EVALUATION OF BLOCK PAVEMENT DESIGN PROCEDURES

R.S. ROLLINGS, U.S. Army Engineer Waterways Experiment Station

ABSTRACT

Recently, the design of interlocking concrete block pavements has received considerable attention in the literature and there are now a number of different procedures proposed. The designer now has the problem of the need to evaluate the different design methods. This paper evaluates the various design methods and discusses how a block pavement behaves under load, the concept of 'lock-up', the influence of block shape and block thickness, construction, and comparative costs of various types of pavement. It is concluded that the selection of a design procedure depends on the specific problem to be solved. An integral part of the design is the selection of appropriate quality materials and construction standards. Evaluation of costs of a block pavement is a complex problem but should at least consider initial costs, maintenance, design performance levels, specific problems, traffic and aesthetics.

INTRODUCTION

At the First International Conference on Concrete Block Paving in 1980 there were relatively few papers on analysis and design of block pavements. However, by the Second International Conference in 1984 this topic had received considerable study, and 39 per cent of the papers presented at the conference covered design and analysis. Interest in this area has continued, and additional publications on the topic have been presented. There are now a number of different proposed design procedures for block pavements, and an engineer faces a perplexing problem evaluating the competing proposed design methods.

OBJECTIVE OF DESIGN

A pavement design method should allow an engineer to select thicknesses and qualities of materials that will, with reasonable confidence, economically support the design traffic loads and repetitions at some minimal performance level. Typical selected performance criteria used are degree of rutting, cracking, or smoothness. Every design must address the problems of establishing some standard minimum design performance level for the pavement, selecting a thickness for each pavement layer, assigning quality requirements for materials to be used in the pavement, and determining construction standards. The proposed block pavement design procedures provide variable results because they handle these problems differently.

Design procedures that yield different results are not a problem unique to block pavements. It is not at all uncommon for conventional pavement design procedures to give very different results. For example, Table 1 shows designs for similar traffic and subgrade conditions from several standard design sources. These designs are different because they reflect the sources' variations in desired performance of the pavement, experience, design philosophies, climate, commonly available construction materials, acceptable level of maintenance, etc. No one design is necessarily better than another; they simply reflect different approaches to the problem and local conditions. Consequently, the variability in the proposed block pavement design procedures is not surprising. For an engineer to select a procedure to use he must evaluate how well the assumptions and basis of the design procedure address the problems of the pavement he must design and build.

TABLE 1

SAMPLE DESIGNS FROM VARIOUS SOURCES FOR SIMILAR TRAFFIC AND SUBGRADE CONDITIONS

Source	Thickness of AC Surface (mm)	Thickness of Granular Base (mm)	Thickness of Granular Sub-Base (mm)
U.S. I	50	125	250
U.S. II	50	125	355
U.S. III	125	100	320
Europe I	70	160	220
Europe II	70	85*	250
Europe III	80	140*	220
Australia	100	260	-

* Asphalt concrete (AC) base.

BLOCK PAVEMENT BEHAVIOUR

The first step in evaluating a block pavement design procedure is to establish how the pavement behaves and carries its loads. Fig. 1 shows typical conventional rigid, flexible, and block pavements. The rigid pavement distributes applied surface loads to the underlying soils through slab bending. Failure generally occurs as progressive fatigue cracking of the concrete slab, thereby reducing the ability of the slab to carry loads through bending. The flexible pavement distributes the surface load through layers of progressively poorer quality materials until a stress level is reached that the subgrade can withstand. Classical failure of flexible pavements is upheaval of the surface adjacent to the traffic lane due to shear movement in the subgrade. When stiff stabilised layers are used in a flexible pavement, or short (e.g. 2 m x 2 m) slabs that cannot completely distribute loads by bending are used in a rigid pavement, the load distribution system includes aspects of both flexible and rigid pavements.

A block pavement is essentially a flexible pavement. It requires a basecourse or a base and sub-base course to distribute loads to the subgrade. Fig. 2 shows a classical flexible pavement shear upheaval in a block pavement subjected to 111 kN tandem axle traffic in a test conducted at the U.S. Army Engineer Waterways Experiment Station (Rollings 1983). Despite the large magnitude of the upheaval these 60 mm blocks have maintained the surface without damage or dislodgement. Plate load tests by a variety of investigators have generally found that the block surface distributes loads over a wider area than a conventional asphalt concrete surface. Also, the block surface tends to stiffen somewhat under traffic.

