Structural Design of Highway Pavements Surfaced with Concrete Block Pavers

This note sets out the design procedures for highway pavements constructed with concrete block pavers. It applies to all pavements subjected to the usual road spectrum of axle loads up to 18,000 kg and trafficked by up to 25,000,000 cumulative standard axles, including both highway pavements and pavements where the traffic is similar in character to or less damaging than highway vehicles.

Definitions

Pavers

Hand sized concrete units bedded in sand so as to form a flexible concrete pavement surfacing material. In the UK, most pavers are rectangular of plan dimensions 200mm x 100mm and of thickness 80mm for most trafficked roads or 60mm and 65mm thickness for lightly trafficked roads. They are usually laid to herringbone pattern in order to ensure full interlock and surface stability. Concrete block pavers should comply with BS6717: Part 1.

Laying course (bedding sand)

Layer of material on which pavers are bedded. Research has shown that naturally occurring sands from relatively recent deposits (Quaternary beds) having as little material as possible passing a 75 micron sieve perform best in trafficked pavements. In particular, for channelised traffic such as buses at bus stops the proportion of bedding sand passing a 75 micron sieve should be limited to no more than 0.3%. For most normal roads, 1% is the upper limit.

Subgrade

Upper part of the soil, natural or constructed, that supports the loads transmitted by the road. The strength of the subgrade is an important input to the design procedure. The subgrade strength is measured by the California Bearing Ratio (CBR) test and is expressed as a % of the CBR value of a standard limestone material.

Subgrade improvement layer (capping layer)

Layer of granular or treated material at the top of the subgrade to provide an improved foundation for the pavement. It is used over subgrades where the CBR is less than 5% to provide a firm working platform over which a road can be constructed. One of its functions is to mobilise reaction to compaction of materials installed above. It usually comprises locally available low cost material such as crushed concrete, hardcore or pooly graded crushed rock, possibly with clay included (known as "hoggin" in the south of England).

Sub-base

One or more layers of material paced immediately above the subgrade or capping. Together with the capping, the sub-base comprises the road foundation, ensuring that the courses above are adequately supported so that their full potential is achieved. The Department of Transportís "Specification for Highway Works" gives details of two common sub-base specifications. Clause 803 defines DTp "Type 1" granular sub-base material and Clause 804 defines "Type 2". These materials are commonly referred to as Type 1 or Type 2. Type 1 is higher quality material and is more likely to retain its engineering properties under adverse conditions of moisture content and trafficking during construction. Sometimes, crushed rock is stabilized with cement to form a stronger sub-base.

Roadbase

One or more layers of material placed above the sub-base that constitute the main structural elements of a flexible pavement. The roadbase is usually bitumen or cement treated crushed rock and there is a large collection of Department of Transport specifications. For example, four types of cement stabilized material are commonly specified; CBM1, CBM2, CBM3 and CBM4 (CBM = Cement Bound Material) which are defined in Table 10/8 of the DTp Specification. Essentially, each of the four types has the followin 7 days cube compressive strength:

CBM1	4.5N/mm^2
CBM2	7.0N/mm^2
CBM3	10.0N/mm^2 (often referred to as "lean concrete")
CBM4	15.0N/mm^2

Bitumen bound roadbases fall into two types. Asphalt materials (Hot Rolled Asphalt is common) comprise various materials in a bitumen matrix such that the asphaltís strength derives from the stiffness of the bitumen. Bitumen macadam comprises various materials coated with bitumen such that the bitumen glues the constituents together. Tar macadam (colloquially "tarmac") was used traditionally but bitumen, an oil derivative, has largely replaced tar, a coal derivative. The term macadam means crushed material graded such that the finer fractions fill the voids of the coarser parts to form a dense and strong unbound material. Dry bound macadam refers to roadbase material in which unbound stones are compacted in a dry state and wet mix macadam refers to similar material in which compaction is assisted by the addition of lubricating water.

