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ROAD FOUNDATION DESIGN FOR MAJOR UK HIGHWAYS

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by B Chaddock and C Roberts

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Client:	**Asset Management Performance, Pavements, SSR** **Highways Agency** **(Mr W Lloyd)**

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Executive summary

The Design Standard HD 26 (2006) provides pavement designs for flexible construction (including pavements previously known as flexible composite), rigid (continuous) construction and rigid (jointed) construction. The pavement design thicknesses are based on four foundation stiffness classes FC1, FC2, FC3 and FC4, which are defined as the long-term, equivalent half-space stiffness of the composite foundation under the completed pavement of 50, 100, 200 and 400 MPa respectively.

Interim Advice Note IAN 73 (2006) provides foundation designs for the four foundation classes. Two design approaches are given in IAN 73 (2006). The first approach is for ‘Performance Related Designs’ that cover all four foundation classes and provide flexibility to the designer. These designs recognise that not all materials of a particular type necessarily have equal engineering properties. Consequently, the Performance Related Designs are only to be used in conjunction with the ‘Performance Related Specification’ for foundation materials given in IAN 73 (2006) in which the foundation is tested in situ. This procedure gives the client some assurance that the foundation is likely to achieve its designated long-term support for the overlying pavement. The second approach provides a limited number of conservative ‘Restricted Designs’ for foundation classes FC2 and FC3 (and foundation class FC1 on non-Trunk Roads) that are primarily intended for schemes of limited extent.

This report describes how the methods to design foundations for the four foundation classes evolved. A description is given of a ‘two-stage’ design method that is based on the most conservative of the designs for the ‘shortly after construction’ and the ‘long-term’ stages in the life of a road. Then an outline is given of a procedure to check foundation designs at an ‘intermediate stage’ to reduce risk of non-compliance with the Performance Related Specification when adequate information on material properties and the construction programme is available. Finally, for simplification, a ‘single-stage’ method is described that produces conservative designs.

The design methods use a linear elastic, multi-layer model of road foundations that consists of subbase and/or capping on a layered subgrade, whose bottom layer is a stiff, semi-infinite structure. These foundations are theoretically loaded by a standard wheel load and selected structural responses are calculated and compared with criteria that are chosen to limit subgrade deformation and foundation deflection. The model has been calibrated to replicate the previous designs given in HD 25 (1994) to provide continuity of experience. Given the stiffnesses of the upper foundation layers, the model is used to calculate values for subbase/capping thickness that satisfy the dominant design criterion and produce the designated foundation class. The success of the model is crucially dependent on realistic values of stiffness being selected for the upper foundation layers. It should be understood that these stiffnesses will often differ markedly from the stiffnesses measured in the laboratory where environmental effects of moisture and frost and, for bound materials, the degrading effects of cracks are not taken into account. In addition, minimum subbase thicknesses are imposed of 150 mm for FC1 and FC2, 175 mm for FC3 and 200 mm for FC4.

The designs of IAN 73 (2006) were produced using the single-stage design method. This report describes the derivation of both Performance Related Designs and Restricted Designs. Examples of Performance Related Designs are given for all four classes of capping/subbase only foundations as well as designs for classes FC2 and FC3 of subbase on capping foundations. Pre-selected thicknesses of capping of between 150 mm and 250 mm, depending on subgrade CBR (California Bearing Ratio) strength, were adopted as a practical option for these subbase on capping designs. Although the design examples proposed are considered to be pragmatic, the theoretical method described will allow alternative designs to be produced. Restricted Designs are provided for a limited number of materials and are confined to foundation classes FC2 and FC3 for subbase only foundations and to foundation class FC2 for subbase on capping foundations. The conservatism of these designs is attained by use of increased layer thicknesses and/or superior materials over that required for equivalent Performance Related Designs.

All example designs are provided as charts and, for the Performance Related Designs, equations are also given to permit interpolation of the graphical data with reasonable precision.

1 Introduction

Previously, Powell et al (1984) described a method for designing bituminous pavements that was based on road trials, which were analysed by a theoretical model of the pavement and its foundation. In this model, the pavement and foundation were represented by a series of linear elastic layers on a soil subgrade and were loaded at the pavement surface to simulate traffic. The model predicted the values of stresses, strains and deflections that were induced within this loaded structure. For design, materials for the pavement and foundation were chosen and their layer thicknesses calculated to ensure that the traffic induced strains at critical locations in the pavement and foundation were less than permissible values. The allowed values of these target strains were derived from an analysis of roads on the UK network and were chosen to achieve a desired structural performance.

As part of this design procedure, the road foundation was initially designed to act as a construction platform for the pavement. For subbase laid directly on soil subgrades, Powell et al (1984) describes empirical trafficking trials in which values of subbase thickness to support various amounts of construction traffic were deduced for a range of subgrade CBR strengths. The linear elastic, multi-layer model was also adopted, where a load was applied directly to the foundation surface to simulate construction traffic loading. The transient stresses transmitted to the soil subgrade induced elastic subgrade strains that were limited to prescribed values by choice of subbase thickness. The two methods of selecting subbase thickness were in adequate agreement. For subbase on capping designs of the Department of Transport (1985) then in current use, values for capping thickness were shown by Powell et al (1984) to be conservative. This work by Powell et al (1984) formed the basis of the national UK Standards for road foundations given in HD 25 (1994).

Use of these “standard” foundations was aimed at avoiding the construction of weak foundations, which could markedly affect the pavement construction. By pre-selecting the foundation structure, pavement design was simplified to a choice of pavement materials and their thicknesses. A degree of flexibility, however, to take advantage of available materials was also encouraged by permitting self compensating changes in foundation and pavement design, as long as assurance could be given that the final design could be constructed without major difficulty. The use of materials superior to traditional unbound granular materials was not encouraged by this approach as an analytical design with justification of material parameters adopted and a departure from Standards was required for each specific road scheme. A more formalised approach was required in which reductions in pavement thickness were readily quantified when pavements were built on superior foundations of defined quality. This new approach, initially described by Nunn (2004), is now incorporated into the Pavement Design Standard HD26 (2006).

The Design Standard HD 26 (2006) provides pavement designs for flexible construction (including pavements previously known as flexible composite), rigid (continuous) construction and rigid (jointed) construction. The pavement thicknesses are based on four foundation stiffness classes, which are defined as the long-term, equivalent half-space stiffness of the composite foundation under the completed pavement, as follows:

- Foundation Class 1 ≥ 50 MPa;
- Foundation Class 2 ≥ 100 MPa;
- Foundation Class 3 ≥ 200 MPa;
- Foundation Class 4 ≥ 400 MPa.

The pavement thicknesses are reduced when supported by stronger and stiffer foundations.

Interim Advice Note, IAN 73 (2006) provides designs of road foundations for the four foundation classes. Two design approaches are given in IAN 73 (2006).

The first approach is for ‘Performance Related Designs’ that cover all four foundation classes and provide flexibility to the designer. The Performance Related Designs recognise that not all materials of a particular type necessarily have equal engineering properties. Consequently, the Performance Related Designs are only to be used in conjunction with the ‘Performance Related Specification’ for foundation materials given in IAN 73 (2006) in which the foundation is tested in situ to give the client some assurance that the foundation is likely to achieve its designated long-term support for the overlying pavement.

The second approach provides a limited number of conservative ‘Restricted Designs’ for foundation classes FC2 and FC3 (and foundation class FC1 on non-Trunk Roads) that are particularly intended for schemes of limited extent.

This report describes the role of the foundation and the development of the design method on which the designs of IAN 73 (2006) are based. The design method is calibrated to replicate the previous designs given in HD 25 (1994) to provide continuity of experience. The design method is used to produce examples of Performance Related Designs. The report also describes the derivation of the Restricted Designs that are provided for a limited number of materials.

2 The role of the road foundation

The foundation is the structure that is required to carry out the following roles:

- To protect the subgrade against the effects of the environment.
- To provide a platform on which to construct the pavement.
- To provide support to the overlying pavement throughout the service life of the road.

The road foundation comprises the subgrade and a subbase layer. A capping layer or soil improvement layer may also be used between the subgrade and subbase. Capping and subbase materials have a low thermal conductivity and therefore placement of these materials on the subgrade insulates it, to some degree, from damage by frost. Foundation materials may also protect the subgrade from the effects of rainfall.

During road construction, the upper foundation layers reduce the stresses induced in the subgrade by construction plant and vehicles that cause subgrade deformation. Good design of the foundation layers for the anticipated site traffic can control this deformation.

Once the road is opened to traffic, a well designed pavement and foundation act together to reduce the stresses on the subgrade caused by traffic loading in such a way that the deformation in the subgrade is limited to an acceptable level during the service life of the road. The foundation also provides support to the pavement layers so that traffic induced stresses within the pavement are controlled and pavement life is maximised.

3 The foundation design method

3.1 Outline

The foundation design procedure presented in this report and illustrated in Figure 1 is a two-stage process. The initial stage shortly after construction ensures that the foundation can be used by construction traffic without excessive deformation; the latter stage estimates the long-term support of the foundation for the pavement towards the end of its design life.

