Subgrade Stability

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Subgrade stability refers to the strength and deformation properties of a soil. Both properties significantly influence (a) the response of a subgrade to the heavy repeated loading of construction traffic and operations, (b) the ability to place and compact overlying material layers, and (c) the long-term performance of the pavement subgrade. Ideally the subgrade should be strong enough to prevent excessive rutting and shoving and sufficiently stiff to minimize resilient deflection. Techniques and procedures currently used for characterizing soil type seem adequate, but those for evaluating field soil moisture regime are inadequate. The procedures described can be used to evaluate this regime. Subgrade stability requirements are primarily dictated by pavement construction considerations. Analyses of equipment sinkage and paving material compaction operations indicate that a minimum in situ California bearing ratio (CBR) of 6-8 is required. Many typical fine-grained soils do not develop CBR in excess of that when compacted at or wet of AASHTO T99 optimum water content. Thus, remedial procedures must be followed frequently to provide adequate subgrades for pavement contraction. Three such procedures—undercut and backfill, moisture-density control, and admixture stabilization—are described and evaluated. Undercut and backfill and admixture stabilization offer the greatest potential for permanently improved performance of the completed pavement.

Subgrade stability refers to a soil's strength and deformation properties, which significantly influence (a) the response of a subgrade to the heavy repeated loading of construction traffic and operations, (b) the future success of placement and compaction of overlying layers, and (c) the long-term performance of the pavement subgrade. Ideally the subgrade should be strong enough to prevent excessive rutting and shoving and sufficiently stiff to minimize resilient deflection.

To ensure adequate stability, certain minimum strength and stiffness levels must be achieved in the subgrade soil to the depth influenced by construction traffic as well as by vehicles using the completed pavement. Because the magnitude of the wheel load, tire pressure, and the relative stiffness of the various layers determine depth of influence, subgrade stability must be defined for a given loading and traffic condition.

CHARACTERIZATION OF FIELD CONDITIONS

Recent studies (1, 2) have demonstrated that for fine-grained soils the major factor that influences strength and stiffness is water content. A recent Indiana study (3) showed that "Water content appears as the dominant variable (with regard to strength) in the field and Standard Proctor regressions."

Inadequate subgrade stability is generally associated with a moisture content that exceeds the optimum as measured in the AASHTO T99 compaction test. In all cases of inadequate subgrade stability evaluated in an Illinois study, field moisture contents were significantly wet of optimum. Knight (4) has indicated that, if the soil moisture content is greater than optimum, the cone index will generally be less than 300, an equivalent California bearing ratio (CBR) of 6 or 7.

A study of placement moisture contents (1) for a variety of soils from two Interstate highway sections (District 5, Paris, Illinois, I-57 and I-70), each approximately 16 km (10 miles) long, revealed that sizable quantities of the subgrades were placed wet of optimum. The compaction moisture content averaged 97.2 percent of optimum and had a standard deviation of 15.1 percent of optimum for the 1213 observations. On these projects 43 percent of the soil embankment was placed wet of optimum, 20 percent above 110 percent of optimum, and 7 percent above 120 percent of optimum. Similar data developed by the Illinois Department of Transportation (DOT) and others also indicate the potential of embankment construction with soils wet of optimum.

In many cases the field moisture contents at the borrow areas in the above studies were probably higher but were reduced by aeration during placement and compaction. Since compaction wet of optimum apparently occurs frequently, subgrade stability problems are bound to be common. The field identification of potential subgrade stability problem areas requires knowledge of the soil type and the moisture content. Density has a very minor influence on soil strength and stiffness when compacted wet of optimum, assuming that densities in the region of 95 percent of maximum (γ_D max) are achieved.

Soil Type Considerations

The current uses of pedologic soils information, previous soil reports, geologic data, drilling, sampling, and testing activities for considering soil type are fairly well defined. The early work of Thornburn and Liu (2) at the University of Illinois and the Illinois DOT Soils Manual (5) serve as excellent sources of information on the properties, characteristics, and distribution of surficial soil deposits in Illinois. Similar data have been developed by other transportation agencies. It should be noted that soil type and distribution do not change with time. If particularly bad soil types are not detected during the soils investigation, they can be easily located and identified during construction.

The adverse effects (loss of strength and reduction of stiffness) of a high moisture content vary according to soil type. Compare, for example, the CBR-water relations in Figures 1 and 2. The high-plasticity Drummer B (Figure 1) is fairly insensitive to moisture content change, while the low-plasticity Fayette C (Figure 2) is extremely sensitive. Illinois data (1) indicate that the resilient moduli of soils with high clay contents and high plasticity are less sensitive to moisture content increases than the soils of higher silt content and lower plasticity index (PI). Permanent deformation data developed for typical Illinois soils [Figure 3 for AASHTO Class A-7-6(28) and Figure 4 for AASHTO Class A-4 (9)] also indicate that soil type has an effect on moisture sensitivity.

It is therefore important to have adequate soil characterization data for consideration of potential subgrade stability problems. Soil texture and plasticity appear to be the two major factors that need to be considered.

Moisture Considerations

The most significant factor influencing the strength and stiffness of any fine-grained soil is moisture content. Unfortunately soil moisture content in the field shows tremendous spatial variability and is constantly changing with time. The intricacies of moisture movement and moisture content changes in soils have been well documented by Dempsey and Elzeftawy (6).

Although it is not practical to accurately predict field soil moisture content as a function of location, depth, and time, significant advances are being made in that regard, and the available technology certainly is of great value in rendering improved qualitative engineering decisions concerning field moisture conditions. It is very important to acknowledge the fact that soil moisture content will change after placement.

Several procedures are available for characterizing field moisture conditions. The more useful ones are described briefly below.

Natural Soil Drainage Classes

The Soil Conservation Service of the U.S. Department of Agriculture uses seven natural soil drainage classes. The brief descriptions of these classes that follow have been adapted from more complete descriptions in the Soil Survey Manual (7). These soil drainage classes refer to the soil moisture equilibrium in the natural landscape and should not be confused with surface drainage, which is influenced by human activity.

