Analytical and Experimental Investigations of Operating Mechanisms in Reinforced Asphalt Pavements

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Reinforcement of asphalt pavements has become a feasible alternative within the past decade, largely because of grids. Whether reinforcement is an effective alternative for any given situation, however, must be established on a performance and economic basis. Potential performance benefits include reductions in rutting, cracking, and layer thickness, plus extended pavement life. The effectiveness of reinforced pavements depends on the interaction between reinforcement and the asphalt mix. Such interaction is provided by a number of mechanisms including interlock, bond, confinement, and membrane effects. The extent to which a mechanism dominates the operation of a given reinforcement depends on the geometry, strength, and the elastic properties of the grid involved. The effects of various geometric properties of reinforcements on the effectiveness of grids through the mechanisms under which they operate are discussed. The test results showed that the interlock operating mechanism is governed mainly by the grid opening size and the thickness of strand. The bond operating mechanism is governed mainly by the grid surface area.

The notion of reinforcing asphalt pavement has existed for many years. A few attempts have been made to use metallic and other materials to minimize pavement cracking (*1*,*2*). These attempts were not based on fundamental considerations, however, and they were not cost- and performance-effective (*3*).

The advent in the late 1970s of a new generation of high-strength polymer meshes, known as "grids," indicated that under certain circumstances reinforcement could be a viable option for reducing pavement rutting, cracking, and layer thickness. Results of the early research (*4*) showed that the use of grids to reinforce asphalt pavements can result in reducing surface rutting by a factor of 2 or more and increasing fatigue life by four to five times. These laboratory results were subsequently supported by data and observations gathered from field trials in many parts of the world. However, with the availability of many types of grids on the market and a wide variety of design conditions, pavement engineers are faced with having to determine whether reinforcement is an effective option under any given situation.

With the advances in chemical products technology, more polymer materials that can be used for asphalt pavement reinforcement have become available. These include textiles, fiberglass, and grids. Because of their low modulus, high elongation, and sheet structure, the use of textiles in heavy-duty asphalt pavements does not appear to be feasible (*5*). Although fiberglass-reinforced plastic seems to have some advantages compared with other reinforcement materials, it is a relatively expensive material and, therefore, its use in pavement reinforcement may not be cost-effective. The process for selecting the best alternative and implementing it involves the following stages (*6*):

1. Identification of critical design factors,
2. Selection of the best reinforcement for the application,
3. Economic analysis,
4. Determination of the appropriate installation or construction method, and
5. In-service monitoring.

OBJECTIVES OF THE PAPER

This research has been carried out to investigate the effects of various reinforcement types and properties on the effectiveness of their operating mechanisms. The following are the specific objectives of this paper:

1. To briefly review reinforcement alternatives (types and locations in the pavement structure), major variables (pavement layer and reinforcement properties, etc.), and functions (rutting, fatigue cracking, and reflection cracking).
2. To identify the grid operating mechanisms (interlock, bond, confinement, and membrane effect) to provide behavior that is compatible with the asphalt layer.
3. To experimentally verify the operating mechanisms identified in Objective 2 above, so that a basic understanding of the reinforcement behavior can be provided.
4. To determine the most important parameters that govern the performance of grid-reinforced asphalt pavements.

The work presented in this paper deals with the two main reinforcing mechanisms, that is, interlock and bond. Quantifying confinement and membrane mechanisms requires more

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complex test facilities and therefore it is not discussed in this work.

ASPHALT PAVEMENT REINFORCEMENT

The term "reinforcement" generally means the inclusion of certain materials with some desired properties within other materials that lack these properties. Many reinforcement applications have been used to enhance the tensile strength of other media such as retaining walls, portland cement concrete, slope stability measures, embankments, and asphalt pavements (*4*).

