Design and Behavior of
Soil-Fabric-Aggregate Systems

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The use of fabrics made of man-made fibers is having an increasing impact on the construction techniques used for and the technology of soil-aggregate systems. Certain fabrics, when placed between a soft subgrade soil and a layer of aggregate, will significantly improve the performance of the system. The fabrics are especially effective in improving the performance of those systems that have very soft subgrades and hence high deflections and a high tendency toward rutting. Although it can be demonstrated that fabrics can significantly improve the performance of soil-aggregate (S-A) systems that have soft subgrades, there are no reliable procedures available to guide in the thickness design of these systems or in the selection of the appropriate fabric properties. This paper is a first attempt to explain why and how a fabric affects the behavior and performance of a soil-fabric-aggregate (S-F-A) system and describes the development of a design procedure for S-F-A systems that use MIRAFI-140 fabric. The four basic mechanisms by which fabrics affect the behavior and performance of S-F-A systems include (a) confinement and reinforcement of the aggregate layer, (b) confinement of the subgrade soil, (c) separation of the soil and the aggregate layers, and (d) introduction of filter medium to facilitate drainage. Repeated plate-load tests on small- and large-scale S-A and S-F-A systems in a laboratory setting are described. The results of these tests are analyzed by using elementary theories and techniques, and a design procedure for S-F-A systems that use the MIRAFI-140 fabric is developed. An example of a typical design curve for S-A and S-F-A systems is included.

Nonwoven plastic filter fabrics are becoming important component materials for many civil engineering applications. Within the past decade, many construction projects in North America and Europe have included these fabrics as parts of the systems (1). They have been used for such varied purposes as subgrade stabilization, construction of underground drainage systems, and control of erosion and sediment runoff. The systems that use these fabrics are generally performing well and are economically competitive with systems that use more traditional designs and construction methods.

This report deals primarily with the use of these fabrics in the design and construction of haul roads or other temporary road systems, which conventionally consist of layers of unsurfaced aggregate material placed directly on marginal subgrades. The use of nonwoven plastic filter fabrics in these types of applications falls in the general category of subgrade stabilization and involves placing a layer of fabric on top of the soft subgrade before the placement of the aggregate layers. The presence of the fabric between the subgrade and the aggregate layer potentially affects the behavior of such road systems in several ways, such as

1. Confining and reinforcing the aggregate layer by providing a tensile capacity along its bottom,
2. Altering the failure mechanisms in soft subgrade soils by distributing the stresses more evenly over the subgrade (which results in less abrupt deformation patterns in the subgrade),
3. Maintaining a clean separation of the aggregate and the soil layers by preventing intermixing of the aggregate and soil materials, and
4. Allowing water to pass freely from weak saturated subgrades into the aggregate material without the intermixing of soil and aggregate (this allows consolidation of the soil, which strengthens and stabilizes the subgrade).

These effects caused by the use of fabrics in the systems result in practical and potentially economical advantages in that the depth of the layer necessary for good performance of the road systems is generally reduced when fabric is used. This has been demonstrated in field applications from which it was concluded (2) that "the horizontal placement of fabrics or membranes between soft clay subgrade and crushed-stone base can offer substantial savings in design thickness."

Because of the increasing use of fabrics in road construction, there is a need for a simple and practical method of using measured field conditions and predicted traffic data to determine the design of road systems, both those that include fabrics and those that do not. This study was undertaken to determine the effects of including a fabric in a road system, the effects of various fabric properties on system performance, the development of tests and procedures for obtaining subgrade input parameters from field-test data, and the development of a design method for temporary haul road systems that include fabric.

The laboratory-testing program included extensive soil-characterization investigations and two types of scale-model testing of road systems. Large-scale three-dimensional representations of road systems were used for testing with static loads, repeated loads, and loads to failure. Small-scale, two-dimensional model systems were used for extensive repeated-load tests.

Because only one fabric—MIRAFI-140—was used in this research, these results and conclusions apply specifically only to construction of road systems that use this fabric. The general concepts derived herein may be considered for design of road systems that use other fabrics, but caution must be taken in extending these results to other fabrics until comparable testing or evaluation can be performed on systems incorporating the specific fabric under consideration. These results also have implications toward such applications as higher quality pavement systems and railroad ballast construction, which could be studied through continuation and extension of this research.

PRELIMINARY OBSERVATIONS

Behavior of Soil-Aggregate Systems

The haul roads and other temporary road systems considered in this study are assumed to be unpaved aggregate layers placed directly on in situ subgrades. These shall be referred to as soil-aggregate (S-A) systems. Of greatest concern are the fine-grained silty and silty clay subgrade soils that have low bearing capacities, because pavements constructed on these types of soils frequently develop severe rutting under traffic loading and require periodic maintenance to keep these roads passable.

The introduction of a fabric into a pavement system is accomplished by placing the fabric directly on the unprepared, or minimally prepared, subgrade before the placement of the aggregate materials. These sys-

tems are referred to herein as soil-fabric-aggregate (S-F-A) systems.

Some characteristic differences that have been observed between the behavior of S-A and S-F-A systems are categorized below (2):

1. S-A systems require aggregate layers of greater thickness than do S-F-A systems to carry the same traffic; conversely, for a given aggregate thickness, S-F-A systems can support more applications of traffic than can S-A systems without severe rutting.
2. Deformation or rutting patterns in S-A systems are more localized and more severe than in comparable S-F-A systems; maximum permanent deflections are less in S-F-A systems than in S-A systems for the same traffic.
3. In S-A systems, rutting under traffic is usually accompanied by intermixing of the aggregate and subgrade materials, but in S-F-A systems, there is a clean separation of the aggregate and subgrade layers, which maintains a distinct interface between the materials.

Mechanisms

The observed differences in behavior between S-A and S-F-A systems are indicators of the mechanisms by which the fabrics improve the performance of S-F-A systems over that of S-A systems. These mechanisms include

1. Confinement and reinforcement of the aggregate layer,
2. Confinement of the subgrade soil,
3. Separation of the soil and the aggregate layers, and
4. Introduction of a filter medium that permits the free flow of water from the soil into the aggregate layer and also prevents the migration of fine particles from the soil into the coarser aggregate layer.

Confinement and Reinforcement of Aggregate Layer

Granular materials characteristically have no tensile strength. Consequently, when a layer of aggregate supported by a soft subgrade is subjected to an applied load, the load-distribution effectiveness of the aggregate layer is limited by the shear stresses that develop at the interface between the aggregate layer and the subgrade. A layer of fabric can increase the effective shear strength at this interface and thereby increase the load-distribution effectiveness of the aggregate layer. In effect, the fabric in this system serves much the same function as does reinforcing steel in concrete; i.e., it provides a component that can absorb some of the tensile forces in the system.

The effects of fabric reinforcement on the aggregate layer, and to some extent the soil subgrade, can be seen in the results of a finite-element analysis of one of the two-dimensional test models (3). Figure 1 shows the variation in the horizontal strain with depth in typical S-A and S-F-A systems under load. The fabric properties used in this analysis were the same as those used later in the test program. These results show that the fabric reinforces the aggregate layer by restricting the horizontal strains in the aggregate layer, which reduces the critical horizontal strains at the soil-aggregate interface. In this analysis, the aggregate was assumed to have a high modulus in compression but a very low modulus in tension. These strain results from theoretical analyses are consistent with the observed behavior of S-F-A systems reported elsewhere (4).