1. Very poorly drained: Water is removed from the soil so slowly that the water table usually remains at the surface. Soils in this drainage class usually occupy level or depressional sites and are frequently

Figure 1. CBR as a function of water content for Drummer B.

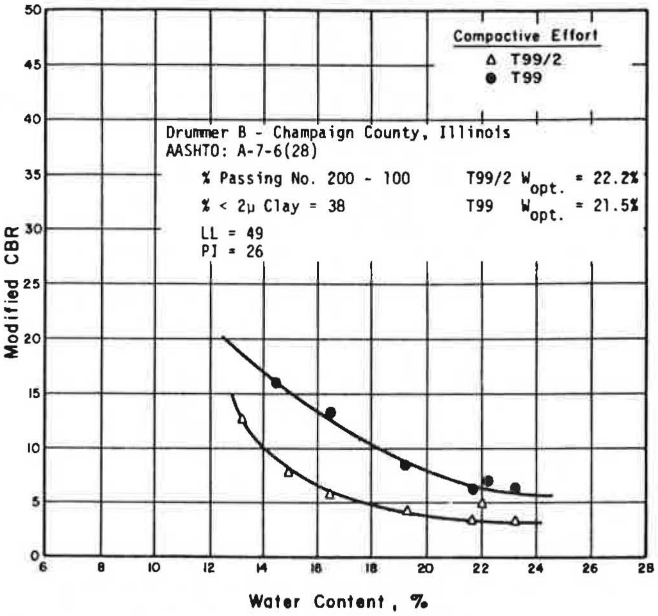


Figure 2. CBR as a function of water content for Fayette C.

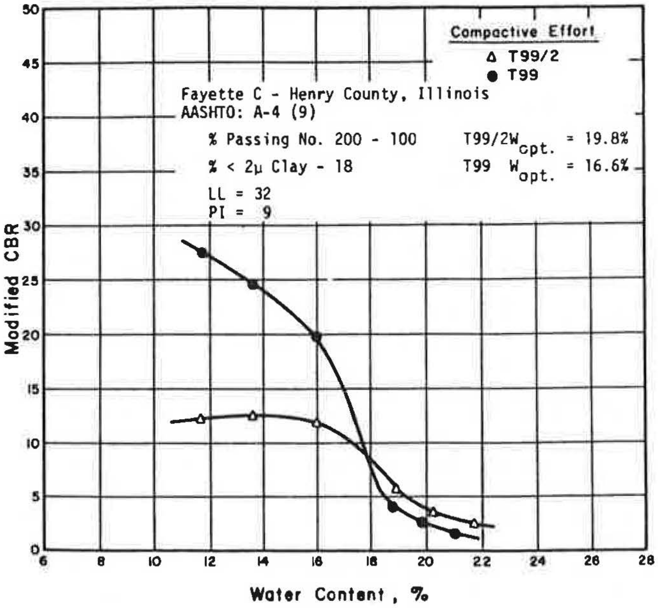


Figure 3. Permanent deformation behavior of Drummer B.

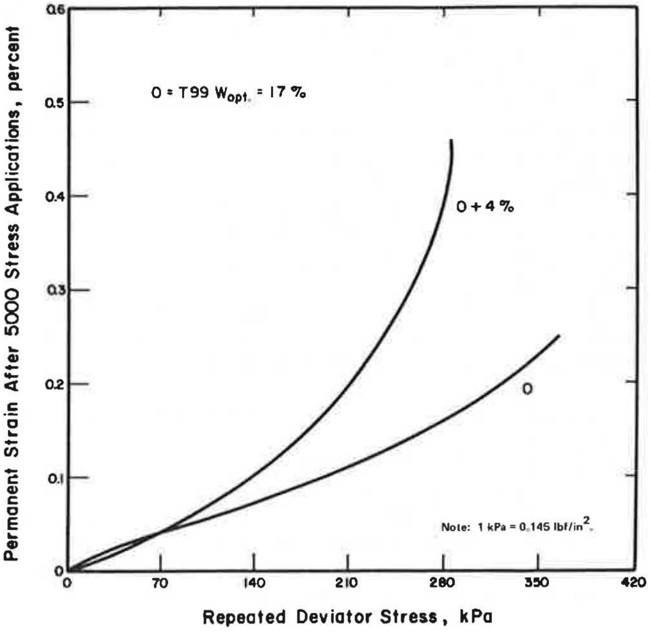
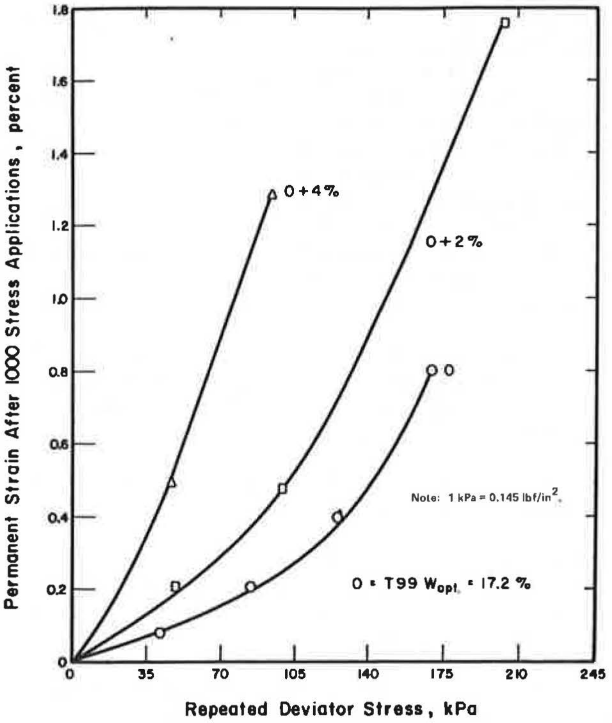


Figure 4. Permanent deformation behavior of Fayette C.



ponded. They are predominantly gray and show distinct evidence of gleying. Some have dark and mucky surfaces.

2. Poorly drained: Water is removed slowly so that the soil remains wet most of the time and the water table is often near the surface. These soils are predominantly gray, often with dark surface horizons and some yellow mottling in the subsoils.

