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Geogrid Reinforcement of Asphalt Pavements and Verification of Elastic Theory

A.O. ABDEL HALIM, RALPH HAAS, AND WILLIAM A. PHANG

The idea of reinforcing flexible pavements has existed for some years, and a few attempts have been made to use metallic and other materials. These have not been effective. Recently, however, a new, high-strength plastic geogrid material known as Tensar has become available; and pavement reinforcement has been suggested as one of its possible civil engineering applications. Consequently, the first phase of a research program initiated in early 1981 examined the potential of a variety of materials for pavement reinforcement, including geogrids. The conclusion was that these materials did indeed offer potential and should be further evaluated. A comprehensive experimental program of tests of reinforced and unreinforced pavements was carried out in the latter half of 1981 and early 1982. Descriptions are presented of the experimental and analytical program and the comparative results. The results of the unreinforced test sections were used to verify the basic elastic layer theory. The analysis shows that the theory provides a reliable tool to predict flexible pavement responses under the design load. A calibration factor that includes the effect of the dependence of elastic moduli on stress level was suggested; the result is a better agreement between predicted and measured values. The results show that the plastic geogrid used was effective as a reinforcement, in terms of carrying double the number of load repetitions or implying a substantial saving in asphalt thickness and minimizing fatigue cracking.

Many existing roads are becoming inadequate because of rapid growth in traffic volume and axle loading. The escalating cost of materials and energy and a lack of resources provide an incentive for exploring alternatives in building new roads and rehabilitating existing ones. Flexible pavement reinforcement is one such alternative. If it could reduce the thickness of paving materials or extend pavement life and be both cost and performance effective, it would be a viable alternative.

Nonmetallic materials, such as fabrics, have been used to a significant degree in some areas of North America and claims have been made that these materials have reinforcement properties. The low strength, high extensibility, and low modulus of these materials make this doubtful. Moreover, there is little if any documented evidence to demonstrate that any fabric reinforces a pavement or extends its life except in warmer climates, where some fabrics may be effective in crack reflection and waterproofing. In view of new technological developments in nonmetallic reinforcing materials, however, reinforcing flexible asphalt pavements may now be worthwhile. The reinforced flexible pavement concept described in this paper includes the initial design analysis, the experimental program carried out to verify the concept, and the analysis and verification of the elastic layer theory.

REINFORCED PAVEMENT CONCEPT

Feasibility Study

In late 1980 a comprehensive research program was initiated to evaluate existing metallic and nonmetallic reinforcing materials, including geotextiles (1). It included the design and implementation of an experimental program as a cooperative effort between Royal Military College (RMC) at Kingston, the Ontario Ministry of Transportation and Communications, Gulf Canada Ltd., and the University of Waterloo.

The primary candidate arising from the evaluation was a new high-strength, plastic mesh or geogrid material known as Tensar. This material is made from polypropylene and is biaxially oriented to give strengths on the order of mild steel in both directions.

Program Objectives

The experimental program was carried out at RMC in Kingston. The design involved varying thicknesses of reinforced and unreinforced full-depth asphalt with varying strengths of subgrade in a 2.4 m x 4 m test pit. For each test series, half the pavement was reinforced with the plastic mesh; and the other half was not. The main goal of the experimental program was to thoroughly investigate, under a variety of controlled conditions, the mechanical behavior and load-carrying capabilities of flexible pavements that had been reinforced with the plastic mesh. When compared with unreinforced (control) sections, the structural benefits of the reinforcement could be evaluated. Also, the results of the program were to be used to verify or modify the basic elastic layer theory and develop initial design procedures for reinforced asphalt pavements.

Review of Reinforced Pavement

Many construction techniques use reinforcement elements strong in tension or bending to enhance the strength and stability of other materials; for example, steel bars are used to reinforce concrete when it is to be subjected to high tensile stresses or strains. Pavement reinforcement has usually been associated with portland cement concrete (PCC) pavements. Here steel reinforcement holds cracks together thereby reducing maintenance and extending life. Also, reinforcement elements have been used in concrete overlays to prevent reflection cracking (2-5).

There has been limited use of reinforcement elements to provide an adequate tensile strength to the asphalt layer (6-8). In most of these investigations analysts constructed models and conducted field trials to assess the effect of using steel or fabric materials to improve the tensile properties of the asphalt layer (9,10). A better approach would be to assess and analyze the behavior of a reinforced pavement and use the results as a basis for design. The types of results expected from these experiments would be

1. Properties of the reinforcement,
2. Mechanical behavior of the pavement under various conditions of traffic and environmental stresses, and
3. An understanding of the basic mechanisms that operate when reinforcement is incorporated in the pavement.

Basis for the Experimental Program

One of the first steps in this investigation was to study the effect of the major variables (1). This analytical phase involved the following steps: (a) evaluate available structural theories, select the most appropriate one, and modify if necessary; (b) apply the selected theory to a range of possible design situations for reinforced pavement structures; (c) identify critical stresses and strains and best location(s) for the reinforcement; and (d) assess the compatibility of the reinforcement material with asphalt concrete.

The results were used to plan an experimental program. This program was intended to verify the basic hypothesis (i.e., that flexible pavements could be reinforced effectively), to provide feedback for updating or modifying the analysis, and to provide a basis for planning and carrying out full-scale field trials. The following sections present details of the experimental part of the investigation.

EXPERIMENTAL INVESTIGATION

Test Facility

Experimental pavement sections were constructed in a test pit at the Royal Military College (RMC) in Kingston. A brief description of the facility follows.

Test Pit

Asphalt pavement sections, reinforced and unreinforced (control), were constructed within a 4 m by 2.4 m by 2 m deep concrete pit. The test pit includes a sump and water distribution system at the bottom that allowed the pit to be flooded to any desired depth.

