THE STRUCTURAL DESIGN AND PERFORMANCE OF CONCRETE BLOCK ROADS

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For both lightly trafficked and heavy duty pavements, the paper describes design methods which are being used regularly in the U.K. It is shown that most U.K. pavements are on low CBR subgrades and that relatively few designs can be used for the great majority of projects. It is shown that the design method developed by the Cement & Concrete Association is a good working method for lightly trafficked pavements and produces cost effective pavements. The British Ports Association design method for heavy duty paving is described, for both new pavement design and for strengthening existing pavements.

Various civil engineering materials are described and a technique for assessing the suitability of granular sub-base materials is suggested. The use of Geoweb materials is discussed and general conclusions are drawn which show that U.K. concrete block paving design methods are now well established and that concrete block paving is being regarded as an orthodox solution for many categories of pavement.

During the late 1970's, work was taking place in several establishments to develop design methods for concrete block pavements. Much of the work was reported at the First International Conference on Concrete Block Paving in 1980 and since then, the amount of effort devoted to understanding the behaviour of concrete block paving has grown. Since the First International Conference, the author has been involved in the design of approximately 400 areas of concrete block paving and has become aware of two areas where very little guidance is available for the designer. Firstly, most of the researchers have confined their attention to developing methods of selecting material thickness and not to establishing the stability and strength requirements for base and sub-base materials. Experience shows that where problems develop in concrete block pavements, the cause is nearly always inappropriate material type specification rather than inadequate course thicknesses. In the U.K., the use of moisture susceptible materials combined with the lack of adequate surface and sub-surface drainage has lead to inadequate performance in many instances In this paper, the author explains how granular materials can be specified in a safer and more cost effective manner so that advantage can be taken of low cost materials without the possibility of their becoming unstable. Secondly, very little guidance is available for lightly trafficked small areas. Again, thickness design guidance is available but this constitutes a minor aspect of the design of such jobs. This paper deals with both of these areas and explains the author's approach to both. The paper also deals with heavy duty pavement design and in particular with the British Ports Association design method which applies to new pavements and to pavements which need to be strengthened. By comparing this paper with that of Barber & Knapton (1), presented at the First International Conference, the way in which heavy duty pavement design has developed can be seen.

Base and Sub-base Construction Materials

During the last fifteen years, a considerable amount of research has been directed towards producing design charts relating thickness of base and sub-base material required to subgrade and traffic characteristics. (2, 3, 4) Although slight differences exist between the results produced by the different researchers, it is now possible for the designer to find sufficient course thickness guidance no matter what level of traffic and subgrade parameters exist. Much less attention has been devoted to providing guidance on the quality requirements of base and sub-base materials: indeed the author is unaware of any attempt by any researcher to develop base and sub-base material specifications appropriate to concrete block paving. Rather, in the U.K., the Department of Transport's "Specification for Road and Bridge Works" (5) has been adopted. This document defines two categories of granular sub-base material, two categories of unbound macadams, three categories of cement bound base materials and three categories of bitumen bound base materials.

These materials are defined in a way which is orientated towards U.K. motorway construction so that when these definitions are borrowed by the concrete block pavement designer, they are not ideal.

The most obvious area in which the use of the D.Tp. document is both inadequate and dangerous is in the specification of granular sub-base material. Clauses 803 and 804 define "Type 1" and "Type 2" granular sub-base materials respectively. Type 1 material is required to be non-plastic whereas Type 2 material may have a plasticity index up to 6.

The author has been involved in several pavement investigations in which surface deformation has been found to be the result of using a Type 2 sub-base material directly beneath concrete block paving and for this reason it is considered that Clause 804 of D.Tp. publication should not be used for specifying material directly below concrete block paving.

Type 1 (Clause 803) material has been found to perform satisfactorily in many situations and is considered to be a safe specification clause. However, in many parts of the U.K., the material is expensive and it is frequently the case that its specification would render the use of concrete block paving too expensive. This is particularly true in the south east of England, which is the most important market for many U.K. manufacturers and contractors. Therefore, the author looked for an alternative means of evaluating sub-base construction material; one which would eliminate those materials which cause surface deformation, but one which would allow materials of lower cost than Type 1. (e.g. hardcore, gravel, grit, course sand, industrial waste materials).

