Subgrade Moisture Variations Studied With Nuclear Depth Gages

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Establishment of relationships between subgrade moisture variations and highway pavement performance would help to solve many highway design problems. In June 1964, a six-year study was begun to relate subgrade moisture variations to soil, climate, and pavement conditions. Correlations after 18 months of data collection have established quantitative relationships between the factors, and indications are that qualitative data will be developed before project termination.

Subgrade moisture data were collected periodically by nuclear depth gages. Fifty field test sites, on typical highway sections, were located near climatological recording stations in north central and northeastern Oklahoma. Subgrade soils data were obtained from samples taken during site installation. Pavement ratings, original highway designs, maintenance history, traffic counts, and similar data were obtained from the Oklahoma Department of Highways. Correlations indicate that most subgrade moisture variations occur on an annual cycle with maximum moisture contents occurring during winter months. Magnitude and frequency of variations are greatly affected by infiltration of runoff where pavements are not impervious. Variations beneath pavements in good to excellent condition were found to be temperature dependent. Design features such as wide sealed shoulders and good surface drainage had significant effects on subgrade moisture variations. Rigid pavements on well-graded sand base courses gave better pavement performance than any other type of design investigated.

•SUBGRADE moisture variations, with resulting changes in volume and strength of subgrade soils, may cause premature highway pavement failure. Development of relations between cause, extent, and effect of subgrade moisture conditions may lead to revised design procedures for improving pavement performance.

Accordingly, the School of Civil Engineering at Oklahoma State University initiated, in June 1964, a six-year study to measure subgrade moisture variations under Oklahoma highways, relate them to soil, climate, and pavement conditions, and, hopefully, develop design recommendations for improving pavement performance.

Nuclear depth moisture and density gages were selected to measure subgrade moisture variations. After preliminary planning (1), 50 field test sites were installed throughout northeastern and north central Oklahoma, 30 in the summer of 1966 and 20 in the summer of 1967. The sites were located on highways of various conditions, designs, and traffic volumes.

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REASONS FOR MOISTURE MIGRATION

Soils moisture migrates as a result of any force which upsets equilibrium in the soil-water system. There are several different viewpoints in the literature concerning forces that cause moisture to migrate. A few of the most widely discussed hypotheses are hydrostatic pressure, capillary pressure, disjoining pressure of aqueous films (often referred to as osmotic pressure), chemical potentials, and temperature gradients. Moisture may migrate through soil in the liquid phase, vapor phase, or a combination of the two, depending on forces causing pore water movement. A more detailed explanation of these factors is available elsewhere (2).

Sources of free water must be present for moisture migration to occur in subgrades. Primary sources of moisture in subgrades are: seepage of water into the subgrade from higher ground, fluctuation of the water table, percolation of water through the pavement surface, migration of water from shoulder slopes or verges, migration of water from water bearing layers below the subgrade, and transfer of water vapor from any of these sources. Figure 1 shows these sources in reference to a typical highway cross section. Pavement sections may not be exposed to all of these sources at once, but any one may provide enough moisture to cause premature pavement failure. Oklahoma highways are susceptible to moisture migration from any one or combination of these sources.

SUMMARY OF PREVIOUS SUBGRADE MOISTURE STUDIES

Several agencies and individuals have conducted extensive subgrade moisture studies in recent years, among them the Missouri Highway Department (3), Aitcheson and Richards in Australia (4, 5), and Russam and Dagg in Kenya (6). In the United States, Mickle and Spangler at Iowa State University (7) and Moore at Texas A&M University (8) have also conducted subgrade moisture research. A summary of these studies is available elsewhere (2).

Research by these agencies and individuals indicates that much remains to be learned about subgrade moisture conditions. Data on all possible factors affecting subgrade moisture conditions should be collected, evaluated, and correlated. A preliminary approach to this problem is described in the following sections.

DATA COLLECTION PROCEDURES

This section describes problems, procedures, and solutions associated with installation of research sites and collection of subgrade moisture data. Other factors influencing moisture variations are also discussed.

