Feasibility of the Use of Existing Analytical Models And Experimental Data to Assess Current Design Methods For Pavement Geogrid-Reinforced Base Layers

Final Report

Prepared for the
STATE OF MONTANA
DEPARTMENT OF TRANSPORTATION
RESEARCH & DEVELOPMENT PROGRAM
in cooperation with the
U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL HIGHWAY ADMINISTRATION
February 10, 1995

Prepared by
Dr. Steven W. Perkins
Department of Civil Engineering
Montana State University
Bozeman, Montana 59717
Office Telephone: 406-994-6119
Fax: 406-994-6105
E-Mail: stevep@ce.montana.edu

PREFACE

The information reported herein was sponsored by the Montana Department of Transportation in conjunction with the Federal Highway Administration. The opinions, findings and conclusions expressed in this publication are those of the author and not necessarily those of the Montana Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification or regulation.

Alternate accessible formats of this document will be provided upon request.

Persons with disabilities who need an alternative accessible format of this information, or who require some other reasonable accommodation in order to participate, should contact the Montana Department of Transportation, Attn: Research Manager, 2701 Prospect Avenue, Helena, MT 59620-1001; Telephone No. (406) 444-6269, TDD No. (406) 444-7696 or Fax No. (406) 444-6204. For more information, contact the MDT Personnel Services Section at (406) 444-3871.

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
MT94-08116		

4. Title and Subtitle	5. Report Date
Feasibility of the use of Existing Analytical Models and Experimental Data to Assess Current Design Methods for Pavement Geogrid-Reinforced Base Layers.	2-23-95
	6. Performing Organization Code
	8. Performing Organization Report No.
7. Author(s) Dr. Steven W. Perkins	
9. Performing Organization Name and Address Department of Civil Engineering Montana State University Bozeman, MT 59717	10. Work Unit No. (TRAIS)
	11. Contract or Grant No. MT94-08116
12. Sponsoring Agency Name and Address Montana Department of Transportation 2701 Prospect Avenue P.O. Box 201001 Helena, MT 59620-1001	13. Type of Report and Period Covered Final July, 1994-March, 1995
	14. Sponsoring Agency Code

15. Supplementary Notes

Preparation in cooperation with the U.S. Department of Transportation, Federal Highway Administration

16. Abstract

In recent years polymer geogrids have been proposed and used to improve the performance of paved roadways and/or to reduce base course thickness. Performance improvements have been demonstrated for design conditions where relatively large rut depths are acceptable and where relatively weak pavement sections have been used. This work was undertaken to examine existing literature concerning laboratory and field experimental studies, and analytical studies pertaining to the inclusion of geogrid polymer materials in roadway pavement sections for the purpose of improving performance or to allow for a reduction in the constructed section thicknesses. The original goal of this study was to examine the feasibility of using existing data from laboratory or field studies and existing finite element models to validate and calibrate the model and then use the model to predict the response of pavement sections not included in the experimental studies.

This study has indicated that this approach is feasible and has been accomplished by a previous project. Furthermore, the literature reviewed in this study has shown conflicting results pertaining to the level of improvement that is realized by inclusion of a geogrid in the base course layer of a pavement section. While additional laboratory and analytical studies may aid in resolving these conflicts it is concluded that the most productive approach at this point is to construct well-instrumented, full-scale field sections to assess improvement levels. These sections should be designed and constructed to include variables identified in previous studies as having the greatest impact on pavement performance.

17. Key Words	18. Distribution Statement
Pavements, Geogrid, Reinforcement, Geosynthetic, Geotextile, Highways	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	39	

TABLE OF CONTENTS

SUMMARY

In recent years polymer geogrids have been proposed and used to improve the performance of paved roadways and/or to reduce base course thickness. Performance improvements have been demonstrated for design conditions where relatively large rut depths are acceptable and where relatively weak pavement sections have been used. This work was undertaken to examine existing literature concerning laboratory and field experimental studies, and analytical studies pertaining to the inclusion of geogrid polymer materials in roadway pavement sections for the purpose of improving performance or to allow for a reduction in the constructed section thicknesses. The original goal of this study was to examine the feasibility of using existing data from laboratory or field studies and existing finite element models to validate and calibrate the model and then use the model to predict the response of pavement sections not included in the experimental studies.

This study has indicated that this approach is feasible and has been accomplished by a previous project. Furthermore, the literature reviewed in this study has shown conflicting results pertaining to the level of improvement that is realized by inclusion of a geogrid in the base course layer of a pavement section. While additional laboratory and analytical studies may aid in resolving these conflicts it is concluded that the most productive approach at this point is to construct well-instrumented, full-scale field sections to assess improvement levels. These sections should be designed and constructed to include variables identified in previous studies as having the greatest impact on pavement performance.

INTRODUCTION

In recent years polymer geogrids have been proposed and used to improve the performance of paved roadways and/or to reduce base course thickness. Performance improvements have been demonstrated for design conditions where relatively large rut depths are acceptable and where relatively weak pavement sections have been used. It is not clear if these same improvement levels can be achieved for other conditions. The work described herein was designed to address this question by the manner described below.

Purpose of Work

This work was undertaken to examine existing literature concerning laboratory and field experimental studies, and analytical studies pertaining to the inclusion of geogrid polymer materials in roadway pavement sections for the purpose of improving performance or to allow for a reduction in the constructed section thicknesses. The thesis put forth in the original proposal was that existing experimental studies were available to provide data to which predictions from existing finite element models, formulated to model reinforced soil behavior, could be compared to validate these models. If this was found to be true, it would then be feasible to use these finite element models to evaluate pavement performance improvement levels over a wide range of variables. This work has demonstrated that this approach is possible and has been accomplished in previous studies. This finding prompted a change in emphasis in this study. The new emphasis became a critical evaluation of existing studies to determine the level of improvement that could be expected by inclusion of geogrids for the conditions examined in the various studies. This evaluation has indicated that conflicting results are obtained from the available studies and has prompted the conclusion that full-scale, well-instrumented field studies are necessary to examine improvement mechanisms and levels.

Background

The current major application area for geogrids in roadways is in the reinforcement of soft and/or compressible subgrade soils for unpaved aggregate roads. The mechanisms associated with an unpaved structure reinforced by placing a geogrid at the bottom of the aggregate layer were described by Giroud et al. (1985). The geogrid influences the base layer through interlocking between the geogrid and the base layer material. This interlocking effectively transmits shear stresses from the base material to the grid, thereby increasing the shearing capacity of the base. This requires, however, sufficient shear strains to mobilize this effect. This effect also reduces lateral movement of the aggregate base and base deterioration, which is especially pronounced for weak base materials. The interlocking between the grid and the base materials also prevents, to some degree, migration of fines into the base or base material into the subgrade.

The geogrid also influences the subgrade soil behavior. Rather than an improvement in subgrade properties, geogrids improve subgrades through a change in the boundary conditions acting on the subgrade. It is claimed that inclusion of the geogrid results in the wheel load being distributed over an effectively larger area, or the vertical stress acting on the subgrade is reduced. If sufficient deformations occur the geogrid becomes concaved and begins to act as a tensioned membrane. The normal stress supported on the top side of the grid will then be greater than that on it's bottom side, thereby reducing the vertical stress acting on the subgrade.

These arguments were used to surmise that similar benefits could be achieved for paved roadways with the cautionary note that many of the effects described above are realized only for relatively large vertical deformations. The successes observed for unpaved road structures has prompted research to examine the influence of geogrids on paved road structures.

DATA BASE SEARCH

Literature searches were performed through the library at Montana State University (MSU) and at the Montana Department of Transportation (MDT). The following data bases were searched at MSU and at the MDT.

1. COMPENDEX PLUS
2. CONFERENCE PAPERS INDEX
3. GEOARCHIVE
4. GEOBASE
5. GEOREF
6. NTIS
7. PASCAL
8. INSPEC
9. Mechanical Engineering Abstracts
10. IHS Int. Stds. and Specs.
11. FLUIDEX
12. Energy SciTec
13. Aerospace Database
14. PAPERCHEM
15. PIRA
16. RAPRA Abstracts
17. DIALOG SourceOne
18. World Transl. Index
19. Engineering Materials Abstracts
20. METADEX
21. TRIS

For the data bases numbered 1-6 the years searched were limited to 1990-1994. A literature search using data bases 1-6 for years prior to 1990 was conducted and documented by White (1991). The remaining data bases were searched for all years. The keywords used for this search were as follows:

(Geotextile or Geofabric or Geogrid) and (Pavement or Paving or Paved or Unpaved or Road or Highway or Airstrip)

Approximately 70 articles were obtained from the above literature searches and reviewed. A bibliography of these articles is given in Appendix I. Those articles found to be pertinent to this study are summarized in the following section and are referenced at the end of this report.

SUMMARY OF RELEVANT PAPERS

The articles identified above were reviewed in light of the objectives of this work. The papers containing information relevant to this study are summarized and discussed below. Papers pertaining to both paved and unpaved roadways are examined.

Paved Roads

Al-Qadi, I.L., Brandon, T.L., Valentine, R.J., Lacina, B.A. and Smith, T.E. (1994), "Laboratory Evaluation of Geosynthetic Reinforced Pavement Sections", Transportation Research Board Preprint, Paper No. 94-0479, 73rd Annual Meeting, Washington DC.

Cyclic circular plate loading tests were performed on pavement sections consisting of subgrade, base and HMA pavement. The sections were reinforced with geotextiles and/or geogrids placed between the subgrade and base level. The subgrade was a weak (CBR=4) silty sand. The base was a dense granite aggregate (AASHTO classification 21-A). A loading pressure of 552 kPa was applied to a 30 cm diameter plate, corresponding to an applied force of 40 kN (9 kip), at a loading rate of 0.5 Hz. The pavement surface was instrumented with LVDT's while applied load was measured. More cycles were necessary to reach a displacement of 1 inch for the geotextile reinforced section (1200 cycles) as compared to the 640 cycles for the geogrid reinforced section and the 160 cycles for the non-reinforced section. This suggests the importance of the separation action of the geotextile and potentially explains why other studies showed no difference in FWD measurements for geogrid reinforced sections.

Anderson, P. and Killeavy, M. (1989), "Geotextiles and Geogrids: Cost Effective Alternate Materials for Pavement Design and Construction", *Geosynthetics '89 Conference*, San Diego, pp.353-360.

The paper describes a case study of a reinforced paved area used as a trucking facility in southern Ontario. The site consisted of marsh lands that had been previously filled and leveled. The geogrid design followed the method proposed by Haas (1984). For certain sections, geotextiles were used as a separation barrier. For these cases, the geotextile was assumed not to contribute to the structural strength of the pavement. Pre-rutting of the aggregate base was accomplished by operating loaded trucks atop the base prior to placement of the asphalt layer. A Tensar SS-1 geogrid having a tangent stiffness of 370 kN/m was used. A cost analysis showed a cost of \$19.88/m^2 for the reinforced section and \$20.40/m^2

Table 1: Pavement Sections Used In The Case Study By Anderson and Killeavy (1989)

Layer	Layer Thickness (mm)		
	Pavement Section		
	1	2	3
	Non-Reinforced	Geotextile Only	Geogrid and Geotextile
AC	40	40	40
AC Binder	65	50	65
Base	150	50	200
Subbase	300	150	0

for the unreinforced section.

Three pavement sections were constructed. The sections are summarized in Table 1. When used, the geotextile and the geogrid were placed between the subgrade and the above lying base or subbase.

The pavement performance was assessed by monitoring pavement cracking and by performing FWD tests. FWD tests showed comparable center deflection values for the three sections when the load application was normalized. Equivalent layer moduli were back-calculated and shown to be higher for the reinforced sections. No difference in cracking between the sections was noted at the time of the report. It was noted that the pavement was subjected to only 1100 ESAL's at the time the report was prepared. No instrumentation was included in the study to monitor conditions within the pavement sections.

Barker, W.R. (1987), "Open-Graded Bases for Airfield Pavements", USAE Waterways Experiment Station, Misc. Paper GL-87-16.

Full-scale tests were conducted using a Tensar SS2 geogrid to reinforce a 6 in. open graded base layer in a heavy-load surfaced flexible pavement. The geogrid was placed in the middle of the base. Traffic loading consisted of a 27 kip single tire inflated to 265 psi, simulating an F-4 aircraft. After 1000 passes, the surface deformation of the reinforced section was 2.7 in while the non reinforced section deformed by 3.4 in.

Barksdale, R.D., Brown, S.F. and Chan, F. (1989), "Potential Benefits of Geosynthetics in Flexible Pavement Systems", *National Cooperative Highway Research Program Report No. 315*, Transportation Research Board, National Research Council, Washington DC, 56p; and Supplement to Report No. 315.

This research was sponsored by AASHTO in cooperation with the Federal Highway Administration and consisted of full-scale laboratory experiments of various reinforced and non-reinforced pavement sections and analytical modeling using a finite element program. The laboratory experiments were performed at the University of Nottingham, England, while the analytical modeling was performed at the Georgia Institute of Technology. The research approach was to experimentally study significant variables affecting pavement performance for reinforced and non-reinforced pavements while simultaneously developing a finite element model that was capable of modeling reinforced pavements, calibrating and validating the model based on the laboratory results and then using this model to perform a parametric (sensitivity) study to examine variables not capable of being studied in the experimental program. It should be noted that this approach aligns closely with that suggested by the PI in his proposal to MDT, and which this feasibility study is designed to examine.

The full-scale experiments were performed in a moving wheel pavement test facility 16 ft by 8 ft in plan using a 1500 lb wheel loading moving at a speed of 3 mph. Up to 70,000 repetitions of wheel loading were applied to the sections in a constant temperature environment. The variables included in the test program consisted of geosynthetic type, location of the geosynthetic within the aggregate base, prerutting the reinforced and unreinforced sections, prestressing the geosynthetic in the aggregate base and base aggregate quality.

