

A New Approach to the Mechanistic Design and Analysis of Concrete Block Pavements

Md Mizanur Rahman[1], Simon Beecham[2] and Elizabeth McIntyre[3]

[1]Natural and Built Environments Research Centre, University of South Australia, Mawson Lakes, SA 5095, Australia
[2]ITEE, University of South Australia, Mawson Lakes, SA 5095, Australia
[3]Concrete Masonry Association of Australia, PO Box 275, St Leonards NSW 1590, Australia
Correspondence e-mail address: Mizanur.Rahman@unisa.edu.au

Abstract :

Concrete block pavements create an 'interlocking'action and become stiffer and stronger due to progressive loading. However, the mechanistic design of CBP is too complex to be undertaken by hand calculation and requires the use of computer analysis. This paper describes themechanistic design procedure of a new software program (DesignPave), which includes: a) both equivalent standard axle load (ESAL) and traffic loading spectrum b) progressive interlocking and stiffness development of the block layerc) stress-strain analysis of a multi-layer pavement systemd) rutting and fatigue criteria suitable for block pavement design. DesignPave was alsoused to observe the effect of traffic loading spectraon the design thickness of base course of block pavements. It was found that two different traffic loading spectra can require significantly differentbase course design thicknesses.

Key Words : Concrete block pavements, Mechanistic design software

1. Introduction

Concrete block pavement (CBP) differs from other form of concrete pavement in that they comprise a layer of rigid paving blocks, which can be either pervious or impervious,laid on either a sand or fine gravel bedding course. The joints of these pavers create an 'inter-locking'action and become stiffer and stronger due to progressive loading. Therefore, the concepts for flexible or rigid pavement design cannot be directly adapted for concrete block pavements. This paper describes the development of a mechanistic design method and its implementation in a new software program, DesignPave, which is available through the Concrete Masonry Association of Australia (CMAA) website[1]. The software is designed with a simple interface that provides a self-guided advance-forward approach, which is capable of both a generic design with restricted conditions for inexperienced engineers and also advanced options for design, analysis, and parametric studiesfor use by highly experienced engineers. DesignPavealso generates design curves displaying the variation of design depth with traffic load. The software also generates customised reports with options for including design depth, drawings of the pavement layer section, costings, as well as a summary of the theory and design methodology. This paper focuses on the methodology and design procedure, and particularly: a) estimation of the equivalent standard axle load (ESAL) and traffic loading spectra, b) progressive interlocking and stiffness development of the block layer, c) stress-strain analysis of a multi-layer pavement system, d) rutting and fatigue criteria suitable for block

pavements.

Miner's Rule was adopted in DesignPave so that a distribution of the traffic spectrum derived from a traffic survey can be used as an input for calculating the required base course design depth. This paper also investigatesthe effect of the traffic spectra on the design depth and demonstrates this relationship using design curves of base course depth against number of axle passing.

2. Mechanistic Design Methodology

DesignPave first estimates traffic data using ESAL, Average Annual Daily Traffic (AADT) or the actual traffic loading spectrum. Then,the program allows users to select the pavement layer systems, includingpaving, bedding, base, sub-base and sub-grade layers. The material properties for each layer are automatically generated or can be selected from a range which was developed from Australian experience[2, 3]. DesignPave then undertakes an iterative elastic calculation for subgrade permanent deformation, which is then used in a damage law to calculate the required design thickness for aspecified design life.The specific mechanistic design methodology and key mathematical formulations are discussed further below.

2.1 Estimating traffic loads

In flexible pavements, ESAL is one of the most commonly used loading inputs for design. ESAL characterises a wide spectrum of axle loads to a standard load by normalizing an axle load (W) by an Equivalent Standard Load (ESL) with a n^{th} power law presented by the following equation.

