EVALUATION, DESIGN AND APPLICATION OF CONCRETE BLOCK PAVEMENTS

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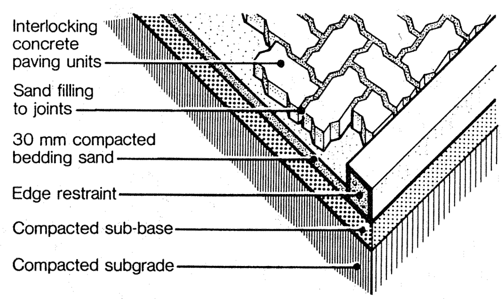
The paper begins by summarising the results of more than 100 accelerated trafficking tests of interlocking concrete block pavements. The factors studied included the type, thickness and laying pattern of the blocks, the choice of bedding and jointing sands, the thickness and quality of the subbase and the effects of variations in subgrade strength.The paper next describes the derivation of a new methodology for the design of block pavements. The method is suitable for both roads and heavy duty industrial pavements. As an illustration of the method selected design nomographs are presented The paper summarises the advantages and disadvantages of block paving compared both with other forms of concrete paving and with conventional flexible pavements. A range of successful applications of block pavements is then described including pavements both in North America and around the world.

Introduction

Block paving differs from other forms of concrete pavement in that it is made from small mass-produced paving units manufactured in a factory rather than insitu. Because of their segmental nature, block pavements can articulate under traffic. This means that, for a given load, the thickness of concrete needed to withstand traffic is less than that required in a conventional rigid pavement. This can lead to savings in pavement costs.

The principal elements of a concrete block pavement are illustrated in Figure 1. Beneath the blocks the pavement is similar to a conventional flexible pavement and comprises a compacted base/subbase laid over a compacted or stabilised subgrade. As shown in the figure the pavers are installed on a thin layer of bedding sand and are spaced 2 mm to 4 mm apart. The joint spaces are filled with sand. This facilitates the generation of horizontal forces between the pavers caused by dilatancy (i.e. a volume increase) in the jointing sand. Dilatancy forces develop during construction and under traffic because the blocks exhibit small shear displacements relative to each other thereby generating shear stresses in the sand. As a consequence, block pavements are capable of achieving substantial distribution of load amongst neighbouring paving units. This means that the blocks act not merely as a wearing course but, rather combine the functions of both the surface and base courses of a conventional flexible pavement. In other words blocks have a significant structural capacity if properly installed.

Figure 1. Elements of a block pavement.



In addition to promoting load transfer the presence of sand in the joints confers two further advantages. First, the problem of surface reflection cracking caused by base deterioration is largely eliminated. Secondly, it is possible to lift and relay any part of the pavement.

Concrete pavers were originally designed to be laid by hand. However, special lifting clamps have been recently developed to handle upto about one square metre of individual blocks laid down in the required pattern on a pallet during manufacture. These clamps either form part of special-purpose self-propelled laying machines or may be attached as needed to ordinary construction equipment such as front-end loaders or forklifts. Tests and experience in Holland, Germany and Australia have shown that such equipment can install up to 600 m^2 per machine shift. This greatly reduces the costs of laying compared to manual methods. In general the installation of interlocking paving requires cheaper and simpler laying equipment than cast-in-place concrete but is more labour-intensive.

Much of the early development of interlocking concrete paving occurred in Europe. In Holland, concrete blocks gradually displaced clay bricks as the preferred medium for segmental paving because of their superior economy and durability (1). In Germany, the first significant test of concrete block paving appears to have been at Neuss in 1936 when rectangular units were successfully tested under heavy traffic (2) . However, the major developments of paving in Germany followed the introduction of shapedunits in the mid-1950's. This led to a proliferation of proprietary paving systems until, by the late 1970's, at least 200 systems were being marketed (3). By the early 1980's, an annual production in excess of 45 million square metres had been achieved by which approximately 36 percent was used in roads and a further 30 percent in industrial hardstandings (4).

By the mid-1960's concrete block paving was firmly established in Central and South America and South Africa and during the 1970's was introduced to Britain, North America, Australia, New Zealand and Japan. More recently, the use of block paving has spread to the Middle East and Asia. Current annual world production is estimated to exceed 100 million square metres of which about 60 percent is used in trafficked areas.

Evaluation of Block Paving

Before design methodologies or construction specifications for interlocking concrete block paving can be evolved it is necessary both to identify and to evaluate those factors that influence block paving performance under traffic. This has involved an extensive series of tests of block pavements worldwide. The test methods that have been used to study block pavements include:

i)Accelerated trafficking trials of full-scale prototype pavements.(5-10)

ii)Load distribution studies (11-14). These have usually involved simple static plate load tests of block paving courses tested either alone or in combination with simulated base/subgrade support.

iii)Field trials of actual block pavements (15-18).

From these tests a substantial and well-documented amount of fundamental data has emerged (19).

In the case of road pavements accelerated trafficking studies of full-scale block pavements were initiated using the road simulator at the University of New South Wales in Australia in 1977. Here some 20 prototype block pavements were evaluated to provide the basis of a series of design procedures for block pavements (7,20). This work was later extended in 1979 to embrace tests of more than 100 full-scale block pavements using a Heavy Vehicle Simulator at the National Institute for Transport and Road Research, South Africa (21,22). Concurrently, accelerated trafficking trials of block pavements were also undertaken by the Universities of Canterbury in New Zealand and Newcastle in the United Kingdom (23,24), by the Waterways Experiment Station in the USA,by the Australian Road Research Board (16) and in Japan (10) and the Netherlands (25).

Tests have also been conducted of industrial block pavements. The first tests were conducted in Holland using a circular test track to evaluate a number of block pavement designs for the Europe Container Terminus, Rotterdam (6). These tests were specific to the loading and subgrade conditions expected at the ECT and it was only after 1977 that more general studies were carried out in South Africa (26) and Australia (27) for industrial loadings.

Many organisations have conducted plate load tests of block paving. Such tests yield little indication of how block pavements perform under traffic. Nevertheless, they have provided useful measures of structural equivalency between blocks and other types of pavement material (13) and have served to quantify the ability of block pavers to distribute vertical load (11-14).

Trials of block pavements under traffic have been undertaken in Europe (15), North America (16) and Japan (17). Except for the work of the Danish State Road Laboratory (15), the Australian Road Research Board (16) and research groups in the Netherlands (18), these are not well documented.

Using the extensive data gathered during the various tests described above it is possible to obtain an overview of the response of block pavements . Under traffic, block pavements tend gradually to accumulate rutting deformations (7-9, 21). In this respect the performance of block paving is similar to that of conventional flexible pavements. However, both the amount and rate of accumulation of deformation in block paving tends to be less than in flexible pavements of similar thickness.

