Flexible Pavement Design: Transitioning from Empirical to Mechanistic-Based Design Methods

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INTRODUCTION

A typical flexible pavement structure in Malaysia consists of asphaltic concrete wearing and binder course, unbound granular base and sub-base overlying the subgrade(Figure 1). Presently there is a shift in the approach of flexible pavement structural design from empirical to mechanistic methods. The AASHTO "2002 Guide for the Design of New and Rehabilitated Pavement Structures" (currently under review) is based on mechanistic method rather than empirical method, which is the basis for the 1993 and earlier editions of the AASHTO Pavement Design Guide. Two major organizations, Shell in 1978 and Asphalt Institute in 1981 have produced mechanistic design procedures for the design of flexible pavements. Worldwide, it has been reported that South Africa has long used the mechanistic design method for their pavement design (since late 1970's). Australia in 2004 released their pavement design manual that adopted mechanistic design procedures. Jabatan Kerja Raya Malaysia (JKR) has released in late 2006 a draft flexible pavement design manual based on mechanistic design procedures.

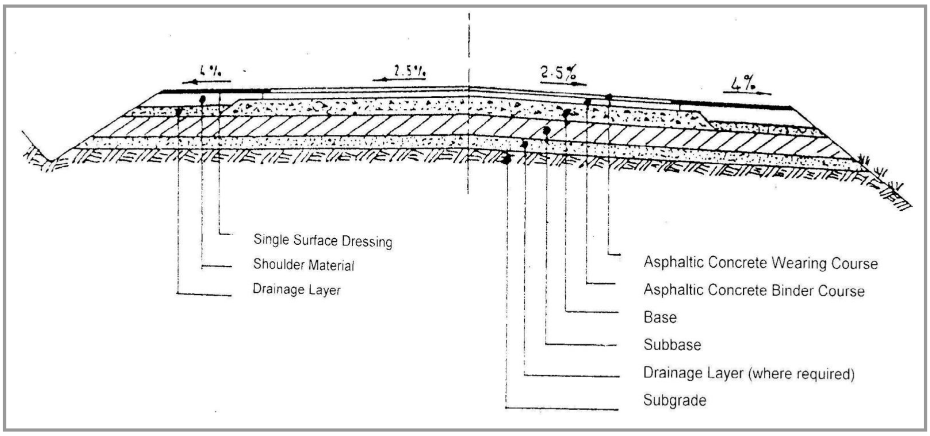


Figure 1: Typical flexible pavement cross-section in Malaysia

EMPIRICAL PAVEMENT DESIGN METHODS

Empirical procedures are derived from experience or observation alone, often without due regard for system behaviour or pavement theory. The basis for the empirical design approach are the empirically derived relationships between performance, load and pavement thickness for a given geographic location and climatic condition. From these relationships, the required pavement thickness, the number of load applications or the occurrence of distresses is a function of factors such as pavement material properties, subgrade type, traffic loading and climate. The Arahan Teknik (Jalan) 5/85 – Manual on Pavement Design, AASHTO 1986/93 Pavement Design Guide and Road Note 29 design methods are empirically-derived design procedures based on the observed field performance. There are a number of limitations to their continued use for pavement design in this country. Among the limitations include the following:

- The AASHTO Guide was based on the 1950s AASHO Road Test data, whereby the conditions are site-specific and is applicable only to those areas with the same characteristics such as soil type, pavement material type and climate. Therefore, its applicability for Malaysian conditions is questionable as Malaysia has a totally different soil and material characteristics and different type of climate.
- In the AASHO Road Test, traffic loadings of about 1,114,000 axle loads had been applied. Extrapolation, to say, 10 million ESALs for pavement design calculations is unrealistic given the high number of loading repetitions and the different conditions assumed such as different subgrade value.

MECHANISTIC-BASED PAVEMENT DESIGN METHODS

The mechanistic-empirical method of design is based on the mechanics of materials that relates an input, such as wheel load, to an output (or pavement response), such as stress or strain. The response values are used to predict pavement distress such as rutting/permanent deformation and fatigue cracking (Figures 2a and 2b) based on laboratory stress and field performance data.

