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Development of Mechanistic-Empirical Flexible Pavement Design in Iran

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Abstract: Recent advances in flexible pavement design have prompted agencies to move toward the development and use of Mechanistic-Empirical (M-E) design procedures. Mechanistic-Empirical (M-E) design combine the elements of mechanical modeling and performance observation in determining the required pavement thickness for a set of design condition. In this study, a Mechanistic-Empirical (M-E) design procedures and algorithm based on KENLAYER software with regard to Iran climatic and traffic conditions is developed. This study also explores present relationships and diagrams based on effective variable on pavement design to facilitate design process.

Key words: Pavement design, mechanistic-empirical, KENLAYER, axle load

INTRODUCTION

Pavement Design is a complex process, since it involves many variable factors, such as dynamic loading, nonlinear material properties and environmental conditions. Usually the design factors for flexible pavement design are divided into four broad categories (Huang, 2003) that are traffic and loading, environment, material and failure criteria.

During the development of the 1986 AASHTO guide, it was recognized that future design procedure would be based on Mechanistic-Empirical principles (National Cooperative Highway Research Program, 2004). Over the past 20 years there has been a tendency for road agencies to direct their efforts toward Mechanistic-Empirical (M-E) method (Prozzi and Madanet, 2002). Probably this was the reason thus AASHTO replaced its 1993 empirical design method with the more reliable Mechanistic-Empirical (M-E) design method in 2004.

Mechanistic-Empirical (M-E) design combines the elements of mechanical modeling and performance observation in determining the required pavement thickness for a set of design condition.

The mechanical model is based on elementary physics and determines pavement reactions to wheel loads in terms of stress, strain and displacement. The empirical part of design uses the pavement responses to predict the life of the pavement on the basis of actual field performance. Specific advantages of M-E design over traditional empirical procedures are that as follow (Timm *et al*., 1998):

- Consideration of changing load types
- Better utilization and characterization of available materials
- Improved definition of the role of construction by identifying the parameters that are most influential over pavement performance
- Relation of material properties to actual pavement performance
- Better definition of the existing pavement layer properties and
- Accommodation of environmental and aging effects of materials

At the present time, AASHTO method (American Association of State Highway And Transportation Officials, 1993) is the most creditable method, which is used in Iran for design of pavement structure. The major drawback of this method of flexible pavement design is its dependency on the specific conditions for which they are derived.

Any change in material, loadings, environmental conditions and assumptions would reduce the accuracy and increase the error. The objective of this study is to present M-E design process in Iran. This process has been defined for pavement design since 2004 (Khavandi, 2004).

DEVELOPMENT OF MECHANISTIC-EMPIRICAL PROCEDURE

The pavement design in this study, is based on valid and creditable scientific-mathematical theories in which factors such as exiting facilities particularly laboratory and other necessary data effective in pavement design such as CBR, temperature, etc have been defined. Figure 1 shows the process proposed for the proposed M-E

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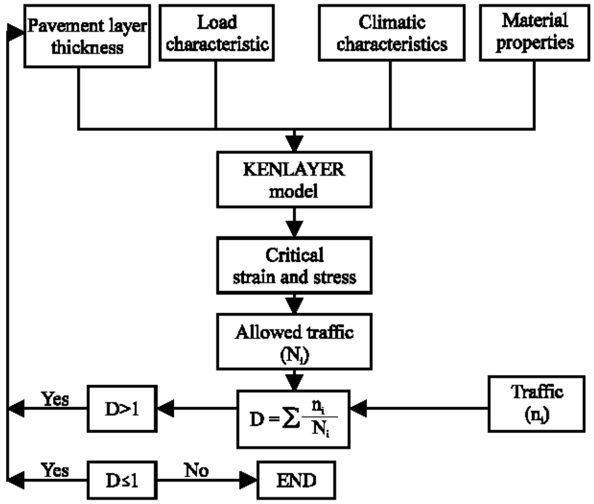

Fig. 1: Axle proposed M-E design flowchart

design. One advantage of the process, common to most M-E design processes is iterative loops.

