CIVIL ENGINEERING STUDIES

Transportation Engineering Series No 30

UILU-ENG-80-2019

DESIGN PROCEDURES FOR SOIL FABRIC-AGGREGATE SYSTEMS WITH MIRAFI 500X FABRIC

by

ERNEST J. BARENBERG

A Report of the Investigation of
The Behavior of Soil-Fabric-Aggregate Systems

conducted by
DEPARTMENT OF CIVIL ENGINEERING
ENGINEERING EXPERIMENT STATION
UNIVERSITY OF ILLINOIS
in cooperation with
CELANESE FIBERS MARKETING COMPANY

UNIVERSITY OF ILLINOIS
AT URBANA-CHAMPAIGN
URBANA, ILLINOIS

OCTOBER, 1980

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Design Procedures for Soil-Fabric-Aggregate Systems with Mirafi® 500X Fabric

by

ERNEST J. BARENBERG

INTRODUCTION

Earlier design procedures for soil-fabric-aggregate (SFA) systems were based on the concept of limiting to acceptable values the ratio of vertical stress transmitted to the subgrade to strength of the subgrade (σ_z/c) (1). In that initial report it was shown that SFA systems with a fabric or geotextile could tolerate higher σ_z/c ratios without failure than corresponding systems without fabric. Conversely, it was shown that, for the same loading conditions, systems with fabrics could be constructed with a significantly thinner aggregate layer and still provide the same level of performance. Earlier design curves for SFA systems with Mirafi 140 developed around these concepts were presented in the earlier report (1).

A limitation of the results discussed above was that these findings related only to SFA systems with a specific fabric, namely Mirafi 140. All tests from which the design curves were developed were run on systems containing either no fabric or with Mirafi 140 supplied by the Celanese Fibers Marketing Company. At that time the effect of fabric properties on the behavior and performance of SFA systems was not known.

A second study undertaken in 1975 evaluated the effect of fabric properties on the behavior and performance of SFA systems. This was primarily a theoretical study using sophisticated mathematical models to simulate the responses of SFA systems under load. For this analysis the finite element models (FEM) proved to be the most suitable for the specific types of

---

®Mirafi is a trademark licensed to Celanese Fibers Marketing Company.

information desired. These analyses proved to be exceedingly complex because the three separate materials used in these systems (soils, fabrics, and aggregates) each have different constituent relationships. Furthermore, the responses of some of these materials in a composite system, such as a layered SFA system, are not identical to those responses observed when the materials are tested separately.

Despite the difficulties experienced in modeling the SFA system, analyses were made and the findings were verified by the results from the earlier tests on the SFA systems. With the confidence gained from analyses of the specific SFA systems tested, additional systems were analyzed using a range of fabric properties to determine how variations in these properties might affect the behavior and performance of SFA systems (2).

From the results of these analyses it was determined that the properties of the geotextiles in the systems could have a very significant effect on the behavior and performance of SFA systems. Specifically, it was determined that the modulus of the fabric has a profound effect on the strains within the layer of granular material. That is, higher modulus fabrics (fabrics with greater resistance to deformation) resulted in much lower tensile strains in the critical lower portion of the granular layer. These findings are illustrated in Figure 1. More importantly, it was also shown in earlier results that the strains in the fabric are related to the permanent surface deflection, as shown in Figure 2. Thus, it could be concluded that fabric properties, and more specifically, the fabric modulus, will have a significant effect on the behavior and performance of SFA systems.

Field verification of the effect of fabric modulus on the performance of SFA systems was obtained from full-scale studies conducted by the U.S. Army Engineers WES (3). In this study, SFA test sections with fabrics having both high and low moduli were trafficked with full-scale military trucks. Results from these tests confirmed that the sections with the lower modulus fabric, gave significantly better performance than sections without fabric, but that sections with the high-modulus fabric had significantly better performance than sections with the low-modulus fabric. A summary of the Corp of Engineers performance test results presented by Kinney and Barenberg (4) is shown in Figure 3.

In a recent study conducted by the Department of Civil Engineering, University of Illinois, under sponsorship of the Celanese Fibers Marketing Company, Inc., a number of fabrics with different moduli were evaluated to determine more precisely the relationship between the fabric moduli and the behavior and performance of SFA systems. Results of these findings were presented in a Ph.D. thesis by T. C. Kinney, a copy of which was sent to Celanese Fibers Marketing Company in early 1979 (5).

The purpose of this report then is to incorporate these latest results and the earlier findings into a more comprehensive design procedure and more specifically a design procedure for SFA systems with Mirafi 500X.

In the analysis of the results from the full-scale test conducted by WES, Kinney and Barenberg (4) developed a different approach for the analysis of SFA systems. A model was developed by which the fabric modulus could be taken into account in the analysis of stresses in the system. This model, called the fabric tension model (FTM), was then further refined by Kinney (5), and forms the basis for development of the revised design procedures for SFA systems with Mirafi 500X fabric presented herein. Using the proposed model, fabric modulus, subgrade strength, and traffic load are the primary design parameters. Friction developed between the fabric, soil, and aggregate layers can be taken into account, as can the effects of rut depth and the width of rut.

DESIGN OF SFA SYSTEMS WITH FTM

Design of SFA systems with FTM is based on limiting the normal stress transmitted to the subgrade, with the criteria essentially the same as in the earlier design procedure (1). Through application of the FTM model it can be shown that the proportion of load carried by the fabric is a function of: 1) the fabric modulus; 2) the fabric anchorage, particularly the friction between the fabric and the aggregate layer and between the fabric and the soil; and 3) the geometry of the rut including its depth and width.

In its initial condition, when a load is applied to a SFA system, the normal stress transmitted to the subgrade may exceed the allowable load. As the rut deepens, the fabric strains and takes on a permanent tension, and a portion of the load is then carried by the fabric. Rutting continues to deepen with a concomitant increase in fabric tension until the normal stress transmitted to the subgrade is equal to the permissible subgrade stress. At this point the system becomes stable and no further rutting occurs. Increasing tension in the fabric also causes an effective confinement of the aggregate layer resulting in a greater stability in the aggregate layer and greater distribution of the load by the aggregate layer.

Presented herein is a simplified approach to the design of SFA systems with Mirafi 500X fabric. It must be kept in mind that there are subtle influences by the fabric on the behavior and performance of SFA systems which are not taken into account directly in this design procedure. These subtle effects may be accounted for indirectly by adjustments in the design thickness of the aggregate layer in a manner not specifically taken into account by the FTM.

Using the FTM, the design of SFA systems should proceed as follows:

1. Determine the maximum wheel load and contact pressures anticipated on the surface of the SFA system.

2. Determine the maximum permissible stress for the subgrade.

3. Estimate the thickness of the granular layer required. (Thickness of the granular layer can be estimated by determining the thickness of granular layer required for a system with no fabric and assuming 70 to 75 percent of this value for systems with reinforcing fabrics.)

4. Establish the rut geometry including the rut width and maximum rut depth both on the surface of the SFA systems and at the soil-fabric-aggregate layer interface.

5. Using the assumed rut depth geometry, calculate the strain in the fabric.

6. Taking the product of fabric strain times the fabric modulus, calculate the tension in the fabric.

7. Calculate the differential normal stress across the fabric due to the uplifting effect of the fabric.

8. Calculate the permissible vertical stress on the top of the fabric by summing the maximum permissible stress on the subgrade plus the differential normal stress due to the uplift by the fabric tension.

