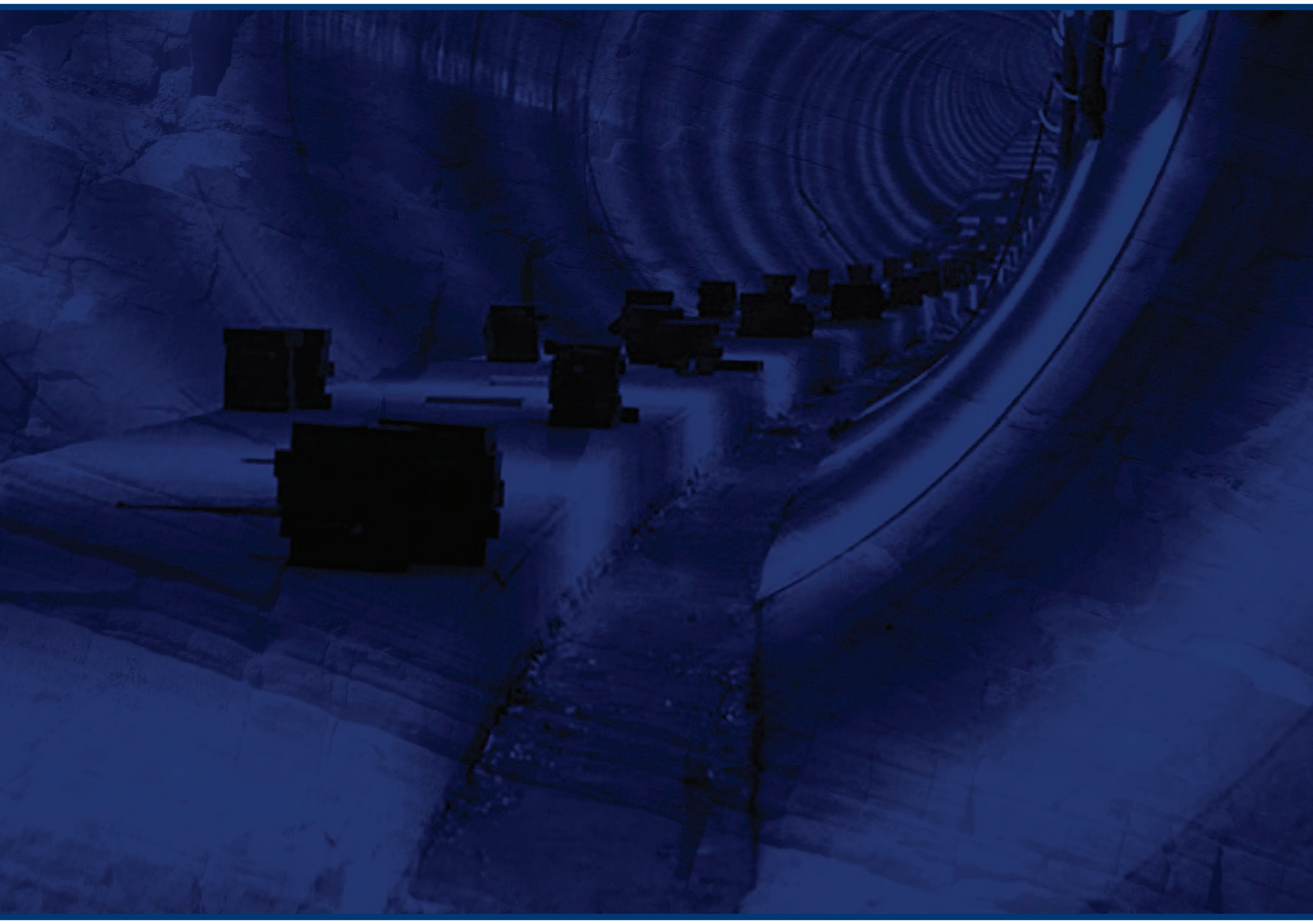
PROCEEDINGS

# 2018 AUSTRALIAN GEOMECHANICS SOCIETY VICTORIAN SYMPOSIUM

# Geotechnics and transport infrastructure

Wednesday, 24 October 2018, 8:00am – 6:00pm
Rydges Hotel, 186 Exhibition Street, Melbourne



