Influence of Temperature and Other Climatic Factors on the Performance of Soil-Pavement Systems

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Typical climatic and environmental data obtained during the AASHO Road Test are summarized. A brief description of the instruments, methods of installation, and measuring techniques is presented. The influence of temperature and climatic factors on the performance of soil-pavement systems are examined, including the effect of the various cover conditions on the seasonal fluctuation of the groundwater level, on the depth of frost penetration, and on the temperature in different parts of the soil-pavement system. In addition, the influence of temperature on the soil-pavement performance as reflected in surface strains and deflections is discussed. Finally, the seasonal fluctuations of strength characteristics of pavement components and of subsurface conditions are evaluated. It is suggested that the data available from the AASHO Road Test can provide a useful basis on which to develop a more complete understanding of the performance of soil-pavement systems.

•THE IMPORTANCE of climatological factors related to the performance of highway pavements was pointed out by Eno in 1929 (15). These factors include temperature, frost, sunshine, wind, humidity, precipitation, runoff, and evaporation. In 1944 Winterkorn (31) used physicochemical concepts to explain how these factors affected the performance of highway structures. Since then, many investigators have attempted to develop measuring techniques and analysis methods that isolate each of these factors. Highway engineers believed that moisture content and temperature of pavement components, as well as depth of frost penetration and groundwater fluctuation, had the most significant effects on pavement performance (5, 13, 32, 33, 36). Ultimately, all these factors derive from the thermal regime on the earth surface (17, 31, 33, 35).

Guinnee (18) reported information concerning subgrade moisture content and its change with time under rigid pavements having various dimensions of the pavement components. Russam and Coleman (23) discussed the effect of climatic factors on subgrade moisture conditions. Croney, Coleman, and Black (13) showed how the distribution of water in soil is related to highway design and performance. Fang and Schaub (16) demonstrated that subsurface conditions influence deflection and strength characteristics of pavement components. Kolyasev and Gupalo (20) showed the relationship of thermal diffusivity and heat conductivity to soil moisture content and density.

Crabb and Smith (12) studied soil temperature under various vegetation covers. Carson (11) analyzed the time variation of soil and air temperature data by use of Fourier techniques and discussed the heat-transfer processes operating in soil.

Kersten and Johnson (10, 19) reported that, both from theoretical and field observations, frost penetration is greatest in soils with low moisture content and least in those with high moisture content. This, of course, is a consequence of the high specific heat of water. Turner and Jumikis (27) discussed the relationships between surface temperature and moisture content and considered problems of drainage, frost heave, and moisture migration in soil upon freezing. Aldrich (4) discussed the fundamentals relating to the penetration of frost below highway and airfield pavements.

Studies of groundwater fluctuation related to climatic factors and soil conditions have been reported by several investigators (7, 21, 24, 30).

Winterkorn (32, 33, 34, 35) and Van Rooyen and Winterkorn (28, 29) investigated, both theoretically and experimentally, thermal conductivity and mass transport in moist soils and similar porous systems.

The major objectives of this paper are to summarize the typical climatic and environmental data obtained from the AASHO Road Test; to discuss the effect of the various cover conditions on the seasonal fluctuations of groundwater level and on the depth of frost penetration; to present temperature data for different parts of the soil-pavement system; to correlate strains and deflections of the system with temperature; and to study the influence of seasonal factors on the strength characteristics of pavement components. The systematic collection of such data is considered a prerequisite for comprehensive analyses of the effects of temperature and other climatological factors on soil-pavement systems.

DESCRIPTION OF THE AASHO ROAD TEST SITE

The location of the AASHO Road Test is northwest of Ottawa, La Salle County, Illinois. The annual precipitation at the site averages about 34 in., of which about 2.5 in. occur as 25 in. of snow. The area has an average mean summer temperature of 76 F and an average mean winter temperature of 27 F. Normally, the average depth of frost penetration is about 28 in. The soil usually remains frozen during the winter except for alternate thawing and freezing of the immediate surface.

The topography of the Road Test area is level to gently undulating with elevations varying from 605 to 635 ft above mean sea level. Drainage is provided by several small creeks, which drain into the Illinois River. Surface drainage, however, is generally slow.

Geologic information indicates that the area was covered by ice during several glacial periods and that the present-day subsurface soils were deposited or modified during these periods. Surface soils were subsequently derived from a thin mantle of loess deposited during a postglacial period. Bedrock, varying from sandstone at the west end of the test road to either a clay shale or shaley limestone at the east end, is found 10 to 30 ft below the surface.

The test facility was constructed along the alignment of Interstate Route 80 and consisted of four major loops (Loops 3 through 6) and two smaller loops (Loops 1 and 2). Loop 1 was not subjected to traffic.

The road test sections were constructed of one type each of soil, subbase, and base material considered typical of national practice. Both flexible and rigid pavements of various design thickness were included. Within the flexible pavement sections, four types of base were included: crushed stone; regular gravel; cement-treated gravel; and bituminous-treated gravel. The details of the construction procedure, field control, and variability of the test results are given in the AASHO Road Test reports (1, 26).

