paction of untreated aggregate surfaces during construction. We confidently reply that it is well worth the cost because compaction preserves the distribution of fines, prevents segregation, and improves the structural support of the layer--all arguments firmly based on bituminous pavement experiences.

Yet, most aggregate surfaces will fluff or loosen with frost cycles or wet seasons, then settle down again under traffic; this behavior continues throughout the life of the surface. I believe that compaction is beneficial but find it hard to convince skeptics in the absence of positive data. Indeed, many low-volume logging roads are built with only traffic compaction of the surfacing aggregate and seem to perform as well as others built with controlled compaction. If the performance of untreated aggregate surfaces built with and without controlled compaction could be compared with type and volume of traffic, the resulting data would be very useful to engineers and managers.

CONCLUSION

The foregoing shows that the properties of aggregates for untreated road surfaces are complex. Specifications must be influenced not only by the characteristics of the rock but also by the climate, the purpose of the road, and nature and volume of traffic. Many complex interactions occur that are not predictable on the basis of laboratory test procedures. Even the characteristics defined by tests are not independent of each other. Yet, there is a strong tendency for engineers who are not well trained in materials to look at each property in a list of specifications as an abstract value and discard or modify those that do not seem satisfactory without consideration of the effects of that property on the overall behavior of the aggregate. This discussion presents no firm recommendations for numeric values because I do not have access to research facilities and personnel. The values cited are based on observation and experience in a particular environment. The objective of this discussion has been to call attention to some of the considerations involved and to stimulate some systematic investigations directed specifically at untreated aggregate road surfaces.

Safety, maintenance cost, user cost, economy, and riding quality all are affected by the aggregate used. Current research, particularly the huge Brazil project (7, pp. 304-340), is showing that fuel consumption and user costs in general are more strongly related to road surface conditions, especially smoothness, than has been recognized up to this time even with untreated surfaces. Long experience has proven that small investments in investigation, design, and quality assurance pay big dividends. However, many road-building agencies are caught in a personnel and budget squeeze that makes such work difficult or impossible. With renewed interest in low-volume roads, rapidly inflating costs, decreasing availability of quality aggregates, and tight environmental controls, it is no longer reasonable to ignore the design factors involved in untreated aggregate surfaces. We must understand the properties of aggregates and derive highly efficient specifications for even very low standard roads.

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Fabric-Reinforced Aggregate Roads—Overview

QUENTIN L. ROBNETT AND JAMES S. LAI

The purpose of this paper is to present an overview of the use of fabrics in aggregate-surfaced roads. Specific areas addressed in the paper are (a) general performance characteristics of aggregate-fabric-soil (AFS) systems, (b) mechanisms that contribute to the fabric-related benefits, (c) various factors that exert a major influence on the performance of AFS systems, and (d) methods of analyzing and designing AFS systems. Data and information sources used in the discussion include pertinent literature and results from a study being conducted in the School of Civil Engineering at the Georgia Institute of Technology. Based on the discussion presented in this paper, use of an interlayer of fabric in an aggregate-surfaced road can lead to either better performance or to substantial reductions in aggregate layer thickness. It is also shown that the behavior of AFS is complex and difficult to analyze with theoretical models. Although numerous thickness design methods are available, most are for specific commercial fabrics and are empirical in nature. No general design procedure is available that can accommodate a variety of fabrics of widely differing properties and, thus, it is difficult for potential fabric users to make economic decisions in selecting fabrics and design thicknesses for various job requirements.

Synthetic engineering fabrics or geotextiles have become increasingly important in civil engineering applications in recent years. The main applications include drainage, erosion control, separation, and reinforcement. Fabrics that perform these functions are termed geotextiles and are defined by the American Society for Testing and Materials (ASTM) as any permeable textile used with geotechnical materials as an integral part of a man-made project, structure, or system.

In railroad and highway support systems, fabrics are used to provide separation between subgrade soil and ballast, subballast, base, or subbase layers and to provide tensile reinforcement to the system. The pumping action of traffic loading combined with high levels of saturation would allow an intermixing of these dissimilar materials were it not for the interlayer or fabric. The fabric provides a reinforcement to the support system by giving tensile resistance and confinement to granular materials. In addition, when large deformations occur, a membrane effect will provide improved load support capabilities.

Fabrics are also being used as an interlayer between cracked, deteriorated pavement surfaces and new asphaltic concrete overlays in order to reduce the rate of reflective crack occurrence.

One of the most common uses of geotextiles is in road construction and area stabilization, where soft, low-strength soil conditions prevail. In this application the geotextile is generally used in conjunction with a locally available aggregate such as crushed stone, shotrock, gravel, or sea shells to develop a structural support layer. For example, roads surfaced only with aggregate are continually being built to provide access to and around construction sites, logging operations, mining and quarrying operations, and as planned stage construction for higher-type roads. Experience with these types of support systems has shown that geotextiles can be cost effective and may allow substantial reductions in the quantity and possibly even the quality of aggregate used.