Confinement of Subgrade Soil

Theoretically, when subgrade soils fail in shear because of loads applied, a slip plane forms as shown in Figure 2 (5), and slippage along this plane results in a

Figure 1. Horizontal strain across section A-A soil-aggregate system and effect of fabric.
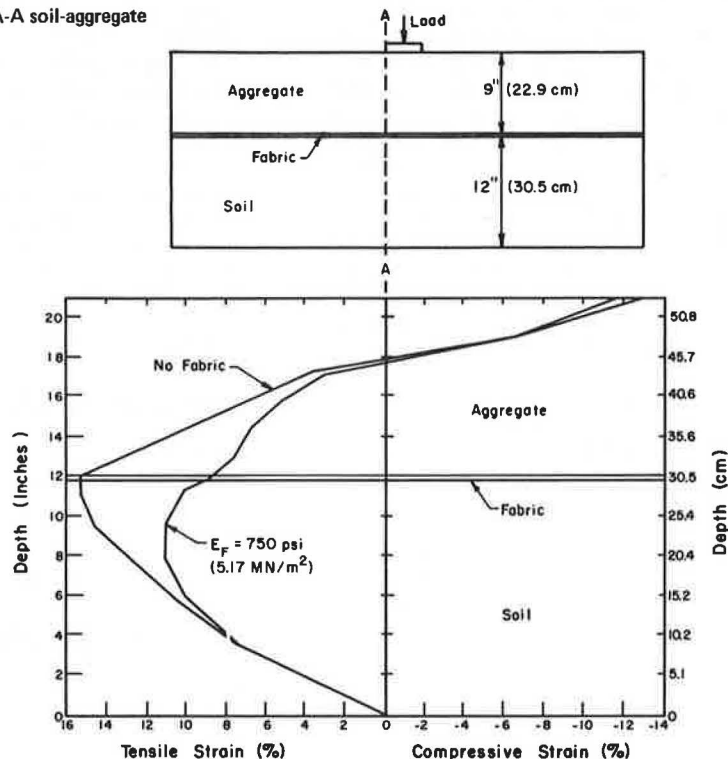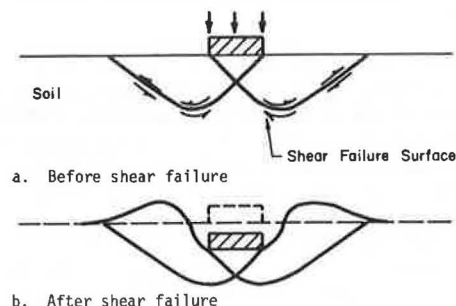
Figure 2. Deformation of loaded soil system.

a. Before shear failure

b. After shear failure

Figure 3. Deformation of loaded soil-aggregate system.

a. Before shear failure

b. After shear failure

deformation pattern. Placing a layer of aggregate on top of the soil as shown in Figure 3 tends to distribute the load somewhat and thus increases the load-bearing capacity of the system. Because of its low tensile capacity, however, the aggregate layer does not significantly increase the soil load-bearing capacity per se. (Note that these deformation patterns are relatively localized.)

Inclusion of a fabric in an S-A system tends to confine the soil as shown in Figure 4. Tensile forces in the fabric, both under the load and away from the loaded area, tend to restrain the upheaval of the soil mass contained within the slip planes, thereby increasing the load-bearing capacity of the soil. (Note that the deformation pattern shown in Figure 4, which was developed from observations of actual failures of these systems, is more evenly distributed and less abrupt than those shown in Figures 2 and 3.) A layer of aggregate material is always needed on top of the fabric to anchor it so that the necessary tensile forces can be developed in the fabric.

Separation of Soil and Aggregate
Layers

Infiltration of fine-grained soils into the aggregate layer is a major cause of failure of S-A systems (6). When the fine-grained soil works into the aggregate materials, it tends to plug the voids, which prevents free drainage of water from the aggregate. In a saturated state, many aggregates exhibit a reduced stability and a reduced load-carrying capacity (7, 8). And as the soil penetrates into the aggregate layer, the aggregate particles in turn penetrate into the soil mass; this intermixing tends to reduce the effective depth and the effectiveness of the aggregate layer. In extreme cases, such as some railroad ballasts, aggregate particles have been found to have penetrated to depths of 3 m (10 ft) or more into the subgrade soil. The layer of fabric inhibits the migration both of the fine soil particles into the aggregate layer and of the aggregate particles into the soil, thus maintaining the separation of the soil and aggregate layers.

Introduction of Filter Medium

Water is a primary cause of distress in subgrade soils. When a layer of aggregate material or a load is placed
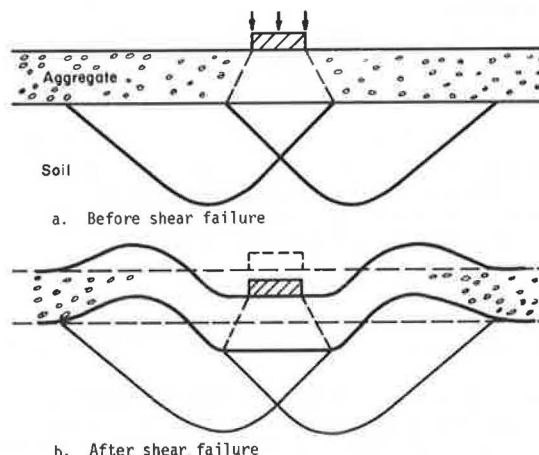
on a saturated soil, the soil mass tends to consolidate. If the water in the soil pores cannot escape, a pore pressure builds up, which reduces the strength of the soil. A layer of a fabric that has small pore openings but a high permeability, placed between the aggregate layer and the soil, can allow water to escape from the soil into the coarser granular material, but will restrict fine soil particles from migrating into the granular voids.

Important Fabric Properties

In addition to the mechanisms discussed above, the fabric properties of toughness, ductility, and fatigue resistance are also important in relating the behavior of the system to load. Fabric porosity and permeability are important characteristics for drainage and layer-separation functions.

We cannot yet define with confidence those fabric properties that control the performance of S-F-A systems. Based on both laboratory and field observations, a high level of toughness appears to be important and is especially necessary to prevent the fabric from tearing during construction. The effects of porosity on performance have not been established for the type of use discussed here, but it is obvious that unless the fabric is adequately porous, the drainage function cannot take place. Fatigue of the fabrics apparently does have an effect on performance of S-F-A systems, but the acceptable stress or strain levels in the fabric to prevent its fatigue in the S-F-A systems has not been established.
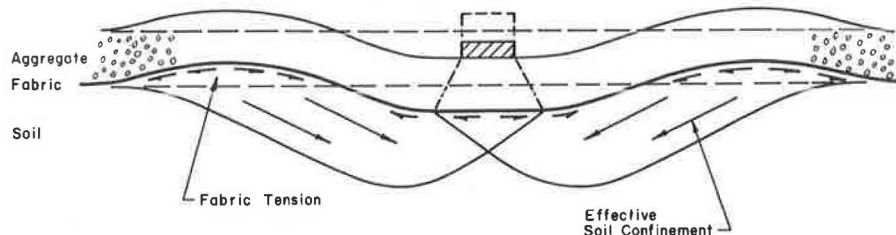
This sketchy framework represents the current state of the art in understanding the behavior and performance of S-F-A systems.