9. Calculate the maximum vertical stress on the fabric using the Boussinesq theory.

10. If the maximum vertical stress on the fabric is greater than the permissible vertical stress on the fabric, increase the thickness of the granular layer and iterate through steps 4 through 9.

Background for these design procedures and criteria is discussed below with comments for design guidance. Details are given in Reference 5.

Loading

All design calculations are based on loads applied by pneumatic tires. The total load refers to the load on a single tire or on a set of duals if the duals are close enough together so that vertical stress from the two tires at the surface of the subgrade overlaps to a significant degree. The design thickness is not very sensitive to the average contact pressure, so any reasonable estimate of the average contact pressure will suffice for this procedure. A contact pressure equal to the air pressure in the tire or slightly less would be a good estimate. For dual tires applied as a single load, a contact pressure of between 0.7 and 0.8 times the air pressure can be assumed. All loaded areas are assumed to have uniform pressure over a circular area.

Permissible Stress on the Subgrade

As indicated by Rodin (6), initial or localized failure of the subgrade starts when the stress on the subgrade reaches π times the shear strength of the subgrade soil (πC). With the previously used Mirafi 140 fabric* it was found that these SFA systems rutted initially, but stabilized with a moderate rut depth provided the stress on the subgrade calculated using the Boussinesq theory did not exceed six (6) times the shear strength of the soil (6C). This approach was validated through field applications with the Mirafi 140 fabric.

Rodin (6) also indicated that total failure of the subgrade would occur when the subgrade soil was stressed to 2π times its shear strength ($2 \cdot \pi \cdot C = 6.28C$). This criteria assumes no confinement of the subgrade soil and a clearly defined loaded area. Some higher modulus fabrics, such as the

*Mirafi 140 fabric is a nonwoven fabric no longer produced by Celanese Corporation.

Mirafi 500X, clearly provide a significant confinement for the soil and cause the aggregate layer to distribute the load somewhat more than assumed by the Boussinesq theory. For these reasons the permissible stress on the subgrade should be adjusted to compensate for the effect of fabric modulus on the failure criterion as shown below:

$$\sigma_{per.} = A \cdot \pi \cdot C$$

where

A is a coefficient related to the confining effects of the fabric on the soil.

C is the shear strength of the soil as previously described in Reference 1.

The following values for A are recommended for use in SFA systems with Mirafi fabrics:

Fabric	Recommended Coefficient Value (A)
None	1.0
Mirafi 140	1.9 = $\left(\frac{6}{\pi}\right)$
Mirafi 500X	2.0

Recommended values for A may also be adjusted for different acceptable rut depths. That is, the values for A should be decreased for greater allowable rut depths and increased for shallow allowable rut depths. Specific adjustment values cannot be given since the effect of A on rut depth is also a function of the fabric modulus. Experience will be necessary to establish how great this adjustment should be with the various fabric properties and rut depths.

Rut Geometry

Rut geometry affects the behavior and performance of SFA systems. This effect seems to be enhanced with the stiffer fabric, but not all effects can be quantified at this time. The two geometrical parameters which can be quantified are the rut depth and the width of the rut at the subgrade surface.

Figure 4a shows a typical rut geometry with critical features. For this purpose, rut depth is defined as the change in elevation from the initial surface position to the final surface elevation at the deepest part of the rut. Rut depth in the subgrade (d) is also shown in Figure 4a. Since nearly all rutting of the surface occurs in the subgrade, the subgrade rut depth "d" can, for practical purposes, be taken as equal to the surface rut depth. It should be noted, however, that with less stable aggregates significant rutting may also occur within the aggregate layer, in which case subgrade rut "d" will be somewhat less than the surface rut.

Rut width in the subgrade "W" is influenced by the thickness of the granular layer and, to some extent, the modulus of the fabric. The effect of fabric modulus on the effective rut width "W" is not well defined.

As shown in Figures 4a and 4b, the effective rut width "W" can be estimated by the equation:

$$W = B + 2\overline{X} \tag{2}$$

where

B is the rut width on the surface of SFA system,

$\overline{X}$ is the spreading effect of the granular layer with or without a fabric.

The value for $\overline{X}$ can be estimated from Figure 4b for the appropriate aggregate depth. The exact position for the curve for SFA systems with Mirafi 500X fabric in Figure 4b is not well defined. Fortunately, the design thickness of the granular layer is not highly sensitive to either "W" or "B", so any reasonable estimate of this value will suffice. Rut width "B" may be estimated by the appropriate width of the tire track (or dual tire set) plus the "wander" (lateral movement) of the tire.

Based on a rut width "W" and a rut depth "d" at the surface of the subgrade, the geometry of the deflected shape of the fabric can be calculated as shown in Figure 5. Assuming a circular arc for the shape of the rut in the subgrade (as an approximation, the circular shape agrees well with the observed shape) (5), the geometry of the estimated rut can be calculated from the equations:

$$R = \frac{9}{80} \frac{W^2}{d} + \frac{5}{16} d \qquad (3)$$

$$\theta = 2 \tan^{-1} \left(\frac{10}{6} \frac{d}{W}\right) \qquad (4)$$

where

R, d and W are expressed in inches and θ in degrees.

With the rut geometry as calculated above, the strain in the fabric can now be calculated from the relationship (Figure 6):

$$\text{Percent Strain in Fabric } (\varepsilon_f) = \left(\frac{4\pi R\theta}{135W} - 2\right) \times 100 \qquad (5)$$

This relationship is based on the observed strains in the deformed fabric and is not a derived relationship. This strain value, when expressed in percent and multiplied by the modulus of the fabric expressed in units of pounds per inch of width per percent strain, yields the tension in the fabric.

Fabric Modulus

Extensive testing under a variety of load conditions is required to provide a satisfactory strain history for the fabric from which the fabric modulus can be obtained. Kinney (5) tested the Mirafi 140 and 500X fabrics and developed some recommended moduli values for these fabrics. The recommended values for the Mirafi 140 and 500X fabrics are:

Mirafi 140 ε_f = 3.00 lb/in. per % strain

Mirafi 500X ε_f = 11.0 lb/in. per % strain

While these are relatively conservative values, they are the values recommended for use until less conservative values can be validated through experience.

Differential Normal Stress

The differential normal stress is the normal stress difference between the top and bottom side of the fabric. The summation of the differential normal stress over the fabric in the loaded region is the portion of the applied load which is carried by the fabric. For practical purposes, however, only the differential stress need be calculated and added to the permissible stress on the subgrade to determine the permissible stress on the surface of the fabric.

Since the deflected shape of the fabric is essentially circular and if it is assumed that stresses normal to the fabric before the deflection remain normal after deflection, then the differential normal stress can be calculated from the relationship:

$$\Delta\sigma_{z-f} = \frac{t_f}{R} \tag{6}$$

where

$\Delta\sigma_{z-f}$ is the differential normal stress across the fabric, in psi.

t_f is the tension in the fabric in pounds per inch.

R is the radius of the circular deflected shape in inches.