3. Imperfectly drained: Water is removed from the soil slowly enough to keep it wet for significant periods but not continuously. These soils are uniformly gray, brown, or yellow in the upper A horizon and are commonly mottled in the lower A and in the B and C horizons.

4. Moderately well drained: Water is removed from the soil somewhat slowly, causing the profile to be wet for short but significant periods. These soils are uniformly colored in the A and upper B horizons, with some mottling in the lower B and in the C horizons.

5. Well drained: Water is removed from the soil easily, but not rapidly. These soils have little mottling, except occasionally deep in the C horizon or below depths of a few meters.

6. Somewhat excessively drained: Water is removed from the soil rapidly. Many of these soils are sandy and very porous, and most are free of mottling throughout the profile.

7. Excessively drained: Water is removed from these soils very rapidly. These soils often occur on steep slopes or are very porous or both.

Figure 5 shows the general relationship of the depth of the water table to the natural slope of the ground surface for each of these soil drainage classes. In medium-textured, moderately permeable soils the depth to the water table varies directly with slope. In finer-textured materials more poorly drained soils occur on steeper slopes, and in coarser materials well-drained soils occur on gentler slopes.

Illinois Drainage Guide

The Cooperative Extension Service and the Agricultural Experiment Station at the University of Illinois, in conjunction with the Soil Conservation Service, have jointly prepared a drainage guide for Illinois soils (8). The primary characteristics used to group the soils in the guide are soil premeability or hydraulic conductivity and the degree of wetness before any drainage practices have been applied. This classification is established for use in drainage recommendations for Illinois soils.

Drainage groups are indicated in tabular form by a number (1-4) combined with a capital letter (A or B). Soil permeability is denoted by the numbers. Definitions are given on the basis of centimeters of water that will move through the soil in an hour as given below:

1. Rapidly permeable [more than 15 cm/h (6 in/h)], moderately rapidly permeable [5-15 cm/h (2-6 in/h)];
2. Moderately permeable [1.5-5 cm/h (0.6-2 in/h)];
3. Moderately slowly permeable [0.5-1.5 cm/h (0.2-6 in/h)]; and
4. Slowly permeable [1.5-5 mm/h (0.06-0.2 in/h)], very slowly permeable [less than 1.5 mm/h (0.06 in/h)].

The capital letter in the drainage group designates the natural soil drainage or wetness before artificial drainage is applied. The natural drainage classes are combined into the two groups below.

A. Poorly drained: Without manmade drainage, the water table would be at or near the surface during the wetter seasons of the year.

Very poorly drained: Without manmade drainage, the water table would remain at, near, or above the surface much of the time.

B. Somewhat poorly drained: Without manmade drainage, the water table would be near the surface only during the very wettest periods.

The various surficial soils of Illinois are listed in the drainage guide (8) by number and type, both numerically and alphabetically. If one knows the soil type and drainage classification, it is possible to qualitatively predict potential subgrade soil moisture problems. A similar approach could be used for other locations.

Rational Method

Dempsey and Elzeftawy (6) have summarized the various rational procedures for predicting field moisture contents; they also present a computer-based model. The U.K. Transportation and Road Research Laboratory (TRRL) procedure (9, 10, 11, 12) was used in this study to demonstrate the effect of soil type and depth of water table on the field moisture content. The procedure has been described in an Organization for Economic Cooperation and Development (OECD) publication (13) and in a University of Illinois report (6).

OECD has indicated that the rational method is a valuable tool for predicting the water content of soils regardless of the soil type. This method considers only a paved, closed system without water movement to or from the pavement surface or adjacent soil masses and is only valid for subgrade profiles that have a relatively shallow water table. Table 1 shows, for typical Illinois soils, the calculated equilibrium water content at several depths in the profile for water table depths of 60, 120, and 240 cm (2, 4, and 8 ft) below the surface. The soils were assumed to be 100 percent saturated at the water table, and the moisture content variation above the water table appeared to be small. It is apparent that, for shallow water table conditions, subgrades will frequently approach 100 percent saturation.

Langfelder (14) demonstrated that the suction-water content relations for compacted typical Illinois soils are basically independent of molding water content and density. The data shown in Table 1 are thus not dependent on initial placement conditions. Placing a soil dry of optimum, or at optimum does not ensure that the moisture content will not subsequently increase.

SITE REQUIREMENTS

Subgrade Stability-Requirements

Subgrade stability requirements are dictated by construction requirements and pavement performance. The most pertinent of these are rutting and shoving and the need to effectively and efficiently place and compact the various pavement layers. The primary pavement performance considerations related to subgrade stability are the resilient deflection of the pavement and the permanent deformation accumulation in the subgrade.

Pavements can be designed to provide adequate performance for a broad range of subgrade support conditions if soil type and moisture conditions (present and future) are carefully assessed. It is important that the design subgrade support be achieved at construction and maintained throughout the desired design life.

Construction subgrade stability requirements are more restrictive than the pavement performance re-

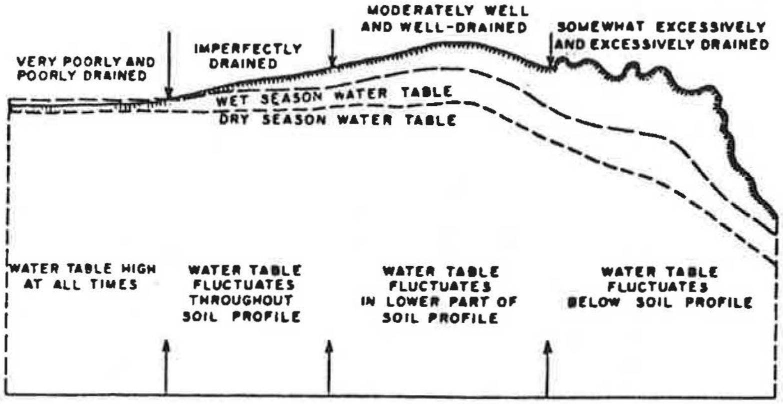


Figure 5. Water-table depth and natural soil drainage relation for medium-textured soils.

Table 1. Influence of water-table depth on soil moisture content.