If reinforcement is to be considered, two basic needs must be established (*7,8*):

1. Intended function of the reinforcement; one or more of (*a*) reduced rutting, (*b*) reduced cracking (fatigue, reflection), (*c*) reduced layer thickness (asphalt, base, subbase), or (*d*) extended pavement life or reduced maintenance, or both.
2. Reinforcement alternatives: (*a*) types and possible locations in the pavement structure, and (*b*) major variables (pavement layer and reinforcement properties, traffic loads and volumes, etc.).

Figure 1 is a schematic illustration of the location alternatives and the major variables. Although only one location would normally be chosen for reinforcements, Figure 1 illustrates several possible ones, depending on the variables listed. The best location for any given set of conditions is determined through a proper structural design, plus construction practicalities.

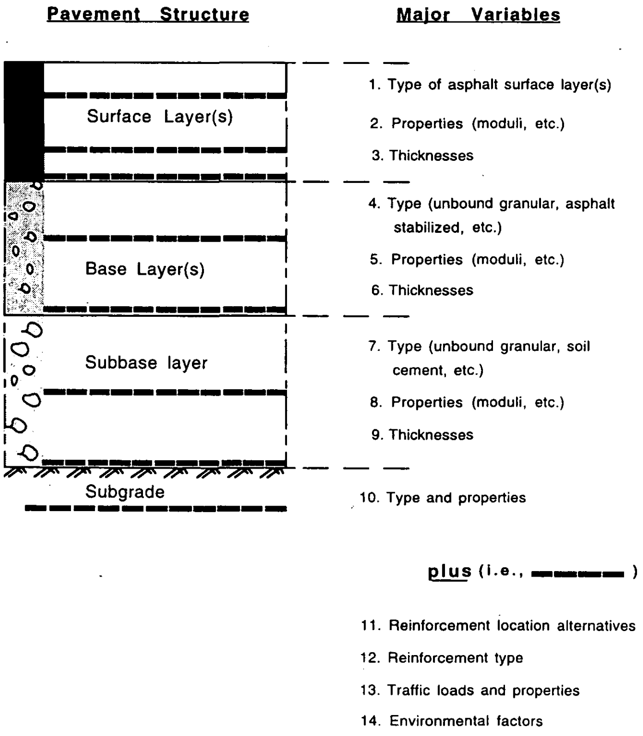

FIGURE 1 Reinforcement location alternatives and some of the major variables.

Examples of how different locations for reinforcement can have a major effect on reduced rutting or extended life, or both, are provided for a very weak subgrade (*9*), for granular base reinforcement on weak to strong subgrades (*10*), and for asphalt reinforcement on weak to strong subgrades (*11*).

Within the entire pavement structure, the asphalt concrete layer receives most of the load- and non-load-induced tensile stresses. However, it is well known that asphalt concrete lacks the ability to resist such tensile stresses, which makes it an ideal medium for reinforcement.

Grids have become more acceptable for pavement reinforcement. The grid bond and interlock with the asphalt matrix (provided by the open mesh structure) and their high modulus and tensile strength (which are comparable with mild steel) make them the most promising materials for asphalt pavement reinforcement applications. Two grid types have been considered for this study: polyethylene and polyester. Properties of the two grid types and their effects on the operating mechanisms are discussed.

OPERATING MECHANISMS OF REINFORCEMENT

Identification of Mechanisms

The effectiveness of reinforced asphalt pavements is governed by the ability of the reinforcement to mobilize a number of mechanisms. These mechanisms can be identified as (*a*) interlock, (*b*) bond, (*c*) confinement, and (*d*) membrane effect. The presence and contribution of each mechanism depend on the characteristics of the asphalt mixture, the reinforcement, and their interaction. The definition of each mechanism and the extent to which a mechanism can dominate the behavior of the reinforcement are discussed.

Interlock is defined as the portion of the mobilized strength of the reinforced layer through anchorage resistance provided between the mesh opening and the aggregates of the asphalt mixture. Optimum interlock can be achieved when the ratio between the dimensions of the opening and the aggregate size is 3:1 to 4:1; this ratio has been observed in this investigation and will be discussed in a subsequent section.

