



heavy duty pavements



THE STRUCTURAL DESIGN OF
HEAVY DUTY PAVEMENTS FOR
PORTS AND OTHER INDUSTRIES

EDITION 4



Interpave

THE PRECAST CONCRETE PAVING
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THE STRUCTURAL DESIGN OF HEAVY DUTY PAVEMENTS FOR PORTS AND OTHER INDUSTRIES

EDITION 4

by John Knapton

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ABOUT THE AUTHOR

John Knapton is a Fellow of the Institution of Civil Engineers and first became involved in the design of heavy duty pavements in the 1970s. He is author of all four editions of these Manuals. His career has been divided between academia and consulting. He held the Chair of Structural Engineering at Newcastle University until 2001 when he left to undertake consulting on a full time basis. He is Chairman of the Small Element Pavement Technologists group which perpetuates a series of International Conferences on block paving, having initiated the first such conference at Newcastle University in 1980. He has published over 100 papers in the field of trafficked pavements and has written three books on ground bearing concrete. He has worldwide experience in the design of port and heavy duty pavements and is presently working on design projects and dispute resolution on many categories of pavements worldwide.

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1. INTRODUCTION

This Manual was commissioned and published by Interpave. The aim of the port pavement design process is to safeguard the pavement from failure over a predetermined period of time or number of cargo movements. There are four categories of failure associated with port pavements, viz:

- **environmental failure**
- **structural failure**
- **surface failure**
- **operational failure.**

Each of these categories may influence failure in one of the other three, so a complete port pavement design must address all of the issues which might lead on a particular project to one or more of these categories of failure. For example, a full port pavement design might comprise the following elements:

- **Sustainable Drainage System (SUDS) design**
- **structural design**
- **surface drainage design**
- **surface operational characteristics**

- provision of underground services
- traffic and storage management markings, signs and structures
- interface with other facilities and structures
- selection of appropriate construction techniques
- working environmental issues
- aesthetics.

This Manual is concerned specifically with the structural design of pavements serving ports and other industries. It includes guidance on pavements designed to accord with SUDS requirements. Designers are advised to take into account all of the above issues plus others which are not listed but which might be of relevance to a specific project. Ignoring one or more component of the whole design process can lead to progressive reduction in pavement serviceability and performance so that ultimately one or more of the four categories of failure will occur.

Three sets of design calculations are included in this Manual.

Design Example 1: Reach Stacker Handling Containers

Design Example 2: Eight Wheel Straddle Carrier Handling Containers

Design Example 3: Distribution Warehouse with Dock Levellers

Also, five Overlay Design examples are included within the Overlay Design section of this Manual.

2. EXECUTIVE SUMMARY

This Fourth Edition of the Manual is an update of the Third Edition published in 1996 and includes for the first time information on permeable paving for SUDS, the adoption of recently published British and European Standards and the inclusion of a large range of diagrams showing patterns of stress throughout heavy duty pavements. It also includes guidance on overlay design which was omitted from the Third Edition, although having been included in the first two Editions. Revisions have also been made to pavement foundation recommendations.

The original research upon which the First Edition was based was undertaken in the 1970s when pavements were analysed by programmable calculator technology. This meant that stresses and strains could be calculated accurately at only one or two special points in the proposed pavement structure. The Third Edition used Finite Element analysis for the first time and this Fourth Edition uses a more detailed Finite Element model.

This Fourth Edition continues the theme of evaluating the Single Equivalent Wheel Load (SEWL) by considering the way in which the pavement is trafficked. Likewise, it continues the principle of separating design into its three essentials, i.e. selection of the surface, proportioning the base and providing a suitable foundation. In making this separation, no accuracy is lost and the design process is greatly simplified such that only one Design Chart is required. That Design Chart may be used to proportion the base course of a heavy duty pavement.

This Fourth Edition has been developed to be easy to use, accurate, comprehensive in the range of materials available and clearly presented with the aid of detailed worked examples.

During the last 25 years, a good deal of experience has been gained in the use of Material Conversion Factors (MCFs) or Material Equivalence Factors (MEFs) so that, within reason, they can now be used as a means of effectively swapping one material for another during the design process and also in the design of an overlay to an existing pavement. This means that when a design has been produced using the Design Chart, the designer can generate many alternative design solutions using different materials and so investigate a full range of solutions.

The Manual has a 30-year pedigree and is regarded as the benchmark by which other heavy duty pavement design methods are evaluated. As far as the Author is aware, its correct use has led to 100% successful pavements.

3. SCOPE OF THE MANUAL

The Manual can be used to design pavements subjected to either highway loading or greater, up to the maximum loads encountered on port and other heavy duty pavements.

3.1 DESIGN OF CONVENTIONALLY DRAINED TRAFFICKED AREAS

Although the Manual can be used for a wide range of combinations of materials, the following have been commonly used and proved successful:

Concrete Block Paving (CBP) on cement bound base

The pavement comprises the following components:

80mm thickness concrete paving blocks

30mm thickness laying course material

Cement bound base

Crushed rock or cement bound sub-base

Capping if subgrade California Bearing Ratio (CBR) is less than 5%

In situ concrete pavement

The pavement comprises the following components:

Plain or reinforced in situ concrete slab

Crushed rock or cement bound sub-base

Capping if subgrade California Bearing Ratio (CBR) is less than 5%

3.2 DESIGN OF PERMEABLE PAVEMENTS FOR TRAFFICKED AREAS

There are three principal systems suitable for permeable pavements using concrete block paving as the wearing surface described here as Systems A, B and C.

SYSTEM A – TOTAL INFILTRATION

This system allows all water falling onto the pavement to infiltrate down through the joints or voids between the concrete blocks, passing through the constructed layers below and eventually into the subgrade. Some retention of the water will occur temporarily in the sub-base layer allowing for initial storage before it eventually passes through. System A is sometimes known as Zero Discharge as no additional water from the new pavement is discharged into conventional drainage systems.

The pavement comprises the following components:

80mm thickness permeable concrete block paving

30mm thickness laying course material

Cement bound no-fines concrete base

Layer of woven geotextile

SYSTEM B – PARTIAL INFILTRATION

This system allows some water to infiltrate through the pavement, as with System A, but a series of perforated pipes or fin-drains is also introduced at the formation level to allow the remaining water to be drained to other systems such as sewers, swales or watercourses. System B can be used in situations where the existing subgrade may not be capable of absorbing all of the water. This system can, therefore, prevent the existing soil from losing its stability.

SYSTEM C – NO INFILTRATION

This system allows for the complete capture of the water using an impermeable, flexible membrane placed on top of the formation level and up the sides of the pavement courses to effectively form a drainage tank. It is used in situations where the existing subgrade has a low permeability or low strength and would therefore be damaged by the introduction of additional water. It can also be used for water harvesting or to protect sensitive existing conditions such as water extraction zones. A series of perforated pipes or fin-drains is placed on top of the impermeable membrane to transmit the water to sewers, watercourses or treatment systems. The pavement comprises the following components:

80mm thickness permeable concrete block paving

30mm thickness laying course material

Cement bound no-fines concrete base

Layer of 2000 gauge polythene waterproof layer lapped to the surface at the perimeter

Crushed rock or cement stabilised sub-base

Capping if subgrade California Bearing Ratio (CBR) is less than 5%

For all three types of permeable paving, the no-fines concrete base would normally be selected to have a 28 days characteristic cube compressive strength of 10N/mm² and can therefore be considered to be structurally equivalent to C_{8/10} Cement Bound Granular Mixture (CBGM), i.e. the standard material used for design in this Manual. A suitable aggregate Particle Size Distribution for no fines concrete is shown below.

Sieve size (mm)	Percent by mass passing
40	100
20	90 - 99
10	25 - 75
4	0 - 15
1	0

Laying course material for permeable pavements should meet the Particle Size Distribution limits shown in the table below.

Sieve size (mm)	Percent by mass passing
14	100
10	98 - 100
6.3	80 - 99
2	0 - 20
1	0.5

3.3 DESIGN PRINCIPLES

The design procedure set out in this Fourth Edition is based upon the principle that pavements are designed to remain serviceable throughout the design life of the pavement. In terms of structural performance, serviceability failure in a heavy duty pavement usually occurs by either excessive vertical compressive strain in the subgrade or by excessive horizontal strain in the base. For pavements with bound bases the tensile strain in the base is the active design constraint whereas subgrade compressive strain is the active design constraint for pavements with granular bases. Surface deformation in the order of 50mm to 75mm will normally exist at failure.

4. ANALYSIS TECHNIQUE

4.1 FINITE ELEMENT METHOD

In order to produce the Design Charts, pavements have been analysed using the Finite Element method in which a model was developed to represent all components of a pavement. Elastic properties and Poisson's Ratio values were chosen to describe the behaviour of each pavement component. Fatigue is taken into account by defining limiting stresses to which the pavement can be exposed for one load pass and then by reducing those stresses to account for the fatigue effect of multiple load repetitions.

4.2 PAVEMENT SURFACE, STRUCTURE AND FOUNDATION

Design involves dividing the pavement into foundation, structure and surface so that the structure (base) thickness can be proportioned to withstand the applied load regime and the foundation can be proportioned to develop adequate support to the base and surface taking into account ground conditions. Highway pavement design procedures include pavement foundation guidance which relates sub-base and capping specification to subgrade strength such that the subgrade is always stressed to a level commensurate with its strength. This technique is replicated here in the Fourth Edition but the thickness of the capping layer has been increased as compared with thicknesses in the three previous Editions to deal with the heavier loads applied on heavy duty pavements. Essentially, historically recent developments in pavement design procedures have separated design into foundation design which is based upon subgrade strength, base design which is based upon loading regime and surfacing design which is based upon operational needs (although in some design methods, the structural benefit of the surfacing material is taken into account, especially in the case of bitumen bound pavements where the surfacing materials have structural properties not dissimilar from those of base materials).

5. CALIBRATION OF THE DESIGN METHOD

5.1 NEED FOR CALIBRATION (JUSTIFICATION OF THE METHOD)

All design procedures based upon mechanistic analysis, including Finite Element analysis, require proven criteria for levels of stress or strain which cannot be exceeded. Usually, these criteria are stresses or strains known to exist in successful designs produced by empirical design methods. By this means, the mechanistic model is effectively calibrated and designs produced by it have the same level of integrity as those produced by the design method used in the calibration exercise. Because the stress regime existing in pavements is so complex, design cannot be based upon evaluating strengths of materials from simple tensile or flexural tests because to do so would fail to account for the complex interactions of stress within a pavement. Any given material does not have a unique tensile, flexural or compressive stress. Those values are dependent on the shape and size of the objects into which the materials are formed and upon stresses existing in other planes. The fact that a cube or a cylinder exhibits a certain strength does not mean that exactly the same material installed in a pavement will have the same strength (even in the case of identically compacted material). The difference between pure tensile strength and flexural strength, which is used in design, is illustrated in TRL Report TRL 615 *'Development of a more versatile approach to flexible and flexible composite pavement design'* (M Nunn, 2004). Table E3 (Appendix E of TRL615) shows that a given class of cement bound material (CBM3), of tensile strength 0.99N/mm^2 has a flexural strength of 1.65N/mm^2 .

5.2 BASIS OF CALIBRATION

In this Manual the limiting stresses upon which the Design Chart is based are determined as follows. A proven semi-empirical pavement design method has been used to assess the levels of stress at critical positions in the following manner. BS 7533-1:2001 *'Pavements constructed with clay, natural stone or concrete pavers. Part 1: Guide for the structural design of heavy duty pavements constructed of clay pavers or precast concrete paving blocks'* has been used to produce design examples covering pavements trafficked by up to 12 Million Standard Axles (MSA). These pavements have then been analysed using the same Finite Element model as is used in this Manual to establish permissible stresses in heavy duty pavements.

The stresses shown in Table 1, which the Finite Element model has demonstrated to exist in pavements designed according to BS 7533-1:2001, are used in this Manual as the critical design

stresses in heavy duty pavement design. In other words, this Manual's Design Chart has been produced using the same Finite Element model which has been used to back-analyse a range of pavements produced by BS 7533-1:2001. This means that the experience and methodology underpinning BS7533-1:2001 has been extended in this Manual to deal with all those pavements likely to be encountered in heavy duty pavement design situations.

Pavements designed according to BS 7533-1:2001 were analysed using the Finite Element model to determine stresses and strains at critical locations in each pavement. The pavement sections developed from BS7533-1:2001 are shown in Table 1.

Table 1 shows the design thicknesses taken from Figure 3 of BS7533-1:2001 and the resulting tensile stresses for different pavement design lives. The final column in Table 1 shows Design Stresses which include a Material Safety Factor of 1.5 in line with other design standards for concrete. These Design Stresses are used in the development of the Design Chart for heavy duty pavements (even in the case of materials other than concrete where the factor of 1.5 is still used). The BS7533-1:2001 pavements in Table 1 were analysed using the same Finite Element model as is used to analyse the heavy duty pavements but this time for a wheel load of only 70kN. This load is typical of the higher Single Equivalent Wheel Loads (SEWLs) which a highway pavement will sustain, taking account of vehicle dynamics and proximity factors.

Table 1: BS7533 pavement course thicknesses used in Finite Element analysis.

* The figure in Figure 3 of BS7533-1:2001 is 130mm based upon construction matters but structurally, 105mm is the correct figure.

Millions of Standard Axles	Base Thicknesses (mm)	Stress in Finite Element Model (N/mm ²)	Design Stress (N/mm ²)
0.25 to 1.5	105*	1.766	1.178
1.5 to 4	145	1.404	0.936
4 to 8	195	1.046	0.697
8 to 12	245	0.791	0.527

Having used the Finite Element model to calculate the stresses shown in Table 1 which exist in pavements designed according to BS7533-1:2001, the output from the heavy duty pavement Finite Element model was used to draw the heavy duty pavement Design Chart. The Design Chart has been produced by establishing base thicknesses which provide similar levels of stress to those shown in Table 1 but for heavier loads supported by thicker bases. Stress contour diagrams and deflected shapes are shown for 56 combinations of Single Equivalent Wheel Load (SEWL) and base thickness as set out in Tables 2 to 8. The results of these 56 analyses are summarised in Tables 2 to 8.

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

Load (kN)	Tensile Stress (N/mm ²)	Deflexion (mm)
750	1.262	0.406
700	1.192	0.383
650	1.117	0.358
600	1.041	0.333
550	0.962	0.308
500	0.886	0.285
450	0.804	0.260
400	0.720	0.236
350		
300		
250		
200		
150		
100		
50		

Table 2. Summary of Finite Element analysis of 700mm thick base pavement.

Load (kN)	Tensile Stress (N/mm ²)	Deflexion (mm)
750	1.452	0.474
700	1.370	0.446
650	1.286	0.418
600	1.199	0.389
550	1.110	0.360
500	1.020	0.332
450	0.925	0.302
400	0.830	0.272
350	0.739	0.244
300		
250		
200		
150		
100		
50		

Table 3. Summary of Finite Element analysis of 650mm thick base pavement.

Load (kN)	Tensile Stress (N/mm ²)	Deflexion (mm)
750	1.686	0.552
700	1.592	0.519
650	1.496	0.486
600	1.396	0.452
550	1.292	0.418
500	1.189	0.384
450	1.081	0.350
400	0.971	0.314
350	0.865	0.282
300	0.751	0.246
250		
200		
150		
100		
50		

Table 4. Summary of Finite Element analysis of 600mm thick base pavement.

Load (kN)	Tensile Stress (N/mm ²)	Deflexion (mm)
750	2.320	0.802
700	2.193	0.753
650	2.062	0.704
600	1.927	0.654
550	1.784	0.623
500	1.647	0.554
450	1.496	0.500
400	1.346	0.450
350	1.200	0.415
300	1.043	0.350
250	0.882	0.297
200	0.715	0.243
150		
100		
50		

Table 5. Summary of Finite Element analysis of 500mm thick base pavement.

Load (kN)	Tensile Stress (N/mm ²)	Deflexion (mm)
750		
700		
650		
600		
550		
500	2.398	0.813
450	2.184	0.735
400	1.970	0.659
350	1.757	0.585
300	1.530	0.507
250	1.296	0.428
200	1.053	0.347
150	0.804	0.267
100		
50		

Table 6. Summary of Finite Element analysis of 400mm thick base pavement.

Load (kN)	Tensile Stress (N/mm ²)	Deflexion (mm)
750		
700		
650		
600		
550		
500		
450		
400		
350	3.023	0.806
300	2.420	0.761
250	2.051	0.639
200	1.678	0.518
150	1.286	0.394
100	0.882	0.267
50		

Table 7. Summary of Finite Element analysis of 300mm thick base pavement.

Load (kN)	Tensile Stress (N/mm ²)	Deflexion (mm)
750		
700		
650		
600		
550		
500		
450		
400		
350		
300		
250		
200	3.023	0.806
150	2.330	0.612
100	1.605	0.415
50	0.835	0.211

Table 8. Summary of Finite Element analysis of 200mm thick base pavement.

6. DETAILS OF THE FINITE ELEMENT MODEL

6.1 AXI-SYMMETRIC FINITE ELEMENTS

The Finite Element model used in developing the Design Chart and in the calibration exercise comprises an axi-symmetric idealisation in which a cylindrical layered system of diameter 12m and depth 6m was modelled by 480 three dimensional axi-symmetric Finite Elements. The following diagrams illustrate how three axi-symmetric Finite Elements are combined to form a pavement course.

In the Finite Element method, each of the two doughnut shapes and the central plug comprise an axi-symmetric Finite Element and the lowest shape is an entire pavement course built from the three Finite Elements. The pie diagram shows the model used. The commercial software used to develop the model is the Sigma/w module of GeoStudio which is available from Geo-Slope International (www.geo-slope.com).

