HIGHWAY DESIGNS TO RESIST SUBGRADE MOISTURE VARIATIONS

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Findings, conclusions, and recommendations of a 6-year study to measure Oklahoma subgrade moisture conditions are presented. General trends in Oklahoma subgrade moisture are described, as are the effects of highway components on subgrade moisture behavior. Resistance of various highway components to subgrade moisture effects is also discussed, and specific recommendations are made for highway design and construction on expansive subgrades. Two modes of behavior, subgrade moisture accumulation and subgrade moisture variation, were found to exist under Oklahoma pavement systems. Combinations of these 2 modes also occurred. Rigid pavements were found to be extremely susceptible to cracking from vertical and lateral subgrade expansion, with resulting infiltration of water to the subgrade. However, rigid pavements performed well until upper subgrade moisture contents approached the liquid limit. Flexible pavements were more resistant to cracking from vertical and lateral subgrade expansion but were susceptible to distress when subgrade moisture contents approached the equilibrium value of 1.1 to 1.3 times the plastic limit. Recommendations include the use of a flexible and impervious base, subbase, or membrane component below the wearing surface of any pavement on expansive subgrades. Improved shoulders at least 8 ft in width are recommended, as is the establishment of equal drainage behavior on both sides of the highway section. More detailed subgrade soil testing techniques are also recommended.

•THIS PAPER summarizes findings and recommendations from a 6-year study of subgrade moisture conditions under existing Oklahoma highways. Conducted by the School of Civil Engineering at Oklahoma State University, the project was formally initiated in June 1964. After preliminary planning (1), the first of 52 field test sites was installed under existing pavement in June 1966 (2). Subgrade moisture and density data were collected periodically with nuclear depth moisture and density probes, which were calibrated for particular Oklahoma soil conditions (3, 4). In addition to subgrade moisture and density data, information concerning the following factors was compiled: precipitation, air temperature, soil type, highway design and construction history, pavement and shoulder performance, traffic, subgrade temperature, and pavement heave or settlement or both.

Data were reduced immediately on collection, and continual evaluations were carried out during the 4-year data collection phase of research. Periodically, overall evaluations were made of all data collected to date (5, 6, 7, 8, 9). Data collection was discontinued in June 1970.

SUBGRADE MOISTURE BEHAVIOR IN OKLAHOMA

This section summarizes research findings concerning subgrade moisture behavior observed under existing Oklahoma highways. More detailed analyses and data from which conclusions were drawn are available elsewhere (5, 6, 7, 8, 10, 11, 12, 13).

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General Conditions Existing in Oklahoma

All sites were located on existing highways in the central and north central-northeastern part of Oklahoma. Annual rainfall in this region varies between 10 and 40 in., increasing from west to east. Monthly rainfall amounts are highly seasonal; more than 12 in. may fall during the spring in the eastern part of the state, and only 2 in. or less may fall during the winter at some western locations. The average monthly mean of air temperatures range from over 80 F during July and August to approximately 30 F during 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. 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 desiccation) and, after remolding, exhibit higher volume change potential than might be predicted from plasticity alone, particularly if compaction is dry of optimum.

Observed Trends in Subgrade Moisture Behavior

Data obtained from the study indicate that 2 basic types of moisture behavior, subgrade moisture accumulation and subgrade moisture variation, exist in expansive Oklahoma subgrades. Factors responsible for each type of behavior are summarized in the following sections.

Subgrade Moisture Accumulation—Subgrade 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 (usually below optimum compaction moisture), to increase without significant variation during an 18- to 24-month period until an equilibrium moisture content of approximately 1.1 to 1.3 times the subgrade plastic limit was reached. The word equilibrium is actually a misnomer because, in most cases, variations in moisture content begin to occur after the equilibrium point has been reached. The prime criterion for subgrade moisture accumulation without significant variation was found to be an impervious pavement system.

For these impervious pavements, moisture accumulation is thought to occur primarily from capillary sources, i.e., prevention of evaporation, but some sites obtain moisture by infiltration from outside paved shoulders. Subgrade temperature gradients were found to cause only small moisture changes (5).

Moisture accumulation noted under older construction in excellent condition probably 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 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 and 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 2 types of sites were subject to large variations. Initial accumulation behavior noted at these sites is also thought to result from general drying of subgrade caused by the previously mentioned drought.