**AUSTRALIAN GEOMECHANICS SOCIETY**
**VICTORIA CHAPTER**

Global Synthetics

# PREFACE

The Victorian chapter of the Australian Geomechanics Society invited academics and practitioners in the field of geotechnical and ground engineering to attend the 2018 Australian Geomechanics Society Victorian Symposium on ‘Geotechnics and transport infrastructure’ held on 24 October 2018.

In recent years Victoria has seen significant investment in transport infrastructure as part of a plan to manage the demands of a growing population and expanding urban fringe. The construction of Melbourne Metro, a second crossing of the Yarra River, rail and freeway upgrades as well as numerous level crossing removal projects are just some of the major transport projects currently underway in Melbourne and regional Victoria. Many of these projects carry numerous complex geotechnical challenges.

The 2018 Australian Geomechanics Society Victorian Symposium covers a variety of geotechnical challenges associated with transport geotechnics and present overviews of current infrastructure challenges, state of the-art practices, innovation, new research results and case studies demonstrating applications of advanced techniques and cost effective solutions in the construction and design of local transport infrastructure. The Symposium brought together professional engineers, researchers, specialist contractors, regulators, educators and students to share and discuss their experiences on the topic of transport infrastructure and associated geotechnical challenges and applications.

## ORGANISING COMMITTEE*

Vladimir Lopez Suarez (Chair)

Daniel King

Richa Shukla Potdar

Erin Lee

David Glover

*a sub-committee of the AGS Victoria committee

## SPONSORS

### Platinum

Global Synthetics Pty Ltd

### Gold

Chadwicks Geotechnics

Acciona Geotech

### Silver

Geotesta

Foundation Specialists Group

## TECHNICAL REVIEWERS

All technical papers in these proceedings, excluding the keynote addresses, were peer reviewed. The reviewers are acknowledged and listed below:

Daniel King (Editor)
Chris Coulson
Joel Gniel
Jay Lee
Jie Li
Nimal Nilaweera
Bhavikh Riyat
Ben Shannon
Sri Srithar
Manh Tran

AUSTRALIAN
GEOMECHANICS
SOCIETY

A technical society of
ENGINEERS
AUSTRALIA

# Mechanistic design of concrete block pavements

Md Mizanur Rahman[1], M. ASCE, Simon Beecham[2], Elizabeth McIntyre[3] and Asif Iqbal[4]

[1]Natural and Built Environments Research Centre, University of South Australia, Mawson Lakes, SA 5095, Australia, PH +61 (0)8 830 25899; FAX +61 (0)8 830 25082; email: Mizanur.Rahman@unisa.edu.au
[2]ITEE, University of South Australia, Mawson Lakes, SA 5095, Australia, PH +61 (0)8 830 23202; FAX +61 (0)8 830 23799; email: Simon.Beecham@unisa.edu.au
[3]Concrete Masonry Association of Australia, PO Box 275, St Leonards NSW 1590, Australia; PH +61 (0)2 8448 5500; FAX +61 (0)2 9411 3801; email: elizabeth@thinkbrick.com.au
[4]Natural and Built Environments Research Centre, University of South Australia, Mawson Lakes, SA 5095, Australia, PH +61 (0)8 830 25899; FAX +61 (0)8 830 25082; email: Asif.iqbal@unisa.edu.au