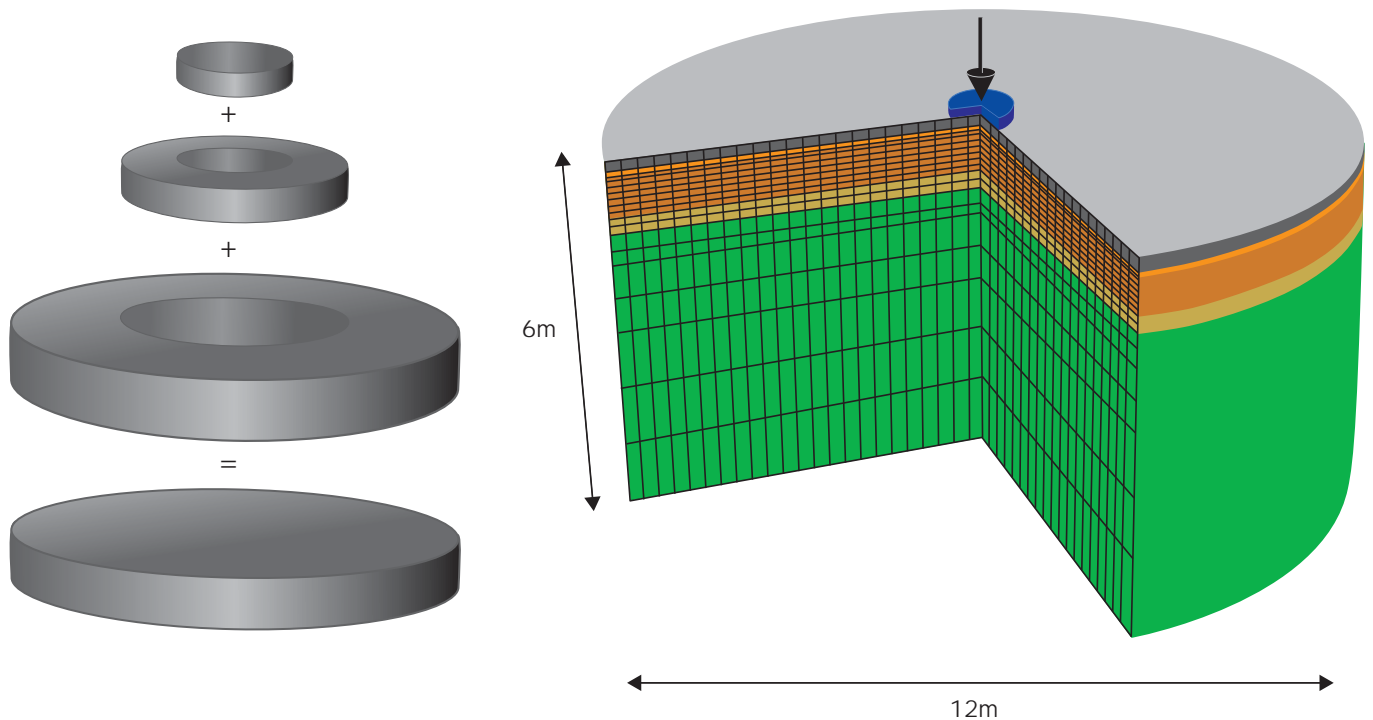


Figure 1.

6.2 SIZE OF FINITE ELEMENT MODEL

As shown in the heavy duty pavement model, Figure 1 comprises 24 concentric Finite Elements forming each 12m diameter pavement layer. The surface (concrete block paving plus laying course material) comprises one layer of 24 axi-symmetric Finite Elements. The base comprises eight layers of 24 axi-symmetric Finite Elements, the sub-base comprises two layers of 24 axi-symmetric Finite Elements and the ground is modelled by seven layers of 24 axi-symmetric Finite Elements down to a depth of 6m (for pavements including a capping layer, the upper layer of ground Finite Elements models the capping). Although not used in the development of the Design Chart, the model allows the simulation of ground strata of different engineering properties. For example, it can model the influence of a layer of peat embedded within alluvial deposits.

6.3 DETAILS OF FINITE ELEMENT MODEL

Each model perimeter node is restrained horizontally and each node at the lowest level is restrained both horizontally and vertically. A patch load is applied at the top centre of the model by applying pressure to the innermost two Finite Elements and adjusting the geometry to ensure that the external radius of the second ring of Finite Elements matches that of the tyre contact patch or assumed container corner casting contact zone. The load patch radius was determined by assuming the load to be applied as a pressure of $1.0\text{ON}/\text{mm}^2$ in the case of pneumatic tyred equipment.

6.4 STRUCTURAL CONTRIBUTION OF CONCRETE BLOCK PAVING SURFACING

The development of the Manual has shown that large variations in surface stiffness have little effect on the performance of the pavement. To illustrate this a series of Finite Element analyses has been carried out using the four values of surface stiffness shown in Table 9.

Each of the four surface stiffnesses was used in a Finite Element model of a pavement designed to withstand a patch load of 300kN over subgrade with a CBR of 3%. Table 9 shows that a change in surface stiffness from $1000\text{N}/\text{mm}^2$ to $8000\text{N}/\text{mm}^2$ leads to a change of only 4% in maximum tensile stress within the pavement base. Most authorities consider that concrete block paving has a stiffness of between $1000\text{N}/\text{mm}^2$ and $5000\text{N}/\text{mm}^2$ which would lead to a variation in stress values in the base of less than 2%. This suggests that any enhancement in structural performance which might be engineered into different types of paving block is of little or no consequence in heavy duty paving. Essentially, paving blocks should be selected on the basis that the surface remains stable under the loading regime.

Conventional 200mm x 100mm plan dimension by 80mm thickness rectangular concrete block paving have been found to meet this criterion. Many non-rectangular concrete block paving also achieve this level of stability.

Note that the above reasoning does not mean that the contribution of the paving blocks to structural performance is small. The main structural benefit of paving blocks is in raising the load through the height of the blocks and their laying course material (110mm). If the blocks and their laying course material are omitted from the Finite Element model, stresses in the base increase significantly. What this analysis shows is that providing the blocks are installed and remain stable, there is no benefit in considering different types of blocks. Additional thickness of blocks, say to 100mm or 120mm, will help but is usually not required and has cost disadvantages.

Stiffness of Surface (N/mm ²)	Maximum tensile stress in Base (N/mm ²)
1000	1.18
2000	1.16
4000	1.15
8000	1.13

Table 9. Effect of change in surface stiffness on tensile stress in base.

7. PAVING MATERIALS

7.1 STANDARD SURFACING AND BASE MATERIALS

With the general introduction of Front Lift Trucks and Reach Stackers capable of placing a fifth heavy container over four stacked containers, concrete block paving has become the normal heavy duty pavement surfacing material. Hydraulically Bound Mixtures (HBM), i.e. Cement Bound Granular Mixtures (CBGM), Slag Bound Mixtures (SBM) and Fly Ash Bound Mixtures (FABM) have been found to be cost effective and low maintenance base materials, although bitumen bound materials are sometimes included. Therefore, in the design method presented in this Manual, HBM supporting concrete block paving is the assumed pavement build-up. This Manual does allow the user to consider other materials but would recommend that they should be specified only when there is a specific need to deviate from what has, over the last 30 years, developed as orthodoxy.

7.2 STRUCTURAL PROPERTIES OF HYDRAULICALLY BOUND MIXTURES

Tables 10 and 11 set out equivalencies and the structural properties of HBM materials. In this Manual, the design process comprises selecting a pavement using the category of CBGM referred to as $C_{8/10}$ (see below) then substituting alternative materials on a Material Equivalence Factor (MEF) basis. Note that in the UK, the term Cement Bound Material (CBM) has been used for many years to refer to cement bound roadbases but this terminology was changed in 2004 with the introduction of BS EN 14337:2004 '*Hydraulically bound mixtures*'.

$C_{8/10}$ is equivalent to CBM3 which was the standard material used in the Third Edition of the Manual which was published in 1996. Adopting one standard base material in the analysis and substituting other materials on a MEF basis greatly simplifies the design process and at the same time facilitates an immediate comparison of alternative design solutions. It is a methodology with which many heavy duty pavement designers are now familiar. It is the Author's experience that this approach is quicker and more rigorous than the alternative approach of using multi-layer elastic analysis software.

7.3 STANDARD $C_{8/10}$ CEMENT BOUND GRANULAR MIXTURE

This Manual's Design Chart allows designs to be developed for pavements including a base comprising Cement Bound Granular Mixture (CBGM) in accordance with BS EN 14227-1:2004 '*Hydraulically bound mixtures – Specifications – Part 1: Cement bound granular mixtures*'. BS EN 14227 includes two classification systems for CBGM. System I classifies CBGM by its

characteristic compressive strength as shown in Table 11 and System II classifies CGBM by its tensile strength and modulus of elasticity at 28 days. Only System I is used in this Manual. Table 10 strengths are related by tensile strength and compression:

$$\text{Mean Axial Tensile Strength} = 0.3 (\text{Characteristic Cylinder Compressive Strength})^{2/3}$$

(Taking the H/D = 2 cylinder dimensional ratio)

(See Table 9.1 of Concrete Society Technical Report No. 34 Third Edition '*Concrete industrial ground floors – A guide to design and construction*'. The Concrete Society 2003.)

7.4 DEFINITIONS OF OTHER MATERIALS COMMONLY USED OR ENCOUNTERED IN HEAVY DUTY PAVEMENTS

- 1 **Concrete Block Paving** – concrete blocks of modular plan dimensions 200mm x 100mm and of thickness 80mm installed into a 30mm thickness bed of compacted sand. Concrete block paving should be manufactured according to BS EN 1338:2003 '*Concrete paving blocks – Requirements and test methods*' and installed according to BS7533. Part 3. (2005) '*Pavements constructed with clay, natural stone or concrete pavers. Part 3: Code of practice for laying precast concrete paving blocks and clay pavers for flexible pavements.*'
- 2 **Heavy Duty Macadam (HDM)** – a mixture of stones and fine material bound with bitumen. The material's strength is derived principally from the Particle Size Distribution, particle shape and origin of the stones and fine material as well as the engineering properties of the bitumen. The term "Macadam" means a combination of coarse and fine stones which are mixed and pressed together to create a mixture which is stronger than the sum of its parts.
- 3 **Dense Bitumen Macadam (DBM)** – similar to Heavy Duty Macadam but with less stringent requirements.
- 4 **Hot Rolled Asphalt (HRA)** – a mixture of mainly fine material with a little larger sized stone bound with bitumen. The material's strength is derived principally from the properties of the bitumen binder. Asphalt is a mixture of either tar or bitumen and fine material in which the particles need not be in intimate contact with each other. Asphalt occurs naturally,

famously in Lake Trinidad but also elsewhere. Hot Rolled Asphalt has been used as the principal surfacing material for UK roads for many years.

Note: See Table 10 which lists the new standards for hydraulically bound materials that are equivalent to the old CBM categories.

- 5 **C_{8/10} Lean Concrete** – a mixture of coarse and fine stones, cement and water, similar to common concrete but with approximately 40% as much cement and water as normal concrete. It has a “characteristic” compressive cube strength of 10N/mm². “Characteristic” strength is a technical term and is the strength below which only one in 20 test samples is allowed to fall. This means the average compressive strength needs to exceed 10N/mm². The actual average compressive strength depends upon the variability of the material. CBM3 or C_{8/10} lean concrete was the Standard material in the Third Edition and has now been replaced with C_{8/10} Cement Bound Granular Mixture (CBGM).
- 6 **Cement Bound Material Class 3 (CBM3)** – similar to C10 Lean Concrete but with an average compressive cube strength of 10N/mm² and a minimum compressive cube strength of 6.5N/mm². CBM3 is important because it was commonly used in UK road design. It was formerly known as “lean concrete”.
- 7 **Cement Bound Material Class 4 (CBM4)** – was similar to CBM3 but with an average compressive strength of 15N/mm² and a minimum compressive strength of 10N/mm².
- 8 **C_{8/10} No-fines lean concrete** – material suitable for use as the base in permeable heavy duty pavements. Comprises 20mm to 5mm Coarse Graded Aggregate stabilised with sufficient cement to achieve the properties of C_{8/10} CBGM.
- 9 **Crushed rock sub-base material** – either Type 1 or Type 2 sub-base material as defined in Clauses 803 and 804 respectively of Highways Agency's *'Specification for Highway Works'* available via: www.standardsforhighways.co.uk
- 10 **Capping** – low cost material of CBR 15% or more capable of being compacted to form a working platform and providing sufficient reaction to allow overlying materials to be compacted. Recycled concrete or selected hardcore are frequently used as capping.

Previous name	New name for BS EN14227 – Parts 1, 2 & 3 (all 2004) <i>'Hydraulically Bound Mixtures – Specifications'</i>
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/mm² and a characteristic compressive cube strength of 10N/mm².

7.5 MATERIAL EQUIVALENCE FACTORS

Table 11 shows the properties of CBGM as defined in BS EN 14227: Part 1: 2004 '*Hydraulically bound mixtures – Specifications. Part 1: Cement Bound Granular Mixtures.*' The tensile strength values in Table 11 are used in Material Equivalence Factor (MEF) analysis which allows materials to be exchanged during the design process. However, the tensile strength values shown in Table 11 can be exceeded within the pavement structure because the extreme condition of pure tension never develops within the pavement. Table 1 includes those values which back analysis shows to be present in pavements designed by a well established empirical design method and it is those values which have been used to construct the Design Chart.

The standard material used to construct the Design Chart in the Third Edition was C10 lean concrete i.e. material with a characteristic 28 days compressive cube strength of 10N/mm^2 or Cement Bound Material 3, i.e. material with an average seven days compressive cube strength of 10N/mm^2 (which is very close to a characteristic 28 days compressive cube strength of 10N/mm^2). This is because the multiplying factor normally used to relate 7 day strength to 28 day strength is 1.2. Therefore, a 7 days average strength of 10N/mm^2 would normally lead to a 28 days average strength of 12N/mm^2 . Given the normal distribution of individual cube strengths, an average strength of 12N/mm^2 would give a characteristic strength of approximately 10N/mm^2 .

C10 concrete was defined in BS 5328-1:1997 '*Concrete – Part 1: Guide to Specifying Concrete.*' The corresponding material in BS EN 14227-1:2004 is $C_{8/10}$, i.e. material with a 28 days characteristic compressive cube strength of 10N/mm^2 and this is now the standard design material used to construct the Design Chart. Note that TRL Report TRL615 '*Development of a more versatile approach to flexible and composite pavement design*' (M Nunn, 2004) recommends that CBM3 be equated with $C_{8/10}$ for design purposes (Table E2 Design classifications).

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**.

Characteristic 28 Day Compressive Strength (N/mm ²)		Strength Class	Mean Axial Tensile Strength (N/mm ²)
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	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

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

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.

Characteristic 28 Day Compressive Strength (N/mm ²)		Strength Class	Mean Axial Tensile Strength (N/mm ²)
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

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

All designs should be undertaken as if for C_{8/10} CBGM. If using alternative materials, Table 13 should then be used to alter the design thickness of the resulting C_{8/10} CBGM base on the basis of Material Equivalence Factors (MEFs).

The flexural strength of a pavement course is proportional to the square of its depth and is directly proportional to its tensile strength. The stiffness of a pavement course is proportional to the cube of its depth and is directly proportional to its tensile strength. In the case of HBMs, Material Equivalence Factors (MEFs) are based upon strength, whereas in the case of bitumen bound materials, MEFs are based upon stiffness.

Using the above reasoning, MEFs by which C_{8/10} CBGM base thickness needs to be multiplied to convert to other materials are shown in Table 13.

7.6 TABLE OF MATERIAL EQUIVALENCE FACTORS

Table 13 includes MEFs for HBMs and other materials, including several grades of concrete defined in BS8500: Part 1: 2006 '*Concrete – Complementary British Standard to BS EN 206-1. Part 1: Method of specifying and guidance for the specifier*' as well as Cement Bound Granular Materials and bitumen bound materials previously defined in UK Highways Agency's '*Specification for Highway Works*' (SHW) which forms part of Highways Agency's Design Manual for Roads and Bridges. SHW is available via:

www.standardsforhighways.co.uk/dmrb/index.htm

Experience in the use of MEFs by heavy duty pavement designers indicates that within a limited range, they can prove to be an efficient means of expanding one design solution into many alternatives, each of similar structural capability. Whenever a material substitution is made, the designer should ensure that the proposed material is suitable for the purpose, taking into account its proposed function and position within the pavement. For example, it would be wrong to introduce say, crushed rock in place of a bound material in a location where stresses could lead to instability of the material. Only those materials with a proven track record in the proposed location should be considered and materials should only be used in conventional combinations. The relationship between relative base thicknesses and allowable stresses is:

$$d_{\text{new}} = d_{\text{stand}} \times (\sigma_{\text{stand}} / \sigma_{\text{new}})^{1/2}$$

Where:

d_{new} = the revised base thickness for alternative material

d_{stand} = the design thickness specified $C_{8/10}$ CBGM

σ_{stand} = tensile strength of $C_{8/10}$ CBGM

σ_{new} = tensile strength of alternative material

For example, if the Design Chart shows the required $C_{8/10}$ CBGM thickness to be 450mm and it is proposed to install $C_{5/6}$, then the correct thickness is $450 \times 1.16 = 522\text{mm}$.

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

Table 13 continued.

Material Grouping	Preferred Pavement Base Construction Material	Material Equivalence Factor (MEF)
Traditional Cement Bound Materials	<i>CBM1</i> (4.5N/mm ² minimum 7-days compressive cube strength)	1.60
	<i>CBM2</i> (7.0N/mm ² minimum 7-days compressive cube strength)	1.20
	CBM3 (10.0N/mm ² minimum 7-days compressive cube strength)	1.00
	<i>CBM4</i> (15.0N/mm ² minimum 7-days compressive cube strength)	0.80
	<i>CBM5</i> (20.0N/mm ² 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
	<i>HRA as defined by SHW</i>	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

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).

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/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

(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).

7.7 STRUCTURAL PROPERTIES OF PAVEMENT COURSES

Typical properties of pavement courses are shown in Table 14. It is assumed that the surface comprises 80mm thick concrete paving blocks installed on 30mm thickness laying course material. Experience has shown that alternative pavement surfacing materials have little influence on overall pavement strength and alternative surfacing materials can be substituted with little influence on overall structural performance. In the Finite Element analysis, the surface has been modelled as a homogeneous 110mm thick layer of material having an elastic modulus of 4,000N/mm² and a Poisson's Ratio of 0.15. This has been found to equate closely with the properties of both concrete block paving and bituminous bound surfacing materials. The Elastic Modulus of C_{8/10} base has been assumed to be 40,000N/mm², which is a high value. By comparison, the UK Highways Agency recommends the following values for Cement Bound Materials.

Type of Material	Elastic Modulus (N/mm ²)	
	Gravel Aggregate	Crushed Rock Aggregate
Cement Bound Material 3	33,000	35,000
Cement Bound Material 4	39,000	40,000
Cement Bound Material 5	43,000	45,000

Table 14. Pavement material properties.

