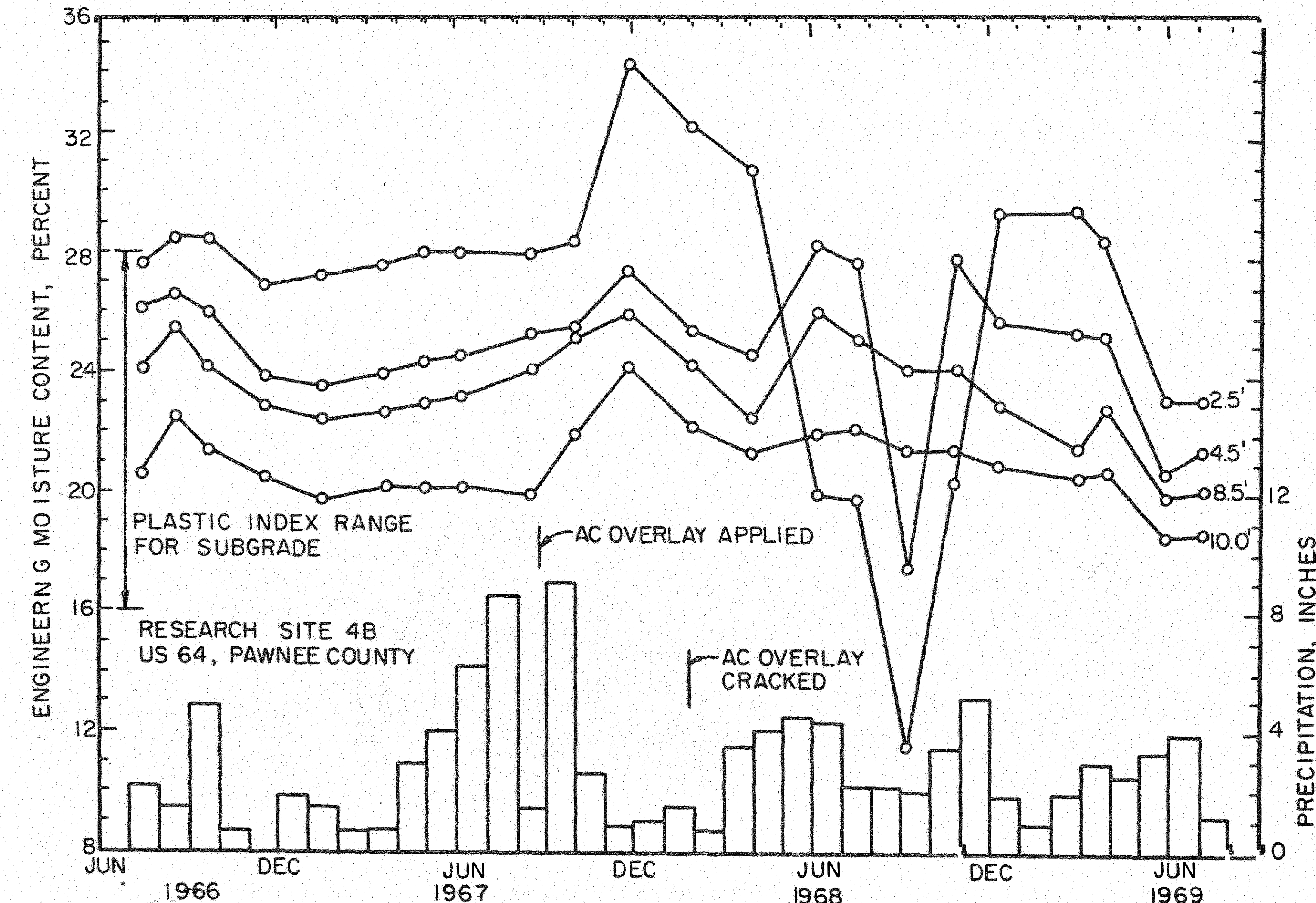


Figure 3.5 Moisture Variations at Selected Levels Beneath Pavement Centerline and Rainfall at Site No. 4

not sealed shoulders were present, and the type of base and subbase material used in the pavement section. Magnitude of precipitation/evaporation-caused variations was almost always higher than those produced by seasonal trends; and at some sites the variations exceeded 10 to 15 percent engineering moisture content over six month periods, with such behavior producing easily noticeable changes in pavement and shoulder condition. At several sites, rainfall infiltration produced moisture contents equal to or greater than the subgrade liquid limit, with resulting loss of subgrade support and rapid pavement deterioration. As mentioned previously, precipitation-dependent and/or seasonal moisture variations were also noted superimposed on a general accumulation trend, though this behavior was observed only in new constuction after 1967.

Effects of Subgrade Moisture Behavior on Soil Volume Change

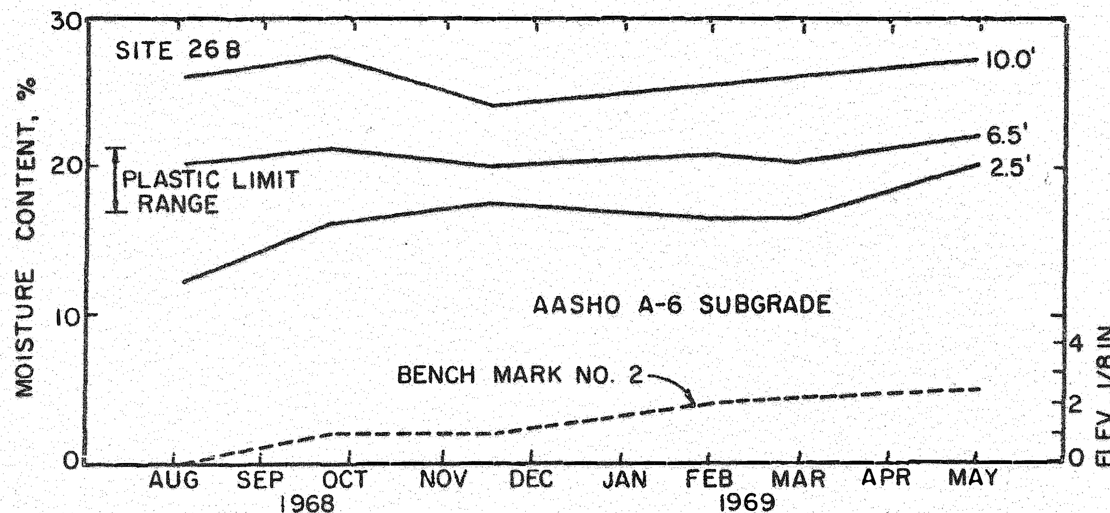
Oklahoma cohesive soils are particularly subject to volume change as moisture content varies. Volume change behavior was obtained from moisture measurements, subsurface bench marks installed at several research sites (Ref 7), and general observations of pavement behavior. At most research sites only the upper five to seven feet of the subgrade made any large contribution to subgrade volume change, with moisture contents below this level remaining relatively constant. Vertical movements were not extremely large, with an empirical relationship of one inch of pavement heave for a 10 to 12 percent increase in engineering moisture content developed from obtained data.

This correlation was extrapolated from smaller recorded measurements to moisture changes required to produce an inch of movement. Values were averages of data obtained at several sites on A-6 and A-7 subgrades.

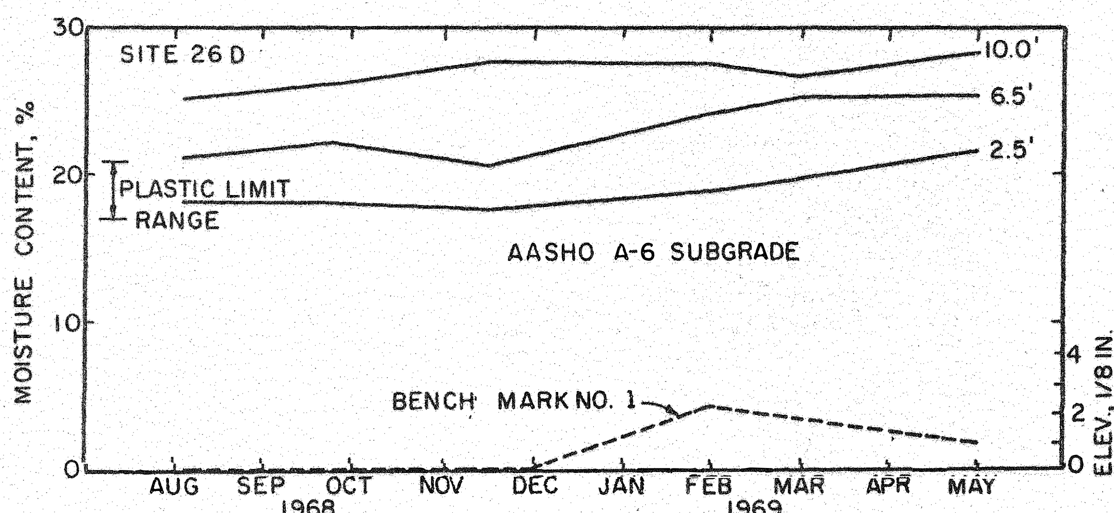
Moisture contents were in the vicinity of the subgrade plastic limit. Typical bench mark/subgrade moisture content data is shown in Fig 3.6 for the pavement centerline and shoulder at Site No. 26, a two-lane PCC pavement over sand cushion, having sealed shoulders with stabilized aggregate base. In the majority of cases, differential vertical movements were encountered; reasons for this behavior will be described later.

However, lateral subgrade expansion probably affects pavement performance to a larger extent than vertical swelling. Cohesive Oklahoma subgrades, compacted under normal conditions, have lower unit swelling potential in their lateral direction than exists vertically (Ref 11). However, appreciable vertical swelling was found to occur in a zone only five to seven feet in depth, with contribution to the swelling effort decreasing from the subgrade surface downward. On the other hand, lateral subgrade expansion takes place over a 24 to 40 foot width, and resulting movements were found to be of appreciable magnitude, in some cases exceeding three to five inches. Tensile stresses in the pavement system, produced by lateral subgrade expansion, caused initial longitudinal cracking of the pavement structure. This cracking was aggravated by flexural stresses from differential vertical heaving, even though the heaving was of rather low magnitude.