Block pavements usually exhibit smaller permanent deformations under traffic than asphalt pavements. However, it should be noted that the converse is often true in the case of elastic deflections. Because of the articulated nature of block paving large elastic deflections of up to 2 mm or more have been observed under truck traffic (5,7). Such large elastic movements would be unacceptable in other types of pavement and would cause cracking of the surfacing. Because the block surfaces are already dissected by a network of joints, large deflections can be tolerated and, except where stabilised bases or subbases are used, are not a design consideration (20,28). For this reason the thickness of unbound granular base or subbase needed in a block pavement is normally less than that required in an asphalt surfaced pavement.

Under traffic block pavements tend to stiffen (5,7,10,18). In some cases this leads to the pavements achieving a quasi-equilibrium or 'lockup' condition beyond which no further deformation occurs (5). Often the increase in stiffness in the block layer that accompanies lockup is substantial and it has been reported that, it may be possible thereafter to increase the loads applied to the pavement without causing damage (5). The development of lockup is contingent upon careful control of construction standards and of basecourse quality. For example, it has been reported that basecourse layers of low bearing values do not permit the development of interlock during the early life of the pavement. Where conditions are favourable for achieving interlock it can be allowed to develop gradually under traffic (5) or may be more rapidly induced by rolling the pavement (26).

Factors influencing block pavement performance

The principal factors which contribute to the performance of concrete pavements under traffic comprise:

i) The shape and thickness of the pavers

ii) The laying pattern of the pavers
iii) The characteristics of the bedding and jointing sands
iv) The quality and thickness of the base or subbase layers.

Each of these factors is now considered in detail.

Block shape and thickness

Some early plate load studies suggested that block shape had no influence on the load-distributing performance of block paving (13,14). However, this was contradicted by later comprehensive accelerated trafficking studies in Australia, South Africa, Japan and the USA (5,7,9). These studies concentrated on measurements of vertical deformation (rutting) in the pavements. Generally pavements laid in dentated pavers tended to exhibit smaller deformations than pavements utilising rectangular pavers (5,7). Moreover, recent Australian and French studies have shown that paver shape also influences the development of horizontal creep under traffic. This creep takes the form of horizontal movements in the direction of traffic and is most pronounced in the wheel paths. Tests show that, for a given laying pattern, rectangular pavers are associated with greater horizontal creep than dentated units (e.g. 29).

The principal blocks used in road and hardstands are shown in Figure 2. Scientific studies appear to have been reported for less than a dozen of these and have tended to concentrate on the most commonly used shapes such as A and U. In order to provide a guide to engineers for the selection of the most appropriate shape of paver for a particular application the Cement and Concrete Association of Australia has devised a general classification of block shape (3) and has incorporated this into their design procedures. Essentially blocks are assigned to one of three categories defined as follows:

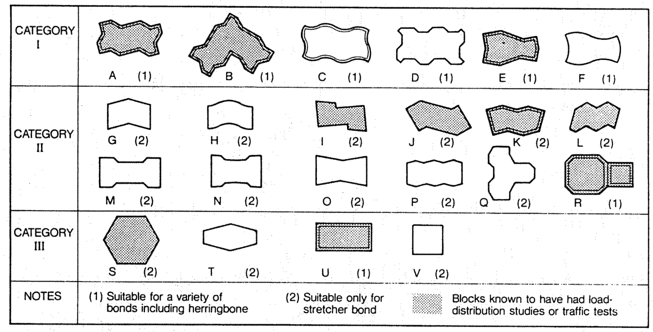
Category I comprises dentated units which key into each other on all four faces and which by their plan geometry when keyed together resist the spread of joints parallel to both the longitudinal and transverse axes of the joints. Generally these units are capable of being laid in herringbone bond.

Category II comprises dentated units which key into one another on two faces only and which, when keyed together, resist the spread of joints parallel to the longitudinal axes of the units but which rely on the dimensional accuracy of laying to interlock on the other faces. With some exceptions, these units can only be laid in stretcher bond.

Category III comprises non-dentated units which do not key together but which rely on their dimensional accuracy and accuracy of laying to develop interlock.

These categories have been superimposed on the various block shapes shown in Figure 2. In the Australian design method it is assumed that only Category I blocks are suited to heavy traffic intensities in excess of 150 heavy vehicles per day. The use of all three categories are, however, permitted for lighter traffic applications such as residential streets although here it is assumed that the thickness of Category II and III paving units must be greater than those needed if Category I units are to be used (30). A similar shape classification has recently been adopted in New Zealand (31).

Figure 2. Principal block shapes.

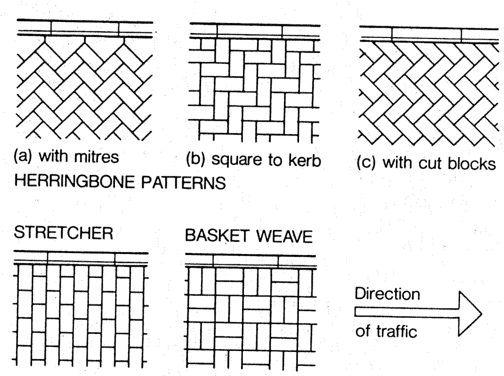


Accelerated trafficking tests have established that an increase in paver thickness is beneficial to pavement performance under traffic (7,9,21). This is manifest as reductions in the permanent deformations and elastic deflections of the pavement and in the stresses transmitted to the subgrade (7).

Laying Pattern

Many of the block shapes illustrated in Figure 2 can be installed in a variety of patterns. Some of the more common of these patterns are shown in Figure 3. Accelerated trafficking tests have been used to compare the performance of block pavements installed in herringbone, stretcher and basketweave bonds (22). In general, the best levels of performance, i.e. the smallest traffic-associated deformations are found in pavements laid in herringbone bond, whereas the greatest deformations are associated with stretcher bond patterns particularly when the bond lines lie along rather than across the direction of traffic (22). The benefits of herringbone pattern are even more pronounced where the pavement has to resist slewing or turning loads (26).

Figure 3. Common laying patterns.



The Bedding and Jointing Sands

The correct choice and installation of the bedding and jointing sands is critical to achieving good in-service performance in block pavements. Both the thickness of this layer and the grading and angularity of the sand have been shown to be critical in influencing the behaviour of block pavements under traffic.

European practice has been to specify a bedding sand thickness, after pavement compaction, of 50 mm. However, it has been reported that much of the early traffic-associated deformation can be attributed to deformation of the sand (22,24). Studies in Australia (7) and South Africa (22) have shown that, if the sand thickness is reduced, the rutting deformations of the pavement also decrease. Currrent practice in these countries is therefore to specify a target sand thickness of just 20 to 40 mm after compaction (32). The validity of this approach has been confirmed by field trials (33).

Laboratory tests (34,35) and accelerated trafficking evaluations (22) have shown that the grading and angularity of the bedding and jointing sand can exert a major influence on pavement behaviour. Should unsuitable sands be used the performance of the pavement may be adversely affected. Indeed, tests have shown that, in some cases a complete failure of the pavement under traffic may occur (22). In particular the use of bedding sands containing plastic fines should be strictly avoided. Under traffic such sands tend to deform excessively and to pump from the joints when wet (22). Specifications for the bedding and jointing sands have been given elsewhere (22).