TESTING PROGRAM

Descriptions of Tests

The program of laboratory testing was divided into three parts: (a) soil characterization, (b) three-dimensional

Figure 4. Deformation of loaded soil-fabric-aggregate system.

large-scale model tests, and (c) two-dimensional small-scale model tests. The tests are described below and the results discussed later.

Soil Characterization

The purpose of these tests was to establish soil-testing methods that could quickly and easily measure the properties of subgrades in situ to provide input parameters for a design procedure. The three testing methods used included the California bearing ratio (CBR), vane shear, and cone penetrometer. These tests were run on several soils at different moisture contents and densities, and general correlations were developed, as is shown in the nomograph in Figure 5. The cone-penetrometer and vane-shear tests were used because these tests are quickly and easily performed in the field; the CBR values are shown because they are familiar to many of the engineers responsible for road design.

Three-Dimensional Tests

Three-dimensional models of S-F-A systems were constructed on the University of Illinois pavement test track. This is a circular track that has a 2.7-m (9-ft) diameter concrete inner-perimeter wall and a 7.6-m (25-ft) concrete outer-perimeter wall, which leaves an annular pit approximately 2.4 m (8 ft) wide between them; the concrete floor of this pit is approximately 1.5 m (5 ft) deep. Details of the test track are given elsewhere (6, 7).

Depth of the aggregate layers in the systems tested ranged from 0 to 38 cm (0 to 15 in). Static and repeated loads were applied to the S-A and S-F-A systems through

steel plates that had diameters of 30.5, 45.7, 61.0, and 76.2 cm (12, 18, 24, and 30 in). The static loads were applied at various levels of stress and to failure, and the repeated loads were dynamically cycled at various levels of stress. Vane shear, cone penetrometer, and CBR tests were run on the subgrade before and after testing the S-F-A systems. The total deformations, permanent deformations, and elastic rebound of the systems were measured during the tests.

Figures 6 and 7 present the factorials of the static-load and the repeated-load tests respectively.

Two-Dimensional Tests

Two-dimensional models of S-F-A systems were constructed in the small box apparatus illustrated in Figure 8. The soil layers were 33 cm (13 in) thick, and the aggregate layers were 7.6 to 22.9 cm (3 to 9 in) thick. Vane shear and cone penetrometer measurements were taken before and after testing. Repeated loads were applied to cause various levels of stress on the subgrade, and measurements of total and permanent deformations and elastic rebound were taken during the tests.

Figure 9 presents the factorial of the repeated-load tests run in the two-dimensional testing program.

Descriptions of Materials

Soil

Subgrades that would cause the most problems in S-F-A systems are fine-grained silty or silty clay soils at a
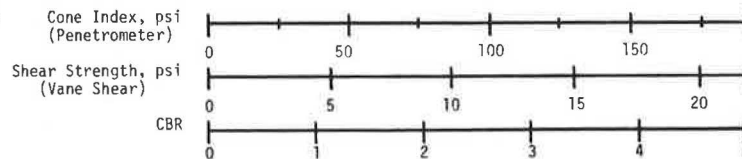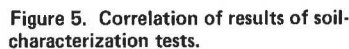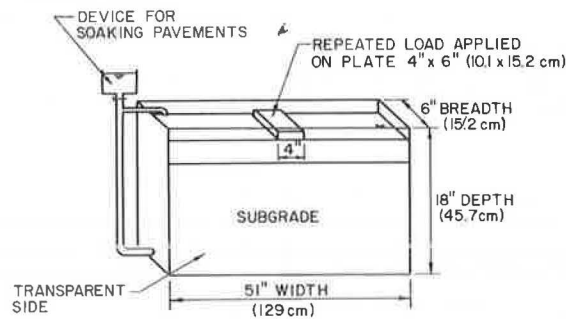
Figure 5. Correlation of results of soil-characterization tests.

Figure 6. Factorial of three-dimensional static-load tests.

Figure 7. Factorial of three-dimensional repeated-load tests.

	None					One					Two				
	0	6	9	12	15	0	6	9	12	15	0	6	9	12	15
500	x	x					x					x			
1000	x	x	x	x			x	x	x			x	x	x	
1500	x	x					x					x			
2000		x	x	x	x		x	x	x	x		x	x	x	x
3000			x	x	x			x	x	x			x	x	x
4000			x	x	x			x	x	x			x	x	x
5000			x	x					x	x				x	x
6000					x					x					x

(Axis labels: Layers of fabric / Depth of aggregate layer (in) / Repeated load on surface (lb))

Figure 8. Schematic diagram of two-dimensional model used in laboratory tests.

moisture content near saturation. The properties of the Goose Lake clay used in this study are given below (1 Mg/m³ = 62.4 lb/ft³).

Property	Value
Liquid limit, %	32
Plastic limit, %	16
Plasticity index, %	16
Optimum moisture content, %	14.7
Max dry density, Mg/m³	1.846
CBR at optimum moisture	5.9

Compactive Effort (blows/layer)	Dry Density (Mg/m³)	Moisture Content (%)	CBR
56	1.51	26.2	0.6
	1.58	23.5	0.8
	1.63	21.1	0.9
26	1.58	23.1	0.8
	1.61	20.5	2.5
12	1.46	26.6	0.7
	1.49	25.0	1.0
	1.47	23.4	1.3

Fabric

The properties of the actual fabric sample used in these tests are shown below and in Figure 10 [1 g/m² = 0.028

Figure 9. Factorial of two-dimensional repeated-load tests.

	None			140			280		
	3	6	9	3	6	9	3	6	9
4		x			x			x	
5			x			x			x
8		x			x			x	
10	x	x	x	x	x	x	x	x	x
20	x			x			x		

(Axis labels: Type of fabric / Depth of aggregate layer (in) / Stress on subgrade (psi))

oz/yd², 1 μm = 0.04 mil, 1 kN = 225 lbf, and 1 (m³/s)/m² = 197 (ft³/min)/ft²]:

Property	ASTM Test	Value
Weight, g/m²	D1910	140
Thickness, μm	D1777	750
Grab strength, wet, kN	D1682	0.53
Retention at 21°C (70°F), %		100
Grab elongation, wet, %	D1682	120
Retention at 21°C (70°F), %		40
Trapezoid tear strength, kN	D2263-68	0.24
Air permeability, (m³/s)/m²	D737	1.27

Both a single layer and double layers of the fabric were used in these tests, as well as an experimental variant of double-weight fabric (MIRAFI-280).

Aggregate

The aggregate used in these tests was a crushed limestone that had a gradation curve as shown in Figure 11.

Figure 10. Typical load versus elongation curve for MIRAFI 140 fabric.