Figure 2a: Fatigue cracking

Figure 2b: Rutting

Mechanistic design methods offer many advantages over the empirical method such as the following [1]:

i. It allows an evaluation of changes in vehicle loading on pavement performance;

ii. New materials can be evaluated through their design properties;
iii. The impact of variability in construction can be assessed;
iv. Actual engineering properties are assigned to the materials used in the pavement;
v. Pavement responses related to actual modes of pavement failure are evaluated;
vi. Databases of materials used as input in pavement design can be developed and updated as information becomes available.

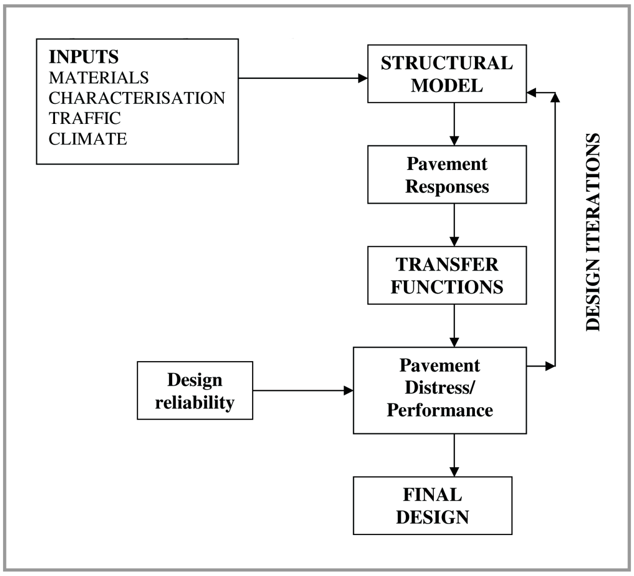


Figure 3: Components of Mechanistic Design Process [2]

The biggest advantage to mechanistic design is that it allows a rapid analysis of the impact of changes in input items such as changes in materials and traffic [1].

FRAMEWORK FOR MECHANISTIC DESIGN METHOD

Figure 3 shows the components of the mechanistic design process [2]. The three main components of the process are input parameters, structural model and transfer functions.

a) Input Parameters

Input parameters consist of pavement configuration, material properties for each pavement layer and expected traffic. Pavement configuration includes the number of layers, the thickness of each layer and type of material for each layer. Material properties that are required as

Table 1: Typical Resilient Modulus and Poisson's Ratio Value [1]

Material	Resilient Modulus (MPa)	Poisson's Ratio
Asphaltic Concrete (21oC)	3,500	0.35
Crushed Stone	150-300	0.40
Clayey Soils	35-100	0.45

inputs include resilient modulus and Poisson's ratio of each pavement component layer (Table 1). The material properties are modified to take into account of the climate such as temperature and moisture from rainfall. Traffic loadings include axle loads, the number of load repetitions, tyre pressure and contact area and vehicle speed. Load repetitions are normally expressed in terms of equivalent 80 kN (18,000 lb) single axle load with dual tyres (ESAL), approximated by two circular loaded areas. Recent advances in weigh-in-motion equipment have made possible the measurement of the actual load spectra of vehicles, but presently available methods use the ESAL method.

b) Structural Model

A pavement structure can be modeled as a multi-layered elastic system or as a finite element mesh representation (Figures 4 & 5). Regardless of whether a layered elastic program or a Finite Element program is used to model a pavement, what is important is that the model, while not perfect, fairly represents the behaviour of pavement in field. Most current mechanistic design methods use layered elastic analysis for evaluating pavement responses (stress, strain and deflection). The analysis is carried out using computer software such as KENPAVE (by Huang), SW-1 (by Asphalt Institute), BISAR/SPDM (by Shell) and CIRCLY (by MINCAD Systems Pty Ltd, Australia).

