FINAL REPORT ON:

A
DESIGN SYSTEM
FOR
PERMEABLE PAVEMENTS
SURFACED WITH
MARSHALLS PRIORA PAVING

BY

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CONTENT

BRIEF

Discussions between David Morrell and John Knapton since 2009 have led to the development by David Morrell of the following brief.

Priora Structural Design Standard Project
Version 3:13th January 2011

Aim
To reassess Marshalls' Permeable Pavements Structural Design Methodology, using the properties of the 'Priora' family of products (the patented joint details), reviewing the original information undertaken at Newcastle University upon which the present approach is based, together with information which has emerged since.
To develop a 'new' (updated) design standard for Marshalls based upon Limit State principles and pavement cost savings as well as a guidance document on how best to use the benefits of Priora interlock with BS7533.
To draft a proposal for research work, as a second phase of work, using falling weight deflection techniques to assess the structural adequacy of permeable pavements.

Development of a new understanding of design
The information upon which the new approach will be based includes, but is not limited to:

Original Priora NUROLF report, in particular the specific advantages of Priora (edge connecting profiles & pavement stiffness)

Marshalls' review of the performance of installed trafficked Priora pavements

Paper by Knapton, Morrell & Cook

Interpave Design Guide, 6th Edition

BS7533: Part 13

British Standard & Highways Agency

Developments in relation to materials

Fourth Edition of British Ports Association port pavement design manual, which includes guidance on Permeable Pavements

Technical data provided by Huesker on the inclusion and impact of geogrids in the subbase and capping layers

Information on confinement systems and their impact on sub-base and capping layer

The use of recycled materials as sub-base and the specification for such

Papers published at international conferences in Sun City (2003), San Francisco (2006), Buenos Aires (2009) – particularly the Tobermore test

NOTE: Phase II is to include the research into the stiffness of pavement design using Falling Weight Deflection (FWD) techniques or using insitu load testing

Details

Based upon the Limit State approach, produce an updated structural design methodology which will allow the user to produce permeable pavement section designs to satisfy commonly encountered applications. This design methodology will maintain the current design loading of vehicle type rather than that of cumulative standard axles (CSA).
The work will also review the current capping layer recommendations;

- allowing for 1% CBR
- consideration of 5% rather than 6% as current “no capping layer required” as many Site Investigation reports’ default is 5% CBR
- Capping layer depth at low CBR and light loading

Therefore, the applications to be considered in the Limit State design method are:

1/ Non-trafficked footways
2/ Domestic scale driveways trafficked by cars
3/ Domestic scale driveways trafficked by light vans
4/ Commercial driveways and car parks trafficked by cars, light vans and delivery vans (up to 7.5t gvw)
5/ Pavements trafficked mainly by light vehicles but by occasional HGVs.
6/ External hard standings trafficked by highway vehicles (e.g. distribution warehouses)
7/ Pavements trafficked by HGVs whose volume can be measured in millions of standard axles
8/ Port pavements and similar with up to 100t axles in the case of Reach Stackers or trains of 12t wheels in the case of straddle carriers

Deliverables

The deliverables will comprise:

A/ A Structural Design Methodology which includes charts and examples for the structural design of each of the above categories, including:-
Updated standards and references
Inclusion of new material properties (change in PEN for DBM etc)
Inclusion of geogrids (dependant on the discussions with Huesker) and if considered appropriate confinement systems.
Review of the 10 years of experience of the current design standard
Inclusion of how to ‘include’ recycled materials (specification etc)

Inclusion of the stiffness of the surface based on the nib design

B/ A report setting out the basis of the design method and the structural benefit of the Priora interlock. This will be largely for Marshalls' internal consumption and training.

C/ A Guidance report on how Marshalls can design in accordance with BS7533 and make 'best' use of the Priora interlock

D/ Training day(s) for Marshalls' staff. (details of how, where, when, who etc to follow)

E/ Draft the scope and deliverables of research into the performance of permeable pavements using FWD techniques. This work may be undertaken at Eaglescliffe and form the basis of a paper for the next Interlocking Concrete Block Paving Conference in Shanghai.

PROPOSED DESIGN SECTIONS FOR DETENTION PAVEMENTS AND INFILTRATING PAVEMENTS

INTRODUCTION

This Report provides revised design guidance for Marshalls Permeable Pavements surfaced with Priora. The guidance is based upon many inputs as this report explains including, most importantly, Marshalls' 10 years experience of the successful use of Priora's previous design tables.

The uniqueness of this report lies in the way it combines two design methodologies. For lightly trafficked pavements, the loads applied by wheels are the critical factor and the guidance for those pavements is based upon their weights. This is known as ultimate load design. For heavily trafficked highway pavements, the pavements are designed on the basis of the cumulative number of standard 8,000kg axles, in line with the UK Highway Agency design approach. This is known as serviceability design.

For pavements trafficked by vehicles applying greater loads than those commonly encountered on highways, the British Ports Association heavy duty pavement design manual (BPA Manual) is recommended. This report does not provide design sections for sucj pavements but instead shows how to apply the method. The 4th Edition of the BPA Manual can be downloaded from Interpave and includes full guidance on heavy duty permeable pavements. The design tables in this Report include a reference to the BPA Manual for both Dention Pavements and Infiltration Pavements.

This Report includes tables for the design of Detention Pavements and Infiltration Pavements surfaced with Marshalls Priora pavers as shown in the photograph on the next page.

The photograph illustrates 200mm x 100mm modular size Priora installed to a herringbone pattern. Research has confirmed that this is the preferred laying pattern from a surface stability perspective and also from a load spreading perspective. This is because it has been tested and has been shown to provide excellent interlock. Other types of Priora and other laying patterns can also be used in those pavements trafficked by cars & light vans, vehicles of weight up to 7.5 tonne and occasional emergency large Goods Vehicles.For all other categories of traffick, the arrangement shown in the photograph should be used.

Marshalls Priora permeable pavers installed in herringbone pattern

PROPOSED DESIGN SECTIONS FOR DETENTION PAVEMENTS AND INFILTRATING PAVEMENTS

DERIVATION OF PROPOSED PAVEMENT SECTIONS

I have derived the thicknesses and material types within the Tables which follow from a consideration of the following sources of information:

1/ NUROLF testing of Priora which confirmed the enhanced stiffness which is provided by the Priora paver. I include the paper by Knapton, Morrell & Cook which describes this testing in the Appendix.

2/ Marshall's survey of pavers which have been installed for several years using the existing design sections. That survey confirmed that generally the areas are performing well. The exception is where severe channelization has led to rutting.

3/ The Tobermore trials, published at the Buenos Aires International Conference on Concrete Block Paving (2009) showed that in the case of channelization, DBM50 is a particularly effective roadbase and significantly outperforms Hydraulically Bound material (HBM), crushed rock and geogrid-reinforced crushed rock. I include the Buenos Aires paper in the Appendix.

4/ Interpave design guide and BS 7533: Part 13: 2009. I include the relevant extracts from this standard in the Appendix.

5/ The US Interlocking Concrete Pavers Institute (ICPI) permeable pavements design method which was described by ICPI's David Smith at the May 2011 Dresden SEPT Workshop. This method helps to establish the cut-off in terms of crushed rock based pavements and asphalt based pavements. The ICPI method is based on the well established AASHTO pavement design method.

6/ The Belgian and German permeable pavement design methods which were described by Anne Beeldens at the May 2011 SEPT Dresden Workshop. These methods extend the use of crushed rock pavements into higher trafficking levels. Germany and Belgium allow fine material in their Coarse Graded Aggregates (CGAs). Their methods rely upon compaction for strength development in CGA. Interpave and ICPI take the opposite approach and rely upon aggregate interlock instead of compaction. This means that in the US and the UK, we need to select aggregates more carefully. They must not be too rounded (Martlesham was on the limit which is why rutting has developed in some channelized parts). The advantage of using coarser crushed rock base materials is that the system does not become clogged. Clogging is a significant issue in Germany and Belgium where it is normal to replace permeable pavers on a regular basis, say every seven years.

7/ Figure 2.1 of Highways Agency's Design Manual for Roads and Bridges (DMRB), Volume 7, Part 2 which is Highways Agency's design chart for DMB50 and HBM roadbases. I have used this chart to establish thicknesses required for more heavily trafficked pavement, i.e. those in which the design switched from a consideration of the axle weight to the number of repetitions of standard 8,000kg axles. This chart is reproduced in the Appendix.

8/ The Material Equivalence Factors (MEFs) which are set out in the Fourth Edition of the British Ports Association (BPA) Heavy Duty Pavement Design Manual. These figures allow one material to be exchanged one for another without detracting from or adding unnecessarily to the performance of the pavement. I have used these factors to swap some of the DMRB asphalt thickness for Priora, i.e. the DBM asphalt thicknesses shown in the tables are reduced by an amount which reflects the structural value of Priora. I include the relevant information from the BPA Manual in the Appendix.

9/ My own experiences of investigating the performance of pavements of all types, both in engineering research and as an expert witness on a worldwide basis investigating reasons for the failure of pavements.

All of the above factors, when given thoughtful consideration have brought me to a position where I consider that the proposed sections are sufficiently accurate to justify a full Finite Element check. That exercise may lead to fine tuning of some of the proposed sections.

USE OF EXISTING INTERPAVE DESIGN DOCUMENT

This Report does not rework the structural parts of the Interpave permeable pavements design manual because I consider that the detailed recommendations contained within that document remain generally valid. For example, I consider that the material specifications remain correct.

However, that document addresses each category of pavement on a fatigue basis. In my proposed sections, I have used the ultimate load method for the design of lightly trafficked pavements since the cumulative standard axle approach becomes less realistic when the actual use of the pavement is by a mix of traffic which deviates significantly from standard 8,000kg axles. This applies particularly in the case of those pavements which are trafficked by vehicles having significantly lighter axle loads than the standard axle of 8,000kg, i.e. all vehicles up to and including 7.5tonne vans.

INCLUSION OF GEOGRIDS

I have also addressed the relevance of geogrids. The Tobermore trials showed that they add little to the longevity of pavements trafficked by Large Goods Vehicles (LGVs) in the case of subgrade CBRs of 5% and above. I include the Buenos Aires SEPT conference paper which describes these trials in the Appendix.

Those trials showed that crushed rocks and geogrid reinforced crushed rocks produced essentially similar rutting and that rutting was much greater than that which occurred in the DBM and HBM test items. However, in the case of lightly trafficked crushed rock pavements, it is likely that the tension which develops within the geogrids will reduce rutting, particularly if aggregate interlock within the Coarse Graded Aggregate (CGA) base is low (e.g. Martelsham). For this reason, geogrid reinforced pavements have been included as alternatives within all of the proposed pavements but they allow a saving in course thicknesses only in the case of subgade CBRs of 4% and less.

The geogrid options are the even numbered ones in the design tables which follow.   Huesker, the geogrid manufacturer, have confirmed that they follow CIRIA guidance which recommends that geogrids are of value only on low CBR soils and that the value increases as the subgrade CBR diminishes.

Therefore, the tables includeheaders which show how using a geogrid effectively lifts the ground conditions by 1% CBR, i.e. when using a geogrid on soils of 4% CBR or less the capping thickness in the case of Detention Pavements or the additional Coarse Graded Aggregate thickness in the case of Infiltration Pavements is as for a 1% higher CBR subgrade. This means that the benefit of geogrids applies only for low CBR soils and the benefit increases with a decrease in CBR which maps correctly onto CIRIA guidance. This is an approach which the geogrid manufacturers would do well to replicate in all of their design guidance and fits better with the research than the approach currently proposed by geogrid manufacturers whereby a constant reduction in pavement thickness is allowed by the inclusion of a geogrid.

THE USE OF CAPPING MATERIALS

In the case of Detention Pavements, the lowest layer comprises 150mm thickness, or more, of Coarse Graded Aggregate over a waterproof membrane. For pavements of CBR 4% and lower, capping material is included below the waterproof layer. Table 6/2 of Highways Agency's "Specification for Highway Works" describes three types of capping material according to Particle Size Distribution and material characteristics. The three types are called 6F1, 6F2 and 6F3.

6F1 is the finest and all of the particles need to pass the 75mm sieve, whereas in the case of 6F2 and 6F3, up to 65% may be retained on the 75mm sieve. Also, 6F1 material may include up to 15% passing the 63 micron sieve and 6F2/6F3 may include up to 12% passing the 63 micron sieve. 6F3 material has less onerous hardness requirements and is best avoided if possible. 6F2 is the preferred material and is the one most used commonly in the UK.

Because all capping materials are allowed to include a significant amount of material passing a 63 micron sieve, they can lose strength when saturated. Therefore, it would not be correct to use them for Infiltration Pavements because such pavements are predicated upon water cascading through each layer of the pavement. Therefore, instead of capping materials, Infiltration Pavements installed over subgrades of 4% or less include additional thickness of Coarse Graded Aggregate which does allow the cascading of water without a strength reduction.

Because Coarse Graded Aggregate has superior structural performance to capping materials, the additional thickness of Coarse Graded Aggregate to deal with pavements installed over low CBR subgrades is less than that of capping. For example, in the case of pavements installed over 1% CBR subgrades, Detention Pavements require 600mm of capping placed below the waterproofing layer whereas Infiltration Pavements require an additional 300mm of Coarse Graded Aggregate.

DESIGN OF TEMPORARY ROADS SURFACED WITH PRIORA

There are many circumstances when a temporary road is required. In the case of Priora, this will mainly occur when a builder will need to use a road or other paved surface during the building of the property/properties being served by the road. In this case, the preferred solution is to install the road up to roadbase level using DBM50 as the roadbase. Before the road enters service as a permeable pavement, 75mm diameter holes will be formed at 750mm centres in orthogonal directions in order to permit the vertical flow of water. These holes will be filled with 6mm single sized grit before the Priora pavers are installed. In the case of the temporary road, the DBM50 may be trafficked directly by up to 5,000 commercial vehicles prior to the making of the holes and prior to the installation of the Priora pavers.