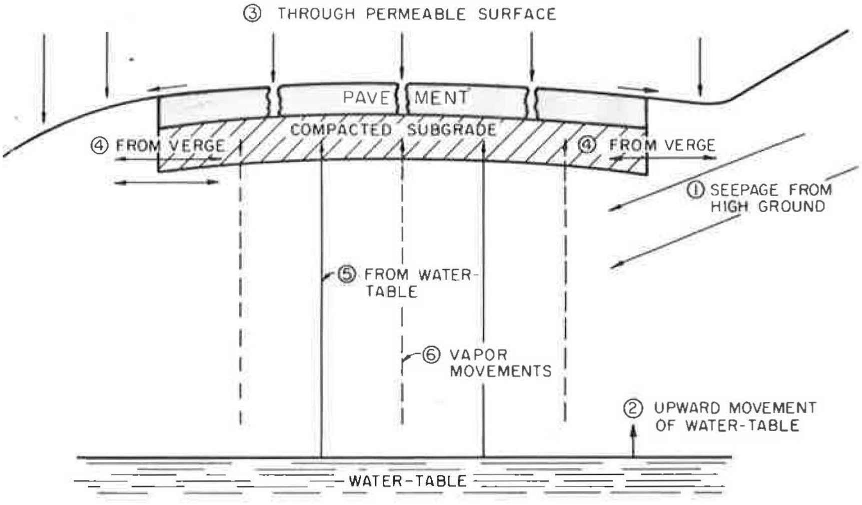

Figure 1. Sources of free water for subgrade moisture migration.

Nuclear Equipment

Nuclear moisture and density gages used for research were purchased from Troxler Electronic Laboratories, Inc., Raleigh, North Carolina. Equipment inventory consisted of (a) 2-Model 200B transistorized scaler, (b) 2-Model 504 depth density probe with combination shield/standard, and (c) Model 104 depth moisture probe with combination shield/standard. Both moisture and density gages measure soil properties indirectly by the radiation backscatter phenomenon. Detailed explanations of operating methodology are given by Moore and Haliburton (9).

Field Test Site Selection

Fifty research sites are presently located in northeastern and north central Oklahoma. Thirty of these sites were installed during the summer of 1966 and 20 during the summer of 1967. Preliminary site selections were made in the office from an official state highway map. Initial locations were selected on the basis of three major criteria (a) on primary Federal-aid highways, (b) within 10 miles of climatological recording stations, and (c) within a reasonable driving radius of Oklahoma State University. Final selection of field research sites was made in the field. The general area of preliminary selection was visited to find an exact location possessing good sight distance in both directions, adequate pavement width, and typical Oklahoma highway cross section, with desired soil conditions and adequate sight distance.

Nuclear Moisture/Density Data

Each research installation consists of three 10-ft long access tubes, one at the edge of each improved shoulder and one at centerline of pavement. At sites with open shoulders, shoulder access tubes were installed through the extreme edges of pavement. Detailed procedures for test site installation are available elsewhere (10).

Two 1-min nuclear data readings were taken at 1-ft intervals progressing from the bottom of access tubes. An extension tube (fitted over the access tube) was used to hold the shield/standard above the hole while the probe was lowered into the tube for readings. Reading levels were adjusted for each tube so that the depth probes (each approximately 18 in. long) would be just beneath the pavement during the last reading. Moisture data at each site are collected on a 6- to 8-week interval, whereas density data are collected at 6-month intervals.

Subgrade Soils Data

Soil samples were obtained from subgrades at each site during installation of access tubes. Samples were taken at 1-ft intervals as access tube holes were augered. Although the method of sampling by augering soil from test holes may not be the most effective method of soil exploration, samples obtained in this manner were adequate for routine classification tests on the material.

Climatological Data

Monthly mean high and low temperatures, as well as precipitation quantities, were extracted directly from Climatological Data—Oklahoma. These monthly bulletins were supplied by the U. S. Department of Commerce, National Weather Records Center, U. S. Weather Bureau, Asheville, North Carolina.

Miscellaneous Data

Highway pavements and shoulders were rated periodically by the Oklahoma Department of Highways, Research and Development Division. Cross section details, traffic volumes, and a construction and maintenance history of each site were obtained from the Oklahoma Department of Highways.

Data collection procedures were devised by research project personnel to obtain information and data related to any factors affecting subgrade moisture movement. Data collected from each site may be found elsewhere (11).

DATA CORRELATION AND EVALUATION

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

Correlation Procedures

Large quantities of compiled data necessitated use of a mechanical sorting procedure for initial general data correlation. Broad categories were selected to describe conditions existing at each research site. Features such as type of pavement, base material, subgrade soil classifications, drainage conditions, as well as climatological data, moisture variations, and dry densities collected from each site were coded on IBM cards. Table 1 summarizes conditions found at each research field site. General trends and relationships were found by sorting cards in many arrays, holding different parameters constant.

Once a general trend had been indicated by initial sorting, investigation of individual sites was begun. The process was found to be most effective if a small amount of sorting was done, followed by visual inspection of any trends obtained, and then additional sorting. Personal knowledge of every site was of the utmost benefit in correlation and evaluation of collected data.