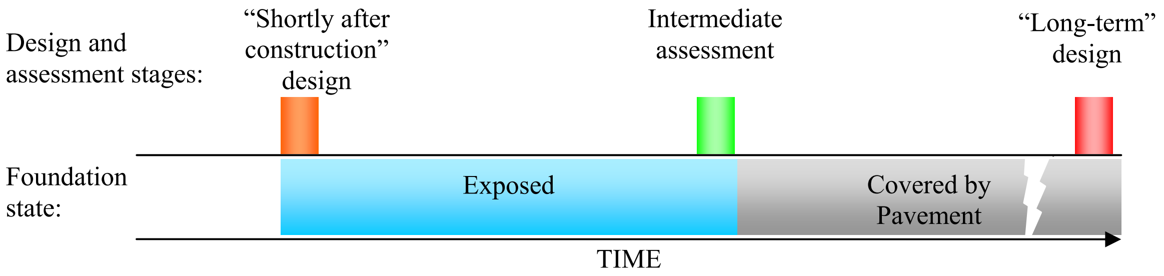


Figure 1. Foundation design and assessment stages

A simplified and pragmatic, single-stage design approach that combines the construction and long-term stages, however, is used as the basis for the foundation designs derived in this report. A method of assessing the foundation at an intermediate stage shortly prior to paving is also proposed to predict whether the foundation will satisfy the Performance Related Specification of IAN 73 (2006).

3.2 Material characterisation

3.2.1 Subgrade

The subgrade layer has traditionally been characterised in terms of its strength, given as a CBR value. HA 44/91 (DMRB 4.1.1) describes methods for the estimation of both the short-term construction CBR strength and the long-term equilibrium CBR strength of the subgrade within the pavement. For design purposes, however, the short-term and long-term CBR values have traditionally been transformed into design stiffness values using the equation given in Powell et al (1984). This equation was derived for soils of CBR in the range of 2 to 15 per cent. Although stiffness rather than strength are preferred for structural design, the methods of characterising the long-term stiffness of a subgrade are not yet fully established. Also, for the construction phase, strength is an important measure for the subgrade. The existing system of characterising the subgrade, based on CBR strength, is therefore recommended until laboratory and in situ equipment and test procedures are sufficiently developed for the wide range of materials likely to be encountered.

Conventional foundation and pavement design utilise an infinitely deep, uniform half-space to represent the subgrade. This mathematical assumption is not a true representation. The upper portion of the subgrade is more important for the pavement response; whereas foundation deflection calculated using the half-space assumption includes a component of displacement from deep in the subgrade and hence results in a larger deflection under a modelled wheel load than is observed in practice. For this reason, it is difficult to simulate the observed pavement support of foundations in the analytical model without some modification to account for the unrepresentative influence of the assumed half-space. This problem is overcome by the adoption of a stiff half-space at a depth in the subgrade selected as described in detail in Appendix A.

3.2.2 Capping and subbase

The design method, ideally, requires consideration of the characterisation of the stiffness of the subbase and capping materials for two primary stages in the life of a pavement; namely the road construction and the long-term stages. During construction, hydraulically bound foundation materials are unlikely to have fully cured, although those materials bound primarily with Portland cement would have achieved a large proportion of their potential structural capacity. In the long-term, all of these foundation materials would have fully cured. The properties of bound materials may be degraded by cracks and their environmental condition with the effects of these factors being different for the construction and long-term conditions. For unbound granular material, confinement by the pavement may result in a higher long-term stiffness. This potential may not be realised during the service life of the road, however, if the material becomes contaminated with plastic fines or contains excess water due to inadequate drainage. For these reasons, it is often assumed that there is effectively only one condition for unbound granular material. The characterisation of the stiffness of the various layers of the foundation must therefore be appropriate to the stage in the life of the pavement and the nature of the material; that is, whether it is an unbound granular material, quick curing hydraulically bound material or slow curing hydraulically bound material.

3.3 Initial stage: Foundation shortly after construction

Shortly after construction of the upper foundation layers, the foundation is subjected to construction traffic. The foundation should provide a deformation resistant platform. As with the foundation design principles presented by Powell et al (1984), the foundation is designed in this work so that it is capable of carrying up to 1000 standard axles (sa) of traffic with no more than 40 mm deformation at the top of subbase. Where a capping is used, a safety factor was adopted in the designs given in HD25 (1994) but has been omitted in the following procedure because quality assurance tests are required for the Performance Related Designs.

Figure 2 illustrates the model used to design the foundation shortly after construction.

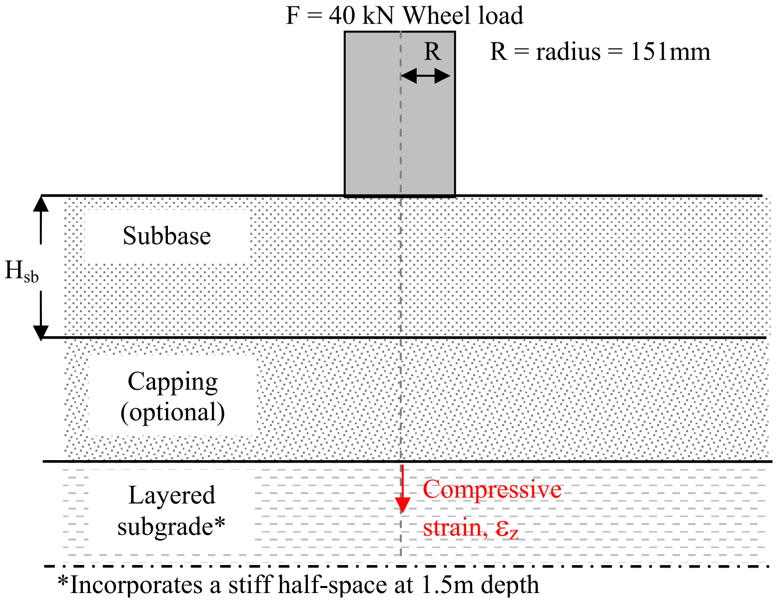


Figure 2. The design model for foundations at construction

In order to design the foundation at construction, the following design criteria are used:

- The vertical compressive strain (ε_Z) in the top of the subgrade. The structural response is limited so that excessive deformation does not occur.
- A minimum subbase thickness (H_{sb}).

The properties of the subbase layer and capping layer, if used, should be estimated for the time when the first construction traffic is carried. The subgrade properties should also be appropriate to the construction phase and estimated using the methods given in Powell et al. (1984) and HA44 (1991).

3.4 Final stage: Foundation in the long-term

In the long-term stage, the foundation is confined within the completed pavement that, for fully flexible pavements, has been represented by the theoretical model of Powell et al (1984) shown in Figure 3. The asphalt pavement layers are combined into a single layer over foundation layers of subbase and, if used, capping that are placed on the subgrade. The critical pavement responses are the horizontal tensile strain at the bottom of the pavement layer and the vertical compressive strain at the top of the subgrade.

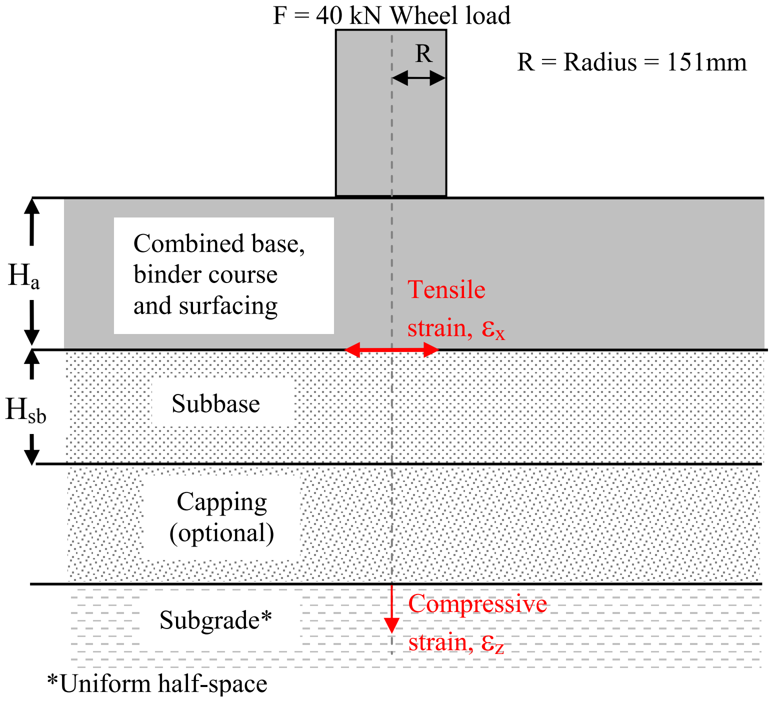
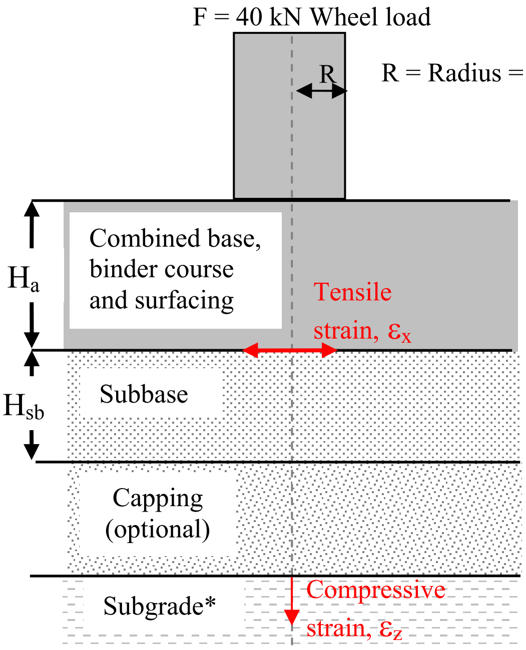