The test section materials consisted of an asphalt surfacing, an aggregate base and a cohesive subgrade. Two types of asphalt surfacing were used, namely a gap-graded hot rolled asphalt and an asphaltic concrete mix. Two types of aggregate base were used. Initially, a weak granular base consisting of rounded sand and gravel was used. This material exhibited excessively poor performance and was replaced by a crushed dolomitic limestone. The subgrade consisted of 18 inches of a low-plasticity silty clay having an in-place CBR of 2.6 and a moisture content of 18%. This same clay was placed at a lower water content beneath this material and had a CBR of 8-10. The subgrade was not replaced from one testing sequence to the next, resulting in an increase of the in-place CBR to a value of 3.2. Two types of geosynthetics were used in the study. One was a very stiff, woven geotextile having a stiffness of 4300 lb/in. The other was a medium to high stiffness biaxial geogrid having a stiffness of 1600 lb/in.

The test sections were instrumented with pressure cells and strain gages. All instrumentation was placed beneath the center line of each test section in the direction of wheel travel. The instrumentation was installed to measure the magnitude and variation with depth of the transient and permanent vertical strains in the base and subgrade, transient and permanent lateral strains at the bottom of the asphaltic layer, at the top and bottom of the base layer and in the geosynthetic, transient vertical stress near the top of the subgrade, transient lateral stress at the top and bottom of the base and temperature in each layer. A profilometer was used to measure the surface profile of the pavement.

Permanent vertical deformation of the asphalt surface was measured for each test configuration. The pavement surface profiles for the various tests are shown in Figure 1. The first test series used the weak aggregate base. The stronger crushed limestone base was used for the remaining test series. The results from test series 1 indicate that the inclusion of a stiff geotextile at the bottom of the very weak sand-gravel base reduces the amount of rut by about 44% for a relatively large rut depth of 0.43 in. in the control section. Furthermore, prerutting did not appear to improve the pavement performance. The results from test series 2 indicate that prerutting a geogrid-reinforced base of good quality results in a 66% reduction in rut depth. Without prerutting, only an 8% reduction in rut depth was realized for the same geogrid-reinforced section. For test series 2, all reinforcement was at the bottom of the base. For test series 3, a very stiff geotextile was used to reinforce the base and was placed either in the middle or at the bottom of the base. For the geotextile placed

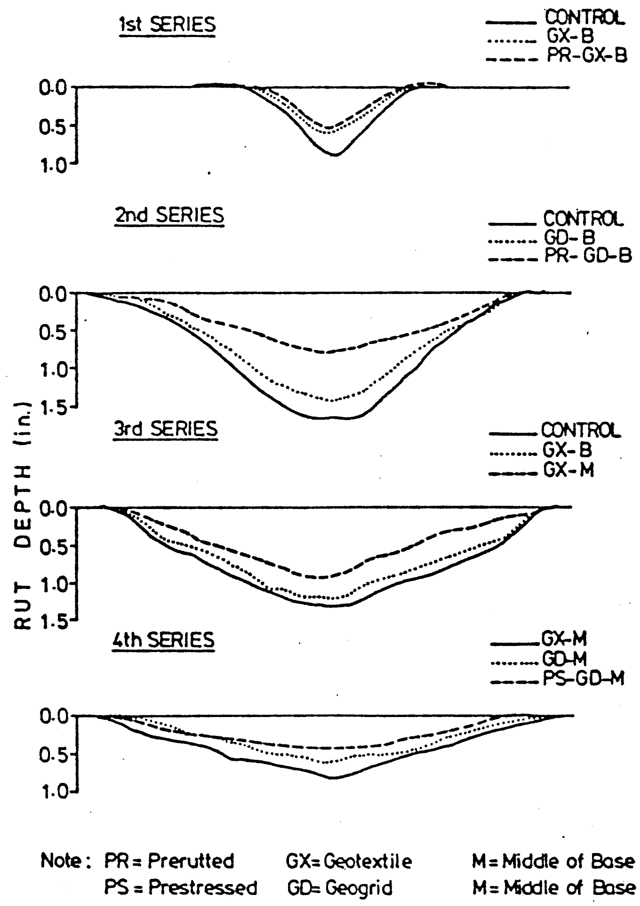

Figure 1: Pavement surface profiles at end of tests for all test series (Barksdale et al., 1989)

at the bottom of the base, a 13% reduction in rut depth was observed. This reduction was improved to 28% when the geotextile was moved to the middle of the base layer. The fourth test series indicated that a lower stiffness geogrid was better than a higher stiffness geotextile when both were placed in the middle of the base. Prestressing the geogrid resulted in some rutting improvement.

Evaluation of pavement performance was also made by comparing the other measured quantities from the tests, such as permanent vertical strain, vertical, lateral and longitudinal resilient strain, and transient stresses. The lateral resilient strain appeared less for the reinforced sections yet no particular trend could be observed regarding the effect of geosynthetic stiffness and placement. The other measures showed little difference between control sections and reinforced sections.

Prerutting of the pavement sections was carried out in the experiments. Prerutting was achieved by applying applications of a wheel load to the top of the aggregate base before the asphalt surfacing was applied. Prerutting was carried out typically until the rut depth was approximately 2 in. Prerutting was shown to result in an overall reduction in surface rutting of the completed pavement by 30% or more. In addition, the vertical stress on the subgrade appears to remain constant during the wheel loading portion of the test for the prerutted section while it was seen to increase at a gradually increasing rate during the test for the non-prerutted section. For the reinforced base sections these observations were clearly due to inducing tensile strains in the reinforcement prior to traffic loading. For the unreinforced sections, showing nearly the same benefit when prerutted, the mechanism is not so clear. The authors claim that the prerutting caused the base material to increase in density, thereby having the same effect as rolling the base with a pneumatic compactor. This results in a stiffer, more dense zone of base material at the top of this layer which is then less prone to rutting. This tends to imply that the base material was not sufficiently compact at the start. This would also tend to imply that a good quality base that was compacted to a high relative density might show the opposite effect due to the fact that this material would tend to dilate when sheared and thereby become weaker.

A finite element model called GAPPS7, developed at Georgia Tech, was used to model the reinforced pavement response. The model was capable of analyzing either plane strain or axisymmetric problems. Like most models of this type, repetitive loadings are applied at a stationary position (i.e. the load does not move across the continuum). Inertial forces and creep are not accounted for. Various constitutive models are available within the program. The resilient modulus of cohesive subgrade materials is expressed as a bi-linear function of the principal stress difference (deviator stress) $\sigma_1 - \sigma_3$. The resilient modulus decreases rapidly with increasing deviator stress and then begins to increase more slowly. For granular materials, the resilient modulus can be expressed by the relationship $E_r = K J_1^N$, where K and N are material constants determined from laboratory tests and J_1 is the first invariant of stress ($J_1 = \sigma_1 + \sigma_2 + \sigma_3$). A so-called simplified contour model is also available which relates the bulk modulus and shear modulus to the mean normal stress and deviator shear stress. These three models represent nonlinear formulations describing the stress dependent nature of an elastic modulus. In addition, a linear elastic, cross anisotropic model was used. This model describes linear elastic moduli that are different in the horizontal and vertical directions.

The finite element model used in the study employed an isotropic non-linear elastic model for the asphalt and subgrade materials and a cross-anisotropic linear elastic model for the base material. The prediction of tensile strain in the base material was essential in determining the level of tensile strain developed in the geosynthetic, which in turn determined, in large part, the benefit provided by the reinforcement. The cross-anisotropic model used for the base was the only model capable of predicting at the same time the relatively large lateral tensile strains in the bottom of the base and the small vertical strains in the bottom and upper part of that layer, as observed in the laboratory tests.

The finite element model was calibrated and verified by using data from an unreinforced pavement section from a previous study (Barksdale, 1984) and from the test data generated from test series 3 of this study. The pavement section from the study by Barksdale (1984) was strong in comparison to the sections described for this study. The finite element model was capable of predicting measured variables to within +/- 20% for the strong section. For the weaker sections used in the study described as part of this work, the finite element predictions were not as good. The strain in the geosynthetic was overpredicted by about 33% when the geosynthetic was located in the bottom of the base. It was under predicted by about 14% when located in the middle of the layer. The vertical stress and vertical strain on the top of the subgrade was under predicted by about 50%. The lateral strains were also under predicted by about 50%. While these predictions could have been more accurate, the conclusion was made that the calculated relative changes in the observed

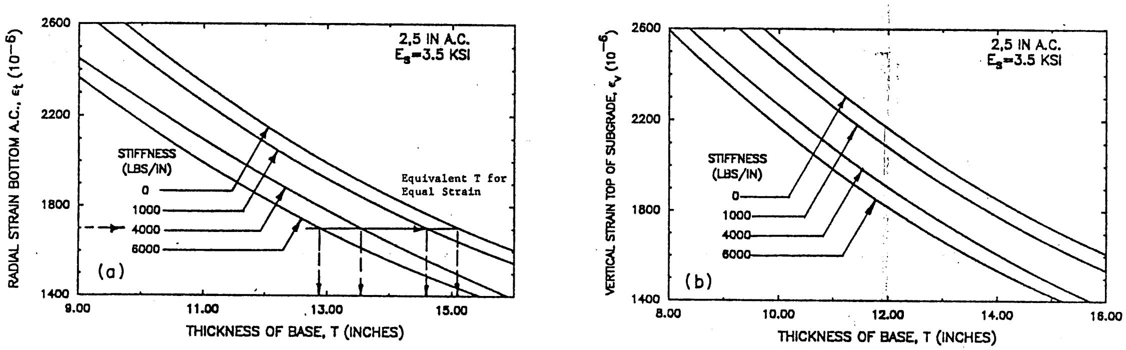

Figure 2: Equivalent base thickness for equal strain: 2.5 in. AC; Subgrade Resilient Modulus $E_s = 3.5$ ksi (Barksdale et al., 1989)

response between the three sections in test series 3 did appear to indicate correct trends. This indicates that relative comparisons should be reasonably good, thereby allowing the model to be used to perform a sensitivity (parametric) study to examine relative benefits of various pavement section configurations. It should be noted that the authors indicate that the analytical predictions of tensile strain in the bottom of the AC layer were not validated by experimental results because these results were inconsistent. Therefore, basing thickness reductions on this measure may be erroneous. The authors point out that van Grup et al. (1988) noted that an extremely stiff steel mesh reinforcement placed at the top of the base reduced tensile strains by 18%. As described below, this tensile strain measure is used to assess improvements in fatigue resistance.

In the sensitivity study the finite element model was used to calculate the lateral tensile strain at the bottom of the AC layer and the vertical strain at the top of the subgrade for a single load application. This was used for evaluations of fatigue resistance and to indicate the degree of rutting that would occur, which in turn was used to evaluate improvement in pavement performance for unreinforced and reinforced sections. Reinforcement improvement was quantified as the reduction in aggregate base thickness for a reinforced roadway giving the same tensile strain (fatigue) and vertical strain (reflecting permanent deformation) as that for the unreinforced section. As demonstrated in Figures 2- 6, the improvement is dependent on geosynthetic stiffness, section strength, subgrade strength, geosynthetic position, and to a lesser degree, the measure used for defining improvement.

To compare actual design situations, the 1972 AASHTO design method was used to determine the unreinforced base thickness for the sections noted in Figures 2- 6. These results, along with the design assumptions, are given in Table 2. The PI has taken these results and used Figures 2- 6 to determine reinforced base thicknesses based on equal radial and vertical strain (ϵ_r and ϵ_v, respectively) for the geogrid positioned at the bottom of the base layer, 1/3 up in the base and 2/3 up in the base. These results are given in Table 3. Table 4 shows the percent reduction in base thickness for the reinforced sections as compared to

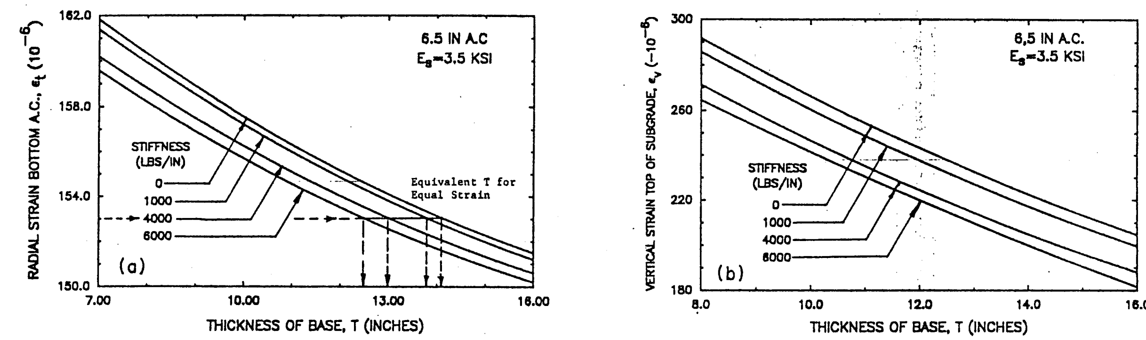

Figure 3: Equivalent base thickness for equal strain: 6.5 in. AC; Subgrade Resilient Modulus $E_s = 3.5$ ksi (Barksdale et al., 1989)

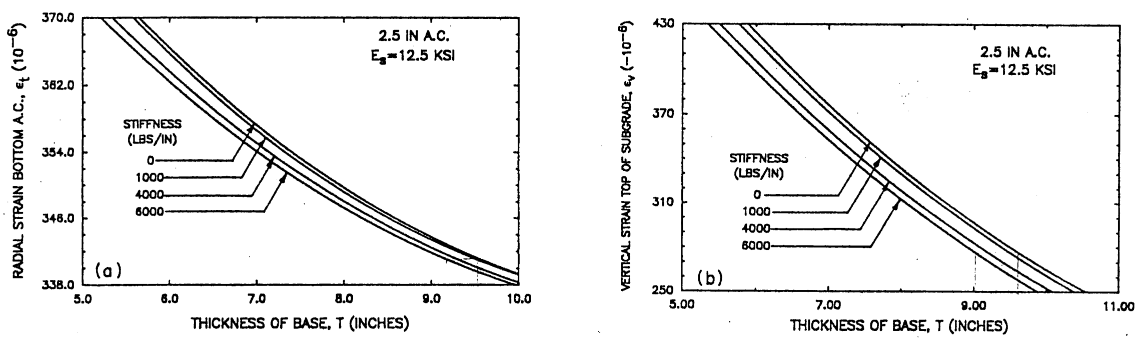

Figure 4: Equivalent base thickness for equal strain: 2.5 in. AC; Subgrade Resilient Modulus $E_s = 12.5$ ksi (Barksdale et al., 1989)