In addition to cracking the pavement structure, the combination of lateral and vertical swelling also opens pavement joints and joints between pavement and shoulders. The amount of pavement movement is usually not enough to greatly affect riding quality of the highway, but opens the way for infiltration/evaporation through the pavement surface. In many cases, cracks were found to extend through the pavement section,



(a) PAVEMENT CENTERLINE



(b) PAVEMENT EDGE

Figure 3.6 Moisture Variations at Selected Levels and Bench Mark Elevations at Site No. 26

base, and subbase, depositing precipitation directly in localized parts of the subgrade. In other instances, pervious base materials distributed the infiltrating water over the subgrade surface, causing a general moisture content increase. In any case, the resulting moisture variations become cyclic and precipitation-dependent, with both moisture variations and differential pavement movement tending to increase in magnitude, producing rapid pavement and shoulder deterioration and poor riding quality. At this point in time, the need for corrective measures is easily noted and maintenance is scheduled. Unfortunately, conditions have progressed to a point where remedial measures do not work effectively. As will be discussed later, for Oklahoma subgrades at least, preventative pavement maintenance should be undertaken before an obvious need for same exists.

Different vertical movement conditions were encountered under moderate and high fill sections. For these sections, moisture movement was downward and toward the outer edges of the fill, caused by shoulder drying, and resulted in shoulder settlements of up to several inches in magnitude during dry periods, with some rebound observed in succeeding wet periods, as may be seen in Fig 3.7.

Vertical swelling was also noted in soils which had no obtainable Atterberg limits, leading to the conclusion that all subgrade soils encountered in the study were expansive, even though classification systems sometimes indicated otherwise. These basically granular soils (AASHO A-3 and A-4) exhibited an empirical relationship of approximately one inch pavement heave for a 16 to 18 percent increase in engineering moisture content. Again, the criteria was extrapolated from relatively small actual measurements. Despite the author's belief that such soils

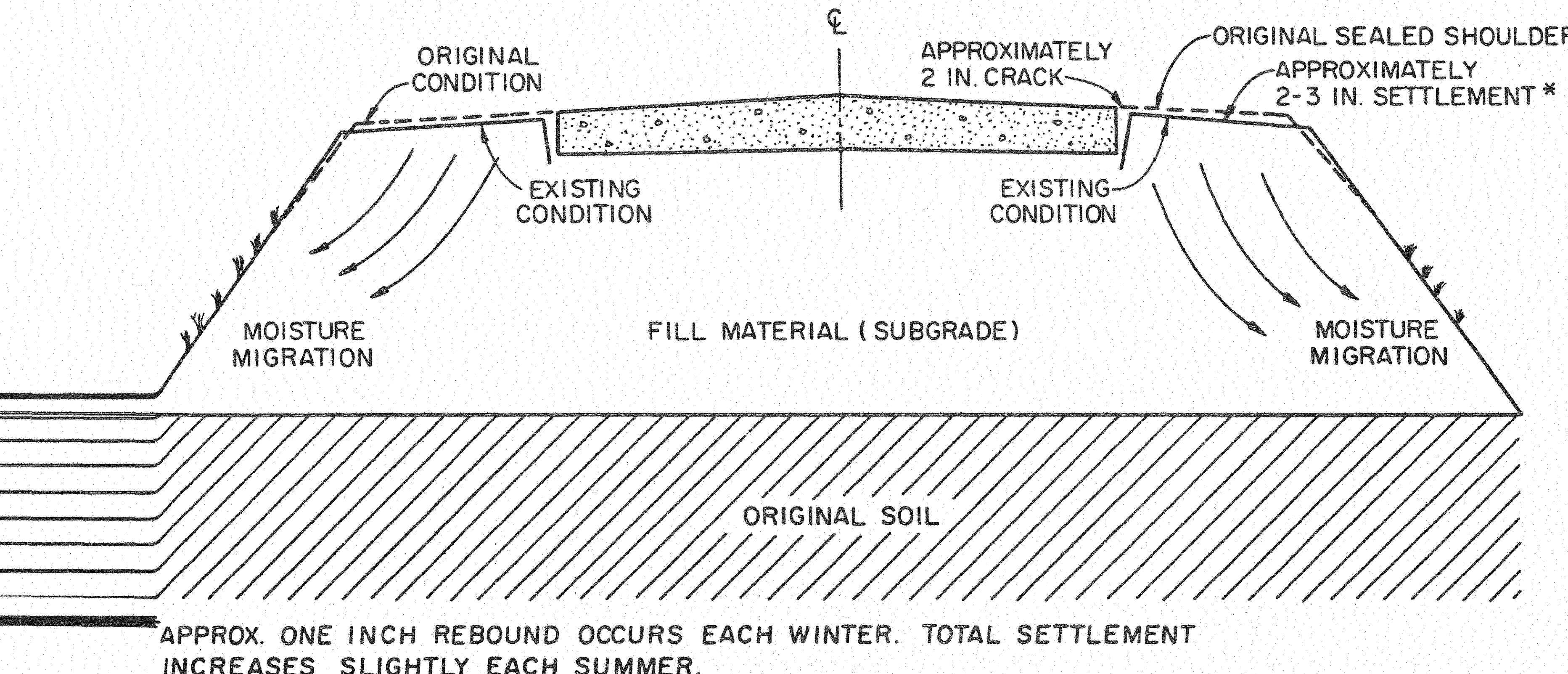


Figure 3.7 Shoulder Conditions Existing at Site No. 29

suffered shoulder settlements because of dryer subgrade moisture conditions under the shoulders. At one site, a relative vertical movement of more than one inch between pavement edge and shoulder edge was observed to occur seasonally over a three-year period (Fig 3.7).

Bench mark measurements at several sites confirmed the above behavior, as in grade and cut sections the pavement edges heaved more than the centerline, from greater magnitude of moisture content variation at the wet-dry interface, while the moisture contents under the centerline remained relatively constant. In fills and transition sections the greatest heave was observed at the pavement centerline with settlements often observed in the shoulders, usually associated with shoulder drying and decreasing moisture content.

Summary

Subgrade moisture behavior under Oklahoma highways was discussed in this Chapter. Subgrade moisture accumulation and variation were found to be the observed modes of behavior and relationships between these modes and highway conditions were discussed, as well as factors that affect and/or determine these modes of moisture behavior. The ability of various highway design components to resist or prevent adverse subgrade moisture behavior is discussed in Chapter 4.

CHAPTER 4. EFFECTIVENESS OF HIGHWAY COMPONENTS IN PREVENTING AND RESISTING SUBGRADE MOISTURE CHANGES

The previous Chapter has indicated effects of highway design on subgrade moisture conditions. However, the converse is certainly of more interest from a design viewpoint. To properly evaluate pavement performance, pavement components which resist or prevent adverse subgrade moisture conditions must be determined. Only then can recommendations for improved highway design be made.

This Chapter discusses various components of pavement systems currently used in Oklahoma highway construction and discusses their resistance to subgrade moisture variations. Additional descriptions of behavior, collected data, and case histories are given elsewhere (Refs 8, 10).

Type of Surfacing

Current Oklahoma highway design procedures involve the use of both flexible and rigid pavements. Flexible pavements are usually constructed of asphaltic materials, while rigid pavements are constructed of Portland cement concrete. The type of surfacing or surface course used was found to have little, if any, effect on observed subgrade moisture behavior. Of more importance was whether same was pervious or impervious. This conclusion should be obvious, as the wearing surface itself simply serves to keep moisture out of the subgrade or else let it infiltrate through cracks.

Rigid pavements were found to be more sensitive to cracking from vertical differential heaving and extremely sensitive to moisture infiltration through joints opened from thermal contraction and lateral subgrade expansion. These adverse tendencies were compounded by apparent minimal joint maintenance performed by the Oklahoma Department of Highways. However, rigid pavements were found to perform adequately for extended periods after initial cracking and resulting infiltration had begun, and maintain relatively good riding characteristics at higher subgrade moisture contents than were observed for flexible systems. The phenomena of pumping, widespread and severe cracking, subgrade shifting, and rapid deterioration did not usually occur until subgrade layers immediately under the pavement reached moisture contents considerably above the plastic limit and sometimes near the liquid limit. This behavior is obviously attributable to the ability of a rigid slab to bridge over local areas of low bearing capacity and to distribute surface loadings over a wide area.

Rigid pavements were encountered placed directly on the subgrade, with various types of materials between the rigid pavement and the subgrade, and with both base and subbase components (though current rigid pavement design criteria does not use these terms). The effect of these components on rigid pavement behavior will be discussed later.

Flexible pavements or pavement systems encountered during conduct of research either consisted of asphaltic concrete surfacing over some other type of base and/or subbase or else asphaltic concrete surfacing over some other type of asphaltic base or subbase. In general, better performance was obtained from multi-layer asphaltic systems, as opposed to asphalt over non-asphalt systems. Flexible pavements were found to be highly resistant to cracking from small differential vertical movements and lateral subgrade expansion, especially when more than one component of the system was composed of asphaltic materials. However, flexible pavements were extremely sensitive to failure by loss of subgrade support when the moisture content of the upper subgrade material approached and exceeded the plastic limit. Failure was characterized by rutting/channelization, followed by raveling and pavement cracking. Cracks usually extended into the subgrade material, and infiltration/evaporation of rainfall produced further deterioration and general cracking. This failure mode is obviously from flexible pavement sensitivity to small changes in local load carrying capacity of the subgrade, as it in itself has limited ability to distribute wheel loads or bridge over localized areas of reduced bearing capacity. Better observed performance of all-asphaltic systems probably results from a thicker layer of asphaltic material which must be cracked to allow infiltration/evaporation than from any outstanding load bearing or load distributing characteristics of same.

While no detailed data on degree of pervious base material saturation were taken during this study, the researchers were certainly aware that bases with high degrees of saturation do not obey conventionally-assumed rules for distribution of wheel loadings, but tend to transmit the loadings directly to underlying layers and produce higher stresses than estimated by conventional design procedures. However, apparent high degrees of base material saturation were not visually observed except at sites where large amounts of pavement deterioration existed, and were usually observed after periods of precipitation. Under these conditions it appears that pervious base material saturation is not a common problem in Oklahoma, thus load-transmitting/distributing qualities of pervious bases are not greatly affected by initial subgrade moisture accumulation.

Effects of different base and subbase materials on flexible pavement behavior will be discussed later.