Water Table Depth[a] (cm)	Calculated Moisture Content (%)			
	Champaign Loam Till	Fayette C Horizon	Muscatine C Horizon	Tama B Horizon
60 cm below pavement surface				
0	19.5	34.0	31.40	32.20
15	19.55	34.1	31.45	32.25
30	19.60	34.3	31.50	32.35
33[b]	19.65	34.3	31.50	32.40
1.2 m below pavement surface				
0	18.8	33.1	31.15	31.40
15	18.90	33.2	31.15	31.50
30	19.05	33.4	31.20	31.55
60	19.25	33.6	31.25	31.70
94[b]	19.35	33.8	31.30	31.80
2.4 m below pavement surface				
0	17.45	31.95	30.55	29.80
6	17.50	32.0	30.60	29.80
12	17.55	32.1	30.60	29.85
24	17.80	32.2	30.65	29.95
48	18.10	32.8	30.70	30.15
72	18.50	33.0	30.80	30.20
85[b]	18.75	33.1	30.80	30.30

Note: 1 cm = 0.39 in; 1 m = 3.3 ft.

[a] Below soil surface. Pavement assumed to be 28 cm thick.

[b] Groundwater level.

quirements. Although load-induced stresses, strains, and displacements are greater in the subgrade during construction than at any other time, the subgrade may also be the most important factor influencing ultimate pavement performance.

Construction-Related Requirements

Sinkage

Equipment sinkage (rutting) is an important construction consideration. Rutting creates an uneven grade that makes it difficult to control the thickness of the subsequent pavement layer. Severe subgrade rutting causes a significant loss in equipment efficiency. Current Illinois DOT specifications indicate that ruts deeper than 5 cm (2 in) are unacceptable. In reality, even shallower ruts are often intolerable because of strict controls on layer thicknesses.

Rutting is bearing-capacity failure and permanent deformation caused by repeated loading at stresses near the shear strength of the material. In terms of equipment mobility, the bearing-capacity portion of the rutting is probably the most significant.

The effects of stress level, number of load applications, and moisture content on the permanent deformation behavior of two typical Illinois soils are illustrated in Figure 6 [AASHTO class A-4 (9)] and Figure 7 [AASHTO Class A-7-6 (29)]. Note that a large portion of the permanent deformation is accumulated during the first few load applications.

Traylor and Thompson (15) used two of the most promising procedures for predicting sinkage on subgrades of varying strengths. Figure 8 (15) illustrates the effect of subgrade strength on sinkage. To limit sinkage of a 40-kN (9000-lbf) wheel load with a 550-kPa (80-lbf/in^2) tire pressure to 12 mm (0.5 in) or less, the subgrade strength should be in the CBR range of 5.5-8.5. For a 6-mm (0.25-in) sinkage, the corresponding CBR strength range is 8.0-8.5. Minimizing rutting damage of the finished grade probably requires a subgrade CBR of at least 6.

Compaction of Paving Materials

The shear strength and stiffness of the subgrade significantly influence the process of compacting pavement materials such as crushed stone, gravel, and stabilized bases. Compaction effectiveness and efficiency are influenced by subgrade support. Results of controlled field compaction tests demonstrate that there are practical, achievable density limits for given types of equipment, layer thickness, and subgrade support.

Field studies summarized by Heukelom and Klomp (16) led to the conclusion that "The degree to which layers of unbound materials can be compacted depends to a large extent on the reaction of the subsoil." When successive layers of materials were compacted over the first granular layer, it was possible to achieve higher levels of compaction in the upper layers as indicated by the dynamic modulus of elasticity.

Heukelom and Klomp suggested, then, that the states of compaction, stability, and decompaction of a granular layer over a subgrade can be examined in terms of the tensile stress condition at the bottom of the granular layer. They indicated that, because of intergranular friction, the vertical component of the stress would permit the granular material to withstand certain radial tensile stress without decompacting or expanding. If the subgrade soil at the granular material-subgrade interface has a very low shear strength, it may not be possible to develop the full potential of the frictional stress needed to resist the radial displacement of the granular layer, and decompaction may follow. A low-modulus subgrade results in high tensile stresses developing at the bottom of the granular layer, which also leads to decompaction.

Barenberg's shear layer theory (17) also demonstrates the importance of maintaining a high shear strength in the soil at the granular material-subgrade interface. The theory shows that the loss of shear strength at the granular material-subgrade interface causes a substantial decrease in load-distribution capability and increases the deflection of the granular layer, thus preventing additional compaction.

Stress-dependent finite-element analyses were conducted to determine the effect of subgrade support on the compaction behavior of granular layers such as crushed stone, gravel, cement aggregate mixture, bituminous aggregate mixture, or pozzolanic aggregate mixture. Realistic loading conditions for a pneumatic roller were used. Figure 9 shows the relations among subgrade compressive strength, roller tire pressure, and thickness of layer for soft and stiff subgrade conditions and can be used to approximate the granular layer and subgrade compaction interaction. If the system cannot withstand sufficiently high tire pressures, field compaction (which involves shear failure in the granular layer during densification) cannot be accomplished. If tire pressures are too high, significant permanent deformation and shoving will develop in the subgrade.

It is apparent that certain minimum levels of subgrade strength and stiffness are needed to ensure adequate compaction. A minimum compaction CBR of approximately 6 seems reasonable and also checks favorably with the minimum stability required for construction sinkage control.

If paving materials are placed in a plastic state, consolidated by using vibratory procedures, and then cured, compaction-related subgrade stability requirements are less stringent. Econocrete is a good example of such a material.

Performance-Related Requirements

Subgrade stability in the completed construction must be at least equal to the value used in establishing the

Figure 6. Stress level and permanent strain relations for Fayette C.