Figure 3. Theoretical pavement design after Powell et al (1984)

This model, however, was not adopted in this work to design the foundation for the following reasons:

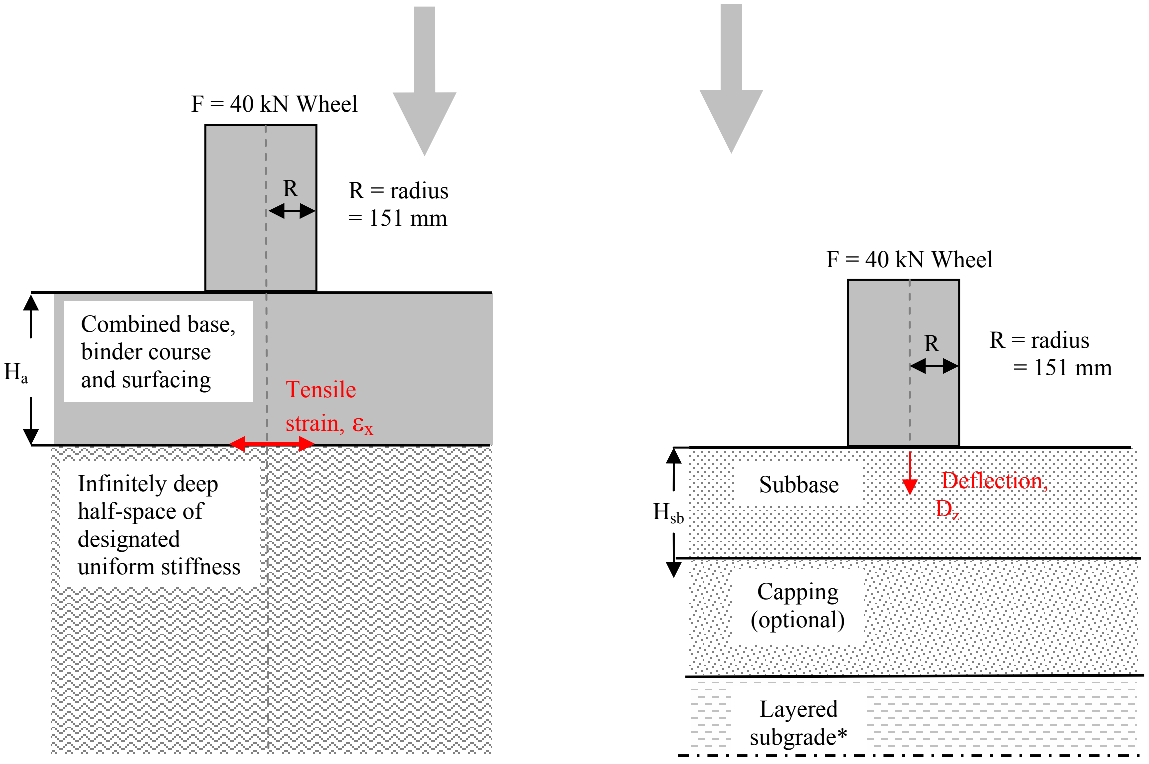
- As properties of the foundation are required to design the overlying pavement, there is the possibility of creating a recursive loop between the thicknesses of the foundation and the pavement layers unless there are constraints on either the foundation or pavement layers.
- There have been numerical problems when using superior foundation materials; that is, bound not unbound materials, in the standard analytical model. The model requires that the position of maximum tensile strain in the pavement be at the underside of the pavement layers and therefore the structural properties of the pavement layers should be superior to those of the layers below. Strong foundation materials with a high stiffness modulus challenge these requirements and can lead to unrealistic designs.
- Nunn (2004) reported work that was a development of the concepts presented by Powell et al (1984). In the more recent document, a fundamental change of approach was adopted in which the foundation layers were treated as a half-space characterised by a uniform equivalent stiffness, whereas previously the properties of each of the foundation layers on an infinitely deep, uniform subgrade were specified as in Figure 3. This change has been effected, in part, to overcome the numerical analytical problems associated with superior materials in the foundation. The foundation half-space was assigned four classes of stiffness 50, 100, 200 and 400 MPa.

For these reasons, the theoretical model shown in Figure 3 and repeated in Figure 4A was split into two parts; namely, the pavement design model and the foundation design model as illustrated in Figures 4B and 4C respectively.



*Uniform half-space

Figure 4A. Theoretical pavement design after Powell et al (1984)



*Incorporates a stiff half-space at 1.5m depth

Figure 4B. Theoretical pavement model after Nunn (2004)

Figure 4C. Adopted theoretical foundation model (Refer to Appendix A)

Figure 4. Evolution of pavement and foundation design

The pavement design model of Nunn (2004) shown in Figure 4B comprises, for fully flexible pavements, the combined asphalt pavement layer as adopted in Figure 4A. This layer, however, is now placed on a half-space of uniform stiffness of 50, 100, 200 or 400 MPa. The critical structural response is, as before, the horizontal tensile strain at the bottom of the pavement layer. The pavement design model confines itself to calculating the combined thicknesses of prescribed base, binder course and surfacing materials that are appropriate for the selected foundation class or half-space stiffness. This approach is also applicable to flexible composite pavements as described by Nunn (2004). The foundation design model of Figure 4C comprises the subbase and capping layers, if used, on a layered subgrade. The critical structural response is the vertical deflection of the foundation. Foundation design to a given foundation class that is described in this report selects thicknesses of prescribed subbase and, if used, capping materials appropriate for the soil subgrade strength.

In order to design the foundation for the long-term stage, the following design criteria are used:

- Surface deflection of the foundation to ensure that it meets the demands of the assigned foundation class.
- A minimum subbase thickness (H_{sb}).

This design stage should encompass the long-term behaviour of the foundation in the completed pavement. The subgrade strength, therefore, should be applicable to the long-term when its equilibrium strength has been attained and be selected, for example, using the methods given in Powell et al (1984) and HA44/91. For bound materials, the stiffness of the subbase and, if used, capping should be appropriate to an age of at least one year and the degrading effect of cracks should be taken into account as these layers approach the end of their design life but still retain significant structural capacity that can be utilised by timely structural maintenance.

In Figure 4C, the loading of 40 kN over a circular contact area of radius 0.151m on the top of subbase is maintained for simplicity although, in practice, the nominal wheel load will be carried over a larger area due to load spreading by the pavement. But a standard loading configuration at the foundation surface and a fixed foundation deflection criterion for a given foundation class are preferable to adopting a variable loading and deflection criteria that is dependent on the particular pavement structure envisaged. This approach should not cause inaccuracies in the above model as long as the layer stiffnesses of the foundation materials are selected such that they are representative of their in situ behaviour under the actual stress conditions encountered. The advantage of the above representation will become obvious in Section 3.6.2 where the above design approach is further simplified by combining the ‘shortly after construction’ and the ‘long-term’ design stages.

3.5 Design criteria

The design criteria to be used in the ‘Shortly after construction’ and ‘Long-term’ design stages are as given in Table 1.

Table 1. Design criteria

Label	Criteria	Permissible values		Stage
ε_z	Vertical compressive strain at the top of the subgrade	Maximum subgrade strain ($\mu\varepsilon$) for:	Soil subgrade CBR range (%)	Shortly after construction
		$\varepsilon_z < (403.7*CBR+1024)*k_f$	>2.5 to ≤5	
		$\varepsilon_z < (-31.03*CBR + 3210)* k_f$	>5 to ≤ 15	
		$\varepsilon_z < (-2752*Log_{10}(CBR) + 5947)* k_f$	>15 to ≤ 30	
		,where k_f = 1		
D_z	Deflection of the foundation surface	Maximum deflection [1] (microns) for:	Foundation class	Long-term
		2960	FC1	
		1480	FC2	
		740	FC3	
		370	FC4	
H	Thickness of the upper foundation layer	Minimum thickness (mm) for:	Foundation class	Both stages
		150 mm	FC1 and FC2	
		175 mm	FC3	
		200 mm	FC4	

{[1]Applied load of 40kN over a circular area of radius 0.151m. Poisson’s ratio of half-space is 0.35}

The vertical compressive subgrade strain criterion (**ε_z**) is based on that adopted by Powell et al (1984) but amended to reproduce the subbase only designs of HD 25 (1994) for a layered subgrade as described in Appendix A. This criterion not only prevents deformation in the foundation, but also acts as a proxy for the minimum level of support available to the subbase layer above. In Powell et al (1984) and HD 25 (1994), where a capping was used, the capping was assumed to be of inferior and variable quality compared to the subbase and the permitted level for strain in the subgrade was reduced by the introduction of a safety factor (k_f). In HD 25 (1994), k_f was approximately 2. In this report, where capping materials are specified, a factor of safety is not adopted (k_f=1) as quality assurance procedures are to be adopted for Performance Related Design foundations.