Great care should be taken when trafficking Coarse Graded Aggregate directly. Whether the Coarse Graded Aggregate can accommodate traffic will depend upon the mechanical properties of the particles and there is the possibility that traffic will simply plough through the material. Therefore, as a general recommendation, traffic should not be allowed to travel over Coarse Graded Aggregate directly. Even though such materials may fail very soon when trafficked directly, when the Priora pavers are installed, their weight ensures that there is sufficient friction between individual particles to prevent failure, providing the CGA has been specified correctly. Particularly rounded stones are susceptible to disruption when trafficked directly. Also, directly trafficking CGA can introduce fine material into the voids which can compromise the hydraulic properties of the material.

PROPOSED DESIGN SECTIONS FOR DETENTION PAVEMENTS AND INFILTRATING PAVEMENTS

PROPOSED DESIGN SECTIONS FOR DETENTION PERMEABLE PAVEMENTS

The sections in the Table apply in the case of subgrades of 5% CBR or more. For pavements over lower CBR values, replace the 50mm sand with the following:
1% CBR 600mm capping or 300mm capping plus Huesker Geogrid
2% CBR 350mm capping or 225mm capping plus Huesker Geogrid
3% CBR 225mm capping or 150mm capping plus Huesker Geogrid
4% CBR 150mm capping or Huesker Geogrid

PAVEMENT USE	EXISTING INTERPAVE/BS7533: PART 13 SECTION	EXISTING MARSHALLS SECTION	PROPOSED MARSHALLS SECTION **NOTE: A LAYER OF 50MM THICKNESS OF SAND IS INCLUDED IN ALL CASES. THE PURPOSE OF THIS IS TO PROTECT THE WATERPROOF LAYER FROM DAMAGE. IT IOS NOT REQUIRED STRUCTURALLY**
Pedestrian and Domestic Driveways	80mm pavers 50mm laying course 250mm CGA Waterproof layer 150mm capping	60mm or 80mm Priora 50mm laying course 200mm CGA Waterproof layer 150mm capping	Alternative 1: 60mm or 80mm Priora 50mm laying course 150mm CGA Waterproof layer 50mm sand Alternative 2: 60mm or 80mm Priora 50mm laying course 150mm CGA Huesker Geogrid Waterproof layer 50mm sand

Cars & Light Vans	X	80mm Priora 50mm laying course 200mm CGA Waterproof layer 150mm capping	<u>Alternative 1:</u> 60mm or 80mm Priora 50mm laying course 200mm CGA Waterproof layer 50mm sand <u>Alternative 2:</u> 60mm or 80mm Priora 50mm laying course 200mm CGA Huesker Geogrid Waterproof layer 50mm sand
Traffic up to 7.5 tonne	X	80mm Priora 50mm laying course 350mm CGA Waterproof layer 150mm capping	<u>Alternative 1:</u> 80mm Priora 50mm laying course 275mm CGA Waterproof layer 50mm sand <u>Alternative 2:</u> 80mm Priora 50mm laying course 275mm CGA Huesker Geogrid Waterproof layer 50mm sand

Emergency Large Goods Vehicles only (100 standard axles cumulative)	80mm pavers 50mm laying course 350mm CGA Waterproof layer 150mm capping	80mm Priora 50mm laying course 80mm DBM (100 Pen) 150mm CGA Waterproof layer 150mm capping	Alternative 1: 80mm Priora 50mm laying course 300mm CGA Waterproof layer 50mm sand Alternative 2: 80mm Priora 50mm laying course 300mm CGA Huesker Geogrid Waterproof layer 50mm sand
One Large Goods Vehicle per week (0.015msa)	80mm pavers 50mm laying course 125mm coarse HBM 150mm CGA Waterproof layer 150mm capping	X	Alternative 1 80mm Priora 50mm laying course 70mm DBM (50 Pen) 150mm CGA Waterproof layer 50mm sand Alternative 2 80mm Priora 50mm laying course 70mm DBM (50 Pen) 150mm CGA Huesker Geogrid Waterproof layer

			50mm sand Alternative 3 80mm Priora 50mm laying course 100mm coarse HBM 150mm CGA Waterproof layer 50mm sand Alternative 4 80mm Priora 50mm laying course 100mm coarse HBM 150mm CGA Huesker Geogrid Waterproof layer 50mm sand
Ten Large Goods Vehicles per week (0.15msa)	80mm pavers 50mm laying course 150mm coarse HBM or 130mm DBM50 150mm CGA Waterproof layer 150mm capping	X	Alternative 1 80mm Priora 50mm laying course 90mm DBM (50 Pen) 150mm CGA Waterproof layer 50mm sand Alternative 2 80mm Priora 50mm laying course

			90mm DBM (50 Pen) 150mm CGA Huesker Geogrid Waterproof layer 50mm sand <u>Alternative 3</u> 80mm Priora 50mm laying course 125mm coarse HBM 150mm CGA Waterproof layer 50mm sand <u>Alternative 4</u> 80mm Priora 50mm laying course 125mm coarse HBM 150mm CGA Huesker Geogrid Waterproof layer 50mm sand
100 Large Goods Vehicles per week (1.5msa)	80mm pavers 50mm laying course 200mm coarse HBM or 130mm DBM50 150mm CGA Waterproof layer 150mm capping	X	<u>Alternative 1</u> 80mm Priora 50mm laying course 115mm DBM50 150mm CGA Waterproof layer 50mm sand

			Alternative 2 80mm Priora 50mm laying course 115mm DBM50 150mm CGA Huesker Geogrid Waterproof layer 50mm sand Alternative 3 80mm Priora 50mm laying course 175mm coarse HBM 150mm CGA Waterproof layer 50mm sand Alternative 4 80mm Priora 50mm laying course 175mm coarse HBM 150mm CGA Huesker Geogrid Waterproof layer 50mm sand

1000 Large Goods Vehicles per week (15msa)	80mm pavers 50mm laying course 300mm coarse HBM or 185mm DBM50 150mm CGA Waterproof layer 150mm capping	X	Alternative 1 80mm Priora 50mm laying course 160mm DBM50 150mm CGA Waterproof layer 50mm sand Alternative 2 50mm laying course 160mm DBM50 150mm CGA Huesker Geogrid Waterproof layer 50mm sand Alternative 3 80mm Priora 50mm laying course 275mm coarse HBM 150mm CGA Waterproof layer 50mm sand Alternative 4 50mm laying course 275mm coarse HBM 150mm CGA Huesker Geogrid

			Waterproof layer 50mm sand
Heavy Duty Pavements for Ports and similar industries	X	X	80mm Priora 50mm laying course Coarse HBM or DBM50 thickness to be obtained using the Fourth Edition of the British Ports Association pavement design manual 150mm CGA Waterproof layer 50mm sand

PROPOSED DESIGN SECTIONS FOR INFILTRATION PERMEABLE PAVEMENTS

The sections in the Table apply in the case of subgrades of 5% CBR or more. For pavements over lower CBR values, add the following thickness to the thickness of the Coarse Graded Aggregate in the Table:
1% CBR 300mm or 175mm and Huesker Geogrid
2% CBR 175mm or 125mm and Huesker Geogrid
3% CBR 125mm or 100mm and Huesker Geogrid
4% CBR 100mm or Huesker Geogrid

Pavement Use	Existing Interpave/BS7533: Part 13 section	Existing Marshalls section	Proposed Marshalls section
Pedestrian and Domestic Driveways	80mm pavers 50mm laying course 250mm CGA	60mm or 80mm Priora 50mm laying course 200mm CGA	Alternative 1: 60mm or 80mm Priora 50mm laying course 150mm CGA Alternative 2: 60mm or 80mm Priora 50mm laying course 150mm CGA Huesker Geogrid
Cars & Light Vans	X	80mm Priora 50mm laying course 200mm CGA	Alternative 1: 60mm or 80mm Priora 50mm laying course 200mm CGA Alternative 2: 60mm or 80mm Priora 50mm laying course

			200mm CGA Huesker Geogrid
Traffic up to 7.5 tonne	X	80mm Priora 50mm laying course 350mm CGA	Alternative 1: 80mm Priora 50mm laying course 275mm CGA Alternative 2: 80mm Priora 50mm laying course 275mm CGA Huesker Geogrid
Emergency Large Goods Vehicles only (100 standard axles cumulative)	80mm pavers 50mm laying course 350mm CGA	80mm Priora 50mm laying course 80mm DBM (100 Pen) 150mm CGA	Alternative 1: 80mm Priora 50mm laying course 300mm CGA Alternative 2: 80mm Priora 50mm laying course 300mm CGA Huesker Geogrid
One Large Goods Vehicle per week (0.015msa)	80mm pavers 50mm laying course 125mm coarse HBM 150mm CGA	X	Alternative 1 80mm Priora 50mm laying course 70mm DBM (50 Pen) 150mm CGA Alternative 2

			80mm Priora 50mm laying course 70mm DBM (50 Pen) 150mm CGA Huesker Geogrid Alternative 3 80mm Priora 50mm laying course 100mm coarse HBM 150mm CGA Alternative 4 80mm Priora 50mm laying course 100mm coarse HBM 150mm CGA Huesker Geogrid
Ten Large Goods Vehicles per week (0.15msa)	80mm pavers 50mm laying course 150mm coarse HBM or 130mm DBM50 150mm CGA	X	Alternative 1 80mm Priora 50mm laying course 90mm DBM (50 Pen) 150mm CGA Alternative 2 80mm Priora 50mm laying course 90mm DBM (50 Pen) 150mm CGA

			Huesker Geogrid Alternative 3 80mm Priora 50mm laying course 125mm coarse HBM 150mm CGA Alternative 4 80mm Priora 50mm laying course 125mm coarse HBM 150mm CGA Huesker Geogrid
100 Large Goods Vehicles per week (1.5msa)	80mm pavers 50mm laying course 200mm coarse HBM or 130mm DBM50 150mm CGA	X	Alternative 1 80mm Priora 50mm laying course 115mm DBM50 150mm CGA Alternative 2 80mm Priora 50mm laying course 115mm DBM50 150mm CGA Huesker Geogrid Alternative 3 80mm Priora

			50mm laying course 175mm coarse HBM 150mm CGA <u>Alternative 4</u> 80mm Priora 50mm laying course 175mm coarse HBM 150mm CGA Huesker Geogrid
1000 Large Goods Vehicles per week (15msa)	80mm pavers 50mm laying course 300mm coarse HBM or 185mm DBM50 150mm CGA	**X**	<u>Alternative 1</u> 80mm Priora 50mm laying course 160mm DBM50 150mm CGA <u>Alternative 2</u> 80mm Priora 50mm laying course 160mm DBM50 150mm CGA Huesker Geogrid <u>Alternative 3</u> 80mm Priora 50mm laying course 275mm coarse HBM 150mm CGA

			Alternative 4 80mm Priora 50mm laying course 275mm coarse HBM 150mm CGA Huesker Geogrid
Heavy Duty Pavements for Ports and similar industries	X	X	80mm Priora 50mm laying course DBM50 or coarse HBM thickness to be obtained using the Fourth Edition of the British Ports Association pavement design manual 150mm CGA

PROPOSED DESIGN SECTIONS FOR DETENTION PAVEMENTS AND INFILTRATING PAVEMENTS

VALIDATION OF THE PROPOSED DESIGN SECTIONS

The above proposed design sections have been checked by carrying out a Finite Element analysis with the purpose of establishing that they each lead provide sufficient protection to the underlying subgrade to endure that rutting will not develop. Also, those pavements which include DBM or HMB have been checked to ensure that fatigue cracking will not occur within those materials. These twin criteria have been checked by comparing the stresses and strains which the Finite Element analysis shows to develop in the subgrade and in the DBM with stresses and strains derived from equations often referred to as *Transfer Functions* which provide values of the stresses and strains which should not be exceeded within the subgrade and within the sub-base. There are many Transfer Functions available. This is because they are empirical equations which have been derived from observations of the performance of pavements of known material properties. Different authoritative highway administrations, including the UK's Highways Agency have monitored the performance of their pavements and have thereby derived Transfer Functions appropriate to their own pavements.

There is no empirical data available relating the performance of permeable pavements to usage. However, permeable pavements comprise conventional roadbuilding materials whose engineering properties are well understood and there is now a reasonable body of data confirming which pavements have been successful and which have been less successful, such as that collected by Marshalls at sites such as Martlesham. These sites can be used to run a check on the veracity of the transfer function selected. By this I mean that if the selected Transfer Function produces results in line with Marshalls' observations of their own pavements, then it can be considered to be as well validated as the Transfer Functions which are in common use worldwide.

In validating the Priora designs, I have selected the most widely used Transfer Functions. These are the following equations which were derived by the US Corps of Engineers. They have been applied by highways agencies in the US and the UK, by Federal Aviation Administration and in the British Ports Association manual for over 25 years and are considered to be well proven.

SUBGRADE STRAIN TRANSFER FUNCTION

Allowable Number of Repetitions =

$$N = 10,000\left(\frac{A}{S_S}\right)^B$$

Where:

N = Number of Repetitions which the pavement can sustain (as established from Finite Element program)
A= 0.000247 + 0.000245.Log(M_r)
S_S = Vertical Strain at upper surface of subgrade
M_r = Resilient Modulus of Subgrade (psi)
B = 0.0658.$M_r^{0.559}$

The relationship between California Bearing Ratio, and Resilient Modulus for the designs being considered is as in Table 1 below.

Table 1. Relationship between California Bearing Ratio and Resilient Modulus

CALIFORNIA BEARING RATIO	RESILIENT MODULUS		VALUE OF CONSTANT A	VALUE OF CONSTANT B
	PSI	**N/mm^2**		
1%	1,450	10	0.00102	3.85
2%	2,900	20	0.00110	5.67
3%	4,350	30	0.00114	7.11
4%	5,800	40	0.00117	8.56
5%	7,250	50	0.00119	9.47
20% **(Coarse Graded Aggregate or Capping)**	29,000	200		

Figure 2 below shows the relationship between vertical strain at the surface of the subgrade and the number of repetitions to failure (called "coverages" by CAA to distinguish the figure from aircraft passes). The points on figure 2 are individual pavements. The four slopes on Figure 2 refer to subgrades of modulus 4,500psi (uppermost line), 9,000psi (blue line), 15,000psi (yellow line) and 22,500psi (lowest line)respectively (3% CBR, 6% CBR, 10% CBR and 15% CBR).