Channelized traffic

Traffic where the vehicle track width and the traffic lane width are virtually the same.

NOTE: Normal lane widths in a highway do not constitute channelized traffic. The exception to this is where traffic commonly queues, say at traffic lights, or at bus stops. This is an important distinction because where traffic is chennelized, the amount of traffic has to be multiplied by three in order to account for its damaging effect.

Standard axle

An axle carrying a load of 8200kg (18,000 lb). The legal axle limit in the UK is 11250kg for a non steering axle and 6250kg for a steering axle. Vehicle designers usually employ all of the legal weights. In design, we need to express axle loads in terms of standard axles. We do this by dividing the each vehicle axle load by the standard axle value and raising the result to the power 3.75. This means that a legal maximum non-steering axle applies 3.3 standard axles and a legal limit steering axle applies 0.4 standard axles. A full double decker bus would weigh about 15,000 kg, with 6000kg applied through the front axle and 9,000kg applied through the rear axle. Calculations show the number of standard axles for such a vehicle to be 2.3. An empty double decker bus would weigh 10,000 kg with 4000kg applied through the front axle and 6,000kg applied through the rear axle. This vehicle would apply 1.1 standard axles. It might be concluded that a service of double decker buses would each apply 2 standard axles as an average.

Cumulative traffic

The number of standard axles a pavement is designed to carry, measured in millions of standard axles (msa). Sometimes, the term cumulative number of standard axles (csa) is used, particularly when the total number of standard axles which will traffic a road throughout its life is being expressed. These figures are determined by multiplying the anticipated number of vehicles per hour by the number of trafficked hours in a day, then by the number of days for which the road is being designed. Finally, the figure is multiplied by the number of standard axeles per vehicle. It may be necessary to consider a mix of vehicles.

Commercial vehicles

Vehicles having an unladen weight exceeding 1500kg. This is an important distinction since it represents the cut off point below which vehicle weights are ignored.

Design criteria

Basis of design

The design of new pavements is based upon the method given in TRRL Report 1132. *The structural design of bituminous roads* and upon experience. In the case of overlay design, either a surface deflection method or the component overlay method, is used according to the type of pavement to be overlain.

Special cases

In some cases, unusual or particularly onerous loading effects or other conditions will need to be taken into account, e.g. the following:
(a) Where channelized traffic is expected, the traffic figures should be multiplied by three before carrying out the design, to allow for the increase in the concentrated application of loads at a particular point on the pavement. Normal lane widths in a highway do not generally constitute channelized traffic but channelized traffic can develop on any road, e.g. on steep hills or approaches to traffic signals.
(b) Where speeds in excess of 30 miles/h are expected, the cumulative traffic should be multiplied by two before carrying out the design to allow for dynamic loading effects.
(c) Pavements constructed over frost-susceptible soils should have an overall thickness of non frost-susceptible material of not less than 450mm.
(d) Materials, whose successful performance is dependent upon compaction being undertaken at critical moisture contents, should only be used when engineering supervision can ensure that a stable construction can be achieved. NOTE: Some materials given in Clause 804 of the Department of Transport Specification for Highway Works (Type 2 materials, see Definitions) fall into this category.
(e) Where relatively few standard axles are to be accommodated (less than 100,000) but where the loading is commonly applied by axles of weighting in excess of 7000kg, the pavement should be designed to withstand either 100,000 standard axles or three times the actual number of standard axles, whichever is greater.

New pavement design

Subgrade assessment

The design California Bearing Ratio (CBR) should be obtained either by direct measurement, or by measurement of the plasticity index of the subgrade material. In the case of direct CBR measurement, the method described in Clause 7 of BS1377 : Part 4: 1990 should be used. In situations where it is possible that the subgrade will become saturated during part or all of the life of the pavement, the method employing the soaking procedure should be used. Alternatively, equilibrium suction index CBR values should be used. In the case of fine grained soils, the equilibrium suction index CBR can be determined from a knowledge of the plasticity index as detailed in Table 1.