The critical stress or strain is the maximum value of that stress or strain that occurs in the pavement system under the given loading conditions. It is crucial to know where the location and what is the maximum value of the critical stress and strain so that materials of adequate strength and thickness can be specified to prevent pavement failure under the actual loading conditions. For a typical flexible pavement consisting of the asphaltic concrete, crushed aggregate base, granular sub-base which is supported by the subgrade, the locations of critical stress/strain are shown in Figure 6.

Two particular locations of concern are tensile strain at the bottom of the asphalt concrete layer and compressive strain at the top of the subgrade. The

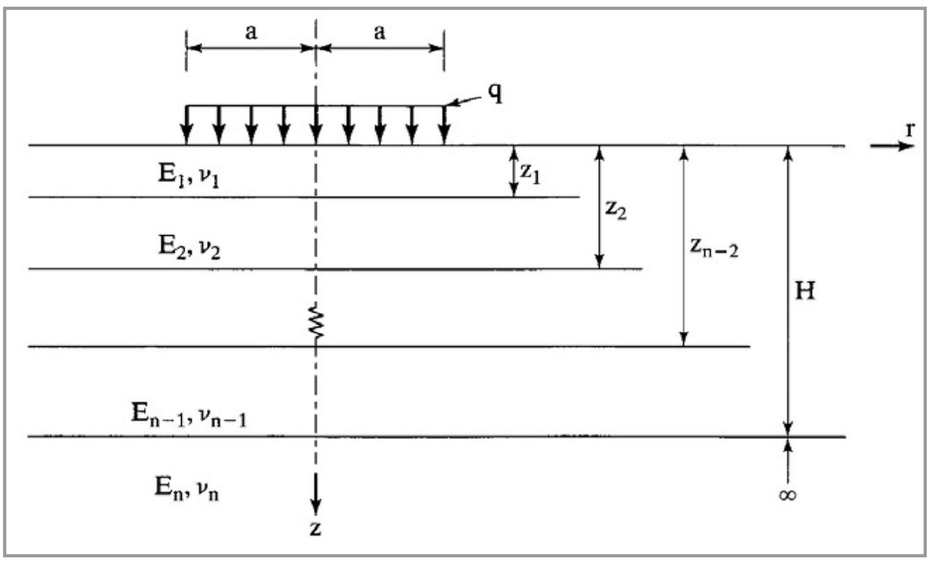


Figure 4: Multilayer elastic model [3]

tensile stress at the bottom of the asphaltic concrete layer under repeated traffic loading will cause cracks to propagate upwards leading to the formation of fatigue cracks. Pavement rutting results from repeated vertical stress on the top of the subgrade. Two other areas of concern are the compressive strain at top of the asphaltic concrete layer and the compressive strain at the top of the crushed aggregate base which leads to the rutting of the pavement structure.

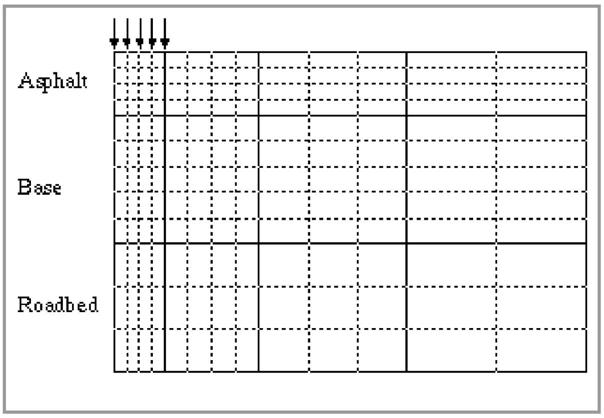
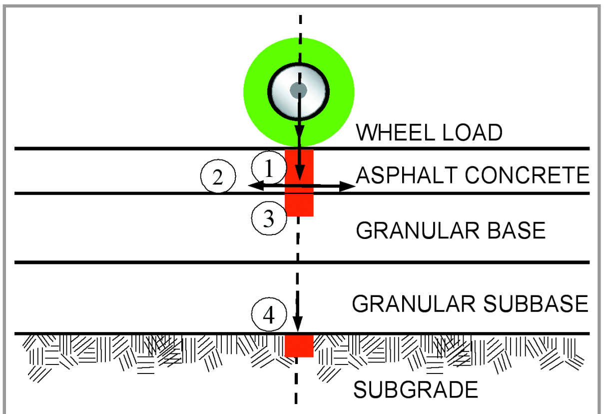