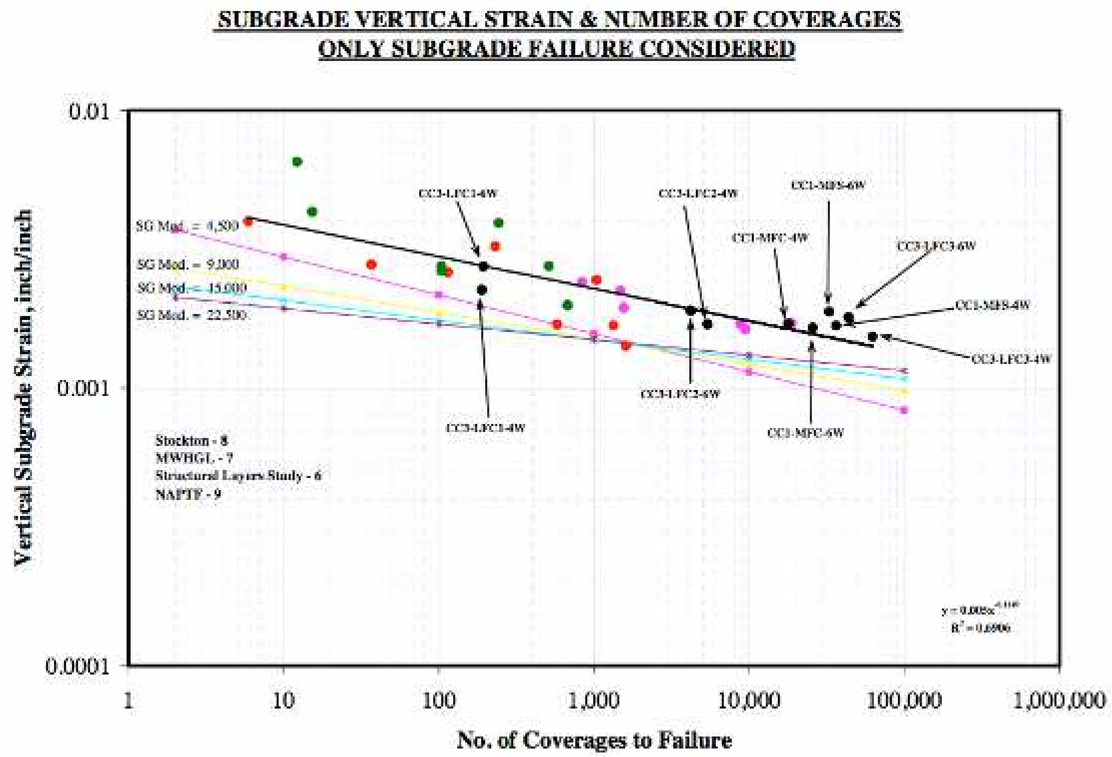
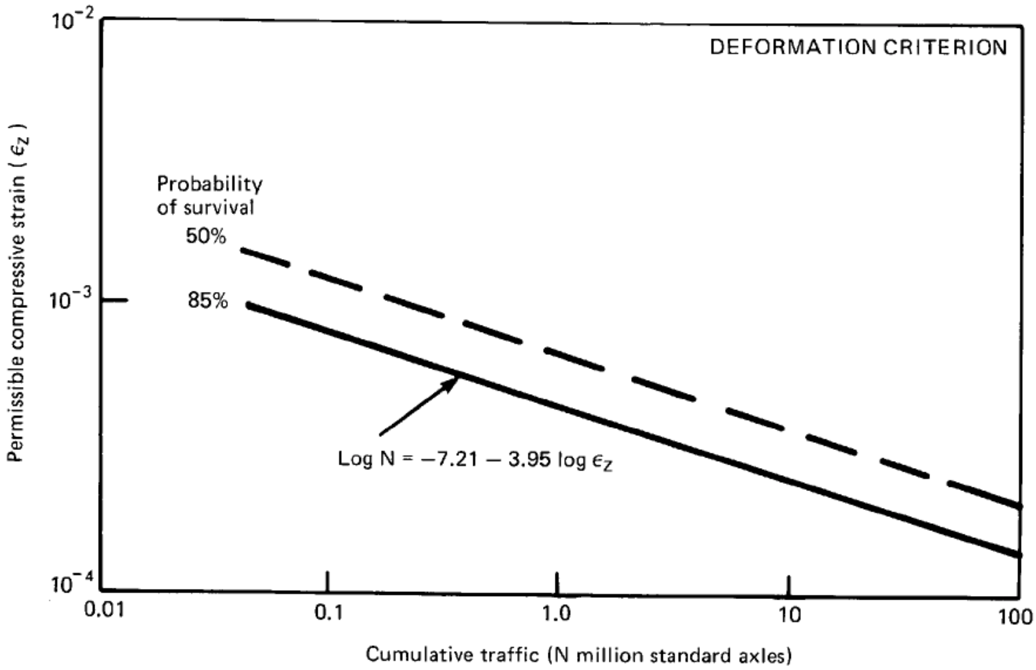


FIGURE 2 LEDFAA 1.2 failure model showing full-scale test data and model curves for four subgrade modulus values.

The figure below shows the relationship between number of repetitions and permissible subgrade strain as set out in TRL's Laboratory report LR1132 "The Structural Design of Bituminous Roads" (Powell, Potter, Mayhew & Nunn, 1984).



(b) Top of the subgrade

Fig. 4 Permissible strains induced by a standard 40kN wheel load at a pavement temperature of 20°C

DENSE BITUMEN MACADAM STRAIN TRANSFER FUNCTION

Allowable Number of Repetitions =

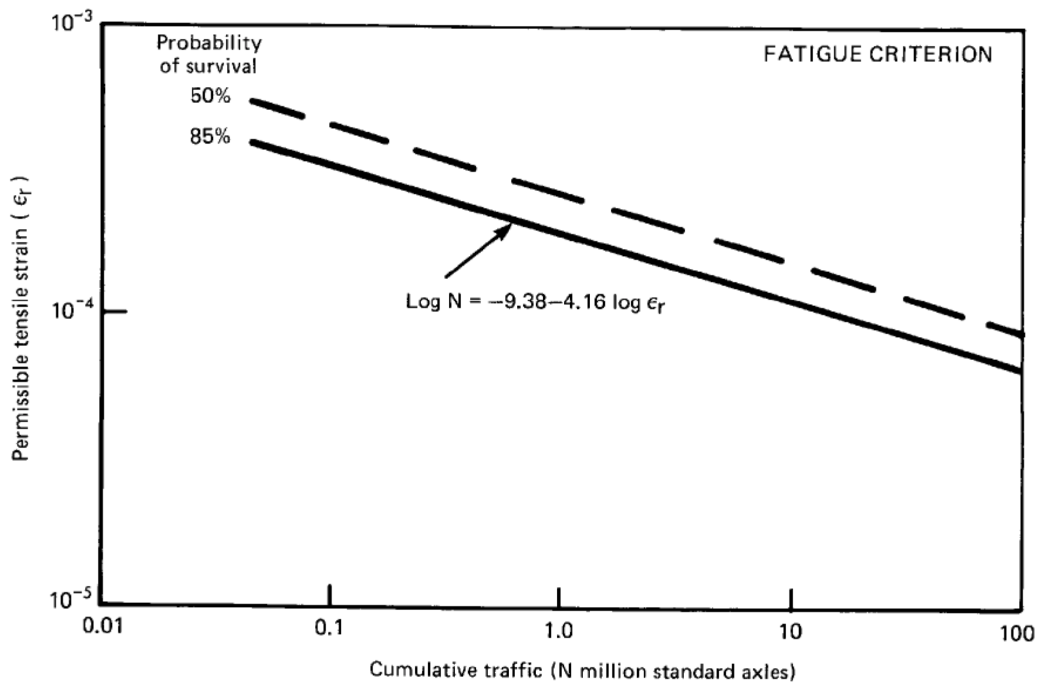
$$N = 10^{x}$$

Where:

N = Number of Repetitions which the pavement can sustain
x = 2.68 -5.Log(S_A) – 2.665 Log(E)
S_A = Horizontal Tensile Strain at underside of DBM (as established from Finite Element program)
E = Elastic Modulus of DBM (psi) (say 600,000psi or 4136N/mm^2) which means:
x= 12.72 – 5.Log(S_A)

The figure below shows the above relationship between number of repetitions and horizontal tensile strain (often referred to as “fatigue strain”) as set out graphically for DBM in TRL’s Laboratory Report LR1132 “The Structural Design of Bituminous Roads” (Powell, Potter, Mayhew & Nunn, 1984).

LR1132 uses a similar relationship to the above equation.



(a) Bottom of dense bitumen macadam roadbase

Using the above chart, LR1132 shows the following relationship between asphalt thickness and number of wheel patch repetitions.

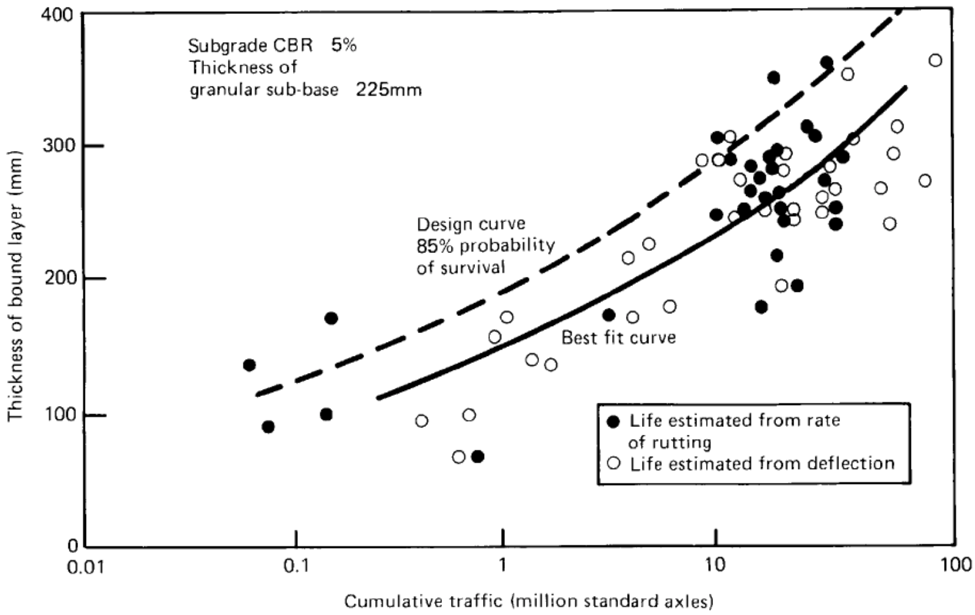


Fig. D1 Relation between thickness and life of experimental roads with dense bitumen macadam roadbase

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The following extract from TRL's LR1132 shows the actual strain relationships used by TRL which differ to a degree from FAA and BPA figures and which take into account the particular characteristics of Highways Agency's DBM. Note that the figures equate to DBM with 100 Penetration bitumen whereas it is now common to use 50 Penetration asphalt. This provides a degree of conservatism in design. For this reason, the FAA fatigue relationships shown in Figure 2 above are more appropriate and can be used in the validation of the design proposals.

In the next part of this report, the above strain relationships are used to check the proposed designs.

17. APPENDIX E

INPUT DATA FOR THE DESIGN MODEL AND AN EXAMPLE OF APPLYING THE DESIGN METHOD

17.1 Data required for design models

To make best use of the design method, the structural properties of the pavement materials and subgrade must be known. The values assigned to each property to calculate critical strains in the standard designs are given below:

Bituminous material

Loading frequency	5 Hz
Equivalent temperature	$20^{o}C$
Modulus of dense bitumen macadam (100 pen)	3.1 GPa
Modulus of hot rolled asphalt (50 pen)	3.5 GPa
Poisson's ratio	0.35

Fatigue criterion:

For dense bitumen macadam (100 pen)	$\log N_f = -9.38 - 4.16 \log \in_r$
For hot rolled asphalt (50 pen)	$\log N_f = -9.78 - 4.32 \log \in_r$
	where N_f is the road life in standard axles and $\in_r$ is the horizontal tensile strain at the underside of the bound layer under a standard wheel load.
Deformation criterion	$\log N_d = -7.21 - 3.95 \log \in_z$
	where N_d is the life of road in standard axles and $\in_z$ is the vertical compressive strain at the top of the subgrade under a standard wheel load.

NO FINES LEAN CONCRETE (HYDRAULICALLY BOUND MATERIAL) STRESS TRANSFER FUNCTION

For those pavements with a no-fines lean concrete base, proposed thicknesses have been checked by applying limiting tensile stresses occurring within the no-fines lean concrete using the relationships shown below which are taken from the Fourth Edition of the British Ports Association Heavy Duty Pavement Design Manual.

5.3 DEVELOPMENT OF THIS MANUAL'S DESIGN CHART

The Design Chart has been developed by searching within Tables 2 to 8 for combinations of base thickness and Single Equivalent Wheel Load (SEWL) which give rise to the following maximum tensile stress values in the standard material used i.e. $C_{8/10}$ CBGM.

Up to 250,000 SEWLs	**1.3N/mm^2**
250,000 to 1.5 x 10^6 SEWLs	**1.1N/mm^2**
1.5 x 10^6 to 4 x 10^6 SEWLs	**0.9N/mm^2**
4 x 10^6 to 8 x 10^6 SEWLs	**0.7N/mm^2**
8 x 10^6 to 12 x 10^6 SEWLs	**0.5N/mm^2**

However, no-fines lean concrete is required to have a strength of $C_{5/6}$ rather than $C_{8/10}$. Therefore, the above tensile strength values need to be adjusted downwards by multiplying them by a factor of 60% to provide the following limiting tensile stresses:

Up to 250,000 standard axles: 0.78N/mm^2
Up to 1,500,000 standard axles: 0.66N/mm^2
Up to 4,000,000 standard axles: 0.54N/mm^2
Up to 8,000,000 standard axles: 0.42N/mm^2
Up to 12,000,000 standard axles: 0.30N/mm^2

PROPERTIES OF MATERIALS USED IN DESIGN VALIDATION EXERCISE

I have adopted the values shown in the following table in the Finite Element design verification exercise.

