THE EVOLUTION AND APPLICATION OF MECHANISTIC DESIGN PROCEDURES FOR CONCRETE BLOCK PAVEMENTS

B. Shackel

University of New South Wales, Australia

SUMMARY This paper describes the evolution of computer-based mechanistic procedures for the design o concrete block pavements for both roads and industrial hardstands. The procedures include sophisticated modelling both of the design traffic and of the properties of the pavement materials. The significance of these models is discussed and their relevance is critically assessed by reference to series of tests of block pavements conducted by the author from 1978 onwards. These tests included both accelerated trafficking trials of a wide range of prototype pavements and FWD studies of pavements currently in service in Australia. The paper concludes with a description of the application o the design procedures to a range of segmental pavements around the world.

1. INTRODUCTION

Much of the early experience in the application of concrete block paving was gained in Europe. Here traditionally such pavements have been designed on the basis of local experience. Usually this has been disseminated as simple design catalogues (eg. 1). These present the designer with only a very limited choice of pavement materials and thicknesses and, moreover, are usually restricted to road traffic only. Such an approach can work well where, as in Europe, the range of soil types, climates and materials are relatively limited and well understood. However, once block paving began to spread beyond Europe to the Americas, Africa, Australia and Asia the limitations of the traditional European design methodology became increasingly apparent. Not only were climatic and soil conditions vastly different from those ruling in Europe but local pavement materials were often different and far more diverse. For these reasons much of the research into concrete block paving conducted outside Europe has been directed towards evolving and evaluating universal design methods for both roads and industrial hardstands.

The requirement for a universal design procedure for block paving may be summarised as follows:

a) The method must be capable of modelling a wide range of soil conditions and climates.

b) The method must effectively utilise a full range of pavement materials including both bound (stabilised) and unbound materials whether these materials are used singly or in combination with one another.

c) The method must be capable of responding to a range of traffic conditions, and must accurately model local traffic distributions, and

d) The method must be capable of handling the very wide range of vehicle loads and configurations that are characteristic of industrial pavements.

The purpose of this paper is to describe the evolution, in Australia, of a design methodology that seeks to achieve the above objectives. This method builds on the results of a series of more than 150 accelerated trafficking tests of full-scale block pavements conducted by the author since 1978.

2. EVOLUTION OF THE DESIGN PROCEDURE

The first Australian design method for block pavements was published in 1976 (2). Like most methods then available in Europe this represented an *ad hoc* procedure which failed to recognise the unique engineering features of concret block paving. In 1978, following accelerated trafficking tests at the University of New Sout Wales this procedure was replaced by an empirically-based method (3,4,5).

The empirically-based design procedure was show to be conservative when compared to earlier methods (6). Nevertheless two criticisms could be directed at the procedure. First, the desig philosophy assumed *a-priori* that the quality of materials and standards of construction achieve in practice would, at least, equal those attained during the accelerated trafficking tests use to derive the design methodology. However, experience showed this was not always the case in Australia. Secondly, the method had only been experimentally verified down to CBR values of 15% (7). Despite these limitations the design method was widely used both in Australia and overseas with more than 10 000 copies being distributed worldwide.

Although the empirical design method worked wel for roads it was limited to the use of high-quality crushed rock basecourses and was not suited to the design of heavily loaded industrial pavements. For these reasons the Concrete Masonry Association of Australia sponsored a computer-based mechanistic design procedure for concrete block pavements which replaces the earlier empirical procedures. This procedure has far greater flexibility in the choice of pavement materials than the earlier method. In particular, it facilitates the use of cement-stabilised base and subbase layers which have been demonstrated to offer a number of performance advantages in block pavements (7,8,9). Moreover, the method permits accurate modelling of the loading conditions for both roads and industrial hardstands.

