THE ANALYSIS AND DESIGN OF CONCRETE BLOCK PAVING SUBJECT TO ROAD TRAFFIC AND HEAVY INDUSTRIAL LOADING

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SUMMARY
This paper reviews the progress that has been made around the world in the analysis and design of interlocking concrete block paving subject both to road traffic and heavy industrial loads such as those applied by forklifts, straddle carriers and transtainers. The paper begins by identifying those aspects of the performance of block pavements under traffic that are relevant to the formulation of design procedures. Design methods currently in use around the world are surveyed and evaluated and new design methods developed in Australia are described. The paper concludes with a critical assessment of the utility of the design methods published to date.

1. INTRODUCTION

In recent years, a substantial body of information has begun to accumulate on the evaluation and design of block pavements. This information has been critically reviewed elsewhere (1,2). The purpose of this paper is to attempt to summarize and evaluate the knowledge that has been made in the development of scientifically-based design methods.

The paper is divided into three parts. The first part is concerned with a review of those mechanisms influencing the behaviour of block pavements under traffic because this has important implications on the choice and critical evaluation of design procedures. The second part evaluates current methods for designing block paving. In the third part, the design procedures developed in Australia are presented and evaluated. Finally, the utility of the currently available design procedures is evaluated and suggestions are made for further research.

2. FACTORS INFLUENCING DESIGN AND PERFORMANCE

Before considering the design of block pavements it is convenient to summarize the principal findings of those block paving tests which have been conducted to date because many of these findings have an important bearing on the development of design methods.

Studies of block pavements have tended to fall into just two categories. These have been reviewed elsewhere. (1) and comprise

(i) laboratory scale experiments designed to determine the load-spreading abilities of blocks (3, 4, 5), assess equivalencies between blocks and other pavement materials (3) and assess parameters suitable for mechanistic analysis of block pavements (6); and

(ii) accelerated trafficking evaluations of full-scale prototype pavements (2,7,8,9,10,11).

The majority of these tests have been directed towards the study of road pavements. However, a limited number of trafficking evaluations of heavy duty industrial block pavements have also been reported (12, 13, 14).

The principal findings of these various studies that are relevant to the formulation and evaluation of design methods may be summarised as follows:

(a) In general block pavements tend to perform in a manner which is similar to conventional flexible pavements, although, as noted below, there are some important differences in behaviour (2,7,8,9).

(b) Satisfactory performance in block pavements can be achieved using a wide range of subbase materials including crushed rocks, and natural gravels and stabilised materials (2,8,9,12).

(c) The performance of block pavements incorporating cement-treated subbases tends to be marginally superior to that of pavements using unbound granular subbases (9,13,15).

(d) The choice of the grading and thickness of the bedding sand is crucial to achieving good levels of performance in block pavements under traffic (7,16).

(e) Shaped interlocking (dentated) blocks perform better under traffic than non-interlocking rectangular blocks (7,8,11). This finding has been disputed by some research workers (e.g. 4). However, as yet unpublished tests of more than 50 segmental pavements conducted by the author in Australia in 1982 and 1983 have confirmed that dentated pavers generally yield less rutting and much smaller horizontal creep deformations than rectangular units.

(f) An increase in block thickness within the range from 60 to 100 mm is beneficial to pavement performance (5,7).

(g) The strengths of the blocks within the range 25 to 55 MPa have no influence on the structural performance of block pavements (6,8).

(h) Pavements laid in herringbone bond generally perform better than pavements laid in stretcher bond (8).

(i) Under trafficking block pavements tend to develop interlock (7,8,9,17,28). This is manifest as increases in the local spreading ability of the blocks and reductions in the rate of accumulation of deformation (7,8,9).

(j) Adequate base support is needed if interlock is to develop (5,17). However, if the rigidity of the base is too high this may inhibit interlock (5).

(k) Limited evidence suggests that interlock may be developed more rapidly where the joint widths are narrow than where they are wide (7,8).

(l) Once a block pavement becomes fully interlocked it attains a stable equilibrium condition which is unaffected by either the amount of traffic (7,8) or by the magnitude of the wheel

load (within the range of 24 to 70 kN) (8).
(m) Once interlock has developed the blocks act as a structural layer rather then merely as a wearing course (7,8,17). Attainment of full interlock may require as many as 20,000 passes of standard wheel load (8). However, it has been shown that the development of interlock can be promoted by rolling the pavement during the final stages of construction (13).
(n) The bedding sand layer, although only included in the pavement as a construction expedient, nevertheless contributes to the structural capacity of the pavement (7,8).
(o) Block pavements can typically exhibit elastic deflections between 1 and 4 mm while, at the same time, yielding only small rutting deformation (7,8).