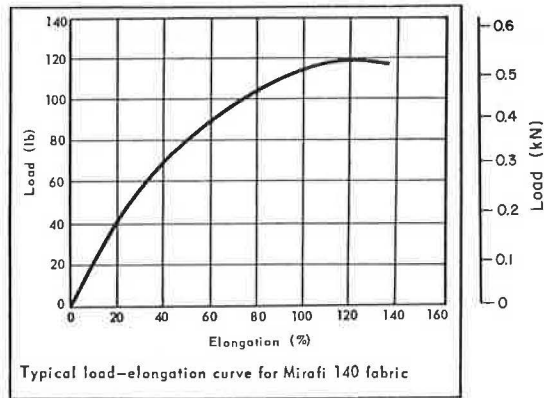Typical load—elongation curve for Mirafi 140 fabric

Figure 11. Gradation curve for aggregate material used in S-A and S-F-A laboratory tests.
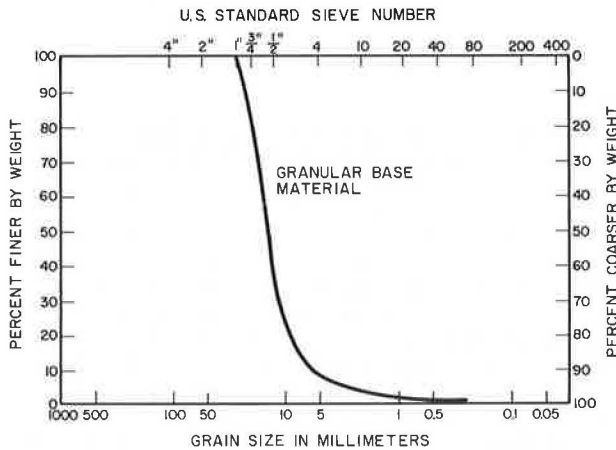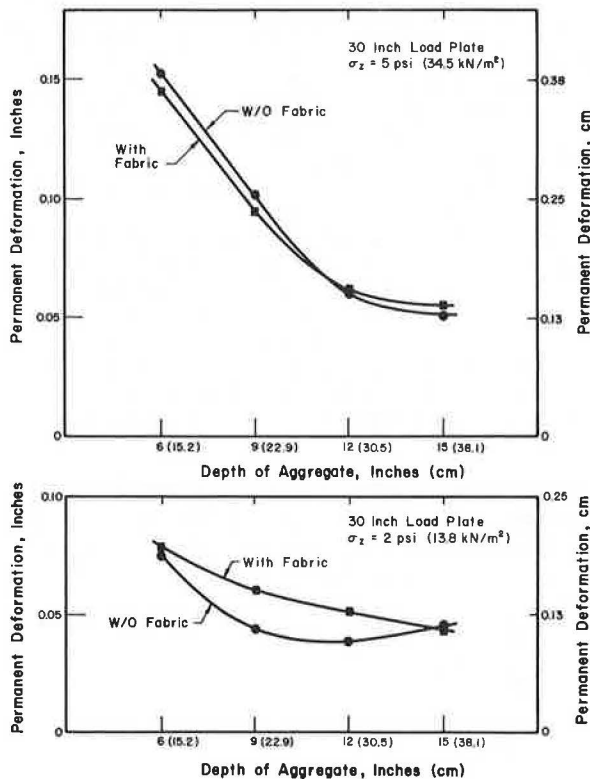

Figure 12. Sample results: three-dimensional static-load tests.

This is an open-graded aggregate, but because of its high angularity was highly stable under applied loads.

Results of Three-Dimensional Tests

Typical results from the three-dimensional static, repeated, and failure loading tests are shown in Figures 12, 13, and 14 respectively. There were no significant differences in the behaviors of the S-A and S-F-A systems in these tests. It was later determined that this lack of difference was caused by the fact that the levels of applied stress and deformation were much lower than those to which typical S-F-A systems for temporary haul roads are subjected. For haul roads at construction sites and similar low-speed, low-volume applications, the deformations and stress levels are often several times greater than those used in the three-dimensional tests. Thus, although the inclusion of fabrics in road systems that have only low levels of deformation may affect their performance, the fabric has no demonstrable effect on the deflections of these systems under load at the low stress levels.

To put the results of the three-dimensional test series into further perspective, it is shown below that, until the ratio of applied stress on the subgrade to the shear strength (σ_z/C) reaches some specific level, the permanent rutting in both S-A and S-F-A systems is very small. Thus, if the shear strength of the subgrade soil is expressed as its cohesion (C), the critical stress level required to cause significant permanent deformation is about πC for S-A systems and 6C for S-F-A systems (compared with σ_z/C ratios of 1 to 2.5 for the three-dimensional test programs). Therefore, in this series of tests, the S-F-A systems would be expected to exhibit little or no permanent rutting.

Results of Two-Dimensional Tests

Typical results from the two-dimensional repeated-load tests are shown in Figure 15, which presents the development of the permanent deformation as a function of

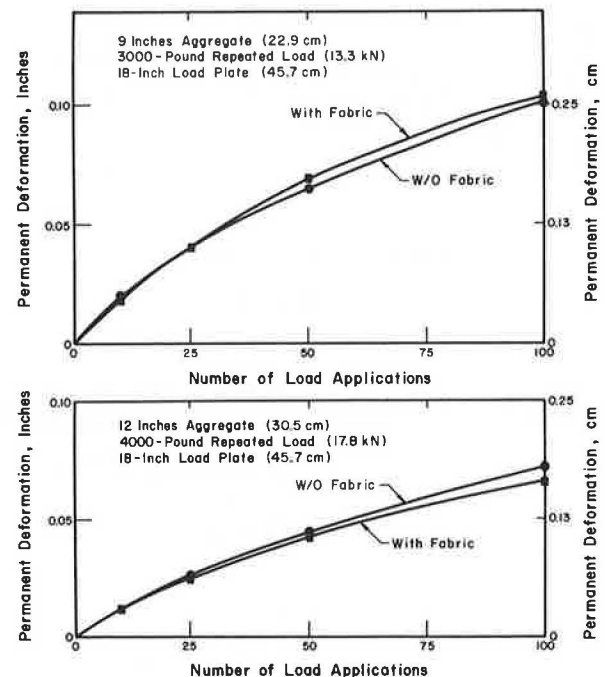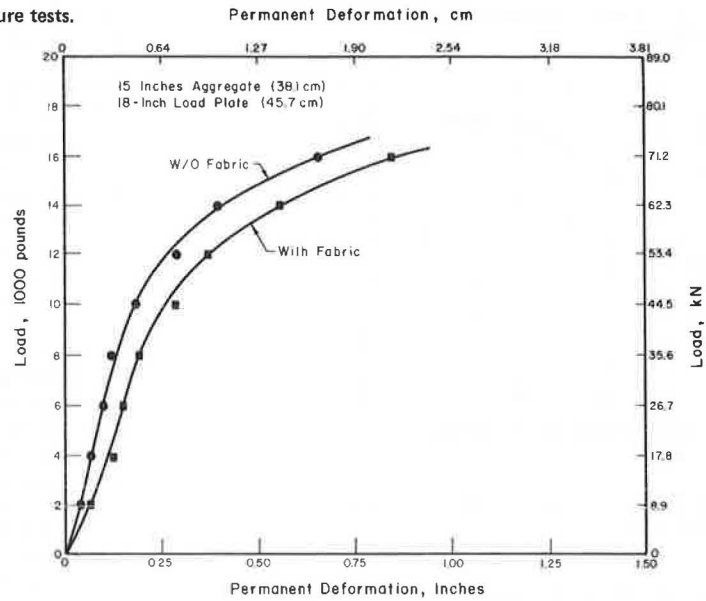Figure 13. Sample results: three-dimensional repeated-load tests.