MATERIAL	ELASTIC MODULUS (N/MM^2 OR MPA)	POISSON'S RATIO
Priora Installed over 6mm grit	2,000	0.4
Coarse Graded Aggregate	1,000*	0.35
Dense Bitumen Macadam 50 Penetration Bitumen	6,000	0.30
Coarse Graded Hydraulically Bound Material	4,000	0.25
Sand	400	0.35
Huesker Geogrid	Enhances the overlying CGA Elastic Modulus from 1,000MPa to 1,500MPa	0.35
5% CBR Subgrade	50	0.45

*** This value requires that Coarse Graded Aggregate meets the Marshalls' specification requirements of a No Fines Value of 200kN. Otherwise, the Elastic Modulus value should be 500MPa.**

APPENDIX

SUPPORTING INFORMATION

The information in this Appendix comprises:

1. Highways Agency Design Manual for Roads and Bridges, Volume 7, Section 2, Figure 2.1.

2. Fourth Edition of British Ports Association Heavy Duty Pavement Design Manual, Tables 10, 11, 12, 13 & 15 plus Design Chart.

3. *"A new design method for permeable pavements surfaced with pavers"* Knapton, Cook & Morrell.Highways & Transportation, January/February 2002, Pp 23-27.

4. Tobermore Trials Paper (Note: includes relevant Interpave design guide paper).

5. Relevant extracts from BS7533: Part 13 2009 (Pages 13 to 16).

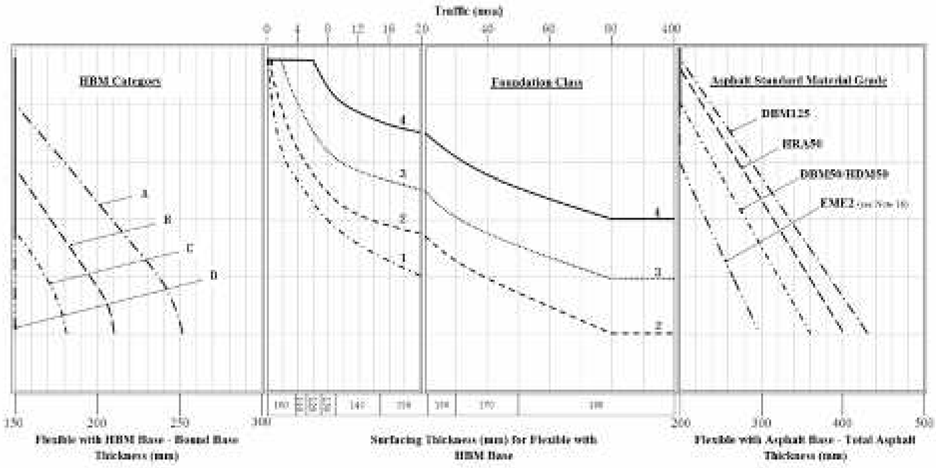

Figure 2.1 Design Thickness for Flexible Pavements

Examples of Hydraulic Bound Base Materials

HBM Category	A	B	C	D
Crushed Rock Coarse Aggregate: (with coefficient of thermal expansion <10 × 10⁻⁶ per °C)	-	CBGM B – C8/10 (or T3) SBM B1 – C9/12 (or T3) FABM1 – C9/12 (or T3)	CBGM B – C12/15 (or T4) SBM B1 – C12/16 (or T4) FABM1 – C12/16 (or T4)	CBGM B – C16/20 (or T5) SBM B1 – C15/20 (or T5) FABM1 – C15/20 (or T5)
Gravel Coarse Aggregate: (with coefficient of thermal expansion ≥10 × 10⁻⁶ per °C)	CBGM B – C8/10 (or T3) SBM B1 – C9/12 (or T3) FABM1 – C9/12 (or T3)	CBGM B – C12/15 (or T4) SBM B1 – C12/16 (or T4) FABM1 – C12/16 (or T4)	CBGM B – C16/20 (or T5) SBM B1 – C15/20 (or T5) FABM1 – C15/20 (or T5)	-

heavy duty pavements

Previous name	New name for BS EN14227 – Parts 1, 2 & 3 (all 2004) *'Hydraulically Bound Mixtures – Specifications'*
Cement Bound Material 1 (CBM1)	Cement Bound Granular Mixture $C_{3/4}$ Slag Bound Mixture $C_{3/4}$ Fly Ash Bound Mixture $C_{3/4}$
Cement Bound Material 2 (CBM2)	Cement Bound Granular Mixture $C_{5/6}$ Slag Bound Mixture $C_{6/8}$ Fly Ash Bound Mixture $C_{6/8}$
Cement Bound Material 3 (CBM3)	Cement Bound Granular Mixture $C_{8/10}$ Slag Bound Mixture $C_{9/12}$ Fly Ash Bound Mixture $C_{9/12}$
Cement Bound Material 4 (CBM4)	Cement Bound Granular Mixture $C_{12/15}$ Slag Bound Mixture $C_{12/16}$ Fly Ash Bound Mixture $C_{12/16}$
Cement Bound Material 5 (CBM5)	Cement Bound Granular Mixture $C_{20/25}$ Slag Bound Mixture $C_{18/24}$ Fly Ash Bound Mixture $C_{18/24}$

Table 10. The previous way of specifying "lean concretes" was changed in the UK in 2004 by the introduction of BS EN14227 *'Hydraulically Bound Mixtures – Specifications'*. This Table provides a descriptive means of relating the old classification system to the new one. However, for design purposes, the Material Equivalence Factors in Table 13 should be used. A mixture referred to as $C_{8/10}$ means material with a 28 days characteristic compressive cylinder strength of 8N/mm^2 and a characteristic compressive cube strength of 10N/mm^2.

Table 11. Classification of Cement Bound Granular Mixtures by Characteristic Compressive Strength. The standard material used to construct the Design Chart is shown in **bold**.

Note: In the case of cylinders H/D is the ratio of the height to the diameter of the test piece.

Characteristic 28 Day Compressive Strength (N/mm²)		Strength Class	Mean Axial Tensile Strength (N/mm²)
Cylinder Strength (H/D = 2)	Cylinder or Cube Strength (H/D = 1)		
No requirement		C_0	0
1.5	2.0	$C_{1.5/2.0}$	0.39
3.0	4.0	$C_{3/4}$	0.62
5.0	6.0	$C_{5/6}$	0.87
8.0	**10.0**	$\mathbf{C_{8/10}}$	**1.18**
12	15	$C_{12/15}$	1.55
16	20	$C_{16/20}$	1.87
20	25	$C_{20/25}$	2.17

Table 12 shows properties of other Hydraulically Bound Materials, i.e. Slag Bound Mixtures and Fly Ash Bound Mixtures, as described in BS EN 14227: Part 2: 2004 *'Hydraulically bound mixtures – Specifications. Part 2: Slag Bound Mixtures'* and BS EN 14227: Part 3: 2004 *'Hydraulically bound mixtures – Specifications. Part 3: Fly Ash Bound Mixtures.'*

Table 12. Classification of Slag Bound Mixtures and Fly Ash Bound Mixtures by Characteristic Compressive Strength.

Note: In the case of cylinders H/D is the ratio of the height to the diameter of the test piece.

Characteristic 28 Day Compressive Strength (N/mm²)		Strength Class	Mean Axial Tensile Strength (N/mm²)
Cylinder Strength (H/D = 2)	Cylinder or Cube Strength (H/D = 1)		
1.5	2.0	$C_{1.5/2.0}$	0.39
3.0	4.0	$C_{3/4}$	0.62
6.0	8.0	$C_{6/8}$	0.98
9.0	12.0	$C_{9/12}$	1.28
12	16	$C_{12/16}$	1.55
15	20	$C_{15/20}$	1.80
18	24	$C_{18/24}$	2.02
21	28	$C_{21/28}$	2.24
24	32	$C_{24/32}$	2.44
27	36	$C_{27/36}$	2.64

Material Grouping	Preferred Pavement Base Construction Material		Material Equivalence Factor (MEF)
Hydraulically Bound Mixtures	Material strength	Relevant Standard	
	$C_{1.5/2.0}$	*to BS EN 14227-1*	*1.74*
	$C_{3/4}$	*to BS EN 14227-1*	*1.38*
	$C_{5/6}$	*to BS EN 14227-1*	*1.16*
	$C_{8/10}$	**to BS EN 14227-1**	**1.00**
	$C_{12/15}$	to BS EN 14227-1	0.87
	$C_{16/20}$	to BS EN 14227-1	0.79
	$C_{20/25}$	to BS EN 14227-1	0.74
	$C_{1.5/2.0}$	*to BS EN 14227-2&3*	*1.74*
	$C_{3/4}$	*to BS EN 14227-2&3*	*1.38*
	$C_{6/8}$	*to BS EN 14227-2&3*	*1.10*
	$C_{9/12}$	to BS EN 14227-2&3	0.95
	$C_{12/16}$	to BS EN 14227-2&3	0.85
	$C_{15/20}$	to BS EN 14227-2&3	0.79
	$C_{18/24}$	to BS EN 14227-2&3	0.76
	$C_{21/28}$	to BS EN 14227-2&3	0.72
	$C_{24/32}$	to BS EN 14227-2&3	0.68
	$C_{27/36}$	to BS EN 14227-2&3	0.63
Concrete			
	C8/10	**to BS8500-1**	**1.00**
	C12/15	to BS 8500-1	0.87
	C16/20	to BS 8500-1	0.79
	C20/25	to BS 8500-1	0.74
	C25/30	to BS 8500-1	0.65
	C25/30	to BS 8500-1 including 20kg/m^3 steel fibre	0.60
	C25/30	to BS 8500-1 including 30kg/m^3 steel fibre	0.55
	C25/30	to BS 8500-1 including 40kg/m^3 steel fibre	0.50
	C28/35	to BS 8500-1	0.62
	C32/40	to BS 8500-1	0.60
	C32/40	to BS 8500-1 including 20kg/m^3 steel fibre	0.55
	C32/40	to BS 8500-1 including 30kg/m^3 steel fibre	0.50
	C32/40	to BS 8500-1 including 40kg/m^3 steel fibre	0.45
	C35/45	to BS 8500-1	0.58

Table 13. Material Equivalence Factors relating $C_{8/10}$ CBGM to other materials.

Note that the thicknesses derived from the Design Charts need to be multiplied by the factors in this table to obtain thicknesses for materials other than $C_{8/10}$.

Note that those materials in italic would not normally be specified as a pavement base but may be used as part of the pavement foundation (see Foundation Design).

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Table 13 continued.

Note: that the thicknesses derived from the Design Charts need to be multiplied by the factors in this table to obtain thicknesses for materials other than $C_{8/10}$.

Note: that those materials in italic would not normally be specified as a pavement base but may be used as part of the pavement foundation (see Foundation Design).

Material Grouping	Preferred Pavement Base Construction Material	Material Equivalence Factor (MEF)
Traditional Cement Bound Materials	*CBM1 (4.5N/mm² minimum 7-days compressive cube strength)*	*1.60*
	CBM2 (7.0N/mm² minimum 7-days compressive cube strength)	*1.20*
	CBM3 (10.0N/mm² minimum 7-days compressive cube strength)	**1.00**
	CBM4 (15.0N/mm² minimum 7-days compressive cube strength)	0.80
	CBM5 (20.0N/mm² minimum 7-days compressive cube strength)	0.70
	No fines Lean Concrete for Permeable Paving	1.00
Bitumen Bound Materials	HDM as defined by SHW	0.82
	DBM as defined by SHW	1.00
	HRA as defined by SHW	*1.25*
Unbound Materials	Crushed rock sub-base material of CBR ≥ 80%	3.00
Concrete Block Paving	Concrete Block Paving as a surfacing (80mm blocks and 30mm laying course)	1.00

Notes: Concrete referred to as C16/20 means concrete with a 28 days characteristic compressive cube strength of 20N/mm². Where two numbers follow C, the first is characteristic compressive cylinder strength and the second is characteristic compressive cube strength.

HDM – Heavy Duty Macadam.

DBM = Dense Bitumen Macadam.

HRA – Hot Rolled Asphalt.

SHW = UK Highways Agency *'Specification for Highway Works'*.

Concrete block paving to be used as surfacing only.

Crushed rock to be used as foundation only.

Bitumen bound materials (HDM, DBM and HRA) may deform under static loading.

Only those steel fibres specifically proven to enhance the strength of concrete to be specified.

In the case of CBM1 to CBM5, the minimum compressive cube strength is the averaged minimum value (as opposed to the minimum measured on any one cube) which is close to characteristic strength. Note that CBM1 to CBM5 are no longer specified in the UK but may be encountered in pavement assessment relating to overlay design.

