Mechanistic Pavement Design

A Homogenized, Icey-tropic Half-What?

By Dr. David E. Newcomb and Dr. David H. Timm

This is the second installment in a series of *HMAT* articles on mechanistic pavement design. The first article (*HMAT*, September/October 2001) introduced mechanistic pavement design and gave an overview of the process. In preparation for the future unveiling of the new 2002 pavement design guide being developed under a National Cooperative Highway Research Program project, it is necessary that the industry gain a working knowledge of the methods used to understand their possible impact on the industry.

The backbone of a mechanistic design procedure is the mathematical model used to compute the stresses and strains in the pavement in response to vehicle loads. These stresses and strains, or pavement reactions are used to estimate the amount of damage done to the pavement by vehicle loads and subsequently how long the pavement will last.

The models are inherently complex, and to describe them any good continuum mechanics professor would use plenty of funny-looking symbols, Greek letters, and fifty-cent words to describe elegant pages filled with equations while economizing on English. To make you feel worse, the professor would explain, "This is intuitively obvious to the casual observer . . ." The objective of this article is the opposite. The reader can take for granted that many great minds have pored over countless articles in mathematical journals and chalkboards to come up with the theories employed in mechanistic design. Here, the basis for the models and some of their features are discussed in plain terms with the idea of providing background for what is to come.

Layered Elastic System

The model most frequently used in mechanistic pavement design is referred to as a "layered elastic system." All this means is different materials comprise layers in a pavement and that the model considers them to behave elastically. Elastic behavior means that however much a material is stretched or deformed due to a load, it will go back to its original shape immediately when the load is taken off (Figure 1). Obviously, this does not always happen in pavements or else rutting and shoving would not occur. It also requires time for asphalt to regain its shape, especially at warm temperatures. But, to try to account for this plastic or viscoelastic behavior would require much more complicated materials testing and pavement models. So, the idea is to start off simply by assuming that the pavement's behavior is mostly elastic.

Two other assumptions made about the materials are that they are homogeneous and isotropic. A homogeneous material is one that is the same throughout. Although soils, crushed stone base, and HMA all have localized areas of inconsistencies, these are considered small enough when compared to the thickness of the pavement layer that they will not have an impact on the pavement as a whole. The term isotropic means that the materials behave the same in all directions. This is unlikely because of the way pavement materials are placed and compacted. Any long and flat pieces will orient themselves sideways giving the material a different modulus or stiffness in the horizontal direction than in the vertical direction. But, again, the complexity of trying to determine this would make the time and cost of materials testing prohibitive.

When using a layered elastic system, the pavement layers are typically considered to extend infinitely in the horizontal direction, and the subgrade is considered to extend downward infinitely as well. Obviously, the pavement only goes to the shoulder or edge of the road, and the subgrade stops somewhere in the earth's crust. However, the edge of the pavement is far enough away from the wheel path that it won't influence the pavement's reaction to loads, and as long as the soil extends to some depth, say 5 or 10 ft, what's below it will not have a big impact on the pavement.

The tire load is modeled as having a circular contact area on the pavement with the stress applied downward uniformly over the area. Also, it is normally assumed that the contact pressure between the tire and pavement equals the inflation pressure of the tire. In reality, tires generally have an elliptical contact area and the stress varies across the width. With radial tires, the sidewalls generally cause most of the stress to occur at the tire edges. However, the distribution of stress changes according to the degree of tire inflation, and so it becomes very difficult to account for it.

The number of tire loads that can be modeled varies, most programs allow up to ten wheel loads at one time. Highway loads are generally handled by looking at a half-axle group, or one side of the vehicle. This is because the tires on the other side of the vehicle usually have little or no effect on the pavement where the half-axle group is being analyzed. Single wheels, dual wheels, tandem axles and tridem axles can be easily accommodated.

A sketch of what a layered elastic model with a tire load looks like is shown in Figure 2. Each material is represented by its modulus value (E) or stiffness and Poisson's ratio (μ) which is a measure of how much "give" a material has; stiffer materials offer more resistance to load. Each layer is defined by its thickness (h). The pressure of the tire (p) depends on how much load (P) is being placed on it and how big a radius (a) the tire has. The computer program can compute the stresses, strains, and displacements anywhere in the pavement system. However, the pavement's reaction to load is normally evaluated in terms of the deflection or displacement (δ) of the pavement on the surface directly below the load, the bending or tensile strain (ϵ_t) at the bottom of the asphalt layer, and the vertical compressive strain (ϵ_c) at the top of the subgrade. The deflection is an overall indication of the pavement system's (including the soil) ability to carry load. The tensile strain at the bottom of the asphalt layer is used to predict the resistance to fatigue failure due to repeated wheel loads. The compressive strain on the subgrade is a measure of the overall strength of the overlying pavement and its resistance to rutting. These will be discussed in greater detail in later installments on this topic.

Finite Element Model

Another type of model that can be used to represent a pavement is called the finite element method (FEM). While the term may not be entirely familiar, those skeletal representations of cars and jets shown on computer screens on educational shows and commercials are most often based on FEM. For a pavement, the mesh might look like Figure 3. The pavement is still divided into layers as already discussed, but each layer is subdivided both vertically and horizontally in a grid system . When a simulated load is placed on the pavement, the pavement reactions to loads are computed for each element or box and at each node where the grid lines intersect. As opposed to the layered elastic model, the layers in an FEM have sides and a bottom to them. These have to be located far enough away from the load to be insignificant to the pavement's reaction to load.

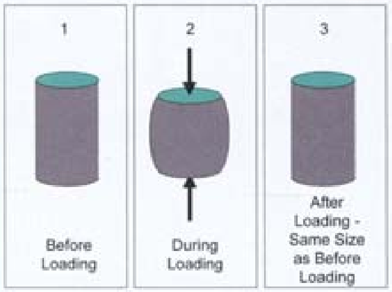

Figure 1. How an Elastic Material Behaves.