Base Courses

Six types of base material were encountered at field research sites, and are/were commonly used in Oklahoma base construction: 1) sand cushion, 2) hot sand-asphalt, 3) asphaltic black base, 4) soil-cement, 5) "stabilized" aggregate, and 6) select material. Design criteria of the Oklahoma Department of Highways actually considers sand cushions and select material to be "insulators" rather than base materials. However, in this report, base material is considered to be the material placed directly below the wearing surface. Sand cushions and select material were encountered as "base" courses for rigid pavement.

Sand cushions consist of sandy material, all of which must pass the one inch sieve and contain 15 to 35 percent of minus No. 200 material. Because of observed behavior, the use of sand cushions has been deleted from current Oklahoma highway design criteria, hopefully for good. Sand cushions were used under rigid pavement to provide a leveling course and perhaps give some subgrade strength, though rigid pavement design normally considers only the thickness of the pavement. In actuality, sand cushions were found to act as water reservoirs and distribution systems, catching water which infiltrated from the shoulders and through rigid pavement cracks and joints, and feeding this water uniformly over the subgrade. As a result, rigid pavements on sand cushions usually experienced only small differential vertical movements. However, continued feeding of water to the subgrade resulted in lateral subgrade expansion and pavement cracking, plus upper subgrade moisture contents at or near the subgrade liquid limit. Once this condition occurs, heavy traffic loadings cause flow of the "plastic" subgrade, displacing/dispersing the sand cushion and placing the cohesive material next to the rigid pavement. Continued infiltration of water through open joints produced pumping, subgrade extrusion, voids under the pavement, severe cracking, and noticeable pavement deterioration. To summarize, sand cushions appear a cheap and worthwhile expedient for rigid pavements used for residential streets, but should not be used under modern highways.

Hot sand-asphalt is a mixture of asphalt and mineral aggregate, composed of sand and fine gravel with or without mineral filler. Sand-asphalt was used as a base or subbase course at many highway research sites. When used in this manner, sand-asphalt was found to form an excellent impervious layer, and the "plastic" properties of asphalt coupled with the fineness of the mineral particles allowed this material to resist the effects of lateral subgrade expansion and vertical differential movement without cracking and becoming pervious, at least better than any other type of material encountered. At several sites, considerable rutting, raveling, and cracking of flexible pavement surfacing was noted but subgrade moisture contents remained roughly constant at their equilibrium value of 1.1 to 1.3 times the plastic limit. In these cases, the sand-asphalt base appeared to have withstood the deformations and remained impervious.

Asphaltic black base is a mixture of asphalt and mineral aggregate composed of course and fine aggregate with mineral filler, i.e., a "lean" asphaltic concrete. Several research sites contained asphaltic black base underneath asphaltic concrete. Observed performance indicates that this material is probably the second best base type tested, as it is impervious and possesses good flexibility. However, its performance is not thought to be as good as that of sand-asphalt, as the larger size of aggregate particles used probably give this material less flexibility, and also present the possibility of larger interconnected voids. Nevertheless, asphaltic black base was found to perform well at the majority of sites where it was encountered.

Soil-cement is a mixture of Portland cement and soil, preferably sands or silts with less than 35% clay. Soil-cement base courses encountered in the study were used primarily in construction of improved shoulders. Soil-cement is relatively impervious, but is relatively rigid compared to more flexible asphaltic materials and may suffer some initial shrinkage cracking. Therefore, when moisture accumulation and resulting volume change occurs, the soil-cement shrinkage cracks expand. This material is extremely susceptible to further cracking from lateral subgrade expansion, as the cemented material possesses very little tensile strength. Once the soil-cement has cracked from lateral subgrade expansion, cracking is almost immediately reflected through the thinly surfaced shoulder, and this random cracking may be observed on almost all Oklahoma highway shoulders applied over soil-cement bases, as shown in Fig 4.1. Once the surfacing has cracked, water will enter, infiltrate through the soil-cement into the subgrade, and additional volume change will occur. The usual behavior is for the shoulders to crack and move up and away from the pavement section, allowing water to infiltrate directly through the open joints between pavement and shoulder. The use of soil-cement directly on any subgrade of even suspected expansiveness does not appear advantageous.

Figure 4.1 Transverse and Longitudinal Cracks in Soil-Cement Base Under Outside Shoulder at Site No. 42, Reflected Through Shoulder Surfacing

However, soil-cement might be considered if a prepared subbase was used beneath it to stop infiltration and provide a buffer layer between it and the expansive subgrade.

Stabilized aggregate is a mechanically stabilized material consisting of blended course aggregate, sand, mineral filler, and soil binder. The resulting product, though highly variable and depending on locally available materials, is nevertheless intended to provide a well-graded and dense compacted layer with reasonable strength properties. Stabilized aggregate base courses were found to perform satisfactorily at sites where little lateral subgrade expansion was noted to occur. At these sites, they provided (by virtue of their density and fine content) a relatively impervious barrier to infiltration, both from the shoulders and through the pavement section. However, stabilized aggregate possesses little tensile strength, and at sites where appreciable lateral expansion was noted, this base did not stop infiltration/evaporation of water through pervious pavement surfaces. If stabilized aggregate bases are to be used when lateral subgrade expansion is expected, an impervious subbase with flexible properties should be used underneath them.

Select material is similar to stabilized aggregate, but is usually considered to be naturally occurring and is governed by somewhat different specifications. In general, select material is considered (by OSHD design criteria) to be somewhat lower in quality than either sand cushion or stabilized aggregate. The above comments concerning stabilized aggregate also apply to select material, and, on the whole, select material was observed to behave not quite as well as stabilized aggregate.

The wide diversity of pavement cross-sections, ages, locations, soil and climatological conditions, etc., existing at project research sites made specific behavior comparisions extremely difficult, though more general correlations could often be achieved. Most of the correlations concerning base materials are available elsewhere (Ref 8), but it should be noted that, comparing subgrade moisture contents under pavement centerlines for research site locations on more or less uniform A-6 or A-7 subgrade and excellent or good-rated pavement, 18 of 23 sites with pervious bases had higher moisture contents in upper subgrade levels than existed at lower levels. On the other hand, 7 of 11 similar pavements with impervious bases had lower subgrade moisture contents in the upper subgrade under their centerlines than existed at lower subgrade levels. Evaluation of amount of moisture variations under pervious and impervious bases, while subjective to some degree, nevertheless indicated that less variation with time existed in upper subgrade levels under impervious bases, and the relative magnitude of variations was also lower.

The subgrade moisture contents for almost all these sections were in the range of 1.1 to 1.3 times the plastic limit, with the upper subgrade moisture levels under the seven impervious base sites being closer to 1.1 than 1.3 times the plastic limit. On the other hand, average moisture content/plastic limit ratios for the sites on pervious bases approached (and sometimes exceeded) the 1.3 value.

These data, plus other information (Ref 8) indicate that a reasonable amount of moisture infiltrates into the subgrade from pervious base courses, even when the pavement is still in acceptable condition.

To summarize, two factors are required for effective base performance in preventing/resisting subgrade moisture changes. First, the base must be impervious, to prevent moisture from reaching the subgrade directly through cracks and joints in the surface course and indirectly through infiltration from the shoulder edges. Secondly, the base material must have some degree of "flexibility" to allow lateral and vertical subgrade movements without cracking and becoming pervious. Asphaltic-type materials were found to exhibit these characteristics better than any other type of base material encountered. If, for strength, economic, or other reasons, another type of base material is used, it should be protected by a flexible, impervious layer either above or below it. As built by current construction methods, asphaltic concrete wearing surfaces should not be counted on to provide imperviousness over long periods, as the coarseness of aggregate used, plus the susceptibility of these surfaces to traffic wear, exposure, and deflection will tend to render them pervious eventually. The component possessing long-term flexibility and imperviousness should be placed underneath the wearing surface.

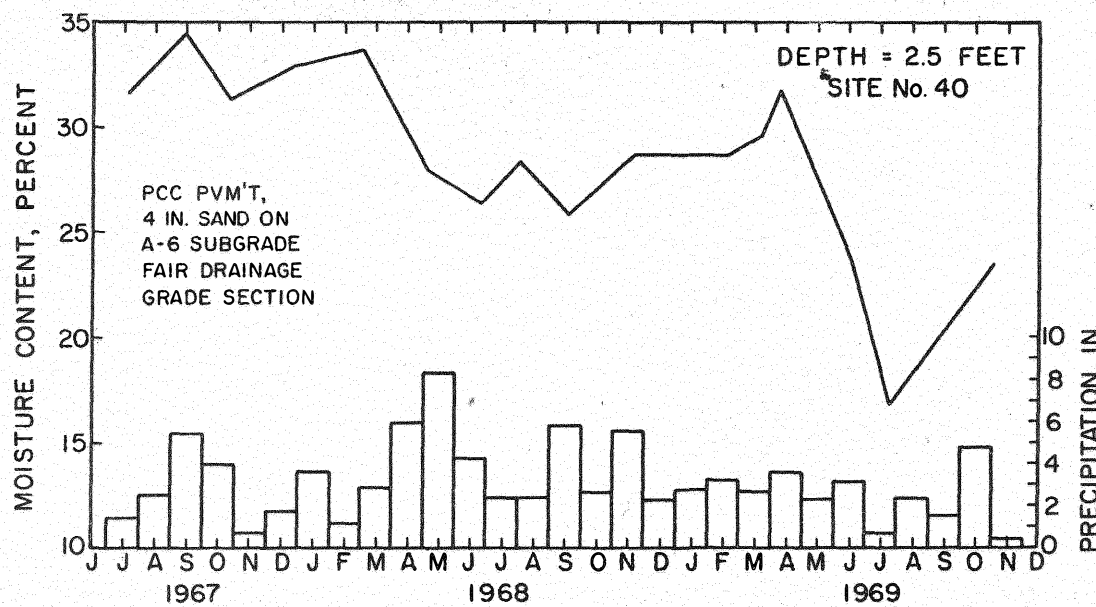
Subbase Courses

Subbase components are used primarily as a means of distributing loads to the subgrade, but can also act as barriers against water infiltration where pervious base courses are used. Subbases are usually constructed of locally available material, chemically treated layers of the subgrade, or sand-asphalt. The type of material used for subbase construction is usually "poorer" in quality than that used for base courses and wearing surfaces, at least from a strength viewpoint. Therefore, the following discussion of subbase behavior is not concerned with load carrying capacity, but with effects on moisture behavior.