To this end, the Peak Shear Stress Ratio (PSSR) criterion to assess the suibability of sub-base materials has been developed. The PSSR is a way of defining sub-base stability numerically. A materials PSSR is determined by using a 300mm x 300mm (12" x 12") shear box with a normal stress of $10KN/m^2$ ($208lb/ft^2$) applied. The PSSR is the ratio of the maximum shear resistance developed by the material, divided by the normal stress. The method is described fully in TRRL Laboratory Reports LR584 (6) and LR785 (7) and the following are the conclusions of LR785:

1. None of the existing test methods and limits (e.g. grading, density, CBR) used for specifying sub-base can be used to distinguish reliably between stable and unstable sub-bases, unless a limit is also imposed on the general type of aggregate (e.g. trade class or petrological type).

2. A 300mm (12") shear-box test carried out at a normal stress of $10KN/m^2$ on dry aggregate, to a standardised grading and compacted to refusal, can be used to distinguish stable from unstable sub-bases, regardless of trade class or petrological type.

The Author has undertaken tests on various sub-base construction materials at moisture contents of optimum, optimum + 2% and optimum + 5%. It has been found that stable sub-bases can be formed from materials which have a PSSR of 4 or more at each of the above three moisture contents when subjected to a normal stress of $10KN/m^2$ ($208lb/ft^2$). Such a value is achieved by most Type 1 materials, by selected hardcore, by some Type 2 materials and by some sands and gravels, but not by plastic materials. For example, in one pavement investigation, a clay bound gravel had PSSR figures of between 1 and 1.8. This material had failed in shear. Whenever PSSR values have been determined and CBR values have been determined for the same material, PSSR values have been more consistent and are considered to be the more reliable way of assessing material stability.

A problem which often occurs with some stable sub-base materials is the loss of laying course sand into the sub-base material, either during construction or by subsequent traffic. Lilley (6) first drew attention to this phenomenon in 1980. The author has found that blinding an open textured sub-base material is often not a solution to the problem: the blinding material often bridges larger particles and is subsequently shaken out. A preferred solution is the use of a geofabric between the bedding sand and the sub-base; this allows the migration of moisture but retains the solid particles and therefore retains the integrity of both the bedding sand and the sub-base material. It is frequently the case that the designer provides a bound roadbase between the bedding sand and the sub-base: indeed, following the poor performance of several areas in the U.K., this is becoming more prevalent, even for areas subjected to only minor traffic. The author considers that the use of a bound roadbase should be limited to relatively few pavements and that the provision of a stable sub-base is sufficient for the great majority of paved areas. Many pavements are inevitably on the boundary between requiring a roadbase and not requiring one. Such pavements have been found to perform well if the roadbase is omitted and the sub-base is stabilised by a 3-D geogrid i.e. by a "Geoweb" see figure 1.