MTS Loading System

The loading system at the RMC Structural Engineering Laboratory includes three independent closed-loop electrohydraulic actuators and ancillary equipment designed and packaged by Material Testing Systems, Co. Ltd. (MTS). For this investigation a hydraulic actuator rated at 50 kN (11.25 kips) was used.

Controlled Variables

Test Loops

The experimental program was divided into five series of tests, called loops. The test pit was set up for each series (or loop); half of the pit was reinforced and the other half was left as a control section. For each loop the asphalt thickness and the subgrade condition (either dry or saturated) were the controlled variables. Between four and nine tests were performed for each loop, and each test was performed on a different section of the test pit. The five loops are described in Table 1.

Table 1. Test loops and controlled variables.

Loop No.	Test No.	Asphalt Thickness (mm)	Subgrade Condition	Description
1	1	150	Dry	Control
	2	150	Dry	Reinforced
	3	150	Saturated	Reinforced
	4	150	Saturated	Control
2	1	165	Dry	Control
	2	165	Dry	Reinforced
	3	165	Dry	Reinforced
	4	165	Dry	Control
3	1	250	Saturated	Control
	2	150	Saturated	Reinforced
	3	150	Saturated	Reinforced
	4	200	Saturated	Control
	5	250	Saturated	Control
	6	150	Saturated	Reinforced
4	1	200	Dry	Reinforced
	2	200	Dry	Reinforced
	3	250	Dry	Control
	4	250	Dry	Control
	5	250	Saturated	Control
	6	250	Saturated	Control
	7	200	Saturated	Reinforced
	8	200	Saturated	Reinforced
	9	200	Saturated	Reinforced
5	1	115	Dry	Control
	2	115	Dry	Control
	3	115	Dry	Reinforced
	4	115	Dry	Reinforced

Objectives of Test Loops and Testing Sequence

The main objective of the experimental program was to determine and compare the reinforcing effects of the geogrid in the asphalt pavement. The design of these test loops was conducted in a logical manner to assess predetermined parameters related to reinforcement evaluation. For example, the first loop was designed to compare the behavior and performance of the reinforced section with an unreinforced section of the same thickness (150 mm) on a weak subgrade. Permanent deformation and vertical deflections were monitored throughout the test until complete failure occurred on the unreinforced section.

In loop 2, strain carriers were installed at the bottom of the asphalt layer to compare tensile strain in the critical zone between reinforced and unreinforced sections of the same thickness (165 mm) on a stronger subgrade. Results of these two loops were of major importance because they compare the reinforced sections with unreinforced sections under identical geometric, loading, and environmental conditions.

When the first objective was achieved (basic comparisons between reinforced and unreinforced), the second objective was to find the equivalent thickness of the reinforced layer. Loops 3 and 4 were designed to establish a relationship between the thicknesses of the reinforced and unreinforced sections. In loop 3 two unreinforced sections (200 mm and 250 mm) were tested against a thinner reinforced section of 150 mm on weak subgrade. The results of this loop showed that a value of (50 to 100 mm) equivalent thickness might represent the reinforcement effect.

Based on this finding loop 4 tests were performed with an unreinforced section of 250 mm and a reinforced section of 200 mm to confirm the minimum saving value (50 mm). Loop 5 was designed to compare the vertical stresses on the subgrade (strong subgrade) for reinforced and unreinforced asphalt sections of the same thickness (115 mm). Results of the five loops are presented later in the discussion.

Dynamic and Static Loading Patterns

Reinforced and unreinforced pavement sections were loaded through a 300-mm (12-in.) diameter, rigid circular plate placed on the pavement surface. The loading pulse was sinusoidal with a peak load of 40 kN for each cycle and a frequency of 10 Hz. The loading program was designed to represent typical traffic loadings on pavements under operating conditions. The cyclic loading was continued until preselected criteria for failure was reached.

After certain numbers of selected cycles, dynamic loading was discontinued and a static loading sequence (5 to 10 static cycles) was applied as a time lengthened, stepwise approximation of one cycle of loading. In addition to obtaining static load response per se, this static loading sequence was necessary for monitoring the array of displacement gauges, strain gauges, and strain carriers in each section. During static loading 10 kN increments of load were applied, to a maximum of 40 kN, followed by smaller decrements to 0 kN. For loops 4 and 5 this was changed into a single increment and single decrement (0-40-0 kN). Dynamic loading was then resumed.

Test Materials and Preparation of Test

Subgrade Preparation

The subgrade for each loop consisted of a 1.2 m depth of medium to coarse sand. The sand was initially placed in 150 mm lifts and compacted at an optimum moisture content of 11.5 percent using a plate tamper. Before each loop (or series of tests), the original subgrade condition was duplicated by removing the top 150 mm of sand, turning over the next 150 mm and recompacting in two lifts at optimum moisture content. A Troxler nuclear densitometer was used to monitor moisture content and compaction. For selected tests the subgrade was flooded from below to fully saturate the sand up to the sand-asphalt interface.

Asphalt Layer Construction

For the first 4 loops a local MTC grade HL4 hot-mix asphalt was used. A 25 mm lift of hot mix (125°C) was first placed on the subgrade for all tests. The mesh was then placed on half the pit, and the other half was left unreinforced as the control section. Next the reinforced and unreinforced halves were covered with one additional 50 mm of asphalt and compacted using four passes of a plate tamper. Additional uniform 25 mm to 75 mm lifts were placed and compacted to bring the pavement structure to the desired thickness. The density of the pavement was monitored using a Troxler densitometer to ensure uniform asphalt consistency between reinforced and unreinforced test sections. Samples of the asphalt mix were taken from each loop and analyzed at the Gulf Canada Research Centre.