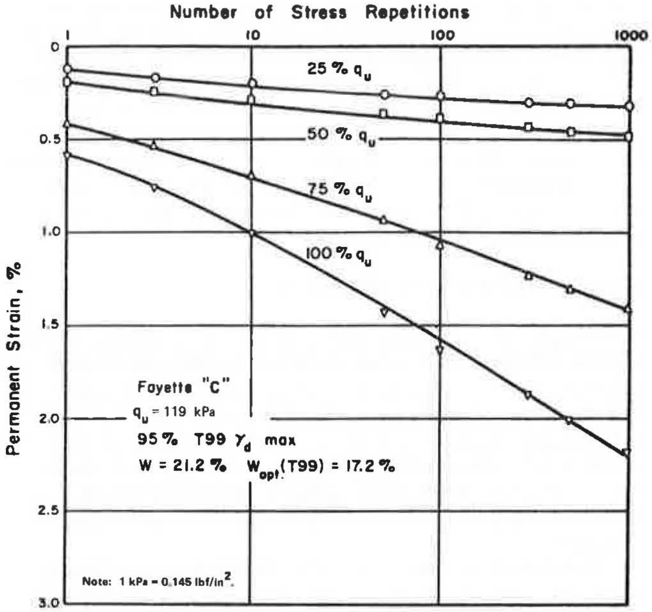


Figure 7. Stress level and permanent strain relations for Muscatine B.

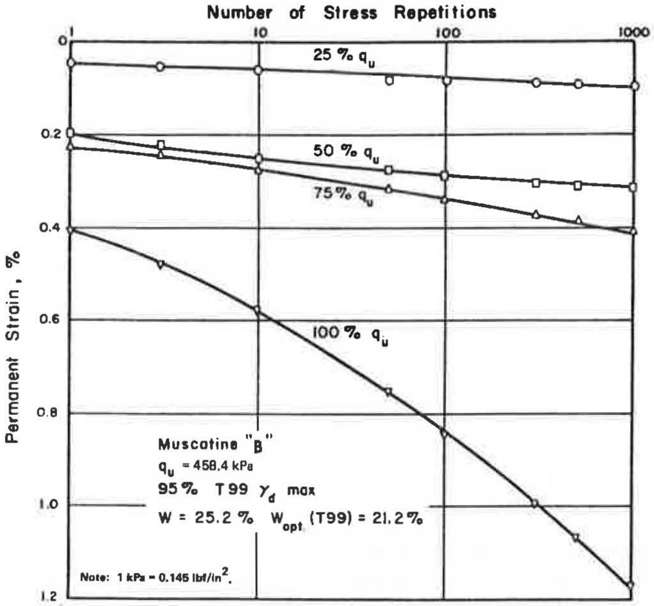


Figure 8. Soil strength-sinkage relations for a 40-kN wheel load.

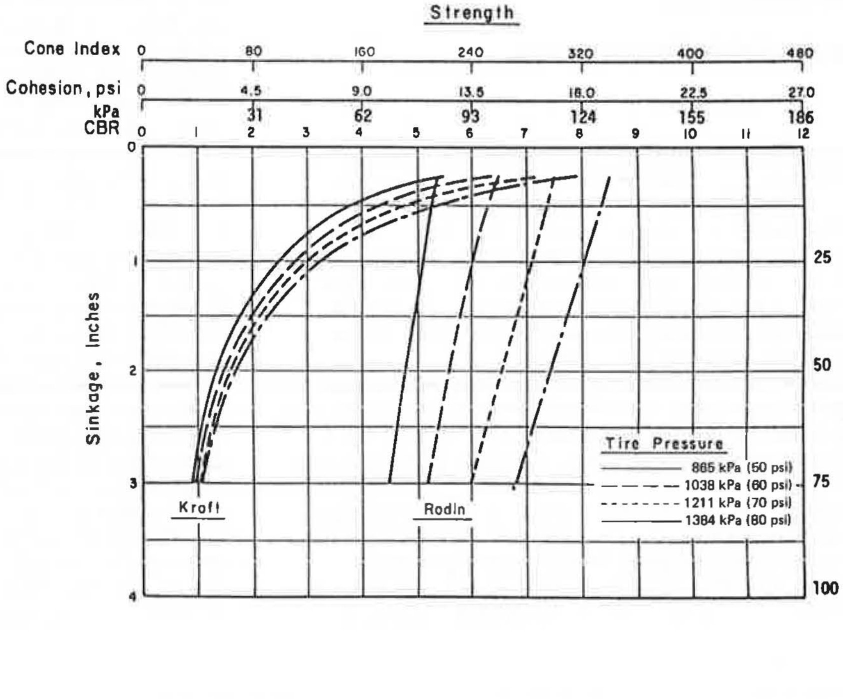
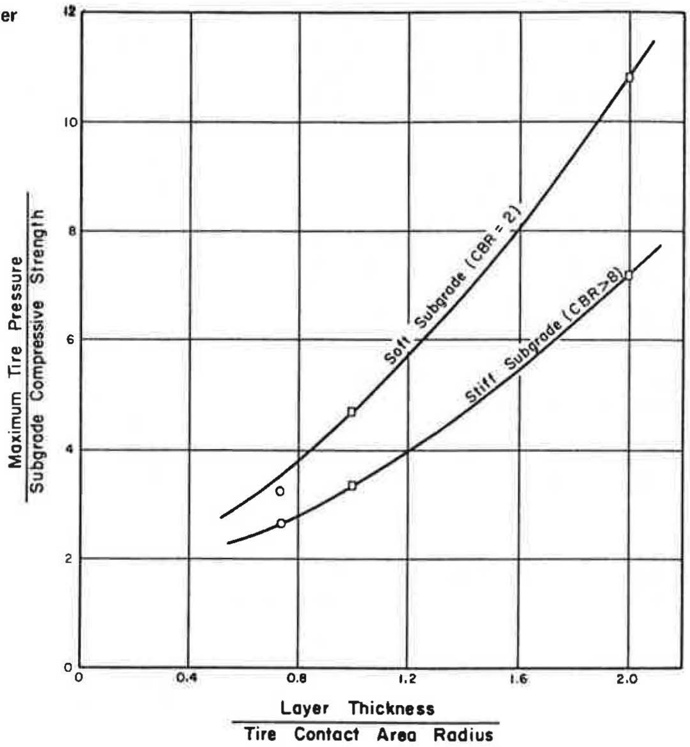


Figure 9. ·Tire pressure-subgrade strength and layer thickness compaction relations.



pavement design. The minimum acceptable level of subgrade support (based on design thickness considerations) should be stated in the project plans and documents. To ensure adequate performance over the design life of the pavement, the subgrade support, which will vary with time, should meet those stability levels assumed in design.