Basecourse

Most materials used as basecourses in flexible pavements have also been successfully used in block pavements. Such materials include crushed rocks, selected gravels, cement stabilised materials, waterbound macadam, lean concrete and asphalt treated bases.

Comparisons have been made of the performance under traffic of block pavements laid on various types of base (21,26). For identical base and pavement thicknesses the best levels of performance (least deformation) are usually achieved by using cement-treated bases closely followed by the use of crushed rocks (21,26). Gravels and waste products such as blast furnace slag have been found to give an inferior performance to crushed rocks, but the worst performance of all base types has usually been associated with bitumen-stabilised bases (21,26).

Immediately after construction infiltration of water may occur through the joints of a segmental pavement (36,37). However, experience shows that normally within six to eight weeks of being opened to traffic, block pavements become largely impermeable. Nevertheless where an unbound granular base is used it is prudent to protect the material against water penetration. This can be accomplished by applying a light ashpalt prime to the base. The use of lean-mix concrete or cement or asphalt-treated bases overcomes this problem.

It is not always necessary to import the base. In many cases, e.g. where the existing subbase is sandy, it is practical and economical to bring the subbase or subgrade up to basecourse quality by in-situ stabilisation. This technique has been used successfully in a number of major block pavements around the world including those at the ECT, Rotterdam (38,39) and the Massey Coal Terminal, Newport News, Virginia (40).

The Design Of Concrete Block Pavements

The author has reviewed design methods for block pavements elsewhere (41). Accordingly only a brief summary of the methods are given here. A mechanistic design procedure for block pavements recently developed by the author is then presented. This is believed to represent an advance on earlier methods.

Review of Current Design Procedures

The methods that are available for the design of block paving roads can be divided into four categories comprising:

i) Design on the basis of experience
ii) Ad-hoc modifications of existing design procedures for conventional flexible pavements.
iii) Empirical designs based on full-scale trafficking tests
iv) Mechanistic designs based on the determination of design parameters from laboratory tests or prototype 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 Europe this simple approach can yield satisfactory results. The design procedures are often presented as a design catalogue which encapsulate local knowledge (42,44) but which tend to make little distinction between different subgrade conditions of wheel loads. The most comprehensive example of a design catalogue is that developed in South Africa (44). Here local experience has been backed up by both accelerated trafficking tests and mechanistic analyses.

Ad-Hoc Modifications of Flexible Pavement Design Procedures. Here it is assumed that the pavement can be designed by established flexible pavement design procedures and that the blocks and bedding sand can be substituted for part of the conventional design. The earliest example of this approach was developed in Argentina (11). It was assumed on the basis of experiments that the paving blocks were equivalent in performance to 2.5 times their thickness of granular subbase. Later load distribution studies in the United Kingdom established that 80 mm thick pavers laid on 50 mm of bedding were structurally equivalent to 160 mm of rolled asphalt (13). More comprehensive accelerated trafficking studies in Australia (7,17) established that, depending on the particular criterion of performance adopted as the basis for equivalency, concrete blocks were between 2.1 and 2.9 times more efficient than a crushed rock base and between 1.1 and 1.5 times more efficient than a dense-graded asphaltic concrete. Subsequent trafficking tests in the USA by the Corps of Engineers (9) indicated that, conservatively, the effective cover of a block/sand course could be assumed to be 165 mm (6.5 inches).

Concepts of materials equivalency have also been used to modify established design procedures for heavy duty pavements. The design procedure most favoured as the basis for the design of industrial block pavements has been that proposed in the USA by the Corps of Engineers for heavy duty pavements (45). Adopting this approach equivalencies ranging from between 2 (31) and 2.85 (46) have been used to substitute blocks for granular base material. In Australia the procedure has been modified to take into account mechanistic analyses specific to block pavements and which relate subbase thickness to subgrade CBR. Details of this design procedure have been given elsewhere (41).

In the case of block pavements utilising cement stabilised subbases it has been common to adapt the design procedures for heavy duty pavements developed in the USA by the Portland Cement Association (47). For example, in Great Britain it has been suggested that the combined effects of the pavers plus bedding sand can be considered to be equivalent to 225 mm of soil cement (48). This value may then be substituted into the PCA procedure.

Adopting the concepts of equivalency described above, it becomes a simple matter to design a block pavement using well established flexible pavement design procedures which incorporate measures of subgrade strength such as CBR. Examples of such methods have been published in Britain by the Cement and Concrete Association for roads (49) and in America by the NCMA for both roads (50) and industrial pavements (51).

A criticism of these design methods is that they fail to recognise or exploit those advantages peculiar to block paving such as the development of progressive stiffening and lockup or the ability to tolerate large transient deflections.

Empirically-Based Design Methods. Although many workers have used tests of prototype interlocking concrete pavements to obtain materials equivalencies or substitution ratios, only one design method appears to be wholly based on accelerated trafficking tests. This is the method developed by the author at the University of New South Wales for the Cement and Concrete Association of Australia. The method was first published in 1978 (20). Subsequently, following trafficking tests in South Africa designed to verfiy the procedure (21), the method was slightly revised in 1979 (5). The method is restricted to block pavements subjected to highway loadings and which incorporate unbound granular bases.

It has proved possible to use data gathered during accelerated trafficking tests of full-scale prototype block pavements to develop statistically based models to relate, for a given subgrade strength, the block and base thicknesses to such measures of performance as rut depth (20,21). These models have been extended to cover the full range of subgrade conditions using mechanistic analyses (20,28,41) to yield an Australian design method that has been used successfully in a variety of climates both in Australia and elsewhere since the late 1970's (30,33).

Mechanistic Design Methods. Several mechanistic procedures for the design of block pavements have been described. The first was developed in South Africa (12). Here the block pavements were analysed as homogenous isotropic flexible mats overlying a flexible subgrade whose strength was defined in terms of CBR. The second mechanistic analysis was reported in Britain in 1979. The method was based on a three layer linear elastic analysis of the pavement (24). This method yields conservative estimates of base/subbase thicknesses.

Recently a variety of mechanistic procedures utilising the methodology of conventional flexible pavement design have been developed (4,52). Usually these analyses are concerned with computing the tensile strains in a bound base and thereby defining the fatigue life or with determining the vertical compressive strains in the pavement and using these to predict the rutting that will develop under traffic. 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. To date, the most effective application of mechanistic methods has been in the design of block pavements incorporating bound subbases such as lean concrete (52,53) or cement stabilised granular materials (41).

A New Mechanistic Design Procedure

As noted above, by early 1984, a variety of procedures had become available for the design of concrete block pavements. Comparison shows that there is little agreement between the results given by the various methods. Accordingly there is an urgent need to develop generalised design procedures which can embrace the full range of block shapes, base materials and subgrade conditions for both roads and industrial pavements. A computer based design methodology developed to address this problem is now described.