A block pavement carries load as a flexible pavement, and pavement failure occurs primarily through rutting in the layers under the block surface. Cracking, dislodgement of blocks, and spalling are seldom observed and, if seen, are usually due to unusual impact loads, improper seating of the blocks, or severe rutting in the underlying pavement layers. Block pavements

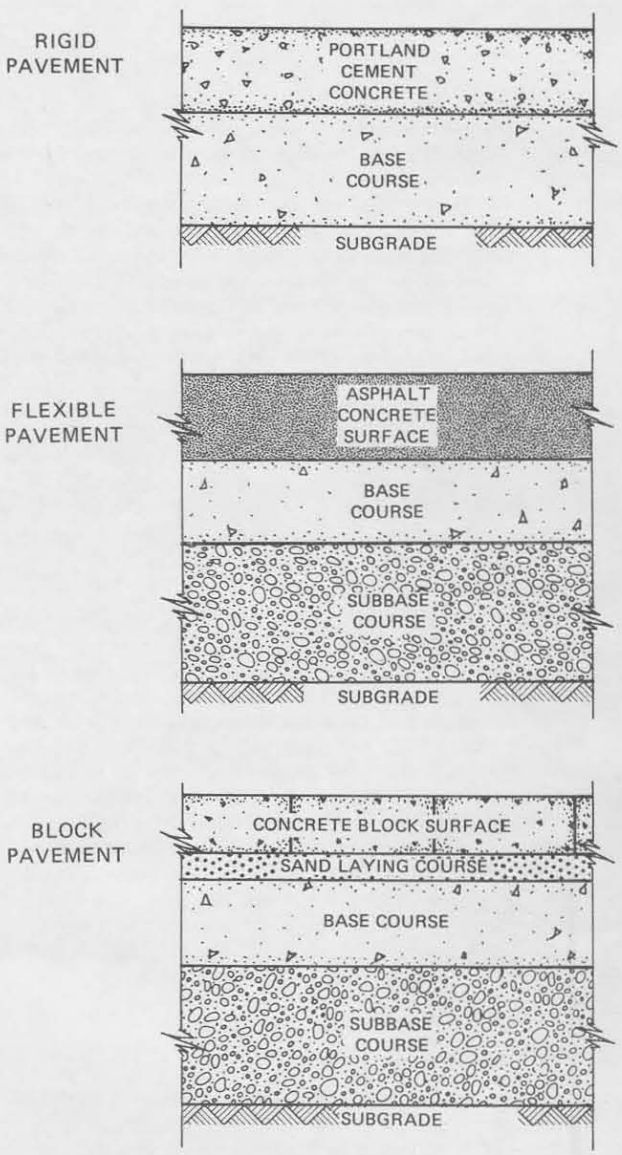

Fig. 1 - Typical pavement types

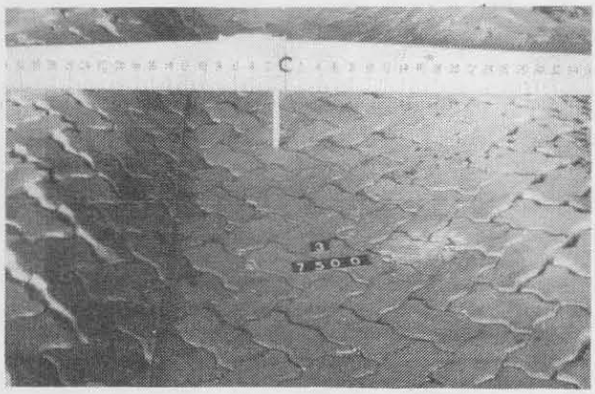

Fig. 2 - Shear upheaval in a block pavement

differ from conventional asphalt concrete-surfaced flexible pavements primarily in their superior load distribution characteristics and the high strength, abrasion resistant surfacing. Blocks have unique characteristics that must be considered in design. Some of these unique characteristics include the concept of 'lock up', block thickness, and block shape.

THE CONCEPT OF 'LOCK UP'

Trafficking tests of concrete block pavements led Shackel (1979) to originally define the term 'lock up'. Since then this concept has been the subject of lively debate at any meeting concerning concrete block pavements. Shackel observed that block pavements that did not rapidly fail tended to reach a limit rutting level fairly soon, and further traffic did not result in additional rutting. This achievement of an early limit of rutting was termed 'lock up'. The 'lock up' concept has led to proposals that design of block pavements need only be based on the deformation to 'lock up', and thereafter the pavement is immune to any further rutting by traffic.

'Lock up', however, is one typical response to be expected from a flexible pavement whether it is surfaced with asphalt concrete or concrete blocks. Fig. 3 shows the rutting of selected traffic tests of conventional asphalt concrete-surfaced flexible pavements subjected to very heavy Lockhead C-5A and Boeing 747 main gear traffic and block-surfaced flexible pavements trafficked by much smaller wheel loads. Both the conventional asphalt concrete and block-surfaced pavements show a similar range of responses that are illustrated in the idealised models in Fig. 3.

If a pavement is under-designed, it will begin rutting immediately, and the rapid rate of rutting will continue unchanged as shown in the idealised model in Fig. 3. Another model in Fig. 3 shows initial rapid rutting, followed by a period of reduced rate of rutting followed by an abrupt shear failure. This type of behaviour might be caused by the fatigue failure of a stabilised layer under the block or asphalt concrete surface, the infiltration of water causing a loss in strength in underlying layers, or a sudden increase in the weight of the traffic vehicles. There are also two models showing initial rapid rutting followed by some reduced rates of rutting. The slow rutting model is representative of the situation that has been termed 'lock up' and it is possible for either conventional asphalt concrete surfaced or block surfaced pavements. A pavement may also be over-designed for the applied traffic, in which case the final model shows a small initial or even no deformation that then remains constant with further traffic.