$$N = \left(\frac{W}{ESL}\right)^{n} N_a \quad (1)$$

where Na is repetition of axle load (W), N is repetition of equivalent standard axle load for design. n varies between 2 and 6,although nis commonly assumed to be 4 (fourth power law).
The ESAL method is criticised for CBP as it does not consider the distribution oftraffic in the interlocking of CBP. Therefore,DesignPaveinstead estimates the number of design traffic (N_{DT})using the following equation:

$$N_{DT} = 365 * AADT * DF * \left(\%\frac{HV}{100}\right) * LDF * CGF * N_{HVAG} \quad (2)$$

whereAADT is the Annual Average Daily Traffic in vehicles per day in the first year, DF is the direction factor (proportion of two-way traffic travelling in the direction of the design lane), %HV is the average percentage of heavy vehicles, LDF is the land distribution factor (proportion of heavy vehicles in the design lane), CGF is the cumulative growth factor and N_{HVAG} is the average number of axle groups per heavy vehicle.DesignPaveassists the user in estimating the design traffic as shown in Fig. 1a. The program also accepts a traffic survey as an input of a traffic spectrum from a standard spreadsheet file.Examples of two traffic spectra are shown in Fig. 1b and these are used for analysis in this paper. The cumulative effect of traffic loads from the spectrum is then assessed using Miner's rule, which states that if there are k different stress levels and the average number of cycles to failure at the i^{th}stress, S_i, is N_i, then the damage fraction, C, is

$$\sum_{i=1}^{k} \frac{n_i}{N_i} = C \quad (3)$$

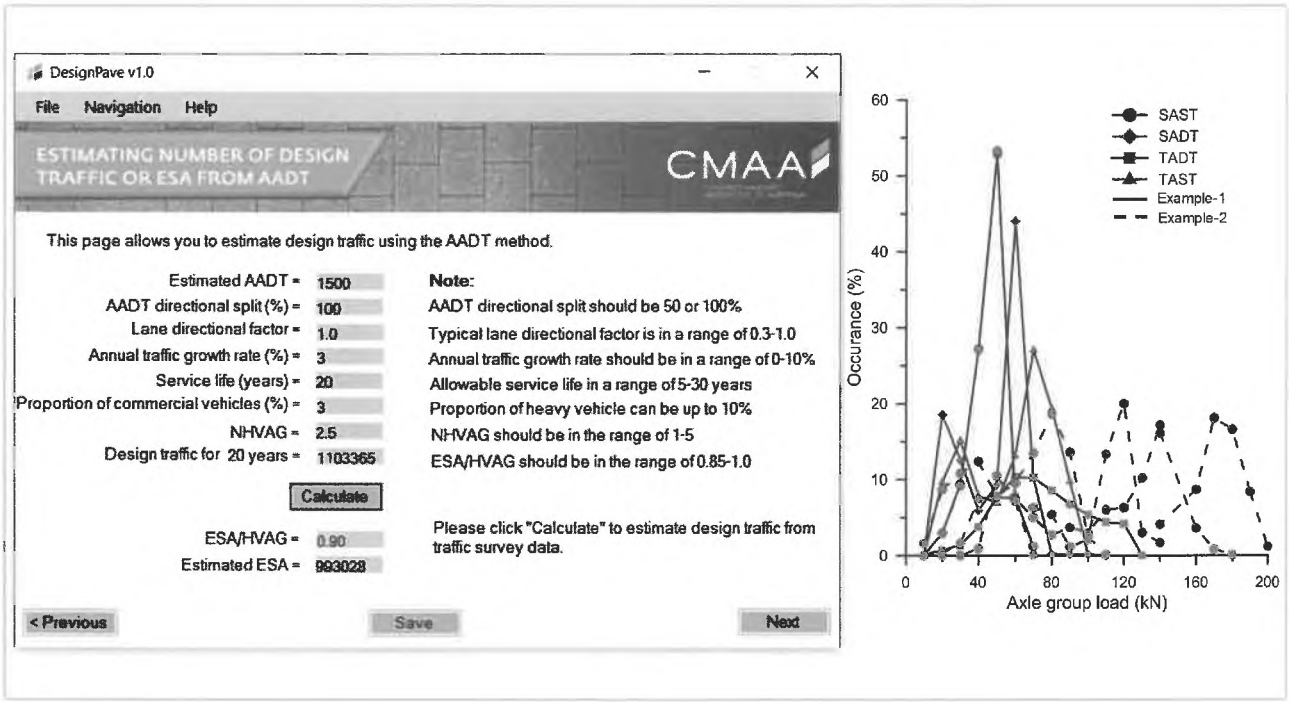


Figure 1. (a) Estimation of design traffic in DesignPave (b) An example of two traffic spectra.