Correlations Between Subgrade Moisture Variations and Related Factors

Relationships and trends in subgrade moisture variations are based on correlation of data collected from 30 research sites during the period of June 1966 to August 1967.

Moisture variations were found to occur in an annual cycle with maximum moisture contents occurring during winter months. Cyclic variations were affected considerably by precipitation at sites located on poor pavements. Most sites where precipitation affected subgrade soil moisture were on rigid pavement sections modified by an asphaltic-concrete overlay. Although variations were cyclic, the general trend appears to be an increase in subgrade moisture content.

Moisture variations beneath pavements with high ratings were felt to be predominantly temperature dependent. High moisture contents occurred during cold seasons and decreased during summer months, but variations could not be correlated to measured precipitation. Moisture variations resulting from temperature changes were usually between 1 and 5 percent. Smallest moisture variations were found beneath newly constructed highways with excellent pavement and shoulder ratings.

Variations in moisture content resulting from infiltration of runoff lagged rainfall by 4 to 6 weeks. This was particularly noticeable at highway shoulders. Figure 2 shows variations beneath the pavement at Site No. 4 which has open shoulders, resulting in high runoff infiltration. Sealed shoulders reduced infiltration, resulting in smaller variations beneath pavements as indicated by moisture variations at Site No. 3 (Fig. 3). Effects of sealed shoulders may be seen by comparing variations in Figures 2 and 3. As shoulder widths increased, moisture variations under pavement centerlines were found to decrease and be less dependent on precipitation.

Moisture contents in shoulders do not always increase as do those of subgrade soils under pavement. Phenomena such as those at Site No. 29 (Fig. 4) often occur in fill sections. Moisture variations at this site indicate downward moisture migration in the shoulders. Moisture contents at shallow depths are decreasing while those at greater depths increase. As moisture content decreases with time, shoulders shrink or settle. Subgrade soil used as a fill material is a clay soil of low plasticity but relatively large lineal shrinkage of 15 to 20 percent. As moisture migration continues, shoulders continue to creep away from the pavement, allowing direct infiltration of runoff into pavement subgrade. Such conditions may be prevented by placing fills at moisture contents equal to those of original subgrade soils. Moisture equilibrium between fill and original soil may reduce moisture migration, reducing settlement and maintenance problems.