Permissible Stress on the Fabric Surface

Permissible normal stress on the top of the fabric is the sum of the permissible stress on the subgrade plus the differential stress across the fabric. Thus, the permissible stress on the fabric can be expressed as:

$$\sigma_{p-f} = \Delta\sigma_{z-f} + A \cdot \pi \cdot C \tag{7}$$

where

$A \cdot \pi \cdot C$ is the allowable stress on the subgrade which is given in Equation 1.

$\Delta\sigma_{z-f}$ is the differential stress across the fabric given by Equation 6.

Actual Stress on Fabric Surface

Actual stress on the fabric surface is calculated using the Boussinesq theory for vertical stresses, to wit:

$$\sigma_z = p \left[1 - \left(\frac{1}{1 + (\frac{a}{z})2} \right)^{3/2} \right] \tag{8}$$

where

p is the average contact pressure in psi.

z is th thickness of the aggregate layer in inches.

a is the radius of the loaded area determined as follows:

$$a = \sqrt{\frac{P}{\pi p}}$$

P is the total applied load in pounds.

EXAMPLE DESIGN PROBLEM

This example design problem is intended only to illustrate the procedures. All inputs are assumed, but were selected to represent typical values. The specific calculations are shown in Table 1.

Assumed Values:

Design load (P) = 10,000 pounds

Average contact pressure (p) = 50 psi (Dual tires)

Subgrade shear strength (C) = 3 psi (CBR = 0.7)

Allowable rut depths (d) = 4, 6, and 8 inches

Fabric modulus (E_f)

Mirafi 140	3.0 (lb/in./% strain)
Mirafi 500X	11.0 (lb/in./% strain)

Estimated Thickness*

No fabric 21 inches

Mirafi 140	15 inches
Mirafi 500X	14 inches

Wheel Path Width (Estimate based on wheel width plus "wander" width)

At surface (B)	30 inches
At subgrade (W)	
Mirafi 140	2 x 8 + 30 = 46 inches
Mirafi 500X	2 x 10 + 30 = 50 inches

As indicated earlier and as shown in Table 1, the effect of the rut width "W" on the final thickness is not very great. If, for example, the rut width for the Mirafi 500X fabric was assumed to be 46 inches, the same as for the Mirafi 140 fabric, then the corresponding reduction in aggregate thickness is 0.2 inches (12.6 to 12.4 inches). Thus any reasonable estimate for the rut geometry will provide a valid answer for the thickness required.

*Any value can be used for estimating thickness; however, if the estimate is significantly in error then more iterations are required.

While the above calculations are straightforward and simple to do on a hand calculator, it would not be practical to redo these calculations for each design attempted. Accordingly, design curves have been developed for wheel loads of 5,000, 10,000, 15,000 and 20,000 pounds (Figures 7 - 10). These curves were developed for typical rut depths and widths for non-surfaced roads (aggregate haul roads and temporary roads). Average contact stress of 80 psi was assumed for all calculations. While the required thickness of the granular layer is not highly sensitive to any of these inputs, if significant variations of these inputs are anticipated, some adjustments in the thickness required would be appropriate.

SUMMARY AND CONCLUDING REMARKS

The design criteria and resulting design curves are believed to be somewhat conservative. In general, the design thicknesses with the Mirafi 500X fabric runs 1-1/2 to 2-1/2 inches thinner than the corresponding layers for use with the Mirafi 140 fabric. With the higher modulus Mirafi 500X fabric, not only can a thinner layer of granular be used, but there is also evidence of a significantly larger factor of safety against occasional overstress. This is clearly shown in the data from the full-scale field tests (3,4) and also in the box tests on model SFA systems (5). Since some of the benefits with the high-modulus fabrics cannot be fully explained or even quantified, a conservative design approach has been presented for use until more definitive data on thicknesses required have been developed and verified.

REFERENCES

1. Barenberg, Ernest J., Dowland, James H., Jr., and Hales, John II, "Evaluation of Soil Aggregate Systems with Mirafi Faric," Civil Engineering Studies, Department of Civil Engineering, University of Illinois, August 1975.

2. Bender, David, and Barenberg, E. J., "Analysis of Soil-Fabric-Aggregate Systems," Unpublished report submitted to Celanese Fibers Marketing Co., June 1977.

3. Webster, Steve L., and Watkins, James E., "Investigation of Construction Techniques for Tactical Bridge Approach Roads Across Soft Ground," Technical Report S-77-1, U.S. Army Engineers, Waterways Experiment Station, Vicksburg, Miss., February 1977.

4. Kinney, T. C., and Barenberg, E. J., "Mechanisms by Which Fabrics Stabilize Aggregate Layers on Soft Subgrades," Report prepared for U.S. Army Engineer Waterways Experiment Station, February 1978 (Publication Pending).

5. Kinney, T. C., "Fabric Induced Changes in High Deformation Soil-Fabric-Aggregate Systems," Ph.D. Thesis submitted to the Graduate College, University of Illinois, Urbana-Champaign Campus, January 1979.

6. Rodin, S., "Ability of a Clay Fill to Support Construction Plant," Journal of Terramechanics, 1965, Vol. 2, No. 4, pp. 51-68.

TABLE 1. TYPICAL CALCULATIONS

FABRIC	RUT DEPTH d	RUT WIDTH w	RADIUS R	ANGLE	FABRIC STRAIN	FABRIC TENSION t_f	DIFFERENTIAL STRESS	COEFFICIENT	PERMISSIBLE SUBGRADE STRESS	PERMISSIBLE STRESS ON FABRIC	REQUIRED AGGREGATE THICKNESS z
	4	46	60.7	16.5	2.67	8.0	.13	1.85	17.4	17.5	13.8
M. 140	6	46	41.6	24.5	6.24	18.7	.45	1.90	17.5	18.4	13.5
	8	46	32.1	32.3	9.81	29.4	.91	1.92	18.1	19.0	13.2
	4	50	71.5	15.2	2.33	25.6	.36	1.95	18.4	18.8	13.3
M. 500X	6	50	48.8	22.6	5.32	58.5	1.20	2.00	18.8	20.0	12.5
	8	50	37.7	29.9	9.85	108.4	2.88	2.02	19.0	21.9	11.8
	6	46	41.6	24.5	6.24	88.6	2.13	2.00	18.8	20.9	12.2
	GIVEN	EQUATION 2	EQUATION 3	EQUATION 4	EQUATION 5	$\varepsilon_f \times E_f$	EQUATION 6	GIVEN	EQUATION 1	EQUATION 7	EQUATION 8