The foundation class assignments are those that were adopted by Nunn (2004) and relate to the support to the pavement by four foundation classes FC1, FC2, FC3 and FC4, which provide an equivalent uniform half-space stiffness of 50, 100, 200 and 400 MPa respectively. The deflections (**D_z**) given in Table 1 are those predicted for these four foundation half-space stiffnesses under an applied load of 40 kN over a circular area of radius 0.151 m.

The minimum thickness (**H**) of the capping/subbase layer for foundation classes FC1 and FC2 is taken to be 150 mm as this thickness is considered to be the minimum practical thickness for spreading and compaction of foundation layers. For foundation class FC3 and FC4, minimum thicknesses of 175 mm and 200 mm respectively are adopted to reduce the possibility of the fracture of a thin, brittle bound layer especially when laid on a soil that is temporarily weaker than expected.

3.6 Application of design method

3.6.1 Two-stage method

Using the design method, thicknesses of foundation layers are calculated that satisfy the prescribed limits placed on the critical elastic responses and, if necessary, are increased to comply with the minimum thickness requirements. Ideally, for efficient design, the appropriate calculations should be carried out for each of the various stages in the foundation's life that are given in Table 2; that is, shortly after construction and in the long-term, and the most conservative design adopted. The material properties should be appropriate for each of these primary design stages.

Table 2. Idealised design stages and required material properties

Construction stage	Timing of design stage	Reference	Material properties	
Unpaved	Shortly after construction	Section 3.3 and Figure 2	Subbase/capping layer stiffness	At time of first trafficking
			Subgrade CBR/stiffness	In the short-term
Paved	Long-term	Section 3.4 and Figure 4C	Subbase/capping layer stiffness	In the long-term
			Subgrade CBR/stiffness	In the long-term or when in its equilibrium condition

3.6.2 Simplified single-stage method

The two-stage method requires detailed information on material properties that are dependent on the particular materials adopted and the site conditions prevailing at various times at each individual construction site. For example, the layer stiffness of a slow curing hydraulically bound material (HBM) will depend on how quickly it cures and the extent of internal cracking. The rate of curing is influenced by ambient temperature, whereas the severity of cracking, in part, may be dependent on the amount of construction traffic the foundation has carried. To produce foundation designs in advance of knowing these site specific conditions requires simplifications and conservative assumptions and this has resulted in the 'shortly after construction' and the 'long-term' design stages being combined into a 'single-stage' design process.

In more detail, these simplifications are as follows:

- The lowest envisaged subgrade strength of the strengths occurring shortly after construction and in the long-term should be adopted.
- For the stiffness of the foundation layers overlying the subgrade; that is, subbase and/or capping, the lowest of the values appropriate for the construction and long-term situations should normally be used at the cost of increased conservatism. This rule should be applicable to unbound materials and also to quick curing materials, but an exception may need to be made for slow curing HBMs. Unless there is evidence to the contrary, the design layer stiffness for various material types should be deduced as follows:
    - For unbound granular material, the likely lowest stiffness will occur shortly after foundation construction as confinement by the pavement may result in a higher long-term stiffness. This deduction assumes that the subbase does not become contaminated whilst in-service and is adequately drained.
    - For quick curing, cement bound granular material that is not trafficked for several days, normally 7 days, from the time of construction, current information suggests that the

likely lowest stiffness of the layer will occur in the long-term. This value is estimated by applying a default long-term degradation factor of 0.2 to an estimate of the fully cured material stiffness. This factor allows for cracks and other degrading processes in the bound material. As most curing will have occurred for these materials by one year, then short-term measurements at an age of 28 days could be extended to one year by accepted ageing factors.

o For other HBMs, the same process as used for cement bound granular material is currently recommended with the exception that IAN 73 (2006) currently requires a lower default long-term degradation factor of 0.1 to be adopted. This factor should be reviewed on a material by material basis as experience of their long-term behaviour in the UK is acquired. In addition, it is emphasised that design amendments may be necessary for slow curing HBMs on a site specific basis to avoid foundation (including subgrade) damage. In these cases, information on which to base the design amendments should be obtained from trials in Demonstration Areas. These design changes would compensate for lower than anticipated stiffness/strength of HBM at the time of paving. Such situations could occur when the pavement construction programme has been accelerated, or delayed to the autumn or even the winter season. In the worse case, quickly overlaying a slow curing HBM when the ambient temperature is low may mean that this material is effectively unbound at the time the pavement is opened to traffic.

{NB. The basis for the choice of the values for the degradation factor is described for a limited number of materials in Appendix B.}

The single-stage design process is illustrated in Figure 5.

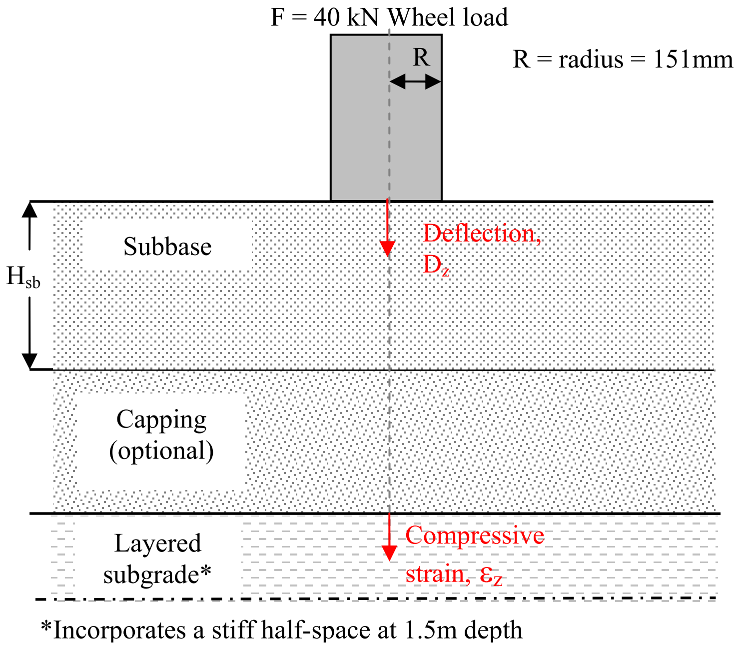


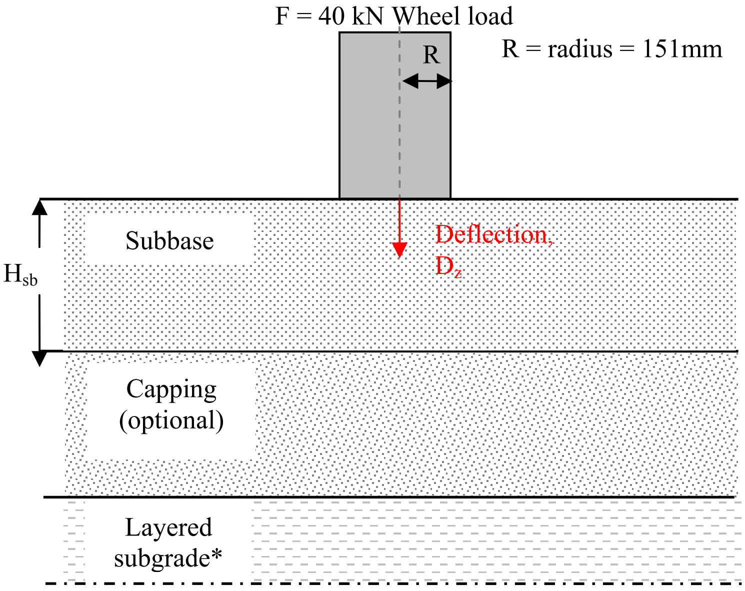
Figure 5. Foundation design: Simplified single-stage method

The single-stage design process is likely to produce conservative designs as it often will use, as inputs, the weakest subgrade strength and the lowest practical layer stiffness envisaged. When the scenarios described above do not apply, or it is inappropriate to adopt this single-stage approach due to excess conservatism, then the more detailed two-stage design process should be used.