3. THE DESIGN OF BLOCK PAVEMENTS - A REVIEW

The various procedures that have been developed around the world for the design of interlocking concrete pavements are now summarised. Broadly these methods can be divided into four categories comprising:

(1) Design on the basis of experience
(2) Ad-hoc modifications of existing design procedures for conventional flexible pavements
(3) Mechanistic design based on the determination of design parameters from laboratory tests.
(4) Empirical designs based on full-scale trafficking tests.

Design on the basis of Experience

Here block and base thicknesses are selected on the basis of experience of road construction on subgrades similar to that under consideration. Where the body of experience is extensive, as in continental Europe, this simple approach can yield satisfactory results. The design procedures are often presented as a design catalogue which encapsulate local knowledge (19,20,21). These catalogues tend to make little distinction between different subgrade conditions or wheel loads. The most comprehensive example of a design catalogue is that developed in South Africa (21). Here local experience has been backed up by both accelerated trafficking tests and mechanistic analyses.

Ad-Hoc Modification of Conventional Design Methods

These methods assume that the pavement can be designed by established flexible pavement design procedures and that the blocks can be substituted for part of the conventional design. Blocks have been reported as being equivalent to between 2·1 and 2·9 times their thickness of crushed rock (2,3,22) and to be between 1·1 and 1·5 times more efficient than asphaltic concrete (22).
Using such concepts of equivalency a variety of design curves for block pavements have been published. These include adaptations of the Corps of Engineers methods (3) and Asphalt Institute procedures (23) in the U.S.A. and of Road Note 29 in Britain (24). Similar modifications of conventional flexible pavement design methods have also been reported in New Zealand (25).

Mechanistic Methods of Design

Mechanistic design procedures for block pavements tend to follow methods developed for asphalt pavements. This means that the performance advantages of block paving are often not fully exploited. Usually the analysis is either concerned with computing the tensile strains in a bound subbase and thereby defining the fatigue life (28) or with determining the vertical compressive stress in the subgrade and using this to predict the rutting that will develop under traffic (17). By trial the thickness of the various pavement layers may be chosen so as to achieve both an adequate fatigue life and tolerable levels of rut deformation.
The principal problem in implementing mechanistic designs is to select representative values of block and subbase moduli. Whilst representative values of subbase moduli are available (e.g. 30) some doubt concerns the block moduli. Here values ranging between 900 MPa (6) and 7500 MPa (28) have been postulated.

Empirical Methods of Design

Based on trafficking tests conducted at the University of New South Wales a hierarchy of empirical methods of block pavement design was published in 1978 (22) and in a slightly revised form in 1979 (27). These methods have the advantage that they are based entirely on the observed response of actual block pavements under traffic and appear to be the only wholly empirical methods available. However, the South Africal procedure (21) is also highly dependent on trafficking tests for its verification.

4. THE AUSTRALIAN DESIGN SYSTEM

In this section of the paper the design procedures that have been developed by the author in collaboration with the Cement and Concrete Association of Australia (CACA) are described. The Australian system embraces both roads and industrial pavements and is being progressively implemented as four interrelated design modules. The design modules share the following common initial stages:
a) The Choice of Unit Shape and Thickness
Trafficking tests have demonstrated that the performance of block pavements is dependent on the shape of block used. Accordingly CACA have devised the classification of block shape described elsewhere (29). A similar approach has also been implemented in New Zealand (25). The block shape is checked for compatibility with the proposed application and the minimum block thickness appropriate to the designated traffic situation is selected (29).
b) The Choice of Laying Pattern
As noted earlier the performance of block pavements has been shown to be dependent on the

laying pattern with the best levels of performance being associated with herringbone bond.
For this reason herringbone pattern is mandated in the design procedures except for very light traffic. This precludes the use of block shapes which cannot be installed in herringbone bond for most trafficked pavements.
Once the block shape, thickness and laying pattern have been selected the general design procedure is as shown schematically in Figure 1.