Figure 14. Sample results: three-dimensional load-to-failure tests.

Figure 15. Sample results: two-dimensional repeated-load tests.
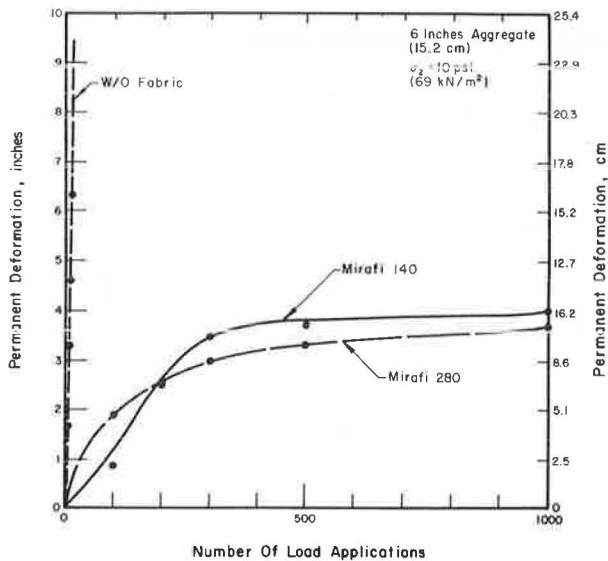
the number of load applications for three test specimens, two that had fabric and one that did not. Those systems that had the fabric tended to reach a level of permanent deformation at which the system stabilized so that further load applications of the same magnitude caused little or no additional permanent deformation. That system that did not have fabric did not stabilize within the number of repeated loads applied, and the permanent deformation continued to accumulate at a nearly constant rate until testing stopped.

Figure 16 shows the failure patterns of typical two-dimensional test specimens of S-A and S-F-A systems. The smooth, wavelike appearance of the subgrade deformation in the S-F-A system suggests that the stresses transmitted to the subgrade soil were distributed over a fairly wide area because of the influence of the fabric, whereas in the S-A system, the transmitted stresses were more concentrated on a smaller area.

Theoretical stress levels on the subgrade were calculated by using a Boussinesq stress distribution (9, 10, 11), and ratios were determined between the calculated subgrade stress and the measured soil strength for each test. These ratios were useful for normalizing the subgrade stress and strength data and providing a criterion for development of the proposed design methodology. Permanent deformations of the load plate at 10 and 100 applications were plotted against the ratio of the calculated subgrade stress to the measured shear strength (cohesion). These numbers of load applications were arbitrarily chosen as most representative of the test series for plotting ease and significance. The curves generated from these results are shown in Figures 17 and 18, in which permanent deformations are expressed as rut depth. (Some of the data points in Figures 17 and 18 are extrapolated values because some of the systems that did not have fabric failed by excessive rutting in fewer than ten cycles, which caused those tests to be halted. However, to provide a basis of comparison the

Figure 16. Failure profile after test: S-A system (left) and S-F-A system (right).

Figure 17. Relationship between rut depth and ratio of subgrade stress to cohesion: (a) at 10 load applications and (b) at 100 load applications.
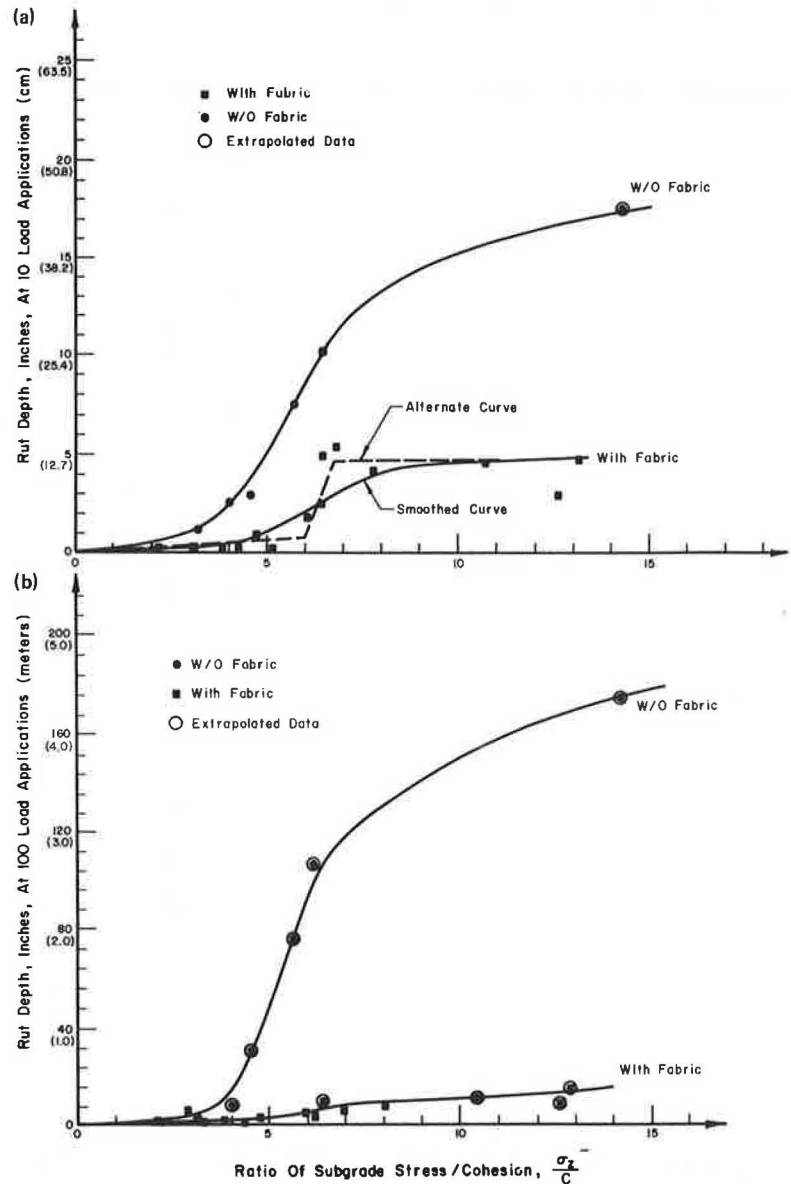
results of those tests were extrapolated on a straight-line basis to predict deformations at the higher number of load applications.)

The results presented in Figure 17 clearly show the significant differences in the behavior of soil-aggregate systems that have fabric and those that do not: (a) the rate of permanent rutting is significantly greater in the S-A than in the S-F-A systems at all stress-to-strength ratios and (b) the S-F-A systems appear to stabilize even at very high stress-to-strength ratios whereas the S-A systems do not. The tendency of these systems to stabilize is significant because it provides a factor of safety against occasional overstress without complete failure of the system.

The results from this phase of the study, as expressed in Figure 17, are the basis for the design methodology and criteria for the S-F-A systems.