3.7 Intermediate stage assessment

Given substantial knowledge of the properties of the various foundation layers and the underlying soil subgrade as well as the pavement's construction programme, an assessment of the likely equivalent half-space stiffness of the foundation during a critical stage in the construction of the pavement becomes feasible. This estimate is worthwhile because the Performance Related Specification described in IAN 73 (2006) requires measurement of the foundation stiffness just prior to pavement construction and compliance of these measurements with target values.

The likely foundation stiffness can be estimated using the foundation model and equations shown in Figure 6 to initially predict foundation deflection (D_z) and then calculate foundation stiffness (E_{hs}).



*Incorporates a stiff half-space at 1.5m depth

The equivalent half-space foundation stiffness, E_{hs} (Pa), can be calculated from:

$$E_{hs} = 2R(1-\nu^2)\frac{P}{D_Z}$$

,where

$$P = \frac{F}{\pi R^2}$$

and R = Radius of the loaded area (m)
υ = Poisson’s Ratio = 0.35
P = Applied stress (Pa)
D_Z = Predicted foundation deflection (m)
F = Applied load (N)

Figure 6. Assessment of foundation stiffness prior to paving

The properties of the foundation layers required for this assessment are summarised in Table 3. For bound materials, the material properties should take into account the temperature and moisture content of the curing environment and the degree of degradation by cracking.

Table 3. Intermediate stage assessment and required material properties

Construction stage	Timing	Reference	Material properties	
Unpaved	Just prior to paving	Section 3.7 and Figure 6	Subbase/capping layer stiffness	At time of paving
			Subgrade CBR/stiffness	In the short-term

The envisaged foundation stiffness is compared with the appropriate specified target foundation stiffness given in IAN 73 (2006) and reproduced in Table 4.

Table 4. Target construction values of equivalent half-space foundation stiffness

Quantity	**Equivalent half-space foundation stiffness (MPa) for:**			
	Class 1	**Class 2**	**Class 3**	**Class 4**
Foundation Class*:	50	100	200	400
Target:	Unbound: 40	Unbound: 80	Fast curing: 300	Fast curing: 600
	Bound: 50	Bound: 100	Slow curing: 150	Slow curing: 300

* Stiffness Modulus used in design

This procedure allows an assessment of whether compliance of the measured construction foundation stiffness with the specified target foundation stiffness is likely to present problems. If so, then the material properties and foundation thickness design could be modified prior to testing in a Demonstration Area on site in the manner described in the ‘Performance Related Specification’ of IAN 73 (2006).

4 Foundation designs

4.1 Performance Related Designs

The single-stage design process was used to produce Performance Related Designs that are given in the following sections under capping/subbase only and subbase on capping foundations.

4.1.1 Capping/subbase only foundations

In applying the design process, values for thickness of various capping/subbase materials laid directly on subgrades encompassing a wide range in CBR strengths were calculated for the four foundation classes. The designs are the minimum subbase thicknesses that satisfy the dominant criterion listed in Table 1.

Selected design examples are shown in Figures 7 to 10 for the foundation classes FC1 to FC4 respectively. These designs are required to have capping or subbase stiffnesses equal to, or greater than, those values stated in these figures. For foundation classes FC2, FC3 and FC4, the subbase stiffnesses of 150, 660 and 2900 MPa respectively were selected in order that the thickness of subbase on a subgrade soil of CBR strength 5 per cent was 225 mm. For foundation class FC2, this specific foundation design was necessary to ensure continuity with the foundation designs of HD 25 (1994). For the superior foundations of class FC3 and FC4, adoption of this standard subbase thickness provides a similarity of designs for different foundation classes that have been shown to be practical in both construction and use. To achieve continuity of design for foundation class FC2 with HD 25 (1994) following changes to the representation of the subgrade and subbase, required calibrating the subgrade strain criteria given in Table 1 for not only this standard foundation but also designs for other soil strengths. This procedure is described in detail in Appendix A. For foundation class FC1, a mean layer stiffness of 75 MPa was adopted. This value is the middle of the range from 50 to 100 MPa, which was considered by Powell et al (1984) to be appropriate for capping material.

The designs shown in Figure 7 for foundation class FC1 are generally of slightly greater thicknesses than the specified capping thicknesses of subbase on capping designs of HD 25 (1994) and were obtained for a capping of layer stiffness 75 MPa.

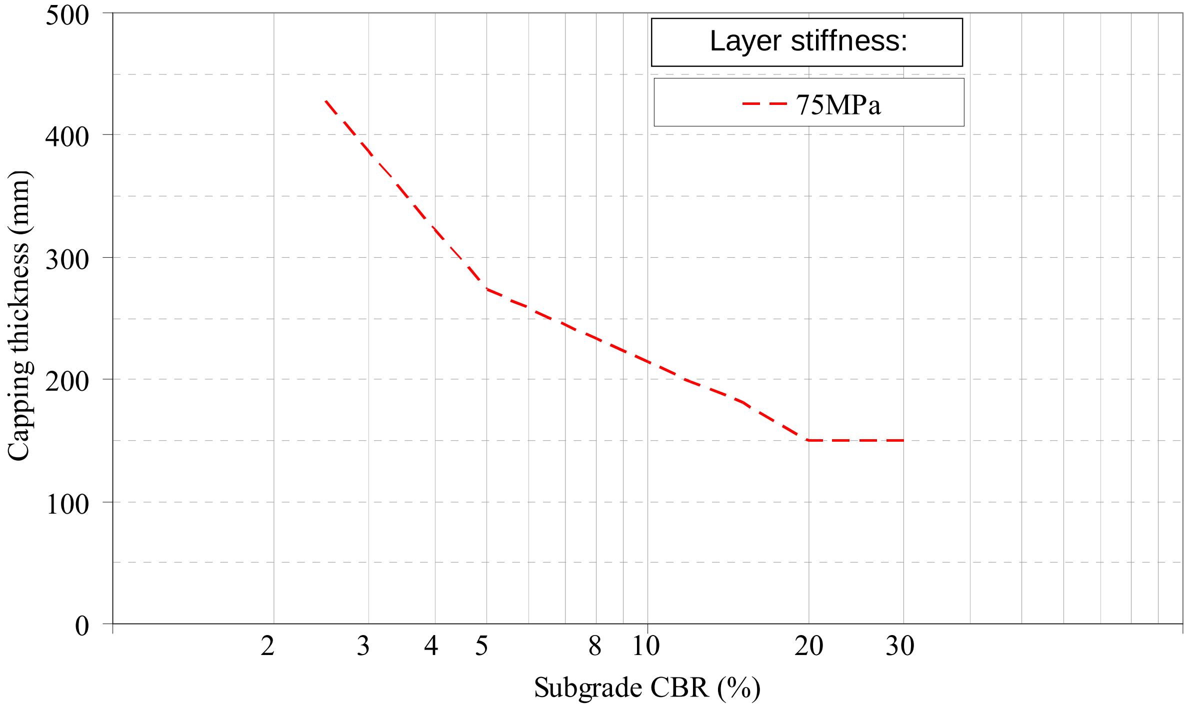


Figure 7. Capping only designs for the foundation class FC1

For foundation class FC2 design shown in Figure 8 for a subbase with a layer stiffness of 150 MPa, the thicknesses of subbase for subgrade CBR values from 15 down to 2.5 per cent were predetermined to be identical to those required for HD 25 (1994) by appropriate choices to the structure of the theoretical model and subgrade strain criteria as explained in Appendix A. Of all the foundation classes, this class most closely relates to the traditional foundations of good quality, unbound granular subbase on clay commonly constructed in the past in the UK.