In developing a design method to embrace both roads and heavy duty industrial pavements it becomes impractical to adopt an empirical approach because it is not feasible to simulate the full range of load magnitudes and vehicle configurations likely to be encountered in industrial situations. For example, the method must be capable of handling wheel loads from as little as 4 tonnes for trucks to 50 tonnes or more for transtainers. The use of axle load equivalencies has been eschewed in the work described here. This, in turn, means it was not practical to adopt existing flexible pavement design procedures because most of these are based on concepts of equivalency.

For the reasons outlined above it was decided to adopt a mechanistic approach to evolving the new design procedure. For convenience this procedure is now described under three headings. These comprise:

1) Materials characterisation
2) Loading characterisation
3) Analysis procedures

Materials Characterisation. Before a mechanistic design procedure can be implemented it is necessary to characterise each of the following pavement elements:

a) the block surface
b) the base/subbase materials, and
c) the subgrade

a) Characterisation of the Block Layer. Several workers have characterised concrete block paving in terms of the performance of an equivalent elastic layer. In most cases (e.g. 12) it has been assumed that this layer is isotropic and linearly elastic. Although recently, alternative non-linear models based on finite element techniques have begun to be developed (25,54) these have not yet been perfected. Accordingly, it was decided to model the blocks in terms of an equivalent linearly elastic isotropic layer. Accelerated trafficking tests conducted at the University of New South Wales have indicated that, early in the life of the pavement, the block layer may be characterised in terms of an equivalent elastic modulus of approximately 3200 MPa(460000 psi). This lies between the values of 900 MPa(130000 psi) (12) and 7500 MPa(1088000 psi) (53) used in earlier mechanistic analyses but is less than values measured in Japan (10) and Europe (18,25). Here, equivalent moduli ranging from about 250 MPa to 17000 MPa (36000-2500000 psi) have been reported. Based on a careful consideration of these data a value of the block modulus of 4000 MPa (580000 psi) has been adopted as being representative of a range of block types as well being adequately conservative.

b) Characterisation of the Base and Subbase. Two types of base and subbase material have been considered. These comprise either unbound granular materials (crushed rock for the basecourse), rock or gravel (for the subbase) or cement treated materials. In contrast to the blocks there is an extensive literature on representative properties of such materials. In the case of unbound base/subbase materials values of moduli typically ranging between 150 MPa and 700 MPa (22000-100000 psi) have been reported (55,56). In the work reported below it was decided to model such materials as being non-linearly elastic by adopting the approach of Barker et al.,(56); this modulus is assumed to be dependent on that of the underlying layers. Seperate models are available for base and subbase materials. In the case of the base it has been assumed that the maximum modulus will not exceed 700 MPa (100000 psi) and that for subbase materials it will not exceed 400 MPa (58000 psi). In all cases the Poisson's Ratio has been assumed to be 0.35.

For cement-bound materials the reported moduli range between approximately 2000 MPa and 30,000 MPa (290000-4400000 psi) (55). In the design procedure described below cement-treated basecourse has been conservatively characterised in terms of a modulus of 3000 MPa (435000 psi). This value is close to that recommended by research workers at the Portland Cement Association (57). For subbase layers of cement-treated material a modulus of just 1000 MPa (145000 psi) has been assumed. Again this value is believed to be conservative. Here a Poisson's Ratio of 0.35 has been adopted.

c) Characterisation of the Subgrade. As in the case of the blocks, base and subbase layers, the subgrade has been characterised in terms of an elastic modulus, E. This is assumed to be dependent on the CBR value according to the following relationship

$$E = 10\ \mathrm{CBR} \qquad (1)$$

Again a Poisson's Ratio of 0.35 has been selected.

<u>Loading conditions</u>. In the case of road pavements, where loads and vehicle configurations are closely controlled by legislation, it is possible to characterise the loading conditions in terms of the maximum permitted axle loads. Such an approach is not feasible, however, for industrial conditions because of the extremely wide range of vehicle types, wheel loads and tyre pressures. Moreover, in many typical industrial situations the pavements must serve under a variety of vehicle types each applying different numbers of load repetitions. Accordingly, when seeking to develop a generalised design method it becomes necessary to find some means to characterise the effects of a wide spectrum of loading conditions. In the work described here this has been accomplished by adopting Miner's linear cumulative damage hypothesis. In this respect the methodology is similar to that already routinely used in the design of rigid concrete pavements (58).

The Miner hypothesis states that, irrespective of the magnitude of the stress, each stress repetition is responsible for a certain amount of fatigue damage. It is assumed that there is a linear rate of fatigue damage irrespective of the order of load application and that fatigue failure occurs when the sum of the damage increments at each level of stress accumulates to unity. The law can be expressed in the form

$$\sum_{i=1}^{n} \frac{n_i}{N_i} = 1 \qquad (2)$$

Where N_i is the number of cycles to failure at stress level i and n_i is the number of cycles actually adopted at stress level i.

Having decided to adopt Miner's hypothesis it remains only to postulate the mechanisms of failure in order to predict the life of the pavement. For the block pavements, two criteria of failure have been adopted for unbound and cement-stabilised bases and subbases respectively. In the case of unbound materials the pavement is assumed to fail by the gradual accumulaion of permanent, rutting deformation. In flexible pavement design, it has been commonly accepted that the rutting deformation can be related to the magnitude of the vertical compressive strain in the top of the subgrade. Various criteria have been proposed to relate the magnitude of these strains to the number of strain repetitions that the pavement can carry before developing unacceptable rutting. These have been reviewed elsewhere by Barker et al., (56). In the design method proposed here the subgrade strain criterion developed by Claessen et al., (59) and which forms the basis of the Shell design procedure for flexible asphalt pavements has been adopted. (This also formed the basis of an earlier industrial block pavement design procedure developed by the author (41)).

In the case of cement-bound base or subbase materials a fatigue failure criterion based on the load-induced curvature of the lower boundary of the base or subbase has been adopted. These relationships between the numbers of stress repetitions needed to cause failure and curvature of soil-cement beam specimens developed at the PCA by Larsen et al., (57) have been adopted to suit the three-dimensional stress and strain conditions in pavements. Separate relationships have been used to characterise either coarse-grained or fine-grained stabilised materials (57).

By combining the failure and damage criteria described above with the Miner hypothesis, it becomes possible by trial and error to determine the thicknesses of base and/or subbase needed to ensure that the cumulative damage factor will not exceed unity. This forms the basis of the design method.

Method of analysis. In order to apply the methodology described above it is necessary to be able to calculate the magnitudes of the vertical and horizontal strains throughout a pavement subjected to any designated configurations of wheel loads. As noted above it is expedient to characterise the pavement as comprising elastic materials. Many computer programs for the analysis of such elastic pavement systems have been developed including such well-known procedures as the CHEVRON, BISTRO, CIRCLY and ELSYM programs. Although such programs can provide accurate comprehensive analyses of layered elastic systems, they are all relatively slow and cumbersome and require large computers. Because it was expected that the block pavement design procedures would typically entail several hundred stress analyses before a solution would be obtained, it was decided to adopt a quicker and simpler, albeit approximate, method of analysis. Here the method of equivalent thicknesses originally proposed by Odemark (60) was selected.