TABLE 1

DATA SUMMARY FOR FIELD RESEARCH SITES

Size No.	Pavement Type	Shoulder Type	Base Course Material	Unified Soil Class.	Typical Cross Section	Pavement Rating	Shoulder Rating	Max. Rainfall	Max. Moisture at Center Line	Drainage Conditions	Liquid Limit	Plastic Limit	Specific Gravity	Maximum Moisture at Hole A	Maximum Moisture at Hole C	Date of Completion	AASHO Classification	Traffic Volume (ADT)	Truck Traffic
1	PCC	Open	SBC	ML	Grade	Exc.	Poor	July	Feb.	Fair	M	M	M	Aug.	Feb.	1931	A-4	L	L
2	AC/PCC	Imp.	SBC	SF	Trans.	Good	Exc.	July	Dec.	Good	L	L	L	Aug.	Dec.	1955	A-3	M	M
3	AC	Imp.	SABC	CL	Grade	Exc.	Exc.	July	Dec.	Good	H	M	H	Mar.	Sept.	1963	A-4	VH	H
4	AC/PCC	Open	SBC	CL	Grade	Poor	Poor	Sept.	Nov.	Fair	H	M	H	Nov.	Sept.	1930	A-6	L	M
5	AC/PCC	Open	SABC	CL	Trans.	Poor	Poor	Sept.	Nov.	Good	H	M	L	Sept.	Sept.	1962	A-6	L	M
6	PCC	Open	SBC	CL	Fill	Good	Poor	May	Nov.	Fair	H	M	M	Aug.	July	1930	A-6	L	H
7	AC/PCC	Imp.	SABC	CL	Cut	Good	Exc.	Aug.	Feb.	Good	VH	H	VH	Feb.	April	1965	A-6	M	M
8	AC/PCC	Imp.	SABC	CH	Grade	Poor	Good	Aug.	Oct.	Good	VH	H	M	Mar.	Aug.	1962	A-7	H	H
9	PCC	Imp.	SBC	CH	Cut	Exc.	Exc.	April	Aug.	Good	VH	M	H	Aug.	Aug.	1959	A-7	VH	H
10	AC	Imp.	SBC	CL	Cut	Good	Fair	April	Aug.	Good	M	M	H	Aug.	Aug.	1963	A-6	H	M
11	AC	Imp.	SBC	SF	Grade	Exc.	Exc.	Aug.	Oct.	Fair	L	L	M	May	May	1952	A-3	H	M
12	AC	Imp.	SBC	CL	Grade	Exc.	Exc.	May	Dec.	Fair	H	M	H	Dec.	Dec.	1965	A-6	M	M
13	AC/PCC	Open	SBC	SP	Fill	Fair	Poor	July	Sept.	Fair	L	L	M	Aug.	Sept.	1951	A-3	L	L
15	PCC	Imp.	SBC	SF	Cut	Exc.	Exc.	Sept.	Nov.	Good	M	M	M	Feb.	Nov.	1952	A-4	M	H
16	AC	Imp.	SABC	CL	Fill	Exc.	Exc.	Aug.	Feb.	Good	H	H	H	Nov.	April	1947	A-6	VL	L
17	AC	Open	SABC	CL	Grade	Fair	Good	July	Feb.	Fair	H	M	H	Feb.	Jan.	1954	A-6	VH	H
19	AC/PC	Imp.	SBC	CL	Grade	Good	Exc.	Aug.	Dec.	Good	M	H	VH	Aug.	Aug.	1966	A-4	H	H
20	AC	Imp.	SBC	CL	Cut	Exc.	Exc.	Sept.	Dec.	Good	H	M	VH	Dec.	Dec.	1954	A-6	VH	H
21	PCC	Imp.	SBC	CL	Grade	Exc.	Exc.	Aug.	Nov.	Good	H	M	H	Dec.	Oct.	1959	A-6	L	M
22	AC	Imp.	SABC	SP	Grade	Good	Exc.	July	Nov.	Fair	L	L	H	Dec.	Dec.	1957	A-3	M	H
23	PCC	Imp.	SABC	CL	Grade	Exc.	Exc.	Aug.	Oct.	Good	VH	H	VH	July	Mar.	1961	A-7	L	M
24	PCC	Imp.	SBC	CL	Grade	Exc.	Good	Aug.	Dec.	Good	H	H	VH	Dec.	Dec.	1955	A-7	VH	H
25	AC/PCC	Open	SBC	CL	Cut	Poor	Poor	Sept.	Nov.	Fair	H	M	VH	Nov.	Nov.	1929	A-6	VL	M
26	PCC	Imp.	SBC	SP	Trans.	Exc.	Exc.	Sept.	Nov.	Good	H	M	H	Sept.	Nov.	1963	A-6	L	M
27	PCC	Imp.	SABC	CH	Cut	Good	Exc.	July	Nov.	Good	VH	H	H	Oct.	Oct.	1960	A-7	VH	H
28	AC/PCC	Open	SBC	CL	Fill	Fair	Poor	Aug.	Nov.	Fair	H	M	H	Nov.	Nov.	1963	A-6	M	M
29	PCC	Imp.	SBC	CL	Fill	Exc.	Exc.	April	Oct.	Good	H	H	H	Oct.	Oct.	1960	A-6	H	H
30	PCC	Imp.	SBC	SF	Fill	Exc.	Exc.	Sept.	Nov.	Good	L	L	M	Nov.	Nov.	1963	A-4	L	L

PCC—portland cement concrete pavement.
AC—asphaltic-concrete pavement.
AC/PCC—portland cement concrete modified with asphaltic-concrete overlay.
Trans.—transition cross section.
Imp.—improved shoulders.
SBC—sand base course.
SABC—stabilized aggregate base course.
L—light.
Exc.—excellent.
VH—very heavy.
H—heavy.
M—medium.
VL—very light.