Taking a high Elastic Modulus value in the model is in fact a conservative assumption. Stiff elements within any structure attract load and, therefore, develop higher internal stresses than more flexible elements.

Dynamic elastic modulus is used in this Manual. Dynamic elastic modulus is the pure elastic response of the material which does not take creep (the tendency of stressed concrete to change shape so as to attenuate stress) into account and is similar to the initial tangent modulus determined in a static test. This means it is higher than the static modulus.

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

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

7.8 SELECTION OF CONCRETE BLOCK PAVING

In the case of concrete block paving, 80mm thickness rectangular units of plan dimension 200mm x 100mm laid to a herringbone pattern and including spacers and chamfers have been found to exhibit a high level of stability and strength. Other types of paving units and other laying patterns may also be satisfactory and users are advised to seek guidance from manufacturers when deviating from the proven rectangular units laid to a herringbone pattern. Note that to achieve enhanced stability, designers may wish to consider specifying the use of laying course material within the joints between the concrete block paving, rather than fine sand as used for highway pavements. This represents a departure from the requirements of BS7533-3:2005 '*Pavements constructed with clay, natural stone or concrete pavers: Part 3: Code of practice for laying precast concrete paving blocks and clay pavers for flexible pavements.*' This will help to avoid surface instability which has been experienced when container handling plant wheels are turned while the plant is stationary. This problem has been experienced when the wheels of Rubber Tyred Gantry Cranes (RTGs) are turned through 90° while the vehicle remains stationary, as shown in Figure 2. However, for normal free running vehicles, conventional fine jointing sand should suffice.

Category 2 laying course material, as defined in BS7533-3:2005, should be used for heavy duty pavements.

Figure 2. Some Rubber Tyred Gantry Cranes (RTGs) can turn their wheels through 90° whilst stationary. This can lead to surface instability.



In some situations, consideration should be given to a joint stabilisation material in order to ensure that the requisite surfacing properties are maintained. With bituminous bound surfacing care needs to be exercised in mix design to ensure surface stability, especially in extremes of climate and in container storage areas. Bitumen bound materials are unsuited to static loading and to equipment making tight turns where wheels may be dragged over the pavement surface. Bitumen penetration value and maximum stone size are important in this regard. Bitumen penetration should not exceed 50 and stone size should not exceed 10mm.

The pavement surface selection is considered to depend on its resistance to wear and other surfacing requirements rather than the contribution which it might make to overall pavement strength, consequently any suitable surface material may be used regardless of the ground conditions.

8. PAVEMENT LOADING

8.1 SINGLE EQUIVALENT WHEEL LOAD (SEWL)

The loading regime to be used is rationalised to a Single Equivalent Wheel Load (SEWL) describing the actual loads. When the design process is started there is usually no unique load value which characterises the operational situation. Consequently it is necessary to gather information known about the loading environment in order to derive the SEWL to be used with the design procedure. Firstly information regarding the types of loads that can be expected is given with factors that should be considered. This is followed by a rational method of deriving the SEWL required for use with the Design Chart.

Figure 3. Front lift trucks handling heavy 40ft containers apply 100t or more through the front axle.

Figure 4. Four wheel straddle carriers apply wheel loads in excess of 20t.



8.2 LOADS APPLIED BY HIGHWAY VEHICLES

Many heavy duty pavements are loaded by highway vehicles or by less onerous plant and equipment. The maximum legal axle load on a UK highway is 11,500kg but surveys indicate that some vehicles are overloaded. It is recommended that in the absence of more accurate data, heavy duty pavements trafficked by highway vehicles or by lighter plant are assumed to be loaded by axles of weight 14,000kg. This takes into account wheel proximity and dynamics. It may be that a heavy duty pavement can be designed for relatively few such vehicles, say 5% of the total vehicles expected to traverse the busiest point in the pavement (because few such vehicles will apply full dynamics).



Figure 5. Highway trailers may have three axles, each applying 11t. The small steel plate may apply even greater load when the trailer is parked.

8.3 CRITICAL LOAD FOR HEAVY DUTY PAVEMENTS

Where loading exceeds highway levels, the usual reason is the handling of containers by off road plant such as Straddle Carriers or either Front Lift Trucks or Reach Stackers. In such cases, the value of the design wheel load depends upon the range of container weights or other materials being handled. Design should be based upon the Critical Load, which is defined as the load whose value and number of repetitions leads to the most pavement damage. Relatively few repetitions of a high load value may inflict less damage than a higher number of lesser load values. The entire load regime should be expressed as a number of passes of the critical load. The evaluation of the critical load and the effective number of repetitions of that load is as follows.

8.4 DISTRIBUTION OF CONTAINER WEIGHTS

Table 16 shows the distribution of container weights normally encountered in UK ports for different proportions of 20ft and 40ft containers. Where local data is available, it can be used in place of Table 16. For each of the container weights shown in Table 16, calculate the damaging effect caused when plant is handling containers of that weight from the following equation:

$$D = (W/12000)^{3.75} (P/0.8)^{1.25} \times N$$

Where:

D = Damaging effect

W = Wheel load corresponding with specific container weight (kg)

P = Tyre Pressure (N/mm²)

N = % figure from Table 16



Figure 6. Straddle carriers are preferred to front lift trucks when significant travel distances are involved and where two or three high stacking occurs.

8.5 CRITICAL CONTAINER WEIGHTS

The container weight leading to the greatest value of D is the critical weight container and all subsequent wheel load calculations should be based upon this load. Experience indicates that when the containers being handled comprise 100% of 40ft containers, the critical load is commonly 22,000kg and when 20ft containers are being handled, the critical load is 20,000kg. In general, mixes of 40ft and 20ft containers have a critical container load of 21,000kg. These values may be used in preliminary design studies. The number of repetitions to be used in design can be calculated accurately using a load value weighted system. However, if the total number of repetitions calculated solely from operational data is used, a negligible error will be generated. In the case of pavements trafficked by highway vehicles, an equivalent wheel load of 70kN may be used.

40ft containers weigh approximately 3,700kg when empty and 30,250kg when loaded to their legal maximum.

Container Weight (kg)	Proportion of 40ft to 20ft Containers				
	100/0	60/40	50/50	40/60	0/100
0	0.00	0.00	0.00	0.00	0.00
1000	0.00	0.00	0.00	0.00	0.00
2000	0.00	0.18	0.23	0.28	0.46
3000	0.00	0.60	0.74	0.89	1.49
4000	0.18	1.29	1.57	1.84	2.95
5000	0.53	1.90	2.25	2.59	3.96
6000	0.98	2.17	2.46	2.76	3.94
7000	1.37	2.41	2.67	2.93	3.97
8000	2.60	3.05	3.16	3.27	3.72
9000	2.82	3.05	3.11	3.17	3.41
10,000	3.30	3.44	3.48	3.52	3.66
11,000	4.43	4.28	4.24	4.20	4.04
12,000	5.73	5.24	5.12	4.99	4.50
13,000	5.12	4.83	4.76	4.69	4.41
14,000	5.85	5.38	5.26	5.14	4.67
15,000	4.78	5.12	5.21	5.29	5.63
16,000	5.22	5.58	5.67	5.76	6.13
17,000	5.45	5.75	5.83	5.91	6.21
18,000	5.55	5.91	6.00	6.10	6.46
19,000	6.08	6.68	6.83	6.98	7.58
20,000	7.67	8.28	8.43	8.58	9.19
21,000	10.40	8.93	8.56	8.18	6.72
22,000	9.95	7.60	7.02	6.43	4.08
23,000	5.53	4.31	4.00	3.69	2.47
24,000	2.75	1.75	1.50	1.25	0.24
25,000	0.95	0.63	0.55	0.47	0.15
26,000	0.67	0.40	0.33	0.27	0.00
27,000	0.72	0.43	0.36	0.29	0.00
28,000	0.53	0.32	0.27	0.21	0.00
29,000	0.43	0.26	0.22	0.17	0.00
30,000	0.28	0.17	0.14	0.11	0.00
31,000	0.03	0.02	0.02	0.01	0.00
32,000	0.03	0.02	0.02	0.01	0.00
33,000	0.00	0.00	0.00	0.00	0.00
34,000	0.05	0.03	0.02	0.02	0.00

Table 16. Percentages of containers of different weights for five different combinations of 40ft to 20ft containers derived from statistics provided by UK ports.

Note: that these figures were derived during the 1970s. There is no evidence to suggest that they are inaccurate but if a designer has information relating to a specific site which differs from the figures in this Table, then those site specific figures should be used.



Figure 7A. The ability of Reach Stackers to reach over containers makes them attractive to operators.

Special plant is available for the handling of empty containers up to eight high as shown below. Care needs to be taken that the container stack remains stable under wind loading. This is sometimes achieved by positioning lower stacks at the perimeter of the stack.



Figure 7B. Special plant is available for the storage of 8 high empty containers.

8.6 TYRES

The contact area of a tyre of handling plant is assumed to be circular with a contact pressure equal to that of the tyre pressure. Some larger items of plant may be fitted with tyres for operating over soft ground. When such tyres travel over concrete the contact area is not circular and the contact stress under the tread bars is greater than the tyre pressure. This has little effect in the case of in situ concrete but may have an effect on the stability of concrete block paving, HDM or DBM surfacing. Container handling equipment with pneumatic tyres is normally operated at a tyre pressure of approximately 1.0N/mm². Some terminal trailers are fitted with solid rubber tyres. Solid tyre contact stress depends upon the trailer load but a value of 1.7N/mm² is typical and the higher pressure is dispersed satisfactorily through the pavement so that the Design Chart can be used directly.

8.7 DYNAMICS

The effects of dynamic loading induced by cornering, accelerating, braking and surface unevenness are taken into account by the factor f_d . Where a section of a pavement is subjected to dynamic effects the wheel loads are adjusted by the factors given in Table 17. In some ports, high speed automated container handling is being introduced. It is recommended that the factors in Table 17 be increased by 50% for such operations, i.e. a value of 10% should be increased to 15% or a value of 60% increased to 90%.

Table 17: Table of dynamic load factors (f_d). Static loads are increased by the percentage figures in the Table.

*Note: that multi-wheel RTGs, i.e. RTGs with say 16 wheels arranged in four undercarriages of four wheels each as shown in Figure 18 perform well over a pavement but for other wheel arrangements, wheel loads may be so great as to require piled runway beams.

Condition	Plant Type	f_d
Braking	Reach Stacker/Front Lift Truck	±30%
	Straddle Carrier	±50%
	Side Lift Truck	±20%
	Tractor and Trailer	±10%
	Rubber Tyred Gantry Crane (RTG)*	±10%
Cornering	Reach Stacker/Front Lift Truck	40%
	Straddle Carrier	60%
	Side Lift Truck	30%
	Tractor and Trailer	30%
	Rubber Tyred Gantry Crane (RTG)*	zero
Acceleration	Reach Stacker/Front Lift Truck	10%
	Straddle Carrier	10%
	Side Lift Truck	10%
	Tractor and Trailer	10%
	Rubber Tyred Gantry Crane (RTG)*	±5%
Uneven Surface	Reach Stacker/Front Lift Truck	20%
	Straddle Carrier	20%
	Side Lift Truck	20%
	Tractor and Trailer	20%
	Rubber Tyred Gantry Crane (RTG)*	±10%

Where two or three of these conditions apply simultaneously, f_d should take into account multiple dynamic effects. For example, in the case of a Front Lift Truck cornering and accelerating over uneven ground, the dynamic factor is $40\%+10\%+20\%$ i.e. 70% so that the static wheel load is increased by 70%. In the case of braking, the dynamic factor is additive for the front wheels and subtractive for rear wheels. In the case of plant with near centrally located wheels (e.g. straddle carriers), braking and accelerating dynamic factors to be applied to the near central wheels are reduced according to geometry.

8.8 LANE CHANNELISATION

Plant movements over a wide pavement do not follow exactly the same course, but wander to one side or the other. If there are lane markings with the lane approximately the same width as the plant, then channelling becomes significant. As the lane width increases relative to the track width of the plant the channelisation becomes less significant with the less channelised travel causing an ironing out effect more evenly over the area.

For straddle carriers stacking containers in long rows and for trucks using dock levelers, the wheels are restricted to very narrow lanes and consequently severe rutting may take place. In such cases the operation techniques of the plant in that area should be reviewed periodically. In some extreme cases, it is recommended that the number of repetitions be enhanced by a factor of five in design.

Within the next few years, it is expected that automatically guided container handling plant will be introduced. This will result in higher speeds and therefore in more onerous dynamics and in fully channelised loading. Advice should be sought from the manufacturer of such plant, or alternatively use the recommendation in Section 8.7.



Figure 8. When operating within container stacks, a straddle carrier tracks the same length of the slab each pass.

8.9 CONTAINER CORNER CASTING LOADS

Static loads from corner casting feet apply very high stresses to the pavement. These stresses can be taken by the concrete or concrete block paving but some superficial damage may occur to the surface.

Containers are usually stacked in rows or blocks and until recently usually no more than three high, with a maximum of five high. However, in recent times containers have been stacked up to eight high in a few locations and this may become more common. Corner castings measure 178mm x 162mm and frequently they project 12.5mm below the underside of the container. Table 18 gives the maximum loads and stresses for most stacking arrangements. Since it is unlikely that all containers in a stack will be fully laden the maximum gross weights will be reduced by the amounts shown. The values shown in Table 18 can be used directly in the Design Chart. In the case of empty containers pavement loads can be calculated on the basis that 40ft containers weigh 3,800kg and 20ft containers weigh 2,500kg.

Stacking Height	Reduction in Gross Weight	Contact Stress (N/mm ²)	Load on Pavement (kN) for each stacking arrangement		
			Singly	Rows	Blocks
1	0	2.59	76.2	152.4	304.8
2	10%	4.67	137.2	274.3	548.6
3	20%	6.23	182.9	365.8	731.5
4	30%	7.27	213.4	426.7	853.4
5	40%	7.78	228.6	457.2	914.4
6	40%	9.33	274.3	548.6	1097
7	40%	10.9	320.0	640.0	1280
8	40%	12.5	365.8	731.6	1463

Table 18: Pavement loads from stacking full containers.

Figure 9. Failure of concrete slab in the vicinity of container corner castings. When the deformation exceeds 12mm, the containers rest on their underside and the slab load becomes small. This is unacceptable for the structural capacity of the containers.



8.10 TRAILER DOLLY WHEELS

There are often two pairs of small or 'dolly' wheels on trailers which are 88mm wide x 225mm in diameter as shown in Figure 10. When the trailer is parked, the contact area of each wheel is approximately 10 x 88mm and stresses are 40N/mm². Some trailers have pivot plates as shown in Figure 5 which measure 150mm x 225mm and produce contact stresses of 2.0N/mm², which is sufficiently low to cause no difficulties within the block paving surface.



Figure 10. These trailer jockey wheels have indented the bituminous material surfacing.

8.11 WHEEL PROXIMITY FACTORS

The active design constraint is horizontal tensile stress at the underside of the base. The only exception to this is in the case of un-dowelled, formed concrete slabs where horizontal tensile stress at the top of the slab becomes critical in the case of corner loading. Such pavements are uncommon in heavy duty pavement design. If one wheel only is considered, the maximum horizontal tensile stress occurs under the centre of the wheel and reduces with distance from the wheel. If two wheels are sufficiently close together, the stress under each wheel is increased by a certain amount owing to the proximity of the other wheel.

Wheel proximity is dealt with by the method described here and requires knowledge of the California Bearing Ratio (CBR) of the subgrade. Wheel loads are modified by the appropriate proximity factor from Table 19. The factors in Table 19 are obtained as

follows. If wheel proximity were not considered, the relevant stresses would be the maximum tensile stress (this is very nearly a radial stress) directly beneath the loaded wheel. If there is a second wheel nearby, it generates tangential tensile stress directly below the first wheel. This tangential stress is added to the radial stress contributed by the primary wheel. The proximity factor is the ratio of the sum of these stresses to the radial tensile stress resulting from the primary wheel. The following equations are used to calculate the stress:

$$\sigma_R = \frac{W}{2\pi} \left[\frac{3r^2z}{\alpha^{5/2}} - \frac{1-2\nu}{\alpha + z\alpha^{1/2}} \right]$$

$$\sigma_T = \frac{W}{2\pi} [1-2\nu] \left[\frac{z}{\alpha^{3/2}} - \frac{1}{\alpha + z\alpha^{1/2}} \right]$$

Where:

σ_R = radial stress

σ_T = tangential stress

W = load

r = horizontal distance between wheels

z = depth to position of stress calculations

ν = Poisson's ratio

$\alpha = r^2 + z^2$

When more than two wheels are in close proximity, the radial stress beneath the critical wheel may have to be increased to account for two or more tangential stress contributions. Table 19 shows that the proximity factor depends on the wheel spacing and the Effective Depth of the slab. The Effective Depth can be approximated from the following formula and represents the theoretical depth of the slab had it been constructed from subgrade material.

$$\text{Effective depth} = 300 \times \sqrt[3]{\frac{35,000}{\text{CBR} \times 10}}$$

Where: CBR = California Bearing Ratio of the subgrade.

As an example, consider a front lift truck with three wheels at

each end of the front axle. The critical location is beneath the centre wheel. Suppose a heavy duty pavement were designed on ground with a CBR of 7% and the wheel lateral centres were 600 mm. From the formula, the approximate Effective Depth of the slab is:

$$\text{Effective depth} = 300 \times \sqrt[3]{\frac{35,000}{7 \times 10}} = 2381\text{mm}$$

By linear interpolation from Table 19 the proximity factor is 1.86. This should be applied twice for the central wheel. This means that the effective single load is scaled up by 0.86 twice i.e. $1 + 0.86 + 0.86 = 2.72$. Note that this is approximately 10% less than 3 so that this type of wheel arrangement effectively reduces load by 10%. For wheels bolted side by side where the wheel centres are separated by less than 300mm, the entire load transmitted to the slab through one end of the axle can be considered to represent the wheel load. An investigation of the actual equivalent wheel load indicates that the actual equivalent wheel load is approximately 1.97 times one wheel load when there are two wheels bolted together at an axle end.

