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Influence of Relative Rigidity on the Problem of Reflection Cracking

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ABSTRACT

Reflection cracking of bituminous overlays on rigid pavements has been known for a long time, and many studies have been conducted based on theoretical and experimental investigations. As a result a number of solutions were tried, but in most cases performance was reported as poor to fair. A recent investigation oriented toward the use of a plastic mesh to reinforce asphalt pavements resulted in the development of a new analytical approach that helps explain the actual causes of reflection cracking in bituminous overlays. The new approach adopts the principle of "relative rigidity" to analyze the pavement structure at the time of construction. Results of the analysis have indicated that the critical interface is the one at the top surface of the softer hot asphalt layer. In addition, the analysis points out the importance of selecting different types of compactors to keep the integrity of the underlying rigid layer. Finally, the analysis emphasized that experimental investigations must consider the critical conditions that occur at the time of construction.

As a result of an experimental program to investigate the effectiveness of plastic geogrid reinforced pavement (1-3), a number of on-road and off-road paved trials were planned and carried out, including two test locations in southern Ontario. (Note that data on the test locations are from two unpublished reports: R.C. Haas, "Notes on the Problems of Installing Tensor Geogrid in Asphalt Pavement Construction," March 29, 1983; and A.O. Abd El Halim, "Report on Tensor Mesh Paving Trial," December 8, 1981.) Some of the problems encountered were buckling of the mesh, cracks after the completion of compaction, and separation between the mesh and the asphalt. Preliminary analyses were conducted to find

out what happened and how these problems could be overcome. In brief, the analysis indicated that two types of actions were the main contributors to the observed problems. The first type of action was caused by certain properties of the reinforcing layer, such as temperature effects, inadequate tension, and imperfection of the geometry of the mesh (still in initial stages at the time of the test trials). The other type of action was caused by the interactions among the compactor, the reinforcement layer, the asphalt layer, and the subgrade. It should be added here that several grid types were used in the second trial (off-road), including differing heat setting treatments, and different ten-

sion methods and fastening techniques. Observations of the problems in the latter trial suggested that the main cause of the problems was the interaction between the aforementioned components rather than the undesirable properties of the reinforcement.

Based on these observations, a third trial was carried out. (Note that data are from an unpublished report by A.O. Abd El Halim, J. Gough, and R.C. Haas, "Off-Road Paving Trials with Tensar Geogrid at Genstar Quarry, Burlington, Ontario, April 27-28, 1983," May 5, 1983.) The third trial differed from the previous two trials in the type of the subgrade under the reinforced layer. Although the underlying layer in both previous trials was relatively rigid (cold asphalt layer in the first and concrete layer in the second), the subgrade in which the third trial was carried out was soft clay. Observations of the third field trial suggested that most of the problems encountered on the other two sections were overcome. It is too early to claim that all the problems have been solved; nevertheless, the results were encouraging.

The most important conclusion drawn from these field trials was that a more in-depth analysis has to be conducted on to the exact structure at the time of construction (e.g., type of compactor, order of rigidities of the layers, and subgrade conditions).

It is postulated in this paper that investigating the pavement structure at the time of construction could provide important answers to one of the most troublesome problems facing the pavement engineers today, namely, reflection cracking. The role of relative rigidity or stiffness mismatch in the components of the structure are postulated as a primary contributor to these problems.

RELATIVE RIGIDITY OF PAVEMENT STRUCTURE

The transfer of stresses among the various components of a multiphase elastic material or a multi-component elastic structure is influenced by the relative stiffness characteristics of the separate components. The influence of relative rigidity on the load transfer characteristics can be illustrated by a flexible plate resting on an elastic soil mass subjected to a uniform load distribution at the surface (Figure 1). The relative rigidity between the plate and the elastic soil mass is governed by two basic parameters: the modular ratio E_p/E_s , where E_p is the modulus of elasticity of the plate and E_s is the elastic modulus of the soil; and the ratio t/a , where t is the thickness of the plate and a is its radius. When the primary mode of load transfer between the plate and the soil mass is flexural interaction between the plate and the soil mass, the dominant relative rigidity parameter R takes the form (4):

$$F = (E_p/E_s) (t/a)^3 \quad (1)$$

When R became large (i.e., $R \gg 1$) the plate behaves as a rigid plate, and as R becomes small (i.e., R

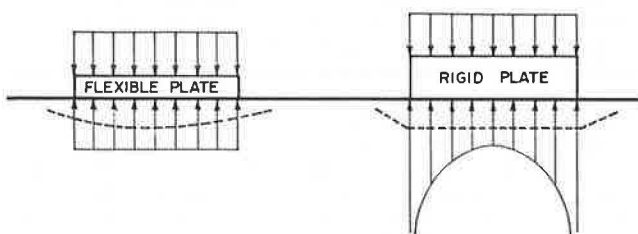


FIGURE 1 Stress and deflection distribution.