## ABSTRACT

Concrete block pavements consist of a layer of rigid, specially shaped and jointed paving blocks that are overlaid on a bedding course layer. The joints of these pavers create an 'interlocking' action, which makes the pavement stiffer and stronger with progressive loading. Therefore the design concepts for flexible pavements cannot be directly adapted for concrete block pavements. Instead a mechanistic design method is required, which is too complex to be undertaken by hand calculation and requires the use of computer analysis. This paper describes the development of a new software program (*DesignPave*), which has been developed in conjunction with the Concrete Masonry Association of Australia. The program's methodology and design procedure involve: a) estimation of the number of design traffic vehicles ($N_{DT}$) and traffic loading spectra; b) modelling of progressive interlocking and stiffness development of the block layer; c) stress-strain analysis of a multi-layer pavement system; and d) application of rutting and fatigue criteria suitable for block pavements. This paper uses *DesignPave* to produce design curves that describe the relation between design thicknesses with $N_{DT}$. The design curves for different layer systems are compared to identify appropriate subgrade CBR and $N_{DT}$ for a layer system. The different layer systems include a granular base course, a granular base course with a sub-base course and a granular base course with a stabilised sub-base course. The *DesignPave* program also produces extensive technical documentation for use in common engineering practice.

*Keywords:* concrete block pavements; mechanistic design software

## 1 INTRODUCTION

Concrete block pavement (CBP) differs from other forms 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 'interlocking' 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 website (CMAA, 2018). The software is designed with a simple interface that provides a self-guided advance-forward approach that is capable of both a generic design with restricted conditions for inexperienced engineers and also advanced options for design, analysis, and parametric studies for use by highly experienced engineers. *DesignPave* generates design curves displaying the variation of design depth with traffic load. It 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 number of design traffic vehicles ($N_{DT}$) and traffic loading spectra; b) progressive interlocking and stiffness development of the block layer; c) stress-strain analysis of a multi-layer pavement system; and 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 investigates the effect on the design curves for different layer systems, including a granular base course, a granular base course with a sub-base course and a granular base course with a stabilised sub-base course. These design curves were compared to identify an appropriate layer system suitable for both the subgrade CBR and the $N_{DT}$.

## 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, including paving, 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 (Shackel, 1992, DesignPave v1.0, 2018, Rahman*, et al.*, 2018). *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 a specified design life. The specific mechanistic design methodology and key mathematical formulations are discussed further below.

### 2.1 Estimating traffic loads

In flexible pavements, equivalent standard axle load (ESAL) is one of the most commonly used loading inputs for design. However, the ESAL method is criticised and often considered inadequate for CBP. This is because the distribution of traffic loading affects CBP and develops interlocking between pavers with progressiove loading. Therefore *DesignPave* instead estimates the number of design traffic ($N_{DT}$) using the following equation and the distribution of traffic loading according to a traffic spectrum as shown in Fig. 1:

$$N_{DT} = 365 \times AADT \times DF \times (\%HV/100) \times LDF \times CGF \times N_{HVAG} \qquad (1)$$

where AADT 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.

*DesignPave* accepts a traffic survey from a standard spreadsheet file as an input of a traffic spectrum. An example of a traffic spectrum is shown in Fig. 1 and is used for analysis in this paper. Each of the axles passing contribute to the damage of a CBP. The cumulative damage 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

$$\Sigma(n_i/N_i) = C \qquad (2)$$

where $n_i$ is the number of cycles accumulated at stress $S_i$ and C is the fraction of life consumed by exposure to the cycles at the different stress levels. In general, when the damage fraction reaches 1, failure occurs. To consider the progressive interlocking of pavers, it is assumed that at least 10,000 axle passes are required to develop full interlocking between the pavers. Therefore the paver stiffness is assumed to be the same as the bedding stiffness prior to 10,000 vehicle passes. After 10,000 vehicle passes, the paver stiffness is used in the subsequent analysis.