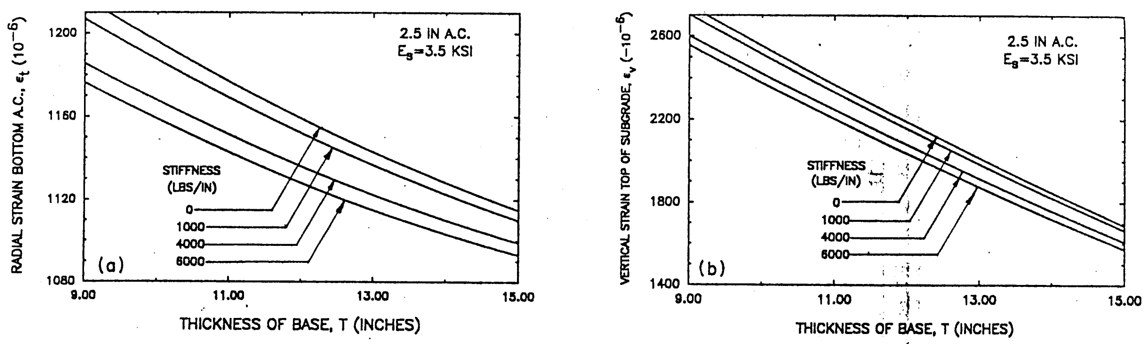

Figure 5: Equivalent base thickness for equal strain: 2.5 in. AC; Subgrade Resilient Modulus $E_s = 3.5$ ksi; geosynthetic 1/3 up in base. (Barksdale et al., 1989)

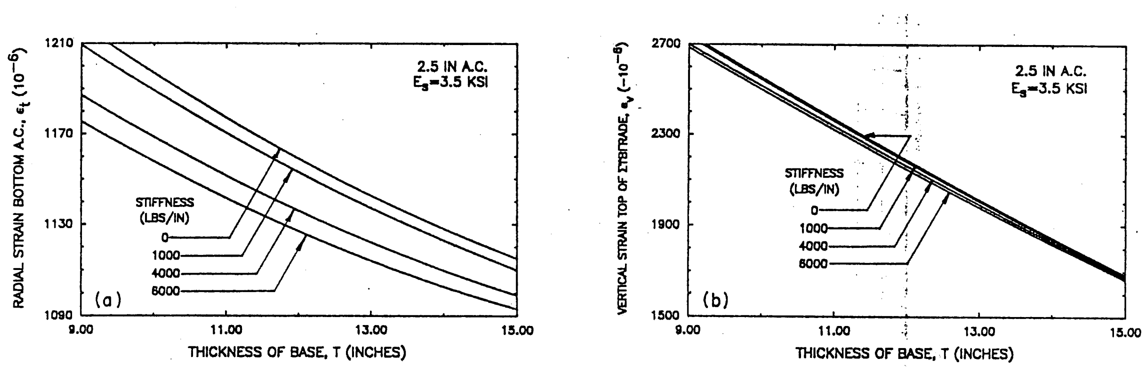

Figure 6: Equivalent base thickness for equal strain: 2.5 in. AC; Subgrade Resilient Modulus $E_s = 3.5$ ksi; geosynthetic 2/3 up in base. (Barksdale et al., 1989)

Table 2: AASHTO design for pavement sections used in sensitivity study (Barksdale et al., 1989)

SECTION	TRAFFIC LOADING(2) ($x10^3$)	SUBGRADE CBR (%)	SUBGRADE E_s (ksi)	SOIL SUPPORT, S	STRUCT. NO. (SN)	SURFACE THICKNESS, T_s (in.)	AGG. BASE THICKNESS, T_B (in.)
1	200	3	3.5	3.2		2.5	11.9
2	200	5	6.0	3.9	2.85	2.5	9.7
3	200	10	12.5	5.0	2.45	2.5	7.5
4	500	3	3.5	3.2	3.62	2.5	15.3
5	500	5	6.0	3.9	3.30	2.5	12.8
6	500	10	12.5	5.0	2.80	2.5	9.6
7	2000	3	3.5	3.2	4.55	6.5	12.4

1. Design Assumptions:

Present Serviceability Index = 2.5
Regional Factor = 1.5

Asphalt Surfacing: $a_1 = 0.44$ $T_{AC} \leq 3.5$ in.
$a_2 = 0.35$ $T_{AC} > 3.5$ in. for T in excess of 3.5 in.

Aggregate Base: $a_3 = 0.18$ $T_{AC} + T_B \leq 12$ in.
$a_4 = 0.14$ $T_{AC} + T_B > 12$ in.

2. Equivalent 18 kip, single axle loadings.

the unreinforced sections. The results from Table 3 can be plotted on the design chart commonly supplied by Tensar (1986), which has been reproduced in Figures 7 and 8 for the improvement measure corresponding to the radial strain at the bottom of the AC layer and the vertical strain on the top of the subgrade, respectively. The solid lines in these figures correspond to the design curve provided by Tensar (1986). Figures 9 and 10 show the corresponding values for percent reduction in reinforced base thickness versus the unreinforced base thickness.

From Figures 7- 10 it is apparent that the finite element study of Barksdale et al. (1989) does not show the degree of improvement given by the Tensar design charts. For unreinforced base thicknesses greater than 7.5 in., the Tensar design curve indicates a reinforced base thickness reduction of 47% to 27%, with this reduction decreasing as the base thickness increases. The finite element study indicates the opposite trend when the reinforcement is placed at the bottom of the base layer. In the finite element study, the thinner unreinforced base thicknesses tend to correspond to stronger pavement sections (i.e. either a stronger subgrade or a thicker AC layer) or to lighter traffic loads. The study indicates that reinforcement is of decreasing value when the pavement section becomes more strong. The Tensar design curve tends to indicate the opposite. For the finite element study, it is only for the reinforcement positions elevated within the base and where the improvement measure is the vertical strain that the Tensar trend is observed. It should be noted, however, that the improvement levels corresponding to these conditions are quite small. In summary, these results indicate that the assessment of the improvement of a reinforced base is dependent on the feature that is to be improved (i.e. fatigue or rutting), the placement of the grid within the layer, the strength of the various components of the pavement section and the

Table 3: Reinforced base thickness for equivalent radial strain at bottom of AC (ϵ_r) and equivalent vertical strain on top of subgrade (ϵ_v) for various geosynthetic positions within base layer

Section	Unreinforced Base Thickness (in.)	Reinforced Base Thickness (in.)					
		Geosynthetic Position					
		Bottom of Base		1/3 up in Base		2/3 up in Base	
		ϵ_r	ϵ_v	ϵ_r	ϵ_v	ϵ_r	ϵ_v
1	11.9	10	9.9	9.9	11	9.9	11.6
3	7.5	7.1	6.9				
4	15.3	13.1	12.8	13.2	14.6	13.2	15.1
5	9.6	9.2	9				
6	12.4	10.9	10.2				

Table 4: Reinforced base thickness percent reduction for equivalent radial strain at bottom of AC (ϵ_r) and equivalent vertical strain on top of subgrade (ϵ_v) for various geosynthetic positions within base layer

Section	Reinforced Base Thickness Reduction (%)					
	Geosynthetic Position					
	Bottom of Base		1/3 up in Base		2/3 up in Base	
	ϵ_r	ϵ_v	ϵ_r	ϵ_v	ϵ_r	ϵ_v
1	16.0	16.8	16.8	7.6	16.8	2.5
3	5.3	8.0				
4	14.4	16.3	13.7	4.6	13.7	1.3
5	4.2	6.2				
6	12.1	17.7				

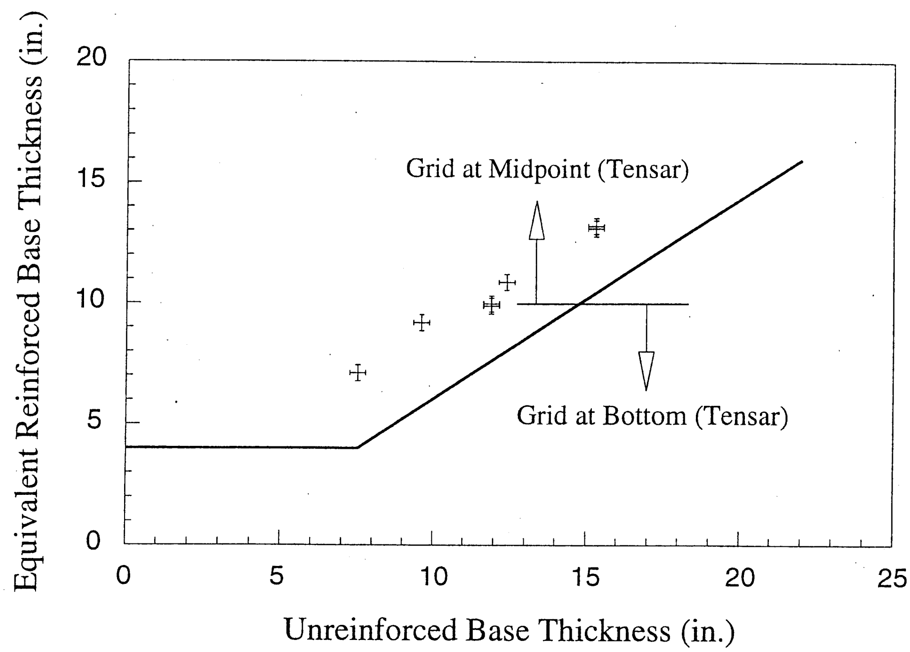

Figure 7: Equivalent reinforced base thickness based on equal radial strain at the bottom of the AC layer

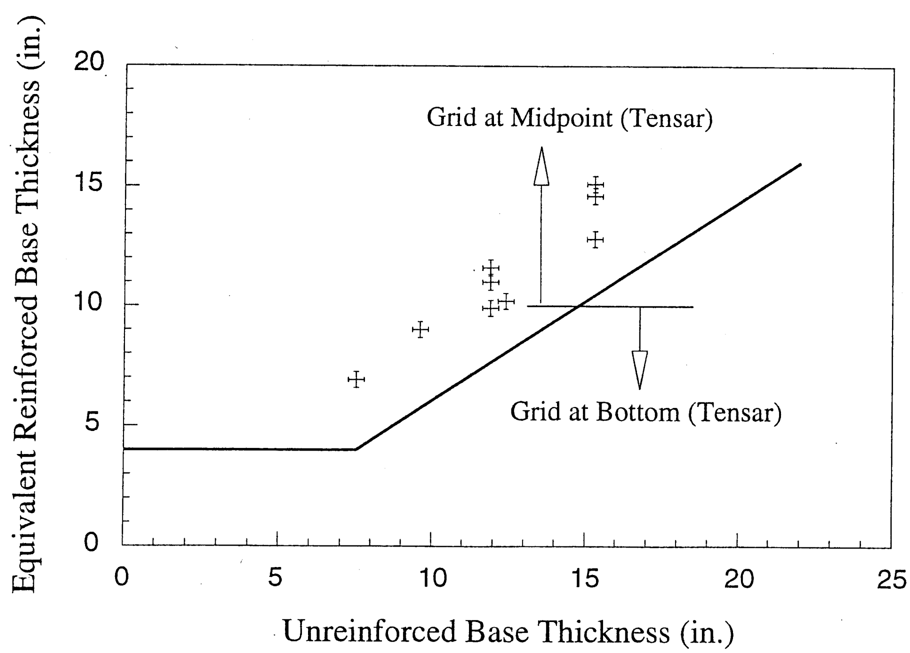

Figure 8: Equivalent reinforced base thickness based on equal vertical strain at the top of the subgrade layer

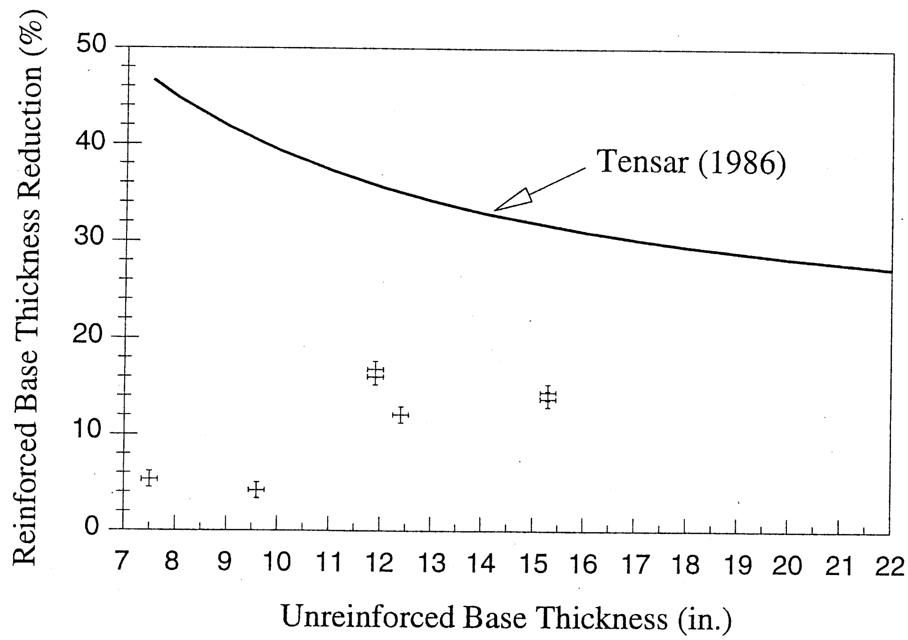

Figure 9: Reinforced base thickness reduction based on equal radial strain at the bottom of the AC layer