<<1) the plate exhibits flexible characteristics. The relative rigidity between the plate and the elastic soil medium affects the mode of load transfer between the two systems and results in displacement and stress distributions in the plate and the soil region. Figure 1 shows the typical contact stresses that will be observed at the plate-soil mass interfaces as the relative rigidity of the system varies from the flexible to the rigid case.

The pavement structure is also a system in which several components interact, and this interactive response is influenced by the relative rigidity characteristics of the various components. In the case of a new asphalt layer on top of a rigid concrete layer, the components include the subgrade, the rigid layer, the compacted and uncompacted hot asphalt, and the compaction device. At different stages of the construction of the pavement structure, the relative rigidity between the various components changes.

THEORETICAL MODELING

Figure 2 shows the four time stages that the existing pavement structure experiences. Case I represents the conditions just before overlay construction has started (time T_0). It can be seen that for this case the top layer is more rigid than the underlying layer, as indicated by the rigidity coefficients R_1 and R_2 , respectively ($R_1 > R_2$).

This structure would be capable of transferring the applied stress due to the traffic load from the upper rigid layer to the underlying more flexible layer. Thus the first assumption is

1. In order to transfer stresses and strains between successive layers, the rigidity of the upper layer must be larger than the second upper layer, i.e., $R_i > R_{i+1}$ for all layers in the structure.

At the time of overlay construction [time T_1 (Case II)], a different structure is developed. First, one more layer with lower rigidity is added to the existing structure; the hot asphalt layer clearly has a low value of rigidity when compared with the rigidity of the concrete layer. It is therefore postulated here that the structure in Case II represents a distorted system as far as the first assumption is concerned. As a result of this distortion in the order of stiffness in relation to the load's direction, the second assumption is as follows:

2. For any layered system, the addition of one or more layers on top of a given supporting structure would not result in any significant increase of the total rigidity of the system if any of the additional layers has a lower rigidity than the rigidity of any of the existing layers.

As shown in Figure 2 (Case II), R_2 of the hot asphalt layer is expected to be much smaller than R_1 of the concrete. As a result of this second assumption, the total rigidity of the system in Case II would be less than the total rigidity of the system in Case I, although more thickness was added. However, at this stage in the construction, the structure in Case II is in stable condition because loads have not been applied onto it. As the compaction of the asphalt starts, a complex situation results. The use of a steel compactor would result in a more distorted structure because of the immediate existence of a high rigid body on top of a structure of lower rigidity. Because of assumption 2, the

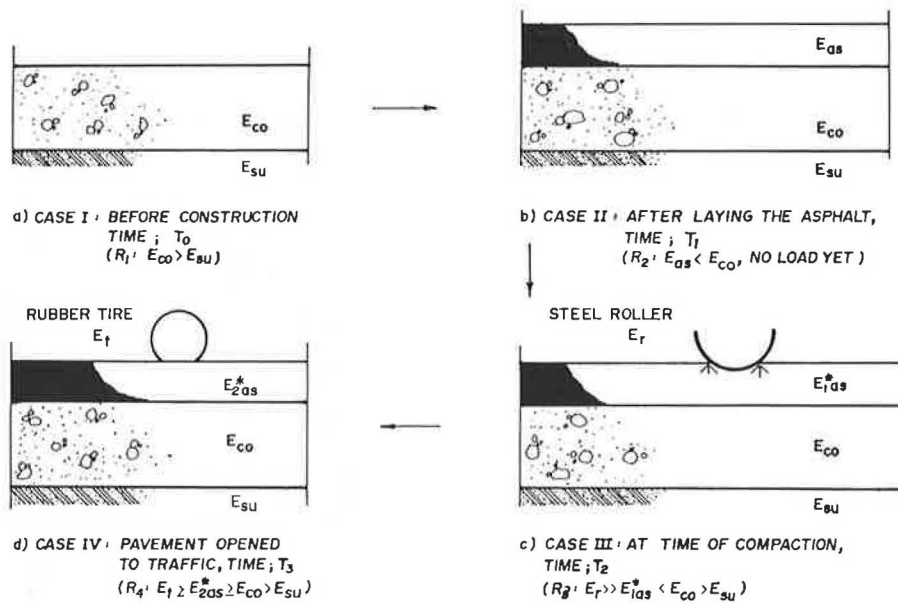


FIGURE 2 Four time stages of a new asphalt overlay.

distortion of the order of rigidities ($R_{load} > R_{asp} < R_{conct} > R_{sub}$) of the system in Case II, the third assumption could be stated:

3. For a distorted system, if a load is applied whose rigidity is extremely higher than the immediate underlying layer, deformation or "failure" should be expected to occur in this layer.