## 2.2 Stress-strain analysis

Solutions for stresses in a homogeneous half space was developed by Boussinesq 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 represented by the following equations:

$$\sigma_z = P[z^3/(a^2 + z^2)^{3/2} - 1] \qquad (3a)$$

$$\sigma_r = \sigma_t = P/2 = P[2z(1 + \nu)/(a^2 + z^2)^{1/2} - z^3/(a^2 + z^2)^{3/2} - (1 + 2\nu)] \qquad (3b)$$

where a is the radius of the circular loading area, p is a contact pressure of 700kPa (from the wheel), z is the depth below the surface, $\nu$ is the Poisson ratio and $\sigma_z$, $\sigma_r$ and $\sigma_t$ are vertical, radial and tangential stresses, respectively. The Boussinesq solutions, as discussed above, are for a homogeneous half space which are not directly applicable to multi-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 (Odemark, 1949). The equivalent thickness for a homogeneous half space is obtained from the following equation:

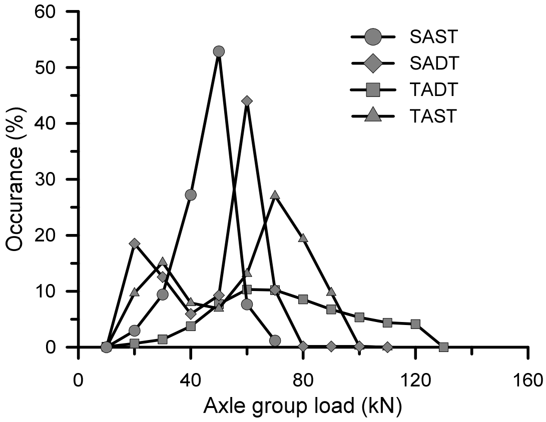


*Figure 1. An example of traffic spectra, which used in the analysis*

$$h_{eq} = nh_i(E_i/E_m)^{0.33}[(1 - \nu_m^2)/(1 - \nu_i^2)]^{1/3} \qquad (4)$$

where n = 0.90, $\nu_i$ and $\nu_m$ 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.

## 2.3 Failure criteria

The failure mechanisms and criteria for unbound and bound (cement treated/stabilised) materials are different. Unbound granular materials, 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 this rutting deformation is related to the vertical compressive strain, $\sigma_z$, at the top of the sub-grade layer. 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 is the Shell design procedure for flexible pavement design. Edwards and Valkering (1974) recommend this method, which can be written as:

$$\varepsilon = 2.8 \times 10^{-2} \times N^{-0.25} \qquad (5)$$

where $\varepsilon$ is the permissible subgrade compressive strain (macrostrain) and N is the number of strain repetitions. A separate fatigue failure criterion must 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 criterion for cemented materials and this has been used extensively in Australia (Austroads, 2012).

$$N = RF[(113000/E^{0.804} + 191)/\mu\varepsilon]^{12} \qquad (6)$$

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 (2012).

## 3 MECHANICSTIC DESIGN AND PARAMETRIC STUDY

For a design number of axles passing ($N_{DT}$), the axle groups are divided according to the traffic spectrum, as shown in Fig. 1. For each axle passing, the contribution of damage is calculated using Miner's Rule, as given in Equation (2). Since the minimum thickness of base course (also for sub-base and stabilised sub-base) is assumed to be 100mm, the cumulative damage (C) is calculated for a given $N_{DT}$. If $C < 1$, then the base course thickness is 100mm. Otherwise, the base course thickness is increased by 5mm in each iteration, until $C < 1$ and the base course thickness is then the design thickness. Using the same principle, *DesignPave* produces design thicknesses with increasing $N_{DT}$ varying from $10^3$ to $10^8$, which for simplicity is referred to hereafter as the 'design curve'.