Subgrade Moisture Variation—At most research sites where moisture accumulation was not in progress, moisture variations were found either to occur seasonally in annual cycles (with maximum moisture contents occurring during winter months) or to be precipitation dependent. Most research sites where purely seasonal moisture variations occurred were on pavement that was rated as being excellent and impervious, and moisture variations had little relation to measured precipitation, particularly under pavement centerlines. It was thought initially that these variations were temperature induced, but, although temperature-induced moisture migration does occur in Oklahoma subgrades, it is of relatively low magnitude, causing only a 1 or 2 percent engineering moisture content variation annually (5). In almost all cases for sites where moisture variations were seasonal and could not be related to rainfall, the great 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. Most seasonal variations under impervious systems did not exceed 5 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. Precipitation-dependent variations were also noted to occur at most sites having open shoulders, despite pavement condition. Many sites where precipitation and evaporation affected subgrade soil moisture were located on rigid pavement sections modified by asphaltic concrete overlay.

As a general rule, upper subgrade moisture variations generally lagged rainfall by 6 to 8 weeks, with longer times being required for variations to occur at deeper depths. Magnitude of variations was highly dependent on overall pavement condition, whether or not sealed shoulders were present, and on type of base and subbase material used in the pavement section. The magnitude of variations caused by precipitation and evaporation was almost always higher than that of variations produced by seasonal trends. At some sites the variations exceeded 10 to 15 percent engineering moisture content during 6-month periods and produced easily noticeable changes in pavement and shoulder condition. At some sites, rainfall infiltration produced moisture contents close to the subgrade liquid limit, with resulting loss of subgrade support and rapid pavement deterioration.

Effect of Subgrade Moisture Behavior on Soil Volume Change

Oklahoma cohesive soils are particularly subject to volume change as moisture content varies. Volume change data were obtained from moisture measurements, subsurface bench marks installed at research sites (7, 11), and general observations of pavement behavior. At most research sites only the upper 5 to 7 ft of the subgrade made any large contribution to subgrade volume change; moisture contents below this level remained relatively constant. Vertical movements were not extremely large. An empirical relationship of 1 in. of pavement heave for a 10 to 12 percent increase in engineering moisture content was developed from obtained data. This correlation was extrapolated from smaller recorded measurements (1/2 to 5/8 in.) obtained at several sites on A-6 and A-7 subgrades. Moisture contents were in the vicinity of the subgrade plastic limit.

However, lateral subgrade expansion probably affects pavement performance to a larger extent than vertical swelling. The unit swelling potential of cohesive Oklahoma subgrades, compacted under normal conditions, is lower in the lateral direction than in the vertical (14). However, lateral subgrade expansion takes place over a 24- to 40-ft width, and resulting movements were found, in some cases, to exceed 3 to 5 in. Tensile stresses, produced by lateral subgrade expansion, in the pavement system caused longitudinal cracking of the subbase, base, and pavement structure. This cracking was aggravated by flexural stresses from differential vertical heaving, even though the heaving was of rather low magnitude.

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, was caused by shoulder drying, and resulted in shoulder settlements of up to several inches in magnitude during dry periods. Some rebound was observed in succeeding wet periods.

INFLUENCE OF HIGHWAY DESIGN FACTORS ON SUBGRADE MOISTURE BEHAVIOR

Subgrade moisture behavior was definitely affected by highway design. The effects of improved shoulder width, drainage conditions, highway profile, traffic, and construction procedure are given in this section. Instances of behavior and detailed case histories substantiating these findings are given elsewhere (6, 7, 12, 13).

Improved Shoulder Width

At all research sites observed, increasing shoulder width reduced the effects of runoff infiltration. Furthermore, in impervious sections with wide improved shoulders, the wet-dry interface or distinct transition point from fluctuation to more nearly stable subgrade moisture content occurred underneath the shoulders, whereas for pavements with open shoulders or narrow improved shoulders it occurred under the pavement. Less severe differential movements from more uniform moisture content were thus expected and observed for impervious pavement with wide shoulders. The wet-dry interface was found to occur approximately 5 to 7 ft from the outside edge of a covered area. Therefore, to keep the wet-dry interface from underneath the pavement, a shoulder width of at least 8 ft is required.