Select material subbases, when used in flexible pavement construction, obviously reduce the total required thickness of asphaltic layers. While economics dictate the use of locally available materials whenever possible, especially if they do not require treatment, it should be remembered that select material has minimal tensile strength and is not completely impervious, thus select material subbases should not be used unless some other portion of the pavement system contains desired impervious and flexibility properties. As currently constructed asphaltic concrete surfacing should not be considered to possess these properties, at least over the long term, some type of asphaltic base material should be used. The use of select subbase under stabilized aggregate base should not be expected to provide high resistance to subgrade moisture changes whenever laterally expansive subgrade soils are encountered. However, the dense and relatively impervious qualities of select subbase are helpful in reducing effects of infiltration from outside the pavement system, and also in protecting the base and wearing surface components from subgrade moisture and volume changes by providing a cushioning effect.

The cushioning effect of select material subbases may be seen by inspecting moisture variations plotted in Fig 4.2, for the upper subgrade levels (2.5 ft) at two sites having relatively similar characteristics, except that Site No. 39 has an eight-inch select material subbase while Site No. 40 does not. The existance of "fair drainage" conditions should allow quite a bit of infiltration into the sand base material, but, as seen in Fig 4.2, quite a bit of subgrade moisture variation damping is produced by the relatively impervious select material subbase.

Lime-treated layers of cohesive subgrades have also been used as subbases, normally at lime contents corresponding to modification optimum for the material. The lime contents used for treatment normally result in reduction of plasticity to approximately zero, and give an increase in workability of the soil. The result is to produce a treated material



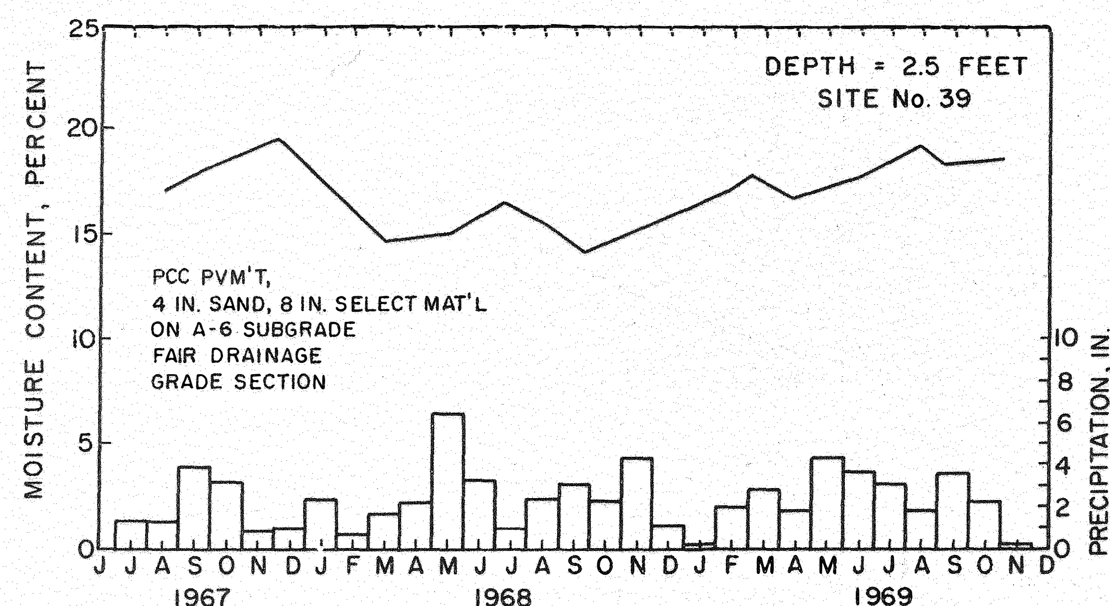


Figure 4.2 Moisture Variations at Depth of 2.5 Feet Beneath Pavement Centerline for Sites No. 39 and 40

with properties similar to that of the select material described previously.

Lime modified subgrade also helps reduce magnitude of moisture variations, as noted in Fig 4.3. The use of a subbase component in addition to impervious base material produced relatively stable moisture conditions in the subgrade for the period of measurement, with relatively low upper subgrade moisture contents. The increase in moisture content at the 1.5 foot level in 1968 is attributed to approximately 16 inches of precipitation during the period March-June 1968. However, because of the use of a relatively impervious subbase the effects of this increase in moisture content were dampened.

The section has improved shoulders over 13 inches of select material base. Disadvantages of building non-continuous bases for pavement and shoulders may also be noted at this site, because appreciable shoulder cracking and separation of the pavement/shoulder joint were noted in early 1969. Water began to infiltrate directly through this joint, and, though dampened by the select material, greater subgrade moisture variations began to occur under the shoulders. This additional moisture also caused an increase in subgrade moisture levels under the pavement centerline, particularly at the 2.5 foot level. If the asphaltic black base and lime-modified subbase had been used shoulder-to-shoulder perhaps some of this moisture content increase could have been prevented, and variations underneath the shoulders reduced in magnitude.

Lime contents used in subbase treatment are not normally high enough to develop particle cementation or crystal growth, therefore this material is probably more pervious than in its natural state. Thus, from a moisture resistance viewpoint, previous comments concerning the use of

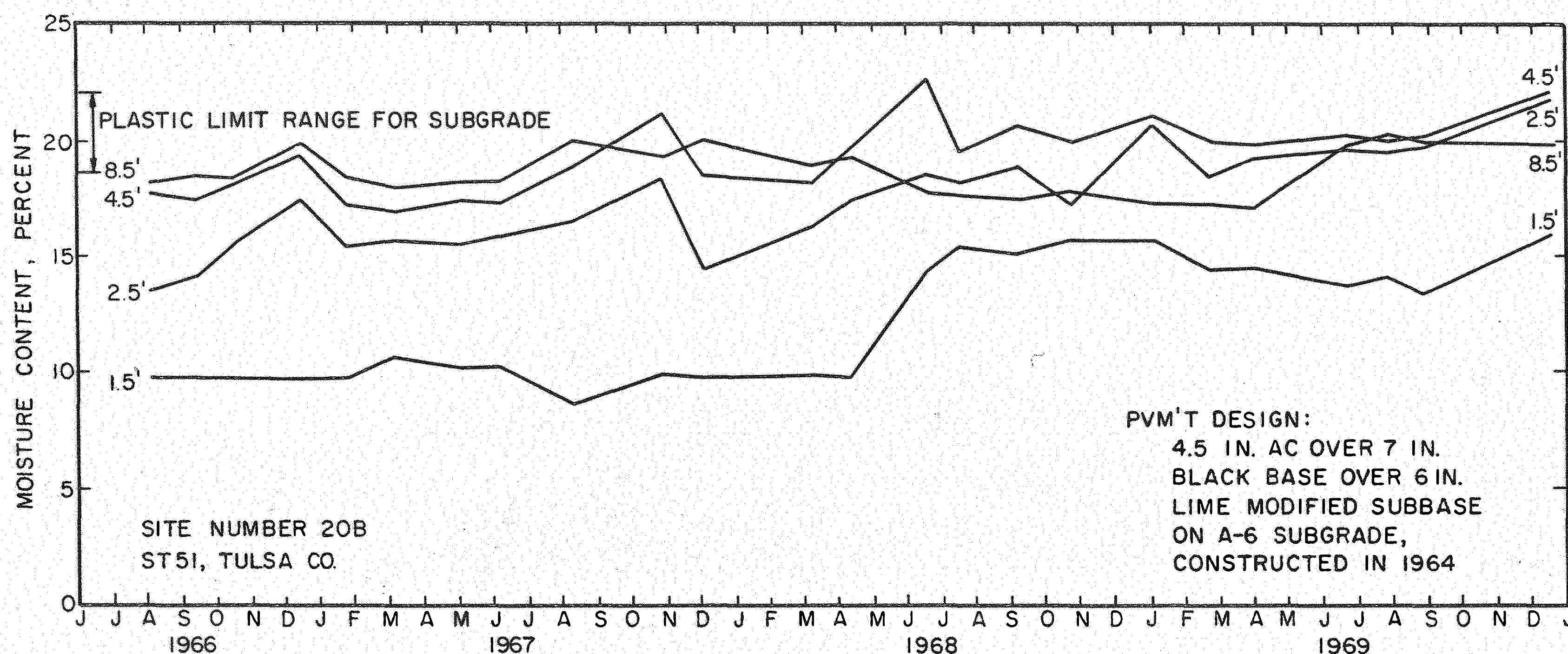


Figure 4.3 Moisture Variations at Selected Levels Beneath Pavement Centerline at Site No. 20

select material subbases are also applicable to lime-modified subbases. Lime treatment of cohesive subgrades to produce particle cementation and appreciable crystal growth is another matter, and will be discussed later.

The effectiveness of sand-asphalt as an impervious and flexible material has been discussed previously, and the same comments should be made concerning its use as a subbase. However, on expansive subgrades, any type of pervious base material should give better performance if a sand-asphalt subbase is used beneath it, assuming the base material does not become saturated. Some consideration should be given to making both base and subbase of sand-asphalt, as this would provide a thicker layer of well-performing material, at least from a moisture resistance viewpoint.

Under rigid pavements, the subbase has a different function in that it is not always considered as a strength component. Therefore, the main criteria for material to be used under rigid pavements is that it be non-expansive, impervious, and have some degree of flexibility, as rigid pavements are highly susceptible to cracking and joint separation from subgrade moisture changes in expansive soils.

Improved Shoulders

Improved shoulders were found to provide a method for reducing infiltration of surface runoff into the base course, subbase and/or subgrade, particularly at pavement edges. In the majority of cases, reduced infiltration from sources immediately adjacent to the pavement permits more nearly uniform moisture variations over a width of the pavement and thus smaller differential volume changes where expansive soils are involved.