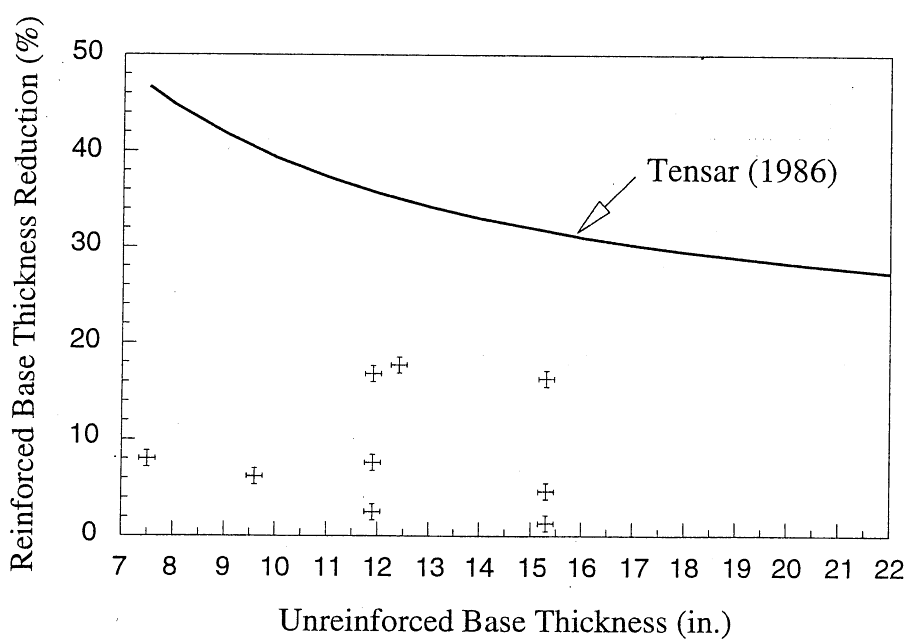

Figure 10: Reinforced base thickness reduction based on equal vertical strain at the top of the subgrade layer

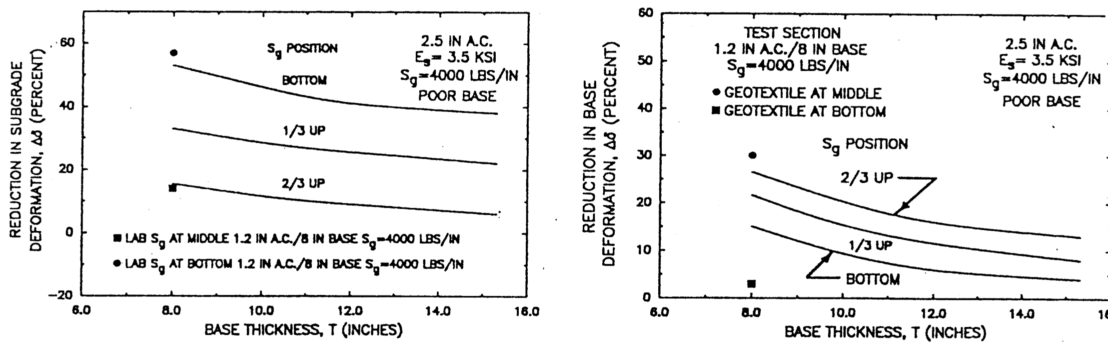

Figure 11: Reduction in subgrade and base permanent deformation

anticipated traffic loading. The authors made the general conclusion that improvement is observed only for relatively light pavement sections that are placed on weak subgrades or have low quality aggregate base. It should be noted that it was the light pavement sections that the finite element model was least capable of predicting its response.

While the vertical strain acting on top of the subgrade is an indicator of rutting, the actual rut depth must be determined from other techniques. A so-called layer strain method was used to determine actual rut depth. The sections were divided into thin layers. Within each layer, the principal axisymmetric state of stress was determined from the finite element model. A previously developed relationship for permanent vertical strain as a function of confining pressure and deviator stress (hyperbolic permanent strain model) was then used to estimate permanent strain, from which a permanent deformation for that layer was determined. It should be noted that the vertical strain at the subgrade level used in the previous figures is a resilient strain and is only an indicator of the tendency for rutting. The permanent strain was calculated from the finite element results for various pavement sections defined in Table 2 and for base material of good or poor quality. The results show that rut depth is due to permanent deformations within the base and subgrade, and that the improvement offered by the geosynthetic is dependent on the relative strength of the two layers. For a base whose strength was relatively weak in comparison to the subgrade, more improvement was observed with geosynthetic positions higher up in the base. When the subgrade was comparatively weak, more improvement was seen when the geosynthetic was placed at the bottom of the base. The results also show that as the base becomes more thick, less reduction in rut depth is observed. These results are summarized in Figure 11.

In summary, the authors claim that the analytical and experimental results show that placement of a high stiffness geosynthetic in the aggregate base of a surfaced pavement designed for more than about 200,000 equivalent 18-kip single axle loads results in relatively small changes in the resilient response of the pavement. This appears to be true for the geosynthetics of the lowest stiffnesses studied. Geosynthetic stiffness was shown to effect reinforcement improvement. Greater stiffness allows greater load transfer to the geosynthetic resulting in lower lateral strains in various sections. Geosynthetic type was shown experimentally to be important. A geotextile having a stiffness 2.5 times that of a geogrid was found to offer the same level of improvement, indicating that frictional characteristics preventing slip are more pronounced in the geogrid. Geosynthetics were found to show little improvement in the overall pavement vertical stiffness even while other measures were found to show improvement. For this reason, FWD tests were said not to be able to detect resulting improvements in pavement performance due to inclusion of a geosynthetic. Preruting was found to improve performance for both reinforced and non-reinforced sections, with the improvement level being very similar. Pretensioning of the geosynthetic also showed improvement but was pointed out that achieving this effect in the field was impractical.

The authors make several recommendations for additional research. Additional work involving the areas of prerutting a non-reinforced base, reinforcement of a poor quality base, and reinforcement of heavy sections with weak subgrades. It was suggested that full-scale field test sections be developed to study these areas.

Chan, F., Barksdale, R.D. and Brown, S.F. (1989), "Aggregate Base Reinforcement of Surfaced Pavements", *Geotextiles and Geomembranes*, V.8, pp.165-189.

A journal article description of the work performed by Barksdale et al. (1989).

Le, T.T. (1982), "The Effects of Engineering Fabric in Street Pavement On Low Bearing Capacity Soil in New Orleans", Ph.D. Thesis, Tulane University, 431p.

The thesis describes the use of various geotextile fabrics in the construction of streets in New Orleans. The fabrics were placed between the subgrade and the base, between the base and the AC layer, or between AC layers for overlays. All the applications pertained to soft clay subgrades. The performance of constructed roadways was monitored by including strain gages within the subgrade (Bison strain gages provided by E.T. Selig, 1970), moisture sensors and DYNAFLECT tests on constructed roads. The conclusion was that inclusion of fabric showed an increase in pavement strength by improving load distribution and acting as a separating membrane. No analytical modeling was performed to predict the observed behavior. Comparisons were not made to predictions from existing design procedures although the data looks sufficiently complete to allow this to be done.

Miura, N., Sakai, A., Taesiri, Y., Yamanouchi, T. and Yasuhara, K. (1990), "Polymer Grid Reinforced Pavement on Soft Clay Grounds", *Geotextiles and Geomembranes*, V.9, pp.99-123.

Experiments on laboratory model and field pavement sections and finite element method analyses were conducted to investigate pavement response with and without geogrid reinforcement. The subgrade was a very soft sensitive marine clay. In the field, this material had led to non-uniform settlement of existing roadways and severe rutting. Model tests were conducted in a concrete box 1.5m by 1.5m by 1m deep. The subgrade clay was reconsolidated into a 0.6m lift. A 0.2m subbase and a 0.15m base were compacted on top of the subgrade. Tensar grids SS1, SS2 and SS3 were used as reinforcement. The grids were placed either at the bottom of the base or subbase, or double grids were used located at the bottom of the subbase and base or at the bottom and mid-height of the base. A 5cm AC layer was used. Cyclic loads were applied through a 20cm diameter plate. The geogrids were instrumented with strain gages. Settlements of the top of each layer were monitored.

Performance was determined by measuring a modulus of subgrade reaction for reinforced and non-reinforced sections. These increased by 30% for reinforcement placed at the bottom of the subbase. Using settlement as the governing criteria, placing a single grid lower (at the bottom of the subbase) gave the smallest settlement. This grid also showed the greatest amount of strain and tensile force for points directly beneath the load, indicating that optimal grid position is such that it can develop the greatest tensile force. Also, a stiffer grid is more effective since it develops a greater tensile force for an equal strain application. For the two grid system, the smallest settlement was obtained for grids placed at the bottom of the base and subbase. To demonstrate a reinforcement effect separate from the membrane effect, a grid was placed in a convex shape such that compressive strains developed throughout the grid. Reductions in pavement settlement were still observed indicating that reinforcement is possible without the membrane effect.

Finite element analysis were performed using three element types. A truss element capable of tension only was used for the grid. A joint element, representing a discontinuous plane and having a normal and shear stiffness, was used to model the interaction between the grid and the soil. 2-d continuum (triangular) elements were used for the AC, base, subbase and subgrade. Isotropic elastic properties were used for all 2-d elements. Results from reinforced and unreinforced analyses showed little difference. This was said to be due to the FEM taking account of the membrane stretching effect only and not the interlocking effect. No information was given on who or how the model was developed.

Field tests were performed on 6 different sections. One was an unreinforced section having greater component thicknesses than the reinforced sections. Grid type and placement position were varied. Modulus of subgrade reaction was found to be less for the reinforced sections and was attributed to poor base compaction. Overall settlement of the roadway was complicated by the fact that the marine clay was underconsolidated such that continual land subsidence was occurring, as well as consolidation settlement due to placement of roadway materials. Maximum rut depth difference between the sections was as great as 2mm. No clear trend in differences due to grid placement position were observed. It was mentioned that it was difficult to place the grid in a concaved shape. Unfortunately, no strain measurements were taken in the grid. Field results were discouraging as well as inconclusive.

Penner, R., Haas, R., Walls, J. and Kennepohl, G. (1985), "Geogrid Reinforcement of Granular Bases", Paper Presented to Roads and Transportation Assoc. of Canada Annual Conf., Vancouver, September

This paper forms the basis of Tensar's (1986) equivalency charts. Cyclic circular (30 cm, 12 in. dia.) plate load tests were performed. A 40 kN load (9 kip, simulating 18 kip dual wheel loads) was applied at a loading rate of 8 Hz. 6 loops, each with 4 sections were tested. The AC thickness was 100 or 75 mm. The base thickness was 300, 250, 200, 150 or 100 mm. The geogrid was a Tensar SS1 and was placed at the bottom, middle or top of the base layer or at both the middle and the bottom of the base. The subgrade had a CBR of 8, 4, 1 or 0.5. The subgrade having a CBR of 8 and 4 consisted of a fine beach sand. The lower CBR was obtained by adding more water to the sand. To obtain a subgrade CBR of 1 and 0.5, the sand was mixed with varying amounts of peat moss.

Loops 4, 5 and 6 used a subgrade having a CBR of 1 and 0.5. The sections were sufficiently weak to allow a rut depth of 2 cm after 100-1000 load cycles. The paper indicates that improvement benefits due to geogrid reinforcement were not observed for a maximum rut depth of 2 cm. Benefits were observed, however, when the maximum rut depth was allowed to increase to 3.8 cm. It should be noted that this larger rut depth is appropriate for lower class, lower volume roads. Granular base reductions on the order of 25% were realized with the number of load cycles necessary to cause a rut depth of 3.8 cm increasing by a factor of 3. The experiments in loop 5 were designed to examine the effects of pretensioning the grid. For these experiments, the pretensioning effect was shown to have a detrimental effect on performance, which is in contrast to the study of Barksdale et al. (1989). Measurements of stress in the grid were not taken so the level to which the grid was prestressed is not known. Loop 6 was designed to examine the effect of geogrid placement where the subgrade was very soft (CBR=0.5). The geogrid was placed either in the subgrade itself (section 1), at the interface between the subgrade and the base (section 2), or at both the subgrade-base interface and at the base midheight (section 4). The unreinforced control section was section 3 which reached a rut depth of 3.8 cm in 4000 cycles. The cycles necessary for this same rut depth for sections 1, 2, and 4 was 9000, 4500, and 15,000, respectively. It is interesting to note that the conventional approach taken to reinforce a soft subgrade by placing the reinforcement directly on top of the subgrade before base is placed, corresponding to section 2, offered little improvement over the control section. The most significant improvement is observed when the grid is properly placed within the base layer, in this case being at the base layer midheight.

Test loops 1-3 were performed on more firm subgrades (CBR=4 and 8) and are the results used to develop the Tensar equivalency charts. The experiments in loop 1 were performed with a subgrade having a CBR of 8, a base thickness of 20 cm and an asphalt thickness of 10 cm. The grid was placed either at the bottom, in the middle or at the top of the base. For a rut depth of 2 cm, 200,000 load cycles were necessary for the unreinforced section while 600,000, 575,000, and 160,000 load cycles were necessary for reinforcement at the bottom, middle and top of the base, respectively. The results also indicated that approximately 10,000 load cycles were necessary before differences in deformation between the sections were observed. For loop 2, the subgrade CBR was 4, the geogrid was always placed at the bottom of the base, and the base thickness was equal to 20, 15, or 10 cm. The unreinforced section had a base thickness of 20 cm and reached a rut depth of 2 cm at 10,000 load cycles. For the reinforced sections with base thicknesses of 20, 15 and 10 cm, 30,000, 25,000 and 11,000 load cycles, respectively, were necessary to reach this same rut depth. Based on these results it is seen that an equivalent reinforced section allowed the base thickness to be reduced by 50%. It should be noted, however, that the two sections used to make this conclusion were underdesigned, reaching a rut depth of 2 cm in approximately 10,000 load cycles. Loop 3 was designed to examine thicker base sections. The paper indicated that the subgrade had lost moisture during the progress of testing making the results difficult to directly interpret. These results were used, however, to develop the equivalency charts, with higher CBR values given to the subgrades that had experienced drying.