The major factors influencing support changes are moisture fluctuation and freeze-thaw action. The effects of moisture on strength and resilient properties have already been discussed. Freeze-thaw softening problems for typical Illinois soils have been considered by Robnett and Thompson (18). Typical detrimental effects (expressed as a reduction in resilient modulus during freezing and thawing) may reduce resilient moduli by a factor of two or three.

The need for careful consideration of the temperature and moisture regime (relative to pavement performance) is obvious. Dempsey and Thompson (19) have developed analysis procedures for considering temperature effects in pavement systems. Frost-action depths can be estimated fairly accurately by using those procedures. The work of Dempsey and Elzeftawy (6) can also be used to determine moisture change with time and space. Moisture movement theory indicates that the projected moisture content as a function of space and time for a given pavement profile is not significantly influenced by the moisture-density condition of the soil at placement.

Summary

Construction operations and pavement performance should be considered whenever one is establishing subgrade stability requirements. In most situations construction-based stability requirements will predominate. It is interesting to note that in an Illinois study (1) the average CBR (immediate penetration) of typical Illinois soils compacted at T99 optimum moisture content to 100 percent of AASHTO T99 maximum density was 8.6 with a standard deviation of 3. Approximately 20 percent of the soils had a CBR of less than 6. Many soils having moisture contents in excess of T99 optimum will have compacted CBR less than 6.

REMEDIAL ACTION

A comparison of subgrade stability requirements with the properties of typical Illinois soils compacted at a range of commonly found water contents indicates that, in many instances, the compacted soil will not possess adequate strength or stiffness or both. Among the appropriate remedial procedures that have been successfully used are undercut and backfill, moisture density control, and admixture stabilization (physical mixing of soil and admixture).

Undercut and Backfill

One popular procedure is to cover the soft subgrade with a thick layer of granular material or to remove a portion of the soft material to a predetermined depth below the gradeline and replace it with granular material. This granular layer distributes the wheel loads over the unstable subgrade and serves as a working platform on which construction equipment can operate.

Two conditions must be satisfied for a firm working platform: First, the granular layer must be thick enough to develop acceptable pressure distribution over the soft subgrade; second, the backfill material must be able to limit rutting under the applied wheel loads to acceptable levels.

Moisture-Density Control

It has been shown above that the stability, or strength and stiffness, of a cohesive soil is influenced primarily by moisture content and, to a lesser extent, by density. Wet of optimum, moisture is the primary factor influencing stability. Given low density or excessively high moisture content (which is generally the problem), it is difficult to achieve a sufficiently good working platform for efficient use of construction equipment and adequate subgrade support for the finished pavement.

On the subject of compaction Wahls (20, p. 99) has said that

> Compaction specifications may indicate the procedure by which the compaction is to be accomplished, the required quality of the compacted materials, or some combination of procedure and required results. The specified procedure may include moisture control, lift thickness, type and size of compaction equipment, and the number of coverages of the equipment. The quality of the compacted material generally is specified in terms of dry density, which is usually expressed as a percentage of the maximum dry density achieved in a specified laboratory compaction test.

He discussed in detail the embankment and subgrade compaction specifications used in the United States. In 1967 he said,

> A statement regarding moisture requirements is included in the specifications for embankments in all but two states and for subgrade in all but nine. However, in approximately 60 percent of the states the moisture conditions for both embankment and subgrades are specified in a qualitative manner which leaves the interpretation largely to the judgment of the inspector.

A major problem in implementing moisture control is the proper establishment of permissible compaction moisture contents. Figures 10, 11, and 12 illustrate the relations among compaction moisture content, CBR, and compactive effort. Previously a minimum CBR of 6 was suggested for adequate subgrade stability. From Figure 11 it is obvious that the compaction moisture content must be less than 110 percent of optimum to ensure a CBR of 6 in half the soils tested. In many instances the on-site soils or borrow materials are significantly wet of optimum and require extensive drying.

That the use of density control in embankment con-

Figure 10. CBR and moisture content-PI relations for typical Illinois soils of CBR 4.

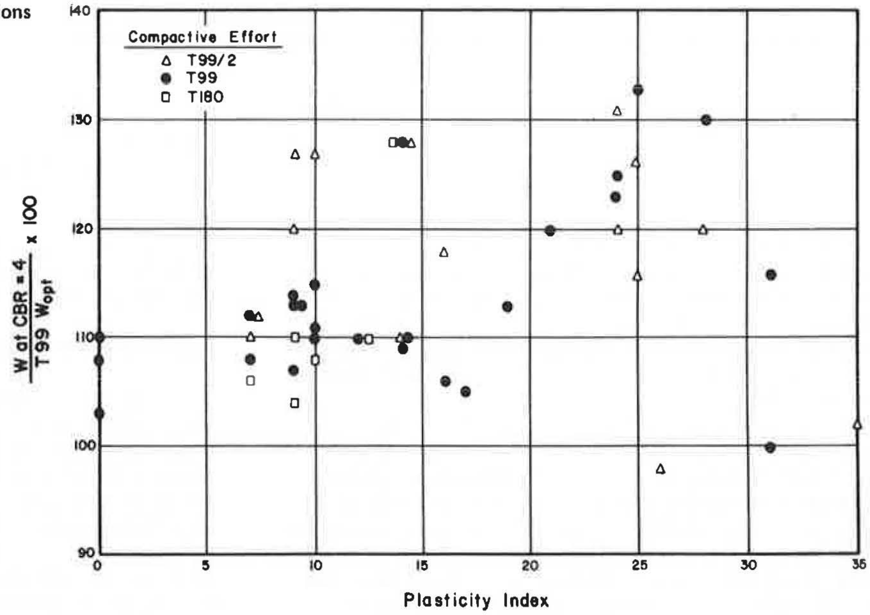


Figure 11. CBR and moisture content-PI relations for typical Illinois soils of CBR 6.