Bond is defined as the portion of the mobilized strength of the reinforced layer provided by the adhesion between the surface of the reinforcement and the asphalt cement of the mixture. As the surface area of the reinforcement increases, higher bond resistance can be obtained, provided that the other geometric properties are constant, that is, same strand thickness and geometry of openings and joints. Also, increasing the asphalt content of the mix will increase the bond developed at the interface between the asphalt and the reinforcement (*4,11*).

The confinement mechanism is provided through the compatibility between the overall properties (physical and geometric properties) of the reinforcement and the characteristics of the asphalt layer. In other words, the confinement mechanism depends on the width of the overall reinforcement in relation to the width of the paved lane. For example, if the width of the reinforcement is significantly less than that of the paved lane, the strength mobilized by the confinement mechanism will be less than the strength mobilized if both widths were identical.

The fourth mechanism that contributes to the overall strength of the reinforced layer is the membrane effect. This mechanism depends on the elasticity of the reinforcement, its position within the asphalt layer, the type of underlying layer (i.e., base, subbase, or subgrade), and the length of the reinforced layer beyond the influence of the loaded area. The membrane mechanism acts to redistribute the applied stresses into a larger area of the base, subbase, or subgrade of the pavement structure.

Factors Affecting the Operating Mechanisms

To enhance the development of the operating mechanisms for a given reinforcement, the selected grid should have properties that are compatible with those of the layer material and particularly the asphalt mixture under a wide range of temperatures. The compatibilities between the aggregate and the opening of the grid, the thermal properties, and the stiffness of the grid relative to the asphalt layer are the key parameters that contribute to the realization of the potential of a reinforced asphalt pavement.

In essence, the factors that affect the reinforcement operating mechanisms can be categorized into three types:

1. Factors related to the geometry of the grid and its physical properties,
2. Factors related to the material properties of the asphalt pavement layer (asphalt content, maximum aggregate size, layer thickness, etc.), and
3. Factors related to installation or construction procedure (paving train interaction with grid, interaction between asphalt layer and compactor, etc.).

It is beyond the objectives of this paper to discuss how the operating mechanisms are affected by the factors related to the properties of the asphalt pavement layer or those related to the installation or construction process. The emphasis instead is on the effects of the grid geometry on mobilizing the various mechanisms.

Table 1 summarizes the factors related to the geometry of a grid reinforcement that can affect the operating mechanisms. The interlock mechanism is affected mainly by the size of the grid openings with respect to the maximum aggregate size, the ratio of strand area to the total area of the grid, and the strand thickness. The bond mechanism is affected by the grid surface area, the geometry of the opening (square or curved corners), and the strand width. The confinement mechanism depends on the dimensions of the grid with respect to the dimension of the reinforced layer, whereas the membrane effect mechanism is a function of the geometry of the grid joints.

The testing program presented in this paper was carried out to investigate the effects of the above-mentioned geometric properties of the grid on the operating mechanisms. Details of the experimental investigation and analysis of test results are discussed next.

EXPERIMENTAL INVESTIGATION

The experimental investigation was carried out at two different testing facilities: Carleton University and the Institute for Research in Construction of the National Research Council of Canada in Ottawa. The laboratory tests consisted of fastening an asphalt concrete slab to steel plates–one fixed and the other mobile (see Figure 2). The slabs were laid flat horizontally and were fully supported by the plates. A tensile load could be applied to the sample by horizontal movement of the mobile plate (no eccentric loading or bending movement was applied).

An actuator driven by a variable-speed electric motor was used to apply the horizontal loads, and a precalibrated load cell, located between the mobile plate and the actuator, measured the loads required to pull the asphalt slab apart. Also, a direct current differential transducer (DCDT) was used to measure the displacements. Both of the measuring devices were connected to a data acquisition unit.