Material properties: Since the phenomenological behavior of any real material is extremely complex, therefore certain idealization of material behavior are inevitable. It is well known that pavement materials exhibit non-linear viscoelastic-plastic behavior and are generally depended on loading time, stress level, temperature and moisture content. It is presently not possible to account for every factor influencing the responses of in-service pavements. Therefore simplifications are necessary.

The most significant material properties in the proposed M-E method, is elastic modulus and poison ratio. Until recently in Iran, traditional CBR test was the only laboratory test performed on base, subbase and subgrade materials. In order to utilize these data in M-E design, the correlation charts for treated and untreated granular base and subbase materials presented in the AASHTO (1993) guide used for granular materials.

In the proposed method, the air temperature data are used to account for the effect of temperature on moduli of asphalt mixture. The relationship between mean pavement temperature (Tp) and mean monthly air temperature (Ta) is based on the depth below pavement surface (z) as presented by Eq. 1 (Asphalt Institute, 1997). The elastic modulus of asphalt layer is calculated using Eq. 2 (Timm *et al*., 1998).

$$T_P = \{[1.8T_A + 32)(1+\frac{1}{\frac{7}{2.5}+4})] - [\frac{34}{\frac{7}{2.5}+4}] - 26\}\times 1.8 \qquad (1)$$

Table 1: Poisson ratio (Timm *et al*., 1998)

Pavement temperature (degree Celsius°C)	Poisson
1	0.20
10	0.20
25	0.35
30	0.50

Where:

T_p = The average Asphalt layer temperature (°C)
T_a = The average air temperature (°C)
Z = The average Asphalt layer thickness (cm)

$$E_{AC} = 170272.6\times e\left[\frac{(T_P+26.2)^2}{-1459.7}\right] \qquad (2)$$

Where:

E_{AC} = Modulus of hot mix Asphalt concrete (kg m^{-2})
T_p = The average Asphalt layer temperature

Annual average elastic modulus of Asphalt layer is determined based on the weighted average modulus of Asphalt layer for each month.

The information of Poisson ratio is also one of the other properties of materials that is required in the proposed M-E method. However, because Poisson ratio has a relatively small effect on pavement responses it is customary to assume a reasonable value for use in design, rather than to determine it from actual tests. In the present study, the Poisson ratio for base and subbase layers is considered 0.4 and for subgrade, 0.5.

Conducted researches and investigations have demonstrated that Poisson ratio of the Asphalt is affected by the pavement temperature. The values of Poisson ratio for the Asphalt based on the changes in temperature are shown in Table 1 (Timm *et al*., 1998).

Traffic: Proper consideration of traffic loading in pavement design requires knowledge of full axle load distribution by the main axle types, including single, tandem and tridem axles. Although the equivalent single axle load concept has been used since the 1960s foe empirical pavement design, the new mechanistic-based pavement design procedure most likely require the use of the axle distribution.

Conducted research has shown that majority of heavy vehicle traveling on paved roads in Iran have axles loads and wheels configurations shown in Fig. 2.

The distance of axles and the distance of wheels from each other are also among the effective factors in the pavement performance which leave some impact on the

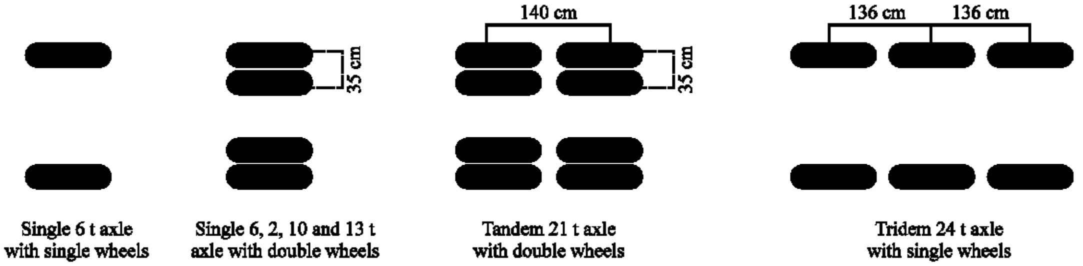

Fig. 2: Axle loads and wheel configurations of vehicle traveling on paved roads in Iran