Figure 5: Finite element model [4]



Note:
1 Compressive strain on top of asphaltic concrete surface – rutting
2 Tensile strain at bottom of asphaltic concrete – fatigue cracking
3 Compressive strain on top of granular base – permanent deformation
4 Compressive strain on top of subgrade – permanent deformation

Figure 6: Critical stress/strain locations in a conventional flexible pavement

c) Transfer Functions

The analysis output of stresses and strains are then used in transfer functions to relate them to the predicted pavement performance. A transfer function is an equation that is used to predict pavement life in terms of number of axles repetitions to failure for major pavement distresses such fatigue cracking of the asphaltic concrete layer or permanent deformation of the subgrade.

Asphalt Institute use the following transfer functions which relates the strains calculated to the number of traffic load repetitions to failure for a particular type of pavement distress [5]:

i) Fatigue Cracking (20% of area cracked):

$$N_f = 0.0796\,(\varepsilon_t)^{-3.291}\,|E^*|^{-0.854} \quad \ldots(1)$$

where:

N_f = allowable number of load repetitions to control fatigue cracking

ε_t = horizontal tensile strain at the bottom of the asphaltic concrete layer

$|E^*|$ = dynamic modulus of the asphaltic concrete mix

ii) Subgrade Permanent Deformation (0.5 in rut depth):

$$N_d = 1.365 \times 10^{-9}\,(\varepsilon_c)^{-4.477} \quad \ldots(2)$$

where :

N_d = allowable number of load repetitions to control permanent deformation

ε_c = vertical compressive strain on top of the subgrade layer

Design charts (Figures 7 and 8) based on mechanistic design method have been developed by Asphalt Institute and Shell to simplify the calculations required for the design of flexible pavements.

IMPLEMENTATION PROBLEMS

Although mechanistic design approach appears to be promising as a suitable and rational design approach for flexible pavements, there are several issues that needs to be resolved before the approach can be implemented. Materials characterisation of subgrade, different types of sub-base and base and asphaltic concrete require the determination of physical properties such as resilient modulus (M_R) and Poisson's ratio (υ). The acquisition of equipment is very expensive and personnel have to be trained to operate the equipment properly in order to obtain consistent and reliable data results.

Traffic loadings require more than just traffic count currently being practiced in this country. Actual traffic axle spectrum is required for a more realistic estimate of traffic loading. This however requires special equipment such as WIM and additional weighing stations and requires more effort in classifying and collecting the actual traffic loading data.

Transfer functions that relate pavement distress (permanent deformation and fatigue cracking) to the number of axle repetitions to failure must be tested and verified in the actual pavement operating conditions. The Asphalt Institute's or Shell's failure criterions are at best only estimates unless properly verified. Verification requires effort in collecting data for the representative test road sections identified for the study. Data collection includes serviceability, traffic, subgrade support, pavement cross-section and environmental conditions necessary for the study.

Software availability should be considered before the implementation of mechanistic design approach. Developing a customized software is time-consuming and requires a lot of effort. However, there are some reliable and affordable software to users such as SW-1 by Asphalt Institute. Also, the KENPAVE software comes free with the purchase of the accompanying pavement design textbook [3].

Finally, there are not many experienced engineers exposed in the mechanistic design of pavements in this country. Seminars and courses should be conducted to expose and train engineers in mechanistic design of pavements. Guidelines for mechanistic design should also be developed. As a starting point, guidelines from other countries experienced in using mechanistic design such as Australia, France and South Africa should be considered as a basis for developing a guideline in this country. Further refinements can then be made through local research and increase data as they become available in the future.