Highway Drainage Conditions

Drainage conditions or rainfall infiltration tendencies or both were found to be closely related to both shoulder slope and ditch design. Steeper shoulder slopes reduced infiltration into the subgrade, and the elimination of ponding by the quick removal of surface runoff in ditches further reduced infiltration at most of the research sites where these drainage conditions existed. Gently sloping shoulder slopes were found to cause greater infiltration of runoff. However, ponding and improper ditch drainage, e.g., where ditches remained full for several days after a rain, caused measurable infiltration despite good shoulder slope conditions.

Nonuniform infiltration, producing differential moisture contents across the pavement section, was found to occur at many research sites. For undivided highways, this behavior usually occurred when the highways were constructed normal to an existing slope, with good drainage on 1 side and a tendency for ponding on the other. However, differential subgrade moisture contents from different infiltration rates were found under almost all 4-lane divided highways. It appears much more difficult to obtain good median drainage, and the median side of the divided highway usually experienced both higher maximum and average moisture contents and greater fluctuations at upper subgrade levels.

Good drainage produced lower average subgrade moisture contents at the cost of higher variation and distinct wet-dry interface behavior. Poor drainage produced higher average moisture contents but less variation.

Highway Profile

Type of highway profile also affected subgrade moisture conditions; pavements on grade or in slight cuts usually exhibit both higher pavement ratings and more nearly uniform subgrade moisture conditions, particularly in the upper subgrade levels. Fill and transition sections usually had lower pavement and shoulder ratings than other sections and also exhibited more moisture content variation, particularly at the pavement edges.

Traffic Volume

Despite several attempts during 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 or rutting or both of these rendered the pavement system pervious, higher traffic volumes produced more rapid pavement deterioration. These data, coupled with observations that pervious bases were not usually found with degrees of saturation high enough 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. This conclusion is also based on the assumption that at least a semirational method of considering traffic loadings and pavement stresses was used in pavement system design.

Current Oklahoma Highway Construction Procedure

Most new construction in Oklahoma is done by stage methods under a long-term planning program. Contracts for grading and drainage structures are usually let and completed, and contracts for base and surfacing are let at some later time. This construction practice results in bringing the subgrade to its approximate final level and then in 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 reach some equilibrium condition compatible with moisture contents in the natural subgrade below and with existing climatological conditions. This equilibrium is likely to undergo seasonal changes, becoming wetter in general during winter months and drier during summer months. Also, precipitation in Oklahoma is usually infrequent but heavy when it does occur. As a result, considerable runoff occurs across the prepared subgrade and produces erosion damage.

Another fairly common practice in Oklahoma is the use of prepared subgrades by farmers for movement of agricultural equipment either prohibited from or hazardous to on-pavement travel. If done for an extended period of time, this practice results in raveling of the subgrade during drier periods and rutting of the subgrade during wetter periods.

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, usually 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 moisture in the uncovered subgrade is likely to be less to a considerable depth than the original compaction moisture. Compaction of cohesive subgrades in Oklahoma is usually done dry of optimum because optimum compaction moisture is 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 5 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 staged construction because many advantages exist for its use, particularly in Oklahoma. However, other methods of staged construction should be considered that would provide better initial subgrade moisture conditions. Current construction practice appears to be aggravating the subgrade moisture problem in Oklahoma instead of minimizing it.

EFFECTIVENESS OF HIGHWAY COMPONENTS IN PREVENTING AND RESISTING SUBGRADE MOISTURE CHANGES

This section discusses various pavement system components currently being used in Oklahoma highway construction and the resistance of components to subgrade moisture variations. Recommendations for use of certain pavement components in particular situations are also given. Additional descriptions of behavior, collected data, and case histories are given elsewhere (8, 9, 10, 11).

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 methods currently favored for all new construction, make it unlikely that construction moisture contents can be maintained for even short periods.

Therefore, it appears logical to develop highway designs that allow subgrade moisture contents to increase to their equilibrium condition as quickly as possible and to stay there. The system should be designed to remain impervious after differential vertical and lateral expansion associated with Oklahoma subgrade moisture accumulation has occurred. Deterioration of Oklahoma highways must be prevented by not allowing the infiltration and evaporation cycle through pervious pavement systems to begin.

Performance of Surfacing

Current Oklahoma highway design procedures involve use of both flexible and rigid pavements. Type of surfacing or surface course used was found to have little, if any, initial effect on observed subgrade moisture behavior. Of more importance was whether the surface was pervious or impervious because 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 longitudinal cracking than their flexible counterparts and were extremely sensitive to moisture infiltration through joints opened from thermal contraction and lateral subgrade expansion. However, rigid pavements were found to perform adequately for extended periods, after initial cracking and resulting infiltration had begun, and to maintain relatively good riding characteristics at subgrade moisture contents higher than those that 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.