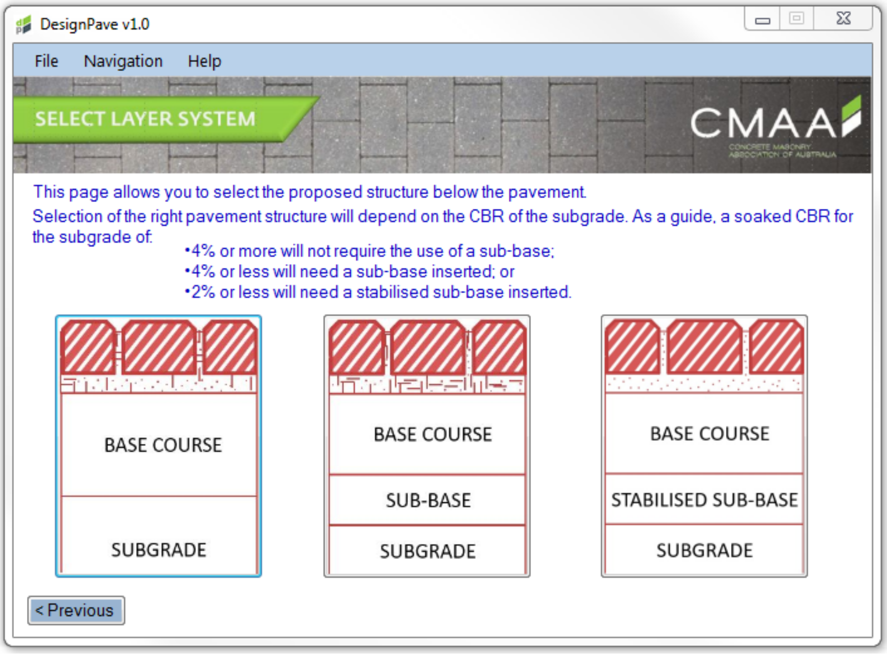
A section of CBP with granular base course comprises of (from upper to lower layers) pavers, a sand or fine gravel bedding layer, a base course layer and a subgrade layer. The granular base course layer is often subdivided into a base course with a sub-base course or a base course with a stabilised sub-base course. Therefore *DesignPave* lets the user select one of the three layer systems: granular base course, granular base course with sub-base course and granular base course with stabilised sub-base course, as shown in Fig. 2. It is recommended from Australian practice that the:

- granular base course layer is suitable for subgrade CBR ≥ 4%
- granular base course with sub-base course is suitable for subgrade CBR ≤ 4% and
- granular base course with stabilised sub-base course is suitable for subgrade CBR ≤ 2%

These design curves can then be used to identify appropriate conditions when either a granular base course with a sub-base or a granular base with a stabilised sub-base is beneficial over a single layer of granular base course. The material parameters for this parametric study are presented in Table 1 and the results are discussed in the following sections.

### 3.1 Base course vs Base course with sub-base course

Fig. 3 shows the required base course thicknesses when $N_{DT}$ increases from $10^3$ to $10^7$ (thick blue line). For a subgrade CBR of 10%, the required base course thickness was less than 100mm up to a $N_{DT}$ of $3\times10^5$ and thus the design base course thickness was the minimum value of 100mm. However, after $N_{DT}$ increases beyond $3\times10^5$, the base course thickness increases with increasing $N_{DT}$. It was also found that the base course thickness increases with $N_{DT}$ for lower subgrade CBR values. The minimum thickness for a CBP with a base course layer and a sub-base course layer was 200mm (100mm base course + 100mm sub-base course). Fig. 3 shows that the thickness of a base course layer with a sub-base course layer is greater than the thickness of only a base course layer for lower $N_{DT}$ values. For example, for a subgrade CBR of 6%, the thickness of a base course layer with an underlying sub-base course layer was greater than the thickness of only a base course layer for a $N_{DT}$ value lower than $1.3\times10^6$ i.e. the use of a sub-base layer is beneficial for $N_{DT}$ greater than $1.3\times10^6$. Therefore a $N_{DT}$ value of $1.3\times10^6$ is the threshold $N_{DT}$ for CBR of 6% for the chosen material properties. It was also found that the threshold $N_{DT}$ decreases with decreasing subgrade CBR. This is consistent with the *DesignPave* recommendation of using a sub-base layer for a subgrade CBR lower than 4%.



This page allows you to select the proposed structure below the pavement.

Selection of the right pavement structure will depend on the CBR of the subgrade. As a guide, a soaked CBR for the subgrade of:

- 4% or more will not require the use of a sub-base;
- 4% or less will need a sub-base inserted; or
- 2% or less will need a stabilised sub-base inserted.