The AASHTO Interim Guide (1981) was used as a basis for comparing results and developing the equivalency charts. The structural number (SN) of each control section was calculated assuming layer coefficients of 0.4 for the asphalt layer and 0.14 for the granular base layer. The layer coefficient for the base for the results from loop 3 was increased to 0.25 due to the drying effect mentioned earlier. The SN for loop 1-3 ranged from 2.07-3.92. The subgrade soil support value (S) was determined from the NCHRP guideline (Van Til et al., 1972) and ranged from 4.3-5.7. The values for SN and S were then used in the AASHTO nomograph to determine the total equivalent 18-kip (80 kN) single-axle load applications, which ranged from 60,000 to 10,000,000 applications. A load correction factor was calculated for each section by dividing the number of 18-kip single-axle load applications by the actual number of load applications necessary to cause failure, where failure was defined as a rut depth of 2 cm. This load correction factor was intended to account for differences in loading conditions between the experiments and actual field moving wheel loads and ranged from 17.5-4.5. The factor implies that had the laboratory section been subjected to actual field loads, a rut depth of 2 cm would have developed after a number of load applications equal to the number seen in the experiments multiplied by the load correction factor.

This load correction factor was then taken to apply to the reinforced sections within a particular test loop, even though in some cases the thicknesses of the various layers was not held constant. This implies that differences in loading conditions between the experiments and the field are the same between unreinforced and reinforced sections within a given test loop. Given the range of the load correction factor, corresponding to different pavement section strengths, it is doubtful whether this would be a valid assumption.

The load correction factor for each reinforced section was then used to calculate the 18-kip single-wheel load applications by multiplying the actual number of load applications experienced in the laboratory tests by the corresponding correction factor. From the AASHTO nomograph, a SN for that section was determined. These SN's ranged from 2.1-3.8. A structural number for the granular base alone was then calculated by subtracting the asphalt layer component from the total SN. A reinforced layer coefficient was then calculated by dividing the SN for the reinforced base by its corresponding thickness. The ratio of reinforced to unreinforced layer coefficients was calculated by using the layer coefficient for the unreinforced granular base given above. For equivalent base layer SN's the ratio of reinforced to unreinforced layer coefficients is equal to the ratio of unreinforced to reinforced base layer thickness. The ratio of reinforced to unreinforced layer coefficients was plotted against the reinforced base thickness and was shown to decrease as the reinforced base thickness approached 25 cm (Figure 12).

The results corresponding to test loops 1-6 are presented in Figure 13. It is noted that the single point used to develop the "rein. mid." line corresponds to loop 4 where the subgrade CBR was 1 and the definition of failure was a rut depth of 3.8 cm. The paper claims that it is reasonable to expect the trend of this line to continue as the reinforced base thickness increases until a layer coefficient ratio of 1 is reached. This appears to imply that moving the grid from the bottom of the base to the middle of the base as the base thickness increases will result in a similar trend as that seen for the experiments where the grid was at the bottom of the base. The study lacks experiments with larger base thicknesses to confirm this.

On Figure 13 the PI has superimposed a curve arising from the design chart provided by Tensar (1986). This chart recommends a minimum reinforced base thickness of 101 mm (4 in) and suggests that the reinforcement be placed at the bottom for reinforced base

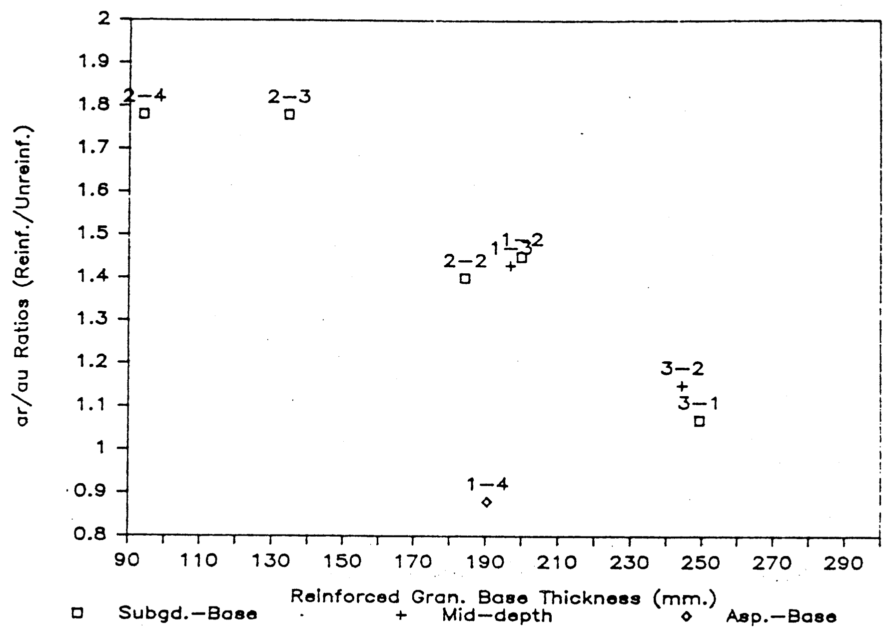

Figure 12: Reinforced to Unreinforced Layer Coefficient Ratio Versus Reinforced Base Thickness For Test Loops 1-3 (Penner et al., 1985)

thicknesses less than 254 mm (10 in) and at in the middle of the layer for larger base thicknesses. The design chart continues to a maximum reinforced base thickness of 380 mm (15 in), which extends beyond the limits of the plot by Penner et al. (1985). From this figure it is noted that the Tensar design chart suggests improvements for reinforced base thicknesses less than 254 mm which have not been demonstrated in the experiments when the grid is placed at the bottom of the base. Furthermore, the design curve suggests a near constant layer coefficient ratio for reinforced base layer thicknesses greater than 300 mm when the grid is placed in the middle of the base. The experimental results have not demonstrated this trend. The design curve could be interpreted to suggest that the grid placement should shift progressively upwards as the base thickness increases, rather than having the grid only at the bottom or the middle. The experimental results tend to suggest the validity of this interpretation but do not offer specific data upon which this may be evaluated. Furthermore, the Tensar design guide does not offer details on how the exact grid placement might be determined.

While the results of this study do indicate a potential benefit for reinforcement of roadways in practice, several problems exist which cause some concern. It is not clear whether the loading condition imposed by the stationary circular plate can be extrapolated to the actual moving load condition imposed by traffic. The study proposes a load correction factor calculated for the unreinforced sections which attempts to account for differing loading conditions, but it is unclear whether this same factor should apply to reinforced sections. The subgrades used in the study were unrealistic in comparison to subgrades encountered in practice. The free draining sand used in the study had the potential for several drawbacks. It is not clear whether the moisture condition necessary to create the lower CBR of 4 could be uniformly maintained during the progress of the experiments. It is expected that excess moisture could readily migrate downwards toward the bottom of the tank. Information on

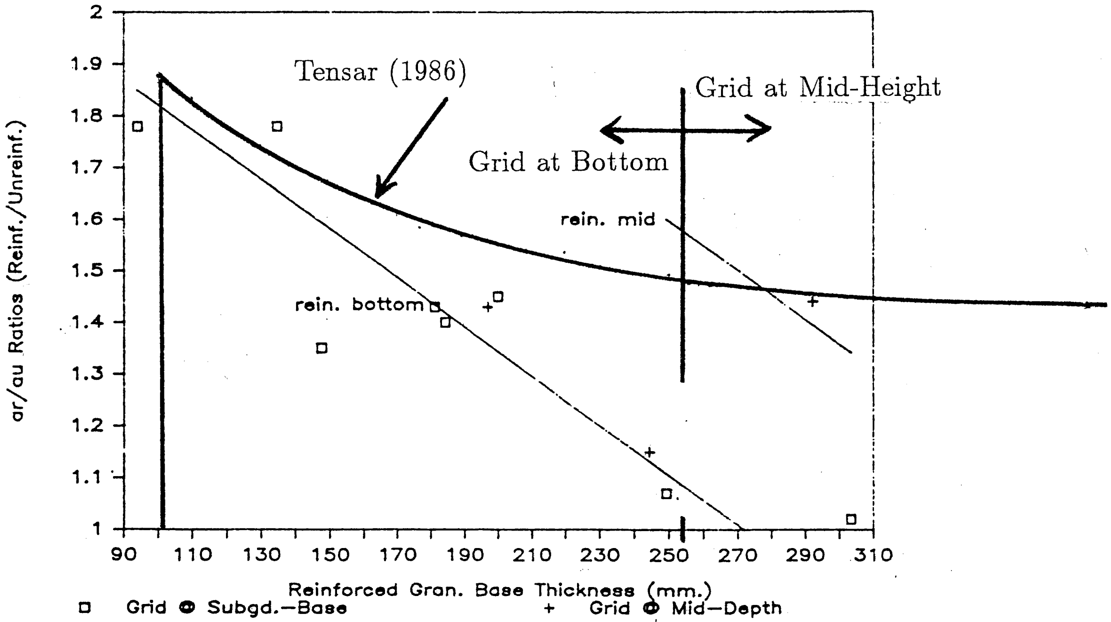

Figure 13: Reinforced to Unreinforced Layer Coefficient Ratio Versus Reinforced Base Thickness For All Test Loops (Penner et al., 1985)

degree of saturation of the sand corresponding to the target test conditions was not provided to further evaluate this problem. The free draining nature of the sand also allowed pore water pressures to dissipate during the progress of loading. Cohesive materials would behave quite differently in that pore pressures would most likely steadily build during the progress of loading causing a gradual weakening of the subgrade. The study applies only to the Tensar SS1 geogrid. Other studies (Barksdale et al., 1988, Miura et al., 1990) have shown the importance of geogrid stiffness on improvement measures. It is unclear as to what recommendations should be followed for other geogrids. The study uses only rut depth to define failure. While this may be the predominant failure mode for the relatively thin sections studied it is unclear whether these results can be extrapolated to thicker sections where fatigue cracking may be the predominant failure mode.

Webster, S.L. (1992a), "Geogrid Reinforced Base Courses For Flexible Pavements For Light Aircraft, Literature Review and Test Section Design", USAE Waterways Experiment Station, Misc. Paper GL-92-6, 24p.

The report summarizes research related to reinforcement of base layers with geogrids. Work performed to assess the reinforcement benefit of geogrids placed within railroad ballast layers has shown that in many cases benefits are realized only after large deformations which may be unacceptable for in-service conditions. There are no laboratory tests or field experience which supports the reduction of the ballast or subballast thickness by the use of a geogrid in the granular layer. Other studies reviewed in this report were also discussed. Based on the literature review, test sections were designed to evaluate the benefit of geogrid reinforced base layers for use in airport pavements for light aircraft. These designs are discussed in the review of the study by Webster (1992b).

Table 5: Calculations of Unreinforced Base Thickness Corresponding to Reinforced Base Experiments From Webster (1992b)

Lane-Item	AC Thick. (in)	Base Thick. (in)	Grid	Subgrade CBR	S	# Appl. Loads	# Design Loads	Load Corr. Factor	Total SN	SN_{gr}	H_{bu} (in)
1-1	2	10	NR	8	5.7	15,000	350,000	23	2.2	1.4	10
1-2	2	10	Bot	8	5.7	100,000	2,300,000	23	3	2.2	15.7
1-3	2	6	Bot	8	5.7	15,000	1,560,000	104	2.8	2	14.3
1-4	2	6	NR	8	5.7	670	70,000	104	1.64	0.84	6
2-1	2	18	NR	3	3.8	1131	800,000	707	3.32	2.52	18
2-2	2	18	Bot	3	3.8	1432	1,012,000	707	3.52	2.72	19.4
2-3	2	12	Bot	3	3.8	282	470,000	1667	3.05	2.25	16.1
2-4	2	12	NR	3	3.8	90	150,000	1667	2.48	1.68	12
3-1	2	14	GB-3022	3	3.8	170	400,000	2358	3	2.2	15.7
3-2	2	14	SS2 Mid	3	3.8	250	590,000	2358	3.15	2.35	16.8
3-3	2	14	SS2 Bot	3	3.8	500	1,180,000	2358	3.6	2.8	20
3-4	2	14	SS1 Bot	3	3.8	285	672,000	2358	3.25	2.45	17.5
4-1	2	14	Grid X	3	3.8	100	250,000	2358	2.76	1.96	14
4-2	2	14	Miragrid	3	3.8	97	229,000	2358	2.75	1.95	13.9
4-3	2	14	Fortrac	3	3.8	117	276,000	2358	2.77	1.97	14.1
4-4	2	14	NR	3	3.8	106	250,000	2358	2.76	1.96	14

Webster, S.L. (1992b), "Geogrid Reinforced Base Courses For Flexible Pavements For Light Aircraft, Test Section Construction, Behavior Under Traffic, Laboratory Tests, and Design Criteria", DOT/FAA/RD-92/25, U.S. Dept. of Trans., Federal Aviation Admin., Washington, D.C.

This study consists of the design, construction and testing of reinforced and non reinforced flexible pavements designed for use in airports for light aircraft. Variables in the study included subgrade strength, base thickness, geogrid stiffness, geogrid type and position of grid. Traffic passes consisted of distributed type passes and channelized passes. The subgrade consisted of a highly plastic clay (LL=67, PI=45). CBR strengths of 3 and 8 were created by compacting the clay at different water contents. The base course material was a crushed limestone that was of marginal quality due to the amount of fines contained in the material. The AC layer was kept at a constant thickness of 2 in. The test sections were constructed in a covered hanger. The test sections were instrumented with multi-depth deflectometers which allow for deflections of the sections to be determined at various depths.

Traffic was applied by a single wheel delivering a 30 kip load over a tire width of 17.25 in. Failure of the test sections was defined as a rut depth of 1 in. while traffic was typically applied until a rut depth of 3 in. was observed. Rut depth was defined as the maximum vertical elevation difference across the pavement along a line perpendicular to the direction of traffic. The various pavement sections included in the experimental program are given in Table 5. The data in this table follows the format of that given by Penner et al. (1985). The grid used for test lanes 1 and 2 was a Tensar SS2 geogrid. Geogrids from other manufacturers were used in lanes 3 and 4. With the exception of lane-item 3-2, all grids were placed at the bottom of the base layer. The PI has calculated the unreinforced base thickness corresponding to each reinforced base experiment following the same approach taken by Penner et al. (1985). These results are given in Table 5. It should be noted that the load correction factors are quite high and should be used with caution.