Wheel Spacing (mm)	Proximity factor for effective depth to base of:		
	1000mm	2000mm	3000mm
300	1.82	1.95	1.98
600	1.47	1.82	1.91
900	1.19	1.65	1.82
1200	1.02	1.47	1.71
1800	1.00	1.19	1.47
2400	1.00	1.02	1.27
3600	1.00	1.00	1.02
4800	1.00	1.00	1.00

Table 19: Wheel proximity factors.

8.12 WHEEL LOAD CALCULATIONS FOR HANDLING PLANT

The following formulae are for guidance only and relate to plant having wheel configurations as illustrated in the diagrams. In cases where plant has an alternative wheel configuration, the loads can be derived from first principles, following a similar approach. In many cases, wheel loads are provided by plant manufacturers and if this is the case, those values should be used. For each pass of the plant, a specific spot in the slab is loaded by all of the wheels at one side of the plant. Therefore, in the wheel load calculations, only one side of the plant is considered. In the case of asymmetrical plant, the heavier side should be chosen.

8.12.1 FRONT LIFT TRUCKS AND REACH STACKERS

Figure 11. Front Lift truck handling 40ft container.



Figure 12. Reach Stacker handling 40ft container. Note how a fifth container can be accessed in the second row.

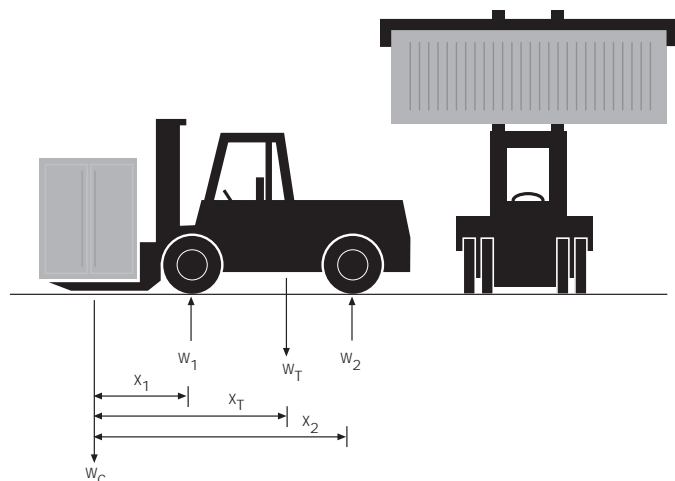


Figure 13. Dimensions and weights used in wheel load calculations.

$$W_1 = f_d \times \frac{A_1 \cdot W_c + B_1}{M}$$

$$W_2 = f_d \times \frac{A_2 \cdot W_c + B_2}{2}$$

Where:

W_1 = Load on front wheel (kg)

W_2 = Load on rear wheel (kg)

W_c = Weight of Container (kg)

M = Number of wheels on front axle (usually 2, 4 or 6)

f_d = Dynamic factor

$$A_1 = \frac{-X_2}{X_1 - X_2} \quad A_2 = \frac{-X_1}{X_2 - X_1}$$

$$B_1 = \frac{W_T (X_T - X_2)}{X_1 - X_2} \quad B_2 = \frac{W_T (X_T - X_1)}{X_2 - X_1}$$

X_1 , X_2 , and W_T are shown in the diagram

W_T = Self Weight of the truck

8.12.2 STRADDLE CARRIERS

Figure 14. Three generations of straddle carriers at Europe Container Terminus, Rotterdam. The one on the left can place a container over another. The one in the centre can place a container over two others and the one on the right can place a container over three others. This evolution took place during the 1970s and the early 1980s.





Figure 15. Eight wheel asymmetric straddle carrier handling 40ft container.

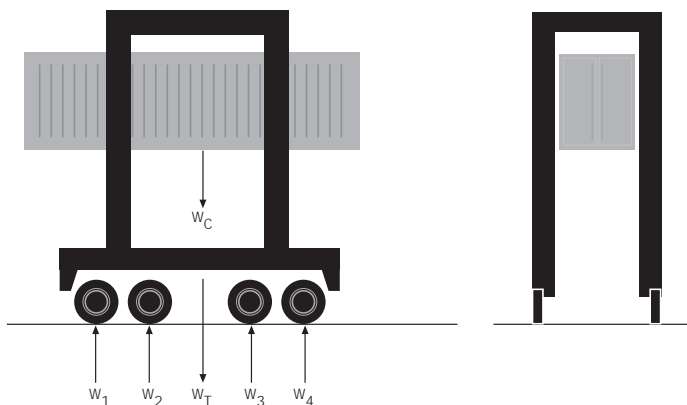


Figure 16. Dimensions and weights used in wheel load calculations.

$$W_i = f_d \times \left[U_i + \frac{W_c}{M} \right]$$

Where:

- W_i = Wheel load of laden plant (kg)
- U_i = Wheel load of unladen plant (kg)
- W_c = Weight of Container (kg)
- M = Total number of wheels on plant
- f_d = Dynamic factor

8.12.3 SIDE LIFT TRUCKS

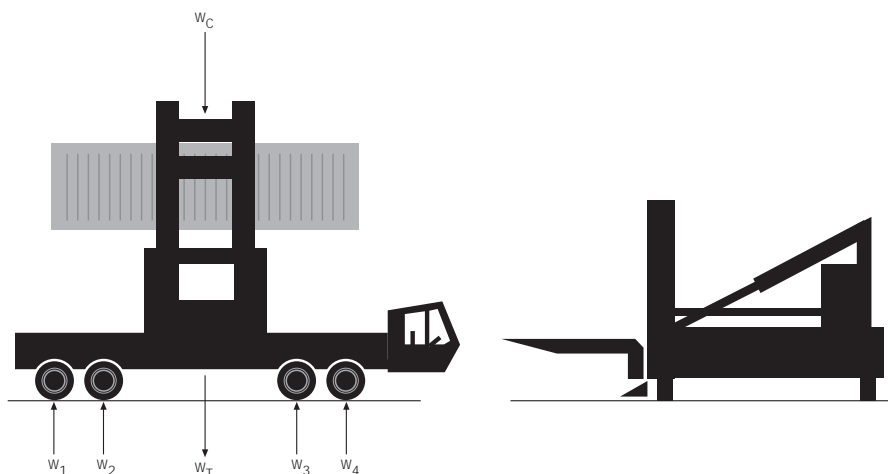


Figure 17. Dimensions and weights used in wheel load calculations.

$$W_i = f_d \times \left[U_i + \frac{W_c}{M} \right]$$

Where:

- W_i = Wheel load of laden plant (kg)
- U_i = Wheel load of unladen plant (kg)
- W_c = Weight of Container (kg)
- M = Total number of wheels on plant
- f_d = Dynamic factor

8.12.4 YARD GANTRY CRANES



Figure 18. Rubber Tyred Gantry Crane (RTG). Individual wheel loads can exceed 50t. This machine has 16 wheels which reduces wheel load and thereby pavement thickness required.

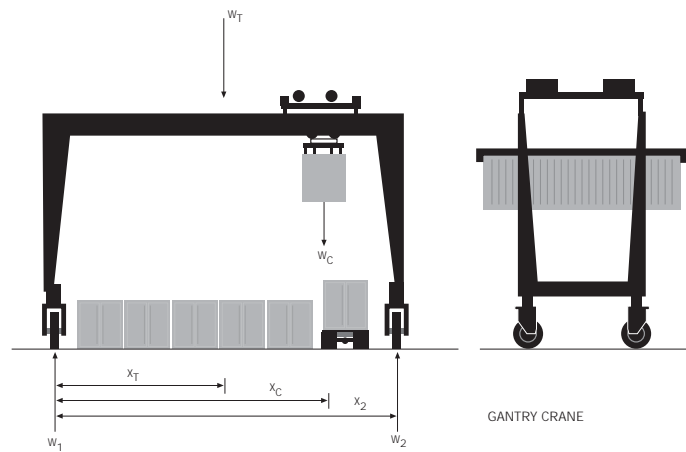


Figure 19. Dimensions and weights used in wheel load calculations.

$$W_1 = f_d \times \left[U_1 + \frac{A_1 \times W_C}{M} \right]$$

$$W_2 = f_d \times \left[U_2 + \frac{A_2 \times W_C}{M} \right]$$

Where:

W_1 = Wheel load of laden plant (kg)

W_2 = Wheel load of unladen plant (kg)

W_C = Weight of Container (kg)

M = Total number of wheels on plant

f_d = Dynamic factor

$$A_1 = 1 - \frac{X_C}{X_2} \qquad A_2 = \frac{X_C}{X_2}$$

U_1 = Unladen weight of gantry crane on each wheel of side 1 (kg)

U_2 = Unladen weight of gantry crane on each wheel of side 2 (kg)

X_2 and X_C are shown in the diagram.

Note: the front and rear wheels may have different unladen loads. This is taken into account by using the equation for both wheels on each side with their respective f_d values.

8.12.5 TRACTOR AND TRAILER SYSTEMS

Figure 20. In some places, specialised off-highway tractor units are used to marshal specially developed trailers. In this case, a special small-wheeled trailer is used to transport containers by sea. The small wheels allow the trailer to enter low headroom decks on-board ships.

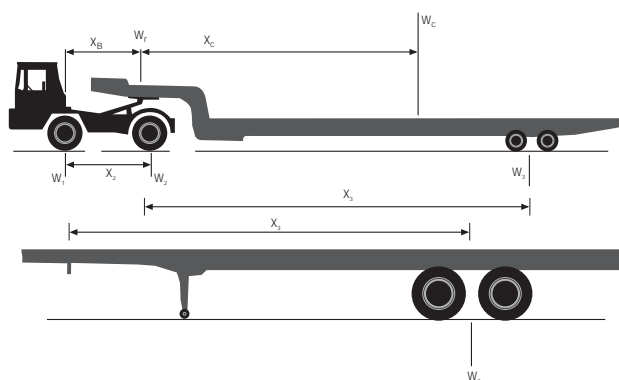


Figure 21. Dimensions and weights used in wheel load calculations.

$$W_1 = f_d \times \left[U_1 + \frac{W_c [1-A] x [1-B]}{M_1} \right]$$

$$W_2 = f_d \times \left[U_2 + \frac{W_c [1-A] x B}{M_2} \right]$$

$$W_3 = f_d \times \left[U_3 + \frac{W_c x A}{M_3} \right]$$

Where:

W_1 = Load on front wheels of tractor (kg)

W_2 = Load on rear wheels of tractor

W_3 = Load on trailer wheels (kg)

W_c = Weight of container (or load) (kg)

M_1 = Number of front wheels on tractor

M_2 = Number of rear wheels on tractor

M_3 = Number of wheels on trailer

U_1 = Load on front wheels of tractor – unladen (kg)

U_2 = Load on rear wheels of tractor – unladen (kg)

U_3 = Load on trailer wheels – unladen (kg)

f_d = Dynamic factor

$$A = \frac{X_c}{X_3} \quad B = \frac{X_b}{X_2}$$

X_c , X_b , X_3 and X_2 are shown in the diagram.

8.12.6 MOBILE CRANES (UNLADEN)

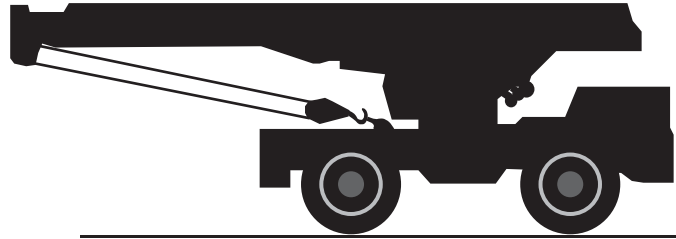


Figure 22. Mobile cranes often use outriggers to enhance stability. This can constitute a critical load configuration.

$$W = W_T/M$$

Where:

W_T = Self weight of crane

M = Total number of wheels on crane

9. FOUNDATION DESIGN

9.1 SUB-BASE AND CAPPING THICKNESS

Foundations typically comprise a sub-base and, in the case of pavements constructed over subgrades of CBR less than 5%, a capping layer. Table 20 shows thicknesses for each of these two layers using Class 1 material in the case of capping and Class 2 material in the case of sub-base (these Classes are defined later in this Section). The capping thicknesses are greater than those commonly used in highway design. The values in Table 20 have been developed to ensure that, as subgrade CBR falls below 5%, stress in the pavement base material remains constant and the deflexion of pavements remains nearly constant. In fact, stress and deflexion cannot both be kept at their 5% CBR values simultaneously. As CBR falls below 5%, deflexion at the centre of the wheel patch increases by the amounts shown in Table 21.

Note that Table 20 assumes that crushed rock sub-base material has a CBR of 80%. Such material may be expensive or unobtainable. As an alternative, hydraulically bound material may be used and this section explains how to first use Table 20 to obtain an unbound crushed rock foundation and then substitute hydraulically bound material. This allows in situ stabilised foundations to be designed. Stabilised foundations are typically stronger than unbound layers so the thickness of the base can be reduced. The way to reduce base thickness is explained in this section.

The differences between stress values in Table 21 are considered to be sufficiently small to be of no consequence. Note that, in developing the capping thicknesses, a particularly high patch load of 750kN was applied at a contact stress of 1N/mm^2 . This led to tensile stress in the base of approximately 2N/mm^2 which would be excessive in routine design. This high load has been selected in order to assess the most adverse effect of low CBR values and is unlikely to be exceeded in practice.

9.2 NEED TO INVESTIGATE SUBGRADE AT SIGNIFICANT DEPTH

Heavy duty pavements cause significant stresses to develop at much greater depths than is the case with highway pavements. Therefore, the CBR of soils must be measured at deeper locations than formation. No specific depth can be given for site investigation. Conventional proof rolling may be insufficient to discover a layer of weak material at depths which may cause a heavy duty pavement to fail.

9.3 SUFFICIENCY OF SITE INVESTIGATION

Weak ground is the most common cause of heavy duty pavement distress and a rigorous site investigation should always be undertaken under the supervision of a geotechnical engineer familiar with the specific site investigation requirements for a heavy duty pavement. Sufficient intrusive investigation must be undertaken to establish variations of soil properties with depth and location. A site investigation undertaken near to the development site should be used only as a guide to the design of a thorough site investigation of the site to be developed. Special care should be taken in the case of weak soils underlying competent ones. In the case of System A and B permeable pavements, the properties of the subgrade when soaked should be used in design.

Table 20. Unbound sub-base and capping thicknesses for various subgrade CBR values.

CBR of Subgrade	Capping Thickness (mm)	Sub-base Thickness (mm)
1%	900	150
2%	600	150
3%	400	150
4%	250	150
5% and greater	Not required	150

Table 21. Increases in wheel patch deflexion as subgrade CBR falls below 5%.

Subgrade CBR Design Stress	Tensile Stress in base (N/mm ²)	Deflexion of pavement surface (mm)	% increase in deflexion as compared with value for 5% CBR subgrade
1%	2.00	0.81	8%
2%	2.01	0.81	8%
3%	2.01	0.79	5%
4%	2.00	0.76	1%
5%	2.00	0.75	-

9.4 ALTERNATIVE SUB-BASE MATERIALS

Although unbound materials are commonly used to construct foundations, in some situations, hydraulically bound materials may be preferred for all or part of the foundation. In this case, the guidelines of TRL publication '*Development of a more versatile approach to flexible composite pavement design*', M Nunn (TRL Report TRL615 (2004)) should be followed. That report defines four Classes of foundations by their "half-space stiffness". This is a different property to the Elastic Modulus values used in the Finite Element Model in this Manual. It is the property which describes the response of the pavement foundation and the subgrade to vertically applied load. In this instance, half-space stiffness is assessed on the basis of the foundation installed over subgrade of CBR 5%.

The four foundation Classes are as follows:

CLASS 1. Half-space stiffness = 50N/mm²

This foundation comprises 250mm of unbound capping material over subgrade of 5% CBR. This would be an unusual foundation solution for a heavy duty pavement but might be encountered during existing pavement assessment in the case of overlay design.

CLASS 2. Half-space stiffness = 100N/mm²

This foundation comprises 225mm of UK Highways Agency Type 1 sub-base material over 5% CBR subgrade (Clause 803 material as defined in UK '*Specification for Highway Works*' Series 800) or, if the CBR of the subgrade is less than 5%, 150mm thickness of Type 1 sub-base material over capping material. All of the foundations shown in Table 20 fall into this Class.

CLASS 3. Half-space stiffness = 200N/mm²

This foundation is identical to a Class 2 foundation, with the exception that it includes C_{1.5/2.0}, C_{3/4}, C_{5/6}, CBM1 or CBM2 instead. This will be a common alternative Class of foundation for heavy duty pavements.

CLASS 4. Half-space stiffness = 400N/mm²

The foundation comprises 225mm thickness of C_{8/10}, C_{9/12} or CBM3 installed over subgrade with a CBR of 5% or more. This alternative might be considered where in situ stabilisation is an option.

In the case of foundation Classes 3 and 4, the switch from unbound materials to bound materials will have a structurally beneficial effect and this can be used to reduce the thickness of the base as explained in the following example.

9.5 FOUNDATION DESIGN EXAMPLES

9.5.1 FOUNDATION DESIGN EXAMPLE 1. CLASS 2 TO CLASS 3 FOUNDATION

Consider a pavement to be constructed over 4% CBR subgrade material for which the Design Chart and Table 20 produced the following design section:

80mm thickness concrete block paving

30mm laying course material

550mm thickness C_{8/10}

150mm thickness UK Highways Agency Type 1 sub-base material

250mm thickness capping material

Subgrade CBR = 4%

In this example, the 150mm thickness of Type 1 material over 250mm thickness of Capping comprises a Class 2 foundation. The designer wishes to use a Class 3 foundation in which the 150mm thickness of Type 1 sub-base material is replaced with a similar thickness of C_{3/4} material. From Table 13, a Material Equivalence Factor (MEF) of 3.0 is selected for the Type 1 material and 1.38 for C_{3/4}.