Table 2: Distance of axels and wheels

Location	Axle distance (cm)	Wheel distance (cm)
The back axle of truck	140	35
The back axle of truck	145	35
The back axle of truck	205	30
The back axle of trailer	200	35
The back axle of trailer	210	35
The back axle of trailer	230	30

degree and intensity of road destruction. Table 2 shows the distance of axles and the distance between the double wheels for different trucks in Iran. In the analyses and graphs presented in this article, the distance between axles and also the distance between the double wheels are considered 140 and 35 cm, respectively (Fig. 2). It is worth mentioning that in the case of Tridem 24 t axle with single wheels, the distance between axles is 136 cm which should also be considered in proposed pavement design (Fig. 2). Tire pressure also considering different types of tires in Iran, the size of the wheels and load on each axle is variable.

MECHANISTIC COMPUTER MODEL

As described earlier and shown in Fig. 1, material properties and load configurations are entered into a mechanistic-based load-deformation computer model.

The mechanistic-based load-deformation model is the heart of M-E design process and determines pavement response to applied loads. There are many models available, including linear layered-elastic, nonlinear layered-elastic, elastoplastic, viscoelastic and viscoplastic.

In proposed M-E method, using the computer software KENLAYER whose validity and credibility is proved by Huang (2003) all pavement are analyzed.

The KENLAYER computer program can be used to analyze a multilayer elastic pavement structure by cumulative damage techniques for a single, dual and multiple-wheel system.

Transfer functions: The empirical component of M-E design is pavement life equation, known as a transfer function. Transfer function use pavement responses calculated by the mechanistic model and predict the life of pavement in terms of fatigue cracking or rutting. In fact, Transfer functions act as a chain between the pavement reactions and appeared damages in the pavements. Transfer functions presented in this study are (Asphalt Institute, 1999; Khavandi, 2008):

$$N_f = 6\times10^{-10} (\epsilon_t)^{-4.59} \tag{3}$$

$$N_d = 1.365\times10^{-9} (\varepsilon_c)^{-4.477} \tag{4}$$

Where:

ε_t = The maximum tensile horizontal strain at bottom of Asphalt layer
E_t = Asphalt layer elastic module
ε_c = The maximum compressive vertical strain at the top of the subgrade
N_f = Number of allowed loads until fatigue cracking occurs
N_d = Number of allowed loads until rutting occurs

After the numbers of applied and allowable loads have been determined, miner hypothesis is used to quantify accumulating damage in terms of rutting or fatigue, over the life of the pavement.

When damage exceeds unity, the pavement has been under designed and thickness will increase. If the damage is much less than unity, the pavement has been over designed and thicknesses are decreased. An optimum design is achieved when the damage is near but not exceeding 1.

Miner's hypothesis:

$$D = \Sigma \frac{n_i}{N_i} \tag{5}$$

Table 3: Variables and their values

Variable	Values
E_{subgrade} (psi)	3000, 7500, 15000
E_{asphalt} (psi)	1.2×10^5, 5.6×10^5, 1.5×10^6
E_{base} (psi)	30000, 35000
E_{subbase} (psi)	15000, 20000
T_{Asphalt} (cm)	10, 8
T_{base} (cm)	15, 30
T_{subbase} (cm)	15, 30
t_{pressure} (psi)	80, 90, 100
$^*t_{\text{pressure}}$ (psi)	95, 105
Axle weight (t)	6, 8.2, 10, 13, 21, 24

*Tire pressure for 24 ton tridem Ax

Where:

D = Total fatigue or rutting damage
n_i = Applied number of i axle
N_i = Allowable number of i axle

PROPOSED EQUATIONS FOR M-E DESIGN

The computational techniques of KENLAYER computer program are complex and cumbersome to be used for routine design. To incorporate KENLAYER structural model into a M-E method, simplified analytical equations that reliably predict KENLAYER response solutions for typical flexible pavements are needed.