This procedure has been widely used in the analysis of flexible pavements (62,62) and on average has been shown to agree within a few percent with stress and strain values calculated by more exact procedures (63).

The method of equivalent thickneses has been incorporated with a computer-based design program which functions as follows:

a) the loads to be carried by the pavements are expressed in terms of a series of design axle loadings. For each axle the following parameters are input.

- the gross axle load
- the number of wheels on the axle
- the tyre pressures
- the number of repetitions of that axle expected throughout the pavement life.

b) The base and subbase layers are specified in terms of being either unbound granular materials or cement-stabilised materials. In the case of cement-stabilised bases or sub-bases the materials are further classified as being either coarse or fine grained.

c) The subgrade is characterised in terms of a soaked CBR value.

d) The thickness of the block layer is specified. (As noted above for most practical cases a thickness of 80 mm will be suitable provided dentated blocks are used).

e) The program selects trial thicknesses of the base or subbase.

f) For each of the design axles the distribution of stresses and strains are computed. In the case of unbound materials the base or subbase layers are automatically subdivided into a number of thinner layers which are assigned values of moduli depending on the stiffness of the underlying layers according to criteria developed by Barker et al.,(56) prior to analysing the structure. In this manner the granular 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 the failure/damage criteria detailed above.

h) Steps (f) and (g) are then repeated for the remaining design axles and the cumulative damage factor is calculated using Miner's Law. If the factor exceeds unity the trial thicknesses are progressively incremented (i.e. steps (e), (f) and (g) are repeated) until the pavement can be shown to have sufficient fatigue and damage capacity to withstand the entire planned spectrum of loading.

Design Curves for Roads and Industrial Block Pavements

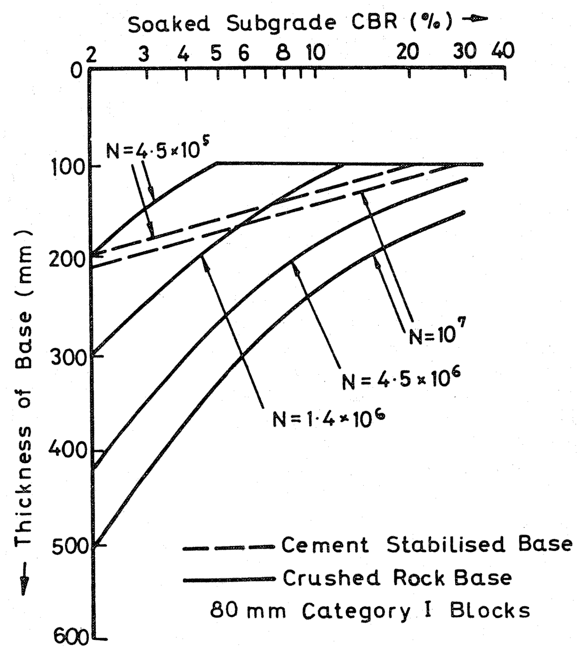
The computer based methodology described above can be used to prepare worst case design nomographs by either designing on the basis solely of the maximum wheel load to be carried by the pavement (and assuming that all repetitions are at this load intensity) or, alternately, by designating specific distributions of wheel loads. This is done for both road and industrial block pavements. In all cases it is assumed that the block thickness is 80 mm (3.15 inches).

Block pavements for roads. Design curves have been prepared for road pavements incorporating either crushed rock or cement-stabilised bases. Here the traffic is assumed to follow the loading spectrum given as Table 1. This table is based on actual traffic measurements. In all cases the tyre pressure has been assumed to be 0.70 MPa (100 psi). The resultant design curves are given in Figure 4 for traffic volumes ranging between 4.5 x 10^5 to 10^7 commercial vehicles over the entire pavement life. From Figure 4 it may be seen that traffic intensity has only a small influence on the thicknesses needed of cement-treated base.

Table 1. Distribution of axle loads.

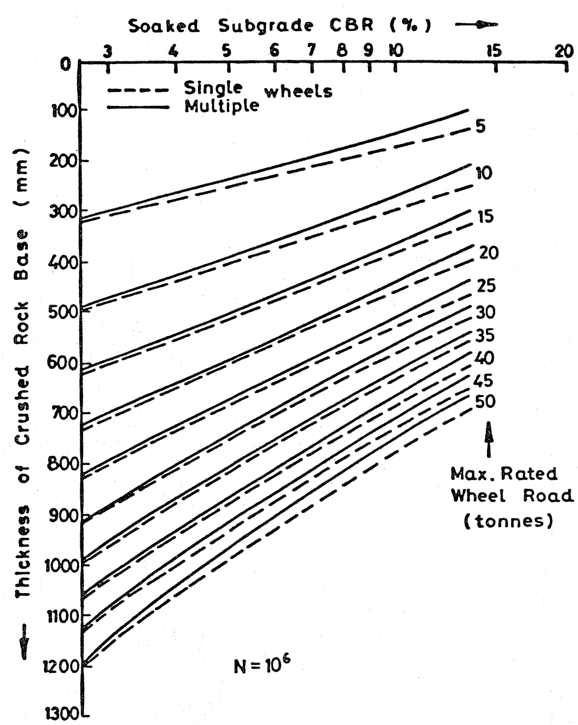
Axle	Single	Single	Tandem	Triaxle
No. of Tyres	Single	Dual	Dual	Dual
Proportion of all commercial vehicles	0.370	0.253	0.285	0.092
Axle load tonnes	Proportion of each axle type			
1	0.00	0.016	0.004	0.00
2	0.029	0.087	0.092	0.186
3	0.092	0.108	0.152	0.128
4	0.271	0.124	0.078	0.055
5	0.533	0.078	0.068	0.090
6	0.071	0.095	0.124	0.442
7	0.001	0.135	0.274	0.099
8	0.001	0.187	0.198	0
9	0.001	0.136	0.010	0
10	0	0.025	0	0
11	0	0.001	0	0
12	0	0.001	0	0
13	0	0.001	0	0
14	0	0.002	0	0
15	0	0.002	0	0
16	0	0.001	0	0

Figure 4. Design curves for road traffic.