*Figure 2. The three layer systems in DesignPave: granular base course, granular base course with sub-base course and granular base course with stabilised sub-base course (DesignPave v1.0, 2018)*

*Table 1: Parameters for CBP layers for different conditions*

| **Layer system** | **Granular base course** | | | **Granular base and sub-base course** | | | **Granular base and stabilised sub-base course** | | |
|---|---|---|---|---|---|---|---|---|---|
| | **Thick -ness (mm)** | **Modulus (MPa)** | **Poisson ratio** | **Thick -ness (mm)** | **Modulus (MPa)** | **Poisson ratio** | **Thick -ness (mm)** | **Modulus (MPa)** | **Poisson ratio** |
| Concrete paver | 80 | 3200 | 0.30 | 80 | 3200 | 0.30 | 80 | 3200 | 0.30 |
| Bedding layer | 20 | 200 | 0.35 | 20 | 200 | 0.35 | 20 | 200 | 0.35 |
| Base course | V[a] | 350 | 0.35 | 100 | 350 | 0.35 | 100 | 350 | 0.35 |
| Sub-base course | --- | --- | --- | V[a] | V[a] | 0.35 | V[a] | 1500 | 0.35 |
| Subgrade CBR | V[a] | V[a] | 0.40 | V[a] | V[a] | 0.40 | V[a] | V[a] | 0.40 |

[a] V = variable parameter. The subgrade CBR (California Bearing Ratio) varied from 2% to 10%. The base course, sub-base course and stabilised sub-base course were designed for axles passing from $10^3$ to $10^8$.

### 3.2 Unstabilised sub-base vs stabilised sub-base

Figure 4 shows the design curves for a base course layer with a normal unstabilised sub-base course layer and a base course layer with a stabilised sub-base course layer for a subgrade CBR varying from 2 to 10% and $N_{DT}$ varying from $10^5$ to $10^8$. It was found that the combined thickness of a granular base course layer with a stabilised sub-base course layer was greater than the required thickness of a base course layer with an unstabilised sub-base course layer for lower $N_{DT}$.

Irrespective of subgrade CBR, a granular base course layer with a stabilised sub-base course layer is generally superior for very high $N_{DT}$ values. It was also observed that the threshold $N_{DT}$ was greater for higher subgrade CBR values. Therefore a granular base course layer with a stabilised sub-base course layer is beneficial for subgrades with low CBR values, which is consistent with the recommendation that a granular base course layer with a stabilised sub-base course layer is suitable for a subgrade CBR ≤ 2%.

However, this study also suggests that the use of a granular base course layer with a stabilised sub-base course layer is not always beneficial for lower subgrade CBR values when $N_{DT}$ is lower than $9 \times 10^7$.

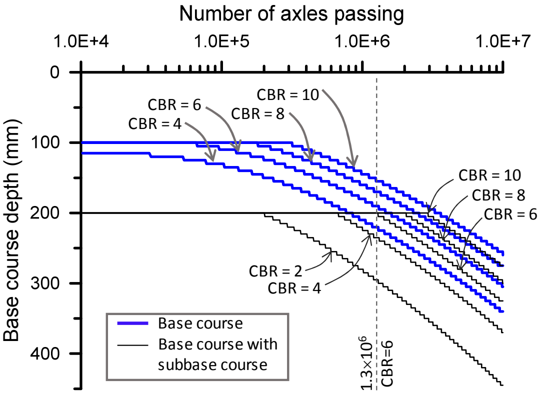


*Figure 3. Comparison of design thicknesses for base course vs. base course with sub-base course*

## 4 CONCLUSIONS

This paper has described the development of a mechanistic design method and its implementation in a new software program, *DesignPave*. One of the key features of *DesignPave* is the ability to use traffic spectra as a traffic loading input, and also the ability to model the interlocking and stiffening of concrete blocks with progressive loading. To demonstrate the program's capability, a standard traffic spectrum was used as input to produce a design curve representing the relation between design thickness and the number of axles passing. The design curves for three commonly used layer systems for CBP, namely a granular base course layer alone, a granular base layer with an unstabilised sub-base course layer and finally a granular base layer with a stabilised sub-base course layer, were used to identify appropriate subgrade CBR values for these layer