The first step in developing theses equations is to create a data base. A 3*3*2*2*3*(2, 1)*(5, 1) full factorial data base totaling 1836 cases was created. Table 3 shows the specific values of pavement variables. Multiple regression was then applied to the response data to develop best fit equations. The results of the regression resulted in the following equations:

Proposed equations for 6 t single-axle with single wheel:

$$\varepsilon_t = 0.150437(0.903339^{T_{\text{asphalt}}\text{Log}E_{\text{asphalt}}})(1.63199^{T_{\text{asphalt}}})(1.006319^{T_{\text{pressure}}})(0.264417^{\text{Log}E_{\text{base}}})(0.99727^{T_{\text{base}}})$$

$$R^2 = 98.96\% \tag{6}$$

$$\varepsilon_C = 0.014951(0.99799^{E_{\text{subgrade}}/\text{Log}E_{\text{subgrade}}})(0.993646^{T_{\text{base}}})(0.999988^{E_{\text{subbase}}})(0.964131^{\text{Log}E_{\text{asphalt}}T_{\text{asphalt}}})(1.000389^{E_{\text{subgrade}}})(0.98703^{T_{\text{subbase}}})$$

$$R^2 = 99.34\% \tag{7}$$

Proposed equations for 8.2,10 And 13 t single-axle with double wheels:

$$\varepsilon_t = 0.259421(0.93637^{T_{\text{asphalt}}\text{Log}E_{\text{asphalt}}})(0.999999^{E_{\text{asphalt}}/\text{Log}E_{\text{asphalt}}})(1.346352^{T_{\text{asphalt}}})(1.004334^{T_{\text{pressure}}})(1.059582^{W_{\text{load}}})(0.22101^{\text{Log}E_{\text{base}}})(0.996338^{T_{\text{base}}})$$

$$R^2 = 98.42\% \tag{8}$$

$$\varepsilon_C = 0.005897(0.997936^{E_{\text{subgrade}}/\text{Log}E_{\text{subgrade}}})(0.992823^{T_{\text{base}}})(0.999987^{E_{\text{subbase}}})(0.969754^{\text{Log}E_{\text{asphalt}}T_{\text{asphalt}}})(1.0004^{E_{\text{subgrade}}})(0.990023^{T_{\text{subbase}}})(1.09869^{W_{\text{load}}})$$

$$R^2 = 99.37\% \tag{9}$$

Proposed equations for 21 t tandem axle with double wheels:

$$N_f = 9.81*10^{-5}(1.098659^{T_{\text{asphalt}}\text{Log}E_{\text{asphalt}}})(1.00002^{E_{\text{asphalt}}/\text{Log}E_{\text{asphalt}}})(0.760816^{T_{\text{asphalt}}})(0.985238^{T_{\text{pressure}}})(84.00339^{\text{Log}E_{\text{base}}})(1.012791^{T_{\text{base}}})$$

$$R^2 = 97.16\% \tag{10}$$

$$N_d = 0.000101(1.011273^{E_{\text{subgrade}}/\text{Log}E_{\text{subgrade}}})(1.092876^{T_{\text{base}}})(1.000057^{E_{\text{subbase}}})(1.372534^{T_{\text{asphalt}}})(0.997774^{E_{\text{subgrade}}})(1.121499^{T_{\text{subbase}}})(4.352647^{\text{Log}E_{\text{asphalt}}})$$