Therefore, 150mm thickness of Type 1 equates with $150 \times 1.38/3.0 = 69\text{mm}$ of C_{3/4}. This means that the alternative bound sub-base is stronger than the unbound sub-base which can be expressed as $150 - 69 = 81\text{mm}$ of C_{3/4}. Taking the MEF of 1.38 for C_{3/4} from Table 13, the additional strength of the bound sub-base can also be expressed as $81/1.38 = 59\text{mm}$ thickness of C_{8/10}. Therefore, the thickness of the base can be reduced by 59mm (say 60mm) so the revised pavement section comprises:

80mm thickness concrete block paving
30mm laying course material
490mm thickness C_{8/10}
150mm thickness C_{3/4}
250mm thickness capping material
Subgrade CBR = 4%

9.5.2 FOUNDATION DESIGN EXAMPLE 2. CLASS 2 TO CLASS 4 IN SITU STABILISED FOUNDATION

Consider a pavement to be constructed over 7% CBR subgrade material for which the Design Chart and Table 20 produced the following design section:

80mm thickness concrete block paving
30mm laying course material
550mm thickness C_{8/10}
150mm thickness UK Highways Agency Type 1 sub-base material
Subgrade CBR = 7%

In the above example, the 150mm thickness of Type 1 material comprises a Class 2 foundation. The designer wishes to use a Class 4 foundation in which the 150mm thickness of Type 1 sub-base material is replaced with a similar thickness of C_{9/12} material created by in situ stabilisation. From Table 13, use a Material Equivalence Factor (MEF) of 3.0 for the Type 1 material and 0.95 for C_{9/12}.

Therefore, 150mm thickness of Type 1 equates to $150 \times 0.95/3.0 = 47.5\text{mm}$ of C_{9/12}. This means that the alternative in situ stabilised sub-base has additional strength as compared with the unbound sub-base and this additional strength can be expressed as $150 - 47.5 = 102.5\text{mm}$ of C_{9/12}. Taking the MEF of 0.95 for C_{9/12} from Table 13, the additional strength of the in situ stabilised sub-base can also be expressed as $102.5/0.95 = 108\text{mm}$ thickness of C_{8/10}. Therefore, the thickness of the base

can be reduced by 108mm (say 110mm) so the revised pavement section comprises:

80mm thickness concrete block paving
30mm laying course material
440mm thickness C_{8/10}
150mm thickness in situ stabilised C_{9/12}
Subgrade CBR = 7%

10. NEW PAVEMENT DESIGN

EXAMPLE 1 – STRADDLE CARRIER PAVEMENTS

This example applies to all plant which has a train of wheels such that one pass of the plant applies several wheel loads. In this example, wheel proximity, handling equipment dynamics and fatigue are taken into account to obtain the Single Equivalent Wheel Load (SEWL). The Design Chart is then used to select the required thickness of C_{8/10} CBGM and the Material Equivalent Factors (MEFs) in Table 13 may then be used to obtain designs for other materials.

10.1 DATA:

Unladen weight of straddle carrier including spreader beam	= 56,310kg
Critical container weight	= 22,000kg
Track width	= 4.5m
Wheel spacings	= 2.4m - 3.6m - 2.4m (see Figure 23)

Number of likely passes of straddle carriers over the most highly trafficked part of the pavement during design life of pavement	= 960,000 passes
CBR of soil	= 5%
Sub-base thickness	= 150mm

Having defined the foundation material properties the C_{8/10} CBGM base material thickness is now calculated which is dependent on the load applied.

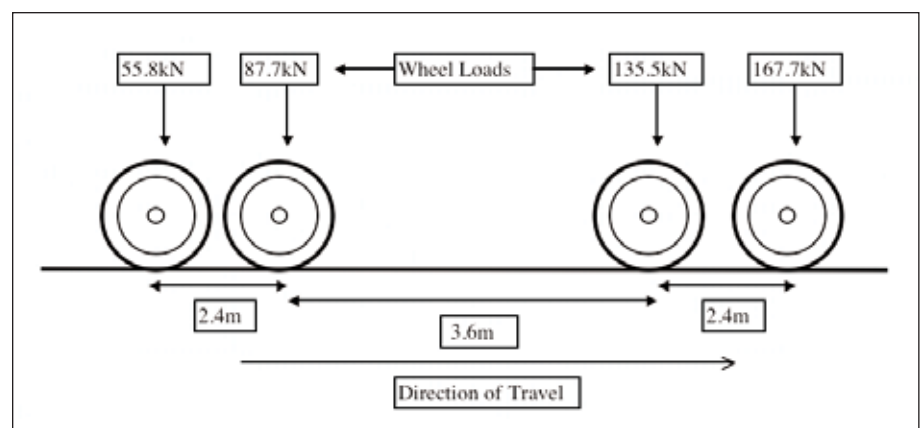


Figure 23. Straddle Carrier wheel loads during braking.

10.2 CALCULATIONS

Total number of wheels on plant (8)
 Wheel load of unladen plant (kg) – $56,310/8 = 7,039\text{kg}$
 Weight of critical container (kg) – $22,000\text{kg}$, see Table 15.
 f_d = Dynamic Factor for braking – $\pm 50\%$ for extreme wheels,
 see next paragraph for inner wheels.

$$\text{Static wheel load} = \frac{7,039}{8} + 22,000 = 9789\text{kg} = 96\text{kN}$$

10.3 WHEEL PROXIMITY

The proximity effect of the wheel loads is now assessed.

$$\text{Effective depth} = 300 \times \sqrt[3]{\frac{35,000}{5 \times 10}} = 2664\text{mm}$$

From Table 18, the proximity factor can be interpolated to be 1.14. Therefore the effective wheel load taking into account wheel proximity is $96 \times 1.14 = 110\text{ kN}$.

10.4 EQUIVALENCING WHEEL LOADS FOR MULTI-AXLE PLANT

Consider the most adverse loading case of braking and apply the appropriate dynamic factor of $\pm 50\%$ to the wheels at the extreme front and rear, applying the increase in load to the front wheels and the decrease to the rear wheels. The inner wheel loads need to be similarly adjusted but using a factor lower than $\pm 50\%$ determined by considering relative distances from the vehicle's centre line. In this case, each extreme wheel is 4.2m from the centre of the vehicle and each inner wheel is 1.8m from the centre. Therefore, the lower braking factor to be applied to the inner wheels is $\pm 21.4\%$ (i.e. $\pm 50\% \times 1.8/4.2$).

Express the four load values which will pass over one spot as an equivalent number of passes of the highest wheel load of 167.7kN as follows. The damaging effect equation is applied to each wheel load in turn:

Front wheel is equivalent to one pass of a load of 167.7kN.

Second wheel is equivalent to $(135.5/167.7)^{3.75}$
 i.e. 0.45 equivalent passes of the front wheel load.

Third wheel is equivalent to $(87.7/167.7)^{3.75}$
 i.e. 0.09 equivalent passes of the front wheel load.

Fourth wheel is equivalent to $(55.8/167.7)^{3.75}$
 i.e. 0.02 equivalent passes of the front wheel load.

All of the repetitions are converted to an equivalent number of repetitions of the heaviest wheel so that the Single Equivalent

Wheel Load (SEWL) used in the Design Chart is derived from the heaviest wheel load. It would be unsafe to convert wheel loads to one of the plant's lower wheel load values.

Therefore, each time the straddle carrier passes over one spot whilst braking, it applies the equivalent of $(1 + 0.45 + 0.09 + 0.02) = 1.56$ repetitions of the front wheel load of 167.7kN. This means that the pavement needs to be designed to accommodate 1.5 million passes (i.e. $1.56 \times 960,000$) of a load of 167.7kN.

10.5 PAVEMENT SECTION FROM DESIGN CHART

The Design Chart can now be used as follows:

- on the vertical axis, the Single Equivalent Wheel Load (SEWL) is 167.7kN
- the appropriate curve is the one corresponding to 1.5 million passes
- the following alternative thicknesses can be used:

- | | |
|---|---------|
| a) C _{8/10} CBGM with CBP | - 200mm |
| b) C _{5/6} CBGM with CBP | - 232mm |
| c) C32/40 Concrete without CBP | - 186mm |
| d) Dense Bitumen Macadam (DBM) with CBP | - 200mm |

10.6 BASE THICKNESS DESIGN WITH ALTERNATIVE DYNAMIC FACTORS

Consider how the pavement section required would change if alternative dynamic factors were used. For example, if the straddle carriers were to brake whilst cornering, the wheel loads would increase by 60% of their static value (i.e. $0.6 \times 111.6 = 67\text{kN}$) so that the wheel loads would be as in Figure 24.

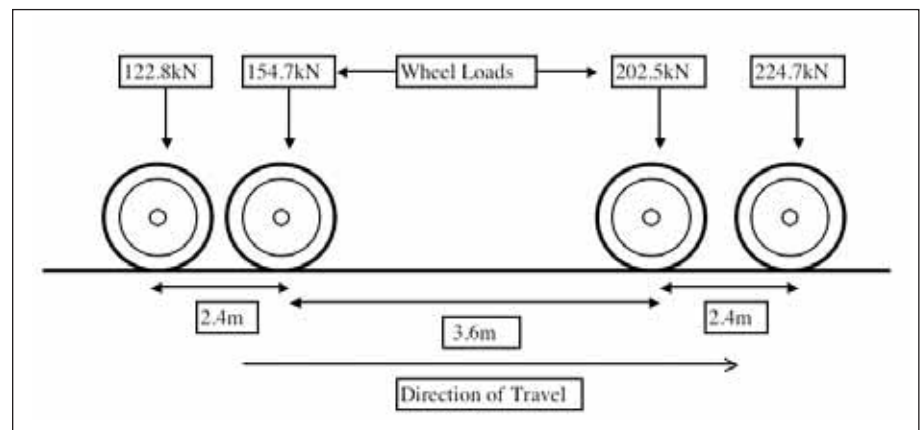


Figure 24. Straddle Carrier wheel loads during braking & cornering.

We now need to express the four load values which will pass over one spot into an equivalent number of passes of the highest wheel load of 224.7kN as follows.

The Damaging Effect equation is applied to each wheel load in turn:

Front wheel is equivalent to one pass of a load of 224.7kN.

Second wheel is equivalent to $(202.5/224.7)^{3.75}$
i.e. 0.68 equivalent passes of the front wheel load.

Third wheel is equivalent to $(154.7/224.7)^{3.75}$
i.e. 0.25 equivalent passes of the front wheel load.

Fourth wheel is equivalent to $(122.8/224.7)^{3.75}$
i.e. 0.10 equivalent passes of the front wheel load.

Therefore, each time the straddle carrier passes over one spot, its outside wheels apply the equivalent of $(1+0.68+0.25+0.10) = 2.03$ repetitions of the front wheel load of 224.7kN. This means that the pavement needs to be designed to accommodate 2 million passes i.e. $2.03 \times 960,000$ of a load of 224.7kN.

The base thickness Design Chart can now be used as follows:

- on the vertical axis, the Equivalent Single Load is 224.7kN
- a 2,000,000 passes curve has to be interpolated between the 1,500,000 and the 4,000,000 curves

The following alternative thicknesses can be used:

- $C_{8/10}$ CBGM with CBP - 340mm
- $C_{5/6}$ CBGM with CBP - 395mm
- $C_{32/40}$ Concrete without CBP - 270mm
- Dense Bitumen Macadam (DBM) with CBP - 340mm

10.7 DESIGN WITH ZERO DYNAMIC FACTORS (FREE RUNNING)

Finally, consider the case where straddle carriers are running freely on a smooth surface so that no dynamic factors need be applied. In this configuration, the wheel loads are as in Figure 25.

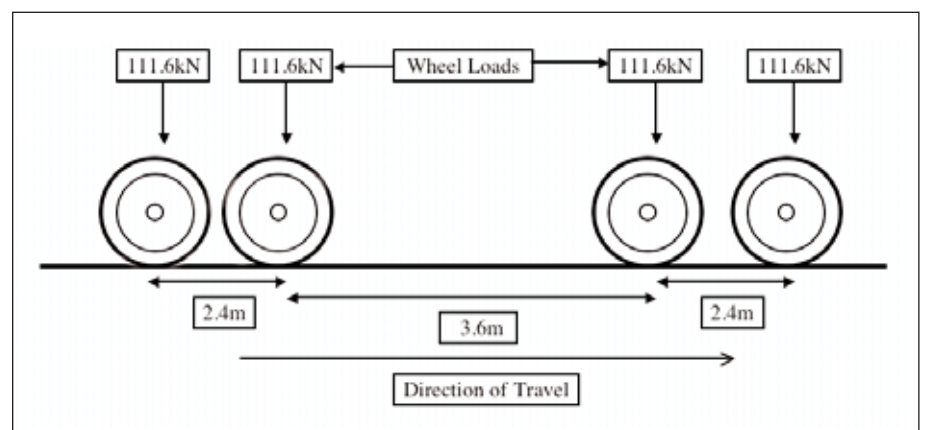


Figure 25. Straddle Carrier wheel loads during free running.

The pavement withstands four repetitions of a wheel load of 111.6kN as each straddle carrier passes so the pavement must be designed to withstand 3,840,000 passes (say 4,000,000) of an Single Equivalent Wheel Load of 111.6kN.

The following alternative thicknesses can be used:

- | | |
|---|---------|
| a) C _{8/10} CBGM with CBP | - 190mm |
| b) C _{5/6} CBGM with CBP | - 220mm |
| c) C30/40 Concrete without CBP | - 180mm |
| d) Dense Bitumen Macadam (DBM) with CBP | - 190mm |

10.8 SUMMARY OF STRADDLE CARRIER DESIGN SOLUTIONS

In the case of plain concrete, different operational conditions led to pavement thicknesses required varying between 162mm and 234mm. In some cases, it may be possible to take advantage of known modes of operation and proportion the pavement courses to meet the thicknesses required exactly. Whilst this may reduce initial construction costs, it has the disadvantage of constraining future operations and may lead to additional complexity in the construction process.

It may prove cost effective to provide an initial pavement which will not sustain all potential operational situations and to allow the plant to become the proof testing system so that small areas may have to be strengthened later. Whilst this staged approach has the advantage of lowering initial costs, this must be balanced against the disadvantage associated with the disruption which may occur should the pavement need to be upgraded later.

11. NEW PAVEMENT DESIGN

EXAMPLE 2 – REACH STACKER PAVEMENTS



Figure 26. Reach Stacker operating in five high container stacks.

11.1 DESCRIPTION OF PROJECT

--This example applies to Reach Stackers and Front Lift Trucks which have one predominantly loaded axle with multiple half-axle wheels.

In this example, pavements of different materials are designed to withstand a five high container handling facility where the containers are handled by Reach Stackers of unladen weight 69,840kg. The Reach Stackers handle 40ft containers and the design California Bearing Ratio (CBR) of the subgrade is 2%. The Reach Stackers have two wheels at each end of their front axle at 660mm centres. The distance between the two inner front axle wheel centres is 2540mm.

11.2 LOADS APPLIED BY REACH STACKERS

When carrying the critical 22,000kg 40ft container, the static laden weight is 91,840kg, of which 73,659kg is applied through the front axle and 18,181kg is applied through the rear axle. Therefore, the static load applied through each front wheel is $73,659/4 = 18,415\text{kg}$.

11.3 WHEEL PROXIMITY

$$\text{Effective depth of } C_{8/10} \text{ base} = 300 \times \sqrt[3]{\frac{35,000}{\text{CBR} \times 10}}$$

$$\text{CBR} = 2\%$$

Therefore effective depth = 3,615mm

Assume load contributed at the inner front axle wheel is critical. Therefore, apply proximity factors for distances of 660mm, 2,540mm and 3,200mm.

From Table 19, this gives proximity factors of 1.93, 1.35 and 1.18 (using interpolation). Using proximity factors from Table 18 extrapolate as attached sheet.

Therefore load at B = $1 + 0.93 + 0.35 + 0.18 = 2.46$

Therefore, the static effective wheel load is $18,415 \times 2.46 = 45,116\text{kg}$

11.4 DYNAMICS

From Table 17 allow:

Braking	0.3
Cornering	0.4
Acceleration	0.0
Uneven surface	<u>0.0</u>
	0.7 = 70%

Therefore, Single Equivalent Wheel Load (SEWL)
 $= 1.7 \times 45,116\text{kg} = 76,698\text{kg} (752\text{kN})$.

11.5 DESIGN LIFE

Assume that the most frequently trafficked part of the pavement sustains 180 passes over one spot per day and that the pavement is to be designed for a life of 25 years. Note that this figure is the number of passes over one spot, which is not the same as the number of containers handled. A detailed consideration of the way in which it is expected that the facility will be managed may be required.

Number of passes throughout design life
 $= 180 \times 365 \times 25 = 1,642,500$.

There is an element of conservatism in the use of this number of repetitions because it assumes full cornering and braking will be applied each time, whereas that situation may be rare. If it can reasonably be predicted that severe braking will be applied only when the Reach Stacker is running straight and that the brakes will not be applied when cornering severely, then the Dynamic Factor could be reduced to either 0.3 or 0.4. Alternatively, full dynamics could be applied and the number of passes could be reduced to say 10% of the calculated value. These judgments can be made only with a detailed knowledge of the proposed operation of the facility. In this example, the full SEWL of 97,360kg is retained and the number of passes is reduced to 250,000.

11.6 USING THE DESIGN CHART FOR REACH STACKER

The Design Chart shows that 670mm thickness of C_{8/10} CBGM is required for the pavement base.

11.7 DESIGN FOR CONTAINER STORAGE

Assume five high storage of containers in blocks.

From Table 18, the design load is 914.4kN. From the Design Chart, the thickness of C_{8/10} CBGM required is 620mm. Therefore, in this instance, Reach Stacker movements are the critical load and the pavement thickness required is 670mm.

In this case, it would not normally be economical to install a deforming Heavy Duty Macadam (HDM) layer because the container stacking load is less than the Reach Stacker Load. However, this may still be an option to consider to permit future stacking of containers exceeding five high. Providing 100mm thickness of HDM allows 122mm to be deducted from the thickness of the C_{8/10} CBGM to leave a required thickness of 548mm.

11.8 DESIGN FOR PAVEMENT FOUNDATION

For 2% CBR subgrade, Table 19 shows that 150mm unbound sub-base and 600mm thickness of unbound capping are required.

11.9 PAVEMENT SECTIONS

Table 13 now allows a range of pavement sections to be selected as follows:

1) Pavement using standard C_{8/10} CBGM.

80mm CBP

30mm Category 2 laying course material to BS7533-3:2005

670mm C_{8/10} CBGM to BSEN14227

150mm crushed rock sub-base material

600mm capping

2% CBR subgrade

2) Permeable pavement (System C tanked detention pavement – subgrade too weak for System A or B).

80mm CBP

30mm Category 2 laying course material to BS7533-3:2005

670mm No-fines Lean Concrete

Layer of 2000 gauge polythene brought to surface

150mm crushed rock sub-base material

600mm capping

2% CBR subgrade

- 3) Pavement using in situ C32/40 concrete with 40kg/m³ steel fibres.