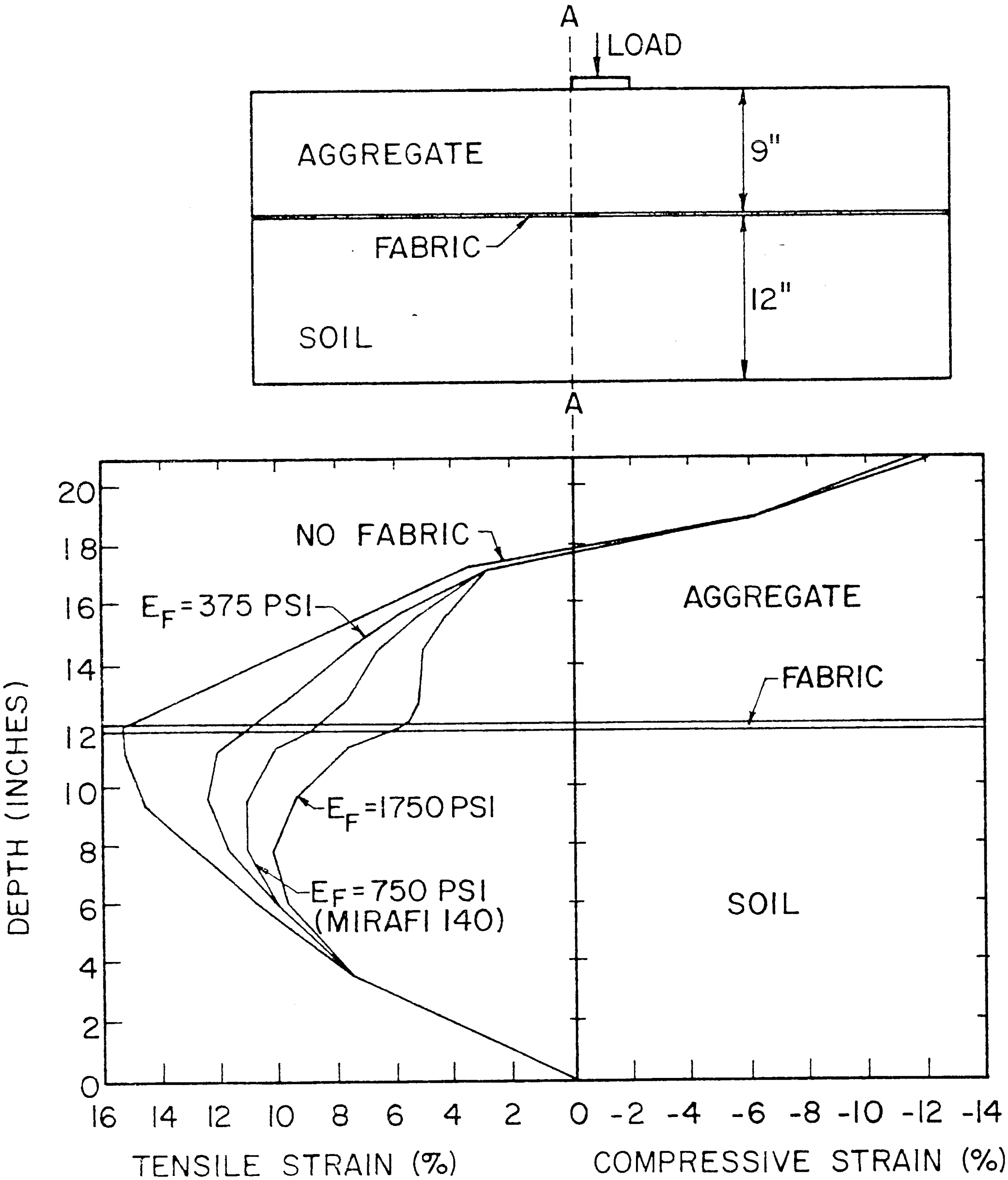


Figure 1. Horizontal Strain Across Section A-A for Soil-Fabric-Aggregate Systems with Fabrics of Different Moduli

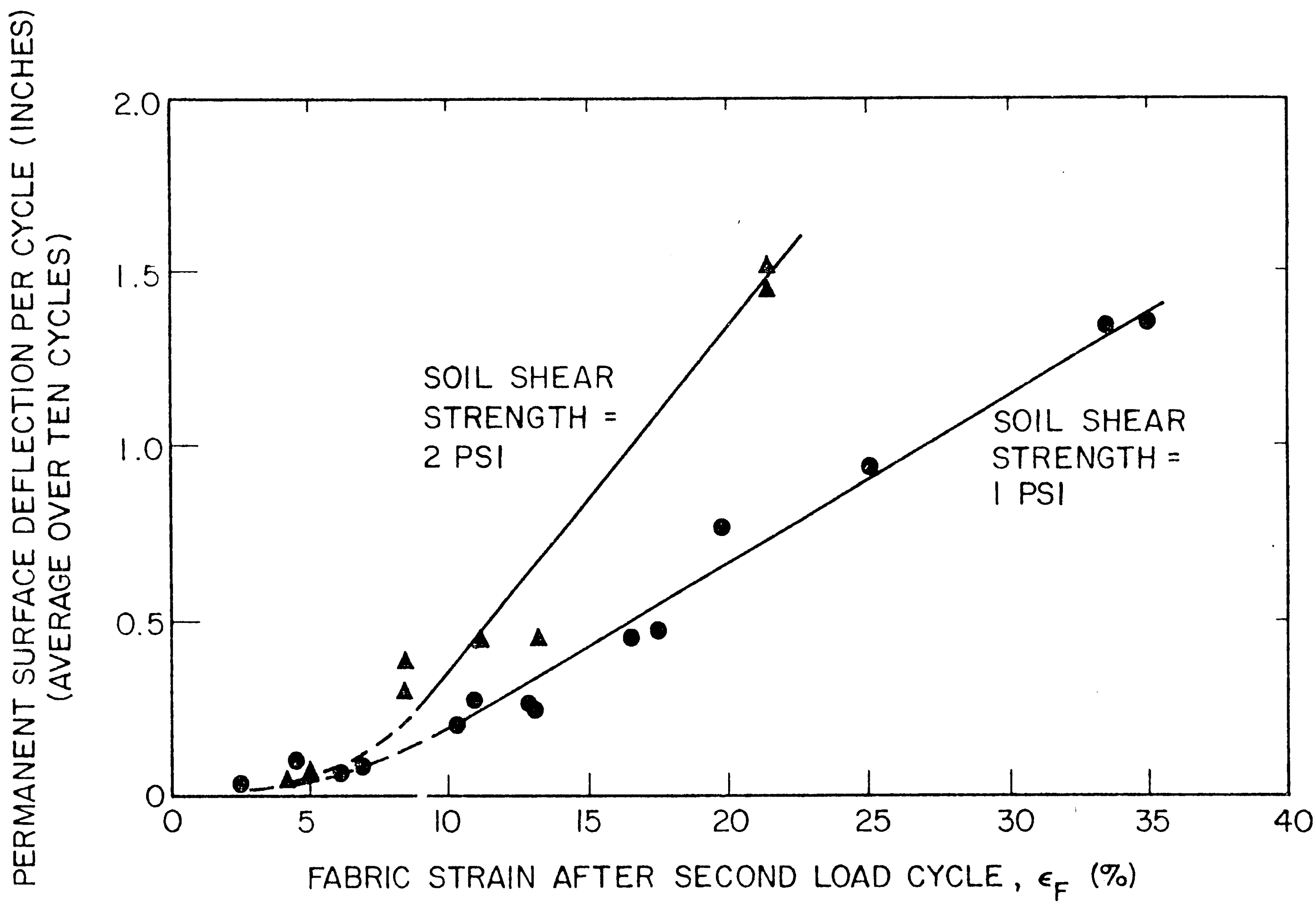
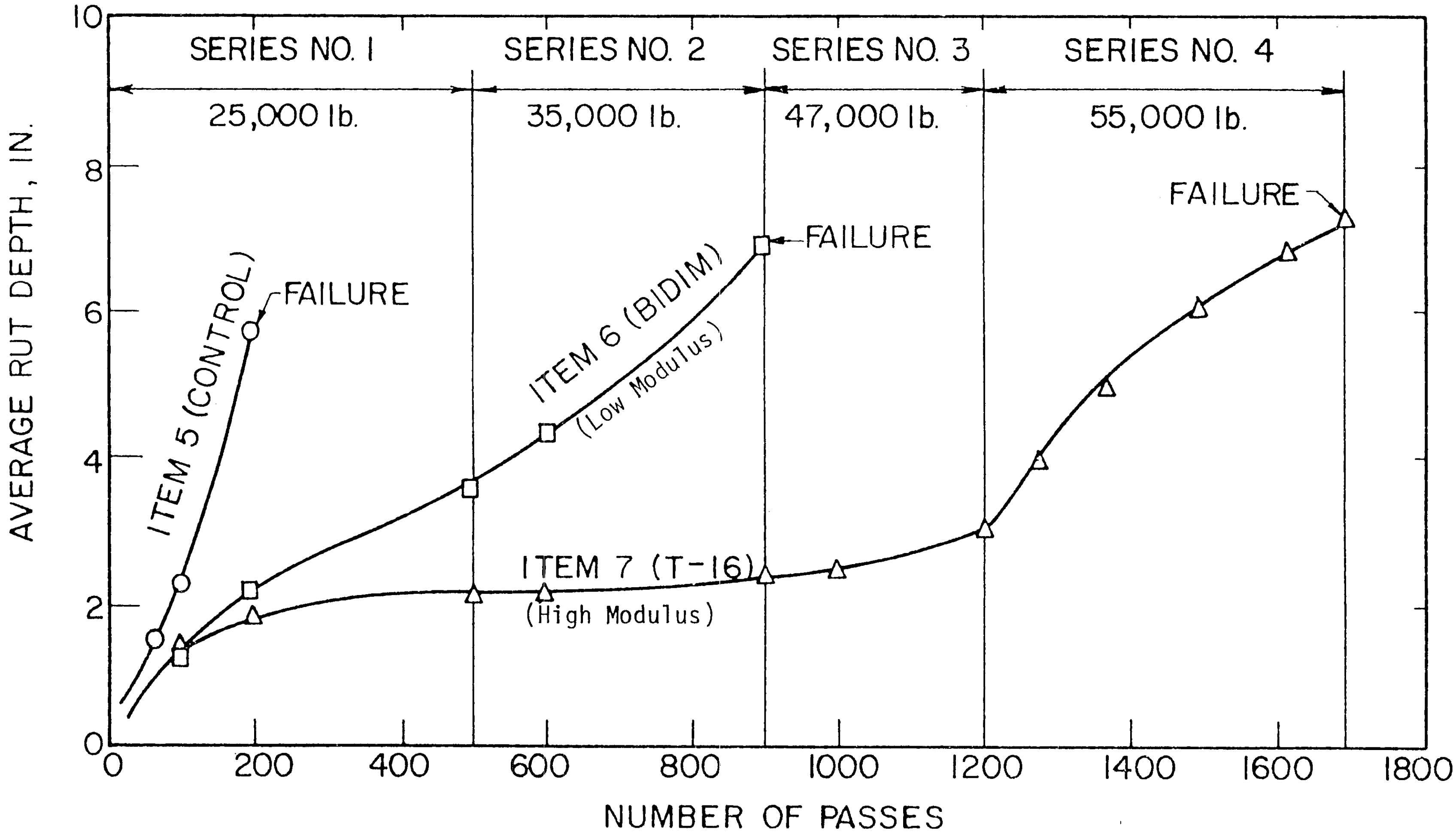