$$R^2 = 99.47\% \tag{11}$$

Proposed equations for 24 t tridem axle with single wheel:

$$N_f = 0.019888(1.130894^{T_{\text{asphalt}}\text{Log}E_{\text{asphalt}}})(0.64516^{T_{\text{asphalt}}})(0.981053^{T_{\text{pressure}}})(26.31047^{\text{Log}E_{\text{base}}})(1.011335^{T_{\text{base}}})$$

$$R^2 = 97.1\% \tag{12}$$

$$N_d = 1.21*10^{-10}(1.000365^{E_{\text{subgrade}}/\text{Log}E_{\text{subgrade}}})(1.08912^{T_{\text{base}}})(1.00003^{E_{\text{subbase}}})(1.480338^{T_{\text{asphalt}}})(61.98078^{\text{Log}E_{\text{subgrade}}})(1.143823^{T_{\text{subbase}}})(5.4122^{\text{Log}E_{\text{asphalt}}})$$

$$R^2 = 99.28\% \tag{13}$$

Where:

T_{asphalt} = Aphalt layer thickness (cm)
E_{asphalt} = Aphalt elastic module (psi)
T_{base} = Bse layer thickness (cm)
E_{base} = Base elastic module (psi)
T_{subbase} = Subbase layer thickness (cm)
E_{subbase} = Subbase elastic module (psi)
E_{subgrade} = Subgrade elastic module (psi)
T_{pressure} = Tire pressure (psi)
W_{load} = Axle weight, tons (this is defined for single axles with double wheels)
ε_t = The maximum tensile horizontal strain at bottom of Asphalt layer
ε_c = The maximum compressive vertical strain at the top of the subgrade
N_f = Allowable number of loads for fatigue control
N_d = Allowable number of loads for rutting control