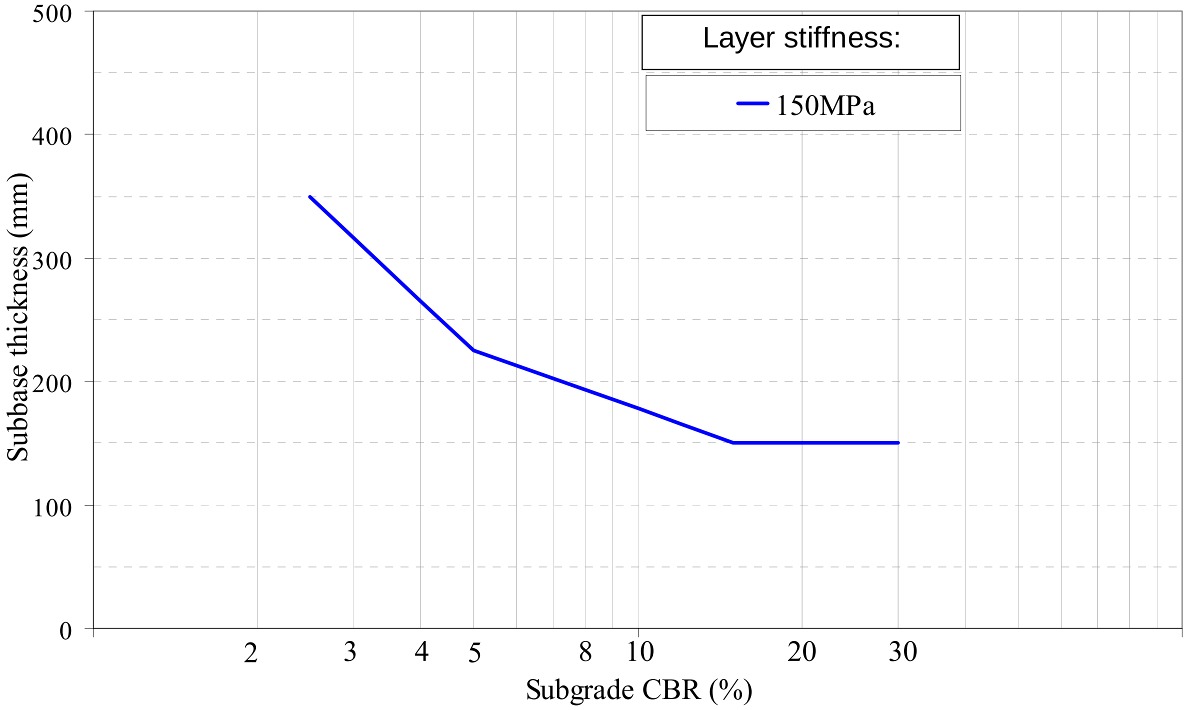


Figure 8. Subbase only designs for the foundation class FC2

As previously described, the subbase thicknesses for foundation classes FC3 and FC4 have been pre-selected as 225 mm for subgrades of CBR strength of 5 per cent. For FC3 shown in Figure 9, lower subbase thicknesses compared to HD25 (1994) are progressively required for subgrade CBR values less than 5 per cent. Marginally thinner subbases than HD25 (1994) designs are also required for subgrade CBR values greater than 5 per cent until, over 10 per cent, the minimum thickness of 175 mm is encountered. For FC4 shown in Figure 10, lower subbase thicknesses compared to HD25 (1994) are also progressively required for subgrade CBR values less than 5 per cent, whereas similar thicknesses are calculated for subgrade CBR values over 5 per cent until the minimum thickness requirement of 200 mm is encountered. The minimum subbase layer stiffnesses for foundation classes FC3 and FC4 and these designs are 660 and 2,900 MPa respectively .

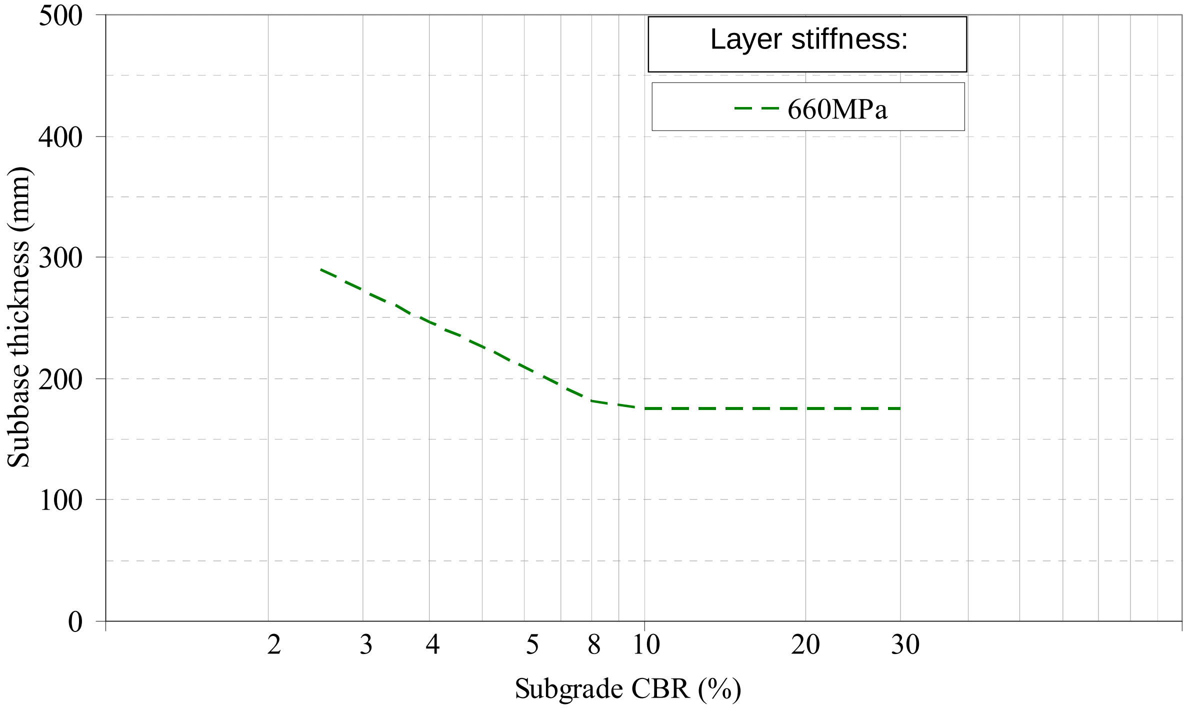


Figure 9. Subbase only designs for the foundation class FC3

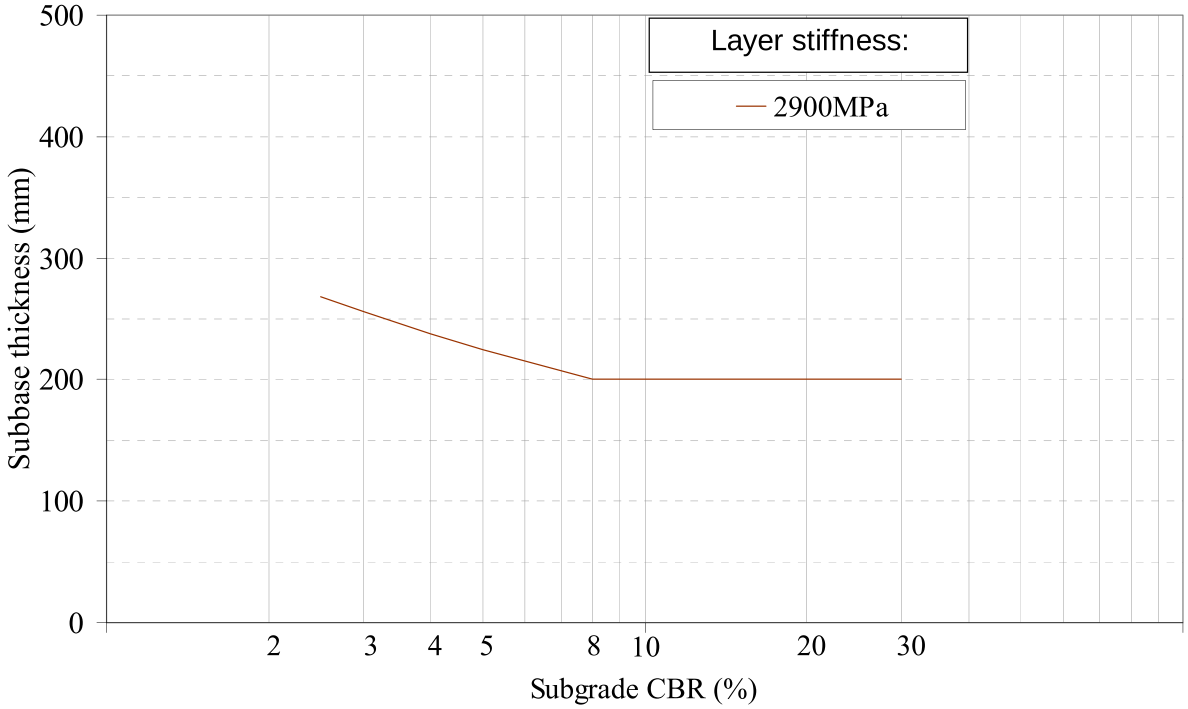


Figure 10. Subbase only designs for the foundation class FC4

Foundation Designs, however, should not be considered as limited to materials with the layer stiffnesses specified in Figures 7 to 10 and their associated thicknesses. If a capping/subbase material is adopted with a layer stiffness that is different from the values selected above for a particular foundation class, then capping/subbase thicknesses can be calculated for this material to produce the required foundation class. The analysis method to generate these capping/subbase only designs is described in more detail in Appendix A. The example designs given in Appendix A also provide a guide to ranges in layer stiffness of capping/subbase for each foundation class that are likely to produce practical foundation designs. There are, however, limitations to the materials that are acceptable for a given foundation class.

Notwithstanding the wide range in potential foundation designs for a particular foundation class, it is useful to reference designs as in Figures 7 to 10 to the HD25 (1994) thicknesses as a convenient benchmark. In particular, the thicknesses in Figures 9 and 10 derived for foundation classes FC3 and FC4 are all less than 300 mm and, with suitable precautions and in-situ density measurements, these layer thicknesses can be laid and adequately compacted in a single layer. This approach is preferable for bound material, especially quick curing hydraulically bound materials, to avoid two debonded layers.