The first step in the development of a mechanistic design procedure is to choose an appropanalysis procedure. Three main approaches e analysis of block pavements have been ribed. Ranked in order of their develop- these comprise:

odified rigid pavement analyses (10,11).
ayered elastic system analyses (12,13).
inite element analyses (14,15).

he case of rigid pavement or slab analyses ers at both the Portland Cement Institute, nnesburg (16) and at CERIB in France (11) sought to characterise the structural per- ance of block pavements by modifying con- ional slab theory. Here the properties of block concrete have been determined by s of plate load tests. The principal lim- tion of this type of analysis is that it ot model the effects of base or sub-base ers. Rather, the analyses required the ire substructure beneath the blocks to be racterised in terms of some equivalent semi- inite half-space. Despite this limitation, work at the PCI, South Africa, has shown t it is possible to derive useful design ormation from modification of slab theory).

ore conventional and widely used approach to use layered elastic theory to analyse block pavement. Such procedures are eady well established for conventional flex- le pavement design. For example, the tional Association of Australian State Road thorities now recommend a hierarchy of nputer-based elastic analyses for the design road pavements in Australia (16). Here a vement is modelled as a succession of layers ch having linear elastic properties. The resses and strains throughout the pavement y then be calculated as functions of the load gnitudes and placement and the layer thick- sses and properties.

e use of both slab and elastic layer theory nores the discrete discontinuous nature of ving blocks but, rather, presupposes that the ock course can be modelled in terms of an uivalent continuous elastic layer whose operties can be determined by plate load sts, accelerated trafficking studies or Fall- g Weight Deflectometer measurements. An ternative to this is to use finite element chniques to model the blocks as an articulated rfacing having defined load or displacement ansference characteristics at the joints tween neighbouring paving units.

nite element studies of block paving have en reported both in Japan (14) and the therlands (15,17,19). The Japanese study s restricted to a consideration of the block rfacing. The Dutch study was more compre- nsive in that the analysis included an ass- sment of a complete block/base/sub-base/ bgrade system.

choosing among the three alternative analy- s described above the use of slab theory was jected because of the difficulty of properly delling the base and sub-base courses. Of e remaining procedures, the finite element thod, although shown to be capable of closely delling the observed load/deflection behaviour of block pavements (19), is more suited as a research tool than for routine design. In particular the method is slow and requires expert adjustment of the model to account for any change in the properties or sequence of the pavement layers. By contrast, a wide range of elastic layer analyses are already in common use for pavement design (eg. 16). These analyses may be quickly and easily varied to model a wide range of pavement types even by technically-naive users.

For the reasons outlined above it was decided to adopt elastic layer theory as the basis for the design method described here. It is important to note that it is not claimed that concrete block pavements perform elastically *per se*. Rather, the performance of the actual pavement is modelled in terms of an equivalent elastic system whose properties vary with time and traffic. This is of some importance because current routine pavement evaluation techniques such as the Falling Weight Deflectometer (FWD) can be used to measure the equivalent elastic properties of real pavements and, thereby, provide the necessary input to the design analysis.

3. THE DESIGN METHODOLOGY

The mechanistic design procedure has been described in detail elsewhere (13,20,21) and only a summary of the method is given here. The procedure implements the following steps:

a) The loads carried by the pavement are expressed in terms of a spectrum of design axle loadings. For roads the distributions of axle types and loads are commonly available from loadometer studies of public highways. For industrial pavements the spectrum can be assembled from data on each type of vehicle to be accepted by the pavement together with data on the distributions of container sizes, weights etc.

b) The base and sub-base layers are specified as being either unbound or stabilised materials.

c) The subgrade is characterised by a modulus value which is commonly inferred from CBR or other simple soil test data.

d) The block thickness and modulus is specified. In general the modulus depends on the block shape and laying pattern. Accelerated trafficking studies (6,8) have shown that, provided dentated blocks are used, a block thickness of 80mm can be chosen for most trafficked pavements irrespective of the loads to be carried provided the pavement is laid in herringbone bond.

e) The program selects trial thicknesses (>100mm) of the base or sub-base.