Fig. 3 illustrates the range of rutting behaviour of flexible pavements. There is a strong similarity between potential rutting behaviour of conventional asphalt concrete and block surfaced pavements. The actual pavement performance is a function of the applied loads and the quality and strength of paving materials and subgrade. It is the strong opinion of this author that the concept of 'lock up' as a unique characteristic of block pavements should be abandoned.

BLOCK SHAPE

Intuitively, a block that interlocks geometrically with neighbouring blocks would seem to be superior to a simple rectangular block. The interlocking projections of the block should resist horizontal movement between blocks. Also the indented shape of the interlocking block provides more vertical surface area where frictional forces could develop. Despite this simple conceptualisation, the actual value of an interlocking block shape compared to a rectangular block shape remains unclear.

Shackel (1979) was the first to propose a quantitative change in pavement performance due to block shape based on traffic test results. This was adopted in Australia by the Cement and Concrete Association in their design guides (Hodgkinson and Morrish 1980). Blocks are identified as type A: interlocking on four sides, type B: interlocking on two sides, and type C: non-interlocking. Performance of type A is considered superior to type B which in turn is considered superior to type C.

This classification by shape has not met with universal acceptance. Rollings (1983) pointed out that the original trafficking data that formed the basis of this classification were biased. In general, rectangular blocks had been tested on lower CBR subgrades, under higher wheel loads, or both when compared with shaped blocks. A review of the available pavement trafficking data by Rollings (1983) concluded that there was no quantitative basis at that time for claiming improved structural performance of shaped interlocking blocks over rectangular blocks. Later both Kuipers (1984) and Knapton (1985) claimed on the basis of experience with heavily-loaded industrial pavements that the rectangular block was distinctly superior to the shaped block. Both rectangular and interlocking blocks performed well under the turning forces of heavy tracked vehicles (Rollings 1983; Ishai and Livneh 1984). Recent trafficking results by Sharp and Armstrong (1985) found that there was no apparent difference in performance between the Australian Cement and Concrete Association designated type A and type B interlocking blocks. Despite disagreement over the value of shaped blocks in thickness design, there does seem to be a consensus of opinion that rectangular blocks must be placed in a herringbone pattern in order to minimise horizontal creep under traffic.