In other words, for the structure shown in Case II at time T_2 , the top layer (hot asphalt) with the smaller value of R will deform under the effect of the steel compactor. This deformation is in addition to the compacting effect produced by the imposed stresses. Furthermore, it is postulated that this deformation is independent of the stress value and only occurs because of the extremely high relative rigidity of the steel compactor in addition to the disorder observed in the rigidities of the pavement. Clearly, this hypothesized deformation could take different modes or shapes, such as cracks, separation, or waving.

In the following section these assumptions are thoroughly investigated and verified by using a multilayer elastic computer program called BISAR (5).

APPROACH OF VERIFICATION

The approach for treatment of the pavement structure in the light of the theoretical discussion is based on the principle of distortion or failure caused by the disorder of the system rigidities. Therefore, the following steps were carried out to verify the presented theory:

1. Establish a criterion that relates distortion to relative rigidity,
2. Use the results of step 1 to prove the concept of disorder rigidities versus matched rigidities,
3. Demonstrate that this concept is independent of the value of the applied load on the pavement structure, and
4. Indicate how to apply this theory once it is approved to the problem of reflection cracking.

Distortion Criterion

In mechanics it is well-known that the radius of curvature of a deflected beam is a function of both the stiffness of the beam and the computed moment. For simplicity of the analysis, a coefficient termed α , which indicates the distortion criterion, is defined as "the slope of deflection of the deflected interface $\tan \theta$ used instead of the radius of curvature; then for one layer a coefficient α would represent the ratio between $\tan \theta_1$ and $\tan \theta_2$ for the two interfaces of the layer in question, as shown in Figure 3."

From the definition,

$$\alpha = \tan \theta_2 / \tan \theta_1 = r_1 / r_2 \tag{2}$$

Clearly, when $\alpha = 1$, the structure could be evaluated as sound (e.g., case of a simple beam), and when $\alpha \neq 1$, the structure is distorted.

For the values of $\alpha < 1$, the failure is at the location of $\tan \theta_1$ (i.e., upper interface) and when $\alpha > 1$, the failure is expected to be in the bottom interface. It is worth noting here that simple beams that fail in tension would have $r_1 > r_2$ at the time of failure (i.e., $\alpha > 1$).

Distorted Versus Stable Structures

The coefficient established in the previous step was used in the analysis of more than 60 different pavement structures (1). Figure 4 represents the geometry and variables considered in this step. The results of this analysis are shown in Figure 5. It is clear from the figure that two different systems exist. The first is group A, which represents the stable structures with relative rigidities in order (i.e., $E_i > E_{i+1}$), whereas the structures in group B represent distorted systems and therefore need to be corrected. The value of α for structures in group B is less than 1, which indicates failure at the top interface (i.e., surface of the structure).

Influence of Stress

The third step of the analysis was carried out to investigate the effect of increasing the load value

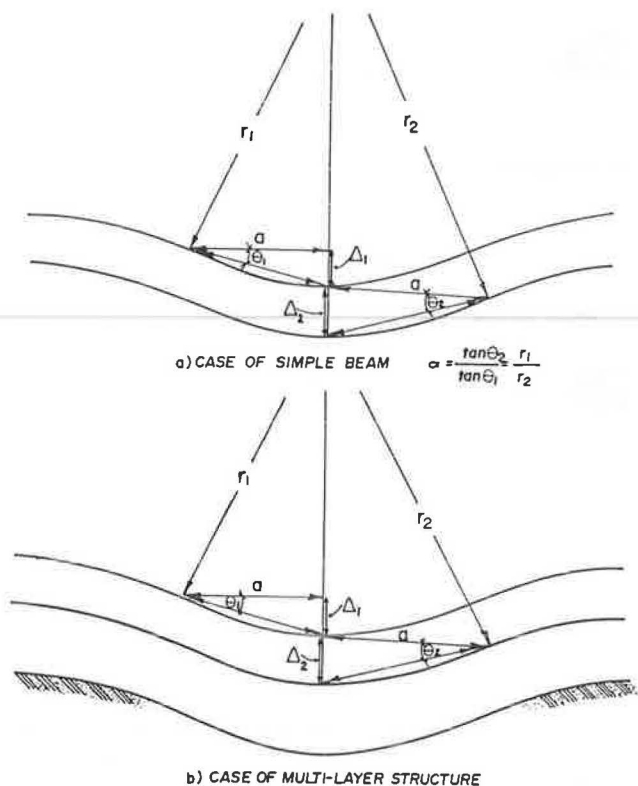


FIGURE 3 Details of the coefficient of distortion.