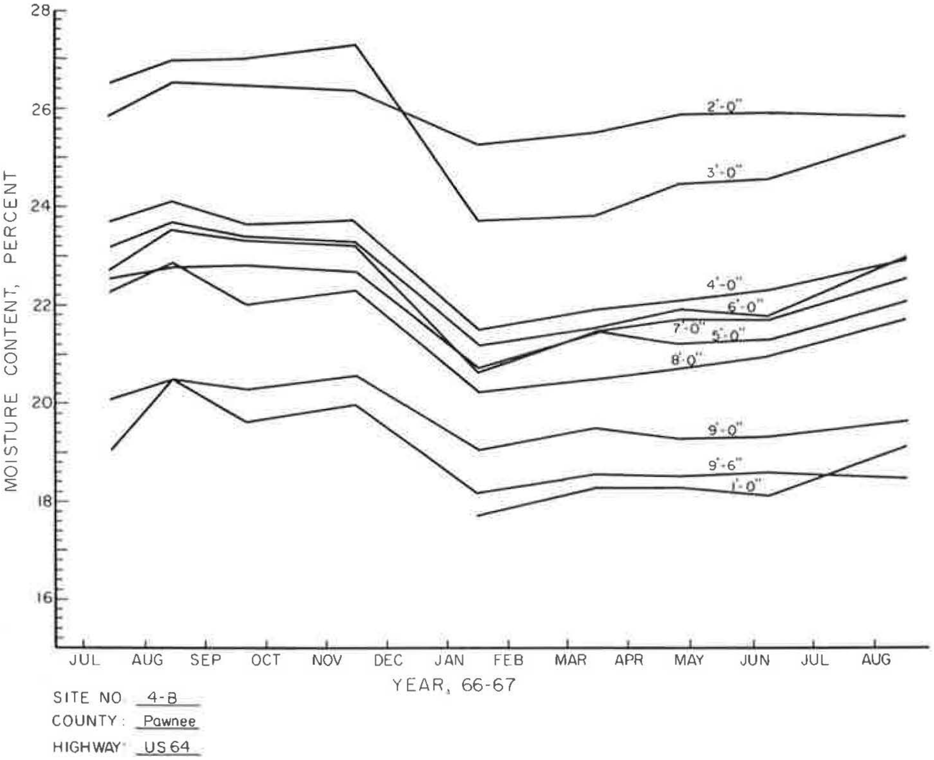

Figure 2. Moisture variations beneath pavement at Site No. 4.

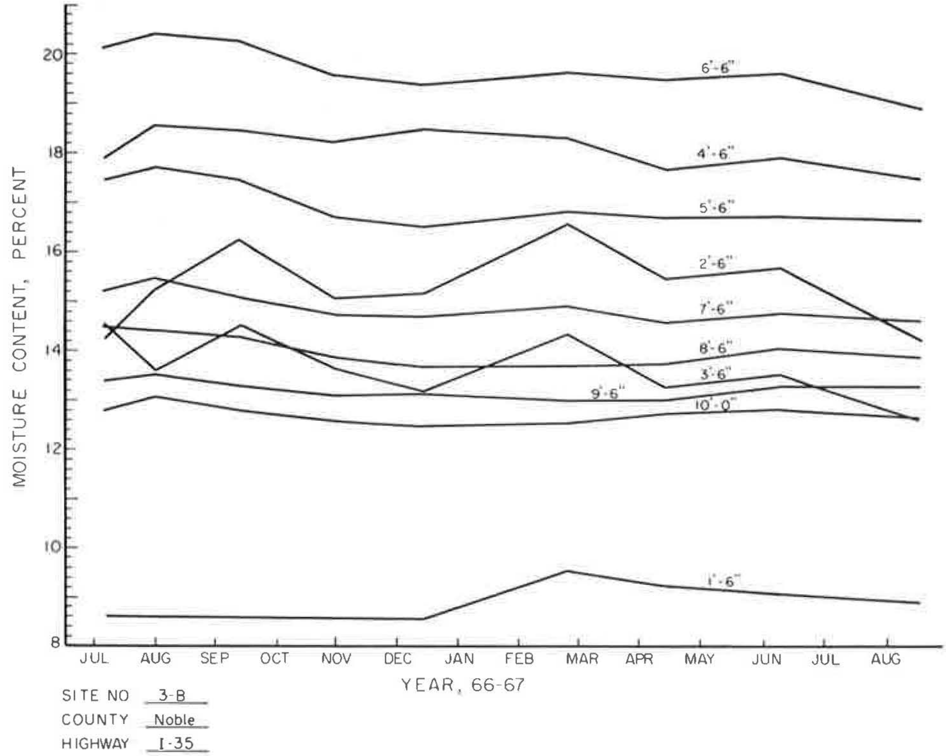

Figure 3. Moisture variations beneath pavement at Site No. 3.