GROUNDWATER FLUCTUATION

Groundwater levels generally fall in the winter period and rise in the spring. Meyer (22) observed in both laboratory and field investigations that groundwater levels fell during the winter as the air temperature decreased and rose approximately the same amount in the spring as the air temperature increased. Schneider (24) also investigated the relationships of air temperature to groundwater levels. He attributed winter water table decline to upward movement of capillary moisture toward the frost layer. Willis et al (30) reported that water table lowering was associated with depth of frost and was accompanied by increased soil moisture in the frost zone about the water table. Benz et al (7) also demonstrated that changes in soil moisture content and water table elevation were associated with soil temperature. As the soil temperature decreased during the winter, the water table fell and the soil moisture content increased in the surface horizons by migration of water from the subsoil.

The groundwater fluctuation study at the AASHO Road Test included three different cover conditions: under uncovered areas, under rigid pavements, and under flexible pavements. In addition, a comparison between nontraffic and traffic areas was undertaken.

A total of 26 water table measurement installations were made on the centerline of all the test loops. Four-inch diameter cores were taken from the pavement surface and holes were bored to a depth of 16 ft. A sand-gravel mulch was placed in the holes to form a base for the pipe through which water table elevations were to be measured. The pipe was lowered into the hole with the top of the pipe approximately ½ in. below the pavement surface. The sand-gravel mulch was compacted around the pipe and brought to within 1 ft of the surface. On the rigid pavement test sections, a concrete mix was placed level to the pavement surface around the top of the pipe. On the flexible pavement a hot-mix asphalt was compacted around the pipe. On the uncovered area the water table installations were placed along the fence line of the right-of-way. To measure the elevation of the water table at each installation, a portable electrical sounding device was designed. The details of the device and the test procedures have been reported by Leathers, Fang, and Donnelly (21).

Groundwater level readings were taken at each location approximately every two weeks from August 1958 to January 1961. Figure 1 shows the groundwater fluctuation with time for the various cover conditions. It may be seen that the groundwater fluctuations were significantly greater under the nontraffic loop (Loop 1) than under the traffic loop (Loop 6). However, under the same traffic conditions, the groundwater fluctuations for both rigid and flexible pavements were similar. For the uncovered area the groundwater level was closer to the ground surface then for the covered area because the rate of infiltration of the uncovered area was greater than for the covered area.

FROST PENETRATION

A device was developed at the Road Test by which determination of "depth of frost" could be made without disturbing the pavement. The system was based on the knowledge that the electrical resistance of a soil-water system changes rapidly upon freezing due to a large difference in resistivity between the solid and liquid phase of water. Pairs of electrodes buried in the soil at 1-in. intervals of depth were connected to leads that extended to the surface. Measurements of the resistance across these electrodes indicated the depth to which the soil-water system had frozen. The details of this system and test procedure are described by Carey and Andersland (9).

Frost depth indicators were installed in both flexible and rigid pavement test sections. There were 28 installations in the rigid pavement test sections and 16 installations in the flexible pavement test sections of Loop 1.

The installations in the rigid pavement tests sections were one per test section and were located at a point 1 ft from the pavement edge and 1 ft from a transverse joint. In sections with a base, the top of the indicator was placed 2 in. below the top of the subgrade. In those sections with no base, the indicator top was placed immediately beneath the concrete pavement surface.

The flexible pavement installations on Loop 1 were located in six test sections. Four of these sections had two indicators each, one in the shoulder material at the pavement edge and the other at the centerline of the section. The other two sections had four indicators each: one in the shoulder material, one at the pavement edge, one at the centerline of the section, and one at the centerline of the traffic lane.

In addition, a total of 20 frost indicators were installed in two test sections in each of the other five traffic loops (Loop 2 through Loop 6). These installations were made at the pavement edge and at the centerline of the traffic lane. In all installations the top of the indicator was placed 1 in. below the top of the embankment soil. Data were taken at least once each month during the frost period.