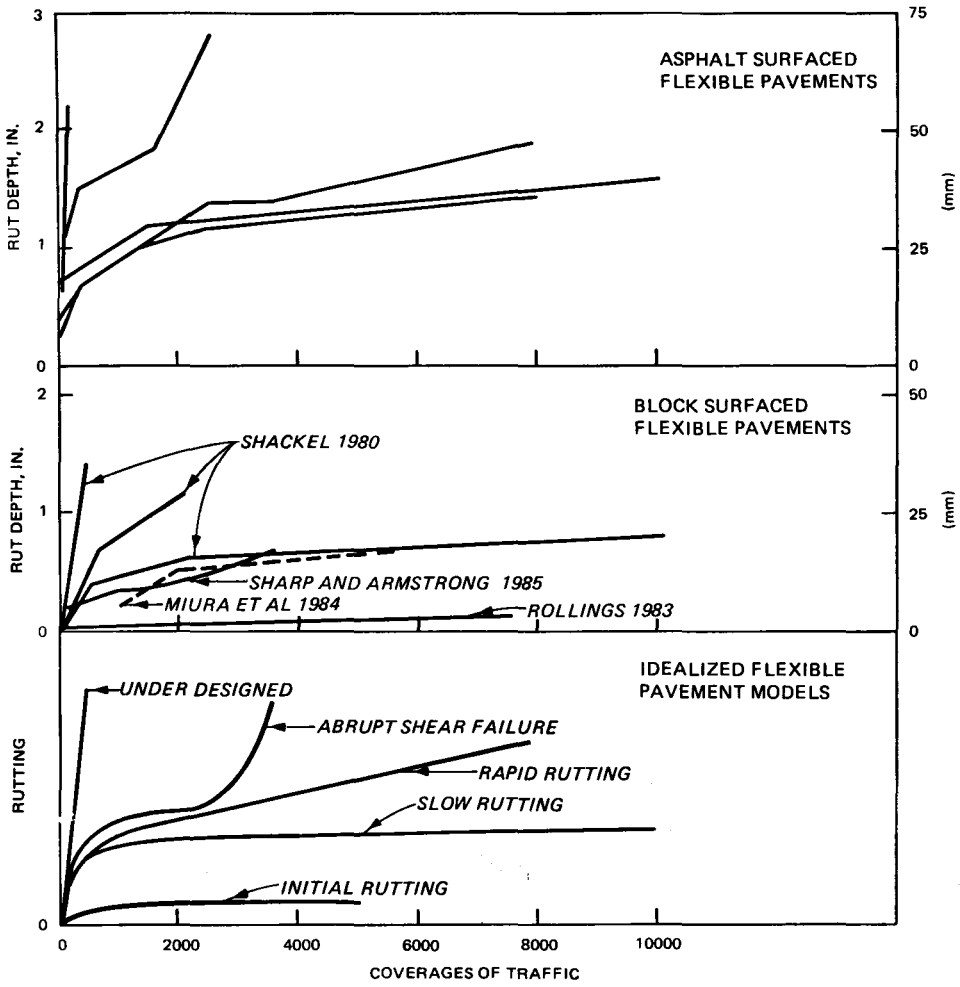

Fig. 3 - Rutting behaviour of pavement types

Opinions on the importance of block shape to the performance of a pavement vary widely, and the data published to date are not conclusive. There are many examples of both rectangular and interlocking block shapes performing well under heavy vertical and horizontal loads. Consequently, requirements to limit use of blocks by their shape appear due more to personal preference and local tradition than to technical requirements.

BLOCK THICKNESS

Plate load tests (e.g. Knapton 1976; Clark 1981; Dutruel and Dardare 1984) have found that block surfaces distribute surface loads to the underlying basecourse better than similar thicknesses of conventional asphalt concrete and that thicker blocks distribute load better than thinner blocks. However, due to the scatter of the data no reliable quantification of this improvement has been made from this kind of test.

Traffic tests of block pavements (e.g. Shackel 1980; Rollings 1983; Miura 1984; Sharp and Armstrong 1985) have consistently found that block thickness is a major factor in decreasing pavement rutting. In general the value of increasing thickness from 60 mm to 80 mm was greater than increasing block thickness from 80 to 100 mm.

Current practice generally limits 60 mm blocks to lightly-trafficked pavements such as pedestrian walkways or residential parking areas. The 80 mm block seems adequate for heavy loads found on highways and port facilities. The 100 mm or 120 mm blocks are used under unusual loads or where a greater safety factor or confidence level is desired.

THICKNESS DESIGN METHODS

Shackel (1985) summarised a variety of different concrete block pavement design procedures. He broadly classed these as experience-based design procedures, empirical design procedures, design based on modifications to conventional flexible pavement design procedures, and mechanistic designs. Within each of these classes there are a variety of different specific design procedures representing different user requirements, failure concepts, agency experience, local climate and traffic, etc. Table 2 shows some of the factors of selected design procedures which can be used to examine the advantages and disadvantages of each design approach.

Experience-based design procedures rely on a history of successful experience with block pavements to select materials and their thicknesses to support the expected traffic. Design is

TABLE 2

SAMPLE BLOCK PAVEMENT DESIGN PROCEDURES

Design Approach	Typical Source	Analytical Stress Model	Failure Criteria	Block Model
experience	manufacturer's literature	none	none	none
empirical	Shackel (1979)	none	10 mm rut	none
modify existing	Rollings (1983 and 1984)	Boussinesq	25 mm shear upheaval	equivalent thickness
mechanisitc	Barber and Knapton (1980)	modified Boussinesq	subgrade and base strain	equivalent modulus of elasticity
mechanistic	Shackel (1985)	layered elastic	subgrade and base strain	equivalent modulus of elasticity
mechanistic	Houben et al. (1984)	finite element block layers supported on layered elastic	calculated deflections	rigid bodies interconnected by springs

inexpensive and relatively straightforward, typically using simplified tables showing thicknesses of basecourse and block required for certain classes of traffic. This approach is probably most appropriate for lightly-loaded pavements such as walkways or residential driveways where a pavement failure is not of major importance. If such procedures are used for heavily-trafficked or critical pavements, the design pavement must use similar construction materials and procedures, have a similar subgrade and climate, and must be exposed to similar traffic loading as the pavements that are the basis of the design recommendations. For example, it would be ludicrous to use experience with lightly-loaded residential pavements on cohesionless subgrades with abundant high quality basecourse aggregates in a dry climate as a basis for selecting pavement designs to be exposed to heavy industrial traffic in a tropical climate and which must be built on soft, clay subgrades using only poor quality basecourse aggregates.

Empirical design procedures subject prototype pavements to controlled traffic to develop experience, guidelines, and relationships for design of future pavements. This approach has the advantage of testing the actual performance of the blocks under traffic loads. However, like the experience-based design procedures, the empirical design procedures are only valid within loads and conditions of the tested pavements. Extending the procedures to larger loads, different subgrade strengths, etc. requires new tests. For example, the empirical design procedure by Shackel (1979) in Table 2 was based on tests using high strength subgrades. When it became desirable to extend this to low strength subgrades, new trafficking tests were conducted by the Australian Road Research Board (Sharp and Armstrong 1985). Shackel (1979) used a failure criteria of a 10 mm rut. Because of the high strength subgrade much of the rutting that occurred in the test must have been due to densification in the sand bedding layer and the underlying base materials. Consequently, it would be very difficult to extend these results to a case where rutting in a soft subgrade was an important part of failure. Empirical design approaches are a significant improvement over purely experience-based approaches because the controlled tests allow some prediction of performance and evaluation of actual block behaviour under traffic. Like the experience-based designs, it is difficult, if not impossible, to extrapolate to conditions different from those used in the original tests.