Table 1. Equilibrium suction index California Bearing Ratio(CBR) values

Type of soil	P I	High water table			Low water table		
		Construction conditions			Construction conditions		
		Poor	Average	Good	Poor	Average	Good
Heavy clay	70	1.5	2	2	1.5	2	2
	60	1.5	2	2	1.5	2	2
	50	1.5	2	2	2	2	2
	40	2	2.5	2.5	2.5	3	3
Silty clay	30	2.5	3	3.5	3	4	4
Sandy clay	20	2.5	4	4.5	3	5	6
	10	1.5	3	3.5	2.5	4.5	7
Silt	-	1	1	2	1	2	2
Poorly graded sand	-	20					
Well graded sand	-	40					
Sandy gravel	-	60					

Notes on this table:
Poor construction conditions apply when the subgrade is not protected from weather and/or site traffic. Good construction conditions apply when the subgrade is protected immediately by a capping or sub-base layer so that the subgrade never becomes wetter than its equilibrium moisture content. Subgrade drainage can have a significant effect on long-term CBR values and needs consideration during the design procedure. Filter drains set at the appropriate level and discharging to a satisfactory outfall or main drainage systems have been found to perform satisfactorily.

Effectively subgrade drainage can have a significant effect on long-term CBR values and needs consideration during the design procedure. Filter drains set at the appropriate level and discharging to a satisfactory outfall or main drainage systems have been found to perform satisfactorily.
On sites where the CBR varies from place to place, the lowest recorded values should be used or, alternatively, appropriate designs should be provided for different parts of the site using the lowest CBR recorded in each part. It may be possible to remove soft spots and therefore ignore those low (CBR values which relate to the removed material). Consideration should be given to using portable CBR measuring apparatus, for example the MEXIprobe has been found to give sufficiently accurate results on fine-grained soils. It is often the case that a large number of CBR measurements undertaken with this type of apparatus is preferable to a relatively few measurements undertaken with the full scale insitu CBR measuring apparatus.
Care should be exercised in the interpretation of site investigation data. In the case of soils whose strength is a function of their moisture content the in-service strength may be much lower than the recorded values. Care should also be exercised in using CBR values measured in summer as artificially high figures may be obtained due to dryness of the soil. Particular care should be exercised with soils having CBRs of 3% or less. It should be recognised that BS 1377 requires that CBRs are quoted to the nearest whole figure, so that for very low CBRs the recorded value will be approximation. Recently, it has become common to express low CBR values to one decimal place.
The surface of the subgrade material should be prepared according to Clause 616 of the Department of Transport Specification for Highway Works. In the case of silty clays the use of a vibrating roller may fluidise the material rather than compact it. In such cases a deadweight roller is preferred.

Design life

Design has to take into account the cumulative amount of traffic which the pavement has to carry, measured either in terms of the number of commercial vehicles per day (cv/d), or alternatively, the number of standard axles. It is suggested that a 20 years design life will be generally applicable unless access for possible maintenance of the roadbase is likely to be difficult or expensive

It may be necessary to reset the pavers during the life of a pavement if the rut depth exceeds 10mm. This may be a result of displacement of the laying course material (bedding sand) and is not necessarily an indication of pavement failure. An inspection of the bound roadbase should be carried out prior to the relaying of pavers to ensure that no structural deterioration has occurred.

Selection of pavement components

Design should proceed according to the flow charts shown in Tables 2a, 2b and 2c. Firstly the design CBR and the amount of traffic expected to use the pavement, expressed in millions of standard axles are determined.

Subgrade improvement layer (capping layer)

If required, the thickness of the subgrade improvement layer is selected according to the subgrade CBR value as shown in Table 2a. Subgrade improvement layer materials should have a CBR of 15% or more and should ensure that the effective CBR offered to the sub-base is at least 5%. This will be achieved if Table 1 is followed.

