Mechanistic Pavement Design Methods – A Road to Better Understanding of Pavement Performance

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Abstract
Mechanistic-based pavement design methods are being developed in different countries in Europe and North America. The main objective of these methods is to adequately predict functional and structural conditions of roads over time. In the Nordic countries research activities have therefore intensified towards a better understanding of factors affecting pavement performances as a good understanding is the key feature of a successful design method. The most important factors that influence the performance and distress development of pavement structures are i) the cross section of the road construction, ii) the climatic conditions the pavement will be exposed to during its entire service life, iii) the traffic (axle) loading of the structure, and iv) the material properties of the different layers in the pavement structure. To be able to predict the functional and structural conditions of a road structure over time a good understanding of these factors is needed, including how they are linked mechanistically to performance and distress development. This paper discusses mechanistic pavement design and gives some examples from related research activities.

Introduction
The transportation infrastructure system is one of the main investments every modern society must make. It is therefore of great importance to base decisions on a well-founded design method and to have a good overview of the maintenance needed during a system’s service life in order to minimize both construction and maintenance costs. Pavement structures wear down and deteriorate under heavy loadings and exposure to climatic conditions such as very hot and cold temperatures, freezing and thawing and precipitation. The pavements must therefore be properly designed to begin with and the service life should be maintained and improved on a regular basis. To date, the main methods used worldwide to analyse and design pavement structures have relied on empirical correlations with past performance. However, these methods have severe limitations regarding performance prediction as background factors are often not very well understood and as they are not based on the principles of engineering mechanics.

New mechanistic-empirical pavement design methods are therefore being developed in different countries in Europe and in North America with the main purpose to adequately predict pavement response and performance. Two European projects have recently been completed: COST 333 “Development of new bituminous pavement design method” and AMADEUS “Advance methods for analytical design of European pavement structures” [3,5]. In both these projects the recommendations are that future pavement design methods should be able to predict functional and structural conditions of a road over time. A new design method in the USA, AASHTO 2002 Pavement Design Guide, also aims in this direction [1]. However, the need to predict road conditions over time puts great demands on the pavement designers. They need access to advanced
laboratory test results of the pavement materials which adequately simulate the most important aspect of the real behaviour of the pavement, traffic and climatic data, together with fast computers capable of handling the increased computational effort to perform the necessary calculations.

**Current Design Methods**

Flexible pavement design deals primarily with structural aspects such as the selection of appropriate materials, characterization of strength or load-carrying properties, and determination of layer thickness. The current design methods in the Nordic countries as well as in most countries in the world have relied mostly on empirical correlations with past performance, index-value-based characterization of material properties such as the layer coefficient, R-value or the California bearing ratio (CBR-value), as well as engineering judgement for design strategy selection.

Of course research has been carried out to justify the engineering judgements and a number of modifications in the design procedure have been made, but these design methods were based on empirical performance equations that were developed using the 1950’s AASHO Road Test data in Ottawa, Illinois in the USA [1,2]. Since then heavy lorry traffic volume has increased substantially. Furthermore the AASHO Road Test program was performed at only one geographic location so it is difficult to incorporate different climatic conditions into an interpretation of the results. Testing was limited to one type of subgrade in all sections and to only a limited number of different base courses and surfacing materials. These limitations along with other factors such as developments in construction techniques, different subdrainage conditions, and the long-term effects on pavements of climate and ageing make the empirical design approach obscure and difficult to apply.

**Mechanistic – Empirical Design Methods**

A mechanistic–empirical design method for a flexible pavement means application of the principles of engineering mechanics to evaluate the response of pavement structures to traffic loading and much improved design methods to carry out distress prediction or how performance changes with time. Using a method based on the principles of engineering mechanics would ensure a fundamental understanding of how the pavement structure responds to a certain action or loading conditions. This more realistic approach should also secure the needed flexibility; in other words, the method should be able to deal with new situations such as new pavement materials and loading situations.

A very important factor when using a mechanistic–empirical design method is the need to use testing equipment and set-ups in the laboratory which adequately simulate the most important aspects of the real behaviour of a pavement. Otherwise we can’t expect that our predictions will reflect real-world factors and results or predict actual pavement performance. This more meaningful approach would rule out some of the classical tests which have long been used in the structural design of pavements, such as the CBR test, and would replace these with tests that would yield more reliable results and therefore lead to more efficient decisions regarding road construction.