**350mm C32/40 to BS8500-1 including 40kg/m³ steel fibre
150mm crushed rock sub-base material
600mm capping
2% CBR subgrade**

Note that this pavement can be installed with no movement joints. There may be some minor cracking but the cracks should be sufficiently narrow to be acceptable.

- 4) Pavement using in situ C32/40 concrete with 40kg/m³ steel fibres including concrete block paving and deforming HDM layer.

**80mm pavers
30mm Category 2 laying course material to BS7533-3:2005
100mm HDM
247mm C32/40 to BS8500-1 including 40kg/m³ steel fibre
150mm crushed rock sub-base material
600mm capping
2% CBR subgrade**

12. NEW PAVEMENT DESIGN EXAMPLE 3 – DISTRIBUTION WAREHOUSE PAVEMENTS

12.1 INTRODUCTION

In this example, pavements are designed for the roads and hardstandings servicing a large distribution warehouse. The pavements are to comprise $C_{8/10}$ CBGM surfaced with concrete block paving. Assume 5% CBR subgrade so the sub-base thickness is 150mm. The pavements are trafficked by Large Goods Vehicles (LGVs) only. Consider the following trafficking conditions.

- Exit road with sharp turns trafficked by 150 exiting trucks per day
- Dock leveller subject to 3 trucks per day
- Hardstanding in which a point takes 20 trucks per day

12.2 DATA

Laden trucks each have four axles of load 110kN and one (steering) axle of load 65kN as illustrated.

Assume wheel proximity factor = 1.1

Braking dynamic factor = 10%

Cornering dynamic factor = 30%

Design life of pavements = 25 years

Number of operating days per year = 365

12.3 DESIGN OF EXIT ROAD

Number of passes of trucks during 25 years design life
 $= 150 \times 365 \times 25 = 1,368,750$.

Number of passes of each non-steering wheel
 $= 1,368,750 \times 4 = 5,475,000$.

Steering axle is equivalent to $(65/110)^{3.75}$ i.e. 0.14 equivalent passes of a non-steering axle. Therefore, effective number of passes expressed in terms of non-steering axles = 191,625. Therefore, total number of equivalent non-steering wheel passes = $5,475,000 + 191,625 = 5,666,625$. (This means the effect of the steering axle is small.)

Non-steering axle static wheel load = $110/2 = 55\text{kN}$.

Apply braking and cornering dynamics and wheel proximity factor to wheel load:

Single Equivalent Wheel Load (SEWL) = $55 \times 1.5 = 82.5\text{kN}$.

Therefore, use Design Chart for 82.5kN SEWL and interpolate half way between 4,000,000 passes and 8,000,000 passes.

Thickness of $C_{8/10}$ CBGM required is 200mm.

Number of passes of trucks during 25 years design life
 $= 3 \times 365 \times 25 = 27,375$.
 Multiply this figure by 5 to account for severe channelisation:
 $27,375 \times 5 = 136,875$
 Non-steering axle static wheel load $= 110/2 = 55\text{kN}$

12.4 DESIGN OF DOCK LEVELLER PAVEMENT

Apply braking dynamics and wheel proximity factor to wheel load:
 Single Equivalent Wheel Load (SEWL) $= 55 \times 1.2 = 66\text{kN}$

Therefore, use Design Chart for 66kN SEWL and use the 250,000 passes design curve. Thickness of C_{8/10} CBGM required is the minimum value of 200mm.



Figure 27. Typical highway legal vehicle.

Number of passes of trucks during 25 years design life.
 $= 20 \times 365 \times 25 = 182,500$.

12.5 DESIGN OF HARDSTANDING

Non-steering axle static wheel load $= 110/2 = 55\text{kN}$.

Apply braking dynamics and wheel proximity factor to wheel load:
 Single Equivalent Wheel Load (SEWL) $= 55 \times 1.2 = 66\text{kN}$.

Therefore, use Design Chart for 66kN SEWL and use the 250,000 passes design curve. Thickness of C_{8/10} CBGM required is the minimum value of 200mm.

12.6 DESIGN SECTIONS

The following section can be used for each category of pavement use:

- 80mm CBP
- 30mm laying course material
- 200mm C_{8/10} CBGM
- 150mm crushed rock sub-base material
- 5% CBR subgrade

Alternatively, C28/35 in situ concrete can be used as follows:

Total equivalent thickness of C_{8/10} CBGM of the above section = 80 + 30 + 200 = 310mm (because concrete block paving has Material Equivalence Factor (MEF) of 1.0).

C28/35 in situ concrete has an MEF of 0.62.

Therefore, thickness required = 310 x 0.62 = 192mm, say 200mm.

Therefore, the following section is also possible:

200mm C28/35 in situ concrete
150mm crushed rock sub-base material



Figure 28. Typical industrial development.

13. OVERLAY DESIGN

13.1 INTRODUCTION

A well designed and constructed pavement should remain serviceable for the period for which the designer intended. During its service life, a pavement is subjected to applied surface stress from traffic and to internal stress caused by restraint to thermal and moisture movement. Even a well designed pavement may be damaged by being overloaded or by being subjected to abnormal internal stress during particularly severe weather. The pavement may remain serviceable throughout its design life or for only part of it but at some stage it may need to be strengthened, otherwise it will have to be taken out of service.

It is recommended that immediately following construction of a new area, a survey be undertaken comprising both a general condition survey and a level survey, using instruments accurate to 1mm. Levelling positions should be as follows:

- (i) in situ concrete: at each corner of each bay.
- (ii) bituminous or block paved surface: one level for each 100m² of paving, at locations which it will be possible to re-establish at a later date.

In the case of a bituminous or block paved surfacing, a secondary level survey should be taken immediately following construction. Levels should be taken in one or more 10m x 10m representative areas, using a 1m grid.

In many types of pavement, once deterioration commences, total unserviceability is imminent and rapid degradation takes place over a short interval, particularly during severe weather. If remedial work is undertaken before deterioration becomes severe, the residual strength of the existing pavement can be taken advantage of so that lower cost strengthening can be undertaken which will extend the pavement's life considerably. It is stressed that the time interval between the onset of degradation and complete failure is rapid and the difference in strengthening cost can rise substantially if strengthening is delayed.

Once the residual strength of a pavement has been assessed, the overlay design technique must be capable of selecting the thickness and properties of strengthening materials. The purpose of strengthening may be to extend the life of the pavement or to allow an existing pavement to carry heavier handling plant. This second reason for strengthening a pavement is of particular relevance to ports.

This Section is concerned with both aspects of pavement strengthening i.e.

- (1) Assessment of residual strength of pavement.
- (2) Selection of thicknesses and properties of additional courses.

Pavement rehabilitation may take place for reasons other than strength, for example to restore skidding resistance or to eliminate ponding. This Section is concerned only with rehabilitation for reasons of strength. The term overlay is used to indicate the provision of extra pavement construction material in order to strengthen the pavement. This term is used henceforth.

If settlement has taken place and the concrete block paving is substantially undamaged, it may be possible to remove them, rescreed the laying course material and relay the concrete block paving without disturbing the underlying materials. If the existing pavement analysis shows this to be inadequate, then an additional thickness of base material will be required. The existing paving blocks may then be re-laid over the new material.

If new blocks are required, either rectangular or proven shaped units may be used. Laying patterns and installation should be in accordance with British Standard BS7533-3:2005, '*Pavements constructed with clay, natural stone or concrete pavers. Part 3: Code of practice for laying precast concrete paving blocks and clay pavers for flexible pavements.*' The only deviation from the recommendations of BS7533-3:2005 is that the block joints should be filled with Category 2 laying course material as opposed to fine sand which is commonly used in the case of highway and other lightly trafficked pavements. Category 2 material should also be used for the laying course. It is recommended that paving blocks are laid in herringbone pattern.

13.2 IN SITU PAVEMENT QUALITY CONCRETE

Three types of pavement rehabilitation are possible but only the latter two should be considered for strengthening purposes:

- (1) Thin bonded topping
- (2) Concrete overslab
- (3) Flexible

A thin bonded topping should be applied when surfacing defects need to be remedied for a largely uncracked pavement. This is a specialist process and should normally be undertaken by a contractor experienced in this type of work. Surface preparation of the existing slab should be specified carefully. Scabbling of the existing surface is preferred and it should be coated with a bonding agent. The maximum thickness of topping should be 40mm because of the likelihood of delamination.

When an increase in pavement strength is required, a concrete over-slab should be used. This may be of plain, reinforced, continuously reinforced or fibre reinforced concrete. It is common practice to position new pavement joints over the old joints. Before any over-slabbing is commenced the existing pavement must be prepared. All defects or causes of failure must be corrected. Extensively damaged areas of existing paving should be replaced. Surface preparation should be the same as for thin bonded toppings.

As an alternative, block paving or HDM/DBM may be used. Care should be taken at joints and cracks to prevent reflective cracking especially when asphalt is used.

13.3 CONVENTIONAL FLEXIBLE PAVEMENTS

The two alternative overlay materials are either additional HDM/DBM or block paving. If paving blocks are used, care should be taken to avoid using laying course material to fill depressions. This may lead to depressions forming in the surface during trafficking. Should the existing bitumen bound material still be in good condition and a greater increase in strength be required, an un-bonded concrete over-slab may be laid over the existing surface or the surface may be cleaned and a course of CBGM applied before the new surfacing material is laid. Bitumen bound material which has deteriorated should be removed by cold planing before overlaying.

13.4 SUMMARY OF OVERLAY PROCEDURES

These overlay procedures are summarised in Table 22.

Concrete Blocks	Rigid Concrete	Asphalt
Lift blocks, re-screed laying course material and replace blocks	Lay concrete over-slabs	Lay additional HDM/DBM
Lift blocks, strengthen base and replace blocks	Lay HDM/DBM	Lay concrete blocks
Remove blocks, remove laying course material, strengthen base and lay HDM/DBM	Lay HDM/DBM or blocks	Lay un-bonded concrete Over-slab
Remove blocks, remove laying course material and lay concrete		Strengthen and lay new surfacing
Remove blocks, remove laying course material and lay blocks		

Table 22: Suggested alternative overlay techniques for four types of existing pavement.

13.5 OVERLAY DESIGN TECHNIQUE

Three techniques are used by pavement engineers to assess the strength of existing highway pavements. These are as follows (with their originating authority):

- (1) Deflexion Beam Method (TRL)
- (2) Falling Weight Deflectometer Method or Pulse Load Method (Shell)
- (3) Component Analysis Method (The Asphalt Institute, USA)

The first is used widely in the UK and allows engineers to design overlays for most types of bituminous highway pavements. A deflexion beam is used to measure the elastic deflexion of the pavement under a standard heavy wheel load moving at creep speed. The measured deflexion may then be used to predict the future structural performance of the pavement and to select strengthening course thicknesses. Nevertheless, because of its limitations with regard to heavier loads in ports and because it is applicable to only bituminous pavements, it is not described fully in this Manual. However, if a port has a road which equates in respect of trafficking and structure to a UK public highway, this method may be used and full details are given in the Transport and Road Research Laboratory Reports Nos. LR 833, LR 834 and LR 835, which are obtainable from:

Transportation Research Laboratory (TRL)
Crowthorne House
Wokingham, Berkshire
RG40 3GA
UK
www.trl.co.uk

13.5.1 FALLING WEIGHT DEFLECTOMETER

The Falling Weight Deflectometer (FWD) or pulse load method is based upon measuring the elastic deflexion in the pavement beneath a 150kg mass which is dropped through 400mm on to the surface of the pavement. An arrangement of springs converts the impact load into an equivalent load of 600kg acting, for a short time, on the pavement. The deflexion is recorded electronically, using equipment in a field vehicle. This method suffers from the same limitation as the TRL method in that it applies only to bituminous pavements subject to highway traffic.

13.5.2 MODIFIED COMPONENT ANALYSIS METHOD

The method used in this section is the Component Analysis Method which was first proposed by the Asphalt Institute, Maryland, USA. A major modification is that, whereas the Asphalt Institute method transforms each course in a pavement to its equivalent thickness of asphalt, in this section the transformation is to an equivalent thickness $C_{8/10}$ CBGM, the standard material used in the new pavement design method.

13.6 PAVEMENT TRANSFORMATION PROCEDURE

The Modified Component Analysis Method is applicable to both rigid and flexible pavements. The transformation to an equivalent thickness of lean concrete is accomplished using Conversion Factors shown in Table 13. Because Cement Bound Granular Mixture (CBGM) is the material to which each course of the pavement is transformed, the method is compatible with the remainder of this Manual.

The existing pavement is transformed into an equivalent thickness of $C_{8/10}$ CBGM. The equivalent thickness of $C_{8/10}$ CBGM is that which would be required to give the same load carrying capability as the existing pavement. The existing pavement constitutes a part of the strengthened pavement, so it is essential to determine accurately the thickness of each of the existing courses and the degree of degradation that each of those courses has undergone.

If records of the original design of the pavement are not available it will be necessary to take either cores or trial holes to obtain this information. Even if records do exist, cores or trial holes should be taken to verify the actual situation. These tests should be carried out so that each one represents approximately 500m² of pavement. There should be a minimum of three tests and a maximum of seven for larger pavements of uniform construction and condition. Where areas of a heavy duty pavement are used for dissimilar types of traffic, then each location should be considered as a separate area for analysis purposes. Similarly if the initial cores show that certain areas of pavement are stronger than others, it may be preferable to divide the overlay area into several zones and each zone should then have at least three cores taken.

In certain circumstances the properties of the materials may have changed since they were initially used, owing to cementing action or intrusion of materials from another pavement course, and it is essential to know whether this has occurred. Sampling should also be used to determine the condition of each course so that the appropriate Condition Factors may be selected. It may be difficult to assess the condition of lower pavement courses, particularly with regard to cracking. In such situations, conservative assumptions should be made.

Once each course has been identified, it is transformed to an equivalent thickness of $C_{8/10}$ CBGM by multiplying its actual thickness by the appropriate Material Equivalence Factor from Table 13. Most of the materials shown are defined in the UK Department of Transport's '*Specification for Highway Works*' (HMSO) or in the British or European Standard cited.

The transformed thickness is multiplied by two Condition Factors. Values for the first Condition Factor CF1 are given in Table 23 and are used for both rigid and flexible pavements.

Condition of material	CF1
As new	1.0
Slight cracking	0.8
Substantial cracking	0.5
Fully cracked or crazed and spalled	0.2

Table 23: Condition factors for cracking and spalling.

Values for the second Condition Factor CF2 are shown in Table 24. CF2 takes into account the reduction in strength of each course as a result of rutting and settlement in the surface of flexible pavements. This is measured as a difference in levels under a 3 metre (10ft) straight edge. If a pavement has deformed, cores should be taken to determine which courses of the pavement are affected. When there is no deformation or cracking, the Condition Factors are taken as 1.0. I.E. the material is as new.

(mm)	(in)	CF2
0 to 10	0 to ½	1.0
11 to 20	½ to 1	0.9
21 to 40	1 to ¾	0.6
40 +	¾+	0.3

Table 24: Condition factors for maximum degree of localised rutting and localised settlement.

The transformation procedure is carried out for each course in the pavement and the sum of the transformed thicknesses is taken as the equivalent thickness of the pavement. The equivalent thickness is used in the design of the overlay.

13.7 PAVEMENT EVALUATION – EXAMPLE 1

A cross section of an existing rectangular pavement of dimensions 40m x 100m is shown in Figure 29.

Rutting up to 35mm has developed owing to shear failure in the C_{1.5/2.0} CBGM. The crushed rock sub-base is intact. The Hot Rolled Asphalt (HRA) surfacing has crazed and spalled but the underlying Dense Bitumen Macadam (DBM) shows only slight cracking. This description applies to the poorest of 8 core samples. Other samples show no rutting but a similar state of cracking and crazing in the rolled asphalt.

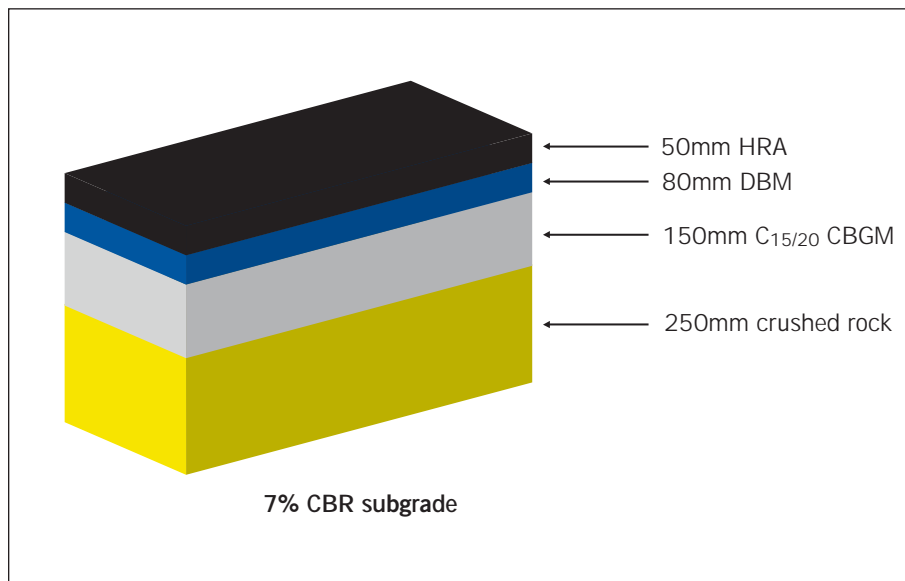


Figure 29. Section through overlay design Example 1.

From the appropriate tables the following table is constructed showing how much each course is transformed to an equivalent thickness of lean concrete and how the thickness are added.

Course	Ac Thickness (mm)	Material Conversion Factor	CF1	CF2	Effective Equivalent Thickness of C _{8/10} CBGM (mm)
Hot Rolled Asphalt	50	1.25	0.2	0.6	5
Dense Bitumen Macadam	80	1.0	0.8	0.6	38
C _{1.5/2.0} CBGM	150	1.74	1.0	0.6	52
Crushed rock sub-base	250	3.0	1.0	1.0	83
Subgrade CBR 7%					
TOTAL					178

The analysis shows this pavement to be equivalent to 178mm of $C_{8/10}$ CBGM. Cores in other areas where no rutting has taken place but where slight cracking in the asphalt surfacing only has taken place, give the following analysis.