The purpose of this paper is to provide an overview of the use of fabrics in aggregate-surfaced roads. Specific areas to be addressed are (a) general performance characteristics of aggregate-fabric-soil (AFS) systems, (b) general mechanisms that contribute to the fabric-related benefits, (c) various factors that exert a major influence on the performance of AFS systems, and (d) methods of analyzing and designing AFS systems.

GEOTEXTILES

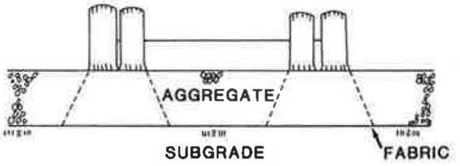
A large selection of fabric products is available commercially. These synthetic fabrics are commonly categorized based on construction and fiber composition. Basically, the two categories of construction are woven and nonwoven; however, the fiber composition may be polypropylene, polyester, nylon, or polyethylene. Polypropylene and polyester are the most common.

Cricital and optimum properties and characteristics of fabric for use in roadways have not been firmly established. Bell and others (1) suggest that tensile strength, modulus, friction-adhesion, creep, bond strength, fatigue, failure elongation, and burst strength are important mechanical properties. Lavin and others (2), Robnett and others (3), and Lai and Robnett (4) have shown the importance of fabric modulus on the performance of AFS systems. Giroud and Noiray (5) in their design method show an effect of both modulus and percentage elongation at failure; Bell and others (1) also suggest that chemical stability, durability, hydraulic conductivity, and constructability considerations are important. Space limitations do not allow extensive discussion of fabrics but Bell and others, Koernes and Welsh, and Rankilor (1,6,7) are excellent sources of information relative to fabric composition and manufacturing processes, fabric properties, test methods, and end-use requirements.

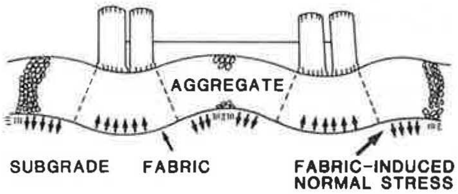
BENEFIT MECHANISMS

Fabrics are used in road construction with a locally available aggregate such as crushed stone, quarry or shotrock, sand, gravel, or sea shells to develop a structural layer. Figure 1a depicts the general geometry of such a system. In this application, the fabric provides reinforcement and separation benefits to the system (1,5,8).

Figure 1. Schematic of aggregate-fabric-soil subgrade system.



a) INITIAL STATE AFTER CONSTRUCTION



b) STATE AFTER SUBSTANTIAL HEAVY TRAFFIC

Reinforcement Function

In the reinforcement function, it is postulated that the fabric serves to improve the performance (often measured by resistance to permanent deformation or rutting) of the AFS system under repetitive vehicular loading due to a number of mechanisms including (a) restraint effect of the fabric on the aggregate and subgrade layer, (b) membrane effect, (c) friction developed at the fabric interfaces that creates a boundary layer effect, and (d) local reinforcement effect.

Restraint Effect

Two types of restraint effects should occur in the AFS systems. The first is related to the reverse curvature of the fabric outside the wheel path and the resultant downward pressure or apparent surcharge applied to the soil (Figure 1b). Such an effect increases the bearing capacity or resistance to shear flow of the soil from the wheel path. A second type of restraint effect occurs when the aggregate particles at the soil-aggregate interface tend to move from under the loaded area but are restrained or given a tensile reinforcement due to the presence of the fabric (9). The strength and modulus of aggregate material are beneficially affected by this increased confinement. The increased aggregate modulus decreases the compressive stress on the soil under the wheel load.

Membrane Effect

As the roadway undergoes large deformation (Figure 1b), the fabric is stretched and develops in-plane tensile stress, the magnitude of which depends on fabric strain and fabric modulus. A stress perpendicular to the plane of the fabric will be induced, the magnitude of which at any point equals the in-plane stress divided by the radius of curvature of the fabric at that point. The net effect is a change in the magnitude of stress imposed on the

Figure 2. Schematic diagram of 8-ft pit test apparatus.

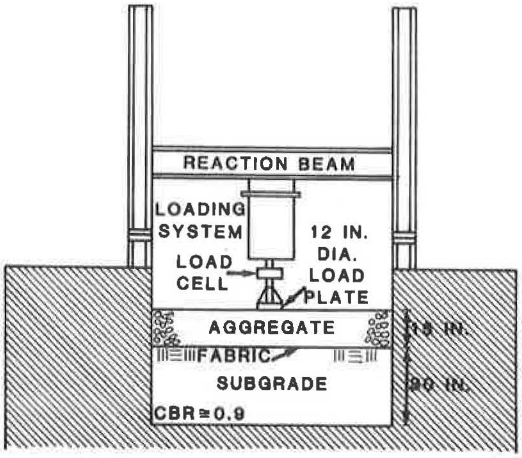


Table 1. Stresses measured by pressure cells in 8-ft pit tests.