Sub-base

If the sub-base is not to be used as an access road, then its thickness should be either 150mm if a subgrade improvement layer (capping layer) is provided or up to 225mm if there is no subgrade improvement layer. If the partly constructed area is to be used as an access road, then the sub-base thickness may have to be increased as shown in Tables 2a or 2b according to whether a capping is to be included according to the amount of traffic which will travel directly over the sub-base. Engineering judgement may be needed in assessing the amount of construction traffic to which the sub-base will be subjected.

When rainfall is expected, it is expedient to cover the sub-base as quickly as possible to prevent saturation and also to protect the underlying materials. Remedial work may be required to the surface of a sub-base which has been used as a construction access road. Excessive trafficking of the sub-base may cause rutting of the subgrade or contamination of the sub-base by subgrade material. In these circumstances removal of the sub-base and remedial works to the subgrade will be necessary.

Roadbase

Table 2c shows roadbase thicknesses for cement bound materials (CBM) and dense bitumen macadam (DBM) roadbases as defined in Clauses 1038,and 908 of the Department of Transport "Specification for Highway Works".

Laying course

This should be in accordance with the recommendations in BS7533 :Part 3. The laying course thickness should be either 50mm (unbound roadbase) or 30mm (bound roadbase).

Pavers

Generally the paver thickness should be 60mm or 65mm for lightly trafficked roads and 80mm for heavily trafficked roads.

Start

Determine design subgrade CBR and number of standard axles using sub-base as an access road

Foundation design option 2a)

Subgrade CBR design value	2 % or less [a,b]	> 2 % - < 3 % [a]	≥ 3 % - < 4 % [a]	≥ 4 % - < 5 %	≥ 5 % - < 10 %	≥ 10 % - < 15 %	≥ 15 % - < 30 %	30 % or greater
Untrafficked	150/150	150/150	Sub-base alone - see Figure 2b)					0/0
Up to four dwellings or 2 000m^2 commercial or standard axles (sa)	150/210	150/180	150/150	Sub-base alone - see Figure 2b)				0/0
Up to 20 dwellings or 200 sa	150/370	150/250	150/170	150/160	150/150	150/150	150/0	0/0
Up to 50 dwellings or 5 000m^2 commercial or 500 sa	150/470	150/340	150/250	150/220	150/200	150/150	150/0	0/0
Up to 80 dwellings or 8 000m^2 commercial or 1 000 sa	150/600	150/450	150/350	150/300	150/250	150/180	150/0	0/0
Large development or 5 000 sa	200/600	200/450	150/450	150/350	150/300	150/250	150/150	0/0

Go to Figure 3 for structural design

NOTE Sub-base and capping are shown thus: 150/350.

[a] Below 4 % a separating membrane is required.

[b] Heavy grade support mesh or fabric may be necessary to enable construction to proceed.

a) Capping and sub-base option

Figure 2a Foundation Design using a Capping Layer

Start

Determine design subgrade CBR and number of standard axles using sub-base as an access road

Foundation design option 2b)								
Subgrade CBR design value	2 % or less [a,b]	> 2 % - < 3 % [a]	≥ 3 % - < 4 % [a]	≥ 4 % - < 5 %	≥ 5 % - < 10 %	≥ 10 % - < 15 %	≥ 15 % - < 30 %	30 % or greater
Untrafficked	Figure 2a)	170	150	150	150	150	150	0
Up to 4 dwellings or 2 000m² commercial or standard axles (sa)	Figure 2a)	250	190	160	150	150	150	0
Up to 20 dwellings or 200 sa	Figure 2a)	310	240	210	180	150	150	0
Up to 50 dwellings or 5 000m² commercial or 500 sa	Figure 2a)	350	270	230	200	160	150	0
Up to 80 dwellings or 8 000m² commercial or 1 000 sa	Figure 2a)	400	310	270	225	180	150	0
Large development or 5 000 sa	Figure 2a)	450	350	310	270	240	225	0

Go to Figure 3 for structural design

[a] Below 4 % a separating membrane is required.