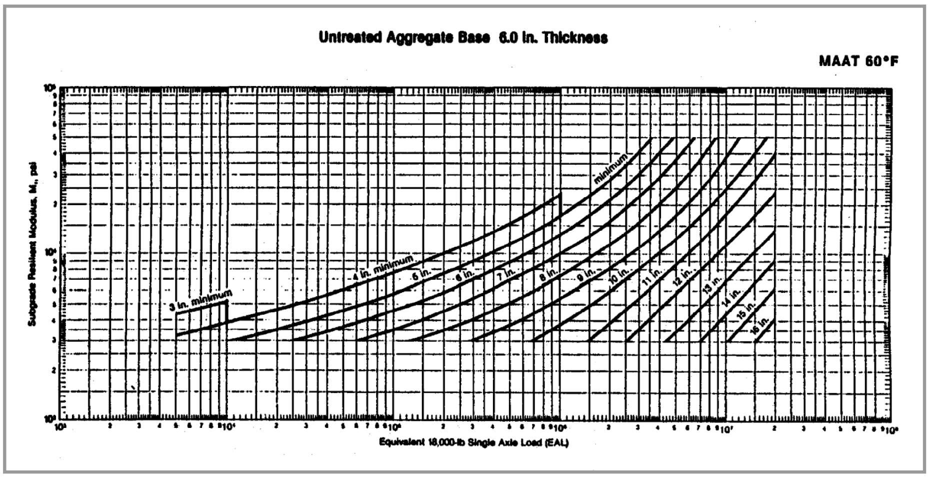


Figure 7: Example of Asphalt Institute's design chart [5]

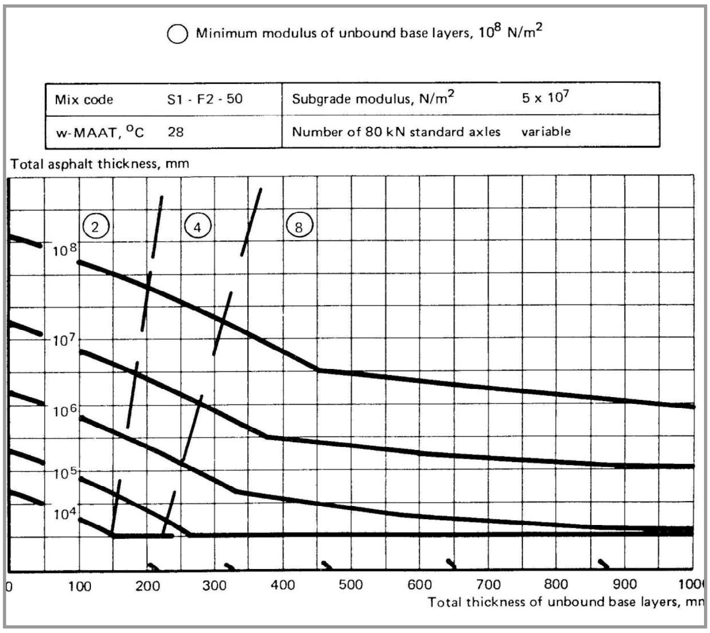


Figure 8: Example of Shell pavement design chart [6]

CONCLUSION

Mechanistic design of flexible pavement has been discussed in the above sections. Presently, the trend worldwide is to use the mechanistic design approach as it provides a more rational and logical approach to pavement design. The advent of personal computers and the availability of commercial software for multi-layered analysis and total pavement design packages have further simplified the rigorous calculations required for mechanistic design. In order not to be left out, Malaysia must initiate it's own mechanistic design procedures so that pavement design procedures are more in line with other advanced countries. Research into local materials characterisation must also be done to reflect the actual properties of materials to be used as data input in the design. ■

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