Pressure Cell No.	Depth from Surface (in)	Offset from ℄ of Load (in)	Stress Normal to Pressure Cell (psi)	
			With Typar 3401	Without Fabric
9	16	0	12.0	15.5
3	20	0	11.0	15.5
4	30	0	-	-
7	42	0	5.5	6.5
8	20	6	8.2	13.0
6	20	12	7.0	7.5
5	20	18	1.6	0.8
2[a]	16	18	3.4	5.0
1[a]	32	30	3.4	3.4

[a] Radial stress; all other stresses are vertical.

subgrade (a reduction under the wheel load and an increase outside of the wheel path). Kinney (9) calculated a reduction of 18 and 37 percent for the effective load transmitted to the subgrade for two fabrics tested.

Lai and Robnett (4) report a change in measured compressive stresses (measured with special pressure cells by using diaphram wire resistance strain gage) under simulated repetitive wheel loading when fabric is included in the aggregate-soil system. Figure 2 shows the test equipment; the cell positions and outputs of the sensitive pressure cells are summarized in Table 1. Pressure cell readings were obtained for surface rutting of about 3-4 in under repetitive loading. Results from pressure cells 9, 3, 7, and 8 show a reduction in the vertical compressive stress directly under the loaded area for the system that contains a fabric compared with an aggregate-soil (AS) system without a fabric. An increased stress was measured for cell 5 for the system with fabric. This cell was located at an offset position approximately where maximum subgrade heave occurred. The membrane curvature at this location would be expected to increase the subgrade stress.

The reduction of the subgrade stress for the system that contains a fabric appears to be due to the membrane effect, although it could also be partly due to an increased load-spreading capability of the confined aggregate. As a result of the reduced subgrade stress, a reduction in the rate of rut formation in the subgrade for a given vehicular loading condition should be expected.

In order to develop fabric-induced stress, substantial vertical deformations, proper geometry, and fabric anchorage are generally required. Barvashov (10) and Raad (11) have suggested prestressing the fabric in order to reduce the system deformation required to get the fabric in substantial tension.

Friction and Boundary Layer Effect

Friction developed along the interface between aggregate-fabric and friction-adhesion of the fabric-soil interface create a boundary-layer or composite material of aggregate and soil immediately adjacent to the fabric. The composite material created due to the presence of the fabric should possess more favorable properties of ductility and tensile strength. The effectiveness of this phenomenon is closely related to the magnitude of friction-adhesion developed at the interfaces. Fabrics capable of developing high friction-adhesion appear to be desirable.

Local Reinforcement

Concentrated stresses due to imposed vehicular loading can cause a punching or local bearing capacity failure at the points of contact between the aggregate and subgrade. Use of fabric between the aggregate and soft soil will serve to distribute the load, reduce localized stresses, and, in general, provide increased resistance to vertical displacement. Bell and others (12) suggested this as a possible mechanism in the stabilization of a road constructed over muskeg.

Separation Function

In the separation function, the fabric serves to prevent the fine-grained subgrade soil from intermixing with the coarse-grained aggregate material and reducing its shear strength and stability. Depending on aggregate gradation, 10-20 percent additional plastic fines can cause a substantial reduction in shear resistance (13,14). From the design standpoint, the aggregate within the intermixed layer is ineffective.

These various mechanisms explain, at least in a qualitative sense, the improved performance or rutting resistance of aggregate layers reinforced with fabric. The contribution of each of the aforementioned mechanisms is difficult to quantify because of the extreme complexity of the AFS system. Kinney (9) has shown through his scale-model studies the confining effect of fabric, and Lai and Robnett (4) have reported on the change in stress state at the subgrade that appears to be due primarily to the membrane effect. Thompson (15), with theoretical studies, has shown the effect of confinement on the moduli of the aggregate and the resultant structural behavior of the AFS system.

The degree of benefit offered to the AFS system for its service life by a fabric depends to a large extent on the mechanical and durability (chemical stability) properties of the particular fabric used. Other factors such as subgrade strength, loading environment, and aggregate properties also have an important influence on the behavior and performance (rutting resistance) of the AFS system.

It should also be acknowledged that the relative contribution of the various mechanisms most likely will be different for railroad ballast-subballast systems or permanent, surfaced highway pavement structures than for the high deformation access or haul road type application.