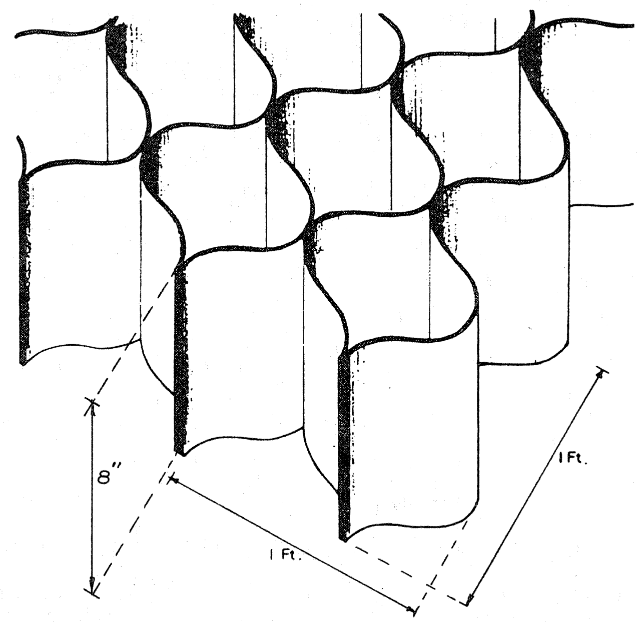


Figure 1

By confining the sub-base into individual cells, the geoweb material adds greatly to the material's strength and stability. Furthermore, the walls of the geoweb accept 30% of applied load directly and so relieve the sub-base of much of the applied load. Geoweb was developed by the U.S. Corps of Engineers, initially for beach stabilisation, but latterly for general roadbuilding. They are now being introduced to Europe and are considered to be particularly applicable to concrete block paving. They have been found to be cost effective in many concrete block pavements, usually when an otherwise unsuitable on-site material can be stabilised. For many types of industrial pavement and for some heavily trafficked highway pavements, it is necessary to provide a roadbase in addition to a sub-base. The U.K. Cement & Concrete Association recommends the use of a cement bound roadbase for all areas subjected to more than 1.5 x 10^6 cumulative standard axles. The British Ports Association (BPA) port and industrial pavement dasign manual (9) recommends the use of lean concrete or pavement quality concrete for all heavy industrial paving and this is considered to be sound practice, although there are examples of wet and dry bound macadam bases performing well in some ports. Usually, bitumen bound roadbase materials would not be considered because of their high costs, although the BPA manual does provide for this.

Mention has been made of drainage and it is considered that the designer should assume that water will enter the pavement throughout its life. Therefore, either a free draining sub-base should be provided or special drainage provisions should be specified. For example, on one road where it was necessary to use a clay bound gravel, french drains were constructed at each side of the sub-base and a 200mm course of single sized 50mm "reject" gravel was constructed as a drainage medium beneath the sub-base. This proved successful and allowed concrete blocks laid over hoggin to carry 35,000 kg axles: without the drainage, the road would not have carried 8000kg axles.

The Design of Lightly Trafficked Pavements

Lightly trafficked concrete block pavements often provide the pavement designer with a greater challenge than heavy duty pavements for the following reasons:

1. such pavements are usually small so that economics require that design costs be minimal e.g. 2 boreholes (often not in the area to be paved) may be taken and if a site investigation report is available, it will be orientated towards foundations to buildings on the site, not towards paving.

2. the client expects a low cost pavement. This usually eliminates bound materials. Usually the engineer is not the leader of the design team and may be under pressure from other professionals or a cost consultant to use inadequate materials.

3. the work may be undertaken by a builder unfamiliar with civil engineering materials who may not appreciate the importance of appropriate plant and methods in ensuring full compaction. In the author's experience, this is the major cause of minor pavement problems.

4. edge, drainage and fixed structure detailing is often inadequate so that the pavement rapidly deteriorates in appearance. Such bad detailing may lead to ponding and subsequent deterioration of the structure of the pavement. These problems can be ameliorated by the employment of a competent contractor.

5. loading is usually poorly defined. Examples eixst of pavements in industrial sites which were designed as car parks but which were used as loading bays. As a general rule, it should be assumed that if a heavy vehicle can physically enter an area, then it will.

6. Utilities may be numerous and backfilling to trenches is usually variable, both in terms of quality of fill material and amount of compactive effort.

The author has designed over 300 schemes which can be classified as lightly loaded during the last six years and has developed techniques and procedures to reduce the risk of problems to a minimum. Before these techniques are described, the following paragraphs and tables show the range of problems encountered and solutions adopted for a broad range of lightly loaded pavements.

Firstly, Table 1 shows the subgrade CBR values by percentage for the designs. The table shows that over 70% of pavements are on soils with a CBR of either 2% or 3% and very few have a CBR greater than 5%. For this reason, it is considered that any design method proposed should be based upon data determined at such CBR values.

CBR	% of all designs with the CBR shown
1 or less	5
2	43
3	30
4	14
5 or more	8

Table 1: Subgrade CBR values by percentage.

The designs can be grouped conveniently into these CBR bands and can be grouped into three bands of traffic, defined in terms of the cumulative number of standard (8200kg) axles which the pavement must withstand. Generally, two types of design are produced, one in which a single course is specified between the block paving and the subgrade and one in which two courses are specified. In both cases, the materials are always unbound; in the single course it is a D.Tp. (Department of Transport) "Type 1" whilst in the second case, a Type 1 over-lies either a Type 2 or some other graded material (The U.K. Department of Transport defines two granular material "Types". Type 1 is free draining and non-plastic. Type 2 may have some plasticity). Table 2 shows the average course thickness for one course designs. The figures in brackets in Table 2 show the values which would have been used by applying Figure 6 of Road Note 29. It can be seen that the values are very similar i.e. in general, the recommendations originally proposed in 1976 (2) are now in general use and are producing economical safe designs.