[b] Heavy grade support mesh or fabric may be necessary to enable construction to proceed.

b) Sub-base only option

Figure 2b. Foundation Design Design Type 1 (SHW Clause 803) Sub-base Material.

Design foundation to either Tables 2a) or 2b)

Add foundation to pavement structure determined as follows

Do any of the conditions in 4.2 apply? If so, apply the appropiate factors given in 4.2a) to c)

Determine cumulative standards axles (msa) for design

Design msa	0.5 to 1.5				> 1.5 to 4				> 4 to 8		> 8 to 12	
CBM3 roadbase thickness (in mm)	130	130	130	130	160	150	145	130	195	180	245	230
or Dense bitumen macadam roadbase 100 pen (in mm)	130	130	130	130	160	150	145	130	170	155	185	170
Laying course (in mm)	30	30	30	30	30	30	30	30	30	30	30	30
Paver thickness (in mm)	50[a]	60	65	80	50[b]	60	65	80	65	80	65[c]	80

End

[a] For clay pavers type PB and concrete pavers only.
[b] For clay pavers type PB only.
[c] There is no long-term evidence concerning the performance in service of 65 mm pavers beyond 4 msa, so this design information has been extrapolated.

Table 2c. Roadbase and Paver Design

<u>Pavement course specification</u>

<u>Materials</u>

In general the pavement construction materials should be specified according to the relevant clauses of the Department of Transport "Specification for Highway Works" shown in Table 3.

Table 3 : Specification for Highway Works Clauses

Category of material	Clause number
Cement bound material 1	1036
Cement bound material 2	1037
Cement bound material 3	1038
Cement bound material 4	1039
Dense bitumen macadam	903
Hot rolled asphalt	904
Type 1 granular sub base material	803
Type 2 granular sub-base material	804
Wet mix macadam	805
Subgrade improvement material	613

In the case of sub-base material for pavements which do not require a stabilized roadbase, the material should comply with Clause 803 or Clause 1036 of the Department of Transport Specification for Highway Works, e.g. Type 1 sub-base material, cement bound material or bitumen bound material.

Laying course (bedding sand) and jointing material

The laying course and jointing material should be in accordance with the recommendations given in BS6717 : Part 3. The laying course material will be satisfactory for most locations, however, where large volumes of heavy vehicles are running in channelized flow, e.g. bus lanes with in excess of 300 cv/d, particular attention to the source of the laying course material is recommended. Natural sands, i.e. uncrushed, from the quaternary geological series have performed satisfactorily.

Pavers

Pavers should comply with BS6717 : Part 1.

Pavement overlay design

Selection of method

Overlay design can be undertaken in one of two ways, either by using a method based on elastic deflection or, alternatively, by using a component overlay design method. The deflection-based method is to be preferred when existing flexible roads are to be overlain. When other types of roads or industrial areas are to be overlain, the component overlay method should be used.

Deflection beam method

The deflection beam method is described in TRRL Reports 833, 834 and 835. In these reports, it is assumed that the overlay material will be a bituminous bound material. By taking the material conversion factors given in Table 4, the method described in the above Laboratory Reports can be adapted to overlaying concrete block pavers. When the method indicates that a 110mm thickness or less of dense bitumen macadam (DBM) or hot rolled asphalt is required as the overlay, concrete block pavers can be used with safety. When it is found that a greater thickness than 110mm is required, then it will be necessary to provide an additional layer of material together with the pavers.