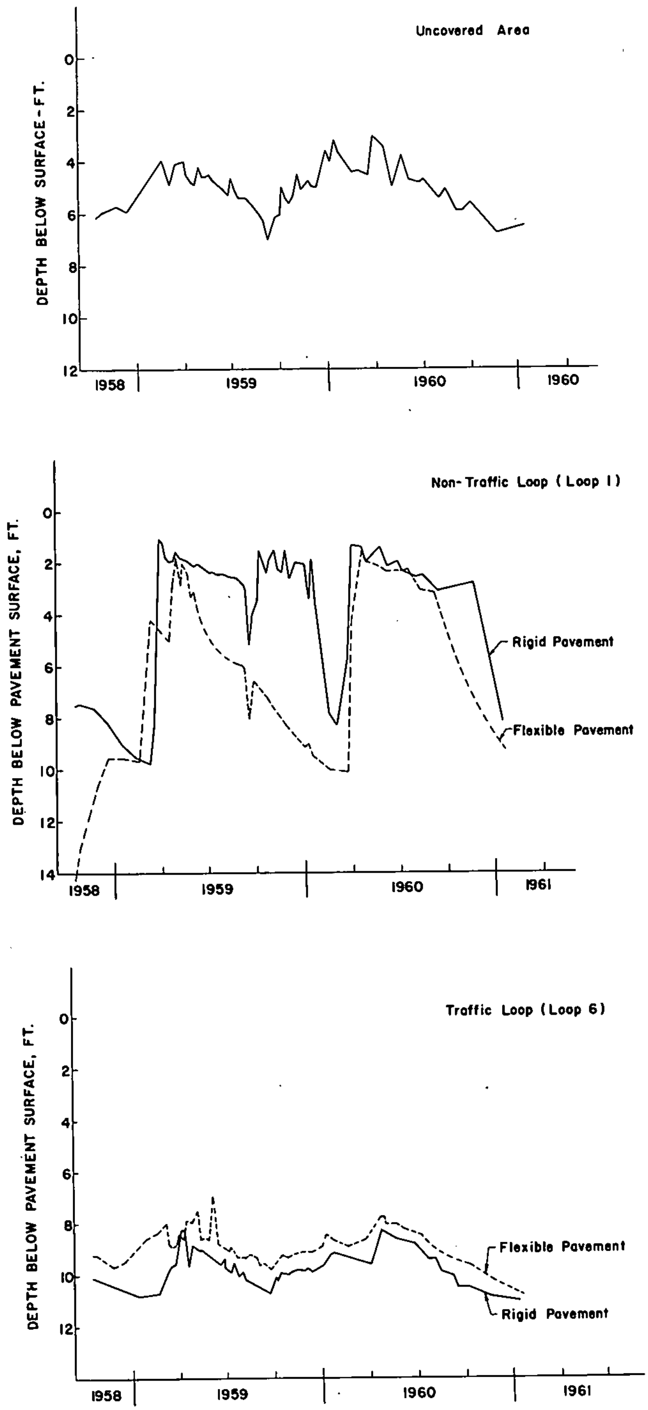

Figure 1. Groundwater fluctuation under various cover and traffic conditions.

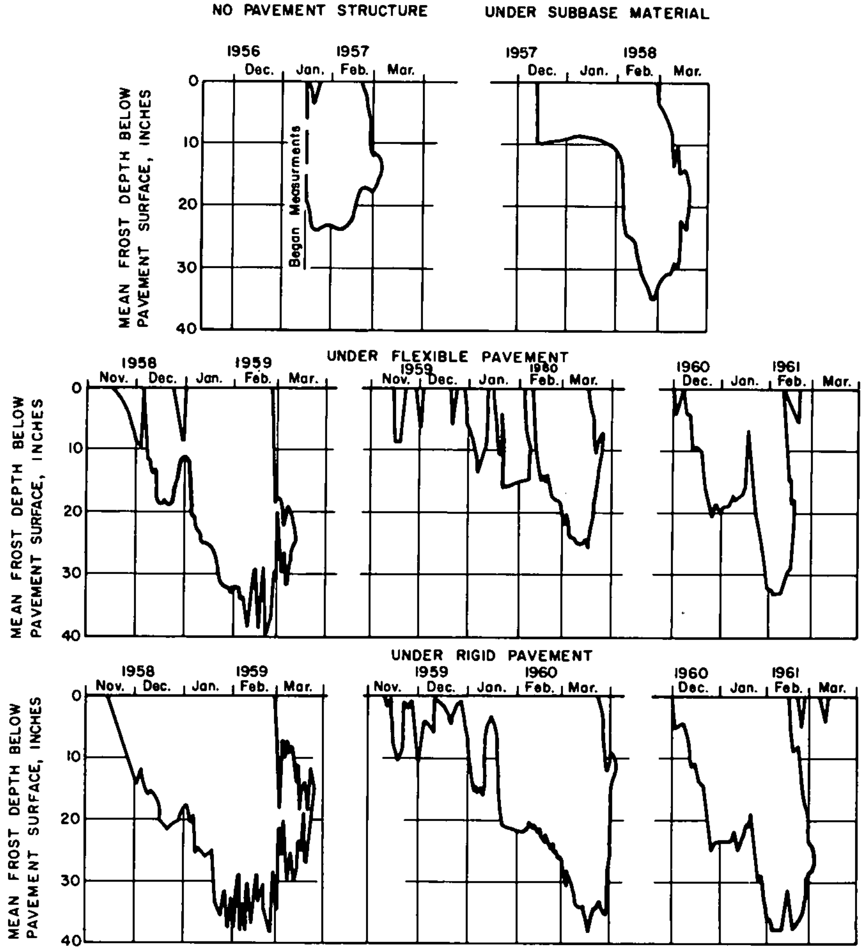

Figure 2. Frost depth under various cover conditions.