Course	Actual Thickness (mm)	Material Conversion Factor	CF1	CF2	Effective Equivalent Thickness of $C_{8/10}$ CBGM (mm)
Hot Rolled Asphalt	50	1.25	0.8	1.0	32
Dense Bitumen Macadam	80	1.0	1.0	1.0	80
$C_{1.5/2.0}$ CBGM	150	1.74	1.0	1.0	86
Crushed rock sub-base	250	3.0	1.0	1.0	83
Subgrade CBR 7%					
TOTAL					281

This shows that in the non-rutted area the pavement is equivalent to 281mm of $C_{8/10}$ CBGM. This difference could be significant in that it may be cost effective to design two thicknesses of overlay, one for the rutted areas and one for the non-rutted area, the Hot Rolled Asphalt is contributing little to the integrity of the pavement and may be removed. A cost-effective design may involve removing the Hot Rolled Asphalt in this rutted area and using the depth so created for the extra strengthening material required.

13.8 PAVEMENT EVALUATION – EXAMPLE 2

A cross section of an existing 8m wide by 200m long road is shown in Figure 30. In this example, CBM1 was encountered in the pavement to be overlain.

Settlement has taken place in the subgrade resulting in local deformations of 100mm over much of the pavement. Each course has this settlement. No cracking or spalling has taken place at the surface, although the layer CBM1 is cracked substantially. From the appropriate tables the following table can be constructed showing how each course is transformed to an

equivalent thickness of $C_{8/10}$ CBGM and how the thicknesses of these materials are added.

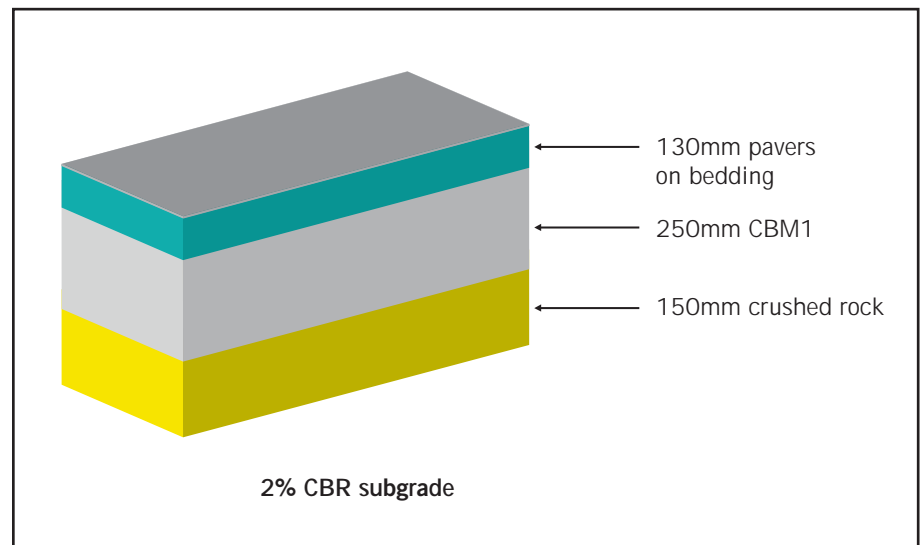


Figure 30. Section through overlay design Example 2.

Course	Actual Thickness (mm)	Material Conversion Factor	CF1	CF2	Effective Equivalent Thickness of $C_{8/10}$ CBGM (mm)
Concrete Blocks and laying course material	130	1.0	1.0	0.3	39
Cement Bound Material 1 (CNM1)	250	1.6	0.5	0.3	23
Crushed Rock sub-base material	150	3.0	1.0	0.3	15
Subgrade CBR 5%					
TOTAL					77

The analysis shows this pavement to be equivalent to 77mm of $C_{8/10}$ CBGM. Had the settlement not taken place, the pavement would have been equivalent to 258mm of $C_{8/10}$ CBGM. In this case, either the pavement was under-designed or no account was taken of a compressible subgrade material. It is possible that the settlement was predicted when the pavement was originally designed, hence the use of concrete blocks.

13.9 PAVEMENT EVALUATION – EXAMPLE 3

A failed in situ C28/35 concrete pavement has previously been strengthened by the application of a Hot Rolled Asphalt (HRA) surfacing course which is still intact. The port is, however, shortly to take delivery of heavier handling plant and wishes to upgrade the pavement further. During the first strengthening operation, photographs were taken of the concrete, which showed it to be substantially cracked (corner cracking and mid-slab cracking) but not spalled or crazed. Slight reflective cracking has occurred in the HRA overlay. There is no rutting. The existing pavement is as shown in Figure 31.

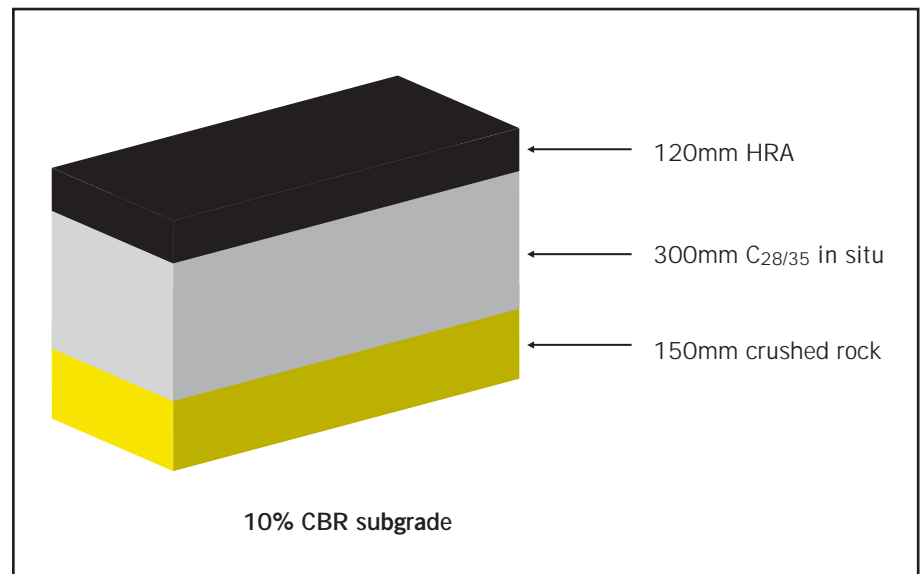


Figure 31. Section through overlay design Example 3.

From the appropriate tables the following table is constructed showing how each course is transformed to an equivalent thickness of $C_{8/10}$ CBGM and how the thicknesses are added.

Course	Actual Thickness (mm)	Material Conversion Factor	CF1	CF2	Effective Equivalent Thickness of $C_{8/10}$ CBGM (mm)
Hot Rolled Asphalt	120	1.25	0.8	1.0	77
In situ Concrete (C28/35)	300	0.62	0.5	1.0	242
Crushed rock	200	3.0	1.0	1.0	67
TOTAL					386

The analysis shows this pavement to be equivalent to 386mm of $C_{8/12}$ CBGM.

The following section describes how, from this information, the selection of the pavement strengthening materials and design of the overlay takes place.

13.10 DESIGN OF OVERLAY

Available overlay Material Equivalence Factors (MEFs) are shown in Table 13. The design procedure is similar for each type of material except that where pavement quality concrete is required as an over-slab, the thickness of equivalent $C_{8/12}$ CBGM slab has to be multiplied by 0.62 before subtracting it from the thickness of the newly designed pavement. This is demonstrated in the following examples.

13.11 DESIGN PROCEDURE

In order to derive the thickness of the overlay it is first essential to design a new pavement structure for the design criteria required, using the new pavement design method. The design criteria are:

- Design Life
- CBR of subgrade
- Single Equivalent Wheel Load (SEWL) of plant
- Type of overlay considered

Full details of the design procedure and calculation the SEWL values are set out in the new pavement design Section.

The designed new pavement consists of a $C_{8/12}$ CBGM base course with concrete block paving surfacing. The equivalent thickness of the transformed pavement is then subtracted from the thickness of the $C_{8/12}$ CBGM base determined from the new pavement Design Chart. This gives the thickness of the overlay. If in situ concrete is to be used, the $C_{8/12}$ CBGM equivalent pavement thickness is multiplied by 0.62 to transform it into an equivalent thickness of C28/35 in situ concrete. This is then subtracted from the thickness of C28/35 concrete required for the new pavement to give the thickness of over-slab required. Note that although the method produces an overlay thickness for $C_{8/12}$ CBGM, other materials can be used as the overlay by using Material Equivalence Factors from Table 13.

13.12 OVERLAY DESIGN – EXAMPLE 4

Existing Situation: An existing pavement comprises the materials shown in Figure 32. The pavement was originally designed to last for 15 years and has been trafficked by straddle carriers operating in narrow lanes. Each straddle carrier has a Single Equivalent Wheel Load (SEWL) of 340kN and the most severely trafficked part of the existing pavement has been subjected to 150 passes per day of straddle carriers of that SEWL. The pavement is in good order except for 15mm deep ruts which occur only in the uppermost Hot Rolled Asphalt course.

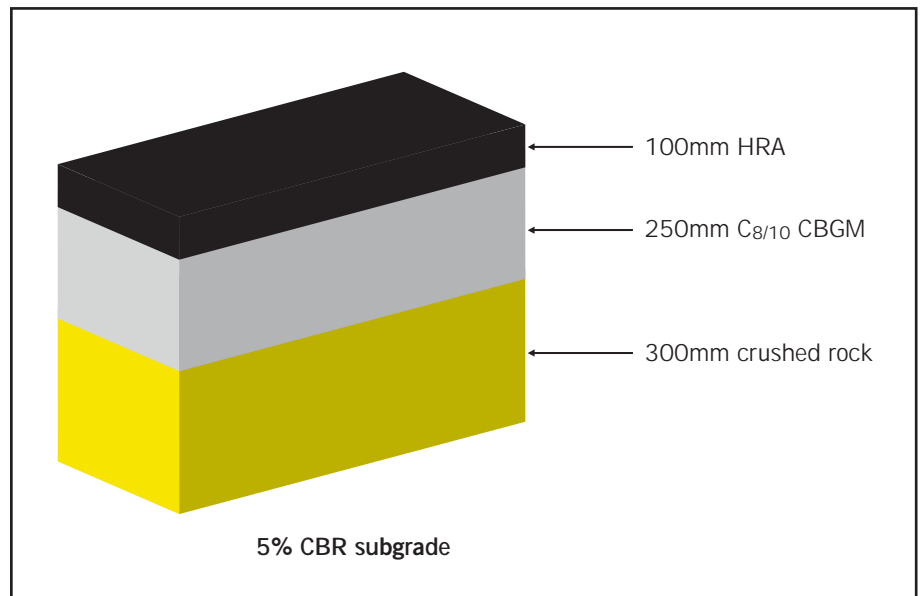


Figure 32. Section through overlay design Example 4.

Proposed use: It is proposed to replace the straddle carriers with front lift trucks (FLT) of SEWL 675kN. The most severely trafficked part of the pavement will carry 200 passes per day of laden FLT. The new pavement is required to last a further 12 years each of 300 working days.

$$\begin{aligned} \text{Number of repetitions of FLT} &= 200 \times 300 \times 12 \\ &= 720,000 \text{ cumulative passes} \end{aligned}$$

Using the new pavement Design Chart the $C_{8/12}$ CBGM thickness required is 625mm (by interpolating between the 250,000 and the 1,500,000 passes curves).

The residual effective thickness of the existing pavement is as shown in the following table.

Course	Actual Thickness (mm)	Material Conversion Factor	CF1	CF2	Effective Equivalent Thickness of $C_{8/10}$ CBGM (mm)
Hot Rolled Asphalt	100	1.25	1.0	0.9	72
$C_{8/10}$ CBGM	250	0.8	1.0	1.0	312
TOTAL					384

Therefore the overlay required is:

$625 - 384 = 241\text{mm}$ so that the strengthened pavement is as shown in Figure 33.

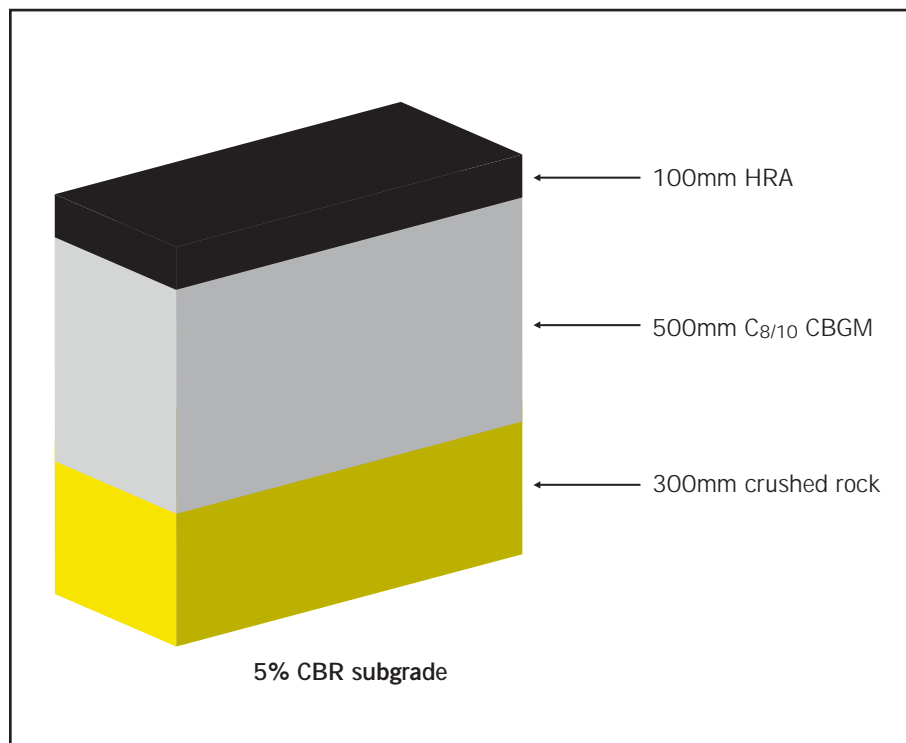


Figure 33. Section through required new pavement for overlay Example 4.

Note that this is not a practical solution, but it forms the basis on which Table 13 can be applied to provide alternative, more suitable overlay materials. A suitable solution is shown in Figure 34.

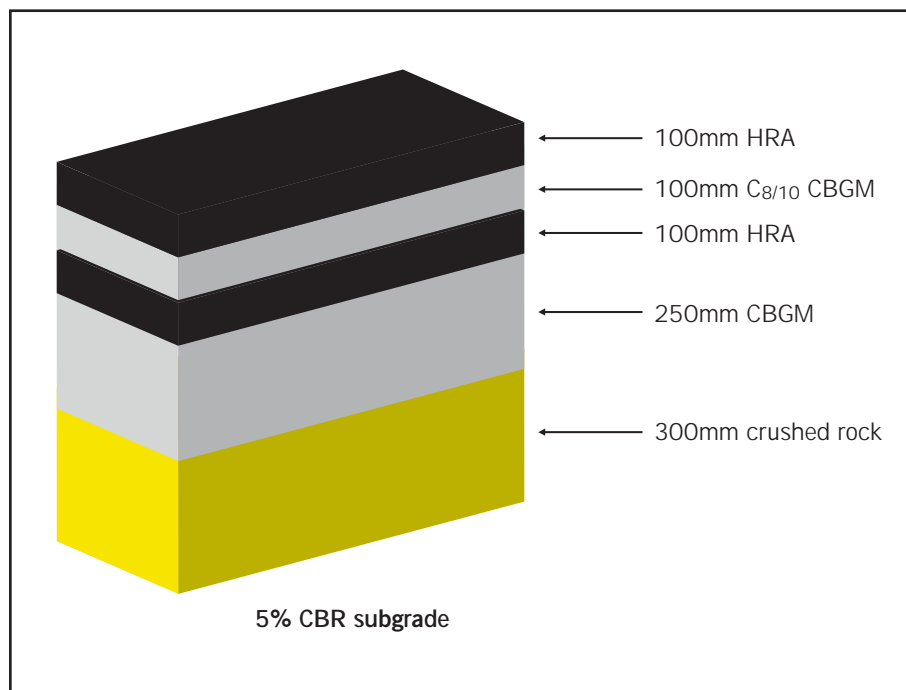


Figure 34. Section through required new pavement for overlay Example 4.

13.13 OVERLAY DESIGN – EXAMPLE 5

Existing Situation: an existing pavement comprises a substantially cracked C25/30 in situ concrete slab overlying 150mm crushed rock sub-base material as shown in Figure 35. The pavement has been trafficked by a terminal trailer system of Single Equivalent Wheel Load (SEWL) 375kN.

The most severely trafficked part of the pavement is subjected to 700 passes per day of a laden terminal trailer. There is no rutting.

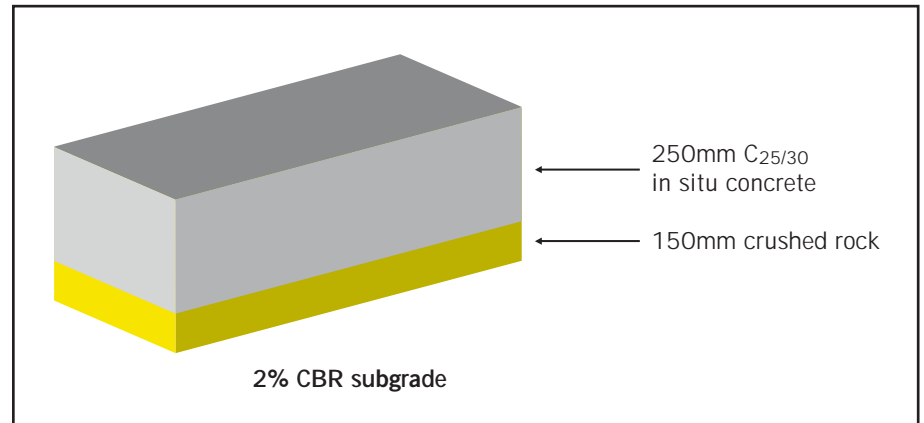


Figure 35. Section of existing pavement Example 5.

Proposed Use: It is proposed to continue with the same operation and two designs are required, one to last 5 years and one to last 25 years, each of 300 working days so that an economic appraisal can be undertaken.