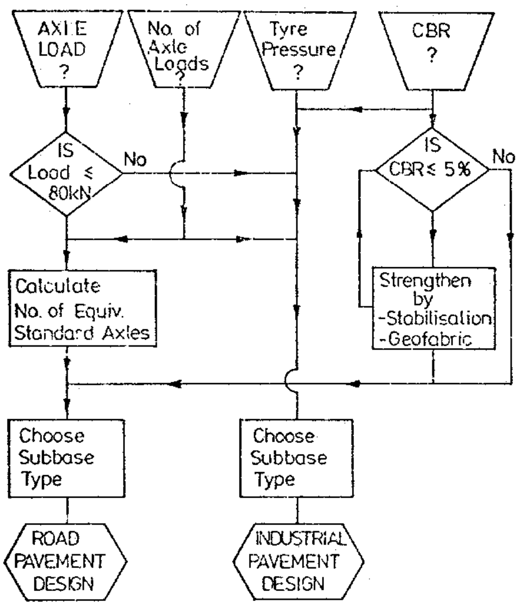

Figure 1: Design Procedure

It may be seen that the input parameters for the design of block pavements comprise:

a) axle or wheel loads (tonnes)
b) Number of axle loads
c) Tyre pressure (MPa)
d) Subgrade strength expressed as CBR (%).

Analyses have shown that these parameters are of different relative importance in the design of roads and industrial pavements. For example, within the range of practical interest, tyre pressure is of little significance in the design of roads and only has a marginal influence in the design of hardstands. As shown in Figure 1 the distinction between road and industrial applications is made on the basis of the maximum axle load. Once this exceeds the maximum load legally permitted on roads (82 kN in Australia) the designer is referred to methods specific to industrial vehicles.
The subgrade strength is expressed as a CBR value. If this is less than 5% then for road pavements, the possibility of subgrade improvement must be considered. Experience with block pavements in Australia shows that suitable forms of subgrade improvement comprise stabilization or, alternatively, the use of a geofabric.
If economics justify subgrade improvement then, for roads, this improved subgrade CBR forms the basis for design. However, a different approach is recommended for industrial pavements.

Here the pavement is always designed on the basis of the CBR value of the unimproved subgrade. This is not intended to suggest that stabilisation of the upper subgrade layers should not now be considered but reflects the fact that because of the deep stress penetration of heavy industrial loads, the top subgrade layer should properly be considered as forming part of the pavement itself rather than the subgrade per se.
The next step in the design procedures is to select the subbase type. Here two options are provided comprising the use of either an unbound granular subbase or a cement-stabilised material. Specifications for each of these categories of material have been given elsewhere (27). As noted above tests have demonstrated that excellent levels of performance in block pavements can be achieved using either type of subbase. The choice of subbase should be made on the basis of cost. In general, the use of cement-treated subbases is to be preferred to crushed rock subbases at relatively low CBR values; typically less than 10%.

Design of Road Pavements with Granular Subbases

This was the first of the design modules to be developed and was based on trafficking tests of block pavements (7,9). The method has been described in detail elsewhere (22,27) and only a resume is given here. The method is based on the observation summarised above that block pavements layed on granular subbases tend to attain a lock-up condition under traffic. Once this is achieved, neither the magnitude of the wheel load nor the number of load repetitions is of any further major significance and little further deformation accumulates under traffic. The design problem then resolves into ensuring that the rutting deformations that develop while interlock is being approached remain within acceptable bounds. Using computer-based statistical techniques (22) combined with the appropriate mechanistic analyses of rutting behaviour (27) it is possible to derive relationships between the deformation at interlock, the thickness of crushed rock subbase and the subgrade strength. Typical relationships for 60 mm and 80 mm category A blocks are shown in Figure 2. (Category A blocks are defined (29) as "dentated units keyed on all four faces which by their plan geometry when keyed together resist the spread of joints parallel to both the longitudinal and transverse axes of the units").
The information shown in Figure was based initially on tests conducted in Australia (7) but was later largely verified by further tests in South Africa (9). The information forms the basis of the current CACA design methods used successfully since 1979 in Australia (29). To apply these curves it is necessary only to specify the terminal pavement deformation that can be tolerated. The CACA design recommendations (29) imply traffic-associated deformations of between 5 mm and 10 mm for heavy trafficked roads, bus-termini etc and rutting of upto 15 mm for lightly trafficked residential