4.1.2 Subbase on capping foundations

The single-stage design process was also used to design subbase on capping foundations. For foundation class FC2, the subbase and capping thicknesses were initially chosen to be those given in HD 25 (1994) to provide continuity of experience. That is, the capping thicknesses varied with subgrade CBR and the subbase thickness was fixed at 150 mm. For foundation classes FC3 and FC4, capping thicknesses were unchanged but constant subbase thicknesses of 175 mm and 200 mm respectively were selected. Foundation class FC1 was not considered in this analysis as less than 150 mm of material for the upper foundation layer was required to satisfy both the deflection and subgrade strain criteria. Capping stiffnesses were varied in the range originally studied by Powell et al (1984). With the subbase thickness held constant, it was necessary to increase its layer stiffness by a factor of up to 3 when the subgrade CBR changed from 15 to 2.5 per cent in order to achieve the required foundation class using the criteria listed in Table 1. Varying subbase stiffness by this amount to match regions of different subgrade CBR strength on site would present problems. Layer thickness is easier to control. Hence, it was decided to design subbase on capping foundations with fixed values of subbase layer stiffness and a subbase thickness that increases with decrease in subgrade CBR.

In the following design examples, capping thickness was also chosen to vary with subgrade strength with thicker cappings assigned to weaker soils. However, the capping thicknesses specified in HD25 (1994) were reduced to values that ranged from 250 mm at a subgrade CBR of 2.5 per cent to the minimum practical layer thickness of 150 mm at a subgrade CBR of 15 per cent. These capping designs are required to act as a working platform for capping construction whilst protecting the subgrade from excessive deformation. Their capability for carrying construction traffic was investigated using an elastic analysis in a similar manner to that described by Powell et al (1984). The amount of traffic estimated by this analysis was between 100 and nearly 400 standard axles (sa) for designs appropriate to soil of CBR strength of 2.5 and 15 per cent respectively. However, less traffic than these estimates should be permitted as construction of the subbase and base layers of the pavement may cause further subgrade deformation. As a consequence, the length of capping that can be constructed prior to overlaying with subbase is likely to be restricted by these capping designs. For example, if only 40sa, or about nine 4 axle, 32 tonne rigid lorries, are permitted on the capping design for a subgrade of CBR strength 2.5 per cent, then only a length of 100m of this capping layer should be constructed. The accuracy of these estimates depends on whether the lower structural performance of capping compared to subbase has been sufficiently well represented in this analysis. If not, or if greater construction traffic carrying capacity is required, then thicker capping layers should be specified.

Subbase thicknesses for subbase on capping structures were calculated, where the thicknesses derived were minimum values that satisfied the dominant criteria of those listed in Table 1. The analysis to generate these designs is described in more detail in Appendix A. The designs for foundation class FC2 are shown in Figure 11 for a capping stiffness of 75 MPa. Designs are given for subbase layer stiffnesses in the range from 150 MPa to 250 MPa. Designs for other values of capping stiffness are given in Appendix A. A minimum thickness of subbase of 150 mm is required for soil subgrades of CBR strength greater than 3, 4 and 8 per cent when subbase layer stiffnesses of 250, 200 and 150 MPa respectively are used.

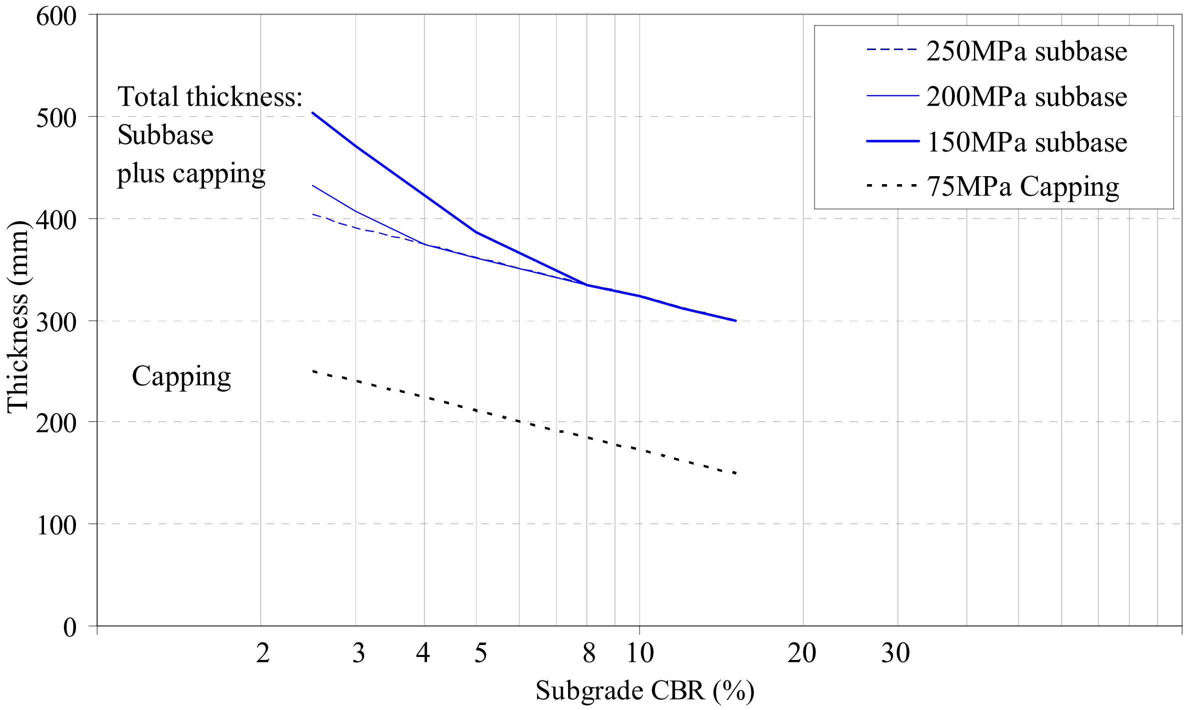


Figure 11. Subbase on capping designs for foundation class FC2

The subbase only design thicknesses for foundation classes FC3 and FC4 were not reduced significantly by the inclusion of the capping layer previously specified. Maximum reductions of about 50 mm and 15 mm were obtained for foundation classes FC3 and FC4 respectively. Consequently, subbase on capping designs are not shown for these superior foundation classes. However, it should be recognised that, although capping of layer stiffness in the range of 50 to 100 MPa is not structurally significant for these superior foundation classes, it can still be beneficial as a construction expedient. Capping can protect moisture susceptible soils and aid construction of the subbase layer on weak soils as well as assisting in achieving adequate thickness control of subbase.

The above subbase on capping designs were proposed as pragmatic and economic options. However, designs of composite structures should not be considered as constrained to materials with these layer stiffnesses and thicknesses. If three of the four variables, thickness and stiffness of subbase and capping are chosen, then the other variable can be determined with the design method to produce a compliant design.

4.1.3 Discussion

The success of the foundation design process is critically dependent on the values of layer stiffness adopted. Both in situ and laboratory test methods can be used to estimate values of layer stiffness of unbound and bound foundation layers. Care must be exercised in choosing the value of layer stiffness to ensure that it is representative of the stage in the life of the foundation that is being considered. The influences that need to be taken into account include the environmental effects of moisture and frost and, for hydraulically bound materials, the extent of their curing and the degrading effects of cracks. Because of these issues, values of stiffness measured on laboratory test specimens often cannot be used directly in theoretical foundation design. As an example for hydraulically bound material, IAN 73 (2006) requires large degradation factors of laboratory measured stiffness of the order of 10 to 20 per cent.

For the single-stage design process, the lowest likely value of layer stiffness encountered shortly after foundation construction and in the long-term is selected for each foundation layer. The stage in the life of the foundation that is most likely to yield the lowest layer stiffness for the various material types of unbound material, quick curing and slow curing bound material was discussed earlier. When the layer stiffnesses of slow curing materials shortly after construction and in the long-term differ markedly, there can be difficulty in developing a foundation design that performs satisfactorily at all times. The solution to this problem may require design changes and/or modification of the foundation and pavement construction practices to avoid foundation damage. When the layer stiffnesses are correctly chosen and acceptable construction practices defined, the single-stage design process should lead to conservative designs that cater adequately for both the construction and long-term stages of a particular foundation.

4.2 Restricted Designs

Restricted Designs are based on the Performance Related Designs but are more conservative because they are not subject to the range of compliance testing required by the Performance Related Specification. This conservatism allows for uncertainty in material performance and construction level tolerances. The designs are particularly intended for use on schemes of limited extent where the cost of applying the Performance Related Specification would be uneconomic.

A Restricted Design is given for foundation class FC1 but according to IAN 73 (2006) it is not intended for use on trunk roads. This is because the increased likelihood of damage during construction would require performance related testing to be carried out to give assurance of the adequacy of this foundation class.

Restricted Designs for use on trunk roads are only given for foundation classes FC2 and FC3 in IAN 73 (2006). Designs are not given for foundation class FC4 because the permitted reduction in thickness of the overlying pavement increases the risk to the client. In this case, it is essential to measure the properties of this class of foundation during construction to give adequate assurance that the long-term foundation stiffness will be achieved.