During the last few years, some have suggested that the application of Figure 6 of Road Note 29 is too conservative. The author considers that to specify sub-base thicknesses less than Figure 6 of Road Note 29 will lead to an unacceptably high proportion of pavements showing surface deterioration and structural failure.

This conclusion is reached partly from experience and partly from an elastic pavement surface deflexion investigation. A computer program is used frequently to predict the elastic deflexion of pavements designed by the author. The program models a pavement elastically, using the British Ports Association (9) method to determine stresses and strains at incremental depths within the pavement and the subgrade. By integrating the vertical strain, the surface deflexion can be obtained. The elastic surface deflexion under a standard 4100kg wheel is approximately 0.32mm or less. Field measurements have confirmed this figure. It is considered that to design pavements with greater flexibility than this, would be foolhardy.

CBR	Sub-base thicknesses for 3 levels of traffic (cumulative standard axles x 10^6)		
	0.1	0.1 to 1.0	1.0 to 5.0
1	450	-	-
2	370(380)	450(400)	-
3	260(280)	350(300	400(400)
4	225(220)	275(240)	325(315)
5 or more	150(180)	200(190)	250(260)

Table2: Thickness of "Type 1" granular sub-base materials in single course designs (RN29 thickness in brackets).

It is stressed that the above values are average values and designs are commonly produced which vary from the figures quoted. These variations, which may be as much as 50%, are due to the following:

1. severe channelisation increases design thickness by up to 20%.
2. lack of confidence in site investigation data increases design thickness by up to 25%.
3. variable fill sites increase design thickness by up to 20%.
4. use of 2-D geogrid reduces design thickness by 10% i.e. it is assumed that the provision of a 2-D geogrid extends the life of the pavement by a factor of 2.5.

The way in which the above factors and many others are applied is a matter of judgement which comes from many years' experience in the design of concrete block paving. This experience is considered to be the most important design ingredient. It is stressed that the assessment of course thickness is considered to be a minor part of the design process: the selection of appropriate materials, the provision of adequate drainage and the correct detailing of edges, fixed structure and levels is of paramount importance.

Regarding the type of paver to be used on lightly trafficked areas it is considered that any unit which can form a herringbone pattern and which has no peculiarities can be used. The type of paver is not regarded as an engineering design variable, except when considering detailing. The problems associated with shaped pavers in heavy duty paving have not occurred in lightly trafficked pavements. It is considered that 80mm thick blocks are appropriate for all lightly trafficked areas, except those areas where commercial vehicles cannot gain entry physically in which case a 65mm or 60mm thick block is adequate.

The Design of Heavy Duty Concrete Block Pavements

Heavy duty pavements can be thought of as being characterised by the need to provide a bound base with possibly a sub-base. The British Ports Association design manual (9) is the most comprehensive document available for the design of heavy duty paving, both for concrete blocks and for other materials. Other methods e.g. Lilley & Walker (3) are based upon extrapolating empirical highway design methods and should be used only where laods are similar to highway laods. The method upon which the BPA manual is based was described by Barber & Knapton in 1980 (1). Since then, the method has been developed into a simple working tool which can be used to design new pavements or to strengthen existing pavements. The BPA manual is unique in the following respects:

1. concrete blocks are considered as a viable alternative to traditional materials and are given similar status.
2. axle loads of up to 100t can be designed for directly, without the need to convert to standard axles.
3. pavement strengthening is covered in addition to new pavement design.
4. the damaging effect of operating plant is determined, taking into account its mode of operation.

The BPA manual was published in 1982 and the pavement strengthening supplement was added in 1983, following research which started in 1973 and which was funded during the period 1977 to 1980 by the U.K. Science Research Council (now the Science and Engineering Research Council).

The need for a manual can be understood by reference to the design of aircraft pavements. By 1956, the International Civil Aviation Organisation had adopted two aircraft pavement design methods, one developed by the U.K. Air Ministry Directorate and the other developed by the U.S. Federal Aviation Administration. Over the last 25 years, both of these organisations have continued to develop their methods and the design of aircraft pavements is now based upon sound theory and practice. (10,11) Some of the features of the two aircraft pavement design methods have been incorporated in the BPA design method, but where aircraft pavement design parameters are inappropriate, concepts applicable to heavy industrial pavements have been developed.