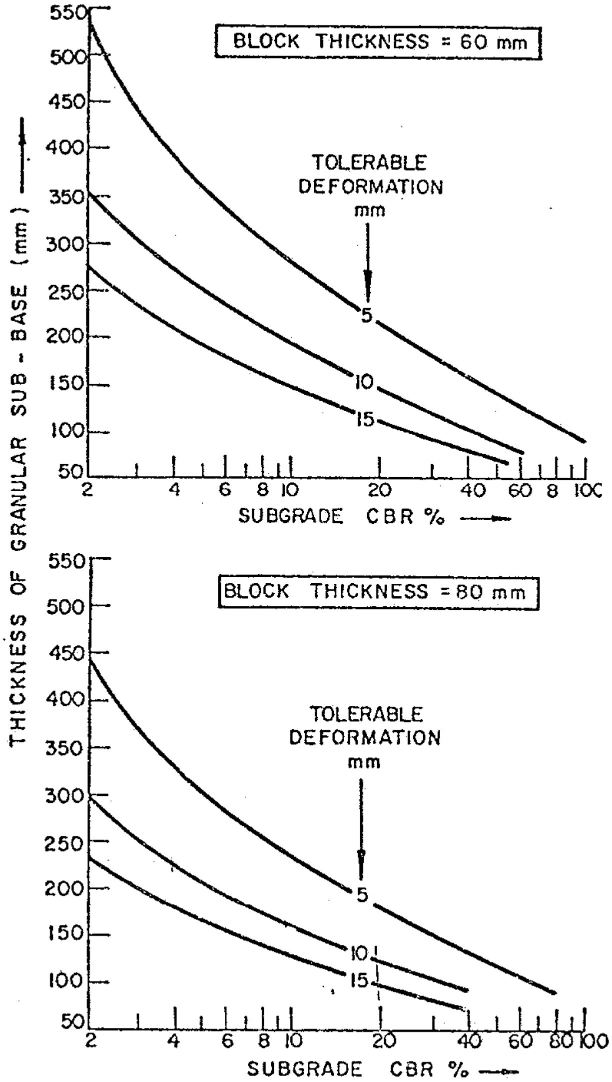

Figure 2: Road Pavement Design Curves (Granular subbase)

streets. Such values are consistent with currently accepted standards of road serviceability (e.g. 30).

Design of Road Pavements with Stabilised Subbases

The effective service life of a pavement incorporating a cement-bound subbase is made up of two parts. During the first phase the subbase behaves as a high modulus (low deformation) material until fatigue cracking eventually occurs. The fatigue life depends on the magnitude of the maximum repetitive tensile strain in the subbase in relation to the tensile strain at break (31). This in turn, depends on the strength of the material (30,31). Once the subbase cracks its effective modulus decreases (31). Thereafter it behaves in a manner similar to a crushed rock. At this time the pavement life remaining can be estimated in terms of the number of repetitions needed to cause unacceptable rutting deformation. This is usually assumed to be a function of the vertical compressive strain in the subgrade (e.g. 32).

In a pavement surfaced with asphalt it is normally required that the fatigue life of the surface be set approximately equal to the service life of the road. This ensures that reflection cracking does not occur in the asphalt surface. Although similar criteria have been applied to block pavements (e.g. 28) they are not really appropriate for two reasons. First, the block surface is already dissected by a network of joints and, therefore, cracking per se is not a problem. Secondly, the bedding sand will not readily propagate cracks form the subbase. Accordingly it is unlikely that subbase cracking will lead to opening of the pavement joints.

For the reasons outlined above, it seems appropriate to specify the life of a stabilised subbase as the sum of both the fatigue (crack) and the rut (deformation) life. This is the approach adopted by the author. Here the computer-based mechanistic design procedure illustrated schematically in Figure 3 has been developed.

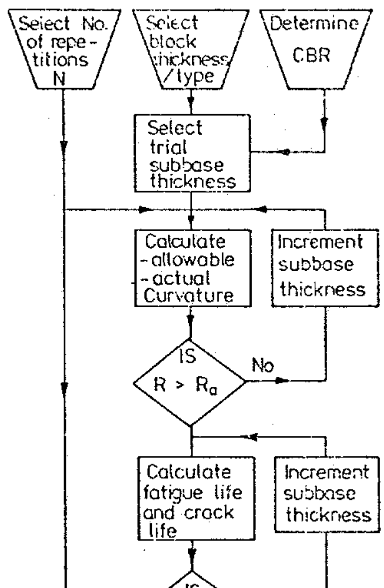

Figure 3: Design Procedure (Stabilised Subbase)