f) For each of the axles in the loading spectrum the distribution of stresses and strains are computed. Here an elastic analysis capable of implementation on 16 or 32-bit microcomputers has been developed and verified. Full details of the procedure have been published elsewhere (22). Where the analysis involves unbound granular materials the base or sub-base layers are automatically subdivided into three thinner layers which are assigned values of moduli which depend on the stiffness of the underlying layers. In this manner materials are treated as being stress dependent (non-linear).

g) Having computed the distribution of stress and strain, the number of repetitions of those stress and strain magnitudes that the pavement can withstand prior to failure are calculated in accordance with failure/damage criteria based on Miner's linear cumulative damage hypothesis (20). In the case of unbound granular base or sub-base materials the vertical compressive strain at the top of the subgrade is selected as the performance attribute. This is then compared with the widely used Shell criterion for the control of rutting in flexible pavements (23,24) to determine whether or not the pavement will perform adequately under the design traffic. In the case of bound base or sub-base the fatigue criteria developed by the Portland Cement Association (25) are used to assess whether the pavement can carry the design traffic without fatigue cracking of the layers.

h) Steps (f) and (g) are then repeated for the remaining design axles and the cumulative damage is calculated. If necessary the trial thicknesses are progressively incremented (ie. steps (e), (f) and (g) are repeated) until the pavement can be shown to have sufficient capacity to withstand the entire planned spectrum of loading. Where both a base and sub-base is to be designed the program first assumes a value of the support to be provided by the sub-base and determines an appropriate base thickness. The corresponding sub-base thickness is then calculated. The computer program includes a number of important refinements. For example, the program models the progressive stiffening of the blocks that has been observed in trafficking tests (6,7). This enables the effect of early construction traffic to be included as part of the design process. Furthermore the programs permit the inclusion of both construction and maintenance costs as design variables so that the relative economy of alternative types of pavement may be readily assessed.

4. IMPLEMENTATION OF THE DESIGN METHODOLOGY

The methodology described above has been developed to be as universal as possible. To implement the procedure and to make it specific to particular local conditions requires only a suitable choice of the input parameters in respect of

a) the loading conditions, and
b) the characterisation of the pavement materials.

Each of these inputs is now considered in more detail.

4.1 Loading conditions

In most developed countries the distributions of axle loads and axle types for road vehicles are available as loadometer studies conducted by state or municipal authorities. Such distributions often vary with time and locale. Usually the traffic load distributions can be adequately modelled as some 50 combinations of axle load and axle configuration. The effects of these 50 load combinations are separately assessed by the design program and their cumulative effect is predicted using Miner's law. This enables the program to adapt to local traffic conditions. This is illustrated in Figure 1 which shows design thicknesses for a concrete block pavement load on either a crushed rock base or a stabilised base for both Australian and North American traffic load distributions. Here the Australian traffic distributions lead to greater pavement thicknesses than the American distributions because there is a higher proportion of overloaded vehicles in the Australian traffic data.