DESIGN

Background

According to the Mohr-Coulomb failure criteria, the shear strength of soils is dependent on two parameters, ϕ and C, as follows:

$$S = C + \overline{p} \tan \phi \qquad (1)$$

where

S = shear strength of the soil at failure,
C = cohesion,
$\overline{p}$ = effective stress (confining stress minus pore pressure), and
ϕ = angle of internal friction.

In soft clay subgrades (CBR < 1), the clay can be assumed to be saturated and, for a so-called undrained condition, the internal friction becomes negligible. This condition implies that loads of short duration will not allow pore pressures to dissipate and, because the load carried by the pore-water pressure (i.e., $\overline{p}$) is zero, the shear strength of the soil is its cohesive strength, i.e., its C-value. Wheel loads exerted on soils in haul roads meet the conditions for undrained loading, so that the shear strength for a clayey soil can

Figure 18. Development of design methodology: (a) S-A system and (b) S-F-A- system.
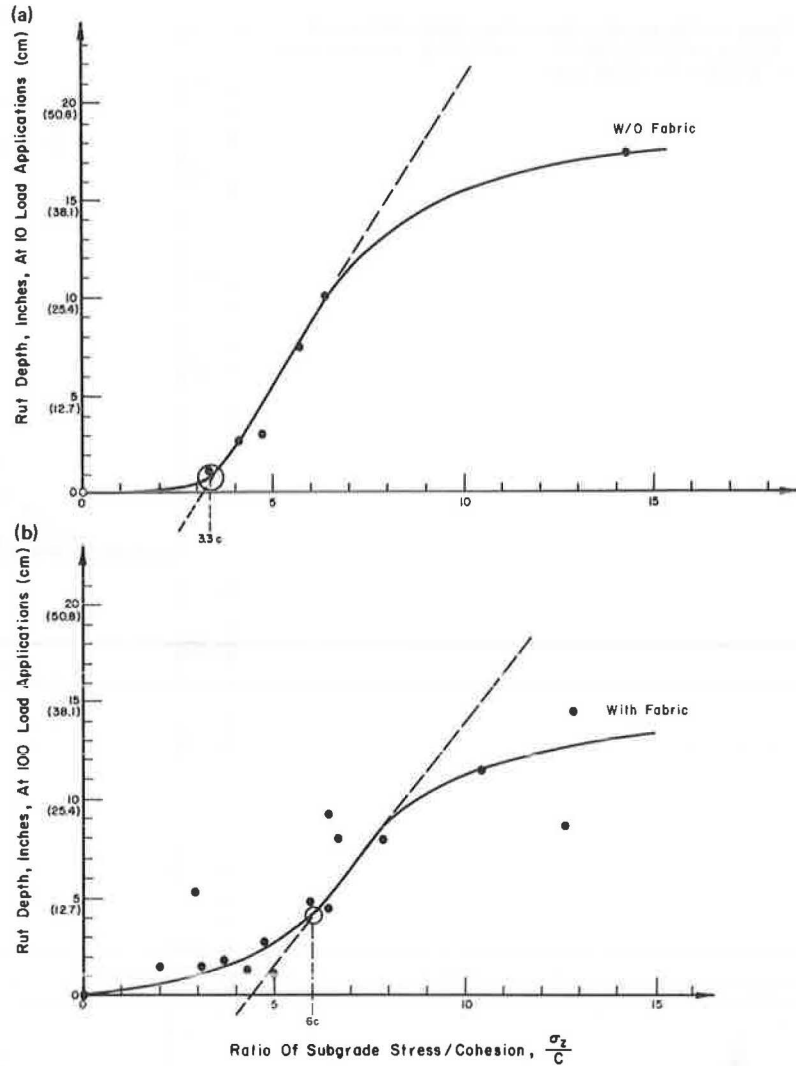
be specified by its cohesion. Thus, for Equation 1, $\phi = 0$ and $S = C$.

Rigorous solutions for computing the shear strength of soils in a $\phi = 0$ condition have been obtained by Skempton (12) and by Prantl (13). These investigators showed that, based on the theory of plastic equilibrium, the ultimate bearing capacity (q_d) for a soil in the $\phi = 0$ condition can be expressed as

$$q_d = (2 + \pi)(\text{cohesion}) = (2 + \pi)C \qquad (2)$$

This formula was modified by both Skempton and Prantl to account for the geometric-loading and depth-influence factors, which leads to a failure criterion of

$$q_d = (2 + \pi)(\text{cohesion})[1 + 0.2(\text{width/length})] \qquad (3)$$

and, for a width-to-length ratio of unity, reduces to

$$q_d = 6.17 \times \text{cohesion} \qquad (3a)$$

Similarly, Rodin (14), in his paper on clay fills, found that the ultimate bearing capacity for a static circular or square footing resting on the surface of a clay support is given by the equation

$$q_d = 6.2 \times \text{cohesion} \qquad (4)$$

This ultimate bearing capacity is the stress condition necessary to produce plastic flow in a soil without a surcharge or other constraint. At a stress less than that required for complete failure, however, local over-stressing may occur and cause localized shear failure. According to Rodin, plastic deformation of a flexible loaded area begins when the stress (q) reaches the level

$$q \approx \pi \times \text{cohesion} \qquad (5)$$

To calculate a value for q that would produce a specific rut depth of 5 cm (2 in), for example, would be nearly impossible and redundant. It can be assumed, however, that the value lies between the imposed limits of πC and $6.2C$. Rodin averaged the two values and implemented a contact-area factor to account for tire geometry, to arrive, rather arbitrarily, at a value of 5C as a limiting stress for the subgrade soil at construction sites. Thus, he recommends, for an allowable 5-cm rut depth, that the applied stress be limited to 5C, where C is the shear strength of the soil expressed as its cohesive strength.

Application of Test Results

Figure 18 shows the relationship between the permenent deformations and the stress-to-strength ratios of S-A

and S-F-A systems. The stress (σ_z) on the subgrade is calculated by using the Boussinesq theory and C. Figure 18 uses the same data as Figure 17, but it is plotted on a different scale and evaluated according to the Rodin theory. From Figure 18a, it is seen that by extending the straight-line portion of the curve, the critical σ_z/C ratio for systems that do not include the fabric can be established at about 3.3, i.e., the allowable stress on the subgrade is 3.3C or approximately πC, which is the value at which Rodin suggests that localized plastic strains are initiated. Under the action of the repeated load applications, these localized plastic flows accumulate and large permanent deformations result.

From Figure 18b, it is seen that the curve for rut depth versus σ_z/C for the systems that include the fabric has a more gradual transition and does not break as sharply as does the curve for systems that do not include the fabric. This is probably due, at least in part, to the restraint of the localized plastic deformations by the fabric, which thus prevents the cumulative rutting from occurring as rapidly as in the S-A systems. As the stress ratio increases, however, the plastic-flow failure becomes more general and the fabric can no longer restrain the plastic deformations. Thus, cumulative rutting occurs at an increasing rate as the stress-to-strength ratio increases. Interestingly, the deviation from the comparable straight-line portion of the curve in Figure 18b occurs at a stress level of approximately 6C, which is the level at which several investigators (12, 13, 14) indicate that full plastic flow would normally occur. If this analysis is assumed to be valid, a design procedure can be developed for the S-A and S-F-A systems by using the Boussinesq theory and the failure criteria proposed.