However, definite improvement in subgrade moisture conditions underneath pavement could be obtained by several modifications in shoulder design/construction techniques. Because of lower traffic loadings carried by improved shoulders and also the stage methods common in modern Oklahoma construction, shoulders are often built after the pavement section has been constructed, using thinner base layers which are often of a different material. The net effect of these techniques is to place a vertical plane of weakness between pavement and shoulder. Lateral expansion and differential vertical expansion of cohesive subgrades tends to cause separation along this plane of weakness, providing a channel for entrance of surface runoff and producing larger moisture variations under the pavement edge. Also, the wet-dry interface which forms under the shoulder causes shrinking and swelling of subgrade material, which developes flexural stresses along this plane of weakness. Characteristic behavior includes separation and relative movement of shoulder and pavement, allowing infiltration through the pavement/shoulder joint (see Fig 4.3 and related discussion in the previous section).

To remedy this situation, the same thickness of subbase and base used for the pavement section should be used under the shoulders, with the same criteria concerning impervious base and/or subbase material applied to shoulder design. This design procedure should result in more uniform subgrade conditions beneath the pavement surface, minimize differential volume change, and preserve the integrity and thus the imperviousness of the pavement/shoulder joint.

Observed data indicate that a wet-dry interface forms under the improved shoulder approximately five to seven feet from the shoulder edge. Thus, to keep this interface from existing underneath the pavement section, a minimum shoulder width of eight feet should be used. Current Oklahoma design procedures appear to satisfy this condition for all cases except the inside shoulder on four-lane divided highways, where the shoulder is approximately four feet in width. This narrow shoulder, coupled with poorer drainage conditions normally encountered in divided highway medians, usually produces higher moisture contents on the median side of four-lane divided highways and also produce larger variations in these moisture contents, as seen in Fig 4.4. The lower traffic loadings of the inside lanes compensate for these more adverse moisture conditions to some degree; nevertheless, at least an eight-foot wide shoulder on the median side of four-lane divided highways would give better performance.

Another important criteria in correct shoulder design is to make both shoulders of equal width. If both shoulders are of equal width and the width is at least equal to eight feet, a more nearly symmetrical subgrade moisture profile will result underneath the pavement, and more nearly uniform moisture increases/decreases will occur, as may be seen when the moisture levels shown in Fig 4.4 for non-symmetrical shoulder conditions are compared with those of Fig 4.5 for symmetrical shoulder conditions.

To summarize, improved shoulders of at least eight-foot width are needed to reduce under-pavement moisture variations for any section placed on expansive subgrades. Better performance occurs when the base and/or subbase courses underneath the shoulder are of the same material and thickness as used under the pavement section, and when the base/subbase courses for pavement and shoulders are placed at the same time, in one continuous shoulder to shoulder layer. Comments concerning imperviousness

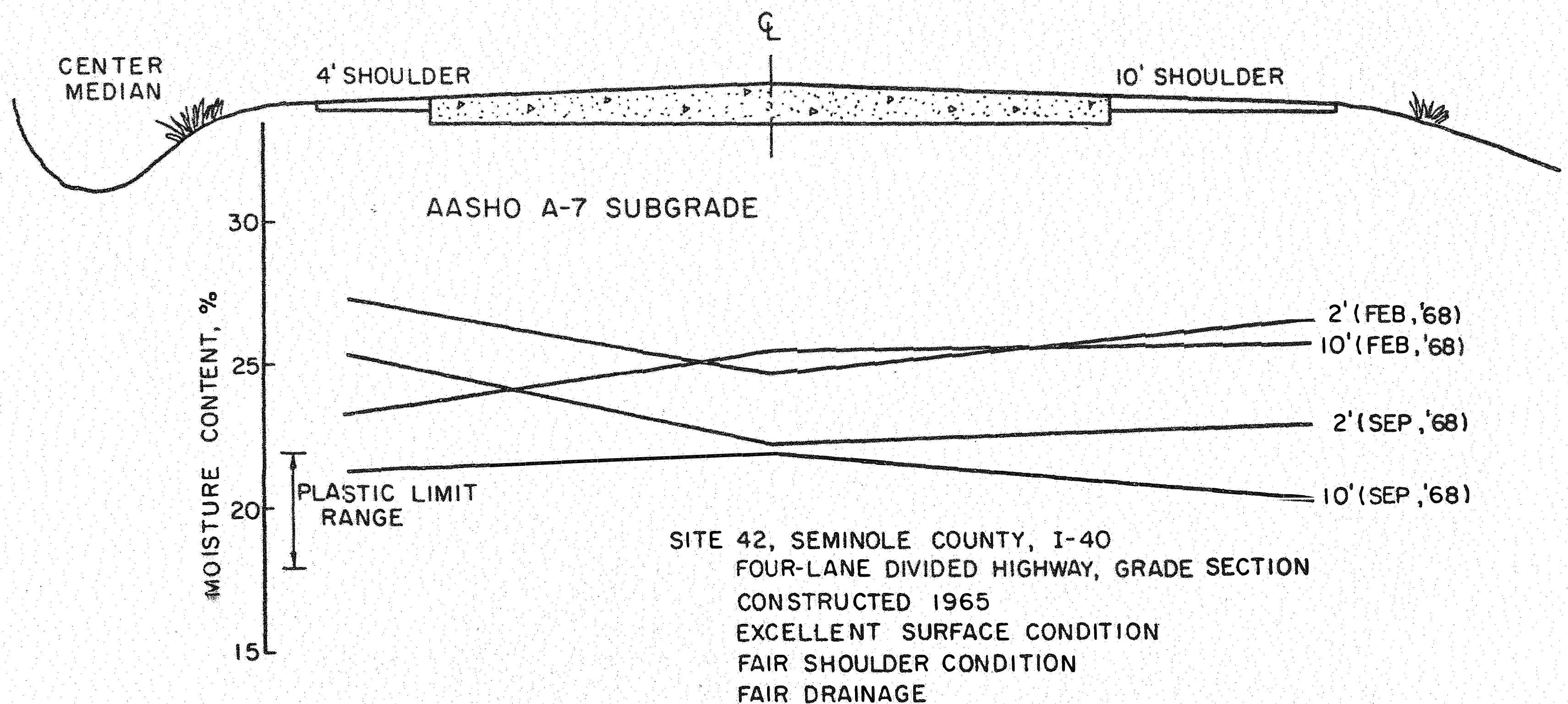


Figure 4.4 Subgrade Moisture Distribution at Site No. 42

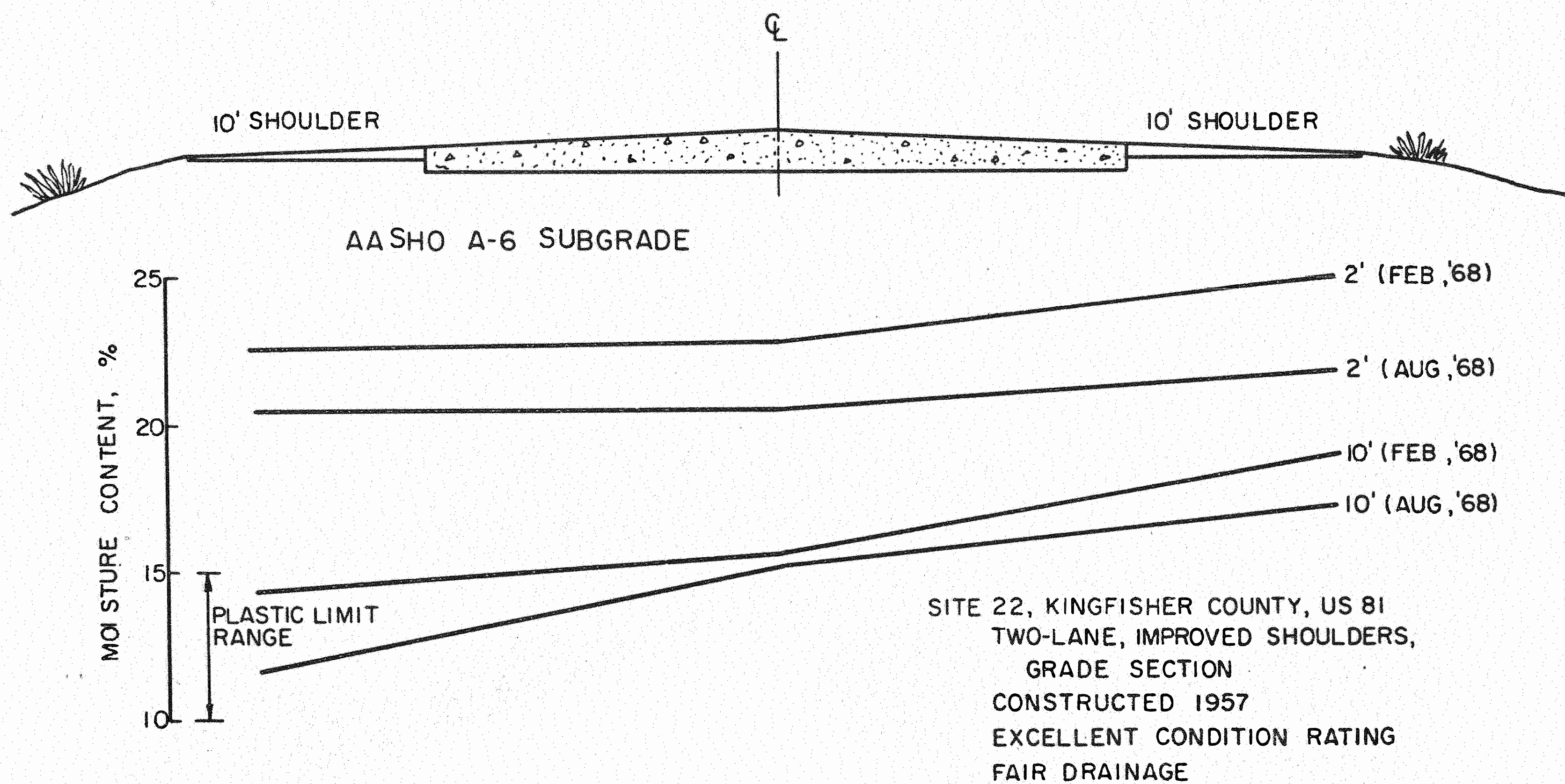


Figure 4.5 Subgrade Moisture Distribution at Site No. 22

and flexibility of base/subbase materials under pavement also apply to improved shoulders.

Highway Drainage Conditions

As previously mentioned, subgrade moisture conditions are definitely related to existing highway drainage conditions and both are closely related to shoulder slope and available drainage ditches. Well designed and constructed drainage ditches combined with steep shoulder slopes reduce infiltration into the subgrade by removing surface runoff as quickly as possible. It was found that normal "good drainage" design criteria resulted in lower average moisture contents under the pavement section, but produced a relatively high degree of moisture variability and a definite wet-dry interface under improved shoulders.