AFS SYSTEM PERFORMANCE

General

Numerous laboratory and field studies are reported in the literature (2,3,8-10,12,16-24) that serve to illustrate the general behavior of fabric-reinforced aggregate layers over soft subgrade soil subjected to repeated surface loading. At the recent International Conference on Geotechnics (25), at least five papers were presented that showed positive structural benefits from the use of fabrics in conjunction with aggregate support layers over soft soil. Normally, the performance of these AS and AFS systems is measured in terms of surface rutting or rut depth. For specific job applications, the tolerable rut depth must be established. For highway vehicles, rut depths as great as 6-8 in might be tolerable, but for off-highway vehicles, even more rut depth might be acceptable. Obviously, if the vehicle becomes immobilized because of contact of the undercarriage with the rutted pavement surface, this is undesirable. Similarly, the deformation that occurs under each wheel load will influence the power required to move the vehicle forward. Hammitt (26) has suggested that an elastic deformation of 1.5 in or less is acceptable in terms of the tractive resistance and commensurate power requirements of the vehicle. Hammitt (26) and others (5,8) also suggest that a 3-in rut depth be used as a design criteria for these unsurfaced roads. Obviously, for higher-type pavements that have asphaltic concrete surfaces, deformations of these magnitudes could not be tolerated.

Figure 3 (24) illustrates the performance of a full-scale road that contains test sections of aggregate (control) and fabric-reinforced aggregate over a soft subgrade [California bearing ratio (CBR) ≈ 1]. Kinney and Barenberg (19) have reported the results of a laboratory repetitive loading study that used small-scale two-dimensional testing apparatus wherein a low modulus and a high modulus fabric were used in conjunction with crushed stone over a soft soil layer. Results of a large-scale pit test wherein AS and AFS (nonwoven fabric) were tested under repetitive loading (Figure 2) have been presented by Lai and Robnett (4). Typical results are shown in Figure 4 (4).

Thus, it is obvious that fabric-reinforced aggregate layers can provide superior performance compared with a similar system that does not contain fabric. The performance of such systems is, however, influenced by a number of factors.

Factors of Influence

The following factors seem to have major influence on the performance of AFS and AS systems.

Soil Properties

Fabric is most often used in conjunction with aggregate roads where soil conditions are poor. AFS systems have been built on soil conditions where the CBR is as low as 0.5 or less. Obviously, for these very low strength conditions, repeated vehicular loadings cannot be placed on the soil without excessive rut development and vehicle mobility problems; rather, a pavement structure of some sort such as aggregate or aggregate-fabric must be placed between the soft soil and the applied wheel loads.

Figure 3. Rut depth as a function of vehicle passes.

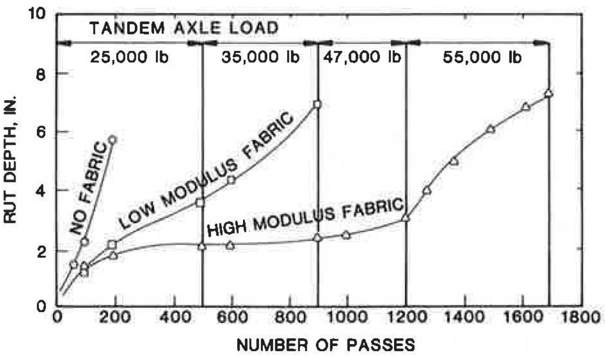
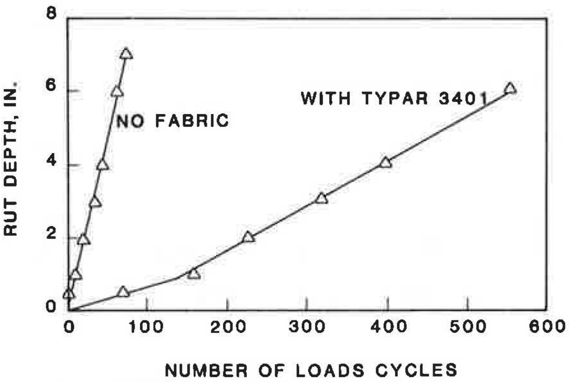


Figure 4. Rut depth versus number of load application plots for 8-ft test pit results.



The typical approach used by many (5,8,14) to establish the tolerable level of imposed subgrade stress has as a basis the theory of plasticity and classical work done by Rodin (27) and Whitman and Hoeg (28). Basically, this approach stipulates that the onset of plastic deformation occurs in frictionless soils ($\phi = 0$) under loading when

$$q_e = \pi c \tag{1}$$

where q_e is the elastic bearing capacity of soil and c is the undrained shear strength of the frictionless soil.

Complete bearing failure occurs when

$$q_{ult} = (\pi + 2) c \tag{2}$$

where q_{ult} is the ultimate or general bearing capacity of the soil.