Tensar Geogrid

The geogrid material is a 50 mm by 50 mm mesh made by stretching both lengthwise and crosswise a sheet of polypropylene plastic with holes punched through it (Figure 1). The resultant mesh has strands that are about 1 mm thick by 3 mm wide at their narrowest and nodes at the junction of strands that are about 10 mm square and about 2 mm thick. The material weighs about 0.210 kg/m², is supplied in 3 m by 50 m rolls, and is estimated to cost about $2/m². Lighter weights and smaller mesh geogrids are available. It has been termed as a geogrid to differentiate it from the conventional geotextile fabrics. Geogrid describes the open mesh structure that allows interlocking with surrounding materials thereby mobilizing its high tensile strength.

The type of geogrid used in this research is designated as AR-1 by the manufacturer; it has been developed to have the following general properties:

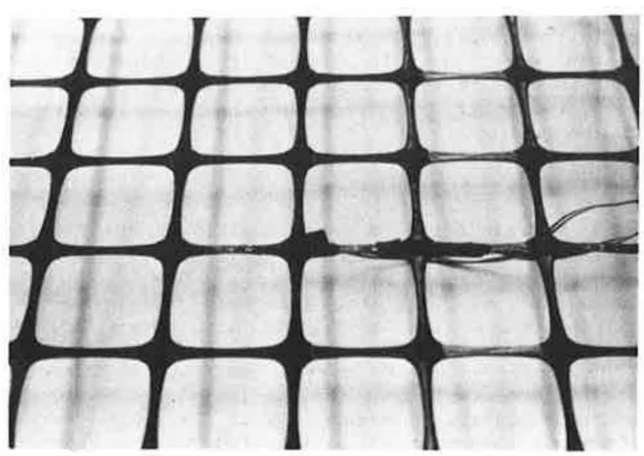

Figure 1. Plastic mesh with strain gauges before placing it in asphalt.

1. High tensile strength,
2. High modulus,
3. Low elongation,
4. Biaxial structure (i.e., strength in both directions), and
5. A grid with desired openings (i.e., 50 mm) for pavement purposes.

Strain gauges were bonded to the top and bottom of the mesh strands in loops 1, 2, 3, and 5. The gauges were attached to a wide area of mesh under the loading plate to monitor the strains induced in the mesh by the loads.

Instrumentation and Data Acquisition

The general arrangement of instrumentation used to monitor the pavement sections during testing is shown in Figure 2. The instrumentation and recording devices are summarized in the following subsections.

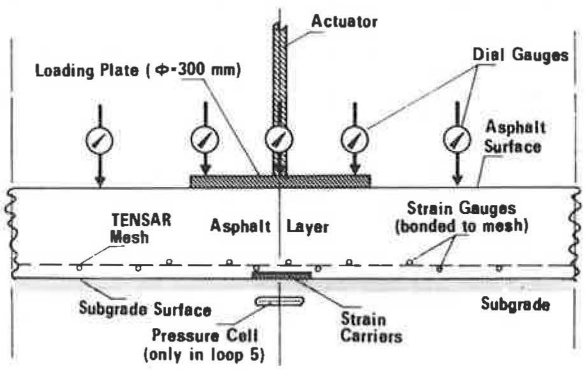

Figure 2. General arrangement of the instrumentation.

Actuator Load Cell and LVDT

The actuator load cell and linear variable displacement transducer (LVDT) are part of the closed-loop, electrohydraulic control system for the MTS actuator. During static load cycles both divices were accessed through the PDP 11/34 computer at pre-programmed intervals to record plate load and displacement (11).

Strain Gauges

Foil-type (120 ohm) strain gauges (SHOWA Y11-FA-S-120) were bonded to the top and bottom of the mesh at locations directly below the loading plate and at radial distances from the load center. The strain gauges were used to record the magnitude and distribution of elastic and plastic tensile strains generated in the reinforcement elements as a result of the loading.

Strain Carriers

Mastic strain carriers were supplied by the Alberta Research Council. Each unit consists of two (120 ohm) strain gauges embedded in a 150-mm square by 12-mm thick mastic plate. The mechanical properties of the mastic are compatible with those of the asphalt concrete. For each test setup of the last four loops, a strain carrier was placed directly under the centerline of the loading plate and at the subgrade-asphalt interface. This location corresponds to the zone of anticipated maximum tensile strains in the asphalt layer.

Dial Gauges

Dial gauges were placed on the rigid loading plate and at radial distances from the plate. The dial gauges were read during static load cycles and were used to determine the elastic and plastic surface deflection profile for a given number of load cycles.

Pressure Cells

For loop 5 a circular plate pressure cell was embedded in the subgrade directly below the center of loading and was used for each test. It was buried about 50 mm below the sand-asphalt interface. Each pressure cell consists of two cylindrical aluminum plates, 133 mm in diameter, fastened back-to-back to give a total thickness of 13 mm. The plates are in the form of a recessed disc made of a 6.5-mm thick annulus surrounding a pressure sensitive diaphragm 2 mm thick. A four-arm strain gauge configuration (Wheatstone Bridge) is bonded to each top and bottom diaphragm of the pressure cells.

The pressure cells were placed in the subgrade to investigate relative vertical stress gradients generated below the loaded areas for reinforced and unreinforced test sections. The pressure cells were calibrated in situ before and after the final test loop by placing the rigid loading plate at the surface of the sand subgrade directly above the pressure cell. The pressure cells were monitored during static load cycles by using a multichannel data acquisition system.

Failure Criteria

Certain failure criteria were established as a means to compare objectively the performance of the reinforced and control sections. Failure was said to have occurred if

1. A permanent deformation of 30 mm was measured,
2. Extensive cracks developed,
3. A steady increase occurred in the measured values of stresses on the subgrade,
4. Surface deflection increased as much as 20 percent, or
5. Horizontal strain at the interface increased by 30 percent.