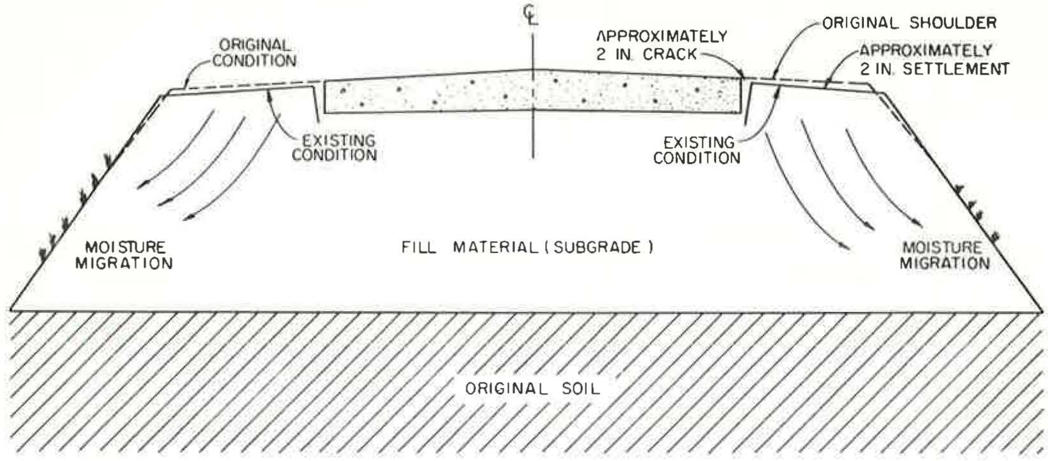

Figure 4. Shoulder conditions existing at Site No. 29.

Compacted sand base courses were found to be predominant beneath pavements with excellent ratings, regardless of age. Sand blankets may disperse moisture, preventing large infiltrations directly into subgrade soils. Compacted sand is capable of holding relatively large quantities of moisture by capillary action or tensile stresses. Runoff infiltration through pavement cracks and joints may be held by the sand and spread over the entire pavement cross section, resulting in negligible effects of infiltration on subgrade soils. Moisture held by capillary forces is drawn from the sand by stronger forces of subgrade clayey soils. Distribution of moisture by sand base courses may produce more uniform moisture conditions in subgrade soils. In cases where sand base courses were present but pavements had not performed satisfactorily, subgrade soil was found to have intruded into the base course. Intrusion of soil, especially clay, into sand blankets increases moisture levels directly beneath the pavement. Conditions of this nature beneath portland cement concrete slabs result in "mud pumping." Asphaltic-concrete pavements may show signs of rutting or complete failure. Sand base courses may produce adverse conditions if moisture is permitted to collect in the sand blanket from improperly designed shoulders. Site No. 28 is an example of improper use of sand blankets beneath pavement. Figure 5 indicates phenomena which occurred during site installation. The test site was installed the day after an evening rainstorm. Once holes were cored through the pavement, water flowed from the sand blanket directly beneath the pavement. Infiltration of rainwater had saturated the open shoulders resulting in formation of an artesian aquifer. Flow was estimated to be at least 2.0 cu ft/min.

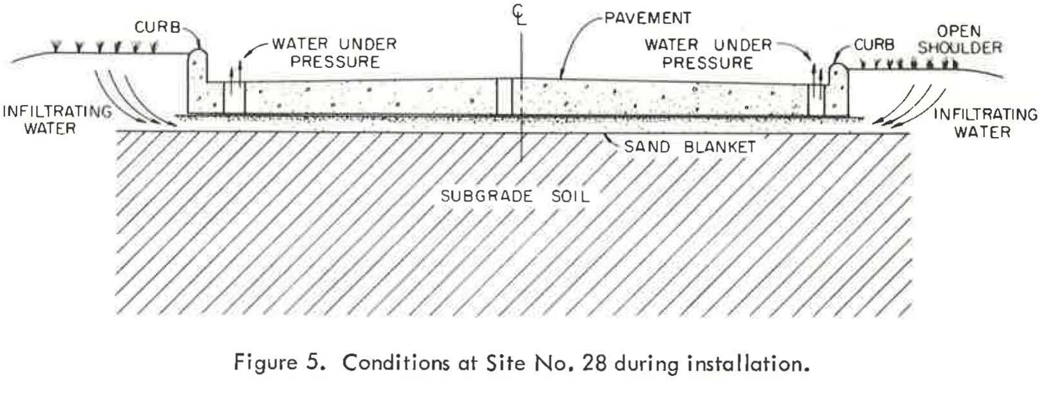

Figure 5. Conditions at Site No. 28 during installation.

French drains or tile drains to remove moisture from the open shoulders during periods of large rainfall would solve problems such as those at Site No. 28.

Type of subgrade soil was found to have no relation to subgrade moisture variations. Absence of any observed correlation of soil type to moisture changes may result from the presence of fairly uniform deposits of Permian and other Paleozoic clay soils in Oklahoma. Although these soils vary somewhat, their origin and stress history are similar.