Skempton (29) modified this equation to take into account geometric loading and depth influence factors and found for a square footing,

$$q_{ult} = (6.17)c.$$

Rodin (27), in his paper dealing with clay fills, states that the ultimate bearing capacity for a static circular or square footing resting on the surface of the clay is

$$q_{ult} = (6.2)c.$$

Thus, to develop rutting in the subgrade, the stress under repeated loading should fall somewhere in the range of πc to 6.2c. For a given amount of rutting, it is reasonable to assume that, as the number of applied loads increases, the imposed subgrade stress must decrease in this range and tend toward the πc value.

A major assumption associated with the foregoing discussion is that a unique and constant relation exists between shear strength and the rutting or permanent deformation a soil undergoes during repetitive application of stress. The rut development in the subgrade soil is influenced not only by the inherent nature of the soil but also by the duration or rate of loading. The soil can be considered as a viscoelastic material, which means that its permanent deformation is not only controlled by the magnitude of applied stress but also by the duration of stress application. As the duration increases, the amount of permanent deformation per load or rut rate should be expected to increase.

Figure 5. Effect of fabric modulus on initial rate of rut formation of AFS systems: 3-ft pit results.

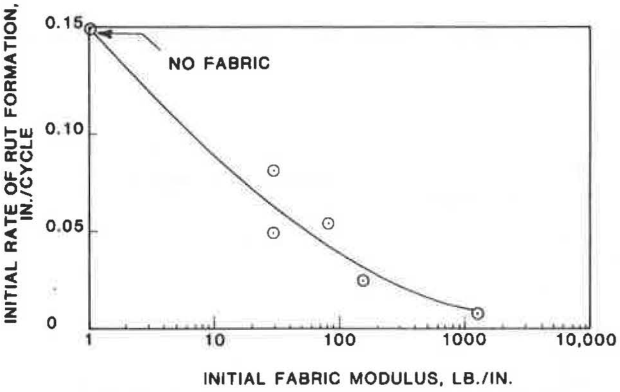


Figure 6. Effect of fabric modulus on number of load applications to cause 2-in or 4-in rut in AFS system: 3-ft pit results.

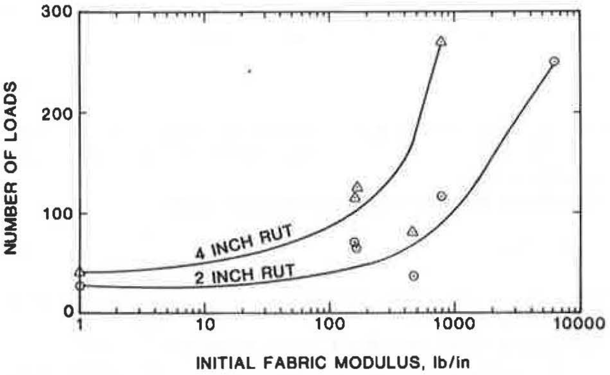
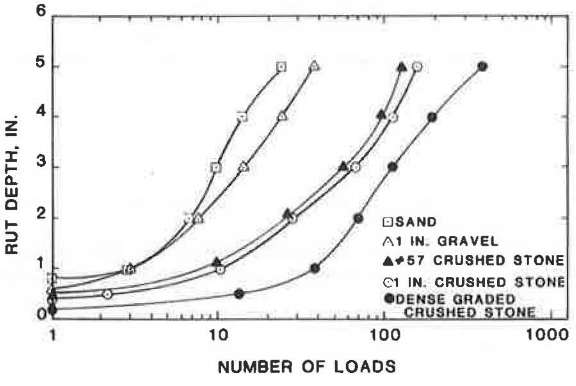


Figure 7. Effect of aggregate type on rutting of AFS systems: 3-ft pit results.



Fabric Properties

Critical and optimum properties and characteristics of fabric for use in roadways have not been firmly established. Bell and others (1) suggest that tensile strength, modulus, friction-adhesion, creep, bond strength, fatigue, failure elongation, and burst strength are important mechanical properties. Lavin and others (2), Robnett and others (3), and Lai and Robnett (4) have shown the importance of fabric modulus on the performance (rutting for a given number of loads and rutting rate) of AFS systems. Typical results from Lai and Robnett (4) are shown in Figures 5 (4) and 6 (4). Giroud and Noiray (5) recognize the significance of fabric modulus and failure elongation in development of their thickness design approach. In their approach, for a given geometry, the effect due to membrane support directly relates to the fabric stress and hence the fabric modulus. Barenberg (30) shows the reduction in design thicknesses of aggregate layer for AFS systems that contain a high modulus woven fabric compared with the systems that contain a lower modulus nonwoven fabric.

We are not aware of any data published wherein other fabric properties are related to potential performance.

Aggregate

A fairly good understanding currently exists as to the factors that influence the repeated load behavior of various aggregates in typical flexible pavement applications. Extensive research has been conducted in the areas of elastic or resilient behavior, the permanent deformation characteristics, and shear strength of various aggregates (15,31-37). However, none of these various studies has specifically addressed the behavior of various types of aggregate in the system wherein fabric is used as a reinforcement.