Another approach to the design of block pavements is to modify an existing conventional flexible pavement design procedure for asphalt concrete surfaced pavements. This approach has the advantage of making full use of past local or agency experience with materials, traffic, climate, etc. but most proposed designs of this type tend to be conservative. The improved load spreading capacity of blocks as compared to conventional asphalt concrete is usually recognised by use of an equivalency factor. An example of this approach is the U.S. Army Corps of Engineers block design described by Rollings (1983 and 1984) where the block and sand layer are credited with 165 mm of the pavement thickness required by the conventional CBR flexible pavement design procedures. The Corps of Engineers CBR design procedure for flexible pavements is based on three principles:

(1) Sufficient thickness of overlying material is provided over any point to reduce the stresses caused by the load at that point to a level that the material's strength as measured by the soaked CBR can withstand. The stresses are calculated using Boussinesq solutions with linear superposition for multiple wheel gear loads. The relation between CBR, stresses, and repetition of stresses is an empirical one developed from accelerated traffic tests using wheel loads up to 333.6 kN. This relation is

based on a failure condition defined to be 25 mm shear upheaval adjacent to the trafficked lane.

(2) Each layer of material is compacted to a degree that ensures the CBR strength assumed in design is achieved in the field, and densification of materials resulting in objectionable surface settlement does not occur under the design traffic.

(3) Material quality as measured by such factors as gradation or Atterberg limits is sufficient to ensure adequate performance under the site's environmental conditions as determined from long-term experience with in-service pavements.

One problem that the CBR approach handles poorly is stabilised layers within the pavement. The Boussinesq solution for a load on an elastic half-space is unable to model the stiff, stablised layers. Generally, this requires use of equivalency factors where 25 mm of stabilised material are assumed to be equal to some thickness of conventional granular material (see Department of Defence 1978 for example). This is a very simple and practical approach, but it is quite poor theoretically.

Barber and Knapton (1980) described a mechanistic approach that converts a layered pavement system into a single equivalent thickness of subgrade material. This is done by equating the flexural stiffness of each existing layer to that of the subgrade material by:

$$h_2 = h_1 \left[\frac{E_1}{E_2} \times \frac{1-V_2^2}{1-V_1^2} \right]^{1/3}$$

where

h_1 = actual layer thickness

h_2 = equivalent thickness of subgrade material

E_1 = actual layer modulus of elasticity

E_2 = subgrade modulus of elasticity

V_1 = actual layer Poisson's ratio

V_2 = subgrade Poisson's ratio.

Once this is done, Boussinesq solutions can be used to calculate vertical strain in the subgrade and tensile strain in a stabilised basecourse. These strains can then be compared to allowable values from conventional pavement design procedures.

Shackel (1985) has proposed using subgrade and stabilised base strains calculated from a layered elastic model as the basis for design. Rollings and Armstrong (1986) have suggested using the flexible pavement layered elastic analysis technique and criteria developed by Barker and Brabston (1975) for analysis of block pavements when in-depth study of the effect of stabilised base is needed. The technique and criteria of Barker and Brabston were recommended because they are compatible with, and use similar failure concepts as, the conventional Corps of Engineers CBR design procedure.

All of these mechanistic analysis approaches suggested by Barber and Knapton (1980), Shackel (1985), and Rollings and Armstrong (1986) require that some equivalent modulus of elasticity be assigned to the block layer to make them fit the analytical model being used. Obviously a layer of modular blocks with sand- filled joints does not behave as a simple elastic layer. Suggested equivalent modulus of elasticity values for blocks have varied from 248 to 17 237 MPa with intermediate values between 3170 and 7450 MPa being used in some design schemes.

Houben et al. (1984) described an advanced analysis scheme that used a hybrid finite element and layered elastic model to investigate block pavements. The blocks were represented as rigid bodies modelled by finite elements interconnected to one another by springs. The sand layer was represented as a supporting bed of springs. Underlying base and subgrade materials were represented as elastic layers. This represents the most comprehensive attempt to analytically model a block pavement, but more research is needed to reliably define input parameters such as the spring constants and to make the model usable.