Table 4 : Material conversion factors for evaluating highway pavement materials

CATEGORY OF MATERIAL	MATERIAL CONVERSION FACTOR Suggested value	MATERIAL CONVERSION FACTOR Range
Cement bound material 1 (CBM1)	2	1 to 3
Cement bound material 2 (CBM2)	2	1 to 3
Cement bound material 3 (CBM3)	3	2 to 4
Cement bound material 4 (CBM4)	3	2 to 4
Pavement quality concrete	4	3 to 5
Dense bitumen macadam	3	2 to 4
Hot rolled asphalt	3.5	
Type 2 granular sub-base material	0.7	0.5 to 0.7
Subgrade improvement material	0.5	0.3 to 0.7

NOTE: The suggested values in this table relate to the stated materials in their common situations. In unusual situations, alternative values may be substituted but will generally not depart from the range. Departures from the suggested values will occur only when there is a specific reason for change. The factors in this table has been derived by adapting those figures initially developed by the Asphalt Institute to ensure that they are compatible with relative thickness given in TRRL Report 1132. The minimum thickness of materials and the nominal sizes of aggregates used in overlays should comply with BS594 and BS4987.

Component overlay design method

In the component overlay design method, the condition of each course in an existing pavement is expressed as an equivalent thickness of a standard material. This allows the current condition of dilapidated materials to be assessed numerically. The standard material chosen is dense bitumen macadam (see Clause 903 of the Department of Transport Specification for Highway Works).

Material Conversion Factor (MCF)

Once each type of material within the pavement is identified, an MCF (Table 4) is assigned to that material. The true thickness of each course in the pavement is then multiplied by the appropriate MCF to obtain the equivalent thickness of DBM.
The equivalent thickness of pavers is given in Table 5.

Table 5 : Equivalent thickness of pavers

Paver thickness(mm)	DBM equivalence
80	120
65	105
60	100

Condition factors

In order to account for any degradation which may have taken place in each course of the pavement since it was first constructed, the equivalent thickness of each course is multiplied by two factors which account for less than perfect condition of the material in the pavement. These two condition factors are, firstly, one (CF1) to be applied to take account of cracking and spalling of the pavement materials and secondly, one (CF2) to account for rutting and settlement. If the deterioration of the surface of the roadbase is a result of failure in the sub-base, the subgrade improvement layer or the subgrade, it may not be possible to overlay the existing pavement.
CF1 and CF2 are determined for each course in the existing pavement according to the condition of the material as shown in Tables 6 and 7.

Table 6 : Condition factor CF1

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 7 : Condition factor CF2

Degree of localized rutting or localized settlement	CF2
mm 0 to 10	11 to 20
11 to 20	0.9

21 to 40	0.6
41 and above	0.3

For consistent results, these factors should be applied by engineers with a working knowledge of a recognized pavement assessment system. If the rut depth is greater than 20mm, the condition of the road foundation should be investigated to determine whether subsurface drainage has been damaged.

Determination of feasibility of overlaying directly

Once the existing pavement has been transformed into an equivalent thickness of dense bitumen macadam, a pavement is designed in accordance with the new pavement design method and that theoretical pavement is then transformed into an equivalent thickness of dense bitumen macadam using the material conversion factors given in Table 4. By comparing the equivalent thickness of dense bitumen macadam in the existing pavement with the equivalent thickness of dense bitumen macadam required for the new pavement, a determination can be made as to whether the provision of a concrete block paver overlay will provide a satisfactory engineering solution. It may be that an additional course of material will have to be provided beneath the concrete block pavers in order to bring the overlain pavement to a satisfactory structural condition.

In the case of condition factor CF1, a degree of judgement is required in establishing the condition of the material, especially for those courses beneath the surface. If there is no alternative evidence it can be assumed that the materials beneath the surface are in a similar condition to those at the surface.

It should be noted that a full investigation of the original pavement can often lead to greater structural adequacy being assumed for the pavement to be overlain. Often this can make the difference between the possibility of directly overlaying with concrete block pavers and not being able to use this procedure. If the levels or required falls for the finished surface after paving are different from those of the existing surface, planing out or regulation with appropriate bituminous material will be required. The effect of such removal or addition should be taken into account during the evaluation for overlaying. It is important that the surface on which laying course material is laid should be such as to ensure a uniform thickness of laying course material everywhere.