The results from Table 5 have been plotted on the design chart due to Tensar (Figure 14). It should be noted that the experimental point giving an improvement greater than that

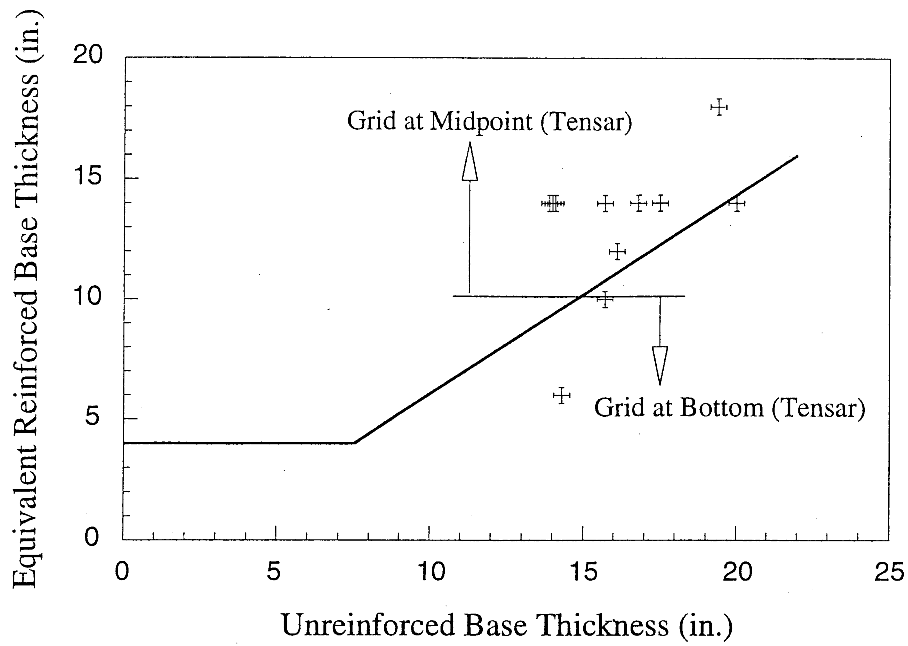

Figure 14: Reinforced to Unreinforced Base Thickness From The Experiments of Webser (1992b)

predicted by the Tensar curve was based on extrapolating the number of design loads from 10,000 to 15,000 to reach a rut depth of 1 in. since the test was stopped at 10,000 load cycles before this rut depth was reached. The 7 points at a reinforced base thickness of 14 in. correspond to the use of various geogrids and grid placement. These results show that the grid stiffer grid (SS2 in comparison to SS1) provides greater improvement. For this base thickness, greater benefits were observed by placing the grid at the bottom of the base. The grids from the other manufacturers performed worse than the Tensar grids. An attempt was made to relate performance to particular grid properties. Some success was achieved by relating performance to the "Grid Aperture Stability by In-Plane Rotation", which was a draft index test at the time of the report. The experimental point corresponding to the 18 in. base would have most likely been closer to the Tensar design curve if the grid had been placed more towards the center of the base. On the whole, these results appear to validate the Tensar design curve. Nondestructive tests were performed on each traffic lane before traffic was applied with the Dynaflect model 8000 falling weight deflectometer. No noticeable difference in impulse stiffness moduli were observed between reinforced and non reinforced sections. The FWD equipment, however, was not able to detect a difference in moduli between the 10 in. and 6 in. sections from lane 1 with a subgrade CBR of 8. For the sections with a subgrade CBR of 3 differences in moduli were observed for differences due to base course thickness.

Yarger, T.L., Harrison, F.E. Jr. and Mayberry, E.W. (1991), "Geogrid Reinforcement and Stabilization of a Highway Subgrade", *Geosynthetics '91 Conference*, Atlanta, GA, V.2, pp.673-689.

A case study is presented which describes the use of a geogrid to reduce the amount of sub-excavation and amount of granular soil backfill for a paved roadway crossing an area of silty organic subgrade soils outside Bozemán, Montana. The conventional approach of sub-excavation would have required the removal of 36 in. of the native subgrade and replacement with 36 in. of AASHTO A-1-b imported granular fill. A combination of geotextile and geogrid was used to reduce the sub-excavation and replacement thickness to 30 in. No instrumentation was included to monitor the roadway. The roadway appears to be performing well.

Unpaved Roads

Bauer, G.E. and Mowafy, Y. M. (1988), "The Interactions Mechanism of Granular Soils With Geogrids", *Proc. Int. Conf. Numerical Methods in Geomechanics*, Ed., Swoboda, Balkema, Rotterdam, pp.1263-1272.

An experimental and analytical study were performed to examine the mechanism associated with the interaction of soil and geogrids during pull-out operations. The study impacts roadway studies for cases where the shear interaction between various geosynthetics and the soil must be described. The study attempted to separate the mechanisms of interlock and surface friction between the grid and the soil. In general, the mechanism of interlock accounted for as much as 85-95% of the pull-out resistance. The size of the grid opening and the average size of the soil particles as well as the soil gradation effect pull-out resistance. It was found that the best interlock was achieved when the maximum grain size of the soil was less than 1/3 the grid mesh opening.

Finite element analyses were performed to predict the experimental results. The hyperbolic model of Duncan was used for the soil. Membrane elements were used for the geogrid. So-called bond springs were used to model the relative slip between the reinforcement and the soil. Spring stiffness was taken as a constant and was used as an input parameter. The choice of a stiffness value was arbitrary and was shown to greatly impact the results.

Burd, H.J. and Brocklehurst, C.J. (1992), "Parametric Studies of a Soil Reinforcement Problem Using Finite Element Analysis", *Computer Methods and Advances in Geomechanics*, Beer, Booker and Carter, eds., Balkema, Rotterdam, pp.1783-1788.

A finite element model representing an improvement of the model developed by Burd and Houlsby (1986) is described. The model was improved by including interface elements to model the interaction between the geosynthetic and the soil, thereby modeling various degrees of slip, or roughness, corresponding to different geosynthetic types. A parametric study showed that large increases in geosynthetic stiffness were necessary to generate a noticeable improvement in performance. It was noted that this level of stiffness may be impractical for common geosynthetics used in practice.

Burd, H.J. and Houlsby, G.T. (1986), "A Large Strain Finite Element Formulation For One Dimensional Membrane Elements", *Computers and Geotechnics*, V.2, pp.3-22

The article discusses the development of a finite element model which includes elements that can be used to model geosynthetic inclusions. The model was developed for the purpose of examining the experimental results of reinforced unpaved roads, but could be extended to include material elements representing an asphalt layer. A large strain formulation was included to account for the extensive rutting that can take place in unpaved roads. This was accomplished by including a modified material stiffness matrix. The point was made that this modification could be easily incorporated into any existing code. Since a large degree of rutting is not tolerable in paved roads this additional feature may not be necessary.

The present model used a simple Von Mises elastic-perfectly plastic model for the subgrade and base material. The geosynthetic was modeled as an isotropic elastic material. The finite element model was used to predict the response of a rigid footing placed on a base material over top a kaolin subgrade with reinforcement between the base and subgrade. The finite element analyses predicted improvement in the amount of settlement for the reinforced sections and overpredicted the ultimate strength of the footing.

Giroud, J.P., Ah-Line, C. and Bonaparte, R. (1985), "Design of Unpaved Roads and Trafficked Areas With Geogrids", *Proc. Conf. Polymer Grid Reinforcement*, Sponsored by Science and Engineering Research Council and Nelton, Ltd., Thomas Telford Ltd., London, pp.116-127.

The paper describes the initial development of a design method for geogrid reinforced unpaved structures. The geogrid reinforcement is within the base layer or at the subgrade-base layer interface for unpaved roads consisting only of a base layer. The authors claim that design methods for geotextile reinforced applications are not suitable because they do not account for the mechanism of interlocking between the grid and soil. The authors also warn that the suggested approaches developed for unpaved roads are not suitable for paved situations due to the fact that tolerable deformations in unpaved roads are much greater, therefore the mechanisms of failure are different. The paper reviews the mechanisms through which geogrids can improve the performance of an unpaved structure.

The optimum depth of reinforcement for a 30 cm wide dual wheel load is 10 to 20 cm below grade. The suggested design method first proportions the wheel load seen for trucks. The base layer is assumed to have a CBR of 80. The subgrade soil is said to be described by its undrained cohesion, which can be correlated to CBR. A secant tensile stiffness is used to describe the geogrid. Frictional properties between the geogrid and the base soil are assumed to be the same as that between base and base material. The design method is largely empirical and consists of determining an unreinforced base layer thickness depending on the number of traffic passes and the strength of the subgrade soil from a design chart. This chart assumes a certain load associated with each pass. The geogrid type is then used to determine the reinforced base thickness reduction ratio. This ratio is as great as 0.75 for applications where the unreinforced base thickness is large (greater than 1 m) corresponding to situations where the subgrade strength is low and the number of traffic passes is large. The ratio is as small as 0.4 for situations where the unreinforced base thickness is relatively small (less than approximately 0.5 m) corresponding to strong subgrades and/or low traffic passes.

Kazarnovsky, V.D. et al. (1989), "The Use of Geotextile in Road Building On Soft Soils", *12th Int. Conf. Soil Mechanics and Foundation Engineering*, Rio de Janeiro, pp.1725-1729.

The paper discusses applications in the USSR. Reference is given to an elasticity based analytical model used to evaluate sites where monitoring has taken place, but no details of the model are given. The paper is very general and provides little in the way of English language references from which more information could be obtained.

Milligan, G.W.E., Fannin, R.J. and Farrar, D.M. (1986), "Model and Full-Scale Tests on Granular Layers Reinforced With A Geogrid", *Proc. 3rd Int. Conf. on Geotextiles*, Vienna, Vol.1, pp.61-66.

A Tensar SS2 geogrid was used to reinforce a granular layer over a weak subgrade in a series of laboratory experiments. A rectangular footing with a length to width ratio of 5 and a circular footing were loaded monotonically and cyclically. A crushed limestone base having a thickness ranging from 15 to 38 cm was placed atop a subgrade having an undrained cohesion ranging from 8 to 33 kPa.

For the rectangular footings with the base thickness equal to 38 cm and for all subgrade strengths very little difference between the reinforced and unreinforced sections was observed. For a base thickness of 20 cm and with the strong subgrade a marked difference in ultimate strength was observed for the reinforced section. This difference was less appreciable for the weak subgrade with permanent deformation being greater for the reinforced section.

For the circular footings little difference between reinforced and unreinforced sections was observed when the subgrade was weak. This was said to be due to the intrusion of the soft subgrade into the base material. For the stronger subgrade the stiffness and ultimate strength was slightly greater when the base thickness was not large. Experiments were not performed where the grid was placed at different levels. These results were used in the finite element analyses of Burd and Houlsby (1986) and Burd and Brocklehurst (1992).

Valsangkar, A.J. and Holm, T.A. (1993), "Cyclic Plate Load Tests on Lightweight Aggregate Beds", Transportation Research Board, Transportation Research Record 1422, pp.14-17.

Laboratory plate loading tests were performed to examine the benefits of using a Tensar SR-1 geogrid used to reinforce an expanded shale lightweight aggregate. The aggregate was placed loose in a test tank and then compacted to a dense state. The final thickness of the aggregate was approximately 90 cm. A circular steel plate 30 cm in diameter was used to apply a cyclic load. It is noted that the PI has conducted monotonic loading experiments on continuous footings resting on a highly angular silty sand and shown that the depth of soil beneath the footing base necessary to avoid boundary effects from the container bottom is approximately 8 times the footing width. The experiments reported in this paper have a soil depth of 3 times the footing width.

The geogrid was placed at depths of 15 and 20 cm below grade. Previous research had shown that grid placement depth had to be less than the footing width in order for improvement to be significant. The experiments showed that inclusion of the geogrid increased the maximum load necessary to cause 12mm of settlement by a factor of 2.2, with no difference being observed between the two grid placement positions. The vertical subgrade reaction increased 3-fold. Grid placement was shown to have some effect on cumulative settlement for cyclic loads, with the lower grid placement giving greater settlement. The density and friction angle of the aggregate was given.

White, D.W. (1991), "Literature Review on Geotextiles to Improve Pavements For General Aviation Airports", USAE Waterways Experiment Station, Misc. Paper GL-91-3, 48p.

This report summarizes previously unpublished data from tests on unsurfaced roads performed by Webster. A poorly graded sand subgrade was covered by 4 in. of crushed aggregate. The unsurfaced road section was loaded with full-scale equipment consisting of a 5-ton military truck and a C-130 aircraft. For the truck traffic, the unreinforced control section reached a rut depth of 2 in. in 2600 passes while it took 5200 passes for a geogrid reinforced section and far fewer than 2600 passes for the geotextile reinforced section. For the C-130 loading, the reinforced sections behaved more poorly than the unreinforced section. This appears to indicate that the load magnitude, which controls the level of shearing in the subgrade, is critical when assessing improvement due to reinforcement.

Upon review of existing design procedures for geotextiles it was stated that the general agreement is that geotextile's main function is to provide separation between the aggregate base and the subgrade. This benefit is observed only when the subgrade is weak (CBR¡3) and prevents loss of the aggregate layer during the initial placement of the aggregate. The geotextile is not considered to offer any structural support.

EVALUATION OF COMMERCIAL FINITE ELEMENT MODELS

An analytical model used to predict the performance of a pavement structure should ideally be capable of predicting the non-linear elastic-plastic response of the various pavement section components. The constitutive models used for the various pavement sections should be capable of registering accumulative permanent deformations with increasing load cycles, while the model used for the subgrade, and possibly for the aggregate base material, should be formulated in terms of effective stresses and be capable of determining the generation and corresponding dissipation of pore water pressures with increasing load cycles. The finite element model would require a special element type for the geosynthetic. A membrane element which can carry tensile loads but has no flexural rigidity would most likely be the appropriate element type. Interface elements should also be used to model the frictional and slip characteristics between the geosynthetic and the surrounding soil. Ideally, the finite element model should be formulated for large strains such that situations corresponding to large surface rutting could be modeled. Based on a review of commercially available finite element models it appears that no model is capable of accounting for all the desirable features described above. Presented below is a brief summary of the features that can be accounted for by various finite element models.

The model GAPPS7, developed at Georgia Tech and used by Barksdale et al. (1989), used an isotropic elastic material model for the AC and subgrade material and a cross-anisotropic model for the aggregate base. A membrane element was used for the geosynthetic where a unique stress-strain relationship could be specified. The model was formulated for large strain, although it was felt that this feature was not fully utilized for the loads imposed.