From the proceeding discussion it is obvious that there are many block pavement design approaches available. Each has its own advantages and disadvantages. In this author's opinion different problems require different design approaches. For example, a walkway or lightly-loaded residential street could be designed very effectively using either experience or empirically developed design procedures. An urban street carrying high volumes of traffic might be most appropriately designed by modifying a local highway department conventional design procedure. This local procedure has already proven effective for local traffic, soils, construction materials, and climate and a simple block equivalent thickness such as proposed by Knapton (1976) could be used with the design procedure. For heavily-loaded vehicles on soft soils such as at a port facility, a modification of the Corps of Engineers CBR procedure as suggested by Rollings (1983 and 1984) and Rollings and Armstrong (1986) might be appropriate. The Corps of Engineers CBR design procedure was developed from tests with large wheel loads on pavements built on low CBR subgrades which is the same problem encountered in many port pavements. A modification of this design procedure would appear to be particularly appropriate for block pavements subject to large loads on soft soils. If the effect of stabilised layers in the pavement needs to be examined in detail then one of the procedures suggested by Barber and Knapton (1980), Shackel (1985), or Rollings and Armstrong (1986) with some effective modulus of elasticity for the blocks would provide a reasonable approach.

CONSTRUCTION AND MATERIALS

A great deal of effort is often expended on pavement thickness design as discussed in the previous section. In actual fact, failure in the field is most often associated with poor construction practice, inadequate materials, or both. A sophisticated design, poorly executed with improper control over materials is doomed to failure whereas a mediocre design well built using appropriate materials will probably perform admirably.

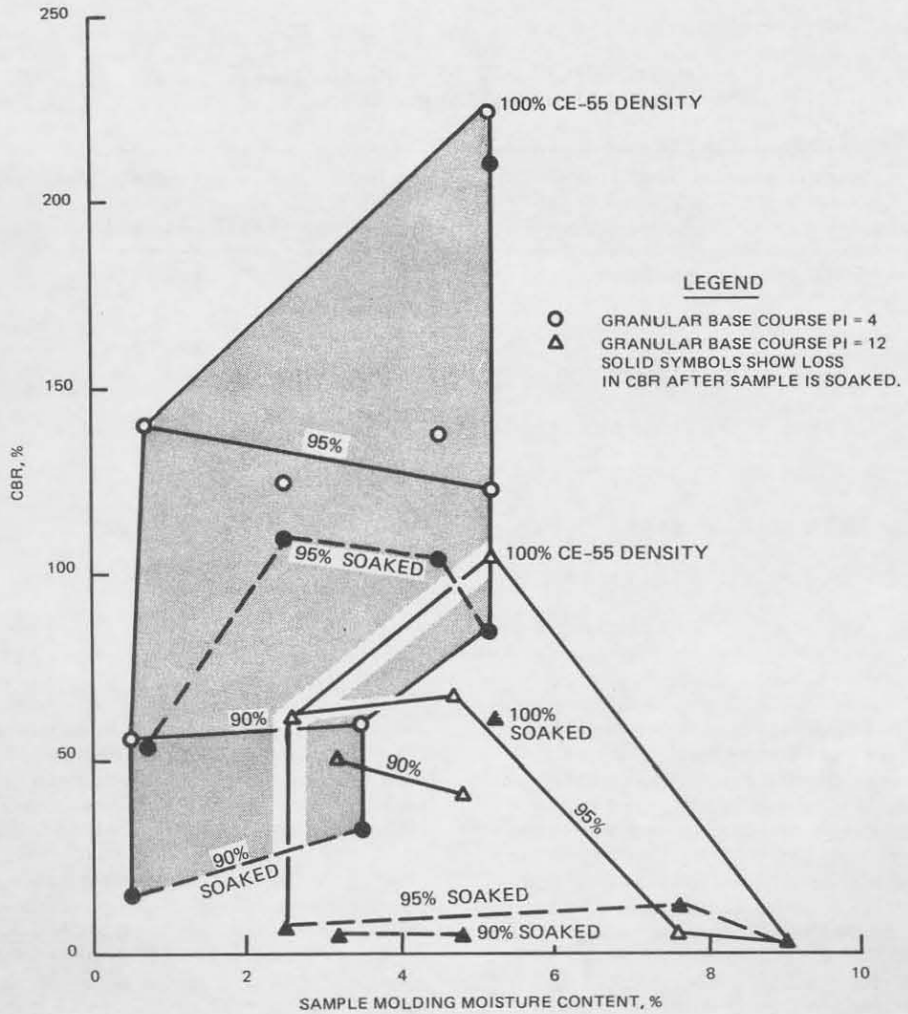

Fig. 4 - Effect of plasticity on materials performance

The effect of compaction and moisture on two gravels can be seen in Fig. 4. These two gravels were used as basecourse material for conventional pavements at two U.S. airfields. They have very similar gradations, but the plasticity index of one is 4 per cent and of the other 12 per cent. Laboratory samples were moulded and compacted to determine the dry density-moisture content compaction curves, and afterwards soaked and unsoaked laboratory CBR tests were run on the compaction samples. The results in Fig. 4 are expressed in terms of the maximum CE-55 density which is equivalent to the more common maximum modified AASHO laboratory density. The optimum moisture content for maximum dry density of both gravels is approximately 5.2 per cent.