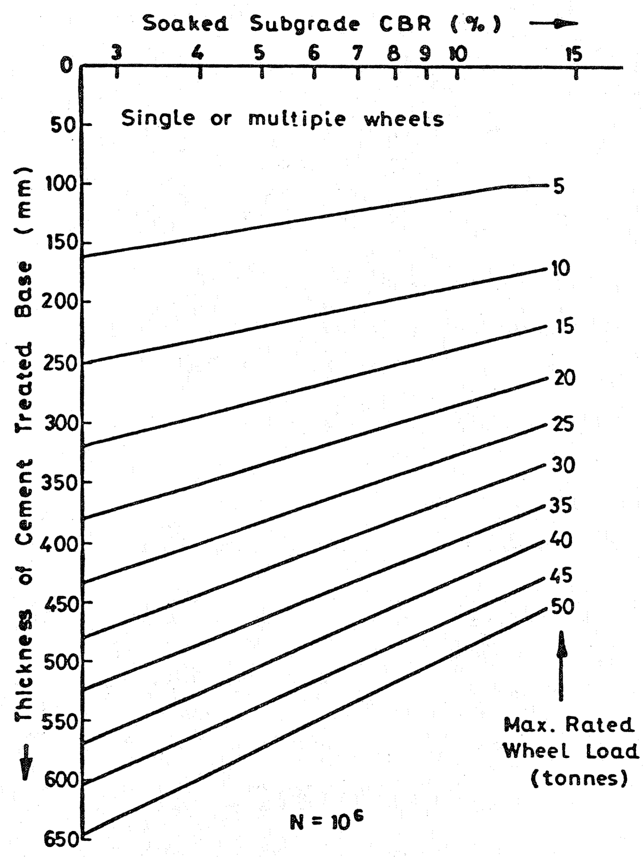
From Figure 4 it may be seen that in general, the thickness of a cement-stabilised base required is less than that needed if the base comprises crushed rock particularly at low subgrade CBR values. The choice of the type of base should be made on economic grounds. However, as noted above, trafficking tests of block pavements (e.g. 21,26,64) indicate that better levels of performance are achieved when using stabilised bases than when using unbound materials.

Figure 5. Design curves for industrial vehicles.



Industrial block pavements. In the case of industrial block pavements, design charts have been prepared for wheel loads ranging between 5 tonnes and 50 tonnes applied by either single or dual wheels via pneumatic tyres inflated to 0.8 MPa (116 psi). Two loading conditions have been considered. In the first of these it has been assumed that all movements of the designated vehicle will be for the fully-laden condition, i.e. that the pavement only experiences one magnitude of load. The second condition is for vehicles such as forklifts handling containers. In practice container weights are widely distributed with a modal value less than the rated container capacity. Details of typical distributions of container weights for various mixes of 20 ft and 40 ft containers have been published in Britain (65). These have been incorporated, in a simplified form, into the design program. Here it has been assumed conservatively that a forklift will exert 35% of its maximum rated front axle load when running unladen and that the remaining 65% of load will vary according to the mix of container sizes being transported. Thus, in order to use the resulting nomographs, the pavement designer has merely to use the curve corresponding to the maximum rated (permissible) wheel load of the chosen design vehicle.

Figure 6. Design curves for industrial vehicles.



Typical design curves for vehicles always running at their maximum rated wheel load are given in Figures 5 and 6 for pavements incorporating crushed rock or stabilised bases respectively. The corresponding design curves for container-handling vehicles are given in Figure 7. From this figure it may be seen that where the loads are distributed over some practical working spectrum the pavements are thinner than for designs based on the assumption of a constant running load.

For heavy wheel loads and low subgrade CBR values substantial base thicknesses may be needed. Although these will often be less than the pavement thicknesses required by alternative forms of pavement it is, nevertheless desirable to make provision to minimise the pavement costs by substituting part of the base by a subbase of lesser quality material. In this respect, design curves have been prepared for the use of a gravel subbase beneath the crushed rock base or of either a stabilised subbase or an in-situ stabilisation of the subgrade beneath a cement-bound base. These curves are given as Figures 8 and 9 respectively.

To use Figures 8 and 9 the pavement designer should first select the thickness of base needed for a subgrade CBR value of 30%. Figures 8 and 9 may then be used to determine the necessary thickness of subbase. In the case of the stabilised materials the subbase may either comprise imported materials or alternatively, if soil conditions permit, can be substituted by an in-situ stabilisation of the subgrade to a depth indicated in Figure 9.

The various design curves presented above represent "worst case" design conditions because, irrespective of whether the load is assumed constant or is specified, to be distributed, only one design vehicle can be handled using the design nomographs. Nevertheless the nomographs can be used to prepare, conservatively, designs for block pavements for a wide range of practical situations. Ideally, however, for optimal design, the full computer-based methodology described above should be adopted.

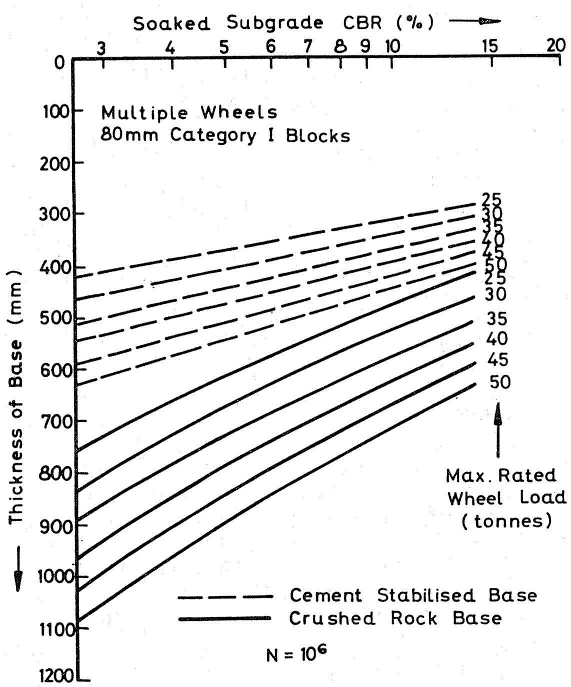


Figure 7. Design curves for container vehicles.

Application Of Concrete Block Paving

Advantages and Limitations of Block Paving

An evaluation of design methods for block pavements such as that presented here shows that in many practical situations interlocking concrete paving can provide a more economical form of pavement than other forms of construction especially over weak subgrades or where heavy wheel loads are to be carried. However, there are several other operational and construction advantages associated with block pavements. These have been reviewed elsewhere (19) and only a summary is given here.

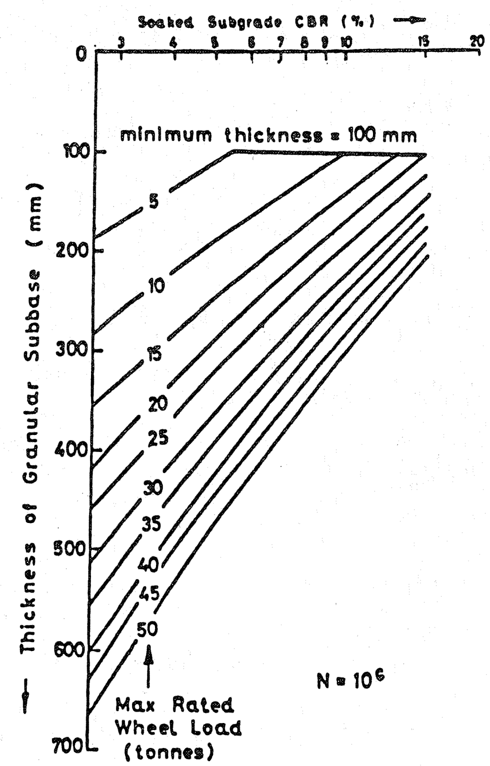


Figure 8. Design curves for unbound subbase.