Design Procedure

A summary of the design method for temporary haul roads built on soft, saturated subgrades and using fabrics of the type tested is presented below. A more detailed explanation is given elsewhere (15).

The first step in the design is the determination of the soil strength. If a ϕ = 0 condition is assumed, the soil cohesion can be measured by cone penetrometer or vane shear tests. Next, the expected loading conditions must be established in terms of wheel or axle loads, from which characteristic values of effective contact pressure and radius of loaded area can be obtained. [The relationships between actual tire pressures and effective contact pressures and other details concerning the determination of subgrade and loading parameters are discussed elsewhere (8).] The designer can then use these input parameters and the relationships described below to determine the required thickness of an aggregate layer to construct a stable roadway. By making thickness design calculations for both S-A and S-F-A systems for each project, the advantages of including a fabric of the type used in these tests can be quantitatively observed and economically calculated.

For determining the aggregate cover required when the fabric is used, the allowable stress on the subgrade should be taken as
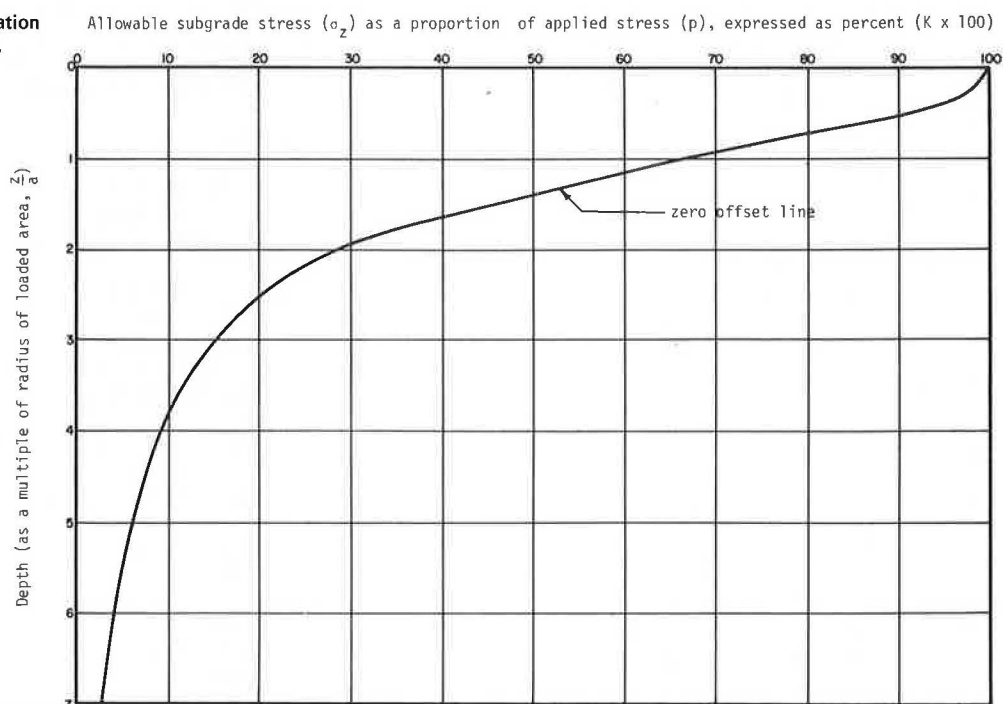
$$\sigma_{z_{allowable}} = 6C \qquad (6)$$

where the ϕ = 0 condition and C = cohesion (or shear strength) of the saturated fine-grained soil are assumed. The allowable stress on the subgrade can then be determined as 6 times this shear strength, which can be expressed as a percentage of the surface contact pressure (p), i.e.,

$$\sigma_{z_{allowable}} \leqslant Kp \qquad \text{or} \qquad \sigma_z/p = K \qquad (6a)$$

where K = proportion of effective surface contact pressure that can be tolerated on the subgrade. The depth of cover required for a given allowable stress is then determined from the Boussinesq theory. Figure 19 is a chart showing stress distribution with depth, the stress at any depth being expressed as a percentage of the surface contact pressure. The allowable stress (expressed as a percentage of surface contact pressure) should be

Figure 19. Graphical representation of vertical stresses (Boussinesq).

Allowable subgrade stress (σ_z) as a proportion of applied stress (p), expressed as percent (K x 100)

Depth (as a multiple of radius of loaded area, $\frac{z}{a}$)

zero offset line

entered on the top of this chart, and the depth of aggregate cover required (in terms of the radius of the loaded area) can be read from the ordinate. From the previously calculated value of the loaded radius (i.e., a), z/a can be reduced to a value for aggregate depth (i.e., z).

The same procedure can also be used to determine the aggregate depth required for systems that do not include fabric. The major difference is that the allowable stress on the subgrade should be taken as

$$\sigma_{z_{allowable}} = 3.3C \qquad (6b)$$

rather than 6C as above. When the cohesive strength is known, the allowable subgrade stress can be expressed in terms of the percentage of surface contact pressure. Figure 19 can again be used to determine a value of z/a, which can be reduced to a value of z, for S-A systems.

Barenberg and others (15) have determined correction factors for high numbers of loadings and suggested empirical values based on design procedures developed by Ahlvin (16). A high number of loadings is considered to be more than 10 000.

Design charts can be constructed to aid in the design process. By assuming appropriate contact pressures, charts of soil strength versus depth of aggregate can be constructed for various wheel loads. A sample design chart (15) is shown in Figure 20. Similar design charts have been developed for wheel loads of 22.2, 44.5, 66.7, and 89.0 kN (5000, 10 000, 15 000, and 20 000 lbf). These charts have been used extensively in the field and appear to be valid and effective design tools for systems using the MIRAFI-140 fabric. Attempts are being made to correlate these design guides with other design criteria to develop more sensitive design procedures that include the effects of the fabric properties.

CONCLUSIONS

1. The use of nonwoven plastic filter fabrics in the construction of road systems can have a significant ef-

fect on the behavior and performance of these systems, especially those systems that normally have large deformations.

2. The use of nonwoven fabrics generally reduces the amount of aggregate needed for the construction of these road systems and the subsequent maintenance required to compensate for rutting.

3. The inclusion of fabrics in these systems tends to stabilize the entire system and prevent the uncontrolled permanent rutting that is apparent in heavily loaded systems that do not include fabric. Thus, the fabric can provide an effective safety factor against complete failure of these systems due to inadequate design thickness or occasional overloading.

4. The properties and behavior of these systems and their components lend themselves to a quasirational approach to analysis of system performance. Design procedures have been developed based on such an analysis.

5. The results of this study also suggest that the use of fabrics might also be beneficial in higher quality road systems and, primarily as a separation medium, between the subgrade and ballast in railroad systems.

6. The properties of the fabrics used in construction of these systems may have significant effects on the behavior of the systems; thus, fabrics with different properties should be evaluated before development of design procedures. The results presented herein were developed from systems that used a specific fabric and should be applied to systems that use other fabrics only after comparative results have been developed for the particular fabric.