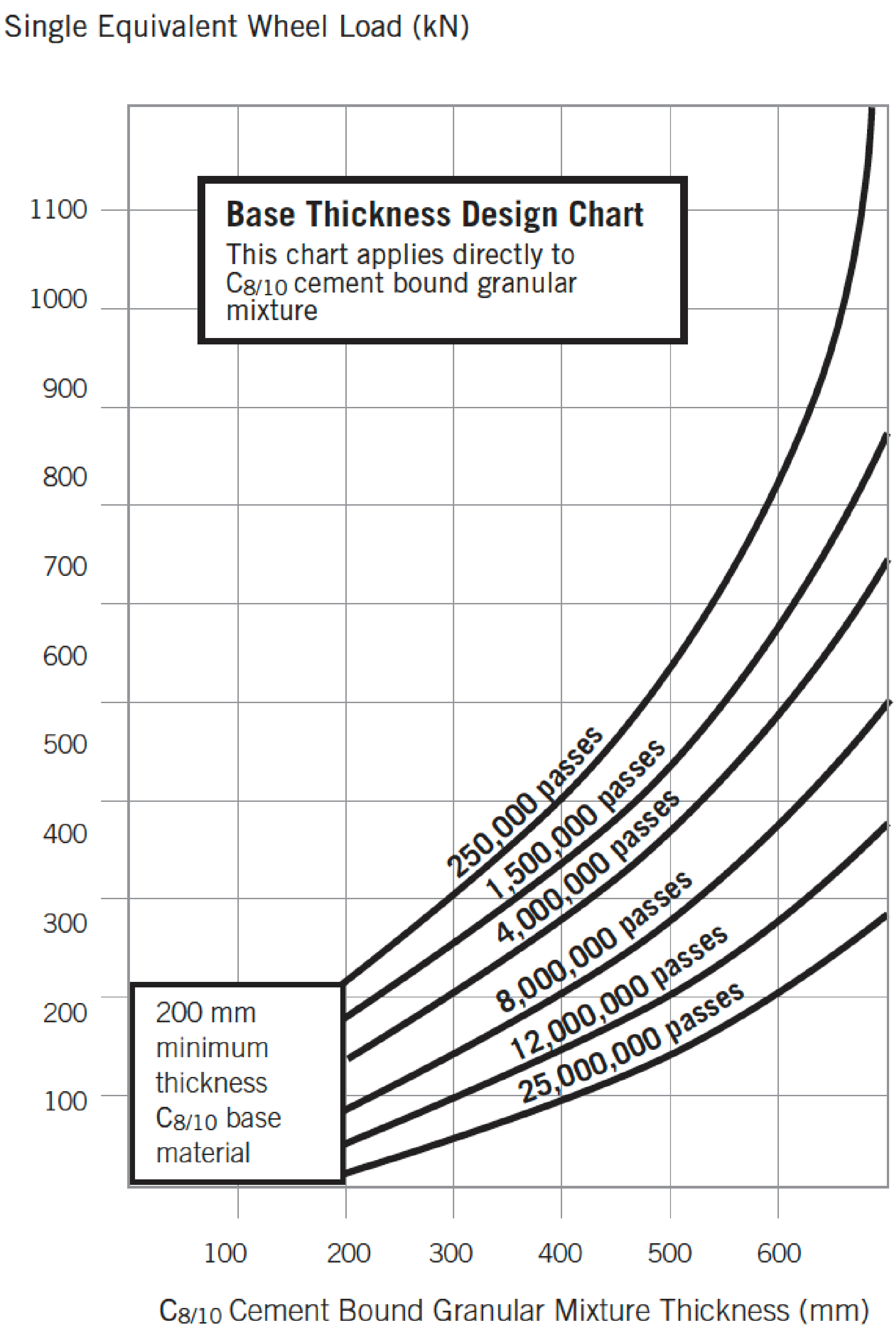
This Manual's Design Chart has been drawn for CBGM with Design Flexural Strength values as shown in Table 1, i.e.:

Up to 250,000 SEWLs 1.3N/mm²
250,000 to 1.5 x 10⁶ SEWLs 1.1N/mm²
1.5 x 10⁶ to 4 x 10⁶ SEWLs 0.9N/mm²
4 x 10⁶ to 8 x 10⁶ SEWLs 0.7N/mm²
8 x 10⁶ to 12 x 10⁶ SEWLs 0.5N/mm²
(SEWL = Single Equivalent Wheel Load)

and these are the values which can be used for $C_{8/10}$ CBGM, even though they may be greater than pure tensile strength values (because the material is not subjected to pure tension but is always subjected to compression in planes orthogonal to the tension plane).

Table 15. Pavement material properties used in producing design charts.

Layer	Elastic Modulus, E(N/mm^2)	Poisson's Ratio
Surfacing (CBP)	4,000	0.15
Base ($C_{8/10}$)	40,000	0.15
Unbound sub-base	500	0.30
Unbound capping	250	0.35
Subgrade	10 x CBR	0.40


Single Equivalent Wheel Load (kN)
Base Thickness Design Chart
This chart applies directly to $C_{8/10}$ cement bound granular mixture
1100
1000
900
800
700
600
500
400
300
200
100
250,000 passes
1,500,000 passes
4,000,000 passes
8,000,000 passes
12,000,000 passes
25,000,000 passes
200 mm minimum thickness $C_{8/10}$ base material
100
200
300
400
500
600
$C_{8/10}$ Cement Bound Granular Mixture Thickness (mm)

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Recent increases in levels of rainfall have led to The Environment Agency introducing guidance on the impact of development on flooding. Environment Agency's publication *Policy and practice for the protection of floodplains* (HMSO) states that: "Inappropriate development within floodplains should be resisted where such development would itself be at risk from flooding or may cause flooding elsewhere. To minimise any increased surface water run–off, new development must be carefully located and designed. Where appropriate, run-off source control measures which may also improve water quality should be incorporated into the development proposal."

A new design method for permeable pavements surfaced with pavers

The Environment Agency's key engineering principles set out in its document are: "Development generally increases the amount of impermeable land in river catchments. This increases the amount and rate of surface water run–off which if unmanaged can increase river flows and the risk of flooding. The adverse effects of inappropriate development, however small, are cumulative and can lead to significant problems in the longer term."

The Environment Agency is empowered by government to advise planning authorities on development and flood risk matters. Government Circular 30/92 states: "The Government looks to local authorities to use their planning powers to guide developments away from areas that may be affected by flooding, and to restrict development that would increase the risk of flooding..."

Prior to the autumn 2000 floods, CIRIA Report C521, "Sustainable urban drainage systems" (1999) had already highlighted the potential drainage problems associated with unchecked urban development. It concludes: "Drainage methods that take account of quantity, quality and social issues are collectively referred to as Sustainable Urban Drainage Systems (SUDS). These systems are more sustainable than traditional drainage methods because they:

- deal with runoff close to where the rain falls;
- manage potential flooding at its source, now and in the future;
- protect or enhance water quality;
- provide a habitat for wildlife in urban watercourses;
- protect water resources from accidental spills and pollution;
- allow new development in areas where existing sewerage systems are at full capacity, therefore enabling new development within existing urban areas;
- are sympathetic to the environmental setting and the needs of the local community, and
- encourage natural groundwater recharge."

The role of permeable paving within SUDS can be appreciated from the CIRIA document's conclusion: "SUDS are made up of a series of structures built to receive surface water runoff working in conjunction with good management of the site. There are four general methods of control:

- porous and permeable pavements;
- filter strips and swales;
- infiltration devices;
- basins and wetlands."

It is clear that all future developments need to address SUDS in order to gain planning approval. Planning authorities will be looking for evidence of innovative design in making their judgements. The inclusion of permeable paving within SUDS, possibly as one element in an overall sustainable environment design package, will greatly enhance the likelihood of a planning application succeeding. This Paper describes research undertaken into permeable flexibly bedded pavers and presents a design method based upon the results of that research.

By Professor J Knapton BSc PhD CEng FICE FIStructE FIHT, ID Cook BSc CEng MICE FIHT and D Morrell BSc MIHT

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David Morrell is New Product Manager at Marshalls Mono Ltd.

Background

The simplistic concept of allowing water to drain through the pavement and into the subgrade so eliminating entirely downstream drainage is unlikely to prove successful in the great majority of UK applications. This is because 96% or more of UK developments will be over clays which are not suited to accepting precipitation directly. In the UK, a permeable pavement is required to absorb 180litre/second/hectare. Whilst there is no difficulty in achieving this with pavement construction materials, most UK subgrades would be able to absorb only a small fraction of this. The remainder has to be retained in the pavement, either to gradually percolate into the subgrade or to be taken through a sub–surface drainage system. Such a system can be designed to constrict the flow and so act as a detention system, detention occurring in either the pavement or the drains (or in both). In view of the above, in addition to its conventional structural requirements, a permeable pavement has to be designed on the basis of the permeability of each of its courses and of the subgrade and it may also have to be designed on the basis of the volume of water which it can retain to attenuate downstream flow.

Allowing water to percolate into clay has the disadvantage that many clays in the UK lose much of their strength when wet. Before the pavement was constructed, the overlying vegetation growing in topsoil acted as a water recycling system. Rainwater entered the topsoil was absorbed by the roots of the vegetation and evaporated through transpiration: the water never reached the clay. With the removal of the topsoil and vegesation, the clay will then begin to absorb the previously recycled water and will weaken. This will cause structural difficulties within the pavement which will be irreversible.

Full scale permeable paving trials

To establish the relationship between paver joint width, jointing material characteristics

Fig 1. NUROLF test site showing waterproof material prior to installation of crushed rock open graded roadbase.

and permeability, a series of preliminary tests was carried out on a single joint between two conventional pavers. Testing was undertaken using a box containing two 200mm x 100mm x 80mm thickness rectangular pavers installed in such a manner that water could be applied to the straight joint between them, collected and measured over time. Rainfall was simulated by a simple graduated vessel filled with one litre of clean water. The water was gradually poured over the joint between two pavers, maintaining a constant head of 3mm. Table 1 shows the results.

Test No	Joint Width (mm)	Minimum joint filling particle size (mmm)	Permeability (litres /sec /hectare)
1	1.7	63	109
2	1.7	63	52
3	1.7	150	196
4	1.7	150	206
5	1.7	212	543
6	1.7	212	625
7	6	212	111
8	6	212	127
9	6	2000	1875
10	6	2000	2272
11	6	2000	2142

Table 1. Results of Newcastle University infiltration tests

These results show that permeable pavers can have a standard joint of 1.7mm or a larger joint of 6mm. If a standard joint is specified, the jointing sand must have no particles finer than 212mm. If a wider joint is used, it must be filled with a sand with no particles finer than 2mm.

The preliminary tests conclude that pavers are suitable as an infiltration medium. They conclude that jointing, bedding and underlying material particle size distribution is critical to the amount of water which can infiltrate a pavement. They show that infiltration well in excess of the UK requirement of 180litre/second/hectare can be achieved with conventional pavers and with pavers developed specifically with infiltration in mind.

A full scale test has been undertaken using Newcastle University Rolling Load Facility (NUROLF) on an area of pavement surfaced with permeable pavers comprising the following specification:

	Permeable pavers
50mm	Laying course material
350mm	Crushed 20mm open graded gravel roadbase material
150mm	DTp Type 1 granular sub–base material (local dolomitic limestone) 4% CBR subgrade material – boulder clay

The 9m long test site was divided into three sections – see Figs 1–4. In the first 3m length, the laying course and jointing material comprised a 4mm particle size brown washed natural gravel. In the remaining 6m length of the test site, the laying course and jointing material comprised Cloburn 6mm washed crushed red micro–granite available in the Central Lowlands of Scotland.

The central 3m of the test included a

Fig 2. Open graded roadbase material installed in NUROLF.

knitted geotextile fabric separating the laying course material from the roadbase material. The whole 9mx2m test site was lined with a 1000 gauge waterproof polyethylene membrane as shown in Fig 1. This allowed the volume of water introduced into the pavement to be measured. The waterproofing enclosed the pavers, the laying course material and the open graded roadbase material shown in Fig 2 but not the underlying sub–base material. At each end of the 9m long trial area, a vertical drain was included in order to assess the level of water standing in the pavement and also to facilitate the removal of water from the pavement – see Fig 3.

The permeable pavers were installed to a 90° herringbone pattern as shown in Fig 4 so that the NUROLF vehicle ran parallel to and normal to the paver joints. In order to simulate the most adverse combination of traffic and climate, the test area was maintained in a saturated condition throughout the whole of the testing. This was achieved by a sprinkler system which was activated before and during all of the testing. Prior to commencing the trafficking, the sprinkler system was activated in order to fill all of the voids in the roadbase with water. It was established that the roadbase material could accept 32% by volume of water. The trial section was filled and emptied three times prior to a fourth filling which was maintained during the trafficking trials.

During the four filling phases, the level of the free water surface within the roadbase was observed and it was noted that a horizontal surface was maintained within the open graded roadbase material, even when all of the water was applied through a single point in the pavement. From this, it was concluded that the water was flowing freely through the roadbase material.

NUROLF applies a vertical wheel load of up to 5000kgf through its offside wheel

Fig 3. Vertical drains installed at each end of NUROLF allow the level of stored water to be measured.

to the centre of the test site over a test length of 9m. It commences a cycle at one end of the site and accelerates linearly over half of the length of the test site so that the load wheel has attained a speed of 2.3m/s at mid point. It then decelerates over the second half of the test site, becomes stationary and undertakes the second half of its cycle by repeating the above in reverse. It undertakes a complete cycle in 53 seconds and in so doing applies a horizontal force of 500kgf always in the same direction, to the pavement.

This combination of a vertical load of 5000kgf and a horizontal load of 500kgf relates closely to the heaviest loading to which a permeable pavement is likely to be subjected. By comparison, the maximum non–steering axle load normally applied by a fully laden commercial vehicle is 9500 kgf, resulting in a wheel load of 4250 kgf.

In this test, 32,000 equivalent standard axles (ESAs) were applied in 40 hours running. Initially, 16,000 ESAs were applied using a wheel load of 3000kg and the remaining 16,000 ESAs were applied using a wheel load of 5000kg.

The results are shown in Figs 5 and 6. In these Figures, the 4mm washed natural gravel laying course material is to the left whilst Cloburn 6mm washed crushed micro–granite is within the central and right hand zones. A knitted geotextile has been included beneath the Cloburn material in the central zone.

The NUROLF results allow the conclusion to be drawn that when axle loads do not exceed 6000kg, permeable pavers will sustain regular channelised loading up to the levels which would be anticipated in even the most extreme situations in permeable paving. The testing was continued to 16,000 ESAs and rutting developed to a depth of 4mm in the Cloburn 6mm washed crushed micro–granite. Where the Cloburn material was separated from the underlying coarse graded gravel by a knitted geotextile, the rut depth was 11mm. The zone installed over 4mm washed natural gravel deformed by 9mm. When the axle load was then increased to 10,000kg, the deformation increased by approximately 70% as shown in Fig 6 and remained at that level for a further 16,000 ESAs.

The above indicates that the deformation arises from an initial compaction of the laying course material and the roadbase material. The conventional gradual development of

Fig 4. Permeable pavers under test at NUROLF.