The values were applied to both control and reinforced sections in all loops to determine the number of load cycles at which failure actually occurred. It was clear from the observations and the test results that a number of factors affected the mode of failure for each loop. Among these factors are the age of the asphalt when the test begins, the temperature, and the subgrade (dry or saturated).

It is noteworthy that the failure of the mesh did not have to be considered in the criteria because the strains on the mesh on all loops did not exceed 30 percent of its yield strain of 15 percent.

RESULTS AND ANALYSIS

The large amount of information collected and analysis conducted makes it impossible to report all results and analysis for all loops. The following presents some typical results.

Results of the First Loop

Results of the first loop showed that permanent deformation resistance of the reinforced pavement was improved, also, the number of cycles to failure were significantly higher. It is important to note that the unreinforced section had failed completely at the end of the test (punched through) whereas the reinforced section remained together. This latter observation suggests that lower levels of tensile strain and vertical stress result from using the reinforcement layer. This observation was to be confirmed in the next test loop.

Results of the Second Loop

Similar to loop 1, loop 2 tests were carried out to compare the performance of control and reinforced sections for the same pavement thickness on a strong subgrade. The results are shown in Figures 3, 4, and 5 and are as follows:

1. The total permanent deformation (i.e., penetration of the loaded plate) for the control section was higher at the end of the test compared with the deformation of the reinforced section at the same number of loading cycles. This confirms the results of loop 1.
2. The total number of repetitions of the 40 kN load to a limiting deformation of 30 mm more than doubled for the reinforced sections (350,000 versus 150,000).
3. No significant plastic tensile strain was measured at the bottom of the reinforced sections compared with the control section (see Figure 5). This result confirmed the explanation given for loop 1 of the low levels of stress and strain induced in the reinforced sections.
4. The value of the elastic tensile strain measured at the bottom of the reinforced layer was less by more than 30 percent than that for the control section.
5. A highly significant observation was the development of tension (fatigue) cracks on the surface of the control sections (initiated at the bottom of the asphalt layer). Clearly, the reinforcement reduces the number and severity of such cracks. This observation also confirmed the reasoning of the failure mode that occurred in the control section in loop 1.

Results of the Third Loop

As the results of loops 1 and 2 indicate, the life of pavement sections, in terms of number of loads carried, can be doubled for the same thickness of asphalt if reinforcement is used. Loop 3 was designed to investigate the equivalent thickness of asphalt that may be saved by using reinforcement. The results shown in Figures 6, 7, and 8 suggest the following:

1. Reinforcement may provide a significant saving of asphalt thicknesses (between 50 and 100 mm) for the conditions of this experiment (Figure 6).
2. No significant plastic strains were monitored in the case of the thinner (150 mm) reinforced sections, but they were significant on the unreinforced sections (Figure 7).
3. The measured vertical elastic rebound for the thinner reinforced section was smaller than the thicker (200 mm) control section and slightly larger than that of the (250 mm) control section (Figure 8). This is another indicator that additional

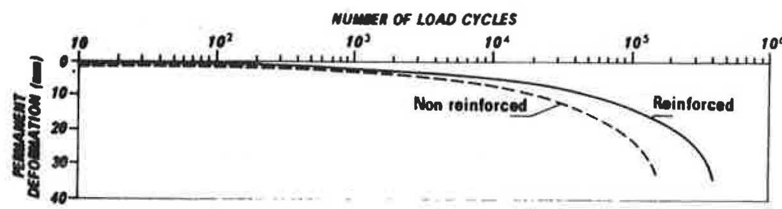

Figure 3. Permanent deformation for loop 2—strong subgrade.

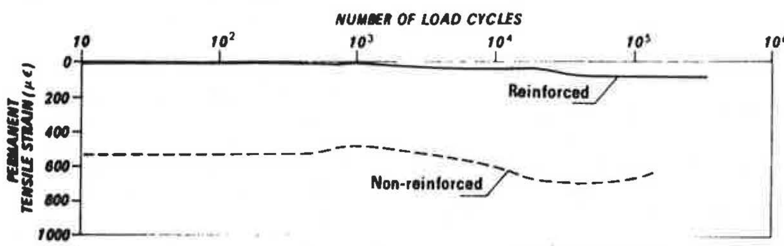

Figure 4. Permanent tensile strain in the asphalt at bottom of layer for loop 2.

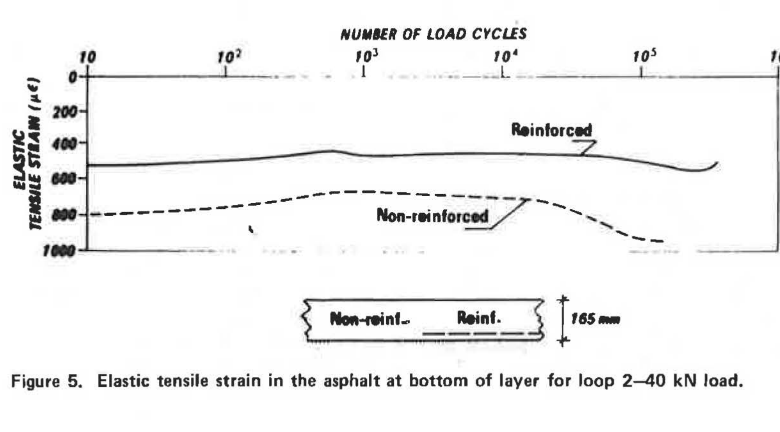

Figure 5. Elastic tensile strain in the asphalt at bottom of layer for loop 2—40 kN load.