2.2 Stress-strain analysis

Solutions for stresses in a homogeneous half space were first presented by Boussinesq at the end of 1800's. The equations were originally developed for a point load at the surface but later the equations were extended for circular wheel loads. The stresses under the centre of the wheel load can be presented by the following equations:

$$\sigma_z = P\left[\frac{z^3}{(a^2+Za^2)^{3/2}} - 1\right] \tag{4a}$$

$$\sigma_r = \sigma_t = \frac{P}{2}\left[\frac{2z(1+\vartheta)}{(a^2+z^2)^{1/2}} - \frac{z^3}{(a^2+z^2)^{3/2}} - (1+2\vartheta)\right] \tag{4b}$$

where a is the radius of the circular loading area, P is a contact pressureof 700kPa (from the wheel), Z is the depth below the surface and ϑ is the Poisson ratio. σ_z, σ_r and tare vertical, radial and tangential stresses,respectively.The Boussinesq solutions, as discussed above, are for a homogeneous half space which are not directly applicable tomulti-layered systems. There are many alternative approaches available for elastic analysis of multi-layered systems. However, pavement engineers seek simpler, albeit approximate, methods for elastic analysis. The most common of these simpler methods is the Method of Equivalent Thickness (MET), which was originally developed by Odemark [4]. The equivalent thickness for a homogeneous half space is obtained from the following equation:

$$h_{eq} = nh_i\left(\frac{E_i}{E_m}\right)^{0.33}\sqrt[3]{\frac{1-\vartheta_m^2}{1-\vartheta_i^2}} \tag{5}$$

where n = 0.90, ϑ_i and ϑ_m are the poisson ratios of the top layer and half space, respectively, h_i is the thickness of the top layer, and E_i and E_m are the moduli of the top layer and half space, respectively.To consider the progressive interlocking of pavers, it is assumed that at least

10,000axle passesare required to develop full interlocking between the pavers. Therefore, the paver stiffness was assumed to be the same as the bedding stiffness prior to 10,000vehicle passes. After 10,000vehicle passes, the paver stiffness was used in the subsequent analysis.

2.3 Failure criteria

The failure mechanisms and criteria for unbound and bound (cement treated/stabilised) materials are different.Unbound granularmaterials, such as crushed rock or gravels in a pavement, are assumed to fail due to the gradual accumulation of permanent rutting deformation in the subgrade layer. In a flexible pavement, it is assumed that the rutting deformation is related to the vertical compressive strain, zat the top of the sub-grade. There are various methods that can be used to relate the magnitude of these strains to the number of strain repetitions that a pavement can carry before developing unacceptable rutting. Of these, the most acceptable criterion was the Shell design procedure for flexible pavement design.Edwards and Valkering [5]recommend this method, which can be written as:

$$\varepsilon = 2.8 \times 10^{-2} \times N^{-0.25} \tag{6}$$

where ε is the permissible subgrade compressive strain (macrostrain) and N is the number of strain repetitions.A separate fatigue failure criterionmust be adopted for a cement-bound base or sub-base in addition to the rutting deformation criteria. Several different fatigue failure criteria have been developed for the design of concrete block pavements.Austroads provides the following fatigue criteria for cemented material and have been used in Australia[6].

$$N = RF\left[\frac{(113000/E^{0.804}+191)}{\mu\varepsilon}\right]^{12} \tag{7}$$

where$N$ is the allowable number of load repetitions, E is the modulus of the cemented material in MPa, $\mu\varepsilon$ is the load-induced tensile strain (microstrain) at the base of the cemented material and RF is the reliability for cemented material fatigue.Recommended RF values can be found in Austroads [6]. This fatigue criteria is valid for cemented materials with moduli varying from 2,000 to 10,000 MPa.

3. Results and Discussion

For impermeable systems, pavers ofthickness80mm are commonly overlaid on a 20mm thick bedding sand layer. DesignPavewas then used tocalculatethe required thickness of the base materialfor a subgrade with CBR of 10. The required base course thickness was found to be 145mm for 1.1x106 vehicles passing over the pavementwith thetraffic spectrum of example 1. The material properties used in this analysis are presented in Fig. 2a. The software also plots a design curve of base course depth against the number of axle passes. Fig. 2b shows a comparison of the design curves for the traffic spectra from examples 1 and 2 in Fig. 2b. It was found that for the same material properties for each layer, as shown in Fig. 2a, the base course thickness increases with a decrease in the subgrade CBR. Interestingly, the traffic loading in example 2 required a larger base course thickness thanthe traffic loading in example 1 for the same number of axle passing. This is because the traffic loading in example 2 had a higher axle group load and percentage of occurrence than in example 1.