Figure 2. Average Experimental Deflection Versus Calculated Fabric Strain



NOTE: 1. Failure defined by WES as when truck differential dragged.
2. Rut depths shown are average over length of each test item.
3. Data compiled and reported by WES. Data not available for other analysis.

Figure 3. Rut Depth as a Function of Vehicle Passes for West Wheel Path. (Ref. 3)

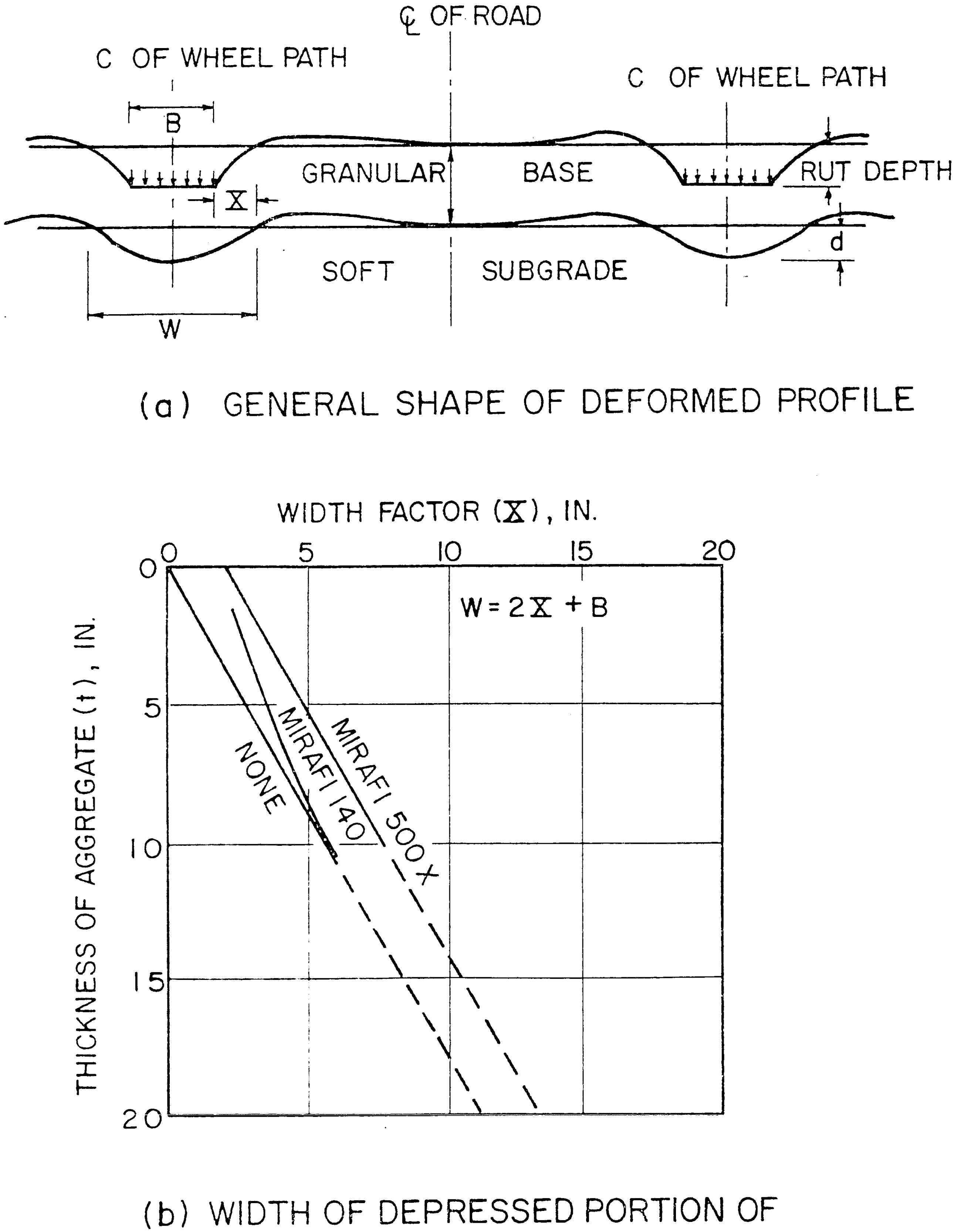


Figure 4. Approximate Width of the Depressed Portion of the Rutted Surface of the Subgrade.