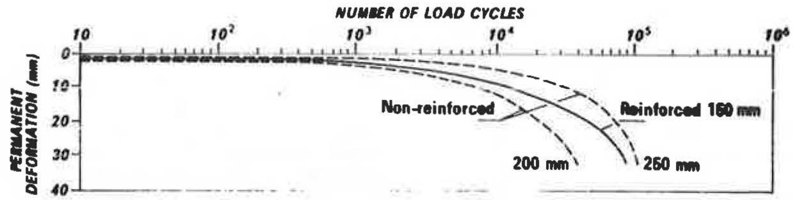

Figure 6. Permanent deformation for loop 3—weak subgrade.

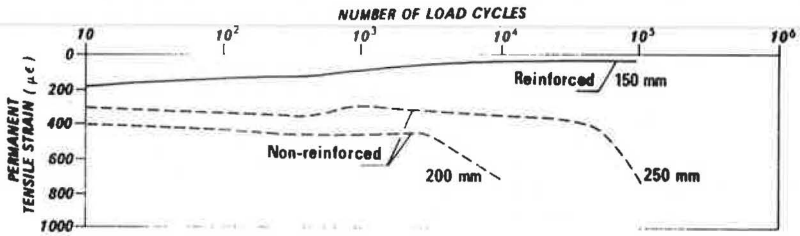

Figure 7. Permanent tensile strain in the asphalt at bottom of layer for loop 3.

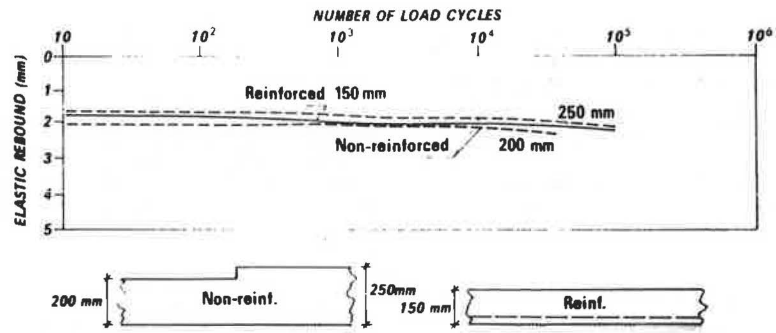

Figure 8. Elastic rebound for loop 3.

structural strength is added to the thinner section by using reinforcement.

The results of this test loop suggest that a minimum saving of asphalt thickness of 50 mm is possible. Of course this remains to be verified for actual field conditions.

Results of the Fourth Loop

The results of this loop (200 mm and 250 mm reinforced sections with dry and saturated subgrade and 250 mm unreinforced sections with dry and saturated subgrade) confirmed the hypothesis of loop 3 that a minimum of 50 mm of asphalt could be saved by using reinforcement. Also, as can be seen in Figure 9, loop 4 strongly confirmed that the elastic tensile strains caused by the 40 kN load in the thinner reinforced section are less than the strains on the thicker (by 50 mm) control section.

Furthermore, Figure 9 shows two other significant differences between the tensile strains measured on the reinforced and unreinforced pavements. First, the unreinforced pavement showed a higher value of residual strain or creep (ε_p in Figure 9-b) which explains the cause of the higher values for permanent tensile strain on this section. Second, the compressive strain on the unloaded adjacent reinforced section was higher than that measured on the unloaded adjacent control section under similar conditions (almost double). This difference is probably caused by the interaction between the asphalt layer and the geogrid reinforcement. Of course this adds to the structural strength of the reinforced pavement.

Results of the Fifth Loop

The last loop featured pressure cells under each test section to monitor the vertical stresses 50 mm under the subgrade interface. The presence of these cells (155-mm diameter aluminum plates) affects the values of the permanent deformation because they act as additional reinforcement for the subgrade layer. However, the major objective of this loop was to monitor the vertical stresses under the loaded sections and to use the data in subsequent analyses.

Figure 10 shows the relationship between the ratio of the measured stress for the control section to the reinforced section versus number of cycles. It clearly shows that the subgrade stress is 30 to 40 percent higher under the control (unreinforced) section.

Comparison of Results

The results of the experimental program have clearly demonstrated significant differences in the performance of the reinforced and unreinforced sections. Results of loops 1 and 2 indicate that reinforced sections of the same thicknesses would carry more than double the number of load cycles to failure compared to the unreinforced sections. The reinforcement reduces the elastic tensile strain at the bottom of the asphalt layer by about 30 percent.

Cracks were observed early on the unreinforced sections and progressed into severe cracks on the surface. On the other hand, very few (hairline) cracks were observed on the reinforced sections at the end of the loading cycles. Two unreinforced sections, one in each loop, were punched through,