The most important factors influencing the performance and distress development of pavement structures are i) the cross section of the pavement structure, ii) the traffic (axle) loading of the structure, iii) the climatic conditions the pavement will be exposed to during its entire service life, and iv) the material properties of the different layers in the pavement structure. To be able to predict the functional and structural conditions of the road structure over time a good understanding of these factors is needed and including, importantly, how they are linked mechanistically to performance and distress development. A schematic overview of the most important factors affecting the performance of pavements is given in Figure 1.
After collecting all the necessary data regarding traffic and traffic growth, location and climate, the different materials to be used and their mechanical properties, the first step in constructing a design is therefore to carry out calculations based on the principles of engineering mechanics of the response of the pavement (i.e., stresses, strains, and deflections) under different wheel loadings and different environmental conditions. The analyses and therefore the testing must include the dynamic behaviour of the loading situation of individual wheels; their number, different weights and tyre pressures need to be considered, as well as environmental variables, such as changing temperature, frost/thaw conditions, and moisture content during the service life of the pavement.

The second step in the analysis is the prediction of structural and functional performance. Structural performance is related to the distress modes. For thin flexible pavements common in the Nordic countries the most important distress mode is usually rutting, but fatigue and cold climate cracking can be of importance as well. Furthermore, functional performance of the pavement such as riding comfort or riding quality needs to be calculated for the road over time.

Figure 2 gives a simple schematic overview of a mechanistic–empirical design procedure after specifying the initial geometry of the pavement at time $t = 0$. An initial time step is chosen, $\Delta t$ (e.g. one week) and traffic and material characteristics for that time step are evaluated, as well as the climate and environmental data for the period. Thereafter the response analysis is carried out with calculations of the stresses, strains, and deflections at different locations in the pavement structure. Now the performance model is applied to relate the response empirically to deterioration. The results are then added to the current damage conditions (which is zero before the first calculations for new roads), giving the status of rutting, cracking, faulting and riding quality at the time $t$. Then a new time step $\Delta t$ is taken, all input parameters are adjusted to correspond to this time period, the response as well as performance calculations are repeated, and the structural changes added to the current structural conditions. After a large number of iterations this procedure reveals the history of accumulated damage and functional performance as a function of time. A life cycle cost analysis (LCCA analysis) can thereafter be performed by comparing the development of different damage histories for a number of different types of pavements (layer thickness, type of material, etc.).
Figure 2. A sample flow diagram of an incremental design procedure.

Some of the benefits of the mechanistic–empirical design method over the empirical methods can be summarized as [1]:

- Inherently better suited to treat the real-life variety of environmental and wheel loading conditions.
- Estimations of new loading conditions, e.g. the damaging effects of increased loads, high tyre pressure and multiple axles.
- Better utilization of available materials.
- Seasonal effects can be included in the design.
- Benefits of providing improved drainage systems.

Furthermore, an additional important benefit of the mechanistic–empirical based approach includes ease of implementing future enhanced or improved knowledge.

Traffic Loading
An important factor affecting pavement performance is the number of load repetitions and the total weight a pavement experiences during its lifetime. In the empirical design procedure all axle loads were converted into a single number of Equivalent Single Axle Loads or ESAL’s. As this does not correspond to the real loading, more detailed information is needed or the full axle load spectra for single, tandem, tridem and quad axles. Based on Weigh In Motion (WIM) data the full axle load spectra can be established.

Material Characteristics
The ability to calculate the response of pavement structures due to vehicle load depends on a proper understanding of the mechanical properties of the constituent materials. This is essential. Most pavements in the Nordic countries are flexible pavements. They are usually built up of bitumen bounded or unbounded granular layers. In general they show complex non-linear viscoelastic-plastic behaviour under external loading. Furthermore, bituminous bounded materials are temperature dependent and the response of unbound material depends on the moisture content.
[4,6,9,11,12,13,14,15,16]. This must be taken into account in a mechanistic–empirical pavement design method in order to achieve a good prediction of pavement performances. However this is both complicated and requires sophisticated laboratory test results and the design analyses become time consuming.