On the other hand, "poor" quality drainage conditions result in higher average moisture contents with less moisture content variability and a less well-defined wet-dry interface.

Assuming that a proper highway design may be developed if conditions can be predicted, there appears to be little to choose between "good" drainage conditions and "poor" drainage conditions. The most important criterion appears to be the establishment of similar drainage conditions on either side of the highway, as in most instances where pavement performance appeared directly related to drainage conditions, radically different drainage behavior was observed on different sides of the pavement section. This condition caused a high moisture content gradient across the section and marked differential vertical and lateral subgrade expansion. Drainage conditions did not appear to greatly affect subgrade moisture behavior once the pavement system became pervious, as infiltration/evaporation through the pavement surface was the predominant cause of subgrade moisture variations.

To summarize, it appears that equal or similar drainage conditions on both sides of the highway are more important than the particular degree of drainage obtained. Better drainage will result in lower average moisture contents and higher subgrade strengths, but at the cost of differential seasonal volume change. Poorer drainage conditions will reduce subgrade strength while reducing the magnitude of seasonal moisture variations.

Highway Profile

As previously mentioned, better performance was obtained for highway sections on grade and in cuts, as compared to transition and fill sections. Better moisture equilibrium in cuts and grade sections was easily related to better performance. Therefore, when pavements are constructed on expansive subgrades, designing a majority of the profile on grade or in cuts should materially improve highway performance. High fills should be avoided if possible and all fill sections should receive some treatment to prevent side drying, which causes decreasing subgrade moisture contents and shoulder settlement. Fill moisture contents should initially resemble those of the natural profile as closely as practicable. For transition sections, attempts should be made to provide equal drainage conditions on either side of the pavement section.

Traffic Volume

Despite several attempts over the period of the study, significant correlations between traffic volume and subgrade moisture-related highway performance could not be established. Even when traffic volume was reduced to the general classifications of "light," medium," and "heavy," the only conclusion found was the obvious one that, after initial cracking and/or rutting rendered the pavement system pervious, higher traffic volumes produced more rapid pavement deterioration.

It is possible that correct correlations concerning traffic volume were not obtained, but the author chooses to believe that initial pavement cracking and loss of imperviousness more often results from moisture changes in the expansive subgrade than from traffic overloads, as loss of pavement system imperviousness usually occurs during the first two or so years after final construction. At this time, the pavement section is usually not carrying the final design traffic volume.

These data, coupled with observations that pervious bases were not usually found with high enough degrees of saturation to negate conventional wheel load distribution assumptions, form the basis for the conclusion that subgrade moisture conditions are more important than traffic volumes in determining initial (and thus, to some extent, final) pavement performance, assuming that at least a semi-rational method of considering traffic loadings and pavement stresses was used in pavement system design.

Construction Procedure

This research study was concerned primarily with determining subgrade moisture behavior under existing Oklahoma highways. Nevertheless, the procedures by which highway sections are constructed definitely affect subgrade moisture behavior, and observations concerning these procedures are relevant to a comprehensive analysis.

As mentioned previously, most new construction in Oklahoma is done by stage methods. Contracts for grading and drainage structures are usually let and completed with contracts for base and surfacing let at some later time. This practice results in bringing the subgrade to its approximate final level, then leaving it for an extended period before a covering or wearing surface is applied. During the interim, several things occur. First, moisture contents in the prepared subgrade will reach some equilibrium condition, compatible with moisture contents in the natural subgrade below and existing climatological conditions. This equilibrium is likely to undergo seasonal changes, generally wetter during the winter months and dryer during summer months. Also, precipitation in Oklahoma is usually of an infrequent but heavy nature. As a result, considerable runoff occurs across the prepared subgrade, producing erosion damage.

Another fairly common practice in Oklahoma is the use of prepared subgrades by farmers for movement of agricultural equipment either prohibited from on-pavement travel or at least hazardous for same. Over an extended period of time, this behavior results in raveling of the subgrade during drier periods and rutting of the subgrade during wetter periods. The author has observed this behavior throughout the state.

As a result of these factors, the original subgrade level is changed and no longer remains suitable for use as a working surface. The base/surfacing contractor is therefore required to scarify and recompact at least the upper portions of subgrade along the highway profile. Also, highway construction in Oklahoma is usually performed in warm spring and hot summer months. At this time the uncovered subgrade is likely to be considerably drier than original compaction moisture, to a considerable depth. Compaction of cohesive subgrades in Oklahoma is usually conducted dry of optimum moisture, as optimum compaction moisture contents are usually either slightly below or at the plastic limit of the material. The end result is to produce a subgrade with an average moisture content in the upper portions of at least five percent moisture content below the subgrade plastic limit. Base and impervious (at least initially) surfacing are immediately applied over this material, and then subgrade moisture accumulation begins.

The author is not criticizing the idea of stage construction, as many advantages exist for its use, particularly in Oklahoma. However, other methods of stage construction should be considered which would provide better initial subgrade moisture conditions. Current construction practice appears to aggravate the subgrade moisture problem in Oklahoma instead of minimizing it. Alternate methods of stage construction will be discussed later.

Summary

This Chapter has summarized the effectiveness of various components in resisting effects of subgrade moisture conditions and also discussed the effect of various pavement components on subgrade moisture behavior. From these findings, definite criteria can be established with a view toward minimizing the effect of subgrade moisture changes on pavement performance. Such recommendations, concerning highway testing, design, and construction are made in the following Chapter.

CHAPTER 5. RECOMMENDATIONS FOR IMPROVING PAVEMENT PERFORMANCE ON EXPANSIVE SUBGRADES

This Chapter presents recommendations for improving pavement performance on expansive Oklahoma subgrades. The author is aware of the great number of hurdles between recommendation, acceptance, and implementation, and the need for reasonable and practical recommendations. He is also aware that recommendations may not be implemented because of practical, economic, commercial, or political reasons. Nevertheless, to obtain better pavement performance on expansive subgrades, the following ideas should at least be considered.

General Philosophy for Highway Design on Expansive Oklahoma Subgrades

Most published criteria for pavement design to resist effects of subgrade moisture are concerned with keeping moisture out of the subgrade. However, particular environmental conditions existing in the more populous areas of Oklahoma, coupled with stage methods currently favored for all new construction, make it highly unlikely that construction moisture contents can be maintained for even short periods. Under these conditions the opposite approach should be tried.

In most cases, moisture contents under new Oklahoma pavements on expansive subgrades can be expected to increase by at least five percent engineering moisture content. This increase will occur over an approximate two year period, to the vicinity of the subgrade plastic limit. Moisture accumulation is primarily from capillary sources. Some additional moisture gain from thermal migration (under pavement centerlines) and infiltration (from shoulder slopes and adverse drainage conditions) is possible. Resulting initial pavement behavior does not greatly affect riding quality, but is sufficient, through slight cracking or loss of subgrade support, to open the way for infiltration/evaporation through the pavement. At this point, prompt maintenance might save the pavement system, but riding qualities and general appearance of the pavement are such that no maintenance appears needed.

Once infiltration/evaporation through the pavement surface begins, resulting cyclic moisture variations, differential pavement movements, and variability of subgrade support increase in magnitude, producing rapid pavement and shoulder deterioration and poor riding quality. It is at this time that maintenance, usually in the form of asphaltic concrete overlay is applied. However, application of overlay at this point in time is not particularly effective. On rigid pavements, asphaltic concrete overlay usually exhibits crack reflection within six months after application and thus does not seal the pavement effectively. On flexible pavements, overlays do not appreciably increase subgrade support, and simply rut as the original surfacing did. Crack sealing in rigid pavements also appears ineffective, even when done at regular intervals. To summarize, once the pavement system has become pervious and remained so for even the short period of one summer/winter cycle, it tends to remain pervious despite all attempts to reseal it.

Therefore, it appears logical to develop highway designs which allow subgrade moisture contents to increase to their equilibrium condition as quickly as possible and stay there. Moisture conditions under pavement and shoulders should either increase at the same rate so that differential movement will not occur or else the system should be designed to remain impervious after differential and lateral expansion associated with Oklahoma subgrade moisture accumulation has occurred. One can design structurally for any reasonable subgrade condition if it remains relatively constant and is known. To prevent deterioration of Oklahoma highways, the infiltration/evaporation cycle through pervious pavement systems cannot be allowed to start. Recommendations made in this Chapter embody this overall philosophy.

Revised/Improved Subgrade Testing Procedures

Obviously, highway engineers cannot prepare a satisfactory design if conditions to be considered are unknown. Lack of available information concerning possible subgrade behavior, *particularly at the time construction details are finalized*, makes solving Oklahoma subgrade problems extremely difficult. The current design procedure, based on the Oklahoma Subgrade Index (OSI), does not appear to be adequate in predicting total behavior of expansive Oklahoma subgrades. The OSI method is easy to use in design and requires a minimum of testing, with the testing routine. Both factors are thus advantageous for its use by subprofessional personnel. However, considering the highly variable behavior of expansive subgrades when combined with different highway components, a more detailed method of analysis/design appears justified. Standard test procedures for expansive subgrades should include determination of vertical and lateral swelling characteristics as well as strength tests under "equilibrium" conditions which are likely to occur for particular pavement systems. Chemical treatment of subgrades (usually with lime) is becoming more and more prevalent and a definite consideration of additional strength properties obtained from this treatment should be incorporated into highway specifications, as the knowledge may prove of vital importance, particularly for correct flexible pavement design.

When the cost of Interstate Highway construction exceeds $1,000,000 per mile, it is irrational to ignore the information obtainable from a comprehensive analysis and exploration of the proposed subgrade, when to do so would add only a slight fraction to the total highway cost and give a much better chance for successful pavement performance.

This point may be reinforced by inspection of Fig 5.1, an Oklahoma Department of Highways flow chart used to explain their long-range highway planning program. As may be noted, subgrade soils analysis and pavement design is not started until the contract for grading has been let, and the total design is completed in an estimated one month period.

While this time period may be adequate for design using the OSI procedure and "standard" pavement sections, the complex behavior of pavement systems on expansive subgrades should necessitate a larger and more thorough attempt to obtain better design information. Because of indications that construction techniques during the grading phase may critically affect final subgrade moisture conditions, the soils investigation/design program should also be undertaken before grading contracts are let.