In a study being conducted in the School of Civil Engineering at the Georgia Institute of Technology, the effect of various types of aggregate on the performance of AFS systems has been studied. The details of one of the testing methods being used have been reported elsewhere (38). The following is a brief summary of the test program:

1. A 3-ft diameter test pit (similar to Figure 2, except smaller) with 15-in thick, soft subgrade, and aggregate layer thicknesses that range from 5 to 13 in;
2. Subgrade soil prepared to vane shear ≈ 4 psi and CBR ≈ 0.9;
3. Fabric placed between soil and aggregate;
4. Repeated loading applied on 6-in diameter plate, plate contact pressure = 70 psi, repetition rate = 20/min, and pulse duration = 0.2 s; and
5. During loading, vertical movement of loading plate is monitored.

Five different types of aggregate (sand, rounded gravel, and uniform and dense-graded crushed granite) were tested. Figure 7 depicts typical performance of the various AFS systems. Note from these data that a substantially different response of AFS systems might be expected with different aggregates. Differences in response can also occur as a result of gradation and density changes.

Loading Conditions

The loading conditions that can affect the performance of AFS systems include magnitude of loading, contact pressure, wheel configuration, duration or rate of loading, number of coverages, and degree of channelization of wheel loadings. The effects of duration of loading on the performance of AFS systems have been discussed previously.

The magnitude of the vertical pressure exerted on top of the subgrade depends on the magnitude of surface loading, tire pressure and contact area, and the thickness and load-spreading ability of the aggregate. Because the crushed stone has virtually no tensile strength, load spreading is controlled primarily by shear resistance and the ϕ of the aggregate (39), which in turn can be beneficially influenced by the reinforcement or confinement provided by a fabric.

ANALYSIS TECHNIQUES FOR AFS SYSTEMS

The capability for analysis of stresses, strains, and deflections in typical AFS systems is needed if a more rational approach to the understanding of the response characteristics and factors of influence for AFS systems is made. For many years, structural analysis of flexible pavements was accomplished by use of the Boussinesq and Burmister elastic theories. These approaches have definite shortcomings due to the inability to represent material response properly. In recent years considerable effort has been expended in developing refined theoretical models for flexible pavement analysis [e.g., viscoelastic methods (VESYS), a shear layer method that allows the aggregate to resist shear but not flexural stresses (39)] and various finite element techniques that can accommodate the typical nonlinear stress-strain response of subgrade soil, aggregate, and crushed stone. Extrapolation of even these refined techniques to analysis of AFS systems provides crude approximations, at best.

The AFS system has interesting and complex features such as the following:

1. Normally undergoes large plastic deformations,
2. Has a thin fabric component with high tensile modulus but very low flexural modulus,
3. Can exhibit slip at the aggregate-fabric or the fabric-soil interface,
4. Can exhibit membrane action, and
5. Can, because of the fabric, have an abnormal confining pressure on the aggregate as deformation progresses and causes the aggregate to become stiffer.

Because of these features, most conventional finite-element techniques, although capable of incorporating nonlinear stress-strain response, cannot accurately model the true AFS system. Raad (11), for example, has attempted to model the AFS system by prestressing a row of elements to enhance the membrane effect and assigning a Mohr-Coulomb approximation for the slippage characteristics of the fabric-soil and fabric-aggregate interfaces. Raad and Figueroa (40) have reported on a comprehensive analysis method for AS systems without fabric. With these approaches the resilient response and the stress and strain state within a low deformation AFS or AS system can be calculated.

Giroud and Noiray (5), Barenberg (30), and Bender and Barenberg (8) use the concept of the Boussinesq theory to estimate the initial state of stresses in an AFS system; they then correct (reduce) the vertical subgrade stress for the fabric-induced stress as rutting occurs. Kinney's fabric tension model (9) is an approach developed to calculate the magnitude of contribution of the fabric tension to the wheel-load-induced stresses in the subgrade of the AFS system.

None of these techniques allows for explicit calculation of the permanent deformation that develops under repetitive traffic loading; rather, typically an algorithm or model such as the one developed by Duncan and Chang (41) and later modified by Barksdale (42) could be used to calculate plastic strains in the system. Giroud and Noiray (5) took data developed by Webster and Watkins (23) and Webster and Alford (24) and empirically derived an expression that relates aggregate thickness, number of loads, load magnitude, soil strength, and rutting for an AS system that contains no fabric.

Thus, based on current literature, no theoretical technique appears to be available for precise analysis of the response of an AFS system subjected to repetitive loading.