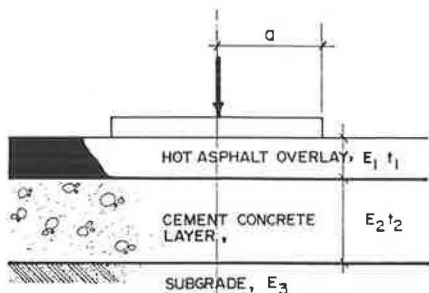


FIGURE 4 Outline of analyzed pavement structures.

and in turn the applied stresses on the computed value of α . As expected, the coefficient α proved to be independent of the value of the stress, as shown in Figure 6. This verifies the third assumption.

The results of these three steps could be summarized as follows:

1. The discussed theoretical modeling is sound;
2. The existence of a distortion in the pavement structures because of the disorder of the layer rigidities is proved;
3. The problem is not stress associated; therefore, reducing or increasing the loads has no effect on the output; and
4. The value of α in all the analyzed structures was less than unity, which indicates that the upper interface is a distorted one.

The presence of a soft layer with lower rigidity can be represented by the practice of overlaying cement concrete pavement at the time of construction. Therefore, the results of these analyses have led to the application of the same approach to investigate the problem of reflection cracking.

Influence of Relative Rigidity on Reflection Cracking

The problem of reflection cracking has been investigated and analyzed by many researchers (5-7). The recommended number of solutions for the problem to date has exceeded 10. These solutions range from using reinforced steel mesh in the asphalt overlay to the breaking of the existing rigid layer into smaller sizes (8-10). However, almost none of these investigations has looked into the problem at the time of construction. In the analysis carried out in this paper, two important results are related to reflection cracking. First, there is the existence of a distorted rigidity system in the pavement structure and the presence of a steel compactor on top of it. Second, the critical interface is shown to be the top one and not the one at the bottom. Most of these solutions treat the structure when it is opened to traffic and therefore analyze the structures in group A in Figure 5, which would suggest a stress-associated problem that must deal with the lower interface. Also, as is shown in the analysis, the

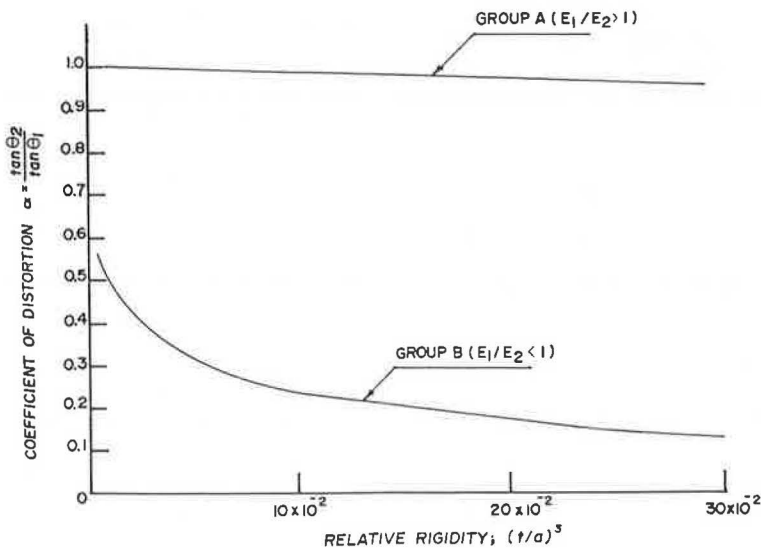


FIGURE 5 Influence of relative rigidity on pavement distortion.