Unsoaked, both gravels are capable of exceeding a 100 CBR which is the common maximum value allowed in design. However, upon soaking, the gravel with the higher plasticity index shows a drastic CBR drop from 105 unsoaked to 62 soaked. The Corps of Engineers requires pavement basecourses to be compacted to 100 per cent of the laboratory density (CE-55 or modified AASHO). If in the field the gravel with the lower plasticity index is only compacted to 95 per cent density, Fig. 4 shows that as long as it is unsoaked it maintains a CBR in excess of 100. If soaked, the CBR shows a considerable decrease varying with the initial compaction moisture content. The higher plasticity index gravel shows the same trends to a more exaggerated degree. Inadequate field compaction of either gravel or use of the high plasticity gravel in a wet environment would be enough to run the most comprehensive design if the original design assumed that a 100 per cent CBR quality material would be used in the basecourse.

Design is more than simply selecting thicknesses of material. Block pavements are not impermeable, nor, for that matter, are conventional asphalt concrete and Portland cement concrete pavements. Consequently, design should be based on soaked CBR or some other soaked strength tests. Soaked strength tests represent a worst case approach. Another possible, less conservative approach would be to select a design CBR on the basis of surveys of in situ CBR values of actual in-service block pavements. Such data for block pavements appear to be very scarce and will be valid only for a local situation with similar climate, subgrade, drainage, ground water flows, etc. Materials used in the sub-base and base should be evaluated by soaked CBR tests, and gradation and Atterburg limits should be established to provide good long-term service.

TABLE 3

COSTS FOR BLOCK PAVING IN PLACE
After Rollings 1983

Year	Location	Project Size (m^2)	Cost ($U.S./m^2$)
1976	Fulda Barracks, Germnay	2700	12.27
1977	El Cerrito, California	860	32.29-37.67
1978	Perth, Australia	-	13.35
	Dover, U.K.	27,000	12.59-16.58
1979	Eastern U.S.A.	-	19.91-32.29
	California	-	32.29-59.20
1980	Netherlands	-	14.96

The sand bedding layer under the blocks in Fig. 1 is a construction necessity, but it is a structural weakness. Blocks are placed directly on the loose sand bedding course. Next, sand is swept into the cracks between the blocks, and the entire surface is then compacted with a vibratory plate compactor. Adequate density to resist densification under traffic is almost never obtained in the sand layer by these procedures. Consequently, it is necessary to keep this sand layer as thin as possible, typically 25 mm, to provide an adequate bedding layer for the blocks but also maintaining surface settlement due to traffic densification of the sand to negligible proportions.

COST

It is impossible to make any categorical statements about the cost of block pavements. As shown in Table 3, costs of block pavements have been reported that vary considerably depending on location, project size, loading, etc. Block pavements are generally recognised to be a low maintenance surface. Consequently, their economic position is enhanced when maintenance costs are included in any comparison with other paving.

Table 4 illustrates some problems in comparing relative costs of paving surfaces. Initial construction costs were estimated for a pavement to support heavy tracked vehicle traffic, and, as seen in Table 4, there is a lot of variation in the costs. The German and Corps of Engineers' designs differ radically from one another regardless of surfacing since they are based on very different approaches, philosophy, experience, etc. If a block pavement cost is to be compared to an asphalt concrete or Portland cement concrete pavement, all designs should be based on related performance philosophies. For example, it would be very difficult to compare the costs of block pavement designed to have a 10 mm rut to an asphalt concrete pavement designed to have a 25 mm shear upheaval or to a Portland cement concrete pavement

TABLE 4

ESTIMATED COSTS FOR HEAVY DUTY PAVEMENTS

	Cost ($U.S.\$/m^2$)
Block surfaced, Corps of Engineers design	33.00
Block surfaced, German design	25.88
Asphalt surfaced, Corps of Engineers design	31.07
Asphalt surfaced, German design	47.83
Portland CC surfaced, Corps of Engineers design	32.27
Portland CC surfaced, German design	46.80

CC: cement concrete

designed for 50 per cent of the slabs to have one or more structural cracks at the end of the design traffic. Also, since these specific pavements were designed for tracked vehicles, the initial cost of asphalt concrete is illusory since maintenance costs would be very high. Comparison of pavement cost is never simple and must consider factors such as maintenance, design level of performance, traffic, special problems such as settlement or utilities, and aesthetics as well as initial costs.

CONCLUSION

Block pavements are flexible pavements that have a high strength, abrasion resistant surface. Design should be based on selecting pavement materials and their thicknesses to avoid rutting in the layers and subgrade beneath the block surface. The block thickness, shape, and laying pattern should be selected on the basis of the expected traffic on the pavement. A variety of thickness design procedures have been proposed for block pavements, and they offer varying advantages and disadvantages. Selection of a design procedure depends on the specific problem to be solved and can vary depending on factors such as job size, type of traffic, amount of local experience, use of stabilised layers, etc. An integral part of any design is the selection of appropriate quality materials to be used is the pavement and establishing required construction standards. Evaluation of the cost of a block pavement is a complex problem but should at least consider initial cost, maintenance cost, design performance levels, any special problems, traffic and aesthetics.