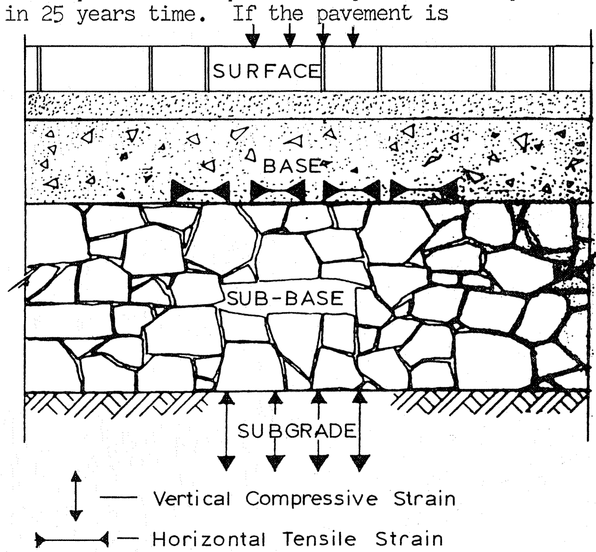
It is interesting to compare the requirements of a pavement to be trafficked by aircraft and industrial handling plant. Compare for example a Boeing 747B and a Clark Y800 D front lift truck (FLT). The former has a maximum take off mass of 353,000 kg of which 4% is transmitted via 16 wheels comprising the main undercarriage. Each of these 16 wheels transmits 21,000 kg to the pavement surface (compare this with 6,000 kg per wheel of the heaviest highway vehicle). The FLT has a front axle load of 90,00kg when transporting a 34,000 kg container under a 7,000 kg telescopic toplift. Therefore, each of the 4 wheels on the front axle transmits 22,000 kg to the pavement: slightly more than the aircraft. From this, it is clear that the need for aircraft pavement design methods which was recognised many years ago now exists for heavy duty industrial pavements.

Unfortunately, aircraft pavement design methods cannot be applied to industrial pavements directly. Surface tolerance requirements are different in both situations. In pavement design, the response of the pavement to dynamic loads is of particular relevance. Aircraft dynamics are totally different from handling plant dynamics. Not only are speeds different, but mass transfer is more acute in many industrial situations and screwing forces are more severe.

Other factors, such as tidally induced variation in water table, storage of heavy cargo, often with point loading and a high probability of overloading are problems not encountered in most aircraft pavement situations. For these reasons and for reasons of ensuring maximum benefit from finance invested in major civil engineering works, it is clear that there exists the need for a comprehensive design manual specifically directed towards industrial situations.

The BPA design manual includes 120 design charts which the engineer uses to ensure that the pavement being designed will remain serviceable for a required period. This means for example, that a pavement could be designed to last for 1 year or for 50 years and the decision as to which design life to select could be made taking into account non-technical parameters. In order to allow design to proceed, the concept of serviceability failure has been included in the manual.

Serviceability failure in a heavy duty pavement occurs either by excessive vertical compressive strain in the subgrade or excessive horizontal tensile strain in the base. The subgrade, the base and the other structural components in a pavement are shown, together with the position of serviceability strains, in Figure 2. In most cases, the critical strain is the tangential tensile strain at the bottom of the base and the design method is based upon keeping the strain value less than that which would distress the material. Although surface deformation can be related to base tangential strain only indirectly, for most heavy industrial pavements, surface deformation (i.e. permanent deflexion) of between 50mm and 75mm could be expected at incipient serviceability failure i.e. if a pavement is designed to have a life of 25 years, ruts up to 75mm deep can be expected to be present in 25 years time. If the pavement is



CRITICAL STRAINS IN HEAVY DUTY PAVING

Figure 2

kept in use beyond this period, the ruts will grow much more rapidly, leading to very rapid pavement collapse. The allowable base horizontal tangential strain , E_h is given by:

$$E_h = \frac{f_c \times 993500}{6 \times E_b^{1.022} \times N^{0.0502}} \qquad (1)$$

Where

E_h = allowable base horizontal tangential strain (microstrain)

f_c = characteristic strength of base material (N/mm^2)

E_b = elastic modulus of base material (N/mm^2)

N = number of repetitions of applied load

In addition to the above equation, a further serviceability criterion is that the subgrade must not suffer too much vertical compressive strain. The design manual includes a second equation relating the allowable subgrade vertical compressive strain (E_v) to the number of repetitions of the applied load (N):

$$E_v = \frac{21600}{N^{0.28}} \qquad (2)$$

Usually, this criterion is automatically satisfied when the tangential tensile strain in the base is within its limit. However, the design manual does allow this secondary criterion to be checked.