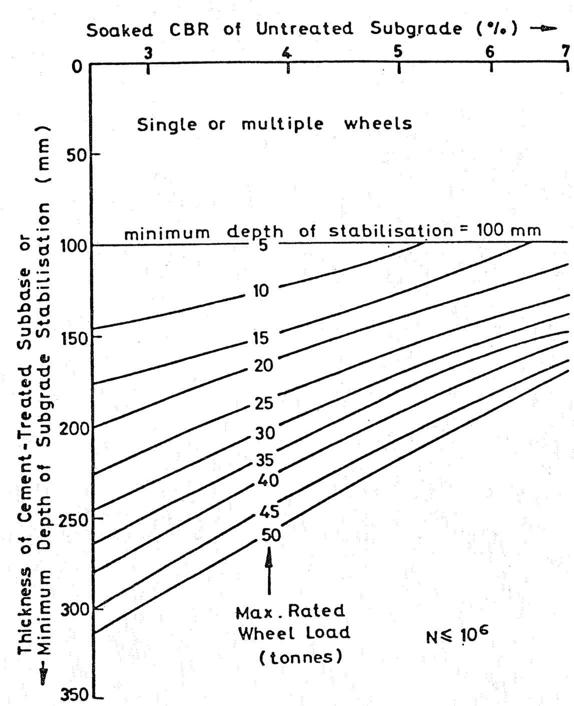


Figure 9. Design curves for stabilised subbase.

The advantages can be stated as follows:

Advantages

a)Block pavements make no use of expensive high energy resources such as asphalt.

b)Interlocking blocks may be cheaply mass-produced to high dimensional and strength tolerances.

c)Interlocking paving blocks can be laid by hand using unskilled labour and only a minimum of very simple construction equipment. However, mechanised laying is also possible.

d)Block pavements may be opened to traffic immediately after construction (i.e. the delays associated with the curing of conventional rigid pavements are avoided).

e)Block pavements may be laid in locations such as steep grades, mountain roads, etc. where the use of normal materials or routine construction equipment is not feasible.

f)Because it is possible to replace readily any areas of local failure in block pavement, maintenance costs can be kept low. In this respect the maintenance costs have been reported to be less than one third of the costs associated with conventional pavements.

g)Block pavements have a long life which is determined primarily by the performance of the subbase and subgrade rather than by any change or deterioration in the blocks themselves. Pavement lives in excess of 20 years have been reported (1).

h)The blocks can be recycled at minimum cost. Not only is the salvage value of a block much higher than for a conventional pavement but the fact that interlocking blocks can be repeatedly lifted and relaid at minimum cost means that ready access is provided to underground services and that trenching and reinstatement of the pavement is both easier and less unsightly than in conventional pavements. Moreover, the correction of loss of pavement profile due to deep underlying settlements is much easier than for conventional pavements.

i)Block pavements generally make better utilisation of concrete than rigid pavements because much bigger deflections can be tolerated.

j)Blocks offer unique aesthetic benefits when compared to other forms of road construction in their ability to integrate and harmonise with the built environment.

k)Unlike asphaltic surfacings block pavements have a high resistance to fuel and oil spillages.

l)Block pavements can be made to be highly resistant to both punching loads and horizontal shear forces generated by the braking, slewing or acceleration of heavy vehicles.

m)Line markings and traffic control markings can be permanently incorporated in block pavements by the suitable use of coloured paving blocks. This reduces road maintenance costs.

n)Block pavements may be excavated without the use of jackhammers. This greatly reduces the noise nuisance associated with roadworks in urban or residential areas.

Limitations

The principal limitations on the use of block pavements concerns the speed of constructing such pavements and the speed of traffic operation after construction. In respect of construction, it must be said that with current technology block pavement cannot be installed as readily as slip-form concrete paving or asphaltic concrete. This disadvantage is partially offset by the fact that, as noted above, block paving can be opened to traffic immediately after installation.

In respect of trafffic operation it is generally considered that operating speeds on block pavements must be restricted to about 60 km/h or less (e.g. 4,27). This restriction stems from concern by engineers that the riding quality of block pavements is not appropriate to high speed traffic operation. To date, few measurements of surface characteristics have been made to verify this subjective assessment of block paving performance. Lekso (15) has tabulated values of bump integrator measurements for four experimental block pavements in Denmark. Generally the block pavements were rated as providing a riding quality which ranged from fair to poor. However, it has been reported that the riding quality tended to improve under traffic (15).

Typical Applications of Block Paving

Experience gained worldwide has established that concrete block paving is well suited to a wide range of applications. Typical examples are now considered for a variety of traffic conditions. For convenience the use of block paving in roads and industrial hardstands will be considered separately.

Road pavements.The application of concrete block paving in roads includes:

a)**City streets.** The ease with which access may be made to underground services, the ability to withstand heavy, slow moving traffic, the low maintenance costs and the aesthetic advantages of interlocking block paving have established block paving as a major alternative for surfacing city streets. Such applications are to be found in many of the great cities of Europe, Australia, South America, Southern Africa, and in recent times North America. For example, extensive use of block paving is to be found in downtown Mexico City, in New York, Vancouver and in Toronto.

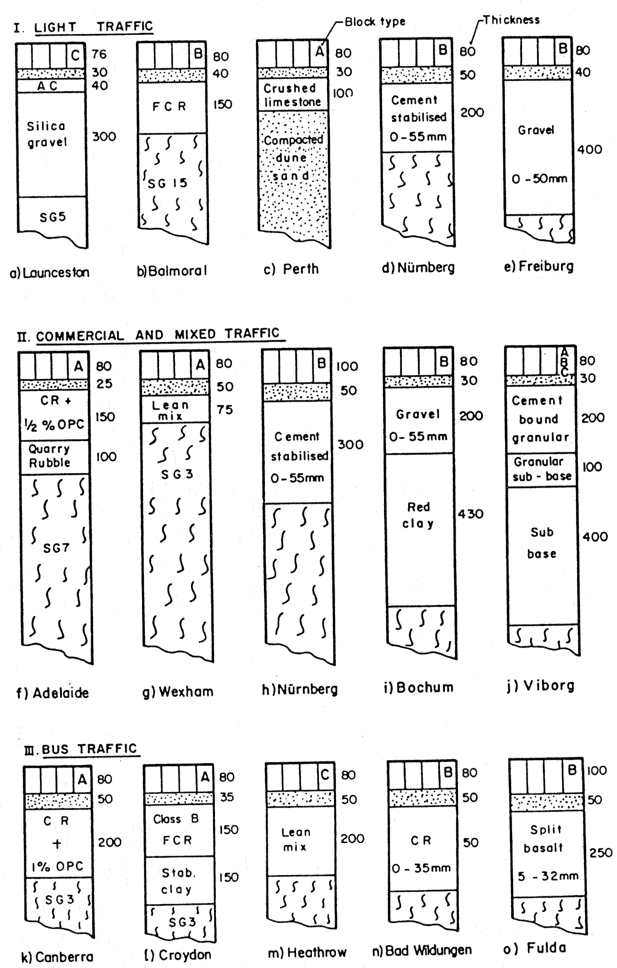
b)**Residential streets.** The flexibility with which block pavements may adapt to changes in land use and road layout, coupled with their high aesthetic value and low maintenance costs has firmly established block paving as a viable form of residential street construction in most developed countries. Such developments are now common in Germany, Holland and Australia and are beginning to appear in North America,notably in California and Florida.