The design procedure is based on a linear isotopic 3-layer elastic analysis. The method involves the analysis of a series of trial thicknesses until a thickness is found which satisfies two independent criteria. These are

a) A Fatigue Criterion based on Curvature

Here the thickness of the subbase is selected to ensure that the curvature of the subbase remains within limits that ensure that a fatigue failure of the subbase will not occur during the planned service life of the pavement according to criteria developed by the

PCI in America (34,35,36).

b) Combined Fatigue and Rutting Criteria
Here the number of repetitions needed to cause cracking in the subbase according to criteria developed by Otte and others (30, 31) is summed with the number of repetitions needed to cause unacceptable subgrade rutting according to the Shell criterion of Claessen et al (32).

The need to satisfy both these criteria arises from the fact that, if used alone, they yield different estimates of thickness. In particular the PCI procedures indicate much longer fatigue (crack) lives for a given subbase thickness than those proposed by Otte (31). It should be noted however, that the PCA procedures (34,35) have been verified by experiments involving single wheel loads ranging upto about 34 tonnes and for subgrade strengths, ranging between CBR values of approximately 2% and 40% (34).
For consistency with the PCA it has been assumed that the modulus of the uncracked subbase is just 2800 MPa. It is assumed that after cracking the material may be regarded as having an effective modulus of just 280 MPa. This assumption is believed to be very conservative according to the recommendations of Otte (31).The effective modulus of the block course has been taken to be 3200 MPa. This value is lower than that assumed by some other workers but is based on trafficking measurements (22). In practice, however, the choice of block-layer modulus has only a minor effect on the selection of subbase thickness. In the case of the subgrade the modulus (MPa) has been assumed to be 10 x CBR. In all layers the Poisson's Ratio has been assumed to be 0.25. Using these values the design chart shown in Figure 4 has been derived for a dual 4.1 tonne wheel load. Because, within the range of practical interest (0.5 to 0.8 MPa), the choice tyre pressure has little effect on the analysis it may be neglected as a design parameter. The block thickness has been assumed to be 80 mm and, for consistency with the tests used to derive the modulus of the block layer it is assumed that Category A block shapes will be used.
The design curves given in Figure 4 are plotted for load repetitions in excess of 10^6 because it is found that little significant saving in subbase thickness can be made at lower repetitions. Generally the thicknesses shown in Figure 4 are similar (although not identical) to the value that would be obtained by substituting the paving block directly for part of the stabilised subbase required by the PCA design procedure for granular soil-cement pavements (36) for traffic repetitions of one million or more.

Design of Industrial Block Pavements

Many engineers have assumed that the design of industrial block pavements may be simplified by expressing the actual traffic conditions as an equivalent number of standard axle loads (33). This enables the use of a single set of design curves expressed in terms of this equivalent

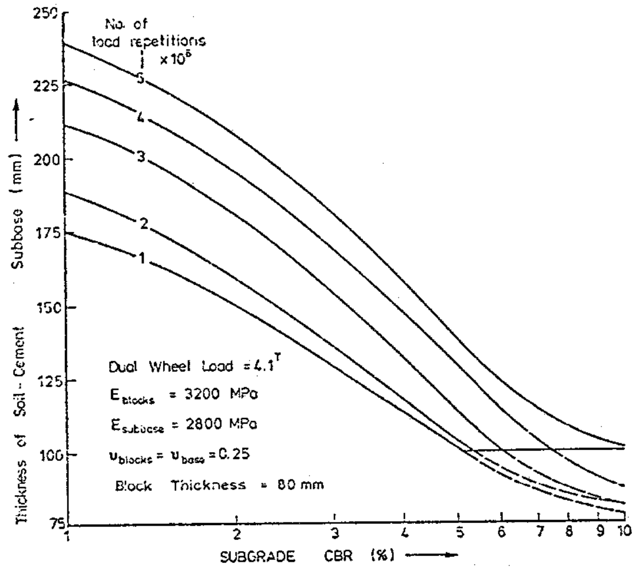

Figure 4: Road Pavement Design Curves (Stabilised Subbase)