It is therefore recommended that a more comprehensive standardized test procedure be developed for routine use, considering factors mentioned previously, and design aids based on these test results be established. To reiterate, only if subgrade conditions are known can adequate solutions be devised.

Recommendations Concerning Type of Surfacing

Portland cement concrete and asphaltic concrete surfacing are the only two choices available to the highway engineer. When constructing pavements on expansive subgrades, it is definitely recommended that the entire pavement system design be based on type of subgrade and other existing conditions, rather than using a "standard" section.

Rigid or Portland cement concrete pavements were found to have lower initial resistance to cracking from vertical and lateral subgrade expansion than flexible pavements. However, they were found to perform adequately (even though cracked) until subgrade moisture contents begin to approach the liquid limit, because of their ability to transmit wheel loadings over a wide area. However, the tendency of rigid pavements to crack with small subgrade volume changes is directly responsible for increasing moisture contents, and once cracking has occurred the deterioration of rigid pavement is only a matter of time. Therefore, rigid pavements should not be used unless underlain by a flexible, impervious material, and load carrying capacities of the pavement should be evaluated by strength tests assuming a subgrade moisture content of 1.1 to 1.3 times its plastic limit. The ability of rigid pavement to effectively carry traffic at subgrade moisture contents close to the liquid limit should indicate its use in areas where poor drainage is encountered, as same normally produces higher subgrade moisture conditions. A *correctly designed* rigid pavement with improved shoulders over sand-asphalt is probably the best design for general use on expansive subgrades.

Flexible or asphaltic concrete pavement was found to resist initial cracking from vertical and lateral subgrade expansion better than rigid pavement. However, when moisture contents approach the equilibrium value of 1.1 to 1.3 times the subgrade plastic limit, heavy traffic produces rutting, raveling, and initial pavement cracking. If the flexible pavement is applied on a pervious base/subbase combination, the infiltration/evaporation cycle begins immediately, and as subgrade moisture contents increase, continued pavement deterioration occurs. Once moisture contents begin to exceed the equilibrium value and subgrade remolding takes place, the time for remedial measures is past.

The inability of observed flexible pavement systems to carry heavy traffic loadings at subgrade moisture contents near the plastic limit is not thought to be an indictment of this basic design, but to result from the inability of current Oklahoma Department of Highways design techniques to predict subgrade strength at these moisture contents. Incorporation of revised soil testing procedures to adequately determine subgrade strengths at or above the subgrade plastic limit and consider volume change behavior should definitely improve the chances for satisfactory long-term flexible pavement performance. Also, flexible pavement construction on expansive subgrades should definitely include the use of a flexible and impervious base, subbase, or membrane component.

Because subgrade strength appears more important in flexible pavement design, these systems should give better performance where "good" drainage conditions are provided, as they are less susceptible to volume changes produced from distinct wet-dry interface conditions and small moisture variations, and would benefit materially from lower average moisture contents and resulting higher subgrade strengths caused by good drainage.

Recommendations Concerning Highway Base Courses

Base courses used in Oklahoma highway construction should, if possible, be non-expansive, flexible, and impervious. Asphaltic-type base materials appear to provide these qualities, resulting in more nearly uniform subgrade moisture contents, better than any other base materials encountered. If, for economic, strength, or other reasons, use of other base materials is contemplated, the subgrade should be protected by use of a flexible, impervious subbase or else a felxible, impervious membrane located somewhere in the pavement system. If an impervious layer is provided in some other portion of the pavement system, mechanically stabilized aggregate or even select material may be used, as long as it does not become highly saturated. Soil-cement should definitely not be used as a base material unless protected from lateral subgrade expansion by an intervening non-expansive, flexible, and impervious layer.

An additional base material for consideration might be obtained by lime stabilization (with approximately eight to twelve percent lime) of subgrade layers. Lime stabilization should produce a high-strength material that is impervious and also may possess some flexibility or tensile strength characteristics. This material could be cushioned from expansive subgrade effects by placing it over a lime-modified subbase, also constructed from the subgrade (using approximately three to six percent lime). Current highway design procedures in Oklahoma do not correctly consider strength increases caused by lime treatment of subgrade soils, but development of such testing procedures and incorporation of this option in design is definitely recommended.

Recommendations Concerning Highway Subbase Courses

If the base component of a highway system is neither flexible nor impervious, these qualities must be supplied by the subbase. If, on the other hand, required qualities are available in the base material then the subbase requirements are not as specific. Subbases were found to provide a buffer layer between the base material and the subgrade, minimizing effects of lateral expansion and damping variations in moisture content. In addition, some reduction in vertical movement is to be expected by simply putting expansive subgrade soil further away from the surface, as only the upper five to seven feet below the pavement were found to vary appreciably in moisture content at most research sites. Sand-asphalt possesses the necessary imperviousness and flexibility if same is desired in a subbase, while lime-modified subgrade, despite some opinions to the contrary, acts as a buffer but does not provide an impervious layer. If an impervious layer of lime-treated subbase is required, stabilization lime contents must be used. Select material also acts as a buffer, but should not be assumed to have either flexibility or imperviousness. Soil-cement should not be used as a subbase if it is expected to remain reasonably impervious and if used severe cracking should be expected.

Recommendations Concerning Improved Shoulders

Improved shoulders at least eight feet in width should be constructed for all pavements on expansive subgrades. Base and/or subbase under the shoulders should be continuous with that of the pavement section, and applied in one continuous shoulder to shoulder lift. Recommendations concerning imperviousness and flexibility of base and subbase materials under shoulders are the same as for wearing surfaces. If construction of improved shoulders does not appear feasible or practical, consideration should be given to the use of rigid pavement with thickened edges, as same should provide better resistance to the higher moisture contents and wet-dry interface conditions likely to exist under pavement without improved shoulders. If flexible pavements without improved shoulders are used on expansive subgrades, a detailed analysis should be made to determine if adequate subgrade support for this system exists, and relatively high maintenance costs should be expected.

Whatever the desired design shoulder width, shoulders on each side of the pavement section should be of equal width.

Recommendations Concerning Drainage Conditions

The varied topography encountered along a highway profile makes specific drainage recommendations impracticable. However, it is extremely important that whatever drainage conditions exist be the same on each side of a particular highway section, though conditions themselves may change along the profile. Special care should be given in transition sections and sections cut through slopes to provide equal drainage conditions on either side of the pavement. Also, despite numerous problems likely to be encountered, drainage conditions for four-lane divided highways should be changed so that the median drains as well as the outside shoulders. As a general rule, flexible pavements appear more suitable for use under good drainage conditions while rigid pavements appear better suited for poor drainage conditions.

mined level, or else when large numbers of complaints are received from the traveling public. As mentioned previously, by this time overlays do not appreciably help the problem, they simply relevel the surface and cover up the mistake for a few months.

A logical assessment of research data indicates that some maintenance to maintain impervious pavements will be required shortly after construction is completed. In addition, a realistic assessment of Oklahoma maintenance practices and available funds indicates that this maintenance should be part of initial construction costs. A possible method for achieving this goal is discussed in the section on revised stage construction procedures.

Recommendations Concerning Current Stage Construction Procedures

If current stage construction procedures are to be used, several slight modifications will improve moisture conditions in the subgrade. First, the subgrade could be prepared to a level above final subgrade grade. This additional material will reduce subgrade drying during hotter seasons and give natural moisture contents more nearly approximating compaction specifications. In addition, this added layer will help to compensate for thickness lost through erosion and settlement. The prepared subgrade should be adequately barricaded so that agricultural and other traffic may be kept off during the interim between subgrade finishing and base/surfacing application. The base/surfacing contractor will then cut the subgrade to final grade and immediately apply base and surfacing. This procedure, while necessitating compaction of additional subgrade layers, should minimize the necessity for the base/surfacing contractor to scarify, recompact, and relevel the subgrade, which is usually done dry of optimum.

An alternative procedure might be the use of moisture retention, compaction aid, and workability agents such as sodium chloride, which would allow the upper layers of the subgrade to be worked and recompacted at higher moisture contents than practicable for raw soil (Ref 12). If this procedure is not feasible, consideration should be given to providing extra rolling time (and thus money) to compact the upper layers of the subgrade wet of optimum. However, required densities may be difficult to obtain as compaction will normally occur at or above the plastic limit under these conditions. Nevertheless, higher initial moisture contents and a clay particle orientation less conducive to volume change would result, and may be worth the additonal effort.

Another alternative procedure would be to cover the prepared subgrade with an asphaltic membrane and allow it to reach equilibrium moisture conditions over a two year or longer period between subgrade completion and base/surfacing application. This technique requires that all traffic be kept off the membrane, as its effectiveness is dependent upon maintaining an intact impervious surface.

Still another alternative procedure would be the use of "deep plow" lime modification of upper subgrade layers to produce a less expansive "buffer" layer, which would maintain more nearly constant moisture conditions in lower portions of the subgrade. This procedure has been attempted experimentally by the Research and Development Division, Oklahoma Department of Highways (Ref 13). However, erosion resistance and trafficability of lime modified cohesive soils is often low, and preliminary testing should be undertaken to determine the correct lime percentage required. At lime contents below modification optimum, the addition of lime may actually increase the plasticity index of the treated material over that of the natural soil. If this behavior is encountered, addition of lime sufficient to completely modify the upper subgrade layers is recommended.

Adoption of one or a number of these techniques on a regular basis should result in more nearly constant subgrade moisture conditions at the time surfacing is applied, and thus reduce the tendency or at least the amount of subgrade moisture accumulation.

Recommendations Concerning Revised Stage Construction Procedures

Recommendations for modification of current stage construction methods were made previously; however, some thought should be given to a more radical revision of the stage construction process, to ensure better long-term subgrade moisture conditions.

The philosophy and methods by which current Oklahoma highways are constructed dictate that the entire base and surfacing courses be applied at one time (see Fig 5.1, p.68). A twenty-year design life is normally used for highways, and required thicknesses of base and surfacing are dictated by magnitude of traffic to be encountered during this interval. However, the ultimate traffic loadings for the pavement system are not usually encountered until late in its design life. Initially, traffic is likely to be substantially below the expected maximum values, and the section is perhaps overdesigned. The considerations of lower than design traffic during initial years after construction coupled with the need for overlay/sealing operations shortly after initial construction and establishment of subgrade moisture "equilibrium" suggest alternative methods of stage construction.