It would be desirable for an analytical technique to be developed for the AFS system that would

1. Handle large displacements,
2. Handle cyclic or repetitive loading,
3. Incorporate nonlinear material behavior including failure,
4. Incorporate a flexible fabric membrane that has tensile modulus but no bending resistance,
5. Allow for slippage on both interfaces of the fabric, and
6. Determine accumulated permanent deformation.

DESIGN OF AFS SYSTEMS

Methods for calculating with a reasonable degree of confidence the aggregate thickness requirements for AFS systems are needed in order to efficiently and economically use fabrics. Such design methods can have two distinctly different approaches. One basic approach might be called a theoretical-mechanistic approach and the other would be empirical in nature. The theoretical-mechanistic approach is one wherein theories for calculating the state-of-stress imposed on the system are coupled with the mechanistic response of the system components. In this approach, it is essential that the theory used be capable of accommodating a complete definition of the mechanistic response of the AFS system to imposed loading for the large deformations involved. The complexity of the AFS system, as suggested by previous discussion, makes it difficult to model the system perfectly and thus calculate the load-deformation response of the system.

Even though a theoretical-mechanistic approach has the distinct advantage of being capable of considering a broad range in component material properties (especially fabric properties), such an approach does not appear to be at a state where it can be incorporated in a thickness-design method. Such an approach, which incorporates certain simplifying assumptions, could be used, however, for parameter studies and sensitivity analyses of the AFS system.

Based on the foregoing, some combination of available theory, fundamental behavior of soil, aggregate, and fabric, experimental and observational data, field experience, and engineering judgment probably offers the most reasonable basis for a thickness-design method. In fact, a combination of these forms the basis for most current design methods.

We are aware of five design methods (43-47) for specific commercial fabric product lines and two more general design procedures, one by the U.S. Forest Service (14), which has had some limited field verification, and one by Giroud and Noiray (5), which is based on simplified theory and limited experimental results published by others. In concept, the procedure by Giroud and Noiray (5) can potentially be used for a broad range of fabrics in that the procedure does require design input concerning fabric modulus and percentage failure elongation; however, at the time it was presented the procedure did not mention any field validation.

The U.S. Forest Service method (14), although implying broad applicability, probably is limited to use with certain nonwoven fabrics because it is based on work by Bender and Barenberg (8).

The DuPont method (43) is based on thickness design concepts developed by the U.S. Army Corps of Engineers (48) and actual full-scale field tests and other performance observations. The Celanese methods (44,45) are based on small-scale laboratory testing (8,9), fundamental material behavior (Rodin's work) (27), Boussinesq theory of stress distribution, and Kinney's fabric tension model (9) for the procedure described elsewhere (45). The Bidim method (46) has as its basis large-scale experiments that use a constructed bentonite subgrade and actual full-scale traffic loadings. The basis of the Imperial Chemical Industries (ICI) method (47) is unknown to us.

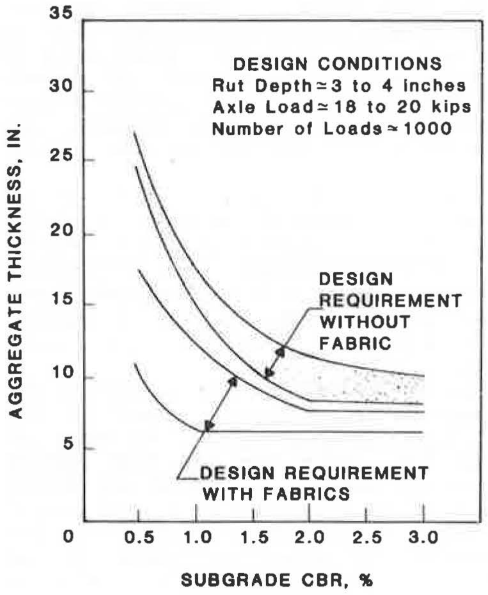
Note that most of these methods do not allow for variations in performance or rut depth. The failure criteria assumed are often unclear. Also, only the DuPont, ICI, Giroud and Noiray, and, to a limited extent, U.S. Forest Service methods allow for traffic density as a design input.

Space limitations do not allow for additional critique and discussion of these design procedures. None are ideal since none appear to explicitly consider all important design inputs. Figure 8 (5,43-46) summarizes the general range in thickness requirements for aggregate-surfaced roads with and without the inclusion of fabric found from these design methods [except the method of ICI (47)] for the design conditions shown.

SUMMARY AND CONCLUSIONS

This paper has briefly reviewed the general performance characteristics of AFS systems, the mechanisms that contribute to the improved performance due to fabric, various factors that affect the performance of AFS systems, and methods of analyzing and designing AFS systems.

Figure 8. Typical aggregate thickness requirements for haul roads with and without fabric.



Based on the discussions presented, the following conclusions appear warranted.