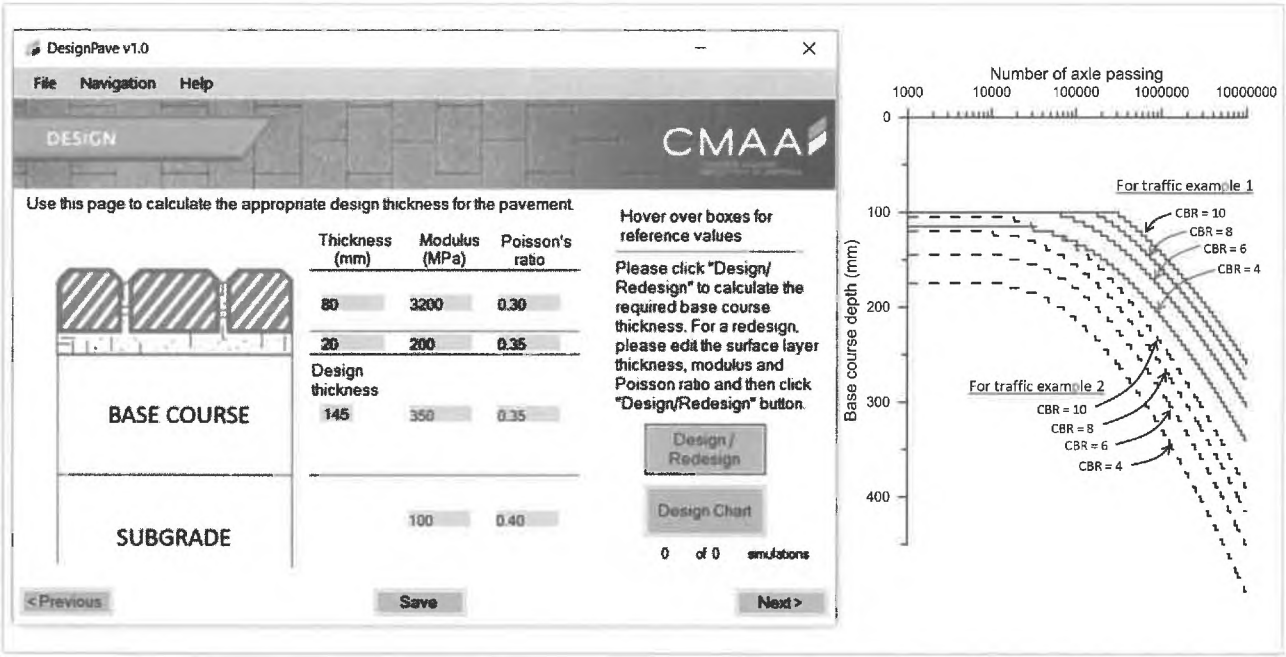


Figure 2. (a) DesignPavescreen shot (b) comparison of design curves for two different spectra.

4. Conclusions

This paper has describedthe development of a mechanistic design method and its implementation in a new software program,DesignPave.To demonstrate the program's capability, two different traffic spectra were used to compare the resulting design curves. It was found that the traffic spectrum with a higher axle group load required an increased base course thickness for the same number of vehicle passes. This finding demonstrates the importance of accounting for detailed traffic patterns rather than using a single average value.

Acknowledgements

We would like to acknowledge the financial support from theConcrete Masonry Association of Australia for the development of DesignPave[2].

References

[1] CMAA. Welcome to the CMAA DesignPage portal. 2018 [cited 2018 29 August]; Available from: http://www.cmaa.com.au/engineering-pavement-software.

[2] DesignPave v1.0, A mechanistic design software for concrete block pavement, M. Rahman and S. Beecham, Editors. 2018, Concrete Masonry Association of Australia.

[3] Shackel, B., Computers as an aid to promoting efficiency in road pavement design and specification, in ASPAC 92: IRF/ARF Asia Regional Pacific Road Conference. 1992: Gold Coast, Queensland, Australia. pp. 150-159.

[4] Odemark, N., Investigations as to the elastic properties of soils and design of pavements according to the theory of elasticity. 1949, Statens Vagins Institute, Stockholm.

[5] Edwards, J.M. and C.P. Valkering, Structural design of asphalt pavements for road vehicles - the influence of high temperatures, in Highways and Road Construction. 1974. pp. 1-9.

[6] Austroads, Guide to Pavement Technology Part 2: Pavement Structural Design, Sydney, NSW: Austroads AGPT02-12.