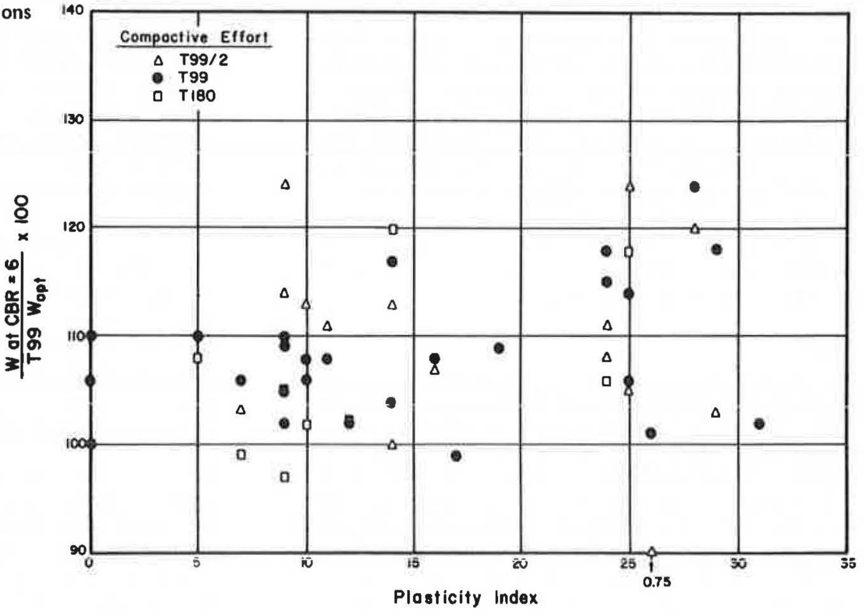
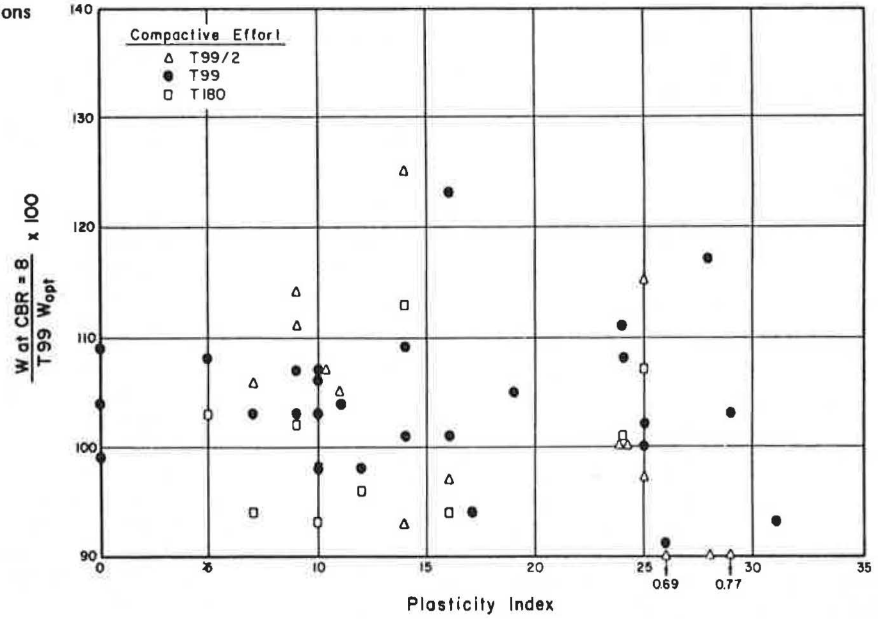


Figure 12. CBR and moisture content-PI relations for typical Illinois soils of CBR 8.



struction as a means of improving subgrade stability is widely accepted is indicated by its overall use in specifications. The use of moisture control is also accepted but generally as a qualitative requirement. The quantification of moisture control would help increase subgrade stability, at least on a temporary basis. Three major problems are involved in the use of moisture-density control as a remedial measure.

1. Specified compaction densities and moisture contents are formulated in the laboratory, so it is necessary to approximate the field compaction method by the laboratory test used. There are data that indicate that the densities and physical properties of samples compacted by laboratory impact methods (most widely used method) may differ significantly from the properties of the same material compacted by construction equipment in the field.
2. It is possible to have an acceptable density but not a stable subgrade because of soil type. No matter how much compactive effort is expended, it is impossible to achieve a stable subgrade with certain soils, particularly if they are wet of optimum.
3. Several major problems are encountered in achieving a specified water content before compaction and then maintaining the water content of the finished subgrade.

Water Content Control

Many present specifications for controlling excess moisture provide for draining the grade and drying the top several centimeters of the subgrade. Drainage of the area will remove surface water, but will not significantly reduce the water content of fine-grained soils. Drying is accomplished through evaporation. Disking and manipulating the soil increase the amount of exposed surface area to increased evaporation that can speed drying. The factors involved in the evaporation process and some models used to predict evaporation are examined below.

Evaporation can be defined as the conversion of soil surface water into vapor in the atmosphere. Three basic conditions are necessary for the evaporation process to occur.

1. There must be a heat supply, because the rate of evaporation increases with the water temperature.
2. There must be a vapor pressure gradient to the atmosphere, which allows removal of the vapor.
3. There must be a continual supply of water from or through the soil profile, because, if there is no water, there is no evaporation.

The first and second conditions are external to the soil and are influenced by climatic factors such as air temperature, solar radiation, humidity, and wind velocity, of which the first two are the most important.

Evaporation reduces the soil water content at the surface, thus increasing soil water suction at the surface. The pressure gradient draws water from the layers below. If the water table is low, the surface materials will be dried; if the water table is high, it is quite possible for the evaporation process to draw a continual flow of water to the surface. A crust can form at the surface, but wet, soft, potentially troublesome soils could remain below.

In order to quantify the potential for drying by evaporation, Thompson and others (21) considered some of the many models for predicting evaporation that have been developed. Most of them use variables that cannot be determined easily, but two models that use commonly available variables have been proposed by Thornthwaite (22) and Hamon (23, 24) to predict evaporation from an open pool of water.

Hamon's (23, 24) simplified expression for potential evapotranspiration is

$$E_p = CD^2P_t \qquad (1)$$

where

E_p = potential evapotranspiration in millimeters per day;
D = possible hours of daily sunshine in units of 12 h;
P_t = saturated water-vapor concentration at the mean temperature in grams per cubic meter; and
C = 0.0055, an empirically developed constant.