One method would be to divide construction into three stages. Initially, the subgrade would be prepared in a manner recommended previously, but moving the time for subgrade exploration, testing, and preliminary pavement design up before the grading contract is let. Then, after the normal time lag, base material would be applied, but only part of the total surfacing thickness would be applied. Surfacing applied at this time should be adequate to carry current traffic, but would be less than the ultimate surfacing thickness recommended for the section. Within a reasonable length of time after initial surfacing is applied and the section opened to traffic, moisture equilibrium should occur underneath the pavement system and the section will be just beginning to start the infiltration/evaporation cycle through the now pervious pavement structure. At this time, usually somewhere between two and five years after initial construction, the final surfacing course should be applied. This course will bring the pavement section up to design thickness and effectively seal the surface from infiltration/evaporation. Moisture "equilibrium" should have been achieved by this time, and as the accumulation phase is completed, sections would be produced where adverse effects of moisture variations should be minimized. If subgrade soil conditions at moisture equilibrium values have been correctly anticipated, excellent highway performance should be achieved, and future maintenance costs markedly reduced. During the design life of the highway, at least one overlay less should be needed, and this in itself would reduce total highway cost.

An alternate procedure would be to use current stage construction methods but then apply surfacing in two stages. This procedure would cause more initial moisture accumulation and relative movement, and might make the final surfacing course needed earlier than for the procedure mentioned above, but should also increase the subgrade moisture resistance of the final section.

Still a third alternate might be to extend the initial stage construction phase to include base and temporary surfacing, with intermediate and/or final surfacing courses to be applied at later dates. This technique might be applicable when "turnkey" or non-stage construction projects are anticipated because of considerations dictating rapid availability of the highway to traffic. The sections could be completed quickly, but provision would be available to counteract adverse subgrade moisture conditions, which would of necessity be built into a "turnkey" project.

Incorporation of these modifications to current stage construction methods should result in a pavement section better able to resist long-term subgrade moisture effects and also reduce total maintenance cost for the system. In effect, initial maintenance is considered as a construction cost, but because initial traffic volumes are usually less than anticipated final volumes, multiple surfacing appears to be a reasonable solution to maintaining pavement imperviousness.

Decisions concerning which of the first two stage construction practices are followed should be based in part on the potential expansiveness of the existing subgrade. It is recommended that whatever criteria is used to predict subgrade performance should also allow evaluation of construction options, and give recommendations concerning whichever appears most suitable for particular subgrade conditions.

CHAPTER 6. SUGGESTED IMPLEMENTATION OF RESEARCH FINDINGS

Implementation of research findings as considered herein is defined to be the incorporation of ideas, techniques, and procedures into routine highway design operations of the Oklahoma Department of Highways. While having some general knowledge of all factors considered in highway design and construction, the author does not have personal detailed knowledge of all particular considerations existing in Oklahoma, and in fact has concerned himself with providing recommendations for increased highway resistance to subgrade moisture effects. While an essential factor in highway design, it is by no means the only factor. It is therefore expected that some recommendations will be termed impractical, at least for routine purposes, while others may be implemented immediately. The third class of recommendations are those worthy of implementation but only after more detailed analysis and proof of their validity.

It is expected that the Research and Development and Design Divisions of the Oklahoma Department of Highways will categorize recommendations of research, consulting with SMV project personnel when appropriate. Future research should therefore be concerned with the third category of research recommendations, those that should be implemented only after definite proof of their validity. The remainder of this Chapter gives general suggestions for obtaining such proof, if it is needed.

Development of Revised Soil Testing Procedures

As mentioned previously, revised soil testing and exploration procedures are recommended for obtaining definite behavior of subgrade soil response to anticipated moisture conditions. If considered feasible, new criteria could best be developed by a joint effort of the Design and Research and Development Divisions of the Oklahoma Department of Highways and qualified soils engineering personnel. Particular format of desired soils data and type of design aids required would be provided by the Design Division, while qualified soils engineers could indicate the particular variables that should be measured by engineering tests. The Research and Development Division should then devise a testing procedure to obtain data on desired variables and convert same into information useful in routine design of highways, using either in-house or outside research. Areas where additional testing and/or exploration are needed have been described previously. All testing techniques required, except those for determining lateral subgrade expansion, currently appear to be covered by either standard or tentative ASTM or AASHO specifications. The amount of research required should not be prohibitive. What is required is a broad overview of the needs of the Design Division plus understanding of engineering properties of expansive subgrade soils. In any case, adequate knowledge of subgrade soil behavior is thought to be of the utmost importance and recommendations in this area should be considered most carefully.

Proof of Suggested Revisions in Highway Design

For any highway design recommendations having possible applicability but only with further proof of validity, evaluation by test road construction is recommended. Test sections could all be constructed at one location, or in various projects throughout the state, depending upon type of evaluation desired and problems associated with placing them in the long-term planning sequence. In any case, once a test section is contemplated, serious concern should be given to locating it on the desired type of subgrade soil and with whatever profile, drainage, etc., characteristics are needed to more nearly simulate the conditions of desired testing. Test sections should obviously be incorporated in new construction to minimize their cost, and procedures for evaluation should be similar to those currently developed and used by SMV project personnel. The amount of instrumentation and frequency of data collection should be increased and emphasis should be in obtaining a maximum of useful data from a minimum number of sites rather than the approach used in this study. Control or current design sections should also be instrumented and evaluated, and placing test sections in proposed new construction should simplify this procedure.

Evaluation of the highway designs by test section should also perhaps be combined with evaluation of different construction techniques, as discussed below. Perhaps consideration should be given to evaluation of particular designs for use on highly expansive subgrades, moderately expansive subgrades, and subgrades with relatively minimal expansive characteristics, though current highway designs appear to work adequately in the latter case.

Proof of Suggested Revisions in Construction Practice

Several recommendations have been made concerning revision of current stage and "turnkey" construction procedures. If any of these recommendations are considered feasible, but only after field evaluation, a test section program similar to that recommended for evaluation of highway designs is suggested. New techniques could be evaluated and compared against current methods at either a combined test section or else on sections scattered throughout the state. Instrumentation and data collection/evaluation techniques should be similar to those contemplated for highway design test sections except that no evaluation of base/surfacing behavior is required. The emphasis should be toward determining effect of construction techniques on the existing subgrade moisture regime and the ability of same to obtain reasonable subgrade moisture conditions during and immediately after final construction of base and surfacing. It is possible that alternative approaches may be desirable, depending upon the particular expansiveness of the subgrade encountered.

Summary

This Chapter has discussed, in a general way, methods of obtaining additional proof of research findings if same is desired. Test section construction, though expensive, is nevertheless an effective method of determining feasibility of research recommendations and evaluating their applicability in different situations. If any test section construction/evaluation is planned, it is definitely recommended that comprehensive planning be undertaken to ensure that useful information is obtained, since the cost of test section construction, instrumentation, data collection, and evaluation is exceedingly high.

In any case, decisions concerning implementation of these findings are the prerogative of the Oklahoma Department of Highways and the author is, for the moment, happy to provide them with food for thought and, hopefully, action.

REFERENCES

1. Haliburton, T. Allan, "Interim Report I: Preliminary ~~Planning~~" Subgrade Moisture Variations Research Project, School of Civil Engineering, Oklahoma State University, Stillwater, June, 1966.

2. Heiliger, Wayne L. and T. Allan Haliburton, "Interim Report II: Access Tube Installation," Subgrade Moisture Variations Research Project, School of Civil Engineering, Oklahoma State University, Stillwater, January, 1967.

3. Osterhout, Ronald and T. Allan Haliburton, "Interim Report VII: Subgrade Temperature Measurement," Subgrade Moisture Variations Research Project, School of Civil Engineering, Oklahoma State University, Stillwater, May, 1969.

4. Manke, Phillip G. and E. Walter LeFevre, "Interim Report III: A Preliminary Standardization and Calibration Procedure for Nuclear Moisture/Density Gages," Subgrade Moisture Variations Research Project, School of Civil Engineering, Oklahoma State University, Stillwater, May, 1967.

5. Moore, Raymond K. and T. Allan Haliburton, "Interim Report IV: Suggested Nuclear Depth Gage Calibration Procedures," Subgrade Moisture Variations Research Project, School of Civil Engineering, Oklahoma State University, Stillwater, January, 1968.

6. Marks, B. Dan and T. Allan Haliburton, "Interim Report VI: Evaluation of Collected Data 1966-1967," Subgrade Moisture Variations Research Project, School of Civil Engineering, Oklahoma State University, Stillwater, May, 1968.

7. Shaw, Larry K. and T. Allan Haliburton, "Interim Report VIII: Evaluation of Collected Data 1966-1969," Subgrade Moisture Variations Research Project, School of Civil Engineering, Oklahoma State University, Stillwater, January, 1970.

8. Snethen, Don R. and T. Allan Haliburton, "Interim Report IX: Effectiveness of Existing Highway Designs," Subgrade Moisture Variations Research Project, School of Civil Engineering, Oklahoma State University, Stillwater, May, 1970.

9. Haliburton, T. Allan, "Interim Report V: Data Summary 1966-1967," Subgrade Moisture Variations Research Project, School of Civil Engineering, Oklahoma State University, Stillwater, April, 1968.

10. Haliburton, T. Allan, "Interim Report X: Summary of Collected Data," Subgrade Moisture Variations Research Project, School of Civil Engineering, Oklahoma State University, Stillwater, August, 1970.

11. Srinivasan, Venkatraman, "Aniosotropic Swelling Characteristics of Compacted Clay," Thesis submitted to the Faculty of the Graduate College of the Oklahoma State University in partial fulfillment of the requirements for the Degree of Doctor of Philosophy, July, 1970.

12. Marks, B. Dan and T. Allan Haliburton, "Salt-Lime Stabilization," Final Report, Salt-Lime Soil Stabilization Feasibility Study, School of Civil Engineering, Oklahoma State University, Stillwater, June, 1970.

13. Hartronft, B. C., L. D. Buie, and F. P. Hicks, "A Study of Lime Treatment of Subgrades to Depths of Two Feet," Research and Development Division, Oklahoma Department of Highways, Oklahoma City, 1969.

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