Flexible pavements or pavement systems consisted either of asphaltic concrete surfacing over some other type of base or subbase (or both) or else asphaltic concrete surfacing over some other type of asphaltic base or subbase. In general, better performance was obtained from multilayer asphaltic systems, as opposed to asphalt over nonasphalt systems. Flexible pavements were found to be highly resistant to cracking caused by small differential vertical movements and lateral subgrade expansion, especially when more than 1 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, which was followed by pavement cracking. Cracks usually extended down to the subgrade material, and infiltration and evaporation of rainfall produced further deterioration and general cracking. Better observed performance of all-asphaltic systems probably results more from a thicker layer of asphaltic material that must be cracked to allow infiltration and evaporation than from any outstanding load-bearing or distributing characteristics of the material.

Recommendations Concerning Type of Surfacing

Portland cement concrete and asphaltic concrete surfacing are the only 2 choices available to the highway engineer. When pavements are constructed 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 on use of a standard section.

Initial resistance to cracking from vertical and lateral subgrade expansion was lower in rigid pavements than in flexible pavements. However, rigid pavements were found to perform adequately (even though cracked) at subgrade moisture contents well above the plastic limit because of their ability to transmit wheel loadings over a wide area. The tendency of rigid pavements to crack with subgrade volume change is directly responsible for increasing moisture contents; and, once surface cracking has occurred, the deterioration of rigid pavement is only a matter of time. Therefore, rigid pavements should not be used unless underlaid by a nonexpansive, flexible, impervious material. Load-carrying capacities of rigid pavement should be evaluated by strength tests, assuming that there is 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 above the plastic limit should indicate its use in areas where poor drainage is encountered because rigid pavement normally produces higher subgrade moisture conditions. A correctly designed rigid pavement with improved shoulders over a sand-asphalt layer is probably the best design for general use on expansive subgrades.

Initial cracking from vertical and lateral subgrade expansion was resisted better by flexible pavement than by rigid pavement. However, when moisture contents approached the equilibrium value of 1.1 to 1.3 times the subgrade plastic limit, heavy traffic produced rutting and initial pavement cracking. The inability of observed flexible pavement systems to carry heavy traffic loadings at subgrade moisture contents near the plastic limit is thought not to be an indictment of this design but a reflection of 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 moisture contents 1.1 to 1.3 times the subgrade plastic limit and to 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 nonexpansive, flexible, and impervious base, subbase, or membrane component.

Subgrade strength appears to be more important in flexible pavement design, and, therefore, these systems should give better performance where good drainage conditions are provided because they are also less susceptible to cracking from volume change produced by good drainage and would benefit materially from lower average moisture contents and resulting higher subgrade strengths.

Performance of Base Courses

Six types of base material were encountered at field research sites that are commonly used in Oklahoma base construction: sand cushion, hot sand asphalt, asphaltic black base, soil cement, stabilized aggregate, and select material. Exact definitions of these common highway materials are available elsewhere (8, 9). Sand cushion and select material were encountered as base courses for rigid pavement.

Because of observed behavior, the use of sand cushions has been deleted from Oklahoma highway design criteria. Sand cushions were found to act as water reservoirs and distribution systems, catching water that infiltrated from the shoulders and through rigid pavement cracks and joints and feeding it 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 longitudinal pavement cracking plus upper subgrade moisture contents being at or near the subgrade liquid limit.

Hot sand asphalt was used as a base course at many highway research sites and was found to form an excellent impervious layer. The plastic properties of asphalt that were 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 previously encountered.

Several research sites contained asphaltic black base underneath asphaltic concrete. Observed performance indicates that this material is probably the second-best base type tested because it is impervious and possesses good flexibility. However, its performance is not thought to be as good as that of sand asphalt because the larger size of aggregate particles used probably gives this material less flexibility and also presents the possibility of larger interconnected voids. Nevertheless, asphaltic black base was found to perform well at the majority of sites where it was encountered.

The soil-cement base courses that were encountered were used primarily in the construction of improved shoulders. Soil cement is relatively rigid compared to more flexible asphaltic materials and may suffer some initial shrinkage cracking. These cracks expand when moisture accumulation and resulting vertical and lateral subgrade expansion occur. 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. Once the surfacing has cracked, water will enter and infiltrate through the soil cement into the subgrade, and additional volume change will occur and consequently open the joint between pavement and shoulder. The use of soil cement directly on any subgrade of even suspected expansiveness does not appear to be advantageous.