The results given in this paper have a rather limited scope, compared with the large and diverse field of possible applications open to these innovative construction techniques. However, as a first attempt to develop rational and systematic methods of analysis, design, and application, the success of this research effort supports the important role that scientific investigation can play in the technological advancement of this innovative and promising field of construction.
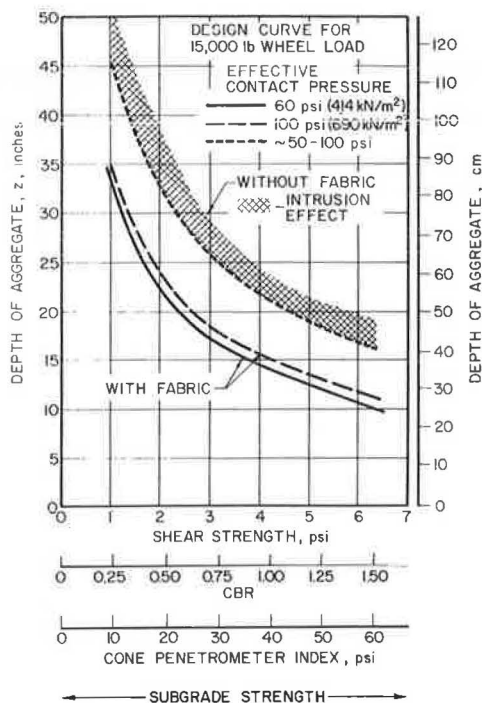
ACKNOWLEDGMENT

Figure 20. Sample design curve.

REFERENCES

1. R. N. Seemel. Plastic Filter Fabrics Challenging the Conventional Granular Filter. Civil Engineering, ASCE, March 1976, Vol. 46, No. 3, pp. 57-59.
2. S. L. Webster and J. E. Watkins. Investigation of Construction Techniques for Tactical Bridge Approaches Across Soft Ground. Soils and Pavements Laboratory, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS, Technical Rept. S-77-1, Feb. 1977.
3. Analytical Modeling of Rock-Structure Interaction. Agbabian Associates, El Segundo, CA; U.S. Bureau of Mines, Final Technical Rept., April 1973.
4. A. McGown and K. Z. Andrawes. The Influences of Nonwoven Fabric Inclusions on the Stress-Strain Behavior of a Soil Mass. Proc., International Conference on Use of Textiles in Geotechnique, Paris, Vol. 1, April 1977, pp. 161-166.
5. K. Terzaghi and R. B. Peck. Soil Mechanics in Engineering Practice. Wiley, New York, 2nd Ed., 1967, pp. 217-225.

6. S. D. Tayabji and E. J. Barenberg. Evaluation of Pavement Drainage Systems Made of Layers of Open-Graded Bituminous Aggregate Mixtures. TRB, Transportation Research Record 532, 1975, pp. 49-63.
7. J. H. Haynes and E. J. Yoder. Effect of Repeated Loading on Gravel and Crushed Stone Base Material Used in the AASHO Road Test. HRB, Highway Research Record 39, 1963, pp. 82-96.
8. E. J. Barenberg and B. P. Hazarika. Use of University of Illinois Test Track to Evaluate Pavement Performance. TRB, Transportation Research Record 572, 1976, pp. 38-50.
9. E. J. Yoder. Principles of Pavement Design. Wiley, New York, 1959, pp. 21-32.
10. C. R. Foster and R. G. Ahlvin. Stresses and Deflections Induced by a Uniform Circular Load. Proc., HRB, Vol. 33, 1954, pp. 467-470.
11. D. M. Burmister. The Theory of Stresses and Displacements in Layered Systems and Applications to the Design of Airport Runways. Proc., HRB, Vol. 23, 1943, pp. 126-144.
12. A. W. Skempton. The Bearing Capacity of Clays. Proc., British Building Research Congress, Vol. 1, 1951, pp. 180-189.
13. L. Prantl. Penetrating Strengths of Plastic Construction Materials. Mathematical Mechanics, Vol. 1, 1921, pp. 15-20.
14. S. Rodin. Ability of a Clay Fill to Support Construction Plant. Journal of Terramechanics, Vol. 2, No. 4, 1965, pp. 51-68.
15. E. J. Barenberg, J. Hales, and J. Dowland. Evaluation of Soil-Aggregate Systems with MIRAFI Fabric. Univ. of Illinois, Aug. 1975.
16. R. G. Ahlvin. Flexible Pavement Design Criteria. Journal of the Aerospace Transport Division, Proc., ASCE, Vol. 88, No. AT 1, 1962.

Rutting Evaluation of Subgrade Soils in Ohio

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The results of several previous investigations have led to the conclusion that rutting criteria should be included in any pavement design methodology that attempts to achieve the goal of improved pavement serviceability. Moreover, in some practical cases, it is necessary to estimate the rutting expected to occur in a pavement system during a certain period. Therefore, it is necessary to develop a scheme for the estimation of rutting. Because it is the foundation of the pavement, the subgrade makes a considerable contribution to its rutting. The objective of this research was to study the rutting in subgrade soils experimentally. The rate-process theory approach was used for the analysis of the results. Five types of silty soils were obtained from four different construction sites in Ohio, and laboratory-prepared samples were used for uniaxial dynamic testing. A direct general relationship that relates rutting to the dynamic modulus and the applied stress level was developed. On the basis of that relationship, a scheme for the estimation of subgrade permanent deformation is proposed and design nomographs for the soils studied were developed. The findings of this study are limited to the types of soils (silty and clayey) tested; further studies should indicate their applicability to other materials also.

In recent years, extensive studies have been carried out to develop various rational pavement design schemes and material-characterization techniques for use in evaluating pavement-component responses to loading and environmental conditions.

The analysis of permanent deformation (i.e., rutting) in a pavement system is an important element of many of the proposed rational pavement design schemes that require detailed consideration of the progressive accumulation of plastic strains in each layer of a pavement subsystem and its supporting layers.

It has been estimated in the AASHTO Road Test that, in some cases, the subgrade layer contributes up to 19 percent of the total pavement system rutting.

Therefore, rutting in the subgrade may be critical, especially for subgrades subjected to saturation for long periods and for weaker subgrades in which excessive permanent deformations are unavoidable. Hence, subgrade rutting should be considered in any new design methodology.

In rational design systems, the soil properties are described by the subgrade modulus or modulus of resilience (M_R), which is dependent on the deviatoric stress, which, in turn, is influenced by load intensity and pavement geometric characteristics. The M_R is also greatly dependent on the type of soil. From the pavement designer's viewpoint, although the knowledge of modulus versus stress and modulus versus type of soil relations are required, this information is not entirely sufficient. To estimate pavement rutting, there are two additional basic requirements: (a) a determination of environmental effects and (b) a determination of the properties affecting soil rutting under repeated loading.

Thus, the problem is to develop a mechanistic procedure for estimating the amount of rutting that will occur in a selected or designed pavement structure to be constructed in an area that has known climatic characteristics.

One approach to the estimation of subgrade rutting involves limiting the vertical compressive strain at the subgrade surface to some tolerable level that is associated with a specific number of load repetitions (1). By controlling the material characteristics and the pavement thickness so that the strain level is not exceeded, a permanent deformation that is less than or equal to the prescribed limit is ensured. The suggested limiting criteria depend on the method of analysis, the stiff-