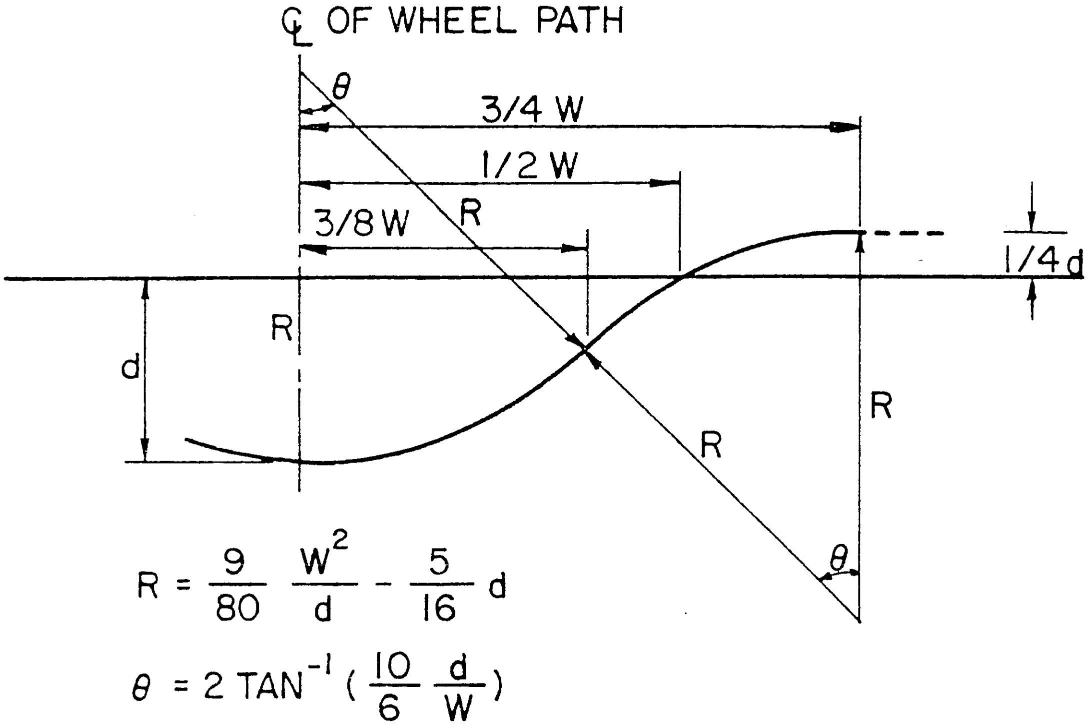


Figure 5. Approximate Deformed Shape of Base Subgrade Interface

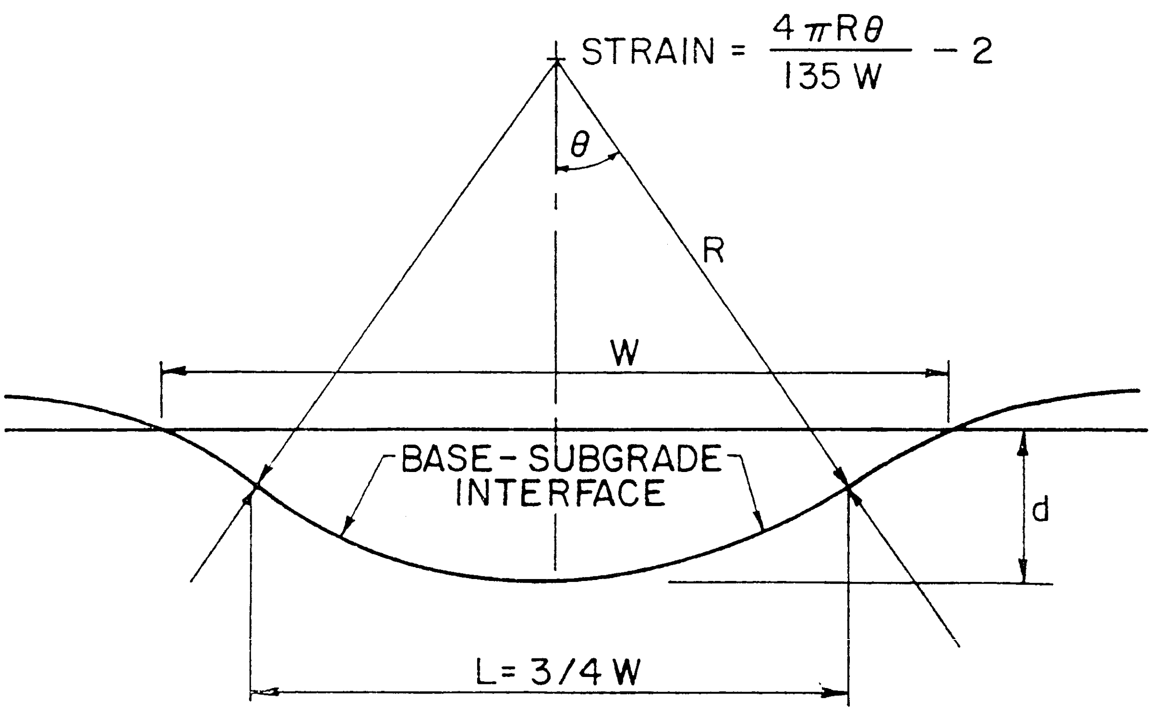


Figure 6. Approximate Elongation and Strain in the Base and Subgrade Along the Interface