The model could not predict permanent deformations and was not capable of modeling the influence of pore water pressures on the strength of the subgrade. This model has not been converted to a personal computer format and has not been used for several years.

The commercial program ANSYS is currently installed on the Civil Engineering Computer Network at MSU. The model contains membrane and interface elements. The membrane elements are used only for linear elastic materials. Other constitutive models include an elastic-perfectly plastic model where the plasticity formulation follows the Drucker-Prager criterion. This type of material model is capable of showing permanent deformations only after the ultimate strength of the material is reached. The material elements within pavement sections operating under normal conditions will most likely not experience stress levels corresponding to the perfectly plastic state. This implies that such a material model would then be incapable of predicting permanent strains.

The commercial program SIGMA/W has been developed specifically for geotechnical engineering problems. The program incorporates several different constitutive models for different soil types. An elastic-perfectly plastic model incorporating the Mohr-Coulomb failure criterion is available. This model will predict permanent deformations only when the failure state of an element has been reached. An elastic-perfectly plastic model that allows for strain softening can be used but only within the context of an undrained analysis where the undrained friction angle is zero. A full elastic-plastic model is available within the context of the Cam-Clay critical state theory. This model is most suited for normally consolidated to lightly overconsolidated clays and can operate in terms of total or effective stresses. This model would most likely work well for cohesive subgrades during wet seasons. Pore water pressure generation models are also available for undrained effective stress analyses. In addition, isotropic linear-elastic, anisotropic linear-elastic and nonlinear-elastic models are available and could be used for the AC material. Interface slip-surface elements are available to model the interaction between the geosynthetic and the soil. These elements are linear-elastic and would not be capable of showing permanent slip.

Like ANSYS, ABACUS is a large multi-purpose finite element code. ANSYS was developed primarily as a package for aircraft and aerospace engineering while ABACUS appears to be more appropriate for soils applications. The reason for this is that ABACUS contains more sophisticated plasticity-based constitutive models. Work performed at the Waterways Experiment Station (Don Smith, Personal Communication) has indicated that ABACUS is capable of predicting the performance of non-reinforced pavement sections reasonably well. This level of success indicates that ABACUS may be one of the more suitable models to explore. ABACUS is not currently available within the College of Engineering. The program can be purchased at an academic rate of approximately $1700/year. The academic package does not include any user support.

The SHRP SUPERPAVE program has developed a multi-module finite element code specifically for analyzing pavement sections. Conversations with personnel at the Texas Transportation Institute indicate that while the program does not specifically include element types for geogrids, other features may be utilized to model this behavior. The PI is obtaining further information on this program.

A program specifically for reinforced earth applications has been developed at a Japanese university and is currently being explored at the University of Colorado at Denver. Several attempts were made to contact the person in charge of this project. Since these calls were not returned no further information on the program is available.

SYNOPSIS OF FINDINGS

The studies examined and summarized in the preceding sections have shown that the inclusion of a geogrid in a pavement section, typically within the aggregate base layer, can have either a positive or a neutral influence on pavement performance. Positive improvements have been both demonstrated in the laboratory using stationary, cyclically loaded circular plates (Penner et al., 1985) and in large scale moving wheel load facilities (Webster, 1992b). The subgrades used in the laboratory study were limited to either a free-draining sand or this same sand mixed with peat moss. This study also generated information for a single geogrid while other studies have demonstrated the importance of geogrid stiffness on the level of performance improvement. The full-scale experiments used more realistic subgrades and relatively heavy loads.

Both studies used rut depth to define pavement failure where the rut depth at failure for the laboratory study was either 0.8 in. or 1.5 in. and 1 in. for the full-scale experiments. While this may be the predominant failure mode for relatively thin sections it is unclear whether these results can be extrapolated to thicker sections where fatigue cracking may be the predominant failure mode.

To generate a design diagram from the experimental results, the study of Penner et al. (1985) applied a load correction factor to the number of cycles necessary to cause failure for the laboratory sections. This load correction factor was intended to account for differences in loading conditions between the experiments and actual field moving wheel loads and ranged from 17.5-4.5. The factor implies that had the laboratory section been subjected to actual field loads, a rut depth of 2 cm would have developed after a number of load applications equal to the number seen in the experiments multiplied by the load correction factor. This load correction factor was then taken to apply to the reinforced section with the closest matching layer thicknesses. Applying this same approach to the full-scale experiments resulted in load correction factors ranging from 23-2358. This approach implies that differences in loading conditions between the experiments and the field are the same between unreinforced and reinforced sections. Given the range of the load correction factor, corresponding to different pavement section strengths, it is doubtful whether this would be a valid assumption.

The studies of Barksdale et al. (1989) and Al-Qadi et al. (1994) have tended to show less significant improvement levels. The experimental component of the Barksdale et al. (1989) study suggested that significant reductions in rut depth may be due more to the prerutting construction operation rather than a reinforcing function of the grid. The analytical modeling tended to not show the same improvement levels as that seen in currently available design methods. The grid stiffness was also seen to be a significant variable. Al-Qadi et al. (1994) showed that geotextiles might be as effective if not more effective than a geogrid, suggesting that the separation function may contribute more performance improvement than reinforcement.

Field studies have been limited to cases where only the surface features of the pavement have been evaluated with no internal instrumentation installed to monitor and compare conditions existing within the pavement sections (Anderson and Killeavy, 1989 and Yarger et al., 1991).

The Tensar Corporation has indicated that moving wheel load experiments are currently being conducted at the University of Alaska, Fairbanks. Results are not available at this point in time. Amad Al-Qadi at Virginia Polytechnic Institute and State University is currently engaged in a project with the Virginia Department of Transportation and a geotextile manufacturer to study the performance improvement mechanisms of geotextiles. The work performed in the laboratory (Al-Qadi et al., 1994) has been extended by constructing instrumented full-scale, in-field test sections. This work is in progress with major results not being available at the time this proposal was prepared.

A review of existing finite element codes indicates that no single code is capable of modeling all the features thought to be important for pavement performance. It appears that the commercial program ABACUS may be the most suited for use in this study due to its success at the Waterways Experiment Station. The SHRP SUPERPAVE program should be given further consideration.

RECOMMENDATIONS FOR ADDITIONAL RESEARCH

The current literature shows conflicting results pertaining to the level of improvement that is realized by inclusion of a geogrid in the base course layer of a pavement section. While additional laboratory and analytical studies may aid in resolving these conflicts it is concluded that the prudent and most productive approach at this point is to construct well-instrumented, full-scale field sections. Results from these sections can be used to examine mechanisms associated with geogrid reinforcement, evaluate improvement levels for variations in parameters that have been shown to influence performance, evaluate current design methods and to provide data to which finite element models can be compared.

Previous studies have identified several variables and construction procedures that show promise for improving the performance of paved roadways. Pre-rutting the aggregate base course layer prior to leveling and placement of the AC layer has been shown to lead to a reduction in rut depth during the life of the pavement. Placement position of the grid within the height of the base and the geogrid stiffness is also important. Certain studies have suggested that geogrids might offer more benefit for poor quality base materials. Recent research has indicated that geotextiles may offer greater improvement levels than that observed for geogrids. Various sites with differing subgrade conditions should be used. It is recommended that full-scale sections be designed and constructed to examine the influence of variations in these parameters.

The test sections should be instrumented to allow comparison of performance variables other than only surface rut depth and to allow for comparison of finite element model predictions to the measured responses. Instrumentation should be installed to measure the following parameters.

1. Surface profile perpendicular to the direction of traffic.
2. Permanent and elastic vertical strain in each pavement section layer.
3. Lateral tensile strain in the bottom of the AC and aggregate base layers.
4. Vertical stress on the top of the subgrade.
5. Lateral stress within the aggregate base.
6. Strain in the geogrid reinforcement.
7. Temperature in the various pavement sections.
8. Moisture content in the aggregate base and subgrade.
9. Pore water pressure in the subgrade.

Mix design characteristics of the asphalt concrete surfacing used for the test sections should be determined. The resilient and permanent deformation characteristics of the low and high quality aggregate base and of the subgrade material should be assessed. The in situ moisture content and shear strength of the subgrade soil should also be determined. A laboratory testing program should be conducted to determine the degradation of the undrained shear strength with increasing water content. Finally, the strength and deformation characteristics of the geogrids and geotextiles used should be determined from the wide width tension test as well as interlocking friction characteristics from direct shear tests.

REFERENCES

Al-Qadi, I.L., Brandon, T.L., Valentine, R.J., Lacina, B.A. and Smith, T.E. (1994), "Laboratory Evaluation of Geosynthetic Reinforced Pavement Sections", Transportation Research Board Preprint, Paper No. 94-0479, 73rd Annual Meeting, Washington DC.

American Association of State Highway and Transportation Officials (1981), "AASHTO Interim Guide for Design of Pavement Structures".

Anderson, P. and Killeavy, M. (1989), "Geotextiles and Geogrids: Cost Effective Alternate Materials for Pavement Design and Construction", *Geosynthetics '89 Conference*, San Diego, pp.353-360.

Barker, W.R. (1987), "Open-Graded Bases for Airfield Pavements", USAE Waterways Experiment Station, Misc. Paper GL-87-16.

Barksdale, R.D. (1984), "Crushed Stone Base Performance", Transportation Research Borad, Transportation Research Record 954, pp.78-87.

Barksdale, R.D., Brown, S.F. and Chan, F. (1989), "Potential Benefits of Geosynthetics in Flexible Pavement Systems", *National Cooperative Highway Research Program Report No. 315*, Transportation Research Board, National Research Council, Washington DC, 56p.

Barksdale, R.D., Brown, S.F. and Chan, F. (1989), "Potential Benefits of Geosynthetics in Flexible Pavement Systems, Supplement To NCHRP Report No. 315", *National Cooperative Highway Research Program Supplement to Report No. 315*, Transportation Research Board, National Research Council, Washington DC, 150p.

Bauer, G.E. and Mowafy, Y. M. (1988), "The Interactions Mechanism of Granular Soils With Geogrids", *Proc. Int. Conf. Numerical Methods in Geomechanics*, Ed., Swoboda, Balkema, Rotterdam, pp.1263-1272.

Burd, H.J. and Brocklehurst, C.J. (1992), "Parametric Studies of a Soil Reinforcement Problem Using Finite Element Analysis", *Computer Methods and Advances in Geomechanics*, Beer, Booker and Carter, eds., Balkema, Rotterdam, pp.1783-1788.

Burd, H.J. and Houlsby, G.T. (1986), "A Large Strain Finite Element Formulation For One Dimensional Membrane Elements", *Computers and Geotechnics*, V.2, pp.3-22

Chan, F., Barksdale, R.D. and Brown, S.F. (1989), "Aggregate Base Reinforcement of Surfaced Pavements", *Geotextiles and Geomembranes*, V.8, pp.165-189.

Giroud, J.P., Ah-Line, C. and Bonaparte, R. (1985), "Design of Unpaved Roads and Trafficked Areas With Geogrids", *Proc. Conf. Polymer Grid Reinforcement*, Sponsored by Science and Engineering Research Council and Nelton, Ltd., Thomas Telford Ltd., London, pp.116-127.

Haas, R.G. (1984), "Structural Behavior of Tensar Reinforced Pavements and Some Field Applications", *Proc. Symp. Polymer Grid Reinforcement in Civil Engineering*, Institution of Civil Engineers, London.

Kazarnovsky, V.D. et al. (1989), "The Use of Geotextile in Road Building On Soft Soils", *12th Int. Conf. Soil Mechanics and Foundation Engineering*, Rio de Janeiro, pp.1725-1729.

Kennepohl, G., Kamel, N., Walls, J. and Haas, R. (1985), "Geogrid Reinforcement of Flexible Pavement: Design Bases and Field Trials", Paper Presented to the Assoc. of Asphalt Paving Technologists, San Antonio, Texas, February.

Le, T.T. (1982), "The Effects of Engineering Fabric in Street Pavement On Low Bearing Capacity Soil in New Orleans", Ph.D. Thesis, Tulane University, 431p.

Milligan, G.W.E., Fannin, R.J. and Farrar, D.M. (1986), "Model and Full-Scale Tests on Granular Layers Reinforced With A Geogrid", *Proc. 3rd Int. Conf. on Geotextiles*, Vienna, Vol.1, pp.61-66.

Miura, N., Sakai, A., Taesiri, Y., Yamanouchi, T. and Yasuhara, K. (1990), "Polymer Grid Reinforced Pavement on Soft Clay Grounds", *Geotextiles and Geomembranes*, V.9, pp.99-123.

Penner, R., Haas, R., Walls, J. and Kennepohl, G. (1985), "Geogrid Reinforcement of Granular Bases", Paper Presented to Roads and Transportation Assoc. of Canada Annual Conf., Vancouver, September

Tensar Corporation (1986), "Granular Base Reinforcement of Flexible Pavements Using Tensar Geogrids, Tensar Tech. Note TTN:BR1, March, Morrow, Georgia, 21p.

Tensar Corporation (1987), "Design Guideline for Flexible Pavements With Tensar Geogrid Reinforced Bases, Tensar Tech. Note TTN:BR2, March, Morrow, Georgia, 28p.

Valsangkar, A.J. and Holm, T.A. (1993), "Cyclic Plate Load Tests on Lightweight Aggregate Beds", Transportation Research Board, Transportation Research Record 1422, pp.14-17.

Van Til et al. (1972), "Evaluation of AASHTO Interim Guide for Design of Pavement Structures", NCHRP Reoprt 128, Highway Research Board.

van Grup, Christ, A.P.M. and van Hulst, R.L.M. (1988), "Reinforcement at Asphalt-Granular Base Interface", *Geotextiles and Geomembranes.*

Walls, J., Penner, R., and Haas, R. (1985), "Final Report on Tensar Reinforced Granular Bases", Report to the Tensar Corp., University of Waterloo, January.

Webster, S.L. (1992a), "Geogrid Reinforced Base Courses For Flexible Pavements For Light Aircraft, Literature Review and Test Section Design", USAE Waterways Experiment Station, Misc. Paper GL-92-6, 24p.