Stabilized aggregate is a mechanically stabilized material consisting of blended course aggregate, sand, mineral filler, and soil binder. The resulting product, although highly variable and depending on locally available materials, is nevertheless intended to provide a well-graded and densely 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 and evaporation of water through pervious pavement surfaces.

Select material is similar to stabilized aggregate but is usually considered to be naturally occurring and is governed by somewhat different specifications. On the whole, select material was observed to behave not quite so well as stabilized aggregate but better than sand cushions.

Most of the correlations concerning base material performance are available elsewhere (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 on pavement rated as being excellent or good, 18 of 23 sites with pervious bases had higher moisture contents in upper subgrade levels than in 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 at lower subgrade levels. Evaluation of amount of subgrade moisture variation under pervious and impervious bases, although subjective to some degree, nevertheless indicated that less variation with time existed in upper subgrade levels under impervious bases and that relative magnitude of variations was also lower.

The subgrade moisture contents for almost all of these sections were in the range of 1.1 to 1.3 times the plastic limit, with the upper subgrade moisture levels under the 7 impervious base sites being closer to 1.1 than to 1.3 times the plastic limit. On the other hand, average moisture content-plastic limit ratios for sites on pervious bases approached (and sometimes exceeded) the 1.3 value. These data, plus other information (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.

Recommendations Concerning Highway Base Courses

Base courses used in Oklahoma highway construction on expansive subgrades should, if possible, be nonexpansive, flexible, and impervious. Asphaltic types of base materials appear to provide these qualities better than any other materials encountered. If use of other base material is contemplated, the subgrade should be protected by use of a flexible, impervious subbase or else a flexible, 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 it is protected from lateral subgrade expansion by an intervening nonexpansive, flexible, and impervious layer.

Recommendations Concerning Highway Subbase Courses

Subbase components are used primarily as a means of distributing loads to the subgrade, but they can also act as barriers against water infiltration where pervious base courses are used. Oklahoma subbases are usually constructed of select material, chemically treated layers of the subgrade, or sand asphalt.

Select material subbases, when used in flexible pavement construction, obviously reduce the total required thickness of asphaltic layers. Even though economics dictates 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 (besides the wearing surface) contains desired nonexpansive, impervious, and flexible properties. 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.

Lime-treated layers of cohesive subgrade have also been used as subbases, normally with lime contents corresponding to modification optimum for the material. The lime contents used for treatment normally result in reduction of plasticity and give an increase in soil workability. The result is to produce a treated material with properties similar to that of the select material described previously.

Sand asphalt possesses necessary imperviousness and flexibility if these qualities are desired in a subbase, and its use should allow inclusion of pervious base materials in highway design. 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 were found to provide a method for reducing infiltration of surface runoff into the base course, subbase, or subgrade or all three, particularly at pavement edges, and thus for producing more nearly uniform moisture variations over the width of the pavement. However, definite improvement in subgrade moisture conditions underneath pavement could be obtained by several modifications in shoulder design and construction technique. Because of lower traffic loadings carried by improved shoulders and also the staged construction common in Oklahoma, shoulders are often built after the pavement section has been constructed and have thinner base layers that are often of a different material. The net effect of this construction technique is to place a vertical plane of weakness between pavement and shoulder. Lateral and differential vertical expansion of cohesive subgrade tends to cause separation along this plane of weakness, provides a channel for entrance of surface runoff, and produces larger moisture variations under the pavement edge. Also, the wet-dry interface that forms under the shoulder causes shrinking and swelling of subgrade material, which develops flexural stresses along this plane of weakness.

Improved shoulders at least 8 ft in width should be constructed for all pavements on expansive subgrades. Base or subbase under the shoulders, or both of these, should be continuous with that of the pavement section and should be applied in 1 continuous shoulder-to-shoulder lift. Recommendations concerning type of base and subbase materials under shoulders are the same as for wearing surfaces.

Whatever the desired design shoulder width, shoulders on each side of the pavement section should be of equal width. If both shoulders are of equal width and the width is at least equal to 8 ft, a more nearly symmetrical subgrade moisture profile will result underneath the pavement and more nearly uniform moisture increases and decreases will occur.