Selection of Grids

To demonstrate the effects of the grid geometric properties (Table 1) on the reinforcement operating mechanisms, two

TABLE 1 Factors of Grid Geometric Properties Affecting Operating Mechanisms

Operating Mechanism	Factors of Grid Geometric Properties Affecting the Mechanism
Interlock	- Size of openings with respect to max. aggregate particle size, - Ratio of strands area to the total area of the grid, - Strand thickness.
Bond	- Grid surface area, - Geometry of opening (square or curved corners), - Strand width.
Confinement	- Dimension of grid with respect to the dimension of the asphalt layer.
Membrane Effect	- Grid joints (i.e., overlapped, cemented strands or continuous merging materials).

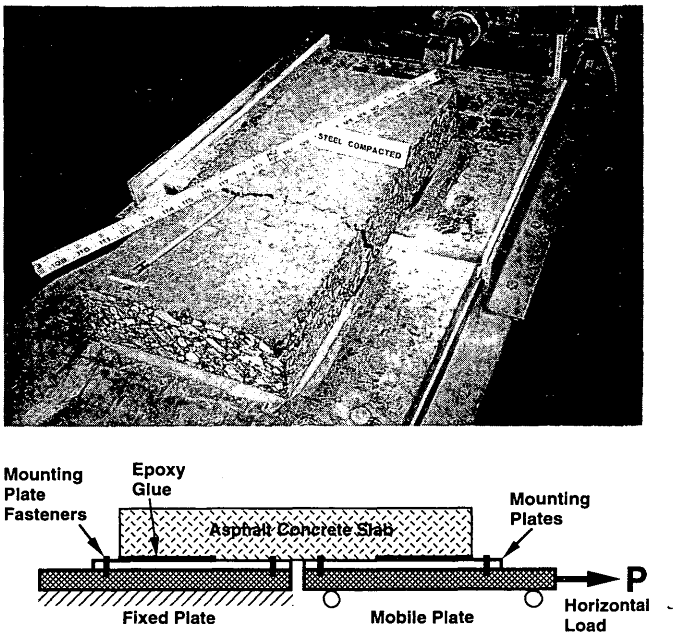

FIGURE 2 Reinforced slab testing machine for selection of grids.

types of grids were selected. These are polyethylene and polyester, which have a variety of geometric properties. Table 2 shows the properties of the grids utilized in the testing program.

The grids shown in Table 2 were selected only on the basis of varying geometric properties and not to demonstrate that one type of grid is ideal for asphalt pavement reinforcement. For example, Grids G3 and G5 were modified (by eliminating every second strand in the longitudinal direction, yielding Grids G4 and G6, respectively) during the experimental investigation to evaluate specific characteristics of the grids and to alter their performance (see Table 2). These modifications resulted in removing between one-third and one-half the number of strands.

Testing Program

Table 3 presents a summary of the testing program, which involves two series of tests. The objective of the first series was to evaluate the effect of various geometric properties on the bond operating mechanism. To achieve maximum bond while minimizing the interlock mechanism, the specimens were constructed in the field as follows:

1. Placement and compaction of the first asphalt lift,
2. Placement of grid reinforcement on top of the compacted surface of the first asphalt lift, and
3. Placement and compaction of the second asphalt lift on top of the grid reinforcement.

The purpose of compacting the first asphalt lift was to ensure that no interlock between this asphalt lift and the grid reinforcement was developed. Hence, the main mechanism mobilized from this construction procedure was bond.

After examination of the results from the first test series, it was decided to include additional variations on the geometric properties for the next series of tests. The variation on geometric properties was achieved by modifying Grids G3 and G5 (see Table 2). Subsequently, a total of five grids were tested to evaluate the interlock operating mechanism. For this series, samples were compacted in the laboratory. The first asphalt lift was not compacted before placing the grid. Rather, the entire slab (i.e., first asphalt lift, the grid, and the second asphalt lift) was compacted as a unit by a vibratory plate. The main mobilized mechanism, therefore, was interlock.