Webster, S.L. (1992b), "Geogrid Reinforced Base Courses For Flexible Pavements For Light Aircraft, Test Section Construction, Behavior Under Traffic, Laboratory Tests, and Design Criteria", DOT/FAA/RD-92/25, U.S. Dept. of Trans., Federal Aviation Admin., Washington, D.C.

White, D.W. (1991), "Literature Review on Geotextiles to Improve Pavements For General Aviation Airports", USAE Waterways Experiment Station, Misc. Paper GL-91-3, 48p.

Yarger, T.L., Harrison, F.E. Jr. and Mayberry, E.W. (1991), "Geogrid Reinforcement and Stabilization of a Highway Subgrade", *Geosynthetics '91 Conference*, Atlanta, GA, V.2, pp.673-689.

APPENDIX I. BIBLIOGRAPHY

American Association of State Highway and Transportation Officials (1981), "AASHTO Interim Guide for Design of Pavement Structures".

Abdelhalim, A.O. (1983), "Geogrid Reinforcement of Asphalt Pavements", Ph.D. Thesis, University of Waterloo, 310p.

Alenowicz, J. and Dembicki, E. (1991), "Model Tests on Temporary Road Behavior", *Int. Reinforced Soil Conf.*, pp.469-470.

Alcnowicz, J. and Dembicki, E. (1991), "Recent Laboratory Research on Unpaved Road Behaviour", *Geotextiles and Geomembranes*, V.10, pp.21-34.

Al-Qadi, I.L., Brandon, T.L., Valentine, R.J., Lacina, B.A. and Smith, T.E. (1994), "Laboratory Evaluation of Geosynthetic Reinforced Pavement Sections", Transportation Research Board Preprint, Paper No. 94-0479, 73rd Annual Meeting, Washington DC.

Anderson, P. and Killeavy, M. (1989), "Geotextiles and Geogrids: Cost Effective Alternate Materials for Pavement Design and Construction", *Geosynthetics '89 Conference*, San Diego, pp.353-360.

Barker, W.R. (1987), "Open-Graded Bases for Airfield Pavements", USAE Waterways Experiment Station, Misc. Paper GL-87-16.

Barksdale, R.D. (1984), "Crushed Stone Base Performance", Transportation Research Borad, Transportation Research Record 954, pp.78-87.

Barksdale, R.D., Brown, S.F. and Chan, F. (1989), "Potential Benefits of Geosynthetics in Flexible Pavement Systems", *National Cooperative Highway Research Program Report No. 315*, Transportation Research Board, National Research Council, Washington DC, 56p.

Barksdale, R.D., Brown, S.F. and Chan, F. (1989), "Potential Benefits of Geosynthetics in Flexible Pavement Systems, Supplement To NCHRP Report No. 315", *National Cooperative Highway Research Program Supplement to Report No. 315*, Transportation Research Board, National Research Council, Washington DC, 150p.

Bauer, G.E., Abd-El Halim, A.D. and Selvadurai, A.P.S. (1989), "Test Control and Data Acquisition of Reinforced Foundations", *Computer and Physical Modeling in Geotechnical Engineering*, Balkema, pp.391-398.

Bauer, G.E. and Mowafy, Y. M. (1988), "The Interactions Mechanism of Granular Soils With Geogrids", *Proc. Int. Conf. Numerical Methods in Geomechanics*, Ed., Swoboda, Balkema, Rotterdam, pp.1263-1272.

Bonaparte, R., Holtz, R.D. and Giroud, J.P. (1987), "Soil Reinforcement Design Using Geotextiles and Geogrids", *Geotextile Testing and the Design Engineer*, ASTM STP 952, J.E. Fluet, Jr., ed., American Society of Testing and Materials, Philadelphia, pp.69-116.

Bourdeau, J.L., Chapuis, J. and Holtz, R.D. (1988), "Effect of Anchorage and Modulus in Geotextile-Reinforced Unpaved Roads", *Geotextiles and Geomembranes*, V.7, pp.221-230.

Burd, H.J. and Brocklehurst, C.J. (1992), "Parametric Studies of a Soil Reinforcement Problem Using Finite Element Analysis", *Computer Methods and Advances in Geomechanics*, Beer, Booker and Carter, eds., Balkema, Rotterdam, pp.1783-1788.

Burd, H.J. and Houlsby, G.T. (1986), "A Large Strain Finite Element Formulation For One Dimensional Membrane Elements", *Computers and Geotechnics*, V.2, pp.3-22

Chan, F., Barksdale, R.D. and Brown, S.F. (1989), "Aggregate Base Reinforcement of Surfaced Pavements", *Geotextiles and Geomembranes*, V.8, pp.165-189.

Christopher, B.R. and Holtz, R.D. (1991), "Geotextiles for Subgrade Stabilization in Permanent Roads and Highways", *Geosynthetics '91 Conference*, Atlanta, pp.701-713.

Cowland, J.W. and Wong, S.C.K. (1993), "Performance of a Road Embankment on Soft Clay Supported on a Geocell Mattress Foundation", *Geotextiles and Geomembranes*, V.12, pp.687-705.

Delmas, P., Matichard Y., Gourc, J.P. and Riondy, G. (1986),"Unsurfaced Roads Reinforced by Geotextiles - A Seven Years Experiment", *Proc. 3rd Int. Conf. on Geotextiles*, Vienna, Vol.4, p.1015-1020.

Douglas, R.A. (1993), "Stiffnesses of Geosynthetic-Built Unpaved Road Structures: Experimental Prgram, Analysis and Results", Geosynthetics '93, Vancouver, pp.21-34.

Giroud, J.P., Ah-Line, C. and Bonaparte, R. (1985), "Design of Unpaved Roads and Trafficked Areas With Geogrids", *Proc. Conf. Polymer Grid Reinforcement*, Sponsored by Science and Engineering Research Council and Nelton, Ltd., Thomas Telford Ltd., London, pp.116-127.

Giroud, J.P. and Noiray, L. (1981), "Geotextile-Reinforced Unpaved Road Design", *Journal Geotechnical Engineering Division, Proc. ASCE*, Vol.107, No.GT9, pp.1233-1254.

Gourc, J.P., Perrier, H. and Riondy, G. (1983), "Unsurfaced Roads on Soft Subgrade: Mechanism of Geotextile Reinforcement", *8th European Conf. on Soil Mechanics and Foundation Engineering*, Helsinki, pp.495-498

Guido, V.A. and Nocera, J.J. (1992), "Eccentrically Loaded Plates on Reinforced Subgrades, *Grouting, Soil Improvement, and Geosynthetics*, ASCE Geotechnical Special Publication

No.30, V.2, pp. 1116-1128.

Haliburton, T.A. and Barron, J.V. (1983), "Optimum-Depth Method for Design of Fabric-Reinforced Unsurfaced Roads", Transportation Research Record 916, Transportation Research Board, Washington, DC, pp.26-32.

Haas, R.G. (1984), "Structural Behavior of Tensar Reinforced Pavements and Some Field Applications", *Proc. Symp. Polymer Grid Reinforcement in Civil Engineering*, Institution of Civil Engineers, London.

Hausmann, M.R. (1987), "Geotextiles for Unpaved Roads-A Review of Design Procedures, *Geotextiles and Geomembranes*, V.5, pp.201-233.

Hopkins, J.L. (1989), "Geotextile Comparisons on Low Volume Aggregate Surfaced Roads", *Int. Nonwoven Fabrics Conf.*, pp.313-321.

Jacobsen, H.M. (1989), "Full Scale In Situ Study of Provisional Road Reinforced By Geotextiles", *Proc. 12th Int. Conf. on Soil Mech. and Fnd. Eng.*, Rio de Janeiro, pp.463-466.

Kazarnovsky, V.D. et al. (1989), "The Use of Geotextile in Road Building On Soft Soils", *12th Int. Conf. Soil Mechanics and Foundation Engineering*, Rio de Janeiro, pp.1725-1729.

Kennepohl, G., Kamel, N., Walls, J. and Haas, R. (1985), "Geogrid Reinforcement of Flexible Pavement: Design Bases and Field Trials", Paper Presented to the Assoc. of Asphalt Paving Technologists, San Antonio, Texas, February.

King, J. (1994), "Geotextiles in Highway Construction and Maintenance", *Technical Textiles International*, V.3, N.4, pp.12-16.

Kokkalis, A. and Papacharisis, N. (1989), "A Simple Laboratory Method to Estimate the In-Soil Behavior of Geotextiles", *Geotextiles and Geomembranes*, V.8, pp.147-157.

Le, T.T. (1982), "The Effects of Engineering Fabric in Street Pavement On Low Bearing Capacity Soil in New Orleans", Ph.D. Thesis, Tulane University, 431p.

Little, P.H. (1992), "Review of Two Euorpean Design Methods for Geotextile Reinforced Unpaved Roads", *Highways and Transportation, Journal of the Inst. of Highways and Transportation*, V.39, N.8, pp19-22.

Mandal, J.N. (1990), "Design of Geosynthetic-Reinforced Roads", *The Indian Textile Journal*, pp.62-68.

Mannsbart, G. and Resl, S. (1993), "An Expert System for the Design of Geotextiles", *Geotextiles and Geomembranes*, V.12, pp.441-450.

Matichard, Y., Rigo, J.M. and Legrand, Ch. (1993), "GEODE: The Design and Selection of Geotextiles in Civil Engineering Applications From the CFGG Recommendations", *Geotextiles and Geomembranes*, V.12, pp.451-460.

Mhaiskar, S.Y. and Mandal, J.N. (1992), "Soft Clay Subgrade Stabilization Using Geocells, *Grouting, Soil Improvement, and Geosynthetics*, ASCE Geotechnical Special Publication No.30, V.2, pp. 1092-1103.

Milligan, G.W.E., Fannin, R.J. and Farrar, D.M. (1986), "Model and Full-Scale Tests on Granular Layers Reinforced With A Geogrid", *Proc. 3rd Int. Conf. on Geotextiles*, Vienna, Vol.1, pp.61-66.

Milligan, G.W.E. and Jewell, R.A. (1987), "Soil Reinforcement: Mechanics and Design", Short Course Presented at Georgia Institute of Technology, April.

Miura, N., Sakai, A. and Taesiri, Y. (1990), "Polymer Grid Reinforced Pavement on Soft Clay Grounds", *Geotextiles and Geomembranes*, V.9, pp.99-123.

Miura, N., Sakai, A., Taesiri, Y., Yamanouchi, T. and Yasuhara, K. (1990), "Polymer Grid Reinforced Pavement on Soft Clay Grounds", *Geotextiles and Geomembranes*, V.9, pp.99-123.

Ontario Ministry of Transportation (1993), "New Initiative-Geogrid Pavement Reinforcement", Research and Development Reports, pg.2.

Penner, R., Haas, R., Walls, J. and Kennepohl, G. (1985), "Geogrid Reinforcement of Granular Bases", Paper Presented to Roads and Transportation Assoc. of Canada Annual Conf., Vancouver, September

Raymond, G.P. (1994), "Geosynthetics for Highway in Ontario", *Technical Textiles International*, V.3, N.4, pp.18-23.

Raymond, G.P., Abdel-Baki, M.S.A., Karpurapu, R.G. and Bathurst, R.J. (1992), "Reinforced Granular Soil For Track Support", *Grouting, Soil Improvement, and Geosynthetics*, ASCE Geotechnical Special Publication No.30, V.2, pp. 1104-1115.

Saha, G.P. and Kabir, M.H. (1988), "Design of Geotextile and Geogrid Reinforced Unpaved Roads", *Int. Geotechnical Symp. of Theory and Practice of Earth Reinforcement*, Fukuoka, Japan, Balkema, pp.233-238.

Sellmeijer, J.B. (1993), "MGEOT: A Low-Volume Road Designer", *Geotextiles and Geomembranes*, V.12, pp.471-477.

Sowers, G.F., Collins, S.A. and Miller, D.G. Jr. (1982), "Mechanism of Geotextile-Aggregate Support in Low-Cost Roads", *2nd Int. Conf. on Geotextiles*, Las Vegas, V.2, pp.341-346.

Valsangkar, A.J. and Holm, T.A. (19), "Cyclic Plate Load Tests on Lightweight Aggregate Beds", Transportation Research Board, Transportation Research Record 1422, pp.14-17.

Van Til et al. (1972), "Evaluation of AASHTO Interim Guide for Design of Pavement Structures", NCHRP Reoprt 128, Highway Research Board.

Tensar Corporation (1986), "Granular Base Reinforcement of Flexible Pavements Using Tensar Geogrids, Tensar Tech. Note TTN:BR1, March, Morrow, Georgia, 21p.

Tensar Corporation (1987), "Design Guideline for Flexible Pavements With Tensar Geogrid Reinforced Bases, Tensar Tech. Note TTN:BR2, March, Morrow, Georgia, 28p.

van Grup, Christ, A.P.M. and van Hulst, R.L.M. (1988), "Reinforcement at Asphalt-Granular Base Interface", *Geotextiles and Geomembranes.*

Walls, J. (1986), "Reinforcement Objective: Road Base Needs To Be Supported", *Geotechnical Fabrics Report*, V.4, N.3, pp.10,12.

Walls, J., Penner, R., and Haas, R. (1985), "Final Report on Tensar Reinforced Granular Bases", Report to the Tensar Corp., University of Waterloo, January.

Webster, S.L. (1992a), "Geogrid Reinforced Base Courses For Flexible Pavements For Light Aircraft, Literature Review and Test Section Design", USAE Waterways Experiment Station, Misc. Paper GL-92-6, 24p.

Webster, S.L. (1992b), "Geogrid Reinforced Base Courses For Flexible Pavements For Light Aircraft, Test Section Construction, Behavior Under Traffic, Laboratory Tests, and Design Criteria", DOT/FAA/RD-92/25, U.S. Dept. of Trans., Federal Aviation Admin., Washington, D.C.

White, D.W. (1991), "Literature Review on Geotextiles to Improve Pavements For General Aviation Airports", USAE Waterways Experiment Station, Misc. Paper GL-91-3, 48p.

Yarger, T.L., Harrison, F.E. Jr. and Mayberry, E.W. (1991), "Geogrid Reinforcement and Stabilization of a Highway Subgrade", *Geosynthetics '91 Conference*, Atlanta, GA, V.2, pp.673-689.