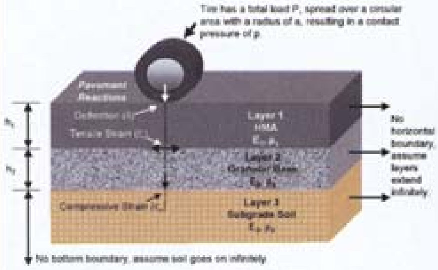

Figure 2. Layered Elastic Model Representation of a Pavement.

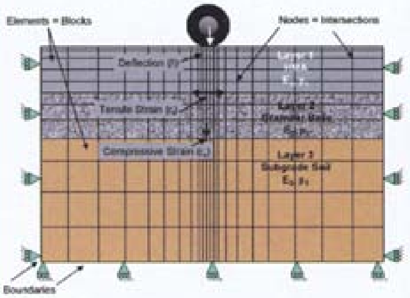

Figure 3. Finite Element Representation of a Pavement.

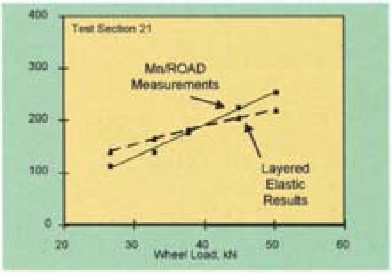

Figure 4. A Comparison of Measured Strains and Computed Strains at Mn/ROAD. (After Timm et al., 1998, Development of Mechanistic-Empirical Pavement Design, *Transportation Research Record No. 1629*, Transportation Research Board, Washington, DC.)

Mechanistic *continued*

The inputs to a finite element model are similar to a layered elastic model: material properties, layer thicknesses, load, tire pressure, etc. However, the material properties in FEM can be more exotic, venturing into viscoelastic or plastic, rather than just elastic. This also assumes that one has the capability of measuring or estimating these properties, which is very difficult to do. An FEM may also be used to simulate moving or dynamic loads on a pavement, whereas a layered elastic model must assume that the load is sitting still or static. To take advantage of this feature, the engineer must have a good understanding of how the materials respond to the moving load.

Figure 3 shows that the mesh in the FEM is not uniform, instead it is more refined in the area of the load and becomes coarser as the distance increases from the tire load. In general, greater mesh refinements provide more accurate results, but the tradeoff is in greater computation time. In order to balance efficiency and accuracy, the fine mesh is only used in the area of interest near the load. In most modern FEM programs, the mesh is generated automatically so the user does not have to bother with it.

Table 1. Comparison of Layered Elastic and Finite Element Method Models.

FEATURE	LAYERED ELASTIC	FINITE ELEMENT METHOD
Pavement System	• Layers extending infinitely horizontally • 3-dimensional	• Layers with boundaries, divided into elements • 2- or 3-dimensional
Material Properties	• Linear elastic • Isotropic • Homogeneous	• Can be linear elastic, non-linear elastic, viscoelastic, or plastic • Usually isotropic • Usually homogeneous
Number of loads	• Usually up to 10	• Usually 1 to 4*, but may have more loads
Type of loads	• Circular • Uniform distribution • Static	• Usually rectangular • May have non-uniform stress distribution • May be dynamic
Output	• Stresses • Strains • Displacements	• Stresses • Strains • Displacements
Chief Advantages	• Simple • Short run times • Used for 40+ years • Realistic results at Mn/ROAD	• Greater flexibility • Can analyze different type of loads • Can tailor material properties • Can analyze cracked pavement
Chief Disadvantages	• Lack of modeling options • Confined to static loads • Confined to linear elastic materials • Confined to uncracked pavement	• Can be very complex • Can be difficult to test materials for input properties

** Tandem loads require a 3-dimensional model.*

The output from the FEM is the same as from a layered elastic model: stresses, strains, and displacements. In the FEM, the strains and displacements are calculated at the nodes (intersections of the lines), and the stresses are calculated in the center of the elements (boxes). If the engineer wants to know what the stresses and strains are at the same point, interpolation is used.

Regardless of whether a layered elastic program or an FEM program is used to model a pavement, it is necessary to know if it is a good representation of the pavement structure. Figure 4 shows the comparison between loads and tensile strains at the bottom of the HMA layer of a pavement section at the Minnesota Road Research Project. The straight line shows what a layered elastic computer program calculates for the strain as loads increase, and the points show average, temperature-corrected strain readings taken from gauges in the roadway. While the comparison is not perfect, the computed strains seem to fairly represent the behavior measured in the field.

Most current mechanistic-empirical design methods use layered elastic analysis for evaluating pavement reactions. One exception is Illinois, which uses the FEM program ILLI-PAVE. It is anticipated that the new 2002 Pavement Design Guide will rely heavily on layered elastic models for its mechanistic-empirical design, with the possibility of having an FEM for special applications. A general comparison of layered elastic and FEM models is presented in Table 1. There are exceptions to the characteristics listed. Regardless of what model is used, the process should make the modeling portion of the design somewhat transparent. In other words, it should not be incumbent upon the user to have an advanced degree in Engineering Mechanics in order to apply the model in design.

In this article, the focus has been on the use of mathematical models in the pavement design process. However, it is also conceivable that the models will be used to develop design procedures that could focus more on such tools as easy-to-use equations or catalogs. It could be that the primary everday use for these models will be the analysis of special conditions on the roadway or in troubleshooting problems.

In the next installment of this series, the characterization of pavement materials for mechanistic design will be discussed in, "It's Still Dirt, Rocks, and Asphalt, Right?" HMAT

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