TABLE 2 Properties of Selected Grids Used in the Testing Program

Grid		Property									
		Opening			Strand		Ratio of Grid Open. Width to Max. Agg. Size	% Openings Area to Total Grid Area	% Surface Area to Total Grid Area	Geometry* of Grid Joints	Tensile Strength (KN/m)
No.	Polymer	Area (mm^2)	Min. Width (mm)	Corner Geometry	Width (mm)	Thick (mm)					
G1	polyethylene	3064	46.8	rounded	4.34	1.47	3.6	83.6	16.4	C.M.	16.0
G2	polyester	339	17.7	square	2.89	1.04	1.3	75.2	24.8	O.S.	30.0
G3	polyester	657	17.0	square	2.77	0.82	1.3	80.7	19.3	O.S.	32.0
G4	polyester	1512	36.8	square	2.77	0.82	2.8	87.9	12.1	O.S.	19.2
G5	polyester	723	25.4	square	6.25	1.3	1.9	48.0	52.0	O.S.	51.6
G6	polyester	3952	62.5	square	6.25	1.3	4.7	71.4	28.6	O.S.	31.0
G7	polyester	2159	48.3	square	8.74	0.96	3.7	64.5	35.5	O.S.	41.0

* C.M. = Continuous Materials
O.S. = Overlapped Strands

TABLE 3 Summary of the Testing Program and Variables Considered

Sample Grid No.	No. of Samples Tested	Sample Dimensions (mm)	MTO Asphalt Mix Type	Site Fabrication	Operating Mechanism Evaluated
Unreinforced G1 G2 G3 G5	12 8 3 8 6	1200x1200 x75	HL3	Field compaction	Bond
Unreinforced G1 G4 G5 G6 G7	4 2 2 3 4 2	300x600 x75	HL3	Laboratory compaction	Interlock

ANALYSIS OF TEST RESULTS

Typical test results for the first test series (evaluation of bond operating mechanism) and the second test series (evaluation of interlock operating mechanism) are illustrated in Figures 3 and 4, respectively. Figure 3 shows that the tensile stresses that are resisted by the bond mechanism decrease rapidly to a very low level. After the grid is fully mobilized and the applied stresses are higher than the grid bond strength, splitting cracks along the interface between the reinforcement and the asphalt mix start to propagate to the ends of the sample, causing a separation that results in a rapid decrease in the tensile stresses (see Figure 3).

It is interesting that the use of Grid G2 or G3 resulted in a decrease in the maximum tensile strength of the reinforced asphalt when compared with the strength of the unreinforced asphalt (see Figure 3). This result would suggest that under certain circumstances (i.e., if bond were the only operating mechanism to be mobilized) a grid can weaken instead of strengthen the asphalt pavement. One should expect no significant increase in the tensile strength of the reinforced asphalt pavements. Similar to the reaction in steel-reinforced concrete, the tensile strength provided to the composite is mobilized after the concrete itself is cracked. In the case of reinforced pavements subjected to horizontal stresses or displacements, the grid will act to provide sufficient strength to maintain and preserve the integrity of the asphalt layer.

Unlike the bond strength (which decreases rapidly), the interlock strength can still be provided by the reinforcement even after the peak stresses have been reached (see Figure 4). The grids of Figure 4 mobilized an effective interlock operating mechanism controlling the tension cracks and resisting stresses to a large degree (i.e., the tensile stresses did not decrease rapidly after the peak stress). The failure was caused by tension (transverse) cracks rather than splitting cracks that had propagated a bit earlier before reaching the peak stresses.

The results shown in Figure 4 emphasize the importance of the grid geometry to its tensile strength. As discussed earlier, Grid G6 is a modified version of Grid G5. In fact, the tensile strength of Grid G6 is approximately 40 percent less than that of Grid G5 because of the removal of every second strand. However, in spite of the lower tensile strength of Grid G6, its reinforced slab resulted in about a 30 percent tensile strength increase when compared with the strength of Grid G5 reinforced slab (see Figure 4). This result is further supported by the fact that asphalt slabs reinforced with Grid G1 gave the best overall performance in spite of the lower tensile strength of G1 (see Table 2).