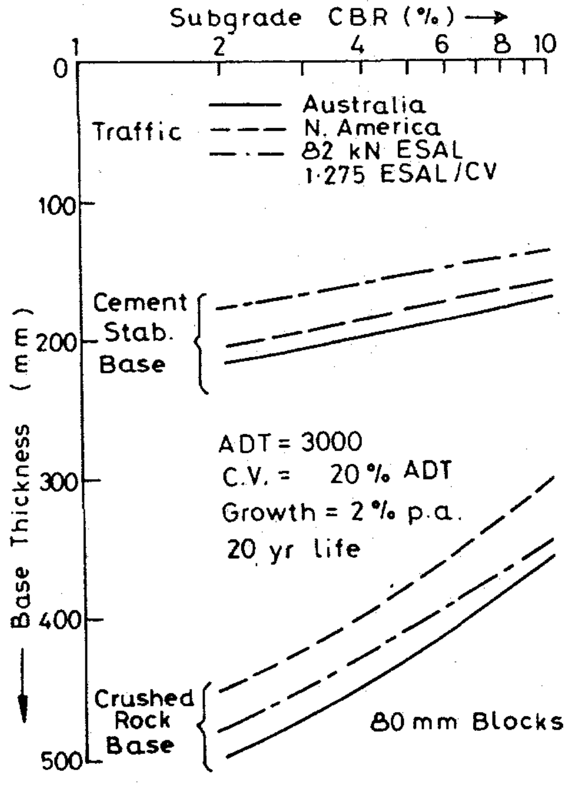

Fig. 1 Design curves for road pavements for various traffic loadings

Where loadometer data are not available it becomes necessary to use the concepts of axle load equivalency. Here the actual traffic is replaced by an equivalent number of standard axle loads (ESAL) based on a knowledge of the supposed average number of ESAL per commercial vehicle in the traffic stream. Such ESALs normally correspond to the maximum legal truck axle load and the number of ESALs is chosen so that, in theory, it will produce the same degree of pavement distress as the actual traffic that it to model. The damaging effects of a amount of traffic varies widely depend- on the pavement materials and the type vement (26). This makes it extremely icult to predict accurately the effects raffic in terms of ESALs unless compre- ive data are already available for the icular pavement type under consideration. data do not yet exist for concrete ck pavements. Accordingly, axle load ivalencies should only be used where full ometer data is unavailable. As shown in ure 1 the use of ESALs to model the traffic lds different thickness from those assoc- ed with loadometer data. Similar results e been obtained for flexible pavements). In the case of pavements incorporating ent-treated bases the use of ESALs leads smaller thicknesses than those associated th loadometer data because the latter corporate overloads to which brittle stab- ised materials are highly sensitive. By ntrast, the use of ESALs lead to greater icknesses of unbound base because here he thickness is relatively insensitive to verloads but rather depends on the average oad level.

the case of industrial pavements the axle oads, repetitions and configurations of each the vehicles using the pavement are con- idered separately. This enables the full pectrum of load from trucks to straddle carr- ers, forklifts, transtainers etc to be fully odelled. Where necessary the distribution of ontainer loads can be readily included in the nalyses using data published earlier (27). uch an approach avoids the need, common itherto, to resort to simplistic and often nappropriate concepts of axle load equivalency eg. 12) or to employ the notion of "design ehicle" (eg. 28). The effects of changes in he loading spectrum for industrial block pave- ents are illustrated in Figure 2 for a vehicle andling containers, From this figure it mav be een that to design the pavement on the ass- mption that the vehicle always runs at its ull rated load capacity leads to the choice of substantially greater thicknesses than where a ore realistic load distribution is used that eflects the variations in container weight ormally encountered in practice.

.2 Materials characterisation

he design methodology requires each of the avement materials to be characterised in terms of a modulus, E, and Poisson's Ratio, ν. The oncrete block course may be characterised in erms of an equivalent elastic layer that eff- ectively replaces the blocks and bedding sand. ere values of the equivalent modulus, E, can e obtained from plate load tests of blocks ested without support (eg. see Ref. 10 - sim- ilar tests are currently in progress at the niversity of New South Wales), from the analy- sis of pressure cell and multi-depth deflecto- eter data in experimental pavements (6,8,29) nd from FWD studies of actual concrete block avements currently in service. Typical results btained by the author for dentated blocks are given in Table 1. These are compared with data for rectangular pavers obtained in the Netherlands (30).