Figure 2 shows the mean frost penetration below the pavement surface for the four cover conditions studied: (a) no pavement structure; (b) under subbase material; (c) under flexible pavement; and (d) under rigid pavement.

It may be seen from Figure 2 that, in general, frost penetration was greater under rigid pavements than under flexible pavements, due to the greater heat conductivity of portland cement concrete. However, it should be noted that there was no subbase material in the case of rigid pavements. In fact, some rigid pavement test sections had neither subbase nor base material.

TEMPERATURE OF THE SOIL-PAVEMENT SYSTEM

Soil temperatures have been shown to vary in a somewhat regular pattern, reflecting both the annual and diurnal cycles of solar radiation. Superimposed on these regular cycles are fluctuations of variable duration and amplitude created by changing climatic conditions. Variation of air and soil temperatures have been reported by many investigators (11, 12, 13, 17, 25). Data are lacking, however, for the temperature variation within the pavement sections and for soil temperatures underneath various types of pavement covers. Data presented here show the temperature variation within the soil-pavement system for flexible pavements, rigid pavements, and their shoulders.

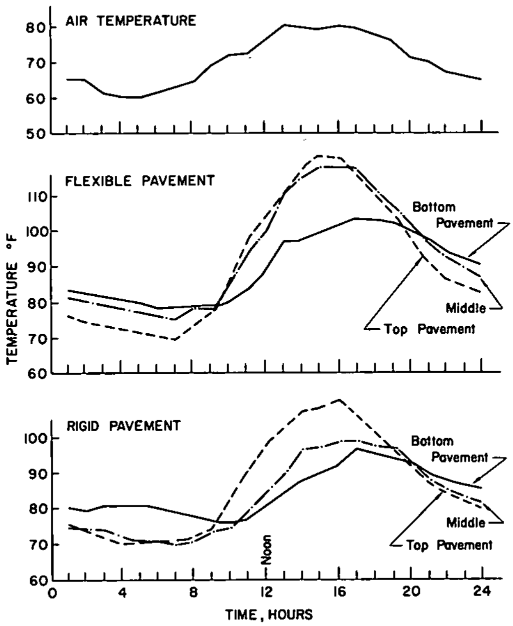

Figure 3. Twenty-four hour temperature study of pavement sections.

At the Road Test, thermocouple rods were used to measure temperatures. For the flexible pavements, thermocouples were located in both the nontraffic loop (Loop 1) and the traffic loops (Loops 2 through 6). Six indicators were placed at each test section: in both shoulder materials, at the pavement edge, at the centerline of the traffic lane, at the centerline of the pavement, and at the centerline of the passing lane. A code designation was given to each thermocouple in order to identify the test section, pavement component, hole number, and placement depth.

For the rigid pavements, thermocouples were located in Loop 1 with three indicators per test section. Two of these indicators were in the center of the section with one placed at the pavement edge and the other placed 1 ft from the centerline. The third indicator was located at a transverse joint, 2 in. from the pavement edge.

These thermocouples were read with a recording device capable of automatically reading 220 thermocouples consecutively at intervals of 5 minutes to 1 hour. Selected readings were made with a Bristol Recording Dynamaster (21).

Thermocouple data were used in the analysis of rigid pavement curl studies and in conjunction with pavement deflection studies for both rigid and flexible pavements. Other analyses were made including a study of 24-hour temperature variations, an investigation of frost depth-temperature relationships, and a study of temperature-depth effects. Typical temperature variation curves are shown in Figures 3 to 5.

Figure 3 shows the results of a 24-hour temperature study and indicates that although temperatures within both flexible and rigid pavement sections exhibited similar trends with time to those of the air temperature, the magnitude of variation of pavement temperature was much greater. Figure 3 also indicates that, in the early morning when the air temperature was low, the temperature of the pavement bottom was higher than that of the pavement surface. When the air temperature rose, the temperature at the top of the pavement surface rose sharply compared with that at the middle and bottom part of the pavement. This phenomenon is explained by the concept of heat conductivity or thermal diffusivity (17).

Figure 4 shows isotherms for the soil pavement system of Loop 1 (flexible pavement). The upper part of the figure was obtained when the air temperature was a maximum (80 F). The lower part was obtained the same day when the air temperature was a minimum (49 F). From these curves it may be seen that, when the air temperature was at its maximum level, the temperature of the underlying granular material decreased with increasing depth under the pavement centerline. When the air temperature was at a minimum level, the temperature of the underlying granular material increased with depth. In all cases, the "penetration" of a given temperature beneath the surfacing was significantly different from that beneath the crushed stone shoulders. When the air temperature was at its maximum level, heat penetrated into the granular material and embankment soil under the pavement surfacing to a greater depth than beneath the shoulders.