Recommendations Concerning Highway Drainage Conditions

The varied topography encountered along a highway profile makes specific drainage recommendations impracticable. However, it is extremely important that existing drainage conditions be the same on each side of a particular highway section to produce more nearly symmetrical moisture profiles, although 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 4-lane divided highways should be designed so that both the median and the outside shoulders drain. As a general rule, flexible pavements appear to be more suitable for use under good drainage conditions, whereas rigid pavements appear to be better suited for poor drainage conditions. For intermediate conditions, correctly designed pavements of either type should work satisfactorily.

Recommendations Concerning Highway Profile

The diverse topography encountered along highway profiles makes specific recommendations impractical. However, research findings definitely indicate that better highway performance is obtained in sections on grade and in slight cuts. Where possible, the highway profile on expansive subgrades should be held to these sections. Any fill or transition sections or both should be partially constructed of select material or lime-modified layers of the subgrade, such that a 5- to 7-ft depth below the bottom of the pavement system is essentially nonexpansive. An alternate procedure might be to compact the fill as closely as possible to natural moisture contents of existing soils and cover the entire fill with an asphaltic membrane. Whenever possible, high fills should be avoided, and, in any case, despite the previously mentioned treatments, shoulder settlements should be expected.

Recommendations Concerning Current Staged-Construction Procedures

If current staged-construction procedures (as described previously) are to be used, several slight modifications will improve moisture conditions in the subgrade. One method might be to compact the subgrade to a level above design final 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 traffic and other traffic may be kept off during the interim between subgrade finishing and base-surfacing application. The base-surfacing contractor could then cut the subgrade to final grade and immediately apply base and surfacing. If this procedure is not feasible, consideration should be given to provide extra rolling time (and thus money) to compact upper subgrade layers wet of optimum. However, required densities may be difficult to obtain as compaction under these conditions will normally occur at or above the plastic limit. Nevertheless, higher initial moisture contents and a clay particle orientation less conducive to volume change would result and may be worth the additional 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 2-year period or longer between subgrade completion and base-surfacing application. Still another alternative procedure would be the use of the deep-plow lime treatment 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 (15).

Recommendations Concerning Revised Staged-Construction Procedures

Some thought should also be given to a more radical revision of the staged-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. However, the ultimate traffic loading for the pavement system is not usually encountered until late in its design life. Initially, traffic is likely to be substantially below expected maximum values, and the section is perhaps overdesigned. The possibility of traffic considered in design being greater than that during initial years after construction and establishment of subgrade moisture equilibrium suggests that alternative methods of staged construction be used.

One method would be to divide construction into 3 stages. Initially, the subgrade would be prepared in a manner recommended previously. 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 should 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 is opened to traffic, moisture equilibrium should occur underneath the pavement system, and its subgrade will be just beginning to start the infiltration and evaporation cycle through the now pervious pavement structure. At this time, usually somewhere between 2 and 5 years after initial construction, the final surfacing course should be applied to bring the pavement section up to design thickness and effectively seal the surface from infiltration and evaporation. Moisture equilibrium should have been achieved by this time, and, as the accumulation phase is completed, sections should be produced where adverse moisture variations would be minimized. If subgrade soil conditions at moisture equilibrium values have been correctly anticipated, excellent highway performance should be achieved, and future maintenance costs should be markedly reduced. During the design life of the highway, at least 1 less overlay should be needed, and this in itself would reduce total highway cost.

An alternate procedure would be to use current staged-construction methods but then to apply surfacing in 2 stages. This procedure should cause more initial moisture accumulation and relative movement and might require the final surfacing course earlier than the procedure mentioned previously. However, it should also increase subgrade moisture resistance of the final section.

Still a third alternate might be to extend the initial staged-construction phase to include base and temporary surfacing, with intermediate or final surfacing courses or both courses to be applied at later dates. This technique might be applicable when turnkey or non-staged-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.

SUMMARY

This paper has described subgrade moisture conditions in Oklahoma as determined by a 6-year research study. Effectiveness of various highway components in preventing and resisting adverse subgrade moisture conditions was also discussed. Recommendations concerning the need for more comprehensive subgrade soil-testing procedures, for use of certain pavement components in particular situations, and for revision of current construction practice to enhance subgrade moisture resistance of pavement systems have also been described. It is suggested that, whenever possible, recommendations made here be applied in routine design and construction of highways on expansive Oklahoma soils.

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