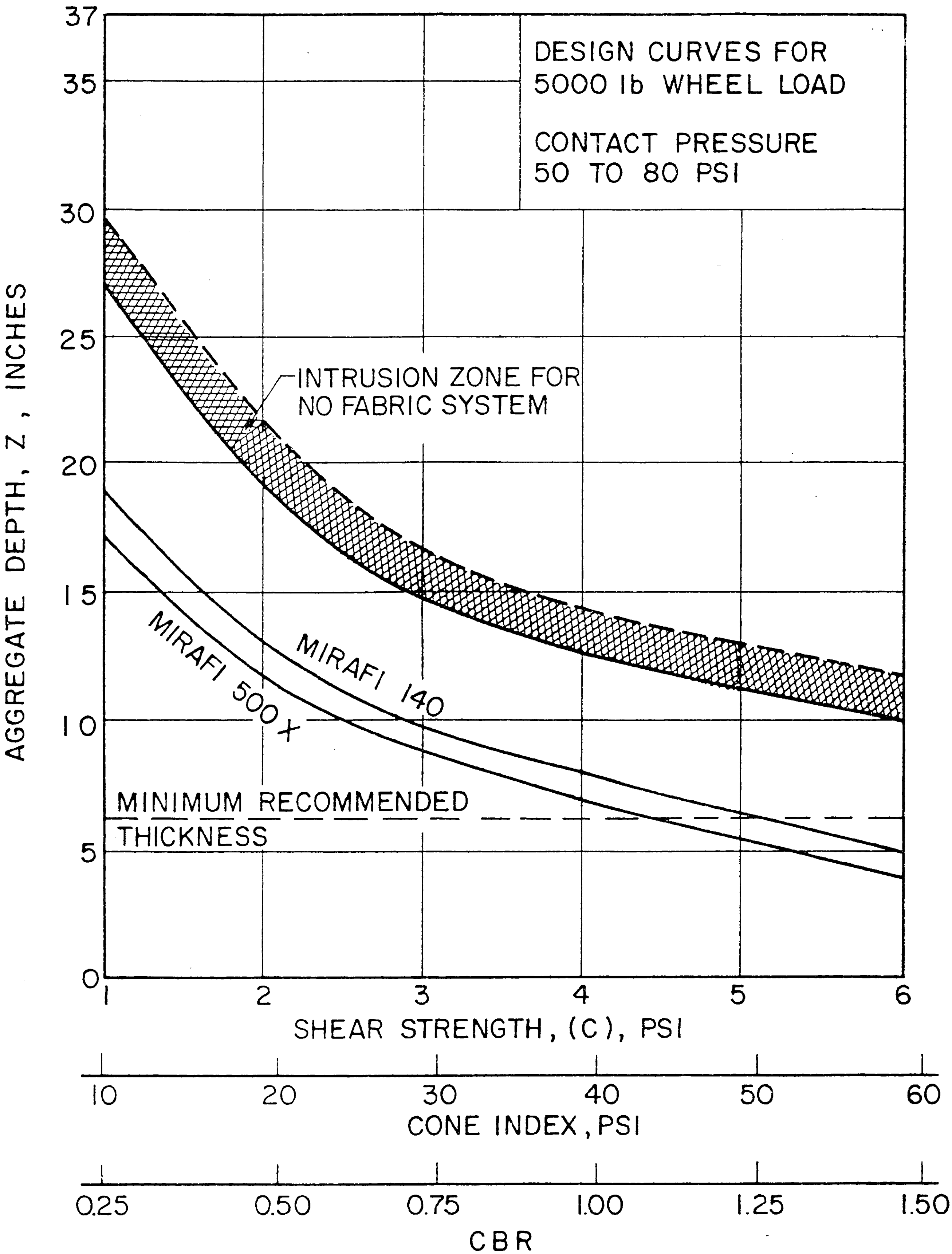


Figure 7. Design Curves for 5,000 Pound Wheel Load.

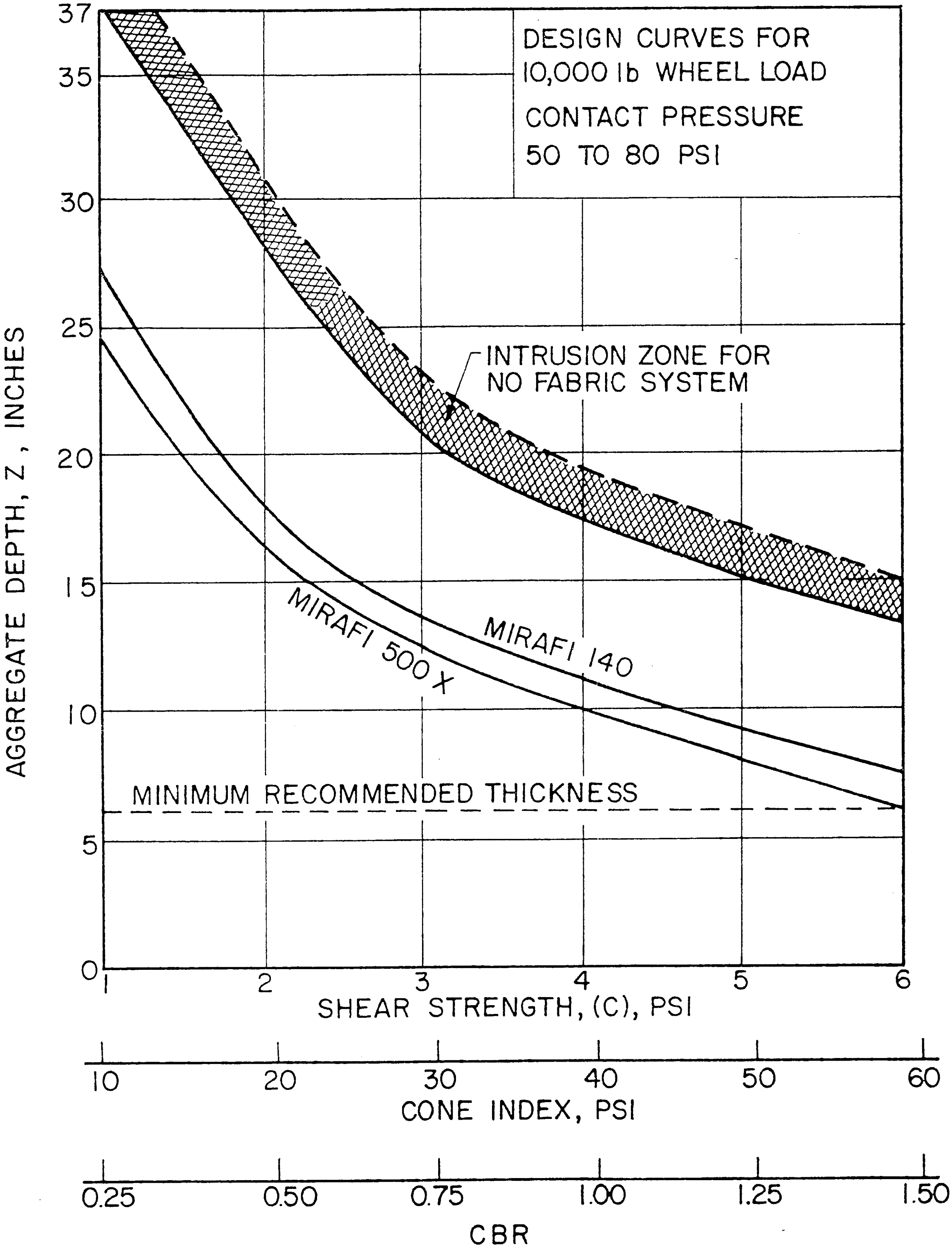


Figure 8. Design Curves for 10,000 Pound Wheel Load.