Temperature vs depth data for a 24-hour period are shown in Figure 5 for a soil-pavement section with rigid surfacing. It may be noted that, as in the case of Figure 4, the daily variation in air temperature had little influence on the temperature of the

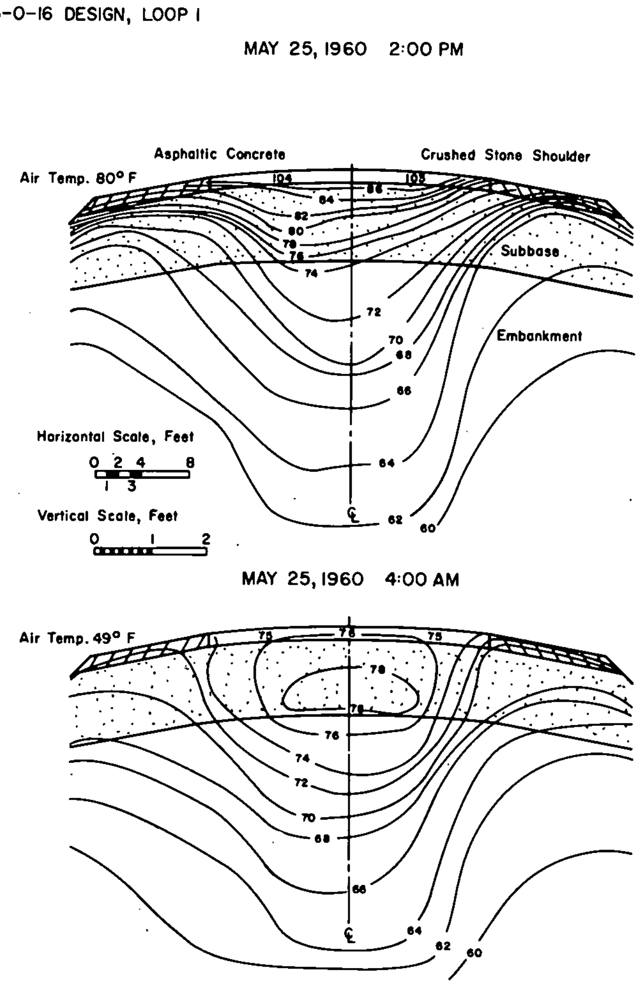

Figure 4. Soil-pavement system isotherms (flexible pavement).

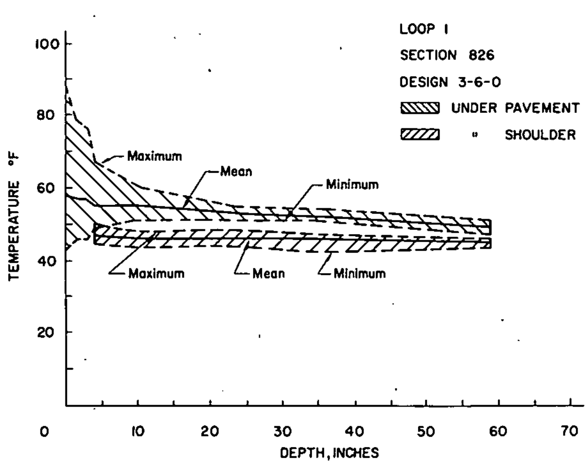

Figure 5. Temperature variations in soil-pavement system (rigid pavement).

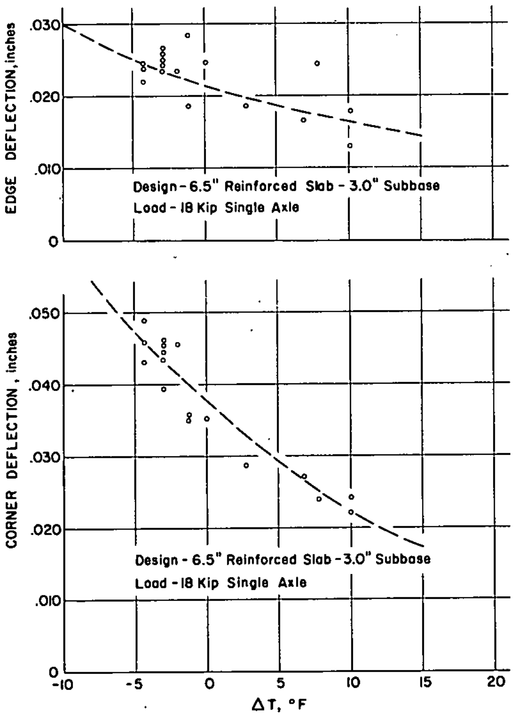

Figure 6. Effect of temperature on deflection of soil-pavement system (rigid pavement).

subgrade. However, the depth of influence may be expected to be a function of both thickness and heat capacity of the pavement materials.

INFLUENCE OF TEMPERATURE ON THE PERFORMANCE OF SOIL-PAVEMENT SYSTEMS

One useful measure of the performance of a soil-pavement system is the static and dynamic deflection of the pavement surface. Studies of the influence of temperature on surface deflections were conducted for both rigid and flexible pavement surfacings at the AASHO Road Test.