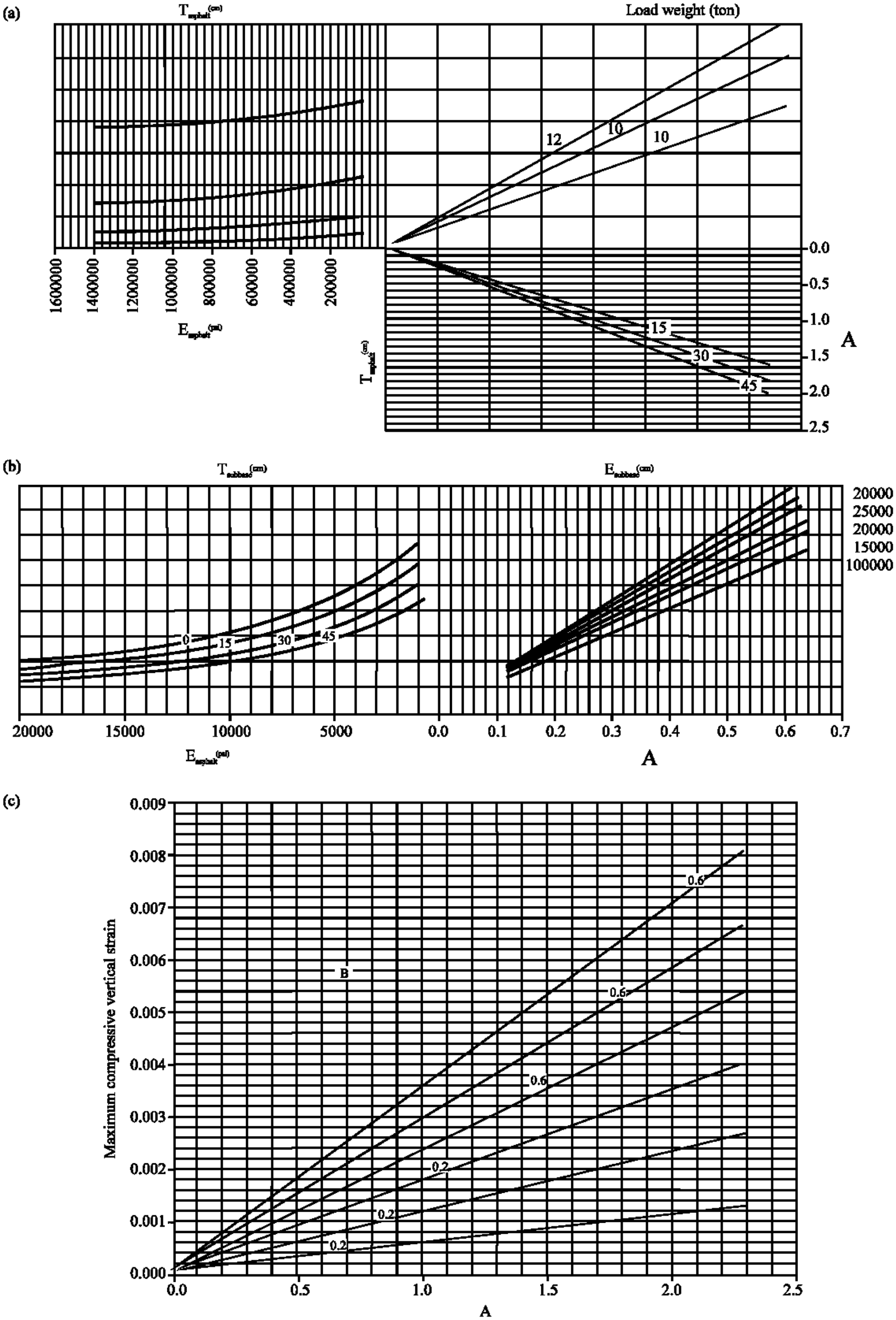

Fig. 3: Design graph for 8. 2, 10 and 13 t single axle with double wheels, (Design criterion: rutting)

DESIGN DIAGRAMS BY M-E METHOD

Some diagrams suggested for proposed equations. A typical diagrams of Eq. 7, is presented in Fig. 3. For using of this diagrams, At first the minimum functional thickness should be selected by determining the pavement layer technical characteristics, in accordance with management and planning organization, second, with existing Asphalt elastic module and selected thickness of Asphalt layer and base layer , from horizontal axis of asphalt elastic module (Fig. 3a), a line is drawn to intersect the minimum asphalt thickness line. Then, a horizontal line in the same direction with diagonal base layer thickness lines is drawn to intersect the minimum selected thickness of this layer from this point a vertical line in the direction of horizontal axis of parameter A is drawn and at last the quantity of this parameter will be determined. All these steps are applied for subgrade elastic module of horizontal axis (Fig. 3b), a vertical line is drawn to intersect the minimum subbase layer thickness curve . A horizontal line is drawn in the direction of base layer elastic module curve to intersect the subbase elastic module curve. From this point a vertical line in the direction of parameter B axis is drawn and the value of this parameter will be obtained.

The maximum compressive vertical strain at the top of the subgrade is determined by using the parameters A and B values are shown in Fig. 3c.

CONCLUSION

This study presented the results of a study to develop a mechanistic-empirical process for pavement design in Iran. The process offers a flexible, comprehensive and simple framework for pavement design. The process starts with load and climatic data and material properties for each layer in the pavement structure. The input parameters of the M-E method proposed in this study, are based on the existing data and facilities particularly environmental data and laboratory equipments in Iran. the structural analysis usually involve a linear elastic, static analysis of the multilayer system, resulting in the pavement response to the loading condition expressed in terms of strains at critical positions in the pavement structure. The pavement response serves as input of the transfer functions. In proposed M-E process, fatigue and rutting transfer functions are considered. This study also presented relationships and diagrams for types of axles loads based on effective variable on pavement design to facilitate design process. One of the most important advantages of the present method in compare to other pavement designs is that, there is no need to use the equivalent load factors for converting the different axels to equivalent single axel load.

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