ACKNOWLEDGEMENT

The support of the Waterways Experiment Station (WES) in gathering and preparing material for this paper is gratefully acknowledged. Comments and suggestions from several personnel in the WES Pavement Systems Division were of great assistance in preparing this paper. Permission of the Chief of Engineers to publish this paper is acknowledged.

REFERENCES

BARBER, S.O. and KNAPTON, J. (1980). Structural design of block pavements for ports. Proc. 1st Int. Conf. Conc. Block Paving, Newcastle, U.K., pp. 141-49.

BARKER, W.R. and BRABSTON, W.N. (1975). Development of a structural design procedure for flexible airport pavements. Tech. Rep. S-75-17, U.S. Army Eng. Waterways Expt Station, Vicksburg, Miss., U.S.A.

CLARK, A.J. (1981). Further investigations into the load-spreading of concrete block paving. Tech. Rep. TR 545, U.K. Cement Conc. Assoc.

DUTRUEL, F. and DARDARE J. (1984). Contribution to the study of structural behavior of a concrete block pavement. Proc. 2nd Int. Conf. Conc. Block Paving, Delft, pp. 29-39.

DEPARTMENT OF DEFENCE (1978). Flexible pavement design for airfields. TM-5-825-2, Washington, D.C.

HODGKINSON, J.R. and MORRISH, C.F. (1980). Interim guide to the design of interlocking concrete pavements for vehicular traffic. Cement Conc. Assoc. Aust. Tech. Note, TN34, March.

HOUBEN, L.J.M., MOLENAAR, A.A.A., FUCHS, G.H.A.M. and MOLL, H.O. (1984). Analysis and design of concrete block pavements. Proc. 2nd Int. Conf. Conc. Block Paving, Delft, pp. 86-99.

ISHAI, I. and LIVNEH, M. (1984). Interlocking concrete block pavement for heavy abrasive caterpillar loading. Proc. 2nd. Int. Conf. Conc. Block Paving, Delft, pp. 183-90.

KNAPTON, J. (1976). The design of concrete block pavements. Rep. 42.515, Cement Conc. Assoc., U.K.

---------- (1985). The structural design and performance of concrete block roads. Proc. Third Int. Conf. on Concrete Pavement Design and Rehabilitation, Purdue Univ., West Lafayette, Indiana.

KUIPERS, G. (1984). The choice of an appropriate block shape for heavy industrial flexible pavements. Proc. 2nd Int. Conf. Conc. Block Paving, Delft, pp. 69-71.

MIURA, Y., TAKAURA, M. and TSUDA, T. (1984). Structural design of concrete block pavements by CBR method and its evaluation. Proc. 2nd Int. Conf. Conc. Block Paving, Delft, pp. 152-59.

ROLLINGS, R.S. (1983). Concrete block pavements. Tech. Rep. GL-83-3, U.S. Army Eng. Waterways Expt Station, Vicksburg, Mississippi.

---------- (1984). Corps of Engineers design method for concrete block pavements. Proc. 2nd Int. Conf. Conc. Block Paving, Delft, pp. 147-151.

ROLLINGS, R.S. and ARMSTRONG, J.P. (1986). Concrete block paving for marine terminals. Am. Soc. Civ. Eng. Specialty Conf. Ports 86, Oakland, Ca. U.S.A.

SHACKEL, B. (1979). The design of interlocking concrete block pavements. In Sharp, K.G. and Metcalf, J.B. (Eds) 'Workshop on Interlocking Concrete Block Pavements'. Australian Road Research Board. Research Report, ARR No. 90.

---------- (1980). A study of the performance of block paving under traffic using a Heavy Vehicle Simulator. Proc. 10th ARRB Conf. 10(2).

---------- (1985). Evaluation, design and application of concrete block pavements. Proc. Third Int. Conf. on Concrete Pavement Design and Rehabilitation, Purdue Univ., West Lafayette, Indiana.

SHARP, K.G. and ARMSTRONG, P.J. (1985). Interlocking concrete block pavements. Australian Road Research Board. Special Report, SR No. 31.

Raymond Rollings graduated BS in Applied Science and Engineering from the U.S. Military Academy, West Point, in 1972 and MSCE in Structures and Soils from the University of Illinois in 1974. He has presented papers and conducted courses both inside and outside the U.S., including a course on concrete airfield pavements at the Royal Military College, Duntroon, in 1985. Ray is a Member of the American Concrete Institute Committees on Fatigue of Concrete and Concrete Pavements and a Major in the Military Reserve. His main interests are rigid airfield pavement design and bomb damage repair, roller compacted concrete, concrete block pavements and concrete overlays. He is the co-author with E.J. Yoder and M. Witczak of the 3rd Edition of 'Principles of Pavement Design', which is currently in preparation.