In order to determine whether a proposed pavement meets the two serviceability criteria it is necessary to determine the actual strains in the pavement when subject to a given loading regime. These actual strains can then be compared with the allowable ones (E_h & E_v) and if they are lower, then the proposed pavement is satisfactory. The actual strains are determined by an analysis technique in which each course within the pavement is transformed into an equivalent thickness of the pavement's subgrade material. For two courses of material to have similar flexural stiffness the term:

$$\frac{h^3 \times E}{1 - V^2} \qquad (3)$$

must be equal for each course.

Where E = elastic modulus
h = course thickness
V = Poissons ratio

Thus a course of thickness h_1, elastic modulus E_1 and Poisson's ratio V_1 can be replaced by a thickness of h_2 of a different material of elastic modulus E_2 and Poisson's ratio V_2 by:

$$h_2 = h_1 \times \sqrt[3]{\frac{E_1}{E_2} \times \frac{1 - V_2^2}{1 - V_1^2}} \qquad (4)$$

When each course of the pavement has been so transformed, strains are calculated at the boundary layer and these strains are compared with limiting strains for the actual material from which the pavement is constructed. Hence the requisite theicknesses are determined. As the pavement has now been replaced by a pavement in which each course has the properties of the subgrade, it is possible to calculate strains due to applied load by the Boussinesq analysis technique. Strains are calculated beneath the wheels of the handling plant, at depths corresponding with the interface between each course of the original pavement.

The U.K. aircraft pavement design manual (10) assigns a Load Classification Number (LCN) to each type of commercial and military aircraft. The greater this number, the more damage the aircraft is likely to inflict on the pavement. An aircraft pavement is then classified according to a Load Classification Group (LCG) system and a given aircraft can use a facility only if its LCN falls within or below the LCG of that facility. The relationship between the 7 LCG's and LCN's is as shown in Table 3.

L C N	L C G
101-120	I
76-100	II
51- 75	III
31- 50	IV
16- 30	V
11- 15	VI
0 and under	VII

Table 3: Relationship between aircraft Load Classification Number and pavement Load Classification Group.

A similar concept to this has been developed for industrial equipment. For each item of plant, a series of Load Classification Index (LCI) ratings can be developed. LCI's can be determined for various operation situations and for various configurations of optional equipment. The procedure for LCI assessment is now described. Once the LCI of an item of plant has been determined, the design charts in the manual can be used to design a pavement, to check an existing pavement, or to strengthen an existing pavement.

To assess the damaging effect of an item of plant in a certain operating situation, the manual uses an equation giving pavement damage D in terms of wheel load W and contact stress P:

$$D \propto W^{3.75} \times P^{1.25} \qquad (5)$$

The unit used to quantify damaging power is the Port Area Wheel Load (PAWL). A 12000 kg wheel applying a contact stress of 0.8 N/mm^2 has a damaging power of 1 PAWL. Therefore, for each wheel, the damaging effect is given by:

$$D = \left(\frac{W}{12000}\right)^{3.75} \times \left(\frac{P}{0.8}\right)^{1.25} \quad \text{PAWLS} \qquad (6)$$

This equation should be applied to all the wheels which will pass over one point of a pavement when the plant is operating i.e. usually each wheel at one side of the plant. The total damaging power of the plant is then the sum of all these PAWL values.

In order to obtain an accurate damaging effect, it is necessary to take into account the variation in cargo weight that the plant will handle. The manual explains this procedure and gives a typical distribution of weights for both 40ft and 20ft containers. Where an approximate PAWL value will suffice, a simple procedure based upon the maximum expected container can be undertaken, giving a conservative PAWL value. It is expected that manufacturers of plant will supply PAWL information as they develop new items of plant, in the same way that aircraft manufacturers do now.

An important consideration in the assessment of PAWL ratings is the dynamics of cargo handling. The loads transmitted to the pavement by the plant depend upon characteristics of both the plant and the type of operation being undertaken. Dynamic factors by which static wheel loads should be multiplied prior to PAWL calculation are shown in Table 4.

Where two or three dynamic factors apply simultaneously, the factors should be multiplied together. For example, a straddle carrier braking and cornering on an uneven surface would have a dynamic factor of 1.5 x 1.6 x 1.2 i.e. 2.88.