load. Such an approach can be justified for the design of road pavements because the tests used to develop and verify the design procedures have usually employed loads equal to the equivalent standard axle load. However, it is not appropriate to industrial pavements where the range of wheel loads varies widely. In this respect the evidence from accelerated trafficking tests summarised above shows that conventional notions of wheel load equivalency are not constituent with the observation that block pavements develop interlock under traffic and that, thereafter, the effects of changes in load magnitude or repetitions have only a marginal influence on performance. For this reason the design methods described here for industrial pavements do not use wheel load equivalency factors. Rather than produce a single set of design curves a series of computer programs have been produced so that the design procedures can be tailored to the precise load magnitude, configurations and repetitions of each designated industrial vehicle.
The design programs have been developed for both unbound and stabilised subbases. The programs are based on established design procedures for heavy duty flexible pavements (35,37) modified by mechanistic analyses specific to block paving and by the use of experimentally determined block/subbase equivalencies (22). Details of the evolution and verification of these procedures have been described elsewhere (38) and only a summary of the methods follows.
For industrial block pavements incorporating granular subbases the design procedure is based on the well-known Corps of Engineers method (37) combined with a mechanistic analysis of the permanent (rutting) deformation characteristics of block pavements described earlier (27). Here it is assumed that the blocks can effectively replace upto 2.8 times their thickness of subbase. For industrial block pavements using a cement-stabilised subbase the procedures are similar to those represented schematically in Figure 3.

The method adopts procedures developed by the PCA in America (34,35) to achieve a computer-based design solution. At the numbers of load repetitions appropriate to most industrial situations (< 10^6) it will be found that the thicknesses indicated by the computer program are similar to those given by the PCA design procedure for Heavy Duty pavements (35) assuming the blocks to be equivalent to about 1.2 times their thickness of cement stabilised subbase. As an illustration of the design methods it is possible to produce nomographs such as those shown in Figures 5 and 6. It is emphasised however, that such nomographs do not cover all configurations of wheel load, vehicle type, tyre pressure etc.

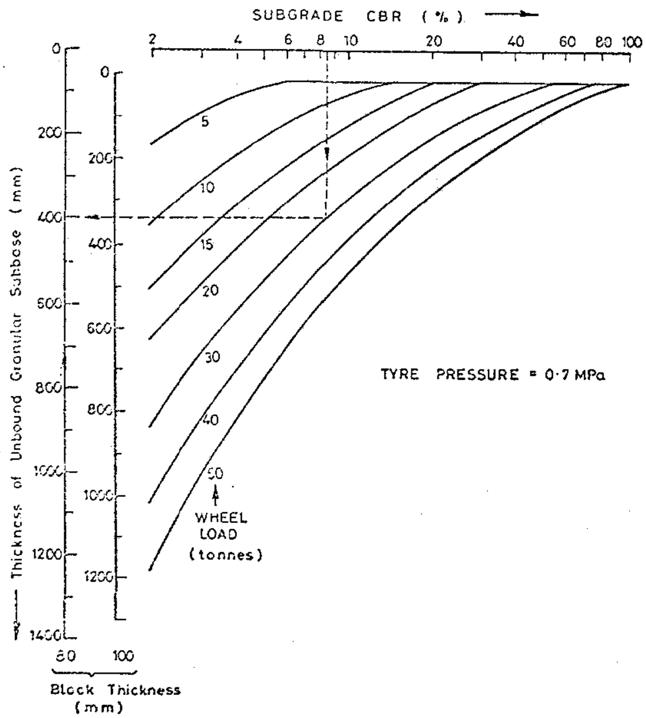

Figure 5: Design for Crushed Rock Subbase

A comparison of Figures 5 and 6 shows that, at CBR values less than about 10% substantial savings in pavement thickness can be made by selecting a cement-stabilised subbase. The final choice of subbase should be made on economic grounds.

Verification of the Design Methods

The Australian design procedures have been tested by trafficking tests described elsewhere (7,8,9, 13,14,15). Of equal importance is the fact that the methods have been used successfully to design and construct a wide range of road and industrial pavements not merely in Australia but also in the U.S.A., Canada and Asia including such major projects as the Massey Coal Terminal, Newport News, Va. This widespread experience suggests that the methods are adequately conservative. Nevertheless, it is of interest to compare the predictions of the Australian design procedures with experience gained in the succ-