Drainage conditions have effects on moisture variations at all sites. Pavements in good condition were associated with good drainage conditions for quick removal of surface runoff. Site No. 3, located on Interstate 35, has typical interstate drainage conditions. Hole A of Site No. 3 is located near the median where runoff may collect and infiltrate into the shoulder. Moisture variations obtained from this hole (Fig. 6) indicate the effect of infiltration. However, Hole C, on the outside shoulder where drainage is very good, is affected very little by rainfall, as indicated in Figure 7. Although drainage conditions at Site No. 3 are good, comparison of moisture variations at each shoulder indicates the large effect of slight differences in drainage conditions on moisture variations.

Type of highway cross section had some effect on subgrade moisture variations. Fill and transition sections were found to produce the worst moisture conditions, resulting in poor pavement ratings. Pavements constructed on grade or in slight cut sections had smaller moisture variations. Moisture conditions at 8- to 10-ft depths in these sections were found to be relatively constant. Based on these observations, it appears that moisture variations are reduced appreciably when initial moisture content of compacted subgrades is similar to the natural water content of existing soil. Moisture migration between subgrade and existing soil results from large differences in their relative moisture contents. Moisture variations were found to be smallest in subgrades where

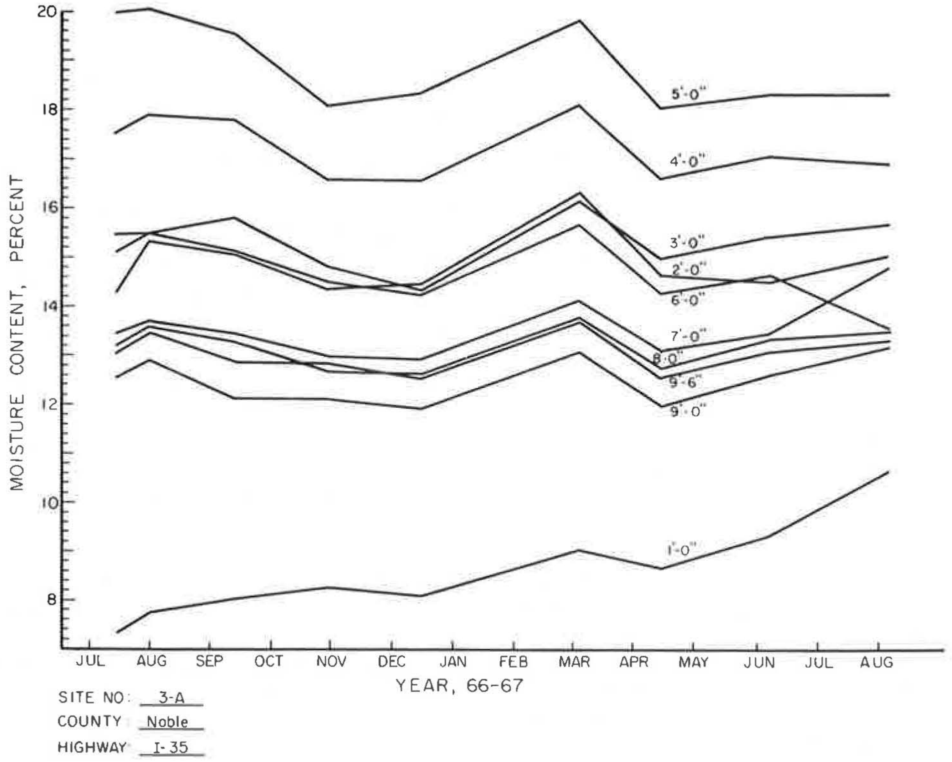

Figure 6. Moisture variations in shoulder near median at Site No. 3.