- (i) 5 years number of repetition = $700 \times 300 \times 5$
= 1,050,000
- (ii) 25 years number of repetition = $700 \times 300 \times 25$
= 5,250,000

Using the new pavement Design Chart, pavements of C_{8/10} CBGM base thicknesses 430mm and 560mm respectively are required.

Course	Actual Thickness (mm)	Material Conversion Factor	CF1	CF2	Effective Equivalent Thickness of C _{8/10} CBGM (mm)
C25/30 in situ concrete	250	0.65	0.5	1.0	192
Crushed rock sub-base material	150	3.0	1.0	1.0	50
Subgrade CBR ≤ 5%					
TOTAL					248

Therefore for each of the two alternative future design lives, the additional thicknesses of C_{8/10} CBGM required are:

$$(i) \quad \begin{array}{l} 5 \text{ years} \\ 430\text{mm} - 248\text{mm} \quad = \quad 182\text{mm} \end{array}$$

$$(ii) \quad \begin{array}{l} 25 \text{ years} \\ 560\text{mm} - 248 \text{ mm} \quad = \quad 312\text{mm} \end{array}$$

The two overlain pavements areas shown in Figure 36.

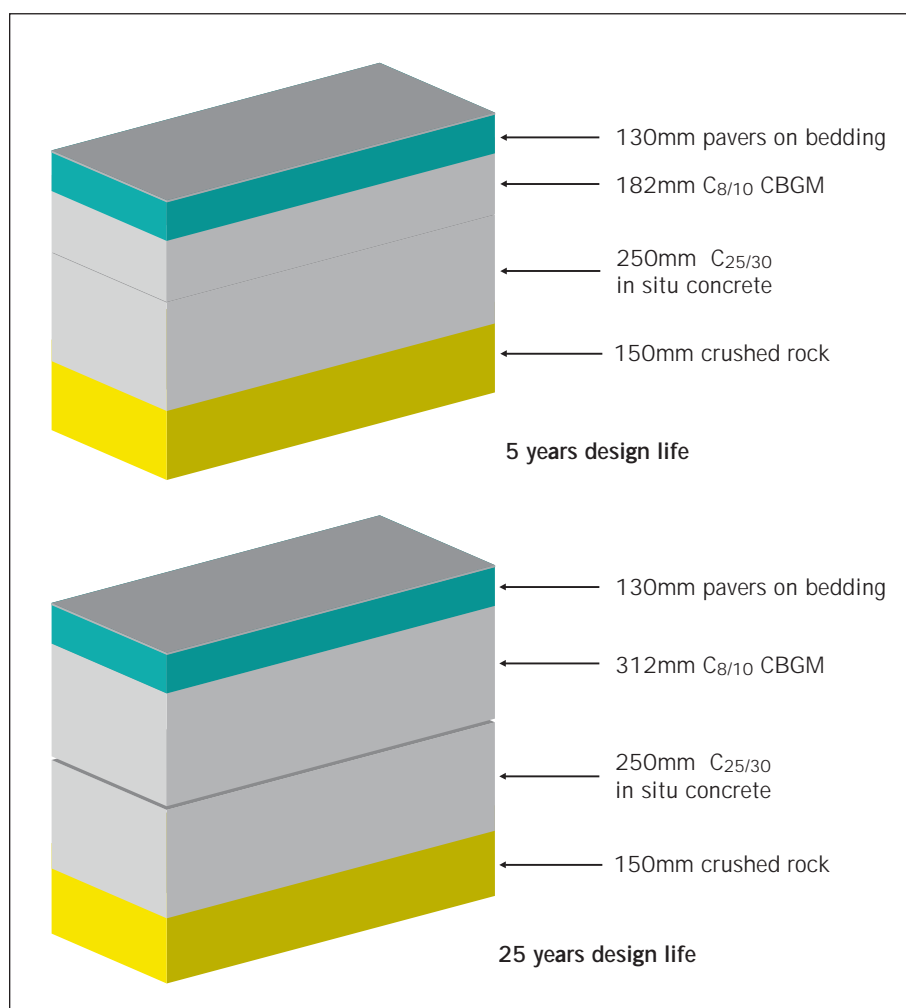


Figure 36. Section of overlay pavement Example 5 for 5 years and 25 years design lives.

13.14 OVERLAY DESIGN – EXAMPLE 6

Existing situation: In example 5, the 25 years design life pavement was constructed and has been in service for 10 years. Rutting is less than 10mm and no other deterioration is evident.

A recent investigation has shown the original CBR values of 2% have changed to 7% owing to long term moisture movement in the subgrade.

Proposed Use: The port proposes to introduce a LO/LO operation involving the use of terminal trailers with SEWL of 300kN. How long is the existing pavement likely to remain serviceable?

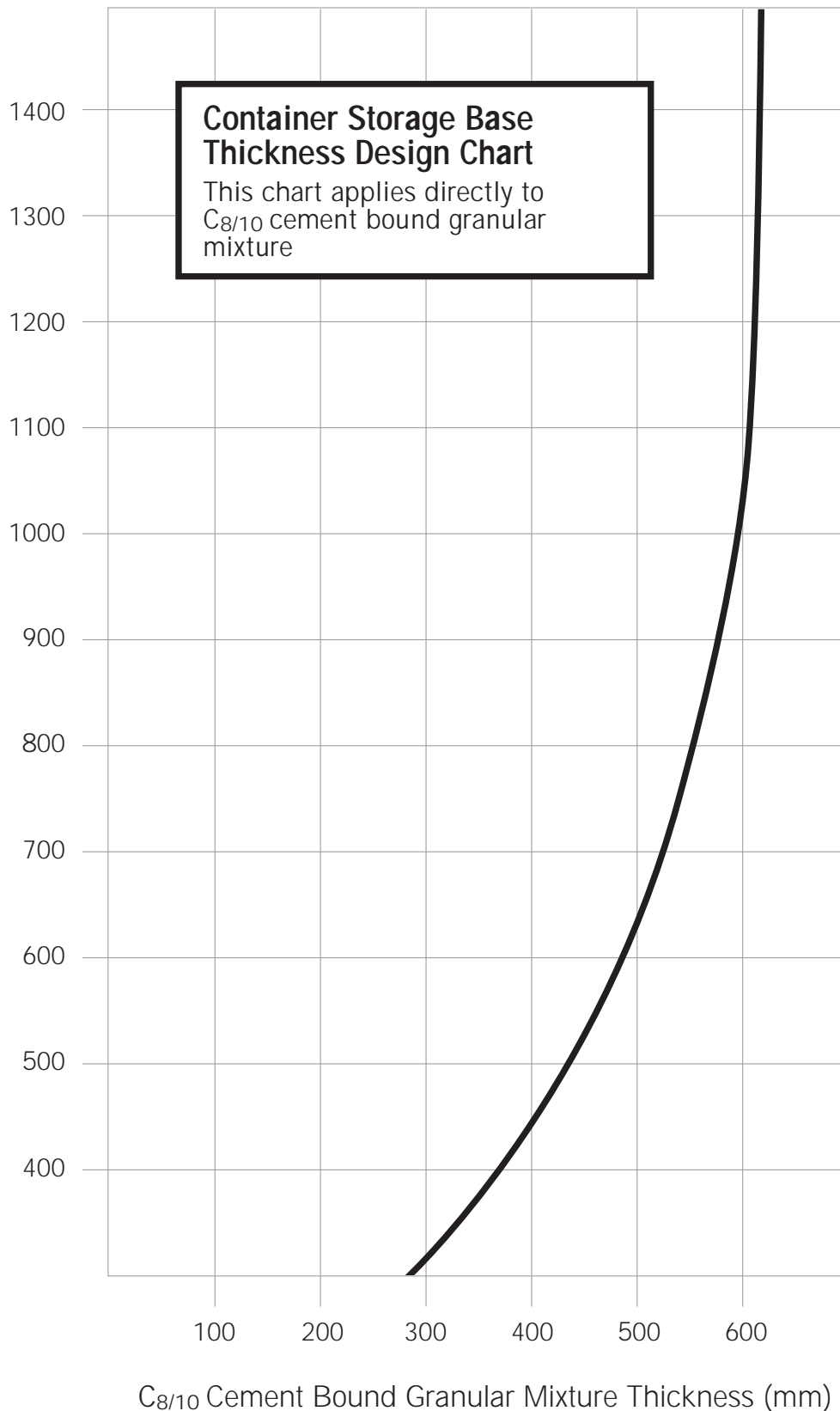
Firstly the existing previously strengthened pavement shown in Figure 36 is analysed to determine its effective $C_{8/10}$ CBGM equivalent thickness in the following table.

Course	Actual Thickness (mm)	Material Conversion Factor	CF1	CF2	Effective Equivalent Thickness of $C_{8/10}$ CBGM (mm)
$C_{8/10}$ CBGM	120	1.0	1.0	1.0	120
C25/30 in situ concrete	250	0.65	0.5	1.0	192
Crushed rock sub-base material	150	3.0	1.0	1.0	50
Subgrade CBR \leq 5%					
TOTAL					362

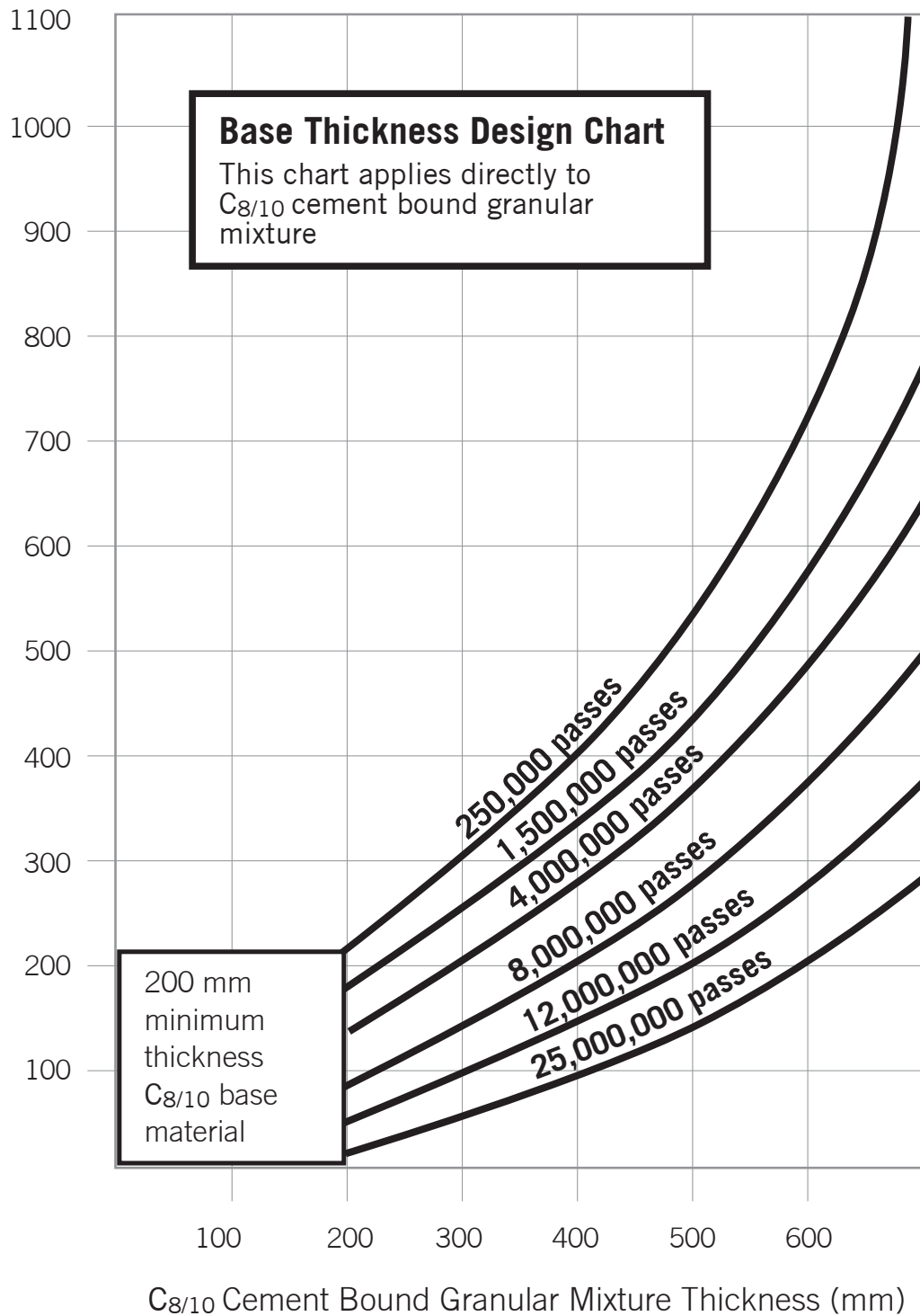
Using the Design Chart shows that a base of 362mm $C_{8/10}$ CBGM corresponds with a design life of 1,500,000 repetitions of a 300kN SEWL vehicle.

14. DESIGN CHARTS

Single Equivalent Wheel Load (kN)



Single Equivalent Wheel Load (kN)



REFERENCES AND BIBLIOGRAPHY

A) BRITISH & EUROPEAN STANDARDS

BS EN 1338:2003 *Concrete paving blocks – Requirements and test methods*. BSI London.

BS 7533-1:2001 *Pavements constructed with clay, natural stone or concrete pavers. Part 1: Guide for the structural design of heavy duty pavements constructed of clay pavers or precast concrete paving blocks*. BSI London.

BS 7533-3:2005 *Pavements constructed with clay, natural stone or concrete pavers: Part 3: Code of practice for laying precast concrete paving blocks and clay pavers for flexible pavements*. BSI London.

BS 7533-13 (Draft) *Pavements constructed with clay, natural stone or concrete pavers. Part 13: Guide for the structural design of Permeable Pavements*. Under development by BSI Committee B/507 Paving units, kerbs, screeds and in situ floorings. BSI London.

BS EN 14227-1:2004 *Hydraulically bound mixtures- Specifications – Part 1: Cement bound granular mixtures*. BSI London.

BS EN 14227: Part 2: 2004 *Hydraulically bound mixtures – Specifications. Part 2: Slag Bound Mixtures*. BSI London.

BS EN 14227: Part 3: 2004 *Hydraulically bound mixtures – Specifications. Part 3: Fly Ash Bound Mixtures*. BSI London.

BS 8500: Part 1: 2006 *Concrete – Complementary British Standard to BS EN 206-1. Part 1: Method of specifying and guidance for the specifier*. BSI London.

BS 8500: Part 2: 2006 *Concrete – Complementary British Standard to BS EN 206-1. Part 2: Specification for constituent materials and concrete*. BSI London.

BS 5328-1:1997 *Concrete – Part 1: Guide to Specifying Concrete*. BSI London. (Now superseded but referred to for historical perspective.)

BS 4987-1:2005 *Coated macadam (asphalt concrete) for roads and other paved areas. Part 1: Specification for constituent materials and for mixtures*. BSI London.

BS 4987-2:2003 *Coated macadam (asphalt concrete) for roads and other paved areas. Part 2: Specification for transport, laying and compaction.* BSI London.

BS 434-1:1984 *Bitumen road emulsions (anionic and cationic). Part 1: Specification for bitumen road emulsions.* BSI London.

BS 434-2:1984 *Bitumen road emulsions (anionic and cationic). Part 2: Code of practice for use of bitumen road emulsions.* BSI London.

BS EN 13877-1:2004. *Concrete Pavements. Part 1. Materials.* BSI London.

BS EN 13877-2:2004. *Concrete Pavements. Part 2. Functional requirements for concrete pavements.* BSI London.

BS EN 13877-3:2004. *Concrete Pavements. Part 3. Specifications for dowels to be used in concrete pavements.* BSI London.

BS 1377 Parts 1 to 9:1990. *Methods of test for Soils for civil engineering purposes.* BSI London.

Part 1: General requirements and sample preparation.

Part 2: Classification tests.

Part 3: Chemical and electro-chemical tests.

Part 4: Compaction related tests.

Part 5: Compressibility, permeability and durability tests.

Part 6: Consolidation and permeability tests in hydraulic cells and with pore pressure measurement.

Part 7: Shear strength tests (total stress).

Part 8: Shear strength tests (effective stress).

Part 9: In situ tests.

B) PREVIOUS EDITIONS OF THIS PUBLICATION

First Edition (1982)

Knapton, J. (1982) *The Structural Design of Heavy Duty Pavements for Ports & Other Industries.*

British Ports Association, London.

Second Edition (1988)

Knapton, J. (1988) *The Structural Design of Heavy Duty Pavements for Ports & Other Industries.*

British Ports Federation, London.

Third Edition (1996)

Knapton, J & Meletiou, M (1996). *The Structural Design of Heavy Duty Pavements for Ports and Other Industries*. ISBN 0 9500347 1 1. Interpave, British Precast Concrete Federation, Leicester, UK.

C) OTHER PUBLICATIONS

Interpave (2008). *Permeable Pavements. Guide to the design, construction and maintenance of Concrete Block Permeable Pavements*. 5th Edition, 2008. Interpave. The British Precast Paving and Kerb Association, Leicester, UK.
Uniclass L534:L217 Available at www.paving.org.uk

UK Highways Agency's *The Manual of Contract Documents for Highway Works, Volume 1, Specification for Highway Works – Series 800, 900 & 1000*.
Available at: www.standardsforhighways.co.uk

Hunter, RN (2000). *Asphalts in Road Construction*. Thomas Telford Publishing, London. ISBN: 0 7277 1683 2.

Kennedy, J (2006). *Hydraulically-bound Mixtures for Pavements. Performance, behaviour, materials, mixture design, construction and control testing*. The Concrete Society, Surrey, UK. ISBN: 1 904482 28 7. See www.concrete.org.uk

Knapton, J (2003). *Ground Bearing Concrete Slabs*. Thomas Telford Publishing, London. ISBN: 0 7277 3186 6.

Meletiou, M & Knapton, J (1987 & 1990). *Container Terminal Pavement Management*. UNCTAD Monograph on Port Management No. 5 (Original document published in 1987 & Supplement published in 1991). United Nations, Geneva.

Nunn, M (2004). *Development of a more versatile approach to flexible composite pavement design*.
TRL Report TRL615 (2004).

Geo-Slope (2007). *Stress-Deformation Modelling with SIGMA/W 2007*. Geo-Slope International, USA.
See www.geo-slope.com



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