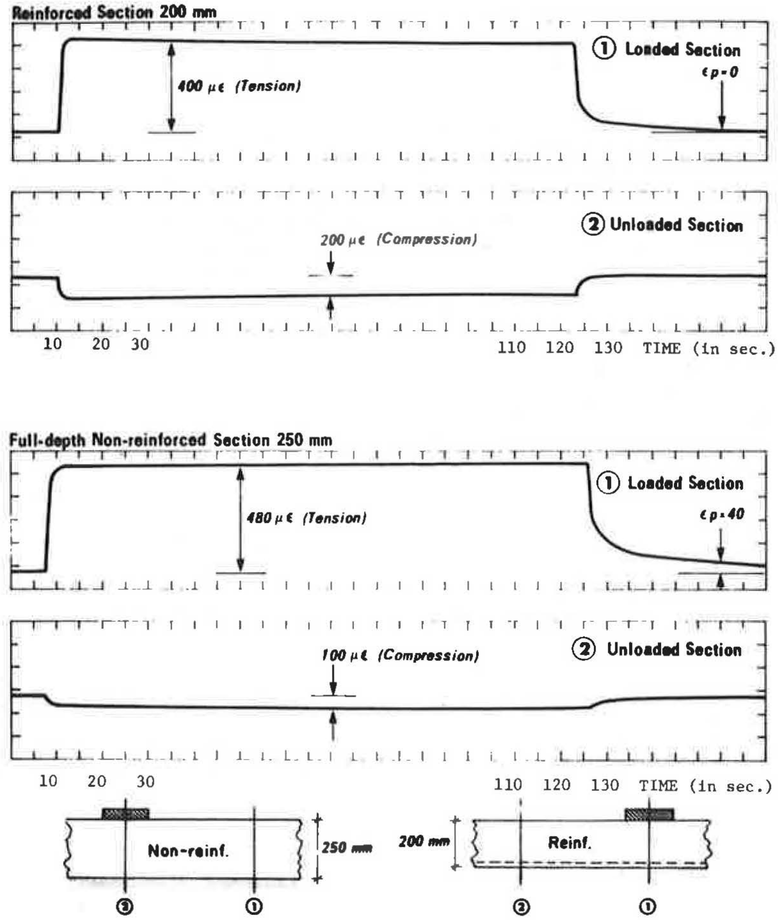

Figure 9. Tensile strain pulses for loop 4—weak subgrade.

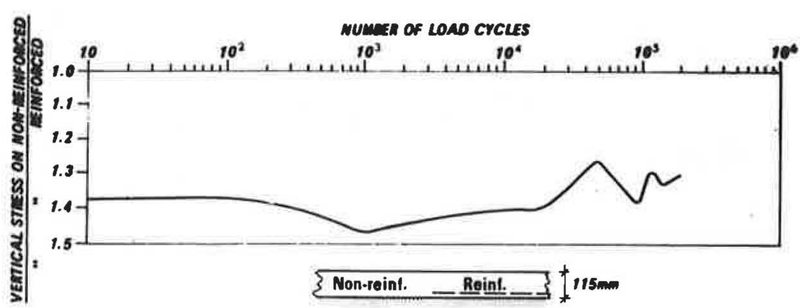

Figure 10. Stress ratio of the unreinforced section to the reinforced section for loop 5—strong subgrade.

whereas the reinforced sections held together even after higher numbers of load cycles.

Results of loops 3 and 4 suggest that a possible saving of between 50 to 100 mm of asphalt material can be obtained by reinforcing the thinner sections. In loop 3, a comparison between the 150 mm reinforced and 200 mm unreinforced sections shows that the thinner reinforced section is significantly stronger than the unreinforced section. The results of this loop suggest that a reinforced section can be 50 mm thinner than an unreinforced section and still show less permanent deformation and less permanent tensile strain under a higher number of load cycles than was applied to the thicker unreinforced section. Furthermore, the presence of the mesh in the thinner sections of loops 3 and 4 resulted in reducing the elastic tensile strain by about 20 percent compared with the strains under the thicker unreinforced layer.

A comparison of the 150-mm reinforced section with the 250-mm unreinforced section of loop 3 shows that the maximum possible saving of asphalt material under the circumstances is about 100 mm. Although the elastic rebound of the 250-mm unreinforced section was less than the elastic rebound of the 150-mm reinforced section, the reinforced section performed better as far as the permanent tensile strain and fatigue cracks were concerned.

The results of loop 5 help to explain the findings of the previous loops. As shown in Figure 10, the ratio between the vertical stresses on the subgrade under the unreinforced sections were 30 to 40 percent higher than the stresses under the reinforced sections. This difference is explained by the effect of the reinforcing mesh. The vertical stresses will be distributed on a larger area under the reinforced section, resulting in less pressure on the subgrade. This difference can be further explained by Figure 11 where deflection bowls at different load cycles are shown for the reinforced and unreinforced section in loop 2. The following differences are apparent:

1. The spread of the deflection bowl for the reinforced section is larger than for the unreinforced.
2. The slope of deflection bowl for the unreinforced is steeper than the slope of the deflection bowl for the reinforced section suggesting higher values for shear and vertical stresses.
3. Fatigue cracks developed on the unreinforced section resulted in a smaller area of stress distribution and higher stress values (10^5 cycles).

Table 2 summarizes some selected results of the five loops.

VERIFICATION OF THE ELASTIC LAYER THEORY

The experimental program also provided the opportunity to examine the validity of the elastic layer theory under simulated field conditions, similar to those assumed in the theory itself. Furthermore, it provided sufficient data to verify asphalt pavement responses (elastic deflections, horizontal tensile strains, and vertical stresses) when subjected to a wide range of variables. Therefore, the results of this program were used to verify the application of a selected elastic layer model to predict responses of the unreinforced pavements.

A multilayer elastic model, BISAR, (12) was used in the analysis to predict surface deflections, horizontal strains, and vertical stresses for the tested sections. The predicted values under the maximum load (40 kN) compared well with the measured values. However, there was experimental evidence to suggest that elastic moduli of pavement layers depend on the level of stress imposed on the layers. Calibration factors were established to modify the moduli so that better agreement is reached between the predicted and measured data.