Figures 3 and 4 also show that the peak stresses resisted by the interlock operating mechanism are much higher than those resisted by the bond operating mechanism. To achieve an effective interlock operating mechanism, the reinforcement grid has to be placed on an uncompacted asphalt lift and

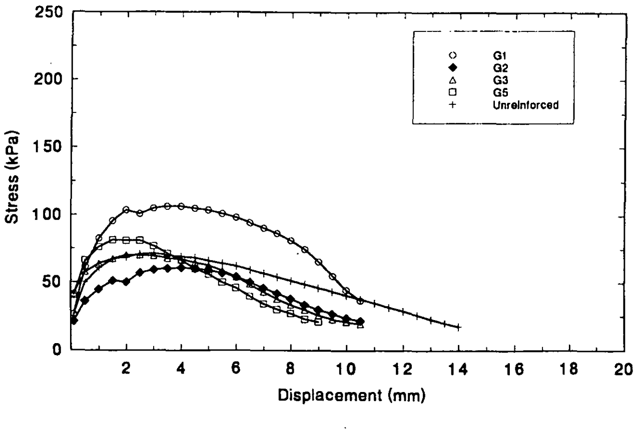

FIGURE 3 Typical stress displacement curves for the evaluation of bond operating mechanism.

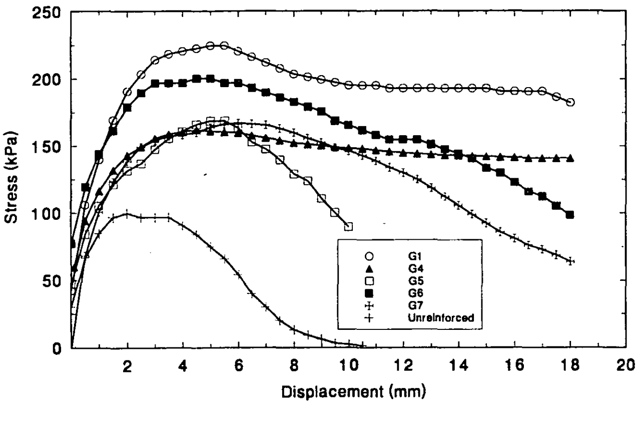

FIGURE 4 Typical stress displacement curves for the evaluation of interlock operating mechanism.

sandwiched between the two asphalt lifts (which was the construction procedure followed for Figure 4 specimens).

Effect of Grid Surface Area

Figure 5 illustrates the effect of grid surface area (area of strands) on the bond operating mechanism evaluated in the first test series. As the grid surface area increases, the peak stress decreases to a point after which it starts to increase.

It is postulated that the effect of the interlock operating mechanism (which cannot be completely eliminated even though the objective of the construction procedure for these samples was to develop bond only) influences the measured strength at lower values of grid surface area. For example, although the surface area of Grid G2 is larger than that of Grid G3, the Grid G2 bond strength is lower. This difference can be explained by Figure 6, which characterizes the measured peak stresses as a function of the grid opening size, showing that the interlock operating mechanism has been developed and is smaller for Grid G2 than for Grid G3.

For grid surface areas greater than 25 percent (of total grid area), however, the bond operating mechanism increases as the grid surface area increases (see Figure 5). For example, Grid G5 has a surface area of 52.5 percent and exhibits a high bond operating mechanism. If the surface area reached 100 percent (which is the case with a fabric sheet), the dashed curve in Figure 5 demonstrates that the bond operating mechanism would have provided the total measured strength and no interlock would have existed.