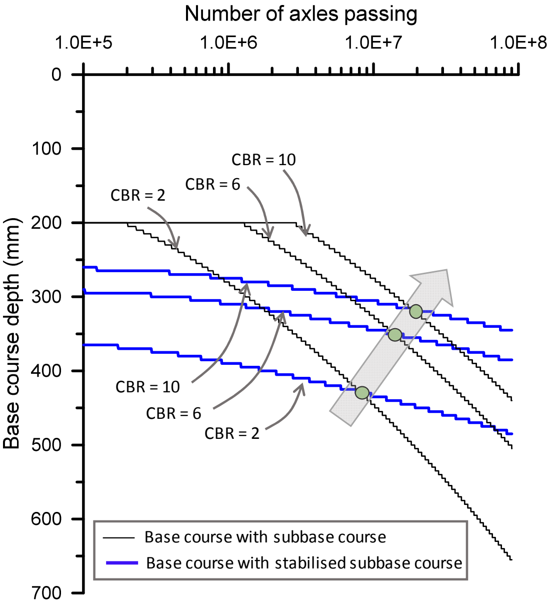


*Figure 4. Comparison of design thicknesses for a base course layer with an unstabilised sub-base course layer and a base course layer with a stabilised sub-base course layer*

systems. It was found that the recommendations in *DesignPave*, as below, were suitable for common engineering practice:

- A granular base course layer alone is generally suitable for a subgrade CBR ≥ 4%;
- A granular base course layer with an unstabilised sub-base course layer is generally suitable for a subgrade CBR ≤ 4%; and
- A granular base course layer with a stabilised sub-base course layer is suitable for a subgrade CBR ≤ 2%.

This finding will help engineers in selecting suitably layered systems. However, the reader should be aware that the findings are based on the specific parameters used in this study.

## 5 ACKNOWLEDGEMENTS

We would like to acknowledge the financial support from the Concrete Masonry Association of Australia for the development of *DesignPave* v1.0 (2018)

## REFERENCES

Austroads (2012). *Guide to Pavement Technology Part 2: Pavement Structural Design*, Austroads Ltd, Sydney, NSW.

CMAA (2018). "Welcome to the CMAA DesignPage portal." <http://www.cmaa.com.au/engineering-pavement-software>. (29 August, 2018).

DesignPave v1.0 (2018)."A mechanistic design software for concrete block pavement." Concrete Mawsonry Association Australia.

Edwards, J. M., and Valkering, C. P. (1974)."Structural design of asphalt pavements for road vehicles - the influence of high temperatures." *Proc., Highways and Road Construction*, 1-9.

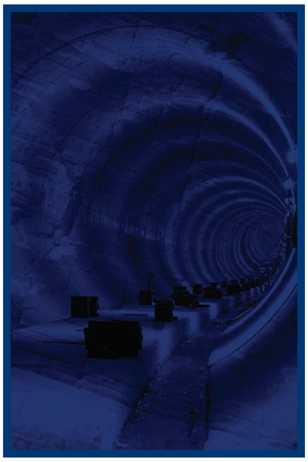
Odemark, N. (1949)."Investigations as to the elastic properties of soils and design of pavements according to the theory of elasticity." Statens Vagins Institute, Stockholm.

Rahman, M. M., Beecham, S., and McIntyre, E. (2018)."A New Approach to the Mechanistic Design and Analysis of Concrete Block Pavements." *Proc., 12th International Conference on Concrete Block Pavement 2018 (12th ICCBP 2018)*, Seoul, Korea, 1-4.

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

2018 AUSTRALIAN GEOMECHANICS SOCIETY
VICTORIAN SYMPOSIUM

# Geotechnics and transport infrastructure



AUSTRALIAN GEOMECHANICS SOCIETY
VICTORIA CHAPTER