An iterative technique was used for the analysis. For example, the analysis started with using an average value for the elastic modulus of the subgrade (based on test measurements). With this value and the measured surface deflection for the section

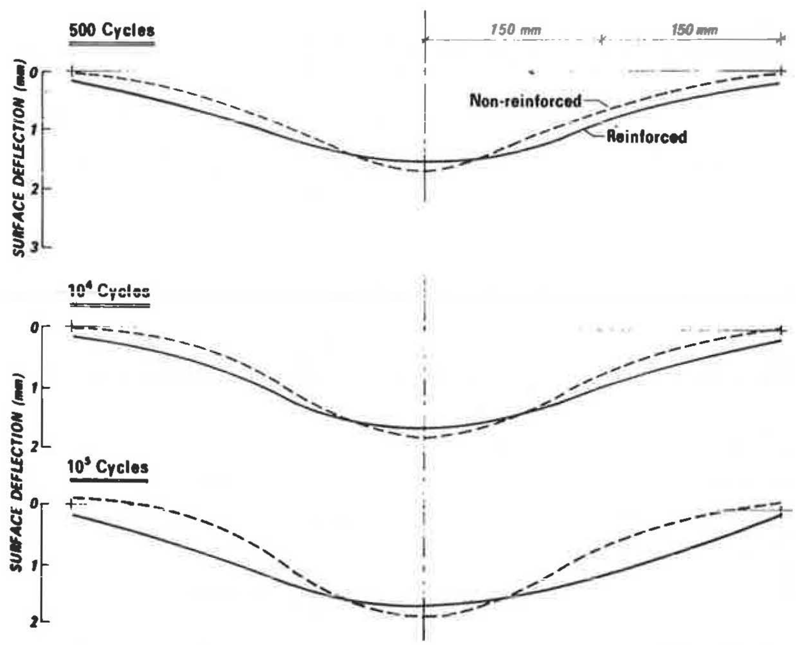

Figure 11. Surface deflection bowls of unreinforced and reinforced sections for loop 2.

Table 2. Summary of selected results.

Loop No.	Section	Thickness (mm)	Total No. of Cycles	Total Penetration (mm)	Permanent Tensile Strain (με)
1	Control	150	100,000	53.0[a]	
	Reinforced	150	100,000	37.0	
			200,000	76.0	
2	Control	165	150,000	30.0	760
	Reinforced	165	350,000	27.1	140
3	Control	255	113,500	31.8	735
	Control	200	37,500	29.3	700
	Reinforced	150	90,000	29.7	0
4	Control	255	135,000	15.0	710
	Reinforced	200	135,000	13.0	180
5	Control	115	300,000	10.2	880
	Reinforced	115	300,000	6.8	80

[a]This section punched through at 100,000 cycles.

considered, an initial value for the elastic modulus of the asphalt layer can be obtained as shown in Figure 12. The relationships shown in the figure were obtained using the elastic layer program, BISAR, for different thicknesses and elastic moduli. Using these initial values of the moduli as input into the program (along with the other elastic constants, thicknesses, number of layers, and load value), the stresses, strains, and deflections in each layer were computed. The iterative process was carried out, by choosing new values of the moduli for both subgrade and asphalt, until the difference between the predicted and measured values of surface deflections and horizontal strains were less than an acceptable value. The highest number of iterations found necessary was seven. The results of this analysis are discussed below.

Comparison of Deflections and Strains Under Maximum Load (40 kN)

This comparison is important because most flexible pavement design methods adopt surface deflections and horizontal tensile strain as criteria for design. As can be seen in Table 3, the predicted values of maximum surface deflection and horizontal strain at the bottom of the asphalt layer are very close to the measured values.

Comparison of Deflections and Strains Under Different Load Values

The results of calculated deflection and strains that assumed constant values of elastic moduli were found to differ from the measured values under different loads. The discrepancy was more pronounced on the thinner sections than on the thicker ones. Perhaps this can be explained by the fact that under the small-load value (10 kN), the effect of the dead weights of the loading system and the asphalt layer (which were ignored in the analysis) represent a significant portion of the actual loading at this small-load value. Obviously this weight would have more effect on the thinner and weaker sections than on the thicker and stronger sections. This explanation is supported by results of the tests shown in Table 4. (The difference is higher for the 165 mm and 200 mm compared to the 250 mm section--26 percent, 32 percent, and 10 percent, respectively.) However, the problem was minimized by introducing calibration factors derived from the measured data. This was done first by using the following model to derive the appropriate moduli:

$$E_p = E_o\ [1 + \sin(C + 2.06P)] \ldots 1 \qquad (1)$$

where

- E_p is the elastic modulus of the asphalt or subgrade layer under load P (kN) in MPa,
- E_o is initial value of elastic modulus of the layer in MPa,
- C is constant and was found to be equal to 28, and
- P is the applied load in kN.

The value of E_o was calculated using the values of E_p for p = 40 kN found in Table 4. The plot in Figure 13 shows the relationship given by the model in Equation 1. Because the values of P in the experimental program were fixed at 10, 20, 30, and 40 kN,

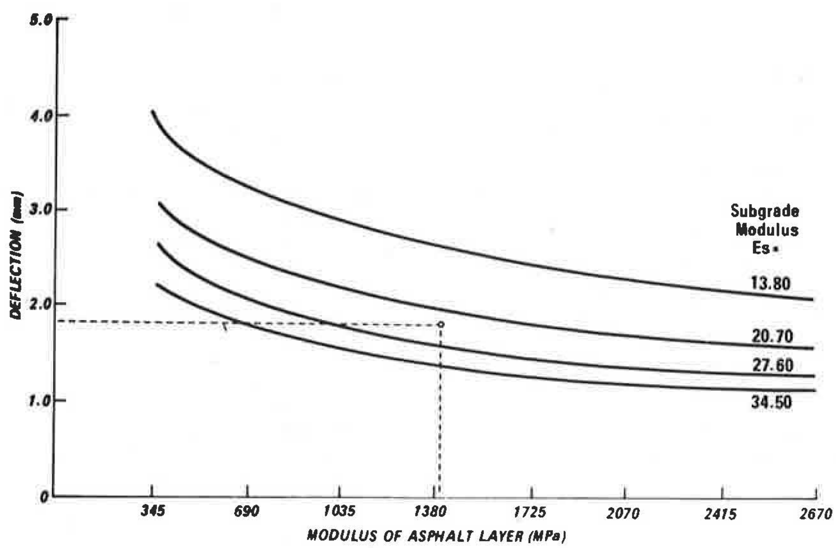

Figure 12. Computed relationships between deflection and elastic moduli for asphalt thickness of 165 mm.