HT&T

r	Rainfall duration (D)									
	Minutes				Hours					
	5	10	15	30	1	2	4	6	10	24
0.12	0.22	0.34	0.45	0.67	1.00	1.48	2.17	2.75	3.70	6.00
0.15	0.25	0.38	0.48	0.69	1.00	1.42	2.02	2.46	3.23	4.90
0.18	0.27	0.41	0.51	0.71	1.00	1.36	1.86	2.25	2.86	4.30
0.21	0.29	0.43	0.54	0.73	1.00	1.33	1.77	2.12	2.62	3.60
0.24	0.31	0.46	0.56	0.75	1.00	1.30	1.71	2.00	2.40	3.35
0.27	0.33	0.48	0.58	0.76	1.00	1.27	1.64	1.88	2.24	3.10
0.30	0.34	0.49	0.59	0.77	1.00	1.25	1.57	1.78	2.12	2.84
0.33	0.35	0.50	0.61	0.78	1.00	1.23	1.53	1.73	2.04	2.60
0.36	0.36	0.51	0.62	0.79	1.00	1.22	1.48	1.67	1.90	2.42
0.39	0.37	0.52	0.63	0.80	1.00	1.21	1.46	1.62	1.82	2.28
0.42	0.38	0.53	0.64	0.81	1.00	1.20	1.42	1.57	1.74	2.16
0.45	0.39	0.54	0.65	0.82	1.00	1.19	1.38	1.51	1.68	2.03

Table 2. Values of Z1 for rainfall duration D and ratio r.

rutting as a result of fatigue does not occur in permeable pavements because in ensuring such pavements have structural stability, sufficient stiffness has been provided to ensure that fatigue is not a significant issue.

The NUROLF results suggest that when axle loads exceed 6000kg, initial deformation will be unacceptable and it will be necessary to introduce stabilisation to the open graded roadbase material. Cement content will depend upon aggregate grading but a figure of 180kg/m^3 has been found to be satisfactory.

The development of significantly greater levels of rutting in the zone including the knitted geotextile had not been expected. Following the testing, an investigation revealed that the reason for this enhanced rutting value is the pressing of the roadbase material into the geotextile during loading. Effectively, during the construction phase, the geotextile spanned from high point to high point over the roadbase particles and the trafficking then stretched the geotextile, pressing it down into the depressions between the roadbase aggregate particles.

Analysis of design rainfall events in the UK

BRE Digest 365 *Soakaway design* (1991) provides guidance on the assessment of the levels of rainfall likely to occur in the UK.

Drainage systems are normally designed on the basis of a specific return period. In many cases a return period of five years is used as a basis for design. At a particular location, for a specified return period, the rainfall depth varies throughout the country and so attention must be paid to the location of the permeable pavement.

The Institute of Hydrology has carried out an extensive analysis of rainfall statistics and has provided a method to determine the relationship between depth, duration and return period (Institute of Hydrology, 1975). The notation **MT–D min** is used to identify a storm. For example, an M5–10 min is the depth of rainfall of a five year return period storm event of 10 minutes duration.

It is conventionally assumed that the depth of rainfall occurring during a 60 minutes storm recurring every five years is 20mm throughout the UK. The depth of rainfall occurring every five years over storm durations other than 60 minutes is obtained as follows. The design rainfall depth for any given return period and storm duration can be found by multiplying 20mm by a factor Z1. Factor Z1 is read from Table 2 which requires a knowledge of "r", the ratio of 60–minute to 2–day rainfalls for a five years return period. Values of r are given in Table 3.

The procedure to calculate rainfall depth for a storm shorter or longer than 60 minutes is:

From Table 3 determine the rainfall ratio r for the location of the permeable pavement.

Use r in Table 2 to determine Z1 for the calculation of the five year return period rainfall total, M5–D min, for different storm durations, D.

Use the following formula to determine the depth of rainfall occurring for rainfall duration D:

M5–Dmin rainfall = M5–60min rainfall x Z1.

City	r–value
Cambridge	0.45
London	0.45
Norwich	0.42
Birmingham	0.39
Bristol	0.39
Liverpool	0.39
Nottingham	0.39
Sheffield	0.39
Southampton	0.39
Belfast	0.33
Cardiff	0.33
Leeds	0.33
Manchester	0.33
Newcastle	0.33
Plymouth	0.33
Edinborough	0.27
Aberdeen	0.24
Glasgow	0.24

Table 3. Ratio of 60 minute to 2–day rainfalls of 5–year return period; r–values for some UK cities.

Assessment of ground conditions

The specification of a permeable pavement structure depends upon the hydraulic and traffic loading characteristics and upon the properties of the subgrade, the ground directly beneath a pavement. Strength and permeability of the subgrade are interrelated – a wet subgrade is usually a weak subgrade.

For most UK soils, the maximum exfiltration available is 3.7x10–3 mm/sec (37litre/second/hectare). This figure should be compared with UK rainfall requirement of 180litre/second/hectare. This indicates that most UK pavements will be required to have a water detention capability.

Specification and structural design

The aggregate roadbase should have a porosity of at least 0.3 to allow void space for water storage. The structural strength of the material should be adequate for the loads to which it will be subjected. The aggregate roadbase should be in accordance with either:

BS882:1992. "Specification for aggregates from natural sources for concrete". British Standards Institute, London.

The roadbase should comprise coarse graded crushed rock meeting the following requirements. The flakiness index, shell content and mechanical properties should be as set out in BS882 for coarse graded crushed rock. The 10% fines value should be 100kN or more. When tested in accordance with 7.2.1 of BS812: Section 103.1:1985, the amount of material passing the 75 micron sieve should not exceed one percent. In the case of blastfurnace slag, the material must be proven to be equal to or superior to the above in all respects.

Providing the above criteria are met, the roadbase material will have a porosity of at least 0.3 and a storage capacity in its voids (volume of voids/volume of roadbase) typically of 30%–35%. A 30% void space means that the volume of the roadbase will need to be 3.33 times the volume of the water stored. The infiltration rate through 20mm graded crushed rock roadbase is over 70,000 litre/hectare/sec and this should be compared with the normally required value of 180 litre/hectare/sec.

To avoid the loss of laying course material into the roadbase, a laying course material which will not invade the surface of the roadbase should be used. The NUROLF trials indicated that Cloburn 6mm washed crushed micro–granite performed satisfactorily in this respect (available from Cloburn Quarry Company Ltd, Lanark, Scotland, ML11 8SR). The Cloburn material has the following properties which should be regarded as minimum acceptable values for alternative materials:

10% Fines Value	370kN (150kN or greater recommended)
Aggregate Crushing Value	14%
Aggregate Impact Value	10 (15 blows)
Plasticity	Non–plastic

A 4mm washed natural gravel performed less well and should not be used in permeable paving. It can be presumed that material having similar geological and mechanical characteristics, particularly grading, will perform similarly. The 6mm Cloburn material (or similar) should be used for the jointing material. The NUROLF trials indicated that such material can be

Fig 5. Deformation of the test pavement in the wheel track following trafficking by 6000kg axles.

introduced into the joints using conventional paver installation technology.

Design thickness of roadbase for storm water storage

The depth of rainfall occurring during a 60 minutes storm recurring every five years in the UK is taken to be 20mm. Table 2 gives values of Z1 which is the ratio of the depth of rainfall occurring in a given period divided by the depth of rainfall occurring in 60 minutes. It is recommended that permeable pavements be designed to store rainfall occurring during 24hrs, unless it can be proven that sufficient exfiltration can occur to ensure that the maximum storage required can be reduced to that required to store rainfall occurring in six hours. The six hour thicknesses should be used only when the subgrade has a Coefficient of Permeability (k) exceeding 10–6 m/sec ie when the subgrade comprises sand or gravel and it is intended that the water entering the roadbase can exfiltrate into the subgrade. In some pavements, there may be sufficient surface or sub-surface drainage provided to allow the six hour figures to be used.

Ratio 24 hours rainfall to 60 minutes rainfall (r)	Roadbase thickness to accommodate six hour rainfall (mm)	Roadbase thickness to accommodate 24 hr rainfall (mm)
0.12	275	600
0.15	250	500
0.18	225	425
0.21	225	350
0.24	200	325
0.27	200	300
0.30	175	275
0.33	175	250
0.36	175	250
0.39	175	225
0.42	150	200
0.45	150	200

Table 4. Thickness of permeable pavement roadbase required to ensure sufficient storage capacity. Thickness ensures upper 40% of roadbase remains unsaturated. Note that the thicknesses shown may need to be enhanced to ensure adequate structural performance. See Table 7.

Table 4 shows thicknesses of crushed rock roadbase required to store either six hours or 24hr rainfall levels. Table 4 is derived using the figures from Table 2 and by assuming that 32% of the roadbase comprises void. Also, it is assumed that only the lower 60% of the voids in the roadbase should be saturated and that the upper 40% should comprise air. Note that

Load Category	Maximum Axle Load Anticipated (kg)
Category 1 – Domestic (GVW = 2000kg)	1000
Category 2 – Light (GVW = 3500kg)	2000
Category 3 – Commercial (GVW = 7500kg)	5000
Category 4 – Heavy (GVW = 44,000kg)	11,000

Table 5. Classification of vehicles.

the thickness of roadbase required depends upon the factor r, the ratio of a 60 minute storm rainfall depth to the 2-day maximum rainfall depth and this varies throughout the UK as shown in Table 3.

Structural design philosophy

The deliberate cascading of water through highway construction materials requires a radical approach to the selection of material thickness and properties. An alternative approach is required for the assessment of loading and material properties need to be selected taking into account the flow of water vertically downwards and the retention of water within the material.

Conventionally, a pavement fails by becoming progressively unserviceable – by developing ruts progressively for example. A permeable pavement, on the other hand needs to be designed to ensure that it is stable. An underdesigned permeable pavement could fail catastrophically when a load was applied. This is because the materials used in the structure have less stability than those used in a conventional pavement. For this reason, the ultimate limit state design approach is adopted. In this approach, firstly loads are predicted and are multiplied by a load safety factor which reflects the degree of accuracy of the prediction. Secondly, material strength is measured and is divided by a material safety factor which reflects the level of consistency which can be expected for that material.

Pavement Design Method

Firstly, levels of traffic loading need to be assessed so that the pavement can be

Factored Load (kg)	Course Thickness (mm): Cement stabilised open graded crushed rock	Course Thickness (mm): Open graded crushed rock
1,400	–	150
1,600	–	150
2,000	–	175
2,800	–	200
3,200	–	250
4,000	–	300
6,000	–	350
8,000	150	150
10,000	200	150
12,100	300	150

Table 7. Pavement course roadbase design thicknesses. Note these need to be adjusted for ground conditions and for Material Partial Safety Factor. See Tables 8 and 9.

Fig 6. Deformation of the test pavement in the wheel track following trafficking by 10,000kg axles.

placed into one of four load categories as shown in Table 5.

Now take the load appropriate to the load category and multiply it by the Load Partial Safety Factor from Table 6.

Level of Certainty of Load	Load Partial Safety Factor
Certain	1.0
Well informed value	1.2*
Anecdotal information	1.5*

Table 6. Load Partial Safety Factors. (* For Category 4 vehicles, maximum Load Partial Safety Factor = 1.1)

Now proportion the pavement section from Table 7.

If the subgrade CBR is greater than five percent, the above roadbase material can be installed directly above the subgrade. In poorer ground conditions, a conventional DTp Type 1 granular sub-base should be installed between the subgrade and the roadbase. In most design situations, an impermeable membrane should be provided between the roadbase and the sub-base. The thickness of the sub-base is shown in Table 8. When sub-base thickness exceeds 150mm, the additional thickness can be provided by capping material whose CBR should be 15% or more.

Subgrade CBR (%)	Thickness of DTp Type 1 sub-base material (mm)
>5	0
5	150
4	250
3	350
2	600
1	Subgrade improvement required

Table 8. DTp Type 1 sub-base thickness required. Note: when sub-base thickness exceeds 150mm, the additional thickness may be provided by capping material.

Finally, apply the Material Partial Safety Factor as follows. The stability of the open graded crushed rock material should be assessed according to Table 9 and the thickness of this course should be multiplied by the appropriate factor from Table 9.

Nature of open graded crushed rock	Material Partial Safety Factor
As stable as DTp Clause 803 material("Type 1")	0.9
As stable as graded20mm crushed rock to BS882	1.0
As stable as rounded 20mm graded gravel to BS882	1.3

Table 9. Open graded crushed rock thickness adjustment for Material Partial Safety Factor.

PERMEABLE PAVEMENTS FOR HEAVILY TRAFFICKED ROADS – A FULL SCALE TRIAL

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SUMMARY

The paper describes a full scale trial in which four test items each of width 4m and length 6m were trafficked by Heavy Goods Vehicles (HGVs) in order to assess the performance of different pavement sections. Each of the four test items comprised tanked permeable pavements in which water was detained within the pavements. The purpose was to compare the performance under traffic of permeable pavements with the following types of base:

Type 1: Unreinforced 20mm/6mm Coarse Graded Aggregate
Type 2: 20mm/6mm Coarse Graded Aggregate stabilised with 3% cement
Type 3: Dense Bitumen Macadam with 5% 50 Penetration bitumen
Type 4: Coarse Graded Aggregate reinforced with two layers of geogrid

The reason for selecting those four base types is that they are each used commonly in the UK. In particular, Types 1, 2 and 3 are included in the UK Interpave document *Guide to the design, construction and maintenance of concrete block permeable pavements Edition 5*[2] and also in the permeable pavements British Standard BS7533: Part 12: 2009[3]. Both the Interpave Guide[2] and the British Standard[3] define six Load Categories of traffic. Load Categories 1 and 2 cover lightly trafficked pavements and recommend Type 1 bases. Load Categories 3 to 6 comprise pavements subjected to increasing levels of heavy traffic, right up to 1000 HGVs per week in the case of Load Category 6 and recommend Type 2 or Type 3 bases. Type 4 bases are frequently specified in the UK as an alternative to the Interpave guidelines for all traffic Categories.