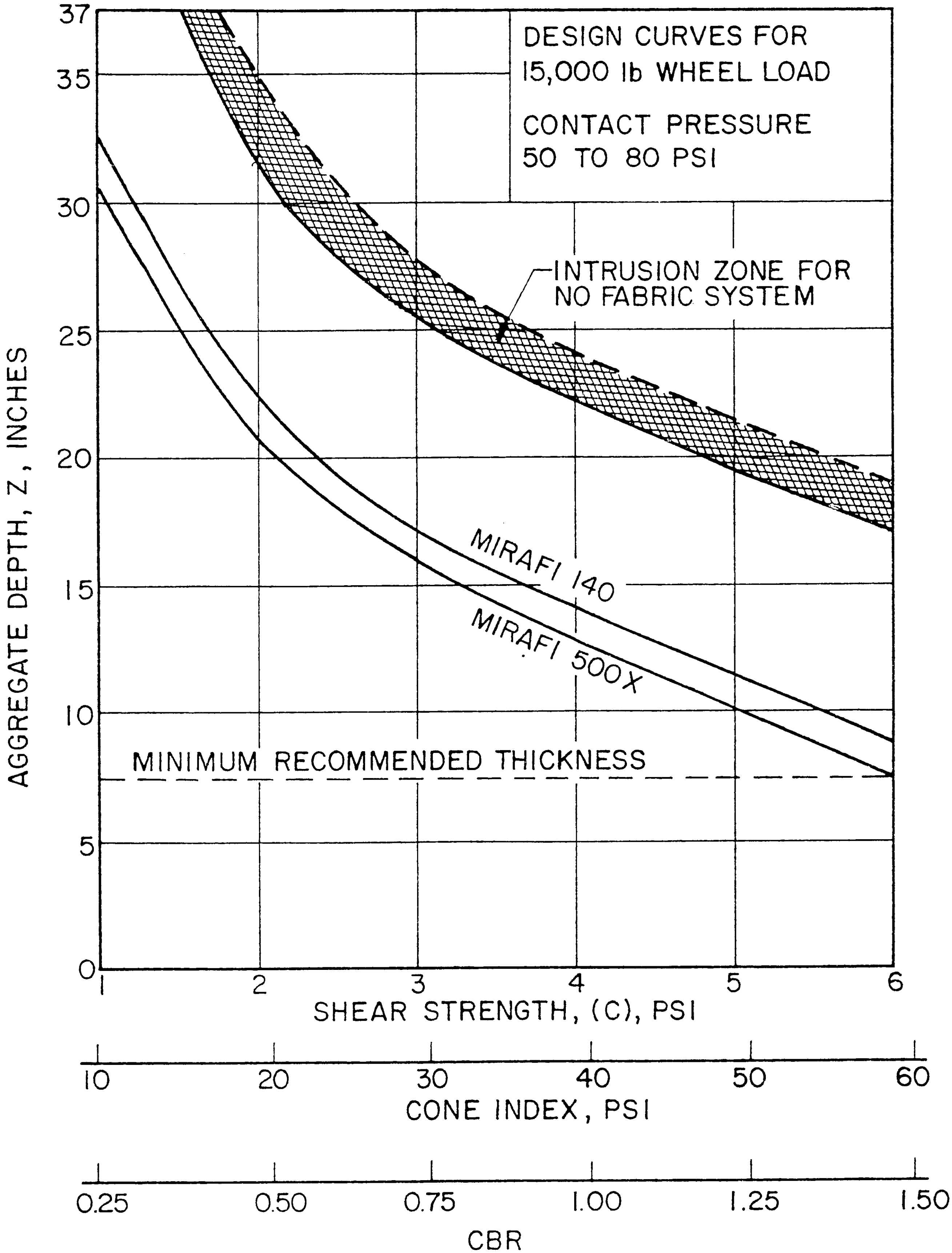


Figure 9. Design Curves for 15,000 Pound Wheel Load.

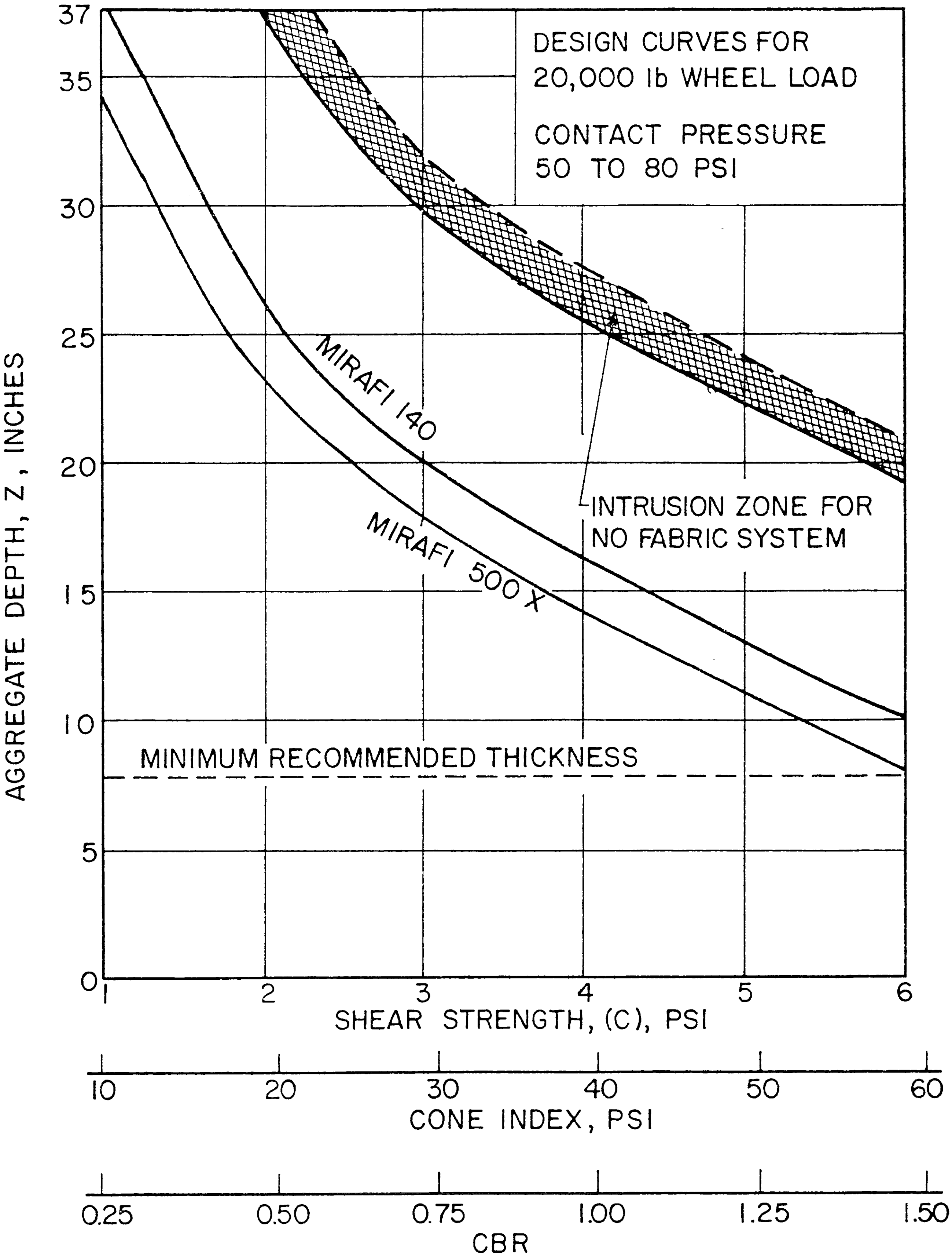


Figure 10. Design Curves for 20,000 Pound Wheel Load.