Table 3. Comparison of measured and predicted deflections and strains under maximum load (40 kN).

Thickness (mm)	Asphalt Modulus (MPa)	Subgrade Modulus (MPa)	Measured Deflection (mm)	Measured Tensile Strain (mm)	Predicted Deflection (mm)	Predicted Tensile Strain (mm)	Error (%) Deflection	Error (%) Strain
115	2,997	33.3	1.57	605	1.54	589	2.0	3.0
165	1,399	23.3	1.81	680	1.80	715	1.0	5.0
200	965	17.6	1.98	805	2.05	765	4.0	5.0
250	1,233	15.2	1.69	440	1.70	452	1.0	3.0

Table 4. Comparison of deflections and strains under different load values

Load (kN)	Calibration Factor, F_p	Asphalt Modulus, $E_p=F_p \times E_{40}$	Subgrade Modulus, $E_p=F_p \times E_{40}$	Thickness (mm)	Measured		Predicted E_{40}		Predicted E_p		Error E_{40} (%)		Error E_p (%)	
					Deflection	Strain	Deflection	Strain	Deflection	Strain	Deflection	Strain	Deflection	Strain
10	0.905	1,266	21.1	165	0.54	243	0.45	179	0.50	200	17.0	26.0	7.0	17.0
20	1.000	1,399	23.3		0.97	358	0.90	358	0.91	358	7.0	0.0	7.0	0.0
30	1.034	1,447	24.4		1.34	475	1.35	536	1.30	518	1.0	13.0	3.0	9.0
40	1.000	1,399	23.3		1.81	680	1.80	715	1.80	715	1.0	5.0	1.0	5.0
10	0.905	873	15.9	200	0.61	282	0.51	191	0.58	215	16.0	32.0	5.0	24.0
20	1.000	965	17.6		1.08	475	1.03	382	1.03	382	5.0	19.0	5.0	19.0
30	1.034	998	18.2		1.51	622	1.54	573	1.49	555	2.0	8.0	2.0	10.0
40	1.000	965	17.6		1.98	805	2.05	765	2.05	765	4.0	5.0	4.0	5.0
10	0.905	1,116	13.8	250	0.51	122	0.42	110	0.47	125	17.0	10.0	7.0	2.0
20	1.000	1,233	15.2		0.93	217	0.85	226	0.85	226	9.0	4.0	9.0	4.0
30	1.034	1,275	15.7		1.31	315	1.27	330	1.23	328	3.0	5.0	6.0	4.0
40	1.000	1,233	15.2		1.69	440	1.70	452	1.70	452	1.0	3.0	1.0	3.0

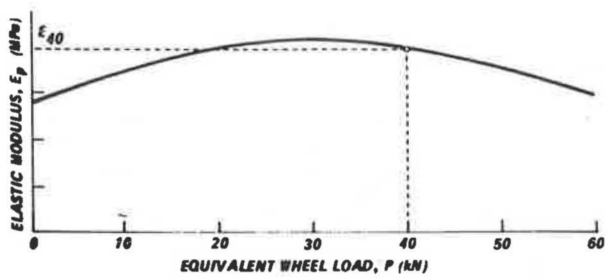

Figure 13. Relationship between elastic modulus of asphalt or subgrade (E_p) and the load (P).

it was easy to derive the following formula from the suggested model,

$$F_p = E_p/E_{40} \quad (2)$$

where

- F_p is the calibration factor obtained from the model and equal to 0.905, 1.000, 1.034, and 1.000 for 10, 20, 30, and 40 kN, respectively;
- E_p as defined before; and
- E_{40} is the elastic modulus used in the analysis for 40 kN.

The analysis assumed that the modular ratio of the two layer system at any load is the same as the ratio used in the analysis at 40 kN. The results of the analysis that considered variation in the elastic moduli were compared with the measured values and with the results of the analysis that assumed fixed elastic moduli (E_{40}). As can be seen from the comparison given in Table 4, the use of the calibration factors significantly improved the predictions of the model in most cases.

Significance of the Analysis

The analysis indicates that elastic layer theory is an acceptable tool to predict and analyze flexible pavement behavior. It also shows that adopting simple modifications, such as calibration factors to establish stress dependency for the elastic analysis, is more efficient and less time consuming than using other more sophisticated models. An interesting observation is that this variation of the theory was found to occur for the lower level of loading which in most cases is not of major concern in flexble pavement design methods. Finally, the most important finding of the study is that if the elastic constants of pavement layers can be determined accurately enough, the elastic layer theory could predict reliably pavement deflections and horizontal strains.

CONCLUSIONS

This paper presents a new, effective method of reinforcing asphalt pavements by using a new, nonmetallic high-tensile-strength geogrid. It also presents a methodology for testing, comparing, and analyzing the behavior of both reinforced and nonreinforced flexible pavements. In addition, important answers are provided to the question of the validity of the elastic theory and its use in flexible pavement design methods.

In view of the worldwide emphasis on energy conservation of resources, reinforced flexible pavements offer a promising alternative to conventional designs. The potential of this new technique can be summarized as follows:

1. Substantial thickness savings of asphalt material, or
2. Up to double the number of load repetitions, and
3 Prevention or minimization of fatigue cracks in the asphalt layer.

This potential of reinforced flexible pavements suggests that developing a construction technology for field installation and full-scale field trials to verify the findings of the experimental program would be worthwhile.

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