The purposes of the full scale trial were as follows:

a/ To check whether the range of Load Categories for which unbound Coarse Graded Aggregate can be used can be extended beyond Load Category 2
b/ To compare the performance of the four base types.
c/ To assess the accuracy of the Interpave/British Standard Guidelines.
d/ To examine whether more cost effective pavements can be installed

PRESENT UK STRUCTURAL DESIGN GUIDANCE

Current UK permeable pavement design guidance is set out in BS7533: Part 13: 2009[3] which was published in March 2009. The guidance was based upon Interpave's previously published data[2] which is shown in Figures 1 to 5. BS7533 includes a few presentational changes but arrives at the same design sections. Both documents are based upon full scale experiments undertaken at Newcastle University in 1999-2000[1]. Those experiments focused upon Coarse Graded Aggregate bases. Since then there has been a massive increase in the use of permeable paving in the UK which has been driven by Sustainable Drainage (SuDS) legislation and by a general awareness of the need to ensure that all development is carried out in an environmentally sensitive manner. As a result of this, permeable pavements are being specified in increasingly heavily trafficked situations so there is a move towards cement stabilisation, bitumen stabilisation and geogrid reinforced Coarse Graded Aggregates.

Figure 1 illustrates the six loading classifications and includes examples of each. The designer has the choice between using a number of large goods vehicles per week or a cumulative number of standard axles. Figure 2 shows resulting design sections for infiltration pavements and Figure 3 shows resulting design sections for tanked (detention) pavements. Those design sections comply with BS7533: Part 13: 2009[3].

Figures 2 and 3 apply in the case of pavements to be installed over subgrades of California Bearing Ratio (CBR) 5% and greater. For pavements to be installed over weaker soils, Figure 4 shows the adjustments to be made to the thickness of the Coarse Graded Aggregate (in the case of infiltrating pavements) or the Capping Material (in the case of tanked/detention pavements).

Figures 2 and 3 show that for Load Categories 1 and 2, the pavement base comprises Coarse Graded Aggregate but for Load Categories 3, 4, 5 and 6, a course of hydraulically bound (i.e. cement bound) Coarse Graded Aggregate is required to stiffen the pavement. This means that for pavements trafficked by one or more large goods vehicles per week, the hydraulically bound course is required by BS7533: Part 12: 2009. The sections shown in Figures 2 and 3 were originally derived from the full-scale research described in Reference 3.

BS7533: Part 13: 2009 provides an alternative design in which a course of Dense Bitumen Macadam (DBM) is included, either as a replacement for the hydraulically bound Coarse Graded Aggregate (for Load Categories 3, 4, 5 and 6) or as an additional course in the case of Load Categories 1 and 2. The reason for the DBM alternative is that contractors often prefer to traffic the permeable pavement during the construction phase. The inclusion of a DMB course protects the Coarse Graded Aggregate (CGA) below from contamination in this circumstance and is therefore commonly installed in, for example, housing developments. When DBM is installed for this reason, it would seem wrong to ignore its undoubted structural contribution to the pavement. Therefore, BS7533: Part 13: 2009 includes Figure 5 which shows the DBM thickness required for different trafficking levels. Of course, DBM is insufficiently permeable to allow its use in a permeable pavement, indeed it is often used in circumstances where its waterproofing properties are advantageous. Therefore, BS7533: Part 13: 2009 requires that 75mm diameter holes are punched through the DBM on a 750mm grid to allow the continued flow of water downwards through the pavement. (The holes are filled with 6mm grit to prevent the loss of laying course material.)

A significant issue which frequently occurs in the design of permeable pavements is where the cut-off point should be for the inclusion of hydraulically bound CGA. This is a particularly relevant matter because experience indicates that many permeable pavements fall into Load Category 3 (one large goods vehicle per week). Presently, such pavements require the inclusion of a hydraulically bound course. One of the objectives of this full scale trial was to establish whether Load Category 3 pavements can dispense with the hydraulically bound course.

Therefore, BS7533: Part13: 2009 includes CGA, hydraulically bound CGA and DBM as the three possible base materials for permeable pavements. A fourth type of base used commonly in the UK is CGA reinforced with geogrid materials. This option was omitted from the Interpave and BS documents but is an alternative which interests those involved in UK permeable pavements. Therefore, geogrid reinforced CGA was added as the fourth Test Item in the full scale trial.

1 DOMESTIC PARKING	2 CAR	3 PEDESTRIAN	4 SHOPPING	5 COMMERCIAL	6 HEAVY TRAFFIC
No Large Goods Vehicles	Emergency Large Goods Vehicles only	One Large Goods Vehicle per week	Ten large Goods Vehicles per week	100 Large Goods Vehicles per week	1000 large Goods Vehicles per week
Zero standard axles	**100 standard axles**	**0.015msa**	**0.15msa**	**1.5msa**	**15msa**
Patio	Car parking bays and aisles	Town/city pedestrian street	Retail development delivery access route	Industrial premises	Main road
Private drive	Railway station platform	Nursery access	School/ college access road	Lightly trafficked public road	Distribution centre
Decorative feature	External car showroom	Parking area to residential development	Office block delivery route	Light industrial development	Bus station (bus every 5 minutes)
Enclosed playground	Sports stadium pedestrian route	Garden centre external display area	Deliveries to small residential development	Mixed retail/ industrial development	Motorway Truck Stop
Footway with zero vehicle overrun	Footway with occasional overrun	Cemetery Crematorium	Garden centre delivery route	Town square	Bus stop
	Private drive/ footway crossover	Motel parking	Fire station yard	Footway with regular overrun	Roundabout
		Airport car park with no bus pickup	Airport car park with bus to terminal	Airport landside roads	Bus lane
		Sports centre	Sports stadium access route/ forecourt		

msa = millions of standard 8,000 kg axles.

Figure 1. UK classification of permeable pavements by loading

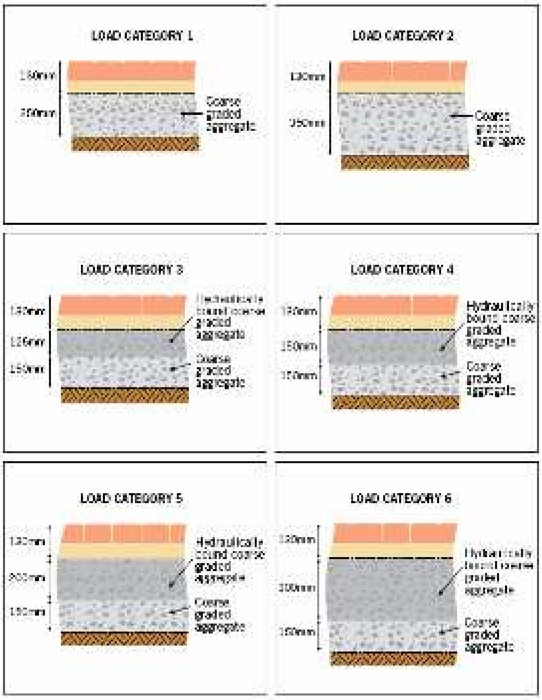


Figure 2. UK recommended sections for infiltrating pavements in which the water infiltrates into the subgrade.

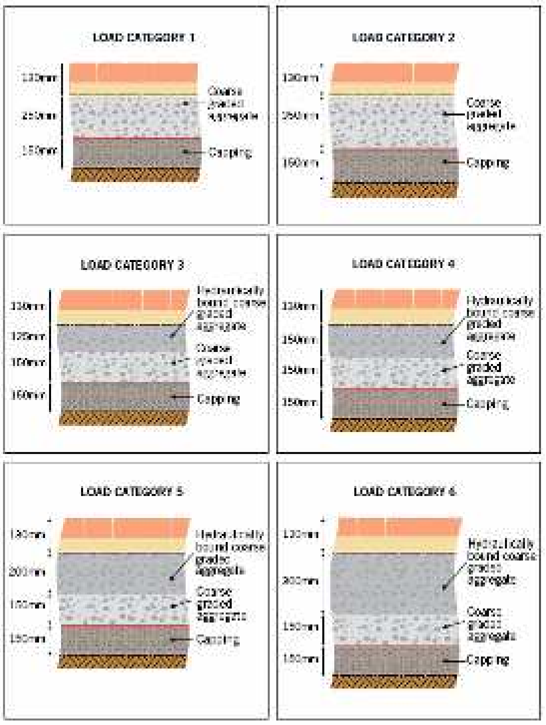


Figure 3. UK recommended pavement sections for tanked pavements according to traffic levels. The waterproof membrane is installed directly above the Capping layer.

CBR of subgrade	Adjustment to thickness of coarse graded aggregate in the case of System A and System B (infiltrating) pavements (mm)†	Total thickness of capping material in the case of System C (detention) pavements (mm)
1%	+300*^	600*
2%	+175^	350
3%	+125^	250
4%	+100^	200
5%	Use thicknesses in Design Chart	150
8%		
10%		
15%		

* Expert guidance should be sought in the case of pavements constructed over subgrades of CBR less than 2%. ^ Subgrades of CBR less than 5% are often too fine to permit sufficient infiltration.

† Note that the additional coarse graded aggregate values in this column can be applied, in the case of System C pavements, instead of the enhanced capping thickness shown in the middle column.

Figure 4. Adjustments to Coarse Graded Aggregate or Capping Material thickness for pavements designed on soils of CBR less than 5%

Total Traffic (Site plus in-service) (Cumulative Standard Axles (msa)	Thickness of Dense Bitumen Macadam (mm)
Up to 1.5	130
1.5 to 4.0	145
4.0 to 8.0	170
8.0 to 12.0	185

Figure 5. Thickness of Dense Bitumen Macadam when such material is used as a roadbase.

DETAILS OF FULL SCALE TEST SITE

The whole 24m x 4m test site was excavated to a depth of 730mm below the existing surface level. The 24m long trial comprised four pavement Test Items, each of length 6m. It was tanked by installing 2000 gauge polythene over the sub-base material and bringing it to the surface at the sides and ends. To simulate the most adverse conditions, water was introduced into the pavement. Figures 7 to 12 illustrate the installation of the full scale trial pavement.

Before commencing installation, three California Bearing Ratio (CBR) tests were carried out in each of the four sections (12 tests in all). Soaked CBR values (96hr soaking) varied between 4% and 7%, with several values congregated around 5% which was therefore taken to be the effective value.

The test site was installed during January 2009 to allow trafficking to take place during February and March 2009.
The area was trafficked by an eight wheel rigid truck shuttling backwards and forwards over each Test Item at a speed of approximately 10 mph (16kph), see Figure 14. The truck was loaded beyond its normal limit to achieve the following axle loads:

Axle 1 (first steering axle) 7,200kg
Axle 2 (second steering axle) 8,000kg
Axle 3 (1st rear axle) 13,580kg
Axle 4 (rearmost axle) 11,100kg

Taking a damaging power factor of 3.75 (often referred to as the Fourth Power Law), the above values suggest that each pass of the truck applies 12 standard axles. This does not take into account wheel load interaction, dynamic load magnification effects or load redistribution between axles by truck suspension. Therefore, it may represent a conservative estimate such that the true effective trafficking levels may exceed the stated values. Whilst the above axle loads are greater than those commonly encountered on a highway, they are nonetheless within the anticipated range of loads applied from time to time by overloaded large goods vehicles.

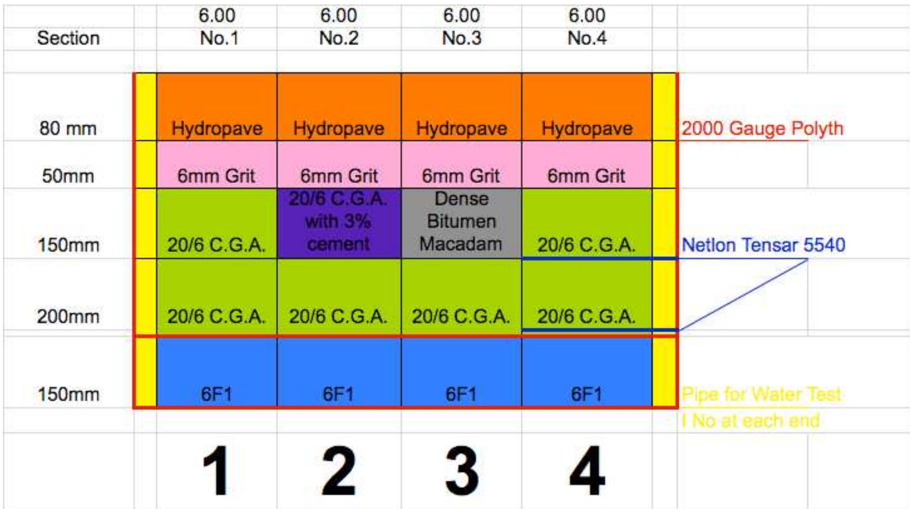


Figure 6. Course thicknesses for Test Items 1 to 4. Note that "6F1" refers to a category of Capping Material as defined in UK Highways Authority's "Specification for Highway Works". The term 20/6 C.G.A. refers to Coarse Graded Aggregate with particles within the range 20mm to 6mm. "Hydropave" is the proprietary name of the permeable pavers used to surface each Test Item.

Figure 7. The test area has been excavated to reveal alluvium clay with a California Bearing Ratio of 5%.

Figure 8. 150mm thickness of compacted Capping Material was installed throughout the test zone prior to installing polythene tanking.

Figure 9. 2000 gauge polythene was installed to achieve tanked conditions for each Test Item.

Figure 10. Test Item 4 required the installation of two layers of a geogrid material known as Tensar SS40. The lower layer is shown here directly over the polythene membrane.
The second layer was installed between two courses of Coarse Graded Aggregate.

Figure 11. Prior to the laying of pavers, a 50mm thick course of 6mm single sized grit was installed in each Test Item.

Figure 12. Permeable pavers were installed to a 45° herringbone pattern.

Figure 13. Values of permanent deformation were measured at locations as marked on the board. Each measurement point occupied a similar position in relation to the paver laying pattern. Measurements were taken by inserting the calibrated wedge between the pavement surface and the straight edge. An initial set of readings was taken prior to trafficking and all reported readings are obtained by first subtracting the initial data set.

Figure 14. Trafficking was by means of an overloaded eight wheel truck which shuttled back and forth at a constant speed of approximately 10mph (16kph).

Figure 15. Typical rut in Test Item 1 after several thousand standard axles.

RESULTS

Figures 13, 14 and 15 illustrate the application of the test load and the recording of permanent deformation resulting from that loading. The loading took place during February 2009 and March 2009. Deformation readings were taken pre-loading then at the following number of standard axles:
120, 360, 600, 1200, 1800, 2400, 3000, 3600, 4200, 4800, 6000

For each Test Item, permanent deformations were recorded at the first quarter point, the centre and the second quarter point.