1. Based on available information, the use of an interlayer of fabric in an aggregate-surfaced road can lead to better performance or, alternately, the fabric will allow reductions (25-40 percent) in aggregate layer thickness (compared with the AS system that contains no fabric) for the same level of performance.
2. Higher modulus fabrics appear to be of greater benefit to performance than lower modulus fabrics. Fabrics can provide reinforcement to the AFS system even before substantial rutting has occurred.
3. Numerous mechanisms responsible for the benefits have been postulated; however, the exact contribution of all these mechanisms has not been quantified.
4. Numerous factors, including component material (soil, fabric, and aggregate) and loading conditions, have major influence over the response of AFS systems. Recognition of these factors and integration of them into design and decisionmaking processes will lead to more predictable performance of the AFS system.
5. The behavior of the AFS system under repetitive loading is complex. Currently, no analytical models are available that correctly model this complex structure. Consequently, calculated structural response (stresses, strains, deflections) are often at best only estimates. Substantial work is yet to be accomplished in terms of analytical model development for the AFS system.
6. At least seven design procedures are available for determining the thickness requirements of AFS systems. Five of these are for specific commercial fabrics, however. These methods are primarily empirical in nature and in general do not consider all important design parameters. There is no general design procedure available that can accommodate a variety of fabrics with widely differing inherent properties and a variety of other design input values. There is need to develop a general, fundamentally sound, design method that can allow the potential fabric users to make valid economic decisions in selecting fabrics and design thicknesses for various job requirements.

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Case for Removing Bridge or Culvert Rails on Low-Volume Rural Roads

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Concrete or masonry bridge rails, parapets, or hubguards (if more than 4 in higher than the roadway surface) on narrow bridges and culverts on low-volume (ADT < 400) rural (LVR) roads are dangerous roadside obstacles. Based on the current state of knowledge it is suggested that, in many instances, striking the end of a rigid bridge-culvert rail is more hazardous to the motorist than traversing the adjacent stream bed or drainage area when rails have been removed. The case for rail removal is supported by the effective widening of the roadway due to rail removal, convenience to farmers in moving wide, low farm equipment, and benefit/cost ratios. The benefits are estimated reductions in annual accident costs and were calculated by using current published data on estimated collision frequencies, accident severity indices, and accident costs. The costs are the estimated costs of rail removal. There is a need for roadside hazard research aimed specifically at the problem of quantifying the hazard of vehicles that strike bridge-culvert rails versus the hazard of vehicles running off the road after rail removal.

The concrete or masonry bridge rails, parapets, or hubguards (if more than 4 in higher than the roadway surface) on narrow bridges and culverts are dangerous roadside obstacles or hazards.

A bridge rail is a longitudinal barrier whose primary function is to prevent an errant vehicle from going over the side of the bridge structure (1). It is apparent, in driving on low-volume (ADT < 400) rural (LVR) roads, that in many instances it would be far better for the vehicle to go over the side of the structure than to strike the bridge rail, especially the end of the rail.

Informal discussions with roadside hazard research engineers at Texas Transportation Institute and Southwest Research Institute of "When is it better, on LVR roads, to strike the rail rather than traverse the ditch next to the culvert or bridge?" resulted in the following consensus: It is almost always better to take to the ditch than hit the bridge rail--unless the ditch is very deep, steep, or the culvert or bridge has a large drop off to its bottom. In other words, the best safety strategy is to remove the bridge rails on narrow LVR structures.

The validity of this consensus is supported by the widely accepted priority of actions or strategies with regard to existing roadside obstacles (hazards) (2; 3, p. 340; 4):

1. Remove the obstacle,
2. Relocate the obstacle to a point where it is less likely to be struck,
3. Use breakaway devices to reduce the severity,
4. Use impact attenuation devices to reduce severity, or
5. Protect the driver through redirection of the errant vehicle (use of guardrails or roadside barriers).

A roadside barrier is a longitudinal barrier used to shield hazards located within an established minimum width clear zone (1).

Strategy 1, removal of bridge rails, is supported by the American Association of State Highway and Transportation Officials (AASHTO) (1, pp. 111, 3, 5, 15).

> ...Current criteria suggest that bridge rails should be installed on all bridge structures; however, the view is now held by some highway engineers that these criteria are too restrictive and in some cases have resulted in the unnecessary use of bridge rails. A possible example of this would be their use on a short structure that spans a shallow stream or drainage area on a low-volume rural roadway. Many such structures do not have an approach roadside barrier to shield the bridge rail end. It is likely that the exposed end of the rigid bridge rail is more hazardous to the motorist than would be the stream or drainage area. Judgment must therefore be used to determine if the overall hazard of the bridge rail and the approach roadside barrier necessary to shield the bridge rail end is less hazardous than the roadside condition being shielded. Warrants for barriers to shield culverts can be established from the criteria in Section III-A....
>
> ...It has been said that a traffic barrier is like life insurance--it is good to have as long as it is not needed. Although this is an over-