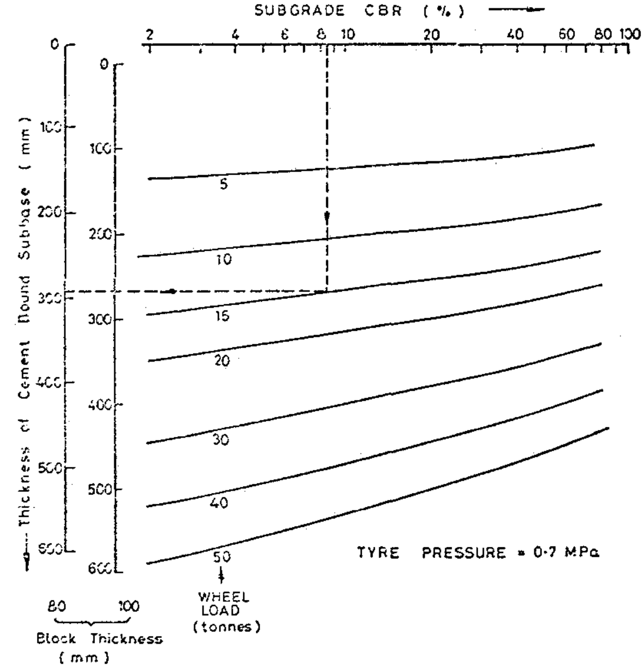

Figure 6: Design for Stabilised Subbase

essful application of block pavements worldwide. The thicknesses given by the Australian procedures have been compared with the actual subbase thicknesses of pavements known to be performing satisfactorily in Australia, Africa, the U.S.A., Canada and Europe. Only pavements for which reliable soils and construction data are available have been studied. These comprise roads, bus termini and industrial pavements, including port and container areas. Details of many of the pavements have been published (e.g. 1,38). Typical comparisons between the thicknesses required by the Australian procedures and the actual constructed thicknesses are shown in Figures 7 and 8.

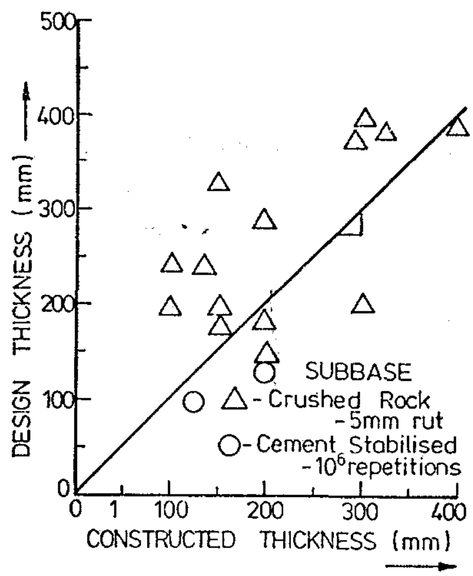

Figure 7: Design comparisons - Road Pavements

Although the range of data shown in Figures 7 and 8 is limited, it is encouraging to note that the Australian design procedures tend in general to yield satisfactorily conservative results. By implication most other design procedures used around the world must also be judged satisfactorily because comparison shows that they tend to often be more conservative than the Australian methods (e.g. 9)

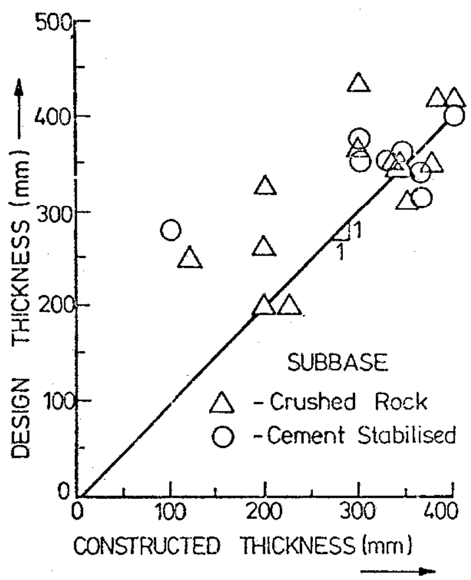

Figure 8: Design comparisons - Industrial Pavements

5. CONCLUDING COMMENTS

A range of procedures is available for the design of road and industrial block pavements. The methods vary widely in the extent to which they recognise the unique response of block pavements to traffic. Those procedures which are based on trafficking tests tend to require lesser subbase thicknesses than methods which are simply ad-hoc adaptations of conventional flexible asphalt pavement designs.

Limited evidence based on actual pavements in service, suggests that most block paving procedures are conservative. Future research should concentrate, therefore, on the further verification and testing of the various design procedures with the objectives of improving their efficiency and cost-effectiveness.

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