A common pavement design problem is where containers or other cargo are stacked but no vehicles or plant use the pavement. An example would be the working area of a gantry crane running on special runway beams. Table 5 gives loads and stresses beneath the corner castings of containers which allows a PAWL value to be assigned to a container stacking arrangement.

The percentage reduction in gross weight shown in column 2 of Table 5 takes account of the likelihood that several containers will not all be fully laden. The reduction factors are similar to those used in the design of multi-storey buildings, when it is considered unlikely that each floor will be fully loaded simultaneously.

A particular problem experienced in many pavements is high contact stresses applied by highway trailer dolly wheels. The manual recommends using a contact stress of 40 N/mm^2 for this situation, so allowing a PAWL rating to be determined for a lorry trailer park. Once the plant PAWL rating or ratings have been determined, one of 8 LCI's can be assigned to the plant. The relationship between PAWL's and LCI's is shown in Table 6.

PAWL RATING	L.C.I.
Less than 2	A
2 - 4	B
4 - 8	C
8 - 16	D
16 - 32	E
32 - 64	F
64 - 128	G
128 - 256	H

Table 6: Load Classification Index

Table 7 shows typical LCI's for various types of plant operating in various situations. It should be remembered that relatively small changes in wheel loads can have a major influence on LCI values. Therefore, where possible, LCI's should be determined for each item of plant involved.

In many industrial situations, a particularly relevant problem is that of strengthening an existing pavement. An existing pavement may be showing signs of distress, or the operator may purchase new and more damaging plant which the existing pavement will not support. In these situations, the engineer will require a pavement design method which takes account of the residual strength of the existing pavement and which allows him to design an overlay comprising one or more courses of new material. The strengthened pavement should act as a coherent structure if full advantage of the residual strength of the existing pavement is to be gained.

Type of Plant	Type of Operation			
	Braking	Cornering	Accelerating	Uneven Surface
Front Lift Truck	1.3	1.4	1.1	1.2
Straddle Carrier	1.5	1.6	1.1	1.2
Side Lift Truck	1.2	1.3	1.1	1.2
Tractor and Trailer	1.1	1.3	1.1	1.2

Table 4: Dynamic Load Factors

Stacking height	Reduction in gross weight (%)	Contact Stress (N/mm^2)	Load on pavement for each stacking arrangement (kg)		
			Singly	Rows	Blocks
1	0	2.59	7620	15240	30480
2	10	4.67	13720	27430	54860
3	20	6.23	18290	26580	73150
4	30	7.27	21340	42670	85340
5	40	7.78	22860	45720	91440

Table 5: Pavement Loads from Container Stacking

Plant Category	Operating Situation			
	Normal Running	Braking	Cornering	Uneven Surface
Highway Vehicle	A	A	A	A
Terminal Trailer	B	B	C	C
Straddle Carrier	B	C	C	C
Small F.L.T. empty container	A	A	A	B
Medium F.L.T. full 20' container	D	D	D	E
Large F.L.T. full 40' container	F	F	G	G
Mobile Crane	B	C	C	C

Table 7: LCI values for categories of plant in various operating situations.

The first stage in the design of an overlay is to assess the strength of the existing pavement. To do this, information should be obtained from construction records supplemented by taking cores throughout the area. The thickness and condition of each existing course is transformed into an equivalent thickness of 12 N/mm^2 lean concrete. The actual thickness of each course is multiplied by a constant taken from Table 8. The factors in Table 8 are a measure of the ratio of the strength of the material concerned to the strength of lean concrete.

TYPE OF MATERIAL	MATERIAL CONVERSION FACTOR
12 N/mm^2 lean concrete	1.0
18 N/mm^2 lean concrete	1.3
30 N/mm^2 pavement quality concrete	1.7
Cement Bound Granular Material	0.7
Soil Cement	0.5
130mm concrete block paving including 50mm sand	1.1
Concrete raft units (2m x 2m)	1.5
Open textured bituminous material stiffened with latex slurry	1.5
Dense bituminous macadam	1.0
Rolled asphalt	0.8
Wet-mix macadam	0.4
Dry-bound macadam	0.4
Type 1 sub-base material over subgrades with C.B.R.$\geqslant$5%	0.3
Type 1 sub-base material over subgrades with C.B.R.$<$5%	0.2
Type 2 sub-base material over subgrades with C.B.R.$\geqslant$5%	0.2
Type 2 sub-base material over subgrades with C.B.R.$<$5%	0.1
Subgrade	0.0

Table 8: Material conversion factors for component analysis method.