Rigid Pavements

Two devices were used for measuring the edge and corner deflections of the rigid pavement sections. The static rebound deflections were measured by means of a Benkelman beam deflection indicator (2, 6) having a probe length from pivot to tip of 10 ft. The Benkelman beam was placed on the shoulder and a standard measuring procedure was followed (2). The dynamic deflections were measured by use of linear variable differential transformers (LVDT) mounted in a $^3/_4$-in. diameter shell and installed at the pavement surface. The movable core foot of the LVDT rested on the top of a reference rod. This rod was anchored securely to a perforated plate located 6 to 8 ft below the pavement surface.

The pavement strain was measured by use of electrical resistance strain gages. The strain gages were cemented at the central transverse joint of each test section.

Deflection and strain measurements taken during the 24-hour studies are plotted (Figs. 6 and 7) against the temperature differential (ΔT) existing in a 6.5-in. slab selected as a standard. [Temperature differential is the temperature (F) at a point $^1/_4$ in. below the top surface of the 6.5-in. standard slab minus the temperature at a point $^1/_2$ in. above the bottom surface, determined at the time the strain or deflection was measured (2, p. 186).]

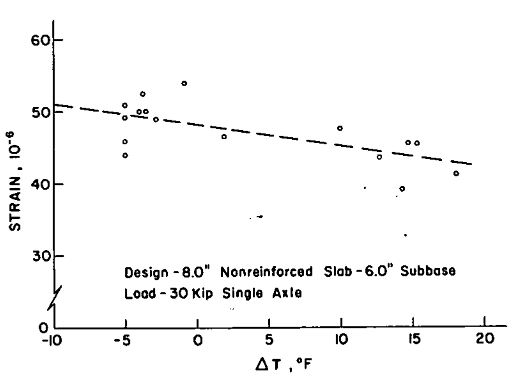

Figure 7. Effect of temperature on strain of soil-pavement system (rigid pavement).

When ΔT was positive, the top surface temperature of the standard 6.5-in. slab was higher than that at the bottom. It may be seen from Figure 6 that, as the temperature in the top of the slab increased relative to the bottom, the pavement strain or deflection decreased. A similar trend may be observed in all three cases shown in Figures 6 and 7.

Flexible Pavements

The influence of mat temperature on pavement deflection has been studied by several investigators (6, 8, 14, 25). Sebastyan (25) pointed out that the rebound deflections of pavements are affected by the mat temperature. He suggested that an average deflection change of 0.002 in. per 10 F variation of temperature may be used to correct the pavement deflections to a standard temperature of 70 F.

A standard Benkelman beam deflection test procedure was used to establish the effect of temperature on the deflection of flexible pavement having different types of base and pavement thickness. Typical data are shown in Figure 8 in which each point shown in the left part of the figure represents the average of all measurements within each loop for test sections having the same surfacing thickness. Measurements were made at four locations in each test section, two in the inner wheelpath and two in the outer wheelpath of the traffic lane. A 12-kip single axle load was used on all loops. The average base and subbase thicknesses were the same for each surfacing thickness.

The right part of Figure 8 represents data from the special base wedge test sections of Loop 6 at the Road Test. The surfacing thickness over all base types was 4 in., the subbase thickness beneath the bituminous and cement base was 4 in., and beneath the stone base it was 8 in. A 30-kip single axle load was used in this special study.

The results of the tests indicate that considerable reduction in pavement deflection may result from a decrease in mat temperatures.