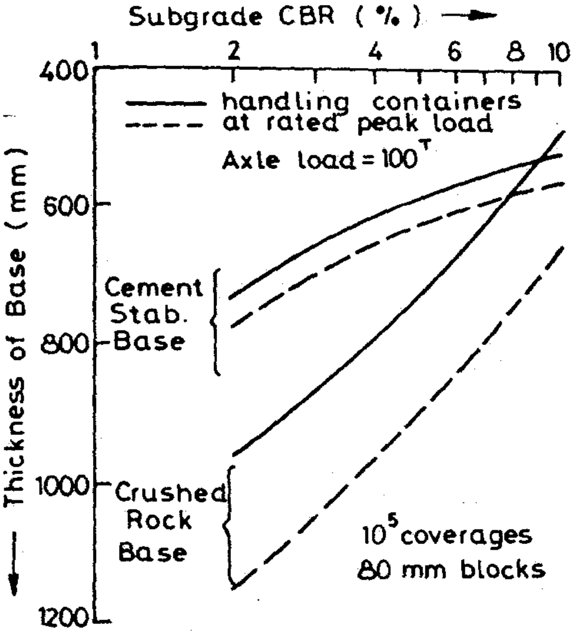

Fig. 2 Typical design curves for industrial pavements

TABLE 1 Typical Moduli for Concrete Blocks

Method of Test	Block-Moduli (MPa)
Load tests of pavement	2800-3400
FWD:	
Dentated	1570-12495 (Mean 3400)
Rectangular (After Ref. 30)	500-7000 (Mean 2975)

Accelerated trafficking tests (6,7,8,9,29) have shown that block pavements progressively stiffen under traffic. This stiffening process takes up to 10 000 wheel passes. To model this effect the design program assumes conservatively that immediately after construction, the block layer is equal in modulus to the basecourse and that it builds up to the full value of modulus (eg. as given in Table 1) during the first 10 000 axle load repetitions.

For base and sub-base materials the parameters E and ν can be obtained from laboratory tests or from FWD field data. Alternatively typical values such as those given in Table 2 may be used.

5. ADVANTAGES OF A COMPUTER-BASED METHODOLOGY

The mechanistic procedure offers the following advantages:

a) The method permits rigorous modelling of the loading conditions and the materials characteristics.

b) It is feasible to consider a wider range of material combinations than is possible by using manual procedures. This aids the designer to achieve a more cost-effective solution than where he is restricted to con-

TABLE 2 Characteristics of pavement materials for elastic layer modelling

Material	Modulus, E (MPa) Range	Modulus, E (MPa) Recommend	Poisson's Ratio(ν) Range	Poisson's Ratio(ν) Recommend
Base:				
crushed rock	200-800	350	0.10-0.50	0.35
stabilised	1000-30000	2300	0.10-0.50	0.35
Sub-base:				
gravel	150-450	225	0.10-0.50	0.35
stabilised	5000-7000	1500	0.10-0.50	0.35

sideration of just one type of pavement or a single type of material as is the case with most design procedures published to date. The choices available to the designer are illustrated in Figure 3 and a typical selection of alternative industrial pavement designs is shown in Figure 4.

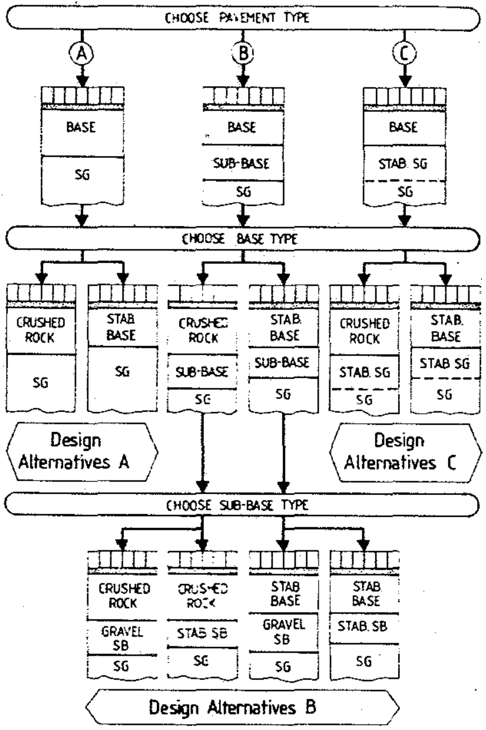

Fig. 3 Pavement design alternatives

c) The methods are systematic and lead the user through a design procedure which ensures that all essential requirements are considered.

d) The methods focus on essentials. By isolating the engineer from the minutiae of complex calculations he is able to concentrate on optimising his design.