Account must also be taken of the less than perfect condition of each course of the existing pavement. This is accomplished by multiplying the equivalent thicknesses by two condition factors, CF1 and CF2. Factor CF1 applies an equivalent thickness reduction for cracked areas. The values of CF1 and CF2 are shown in Tables 9 and 10.

CONDITION OF MATERIAL	CF1
As new	1.0
Slight cracking	0.8
Substantial cracking	0.5
Fully cracked or crazed and spalled	0.2

Table 9: Condition factors for cracking and spalling.

Degree of localised rutting or settlement (mm)	CF2
0 to 10	1.0
11 to 20	0.9
21 to 40	0.6
40 +	0.3

Table 10: Condition factors for maximum degree rutting and settlement.

When the factors in Tables 8, 9 and 10 have been applied to each course of the pavement, the result is a thickness of 12 N/mm^2 lean concrete which the existing pavement is equivalent to. Secondly the BPA design charts can be used to determine how much 12 N/mm^2 lean concrete is required for the strengthened pavement. The difference between that required and that currently existing is the amount to be provided. This does not constrain the designer to use 12 N/mm^2 lean concrete as the strengthening material since when he has evaluated the thickness of 12 N/mm^2 lean concrete required, he can return to Table 8 and determine the thickness of any of the other bound materials which he may prefer to use.

It can be seen that the BPA pavement design manual represents an important step in the understanding of heavy duty industrial pavements. For the first time, the engineer has a design method scientifically based, but when compared to empirical aircraft pavement design methods, it is found to give similar design solutions to those proven over many years: in fact it is slightly less conservative than both UK Department of the Environment method and the US Federal Aviation Administration method. This is mainly due to the more rational assessment of the design loads: both aircraft design methods use the maximum load concept whereas the BPA method examines the spectrum of live load and uses a critical load which is usually 5% to 15% less than the theoretical maximum.

The manual suggests the use of 80mm thick rectangular blocks laid to herringbone pattern. Although it is a point of debate, the author is of the opinion that only rectangular blocks should be used for heavy duty paving. He has considerable experience of less than satisfactory performance of shaped blocks in areas of particularly high screwing forces.

Conclusions

During the last few years, concrete block pavement design in the U.K. has advanced on these fronts:

1. A better understanding of the use of civil engineering materials in concrete block paving has been gained. Unfortunately, much of the learning has taken place against a background of pavements performing poorly. This has inhibited the growth of concrete block paving. There is now sufficient experience and data available to prevent any inadequate materials from being specified and the concept of Peak Shear Stress Ratio should be applied to all sub-base specifications.

2. The widespread use of concrete block paving on small lightly trafficked areas has lead to the development of satisfactory well established design and construction methods. Although some early work of poor quality is still evident, the great majority of work is now designed and constructed competently. A simple calculation shows that a current U.K. market of 2,000,000 m^2/annum requires the continuous employment of 300 layers and 15 designers. (15 designers is obtained by assuming an average size job is 1000 m^2 and takes on average 2 days of design time).

3. Concrete blocks have become an orthodox solution to heavy duty pavement problems for many designers. This is partly due to cost and partly due to the British Ports Association manual. Since the introduction of concrete block paving to the U.K. in the late 1960's it has been a cost effective solution for heavy duty pavements. This has become particularly so during the last four years when producer prices of blocks have fallen as competition has become acute. The influence of the British Ports Association manual lies in the fact that the manual deals with four types of pavement and gives each equal prominence, thus the designer is encouraged to select the type of pavement based upon technical and economic criteria and not upon prejudice or inertia.

Regarding the type of block to be specified, the author is of the opinion that for highway traffic, there is as yet no evidence that shape is a major factor in structured design, except that any shape which cannot make a herringbone pattern should not be used on highways. However, for heavy duty paving, it is considered that rectangular blocks are less susceptible to damage and should always be preferred.

Finally, the author believes that synthetic reinforcing materials will become more important and will often be used in conjunction with concrete block paving. This applies particularly to vertical walled Geoweb materials which will allow low grade aggregates to be used as sub-base material.

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