c)**Rural roads.** Interlocking concrete block pavements have been widely used in rural roads in both Holland and Germany. Such pavements are suitable for use in both flat country and mountainous areas where the terrain precludes the use of normal paving methods or materials.

d)**Bus stops and bus depots.** The ability of blocks to resist fuel and oil spillage and to withstand heavy loads makes block paving eminantly suitable for paving bus stops and service depots. Many examples are now to be found in Europe, Central America, Asia, Australia and Southern Africa. However, the outstanding example of this application is the bus terminus at Euston Station, London. This pavement has already carried in excess of one million buses in about three years (66).

Typical cross-sections for a variety of road pavements which are in use around the world are given in Figure 10. These will be seen to embrace a wide range of pavement materials and subgrade conditions.

Figure 10. Typical block road pavements.



Industrial hardstands. In many countries the most cost-effective use of block paving is to be found in the industrial sphere. The ability of block pavements to withstand concentrated heavy loads and to resist the wheel loads of heavy off-road vehicles such as cranes, forklifts and straddle carriers has made interlocking blocks the first choice for many industrial pavements. Typical examples include:

a)**Container yards.** Increasingly, block paving is displacing other forms of pavement in container handling facilities. The prime example of this is in the Europe Container Terminus, Rotterdam, the world's busiest container port. Here more than 3 million square metres of block paving has been installed. This has been reported to have been cheaper in terms of both construction and maintenance costs than more established forms of paving (38). Other well documented examples of container areas are to be found in South Africa and Australia (67). In North America the use of block paving has been made on a major scale at the Canadian Pacific Intermodal Facility, Edmonton, Canada (designed by the author) and on a trial basis in the Ports of Montreal (68), Los Angeles and Baltimore.

b)**Bulk handling facilities.** By far the largest single area of block paving in the USA has been in the construction of the Massey Coal Terminal, Newport News, Virginia. This pavement was designed by the author using methodology similar to that described above and is well documented (40).

c)**Port and harbour areas.** Where pavements must be constructed on reclaimed land or fills subjected to ongoing settlement the ability to recycle block pavements facilitate their use because deformations due to settlement can be easily remedied. A prime example of such an application is in the Port of Rotterdam where the settlements have often exceeded 1 m without distress to the pavement (69).

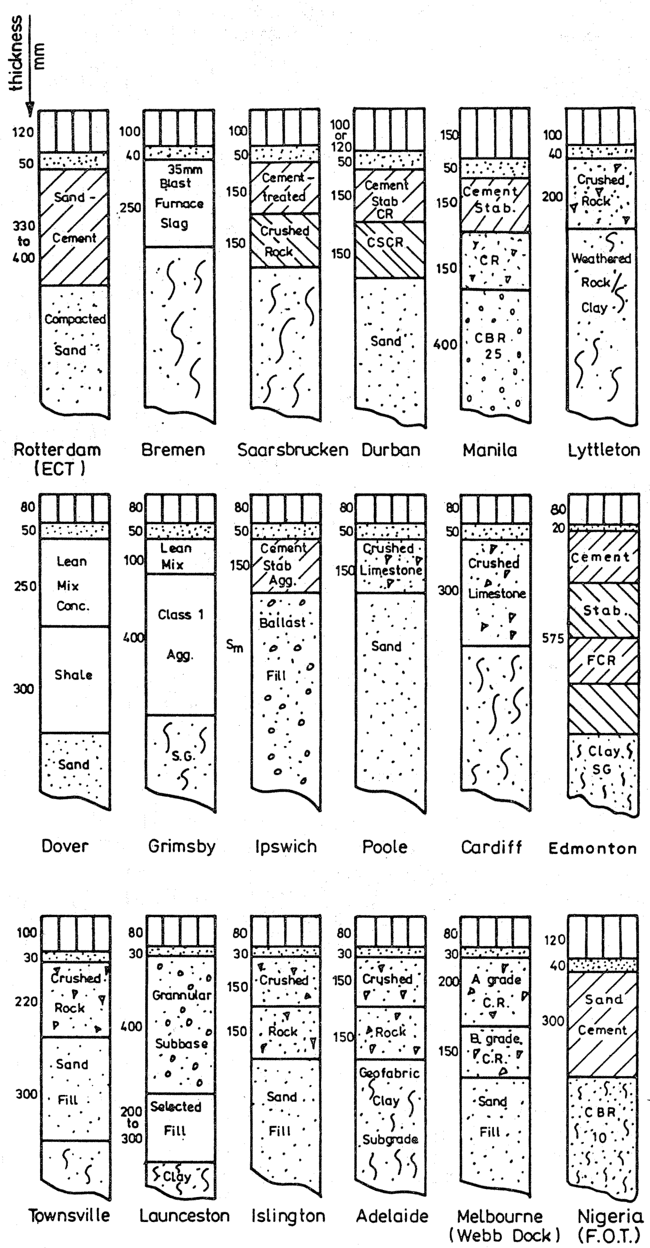
d)**Special purpose areas** The unique features of block paving have encouraged its adoption in many specialised applications where conventional surfacings have proved inadequate or uneconomical. One such application has been on providing surfaces for tracked vehicles(10) and heavy earth moving equipment (30). Other special purpose applications include foundry floors (31) and underground pavements in mines.

Typical cross-sections for a variety of industrial block pavements already in service are given in Figure 11. As in the case of road pavements these will be seen to embrace a wide range of base and subbase materials and subgrade types.

Concluding Comments

Although interlocking concrete block pavements have a long history of successful use, particularly in Europe, it is only recently that basic research into the technology of this type of paving has been conducted. Nevertheless there is already a substantial and well-documented technical base for the use of interlocking concrete paving. This paper has sought to review the principal contributions to this research literature and to outline a comprehensive design methodology for using block paving in both roads and a wide variety of industrial applications. In general, sufficient knowledge and experience of the many applications of block paving already exists to permit engineers to use interlocking paving with confidence. It is to be expected therefore that the usage of block paving will continue to increase around the world as this knowledge becomes more widely disseminated.

Figure 11. Typical heavy duty pavements.



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