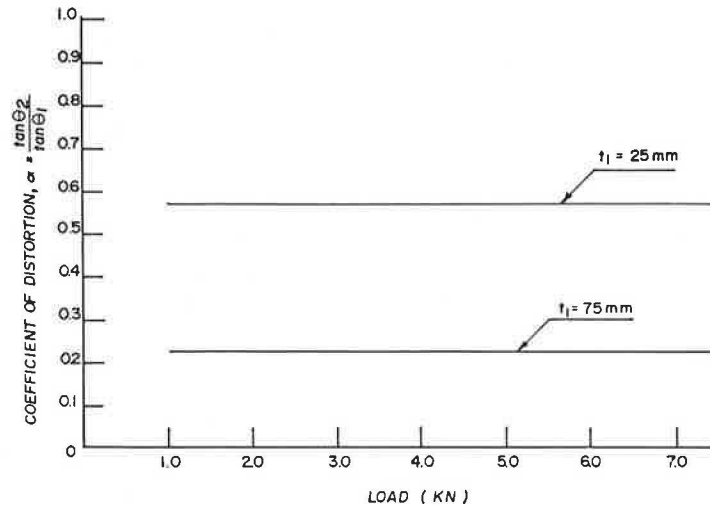


FIGURE 6 Relationship between applied load and coefficient of distortion.

presence of the crack in the existing rigid layer was not considered, yet the results indicate that cracks or deformation would exist in the top surface. Furthermore, the curve in Figure 5 would suggest that existence of cracks in the rigid layer (which could result in reducing its stiffness and therefore its rigidity) helps minimize the problem at the top. This is supported by field evidence that recommends the breaking of the rigid layer into small blocks, that is, increasing the number of cracks at the bottom (10,11). The analysis given in this section would suggest the following:

1. Reflection cracking is a construction problem that can develop at the very time the compactor rolls on the asphalt.
2. Very thin hair cracks could develop at the surface with the possibility of arresting them at the location of underlying crack.
3. These downward cracks would result in a loss in the total thickness of the overlayer and with traffic loading the remaining thickness would crack in fatigue over a short period of time.
4. The effect of cold cycles is not the main cause of reflection cracking; instead it represents a catalyst (the author heard of the same problem on a recent trip to Egypt, where the weather is hot).

CONCLUSIONS AND RECOMMENDATIONS

The analysis carried out in this paper has indicated that two different pavement structures exist, depending on the order of their relative rigidities. The first type is the structure that is designed on stress-strength criterion, whereas the other follows a geometric criterion. Of interest is the relationship between these latter structures and the problem of reflection cracking. Identifying the problem in the light of this new concept is a positive step in the right direction to solve the so-called reflective cracking problem.

Furthermore, the analysis indicated that the critical interface is the top one; therefore a more in-depth analysis has to be given to the interaction between the steel compactor and the new asphalt layer when it is laid on top of a rigid cement concrete layer. Also, although increasing the thickness of the asphalt layer represents a proven solution, it should be noted that the main purpose of this layer is the smooth surface rather than structural

strength. Clearly, the analysis here would reveal that increasing the thickness results in increasing fatigue life, but it would not affect the development of hairline cracks on the top of the layer. From these analyses it would appear that the most promising solution is to reduce the rigidity of the existing concrete layer and hence move the structure from group B to group A of Figure 5.

Finally, the following points could represent a guideline for the solution of the problem of reflection cracking:

1. If the concrete layer is to be kept intact, another compactor such as one with pneumatic tires should be used.
2. If a reinforcement layer is to be used, it must first be considered based on its function in reducing fatigue cracking rather than solving the reflection cracking problem. Furthermore, the presence of a steel reinforcement directly on top of the rigid layer would complicate the problem of reflection cracking, because it would increase the rigidity of the concrete layer at the time of compaction.
3. Investigating the problem in the laboratory should be considered at the time of construction as well as at the time of service.

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Suitability of Using the Falling Weight Deflectometer in Determining Deteriorated Areas in Jointed Rigid Pavements

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ABSTRACT

In this study the suitability of using the falling weight deflectometer (FWD) to determine deteriorated areas in rigid pavements was investigated. The FWD deflection basins of a few hypothetical concrete pavements of three types of deficiency conditions were calculated by using the finite-element analysis computer program WESLIQUID. These computed deflection basins were then compared with the deflection basin of a reference pavement that was in good condition. The three types of deficiency conditions studied were pavements with (a) weak subgrades, (b) voids in the subgrade beneath the concrete slab, and (c) deteriorated concrete slabs. Two FWD loading positions were considered: loading at the center of a pavement slab, and loading near the joint of the slabs. The results of the study indicate that the three different types of concrete pavement distress give three distinctly different FWD deflection basin shapes. The distinction among these three types of FWD deflection basins can be more easily understood by considering the differences between the FWD deflection of the pavement considered and that of a standard pavement of the same dimension that is loaded at the same position ($D-D_s$). The type and extent of the pavement distress could be determined from the shape and the magnitude of the $D-D_s$ plot. The results of the study also indicate that the effects of the joint are insignificant when the applied FWD load is far away from the joint.