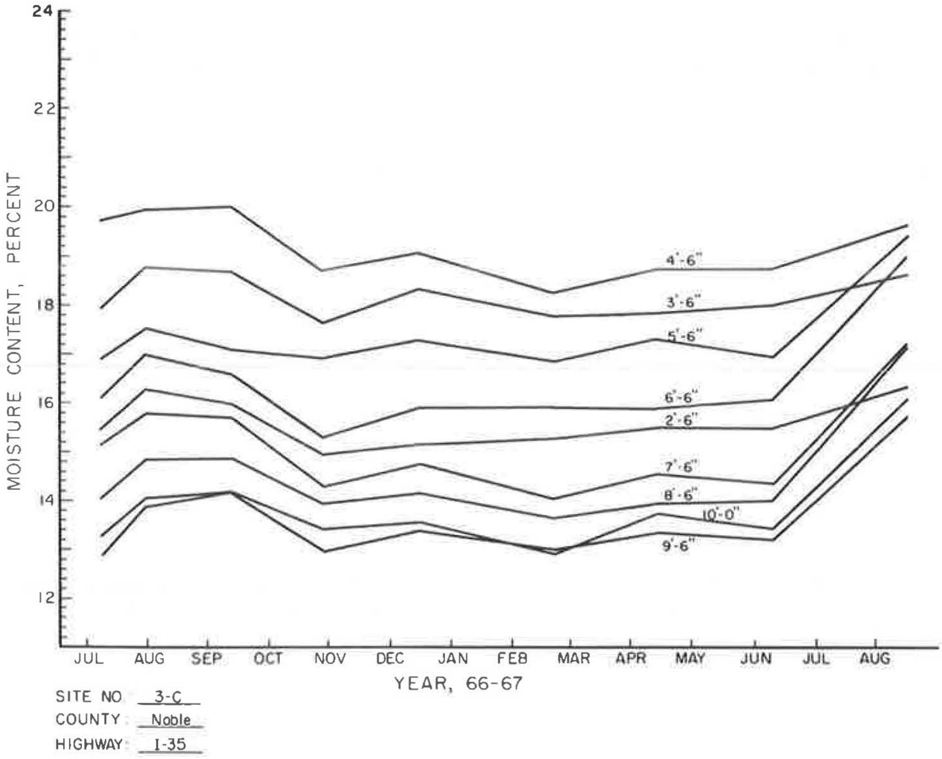

Figure 7. Moisture variations in outside shoulder at Site No. 3.

average moisture contents were below the plastic limit and greayest in soils where moisture contents were within the plastic range.

CONCLUSIONS AND RECOMMENDATIONS

Available data concerning moisture variations beneath Oklahoma highways have been compiled and correlated. Correlation of related factors affecting subgrade moisture movement has produced relationships and trends of subgrade moisture behavior. From the analysis of data discussed previously, the following may be concluded.

1. Most moisture variations occur beneath highway pavements on an annual cycle with maximum moisture contents occurring during winter months. Magnitude and frequency of variations are greatly affected by infiltration of runoff where pavements are not impervious.
2. Moisture variations resulting from infiltration, such as those found in shoulders and beneath most overlays, lag rainfalls by four to six weeks.
3. Subgrade moisture contents appear to be gradually increasing beneath pavements. No stable conditions were indicated by collected data except at sites where the groundwater table was consistently high.
4. In cases where proper design and gradation of sand base courses were employed, moisture variations resulting from infiltration were reduced, producing good pavement performance.
5. Good drainage conditions, necessary to remove runoff completely and quickly, reduce moisture variations from infiltration through shoulders.
6. Soil type was found to have no noticeable effect on subgrade moisture variations beneath Oklahoma highway pavements.

7. Volume changes associated with moisture variations were large enough to form air gaps around access tubes, thus reducing measured values of dry density in summer months.
8. Procedures employed by the subgrade moisture variations research project for measurement of soil moisture by nuclear methods have proved to be accurate, dependable, repeatable, and economical.
9. Installation of field research sites has not been detrimental to highway pavements nor has it obstructed or reduced traffic volumes of pavement sections containing research sites.

These conclusions have substantiated some theories of moisture migration and shown interesting quantitative trends. Research procedures have been verified and guidelines for detailed future study have been establishment. However, data collected from only 60 percent of current field test sites for a 1-yr period are not sufficient to provide final qualitative answers to the subgrade moisture variations problem, though it is hoped such data will be developed before project termination in 1970.

With respect to future project research, the following recommendations are made:

1. Instrumentation of selected research sites to record subsurface soil temperatures should produce additional information related to temperature controlled moisture migration.
2. Additional access tubes should be installed at some sites where wide pavement sections or wide sealed shoulders exist. These holes would produce information better relating amount of shoulder infiltration to moisture variations beneath pavements.
3. Subsurface benchmarks (a rod inside an access tube) should be installed at selected sites to obtain qualitative data concerning seasonal movements of pavement.
4. Correlations between moisture conditions and soil type may be obtained from additional soil sampling at each site. Soil samples obtained from such a program should be of sufficient size to allow extensive testing.
5. Collected data should be reduced and compiled as quickly as possible to allow continuous investigation of site behavior.

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The opinions, findings, and conclusions expressed in this paper are those of the authors and not necessarily those of the State of Oklahoma or the Bureau of Public Roads.

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