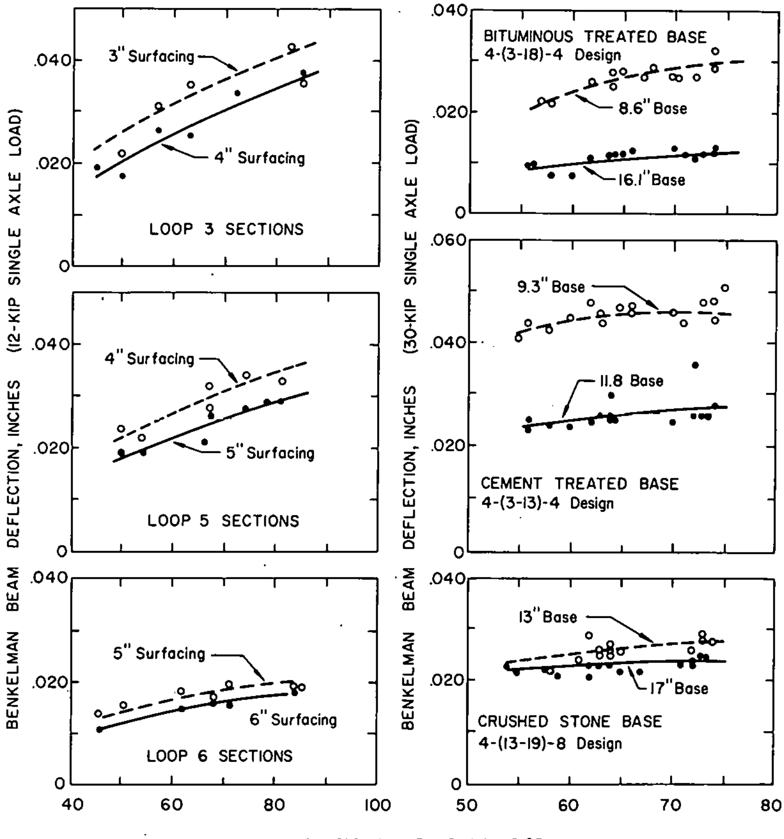

Figure 8. Effect of temperature on deflection of soil-pavement system (flexible pavement).

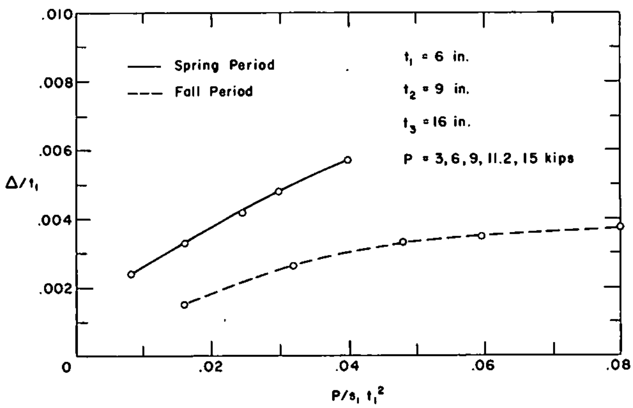

Figure 9. A nondimensional plot of the relationship between soil-pavement system deflection and wheel load (flexible pavement).

INFLUENCE OF SEASONAL FACTORS ON THE PERFORMANCE OF SOIL-PAVEMENT SYSTEMS

The influence of seasonal factors on the performance of soil-pavement systems is discussed in terms of the pavement surface deflections as well as the strength of the pavement components. Only data for flexible pavements are presented. However, similar information for rigid pavements may be found in the AASHO Road Test Report (2).

Deflection

The influence of seasonal factors on flexible pavement deflections have been reported by several investigators (8, 14, 25). The maximum deflection of a flexible pavement usually occurs immediately after the spring thaw and deflections then decrease to a minimum value by fall. It has been observed that a secondary increase in deflection may occur during the latter part of the initial thawing period. This is tentatively attributed to a readjustment in the thermal regime beneath the pavement when some frozen strata still exist at depth. Deflection may also increase in midsummer when pavement temperatures are highest. This increased deflection, however, is believed to result from temperature variations occurring in the bituminous surface course of the pavement and is usually insignificant when compared with the spring thaw deflections. The relationship between deflection and seasonal variation appears to be a function of subgrade soil type, total thickness and type of pavement structure, and rate and characteristics of the spring thawing. At the Road Test, comprehensive studies of this effect with various surface thicknesses were reported and similar conclusions were drawn (2, 6).

Fang and Schaub (16) used nondimensional techniques based on dimensional analysis to provide a rational basis for analyzing the Benkelman beam deflection data of flexible pavements. Data obtained from the AASHO Road Test have been successfully analyzed by such techniques.

Figure 9 shows a nondimensional plot of the pavement deflection (Δ/t_1) vs the wheel load parameter ($P/s_1 t_1^2$) for the spring and fall periods. The parameter P is the wheel load, s_1 is the strength of the surface, Δ is the pavement deflection, and t_1, t_2, and t_3 are the thicknesses of the surface, base course, and subbase respectively. It may be seen that for the spring period, for a given thickness of base or subbase, the pavement deflection increased sharply as the wheel load increased. For the fall period, there was a slight increase in pavement deflection as the wheel load was increased.

Figure 10 shows a nondimensional plot of the pavement surface deflection vs the thickness parameter under a given wheel

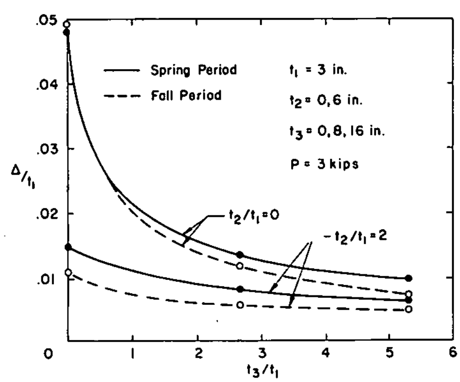

Figure 10. A nondimensional plot of the relationship between soil-pavement system deflection and thickness (flexible pavement).