Values of D^2 and P_t have been tabulated in Hamon's paper (24). For illustration purposes, potential evapotranspiration data (based on Hamon's equation) are presented in Figure 13 (25) for central Illinois. Also shown in the figure is the theoretical percentage of moisture removed from a 0.1-m^2 (1-ft^2) block of soil, 20 cm (8 in) deep.

It should be noted that calculated evapotranspiration is likely to exceed actual evaporation from a subgrade. The methods are for ideal conditions and do not allow for precipitation during the calculated period. Both methods use mean temperature, which does not give as good an indication of potential as radiation, and both include removal of water by transpiration, which will not occur on an earthen surface. Neither method takes soil type into account.

The Hamon predictions are an optimistic appraisal of expected evaporation from the soil. Although some drying can be expected from evaporation, it is improbable that large amounts of water will be removed from the subgrade over a short time span. It is particularly important to note (see Figure 13) that, during periods of low prevailing temperatures, very little drying occurs. The process of tilling may or may not be beneficial, depending on evaporation stage and soil type.

Maintenance of Subgrade Water Content

As previously indicated, many surficial soils are poorly or imperfectly drained. Although one might be able to place a subgrade soil that is in an area of prevailing high water table at or near the optimum water content, it is difficult to maintain that moisture condition. Higher suction in the drier soil will draw the moisture up through the subgrade from the underlying soil until an equilibrium condition is reached. The equilibrium water content with a shallow water table is generally considerably above the optimum water content. In addition, precipitation will cause surface wetting and subsequent moisture increases in the subsurface zone.

Admixture Stabilization

Admixture stabilization (mixing and blending a liquid, slurry, or powder with the soil) is a technique that has been successfully used for improving soil strength and stiffness properties and thus improving subgrade stability.

Those admixtures most widely used for remedial treatment of subgrade soils are lime, lime-fly ash, and cement. Fly ash, cement kiln dust, and lime kiln dust have also been used and frequently are available at a low cost. One particularly attractive characteristic of fly ash and kiln dusts in their low energy value, which makes them very attractive in terms of energy conservation.

Several construction procedures have been used in wet-soil treatment operations. Conventional rotary mixers can readily handle lifts as thick as approximately 30 cm (12 in). Special procedures or deep plowing may be needed to construct thicker layers; the former have been described in detail by Thompson (25). Lime-treated layers as thick as 60 cm (24 in) have been constructed in one lift in Illinois. In some instances, wet borrow soils have been 100 percent treated to form a stable embankment. Admixture stabilization can be accomplished by using borrow pit mixing procedures, or the wet borrow can be spread on the embankment in a normal lift thickness and then stabilized.

Construction specification and procedures for remedial subgrade soil treatment are frequently less stringent than those for stabilization, where the stabilized material may be used as a structural pavement layer. Improved job mobility, fewer working days lost by wet weather, and a general expediting of construction are frequently mentioned benefits of admixture-stabilized subgrades.

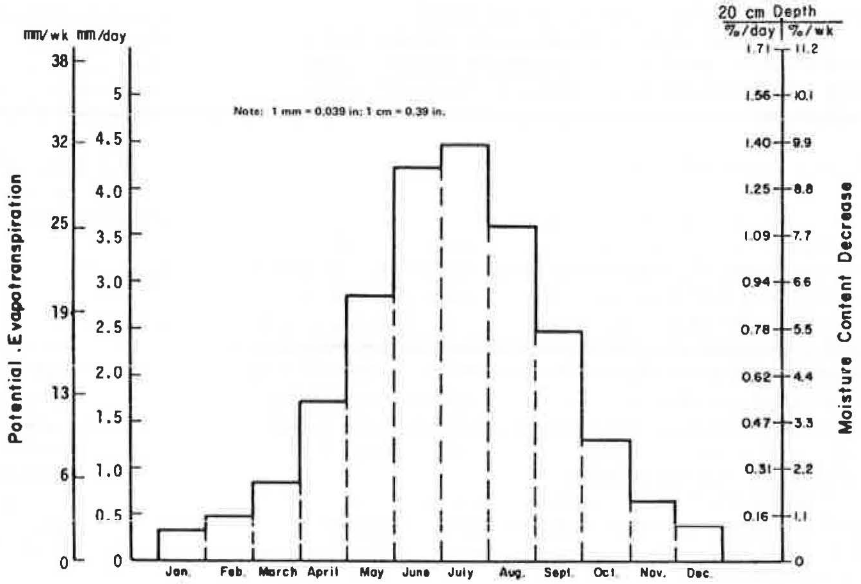
Admixture stabilization is in many instances a very cost-effective procedure. Significant energy savings, relative to other remedial procedures, may also be achieved.

The technologies associated with the various forms of admixture stabilization are fairly well established. Careful consideration should be given to admixture treatment levels, construction techniques and operations, and construction control.

SUMMARY

Soil type and moisture content are the major factors influencing and controlling subgrade stability. The current use of pedologic soils information (previous soil reports, geologic data, drilling, sampling, and testing to identify soil type) is fairly well defined and

Figure 13. Potential evapotranspiration for central Illinois (Urbana data) based on Hamon's procedure.



seems adequate for subgrade stability evaluation. But techniques and procedures currently used to characterize field soil moisture regime are inadequate. It is essential to acknowledge that field soil moisture content is not static but varies constantly with time. The TRRL procedure described in this report can be used to evaluate the field soil moisture regime.

Subgrade stability requirements are primarily dictated by pavement construction demands. Analyses of equipment sinkage and paving-material compaction operations indicate that a minimum in situ CBR of 6-8 is required. Many typical fine-grained soils do not develop CBRs in excess of this when compacted at or wet of AASHTO T99 optimum water content. Thus, remedial procedures must often be used to provide adequate subgrades for pavement contraction.

Three such procedures—undercut and backfill, moisture-density control, and admixture stabilization—were described and evaluated. Undercut and backfill and admixture stabilization offer the greatest potential and provide a permanent solution that has significant carry-over effects beneficial to the ultimate performance of the completed pavement.

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