6. VERIFICATION AND APPLICATION OF THE METHOD

As the methodology has evolved it has been used in the design of many major block pavements around the world including those at the Massey Coal Terminal, Newport News, Va. (31) and the Canadian Pacific International Container Facility, Edmonton. By late 1987 the method was known to have been used for the design of more than 500 000m^2 of industrial pavements alone. Applications currently in service include container yards, port facilities, bus terminii and a wide range of road pavements.

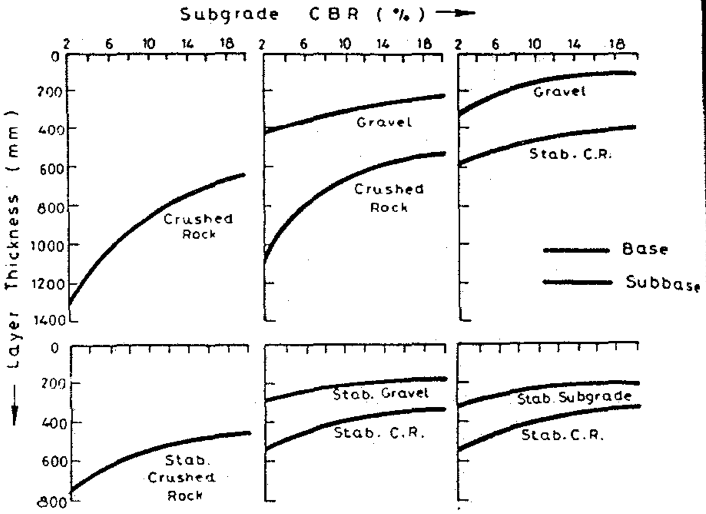

Fig. 4 Typical alternative pavement designs as a function of subgrade CBR

Wherever possible the design method described herein has been compared with the results of alternative design procedures. Comparisons of the pavement thicknesses calculated by the mechanistic procedure are shown in Figure 5 compared to those thicknesses known to be performing satisfactorily in-service. From this figure it may be seen that, in general, the computer-based procedure appears to be conservative.

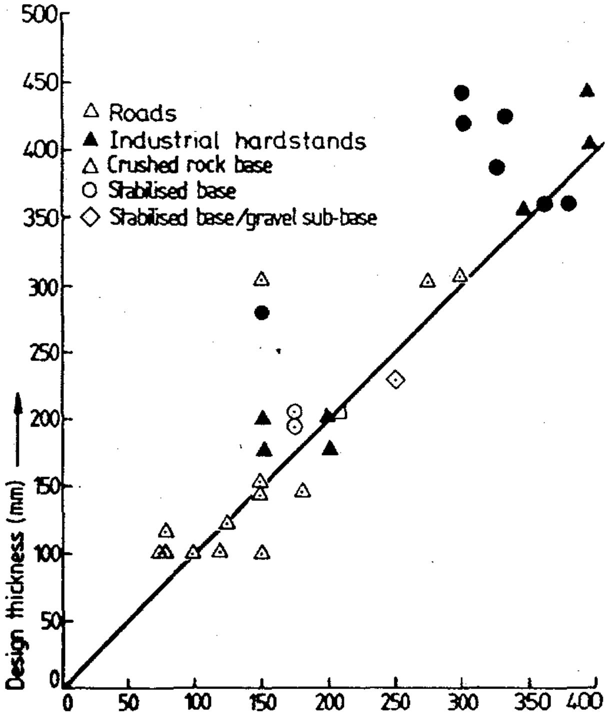

Fig. 5 Comparison of thickness indicated by design program with those found adequate in practice

CONCLUSION

The emergence of mechanistic design procedures provide engineers with powerful tools for studying a wide range of practical pavement engineering problems. An advantage of such methods is that they accurately model complex loading conditions. Moreover, the methods allow the designer to study a wide range of materials used either singly or in combination with other materials. This facilitates the achievement of an optimal and economic design. For this reason mechanistic design procedures are likely to be used increasingly in the design of block pavements in the future.

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