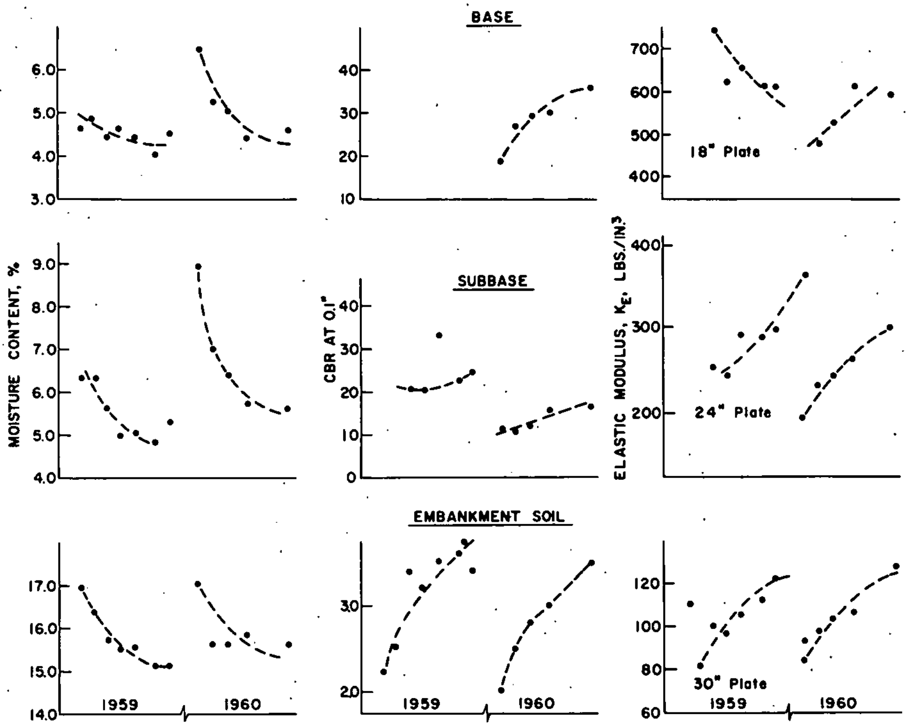

Figure 11. Seasonal variation in strength characteristics of soil-pavement system (flexible pavement) Loop 1.

load for different base thicknesses for both spring and fall periods. It may be seen that, for a given wheel load and strength of asphaltic concrete, the pavement deflection decreased as the subbase thickness increased. As the base thickness was increased from 0 to 6 in., the pavement deflection decreased markedly. The spring and fall variations of nondimensional deflection with thickness were similar.

Strength

The variation of moisture content, CBR, and elastic modulus over a period of two years is shown in Figure 11. All data were obtained from the nontraffic loop (Loop 1). It may be seen that, as may have been predicted, there was a tendency for the strength of the pavement components to increase as the moisture content decreased. It should be noted that tests on the traffic loops have yielded moisture content, CBR, elastic modulus, and density values that were different in magnitude from those obtained in Loop 1 studies. Normally, moisture contents were less, and CBR and elastic modulus values were greater on the traffic loops than on the non-traffic loops. This is believed to be a result of the additional compaction provided by traffic loads.

SUMMARY AND CONCLUSIONS

A brief description of the instruments, methods of installation, and measuring techniques used to obtain climatic and environmental data at the AASHO Road Test, conducted during the period 1958 to 1961, are presented.

The influence of temperature and other climatic factors on the performance of soil-pavement systems can be summarized as follows:

1. Groundwater fluctuations were significantly greater under the nontraffic loop than under traffic loops. Under the same traffic conditions, however, the groundwater

fluctuations for both rigid and flexible pavements were similar. For the uncovered area, the groundwater level was closer to the ground surface than for the covered area.

2. The data indicate that frost penetration was greater under rigid pavements than under flexible pavements, due in part to the greater heat conductivity of portland cement concrete.

3. The 24-hour temperature study indicated that temperatures within both flexible and rigid pavement sections exhibited trends similar to the air temperature, although the magnitude of variation of pavement temperature was much greater. Temperature vs depth data for both rigid and flexible pavements show that the daily air temperature variation had little influence on the temperature of subgrade soils.

4. Correlation of temperature conditions with soil-pavement performance as reflected in surface strains and deflections suggests that there is considerable reduction in pavement strains and deflections as the mat temperature decreases.

5. The influence of seasonal factors on the performance of the soil-pavement system is discussed in terms of the pavement surface deflections as well as in terms of the strength of pavement components. For illustration, only data for flexible pavements are presented. It is shown that there is a significant difference in both deflection and strength between spring and fall for both traffic and non-traffic loops.

ACKNOWLEDGMENTS

Sincere appreciation is extended to W. N. Carey, Jr., and R. C. Leathers, former Chief Engineer for Research and Engineer of Special Assignments of the AASHO Road Test, Highway Research Board, respectively, for their conception of the project and for their supervision of much of the work during the experimental phase.

Professor Hans F. Winterkorn of Princeton University provided constructive criticism and numerous suggestions. Professors J. W. Fisher and T. J. Hirst reviewed the manuscript.

The financial assistance provided by the Pennsylvania Highway Department and the Bureau of Public Roads is gratefully acknowledged.

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