Effect of Opening Size

Figure 7 shows the relationship between the opening size (areas of opening) and the peak stress developed mainly by the interlock operating mechanism (second test series). As the opening size increases, the mobilized interlock operating mechanism increases and resists higher tensile peak stresses. Because more asphalt materials can be accommodated into a larger opening size, higher anchorage resistance can be developed. The anchorages then provide the interlock operating mechanism. This phenomenon is applied for a given strand shape (i.e., rounded or flat), as well as grid joint geometry (i.e., continuous materials or overlapped strands). For example, the polyester grids (G4, G5, G6, and G7) have the same strand shape and the same joint geometry and can be characterized by a Figure 7 curve. The polyethylene Grid G1, however, has a different strand shape and joint geometry and exhibits high peak stress for the following reasons:

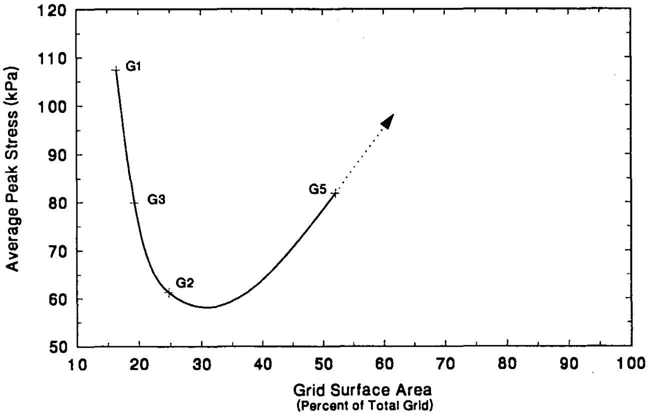

FIGURE 5 Effect of grid surface area on bond operating mechanism.

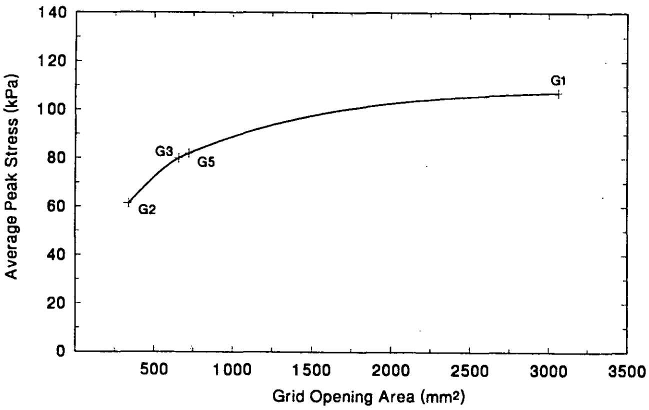

FIGURE 6 Effect of interlock operating mechanism on measured bond operating mechanism of first test series.

1. Grid G1 strands have a rounded shape and smooth surface, whereas Grid G6 strands have a flat shape and sharp edges that cause localized shear stress at the interface between the strands and the asphalt mix.
2. The joints of Grid G1 are of continuous materials (merging between transverse and longitudinal strands), whereas the joints of Grid G6 are of crossed-overlapped strands. The continuous joints provide a biaxial resistance, which in turn provides a better confinement during the interlock operating mechanism.

Figure 7 also shows that no significant gain on the interlock operating mechanism can be achieved for opening sizes larger than about 2000 mm^2 (i.e., the peak stress curve has a flatter slope for large opening sizes). Grids G1, G6, and G7 provide

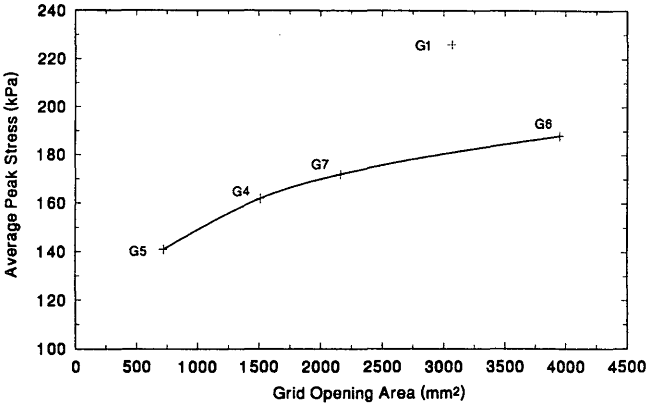

FIGURE 7 Effect of grid opening size on interlock operating mechanism.

higher tensile strength than that provided by the rest of the grids. These three grids have a ratio of opening width to maximum aggregate size of more than 3 (see Table 2). Grid G7, for example, has a ratio of opening width to maximum aggregate size of 3.7. This ratio is 4.9 for Grid G6, but no significant increase in the tensile strength is achieved. It can be concluded, therefore, that the appropriate value for the ratio of grid opening width to maximum aggregate size is 3.6 or a range of 3 to 4 (i.e., 3:1 to 4:1).