The Climatic Conditions and Seasonal Variation of Material Properties

The mechanical parameters of both bounded and unbound layers in pavement structures are seasonally affected. It is therefore important to understand their seasonal variation in order to be able to predict their effect on pavement performance. For instance, asphalt concrete shows visco-elastic-plastic behaviour which is very temperature dependent, and stiffness and permanent deformation characteristics of unbound materials show some moisture content dependency. Environmental monitoring programs where temperature, moisture content and frost penetration in pavements are collected and related to bearing capacity are therefore of great importance [8].

Figure 3. Volumetric moisture content development for a thin pavement structure with unbound base course during a spring thaw period. The moisture content is shown on a contour plot as different colours, as indicated on the vertical bar to the right in the figure.

Figure 3 shows one example from the environmental monitoring program run by the Public Roads Administration in Iceland where the development of volumetric moisture content (the ratio of the volume of water and dry material) is shown at Dyrastadir in Nordurardalur in SW Iceland during the spring thaw period. One can see clearly that as the thawing period starts in early March the moisture content increases initially closest to the surface and then penetrates deeper into the structure before it slowly reverts back to normal values. As the moisture content affects the stiffness of the structure as well as the permanent deformation characteristics increased deterioration or damage is expected during this period if no axle load limitations are applied.
Validation

A very important task in developing a new design method is validating it or calibrating the predictions to observed field performance. Prediction of pavement performance during its entire life is a very difficult task due to many reasons such as deviation of the amount of expected and real traffic, variation of material properties along the road, and different construction techniques and practices [7,10,18]. It is therefore very important to validate the design methods by field testing, such as in Accelerated Pavement Testing (APT), using, for example, a Heavy Vehicle Simulator (HVS) such as the one owned by VTI and VTT in Sweden and Finland respectively.

Figure 4 shows an example of a comparison between a response calculation and real measurements of vertical induced stresses for a thin pavement tested with the HVS at VTI in Linköping in early 2000 and, using the same structure, Figure 5 shows the measured and calculated accumulated permanent deformation as a function of the number of load passes[7].

![Figure 4: Vertical induced stresses as a function of depth for a thin surface treated unbound pavement structure under single wheel loading conditions. Black dots are actual measurements and the different coloured lines are based on response calculations using different techniques. MLET = multilayer elastic theory, FE = finite element, LA = linear elastic analysis, NLE = non-linear elastic analysis.](image)

One can see from Figure 4 the induced vertical stress under the centre of the single tyre load on a thin pavement structure as a function of depth for tire pressure $p = 900$ kPa and axle load $W = 120$...
kN. The figure demonstrates the importance of taking into account the nonlinear base behaviour for thin structures under high loading conditions. The linear analyses overestimate the stresses in the upper part of the structure, but in the lower part of the subbase and in the subgrade both the linear as well as the nonlinear analyses agree quite well with the actual measurements.

Figure 5. Development of rutting or permanent deformation vs. number of load passes for a thin surface dressed pavement structure with unbound base course. Black dotted lines are actual measurements on top of the subgrade, subbase and the base course, and the coloured lines are their predictions.

The calculation of the permanent deformation developments in Figure 5 is based on a simple three parameter model by Tseng and Lytton, (1989) [17], where triaxial test results have been used to adjust the model parameters.

Conclusions

Current pavement design procedures—known as empirical procedures—are based on engineering experience from observations of the relationships between pavement performance, traffic load and pavement thickness for a particular region and climate. The empirical procedures are opaque, not theoretically well founded and difficult to use in new situations. Mechanistic–empirical design procedures are based on material properties and how those properties relate to pavement performance. Mechanistic–empirical based design methods will probably be in use in many countries in the near future. To be able to use such methods we need to obtain information for modelling purposes on factors affecting pavement performances, such as axle loading and configurations, material properties of the different layers, and weather and environmental conditions. In addition, we need information to calibrate and validate such methods if acceptable
agreement between real performance and predictions is to be achieved. Mechanistic procedures allow engineers to tailor pavement designs to specific materials, environments and traffic loads.

References