For each of Sections A, B and C a chart was produced for each of the four Test Items (12 charts in all), each showing 11 rut profiles, one for each of the above 11 levels of trafficking. The numbers shown on the horizontal axis of each chart correspond with the numbers marked on the straight edge shown in Figure 13 – the difference between each measurement point reflects the paving module and is 290mm for the paver and laying pattern adopted.

For each of the Test Items, the maximum rut depth can be read from the corresponding chart on the following four pages. Note that in the case of Test Items 1 and 4, i.e. those including unbound CGA, the initial 600 standard axles produce significantly greater levels of deformation than do subsequent trafficking. This suggests that a degree of conditioning is taking place, possibly reflecting additional compaction being achieved by the test vehicle. The Test Items were all installed to normal UK compaction standards. Therefore, these enhanced deformations should be regarded as representing a realistic expectation of deformations which can be anticipated in construction contracts where large goods vehicles traffic the pavement in a channelized manner.

Taking the above into account, the maximum rut developed in each of the test sites at 6,000 cumulative standard axles of trafficking is:
Test Item 1: 37mm
Test Item 2: 10mm
Test Item 3: 6mm
Test Item 4: 32mm

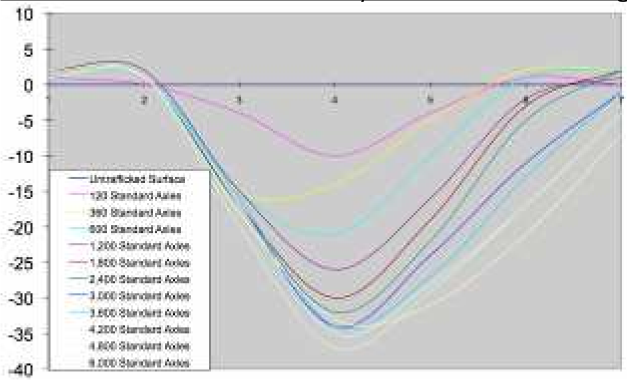
The increase in rutting between 3,000 and 6,000 cumulative standard axles can be used as a means of extrapolating the results from the 6,000 standard axles achieved to say 25,000 standard axles. This is considered to be a reasonable level of extrapolation for the following reasons. Firstly, the level of channelization applied in this test is such that some design approaches would consider that three times 6,000 standard axles had been applied, e.g. the British Ports Association Heavy Duty Pavement Design Manual[4]. Secondly, no account was taken of wheel proximity or dynamics in the test, both of which could be expressed in terms of an enhanced level of standard axles. Thirdly, in each chart, the incremental rut growth after 3,000 cumulative standard axles was consistent.

Based upon the above, the extrapolated rutting at 25,000 cumulative standard axles is:
Test Item 1: 73mm
Test Item 2: 22mm
Test Item 3: 18mm
Test Item 4: 66mm

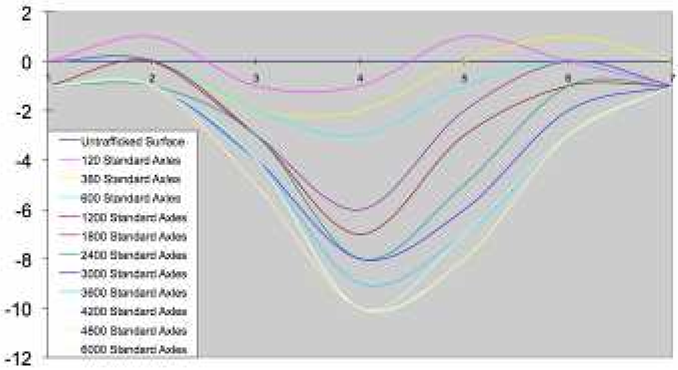
Over a 20 years design life, a Load Category 3 pavement would need to withstand 1,000 Large Goods Vehicles which would apply say 2.5 standard axles each, i.e. say 2,500 cumulative standard axles. The corresponding rut depths would be:
Test Item 1: 30mm
Test Item 2: 7mm
Test Item 3: 5mm
Test Item 4: 27mm

The failure criterion for a flexible pavement is often taken to be 40mm rutting. On this basis, it would be reasonable to conclude that Test Items 1 and 4 and are suitable for Load Category 3 pavements but not for Load Category 4 pavements. Likewise, Test Items 2 and 3 are confirmed as being suitable for Load Category 4 pavements. This also suggests that the design sections shown in Figures 2 and 3 are all correct since for greater levels of trafficking, thicker courses are recommended in line with the normal relationships between course thickness and levels of trafficking for hydraulically stabilized materials. Furthermore, the trial also confirms that the UK recommendations for the use of Dense Bitumen Macadam as set out in Figure 5 are also correct by similar reasoning.

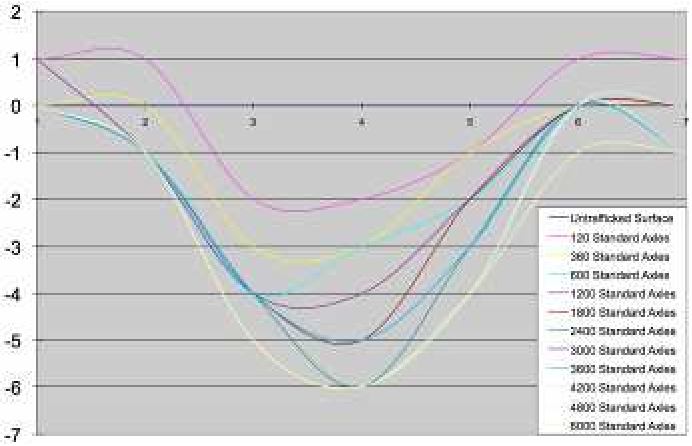
Test Item 1: Unreinforced 20mm/6mm Coarse Graded Aggregate at centre of Test Item



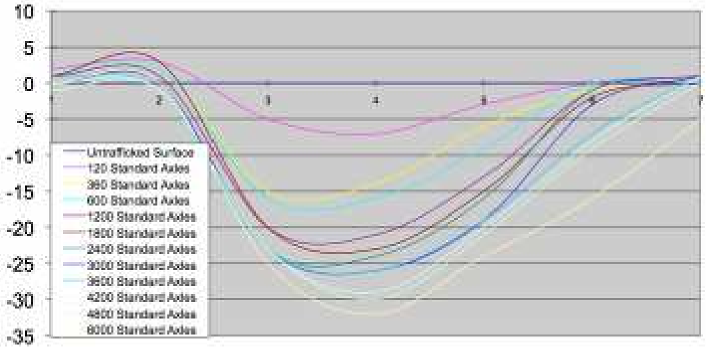
Test Item 2: 20mm/6mm Coarse Graded Aggregate stabilised with 3% cementat centre of Test Item



Test Item 3: Dense Bitumen Macadam with 5% 50 Penetration bitumenat centre of Test Item



Test Item 4: Coarse Graded Aggregate reinforced with two layers of geogridat centre of Test Item



CONCLUSIONS

The following conclusions can be drawn from the full scale testing.

1/ Each of the four materials commonly used in the UK as the main structural course in a permeable pavement have been subjected to full scale trafficking in a controlled test and have been found to develop rutting when subjected to traffic of different amounts according to the following list which is ordered from least rutting to most rutting:

Dense Bitumen Macadam
Hydraulically bound Coarse Graded Aggregate
Geogrid Reinforced Coarse Graded Aggregate
Coarse Graded Aggregate

2/ Whereas UK recommendations require that Load Category 3 pavements (i.e. pavements trafficked by one large goods vehicle per week) should include a cement or bitumen bound base, this has been shown to be a conservative requirement and providing all of the materials are correctly specified and installed as set out in Refs 2 & 3, the cement or bitumen bound course can be omitted for Load Category 3 pavements and instead the thickness of Coarse Graded Aggregate can be increased to 350mm.

3/ The present UK recommendations are safe but for Load Category 3 pavements, cost and time savings may be possible by adopting Conclusion 2.

4/ There is a distinct difference in performance between, on the one hand cement and bitumen stabilized structural layers and on the other hand Coarse Graded Aggregate, whether reinforced or not. Typically, for a given level of trafficking, ruts in the unbound structural courses are between three and four times those which occur in pavements which include a bound structural course.

5/ Even when trafficked by overloaded fully channelized highway vehicles, permeable pavements perform well in that there is no indication that they fail structurally under such load, but rather they progressively deform and develop ruts in line with conventional flexible pavements.

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2 Guide to the design, construction and maintenance of concrete block permeable pavements. Edition 5. Interpave, The Precast Concrete Paving and Kerb Association, Leicester, UK. Uniclass L534:L217, 2008.

3 BS 7533-13:2009 “Pavements constructed with clay, natural stone or concrete pavers> Part 13: Guide for the design of permeable pavements constructed with concrete paving blocks and flags, natural stone slabs and setts and clay pavers”. BSI, London, March 2009.

4 Knapton J (2007). “The Structural Design of Heavy Duty Pavements for Ports and Other Industries. Edition 4” Interpave, The Precast Concrete Paving and Kerb Association, Leicester, UK. Uniclass L534.

BS 7533-13:2009

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Table 6 Loading categories

Category/ application	No. of standard axles	Traffic guide	Application
A/domestic	0	No large HGV	• Patio • Private drives • Decorative features • Enclosed playgrounds • Footways with zero overrun
B/car parking	100	Emergency vehicles only	• Car parking bays and aisles • Railway station platforms • External car showrooms • Sports stadium pedestrian routes • Footways with occasion overrun • Private drives • Footway crossover
C/pedestrian	0.015 msa	1 large HGV/ week	• Town/city pedestrian street • Nursery access • Parking areas to residential development • Motel parking • Garden centre external displays • Cemetery/crematorium • Airport car park (no bus pick-up) • Sports centre
D/shopping	0.15 msa	10 large HGV/ week	• Retail development delivery access route • School/college access route • Office block delivery route • Garden Centre delivery route • Deliveries to small residential development • Fire station yard • Airport car park with bus to terminal • Sports stadium access route/forecourt
E/commercial	1.5 msa	100 large HGV/ week	• Industrial premises • Lightly trafficked public roads • Light industrial development • Mixed retail/industrial development • Town square • Footway with regular overrun • Airport landside
F/heavy traffic	15 msa	1000 large HGV/week	• Main road • Distribution centre • Bus station (bus every 5 minutes) • Roundabout • Bus lane

5.6.2 Selection of pavement course material and thickness

For System A and B select the pavement course thickness and material type from Table 7.

NOTE Table 7 is suitable for subgrades with CBR ≥ 15%.

For System C select the pavement course thickness and material type from Table 8.

NOTE 1 Table 8 is suitable for subgrades with CBR ≥ 15%.

The impermeable membrane is installed at the interface of the coarse graded aggregate and the sub-base. The impermeable membrane is brought to just below the surface of the pavement at its perimeter to maximize the detention volume of the pavement.

Table 7 **System A and B – selection of pavement course material and thickness**

Category/application	Block/laying course mm	Hydraulically bound base mm	Course graded material mm
A/domestic	80/50	—	250
B/car parking	80/50	—	350
C/pedestrian	80/50	125	150
D/shopping	80/50	150	150
E/commercial	80/50	200	150
F/heavy traffic	80/50	300	150

Table 8 **System C – selection of pavement course material and thickness**

Category/application	Block/laying course mm	Hydraulically bound base mm	Course graded material mm	Capping layer mm
A/domestic	80/50	—	250	150
B/car parking	80/50	—	350	150
C/pedestrian	80/50	125	150	150
D/shopping	80/50	150	150	150
E/commercial	80/50	200	150	150
F/heavy traffic	80/50	300	150	150

NOTE Originally 80 mm blocks were used for all types of concrete permeable pavements, but thinner concrete blocks are now available, suitable for specific loadings It is recommended that advice is sought from the manufacturer on recommendation for suitable block thickness.

5.6.3 Adjustment to pavement design for low CBR subgrade

The additional thickness to be provided in the case of low CBR can be taken from Table 9 for System A and System B and Table 10 for System C.

Table 9 Additional thickness of coarse graded material for System A and System B

CBR of subgrade %	Adjustment of coarse graded material mm
1	300 A) B)
2	175 B)
3	125 B)
4	100 B)
5	Use Table 10 for thickness
8	Use Table 10 for thickness
10	Use Table 10 for thickness
15	Use Table 10 for thickness

A) Expert guidance should be sought.

B) Subgrades of CBR less than 55 are often too fine to permit sufficient infiltration.

Table 10 Total thickness of capping material for System C

CBR of subgrade %	Adjustment of capping layer mm
1	600 A)
2	350
3	250
4	200
5	Use Table 8 for thickness
8	Use Table 8 for thickness
10	Use Table 8 for thickness
15	Use Table 8 for thickness

A) Expert guidance should be sought.

5.6.4 Base thickness for site traffic

A permeable pavement can be protected from site traffic by installing a dense bitumen macadam (DBM) over the unbound coarse graded aggregate with holes punched through this layer with 75 mm holes on an orthogonal grid of 750 mm.

NOTE 1 This layer remains in situ throughout the service life of the pavement.

NOTE 2 For load categories C, D, E and F (see Table 6) the DBM replaces the hydraulically bound aggregate course.

NOTE 3 For load categories A and B (see Table 6) the DBM is additional to the unbound coarse graded aggregate.

The thickness of the DBM depends on the number of standard axles which will be applied by site traffic and in-service traffic.

The number of standard axles that will use the base as a service road is shown in Table 11 (taken from BS 7533-1:2001, Figure 2).

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Table 11 Determination of standard axles using the base as a service road

Site traffic	No. of standard axles
20 dwellings	200
50 dwellings or 5 000 m^2	500
80 dwellings or 8 000 m^2	1 000
Large development	5 000

The thickness of the DBM required is taken from BS 7533-1:2001, Figure 3 and is reproduced in Table 12.

Table 12 Determination of DBM thickness for total number of standard axles

Total traffic	DBM thickness mm
Up to 1.5 msa	130
1.5 to 4.0 msa	145
4.0 to 8.0 msa	170
8.0 to 12.0 msa	185