Effect of Strand Thickness

The relationship between the strand thickness and the peak stress developed mainly by the interlock operating mechanism (second test series) is shown in Figure 8. As the strand thickness increases, the mobilized interlock operating mechanism increases. A larger strand thickness would allow anchorages that are formed by the asphalt material. The thicker the anchorage, the higher the mobilized interlock operating mechanism.

Figure 8 shows that Grid G5 does not follow the peak stress curve. Because of the very small opening size of this grid (compared with the other Grids G4, G6, and G7), the mobilized interlock operating mechanism is low. This is also supported by a Figure 7 relationship, which illustrates that the interlock operating mechanism is sensitive to small opening sizes that have areas less than 1500 mm^2 (i.e., the slope of the peak stress is steep for small opening sizes; see Figure 7). Therefore, it is expected that Grid 5 will have a much lower interlock operating mechanism and that the peak stress curve should be fitted to the other grids as shown in Figure 8.

CONCLUSIONS

The following conclusions can be drawn from the results of the analytical and experimental investigations presented in this paper.

1. The effectiveness of reinforced asphalt pavements depends to a large extent on the geometric properties of the grid. An interlock mechanism provides the main component of the reinforcing mechanisms.
2. The grid opening size is the most important geometric property that governs the interlock operating mechanism. A larger opening size would accommodate more asphalt materials to provide anchorages, which increase the interlock operating mechanism.
3. The strength mobilized by the interlock operating mechanism can still be provided even after the peak stresses are reached (i.e., even after cracks develop).
4. The bond operating mechanism is governed mainly by the grid surface area. For grid surface areas greater than about 25 percent (of total grid area), the bond mechanism increases as the grid surface area increases.
5. Grids with thicker strands can mobilize a more effective interlock operating mechanism because of thicker anchorages developed between the strands.
6. The small increase in the slab peak strength is primarily due to the bond operating mechanism, whereas the resistance to large deformation is due to the interlock operating mechanism.
7. To achieve the most effective interlock operating mechanism, the reinforcement grid has to be placed on an uncompacted asphalt lift and sandwiched between the two asphalt lifts.

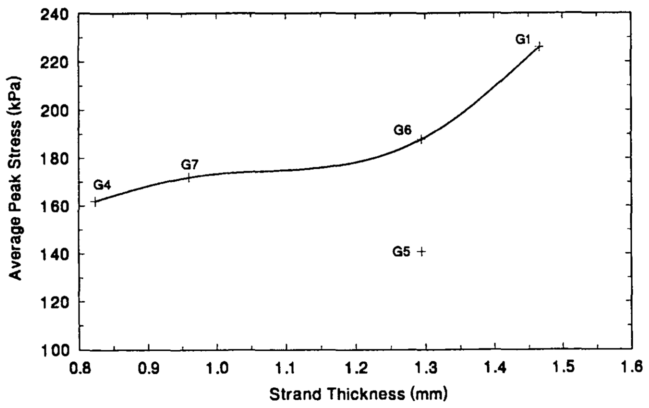

FIGURE 8 Effect of grid strand thickness on interlock operating mechanism.

Finally the research work presented in this paper addresses the main parameters that govern the performance of grid-reinforced asphalt pavements. The testing program followed; although it does not simulate traffic loadings, it does approximate stresses induced by temperature. The test results suggest that when the selected reinforcing grid meets certain geometric characteristics, the reinforced pavement resists the thermal stresses and maintains its integrity.

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Publication of this paper sponsored by Committee on Flexible Pavement Design.