Restricted Designs are given for foundations built solely of capping or subbase and for foundations constructed of subbase on capping. Capping/subbase only designs are provided for foundation classes FC2 and FC3, whereas subbase on capping composite designs are given only for foundation class FC2. The formulation of these designs is described in more detail in Appendix A.

For capping/subbase only foundations, the thickness of the capping or subbase is shown in Figure 12 as a function of subgrade soil CBR strength together with the permitted materials, which are specified in the Specification (MCHW1).

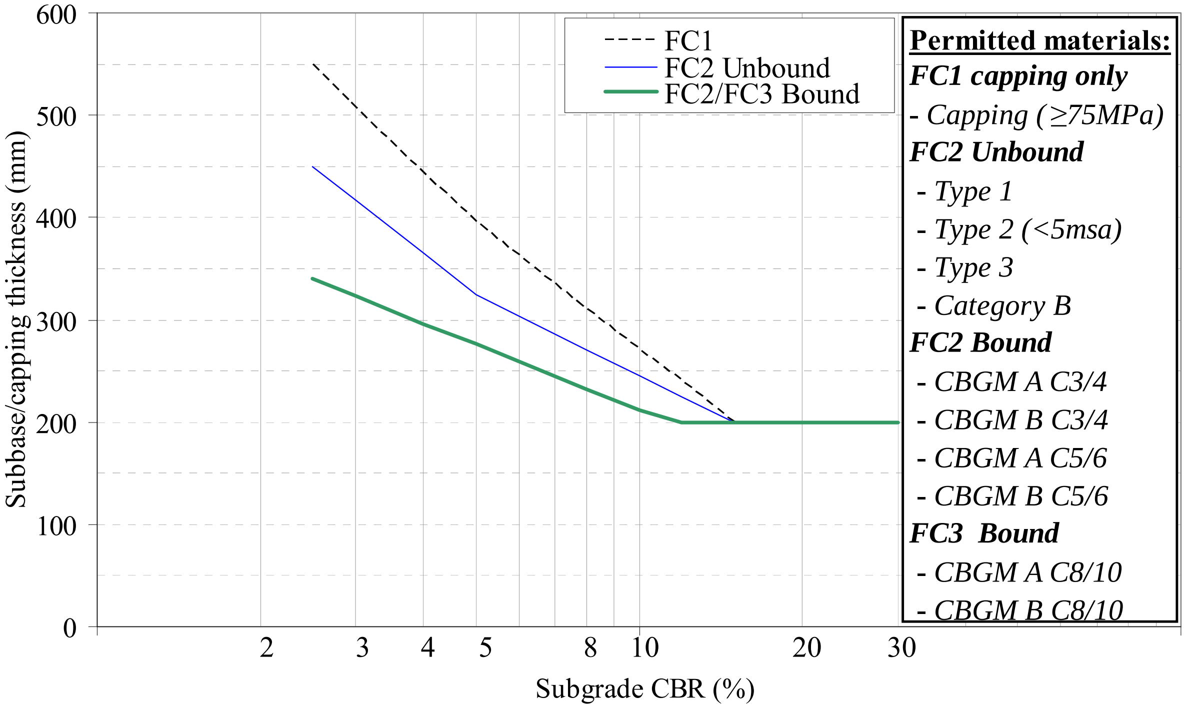


Figure 12. Restricted Designs for capping/subbase only foundations

For subbase on capping foundations, capping thickness is shown in Figure 13 to vary with subgrade soil CBR strength, being 250 mm on soil of CBR 2.5 per cent and 150 mm on soil of CBR 15 per cent. The capping material can be any of those specified in the Specification (MCHW 1, Series 600). The combined thickness of subbase and capping is also given in Figure 13 together with the permitted subbase materials, which are specified in the Specification (MCHW1, Series 800).

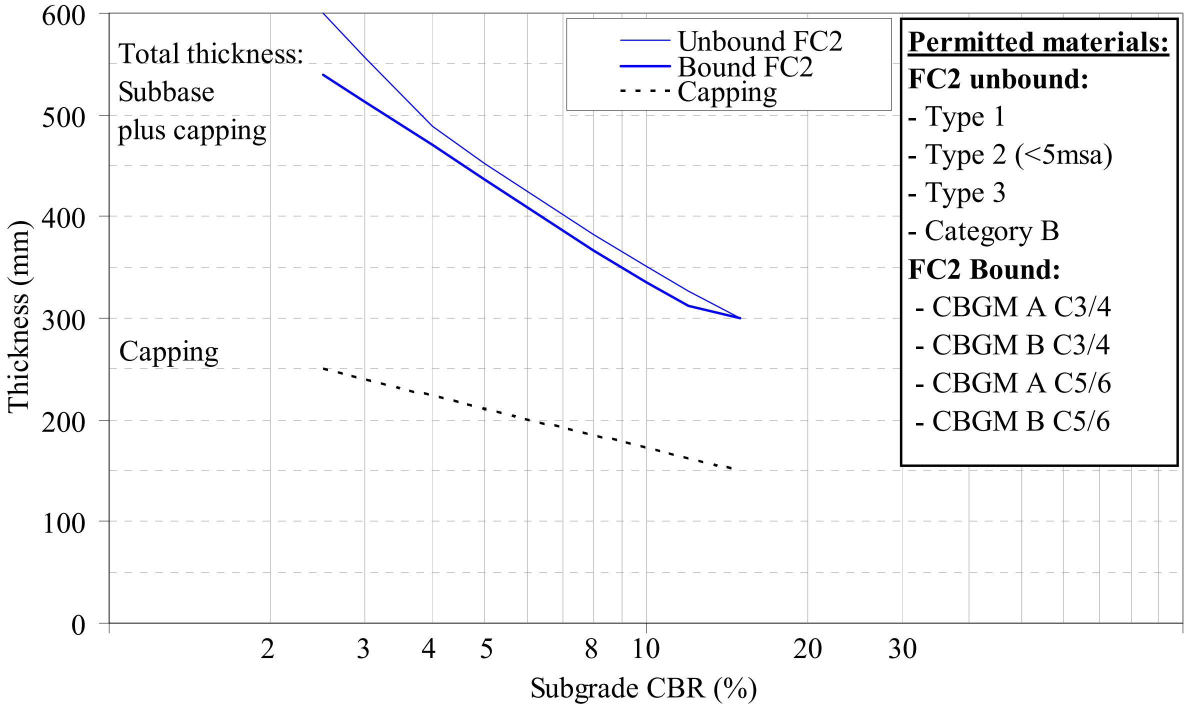


Figure 13. Restricted Designs for subbase on capping foundations

Designs given for foundation class FC3 are restricted to those using a cement bound granular mixture CBGM A or CBGM B of strength C8/10 as subbase. In IAN 73 (2006) other HBMs are currently not included. The designs for foundation class FC2 only allow the use of unbound granular subbase Types 1, 2, 3 and Category B, where the use of Type 2 is limited for design traffic levels up to 5msa, and the use of cement bound granular mixture CBGM A or CBGM B of strength C3/4 or C5/6. Different design curves are specified for bound and unbound materials with, for the same foundation class, unbound material being generally thicker than bound material, especially for low subgrade strengths. Thicknesses derived for these Restricted Designs may be specified as construction thicknesses as an allowance for permitted level tolerances has already been included in the designs.

4.3 Discussion

The Performance Related and Restricted Designs are applicable for soil subgrades of CBR strength over 2.5 per cent. For weaker soil, guidance is given in IAN 73 (2006) on how to improve the soil. The soil treatment adopted will depend on the circumstances existing at each site. As stated in IAN 73 (2006), for methods involving the replacement of weak soils by more suitable material and the lime treatment of cohesive soil, the soil subgrade should be assumed for design to have a CBR strength of 2.5 per cent. Also, for reasonably permeable soil, which is improved by drainage, the design of the foundation should be based on whatever value of soil CBR strength over 2.5 per cent that is achievable in the time available.

The foundation type adopted, either capping/subbase only or subbase on capping, is dependent on economic constraints and the perceived risks to the construction programme; both of which are dictated by the specific circumstances of each site. The availability and cost of materials may favour one foundation type economically, whereas the ease and certainty of construction of an alternative foundation type may reduce risk to delays to the construction programme. For example, a cemented subbase on a strong subgrade may reduce costs whilst capping below a subbase may ease construction problems on a weak subgrade.

5 Conclusion

- A mathematical representation of the foundation has been developed. Design criteria were derived by calibrating the critical responses of the loaded structure to replicate the foundation designs of HD 25 (1994). This provided continuity with past experience. The foundation design process developed comprises two stages; namely, the ‘shortly after construction’ and ‘long-term’ design stages and it requires that the most conservative of these two designs be adopted. A check at an intermediate stage, when appropriate, could reduce the risk of non-compliance with the Performance Related Specification. A simplified, single-stage design process, however, has been used to produce conservative designs.
- Foundation designs have been produced for four foundation classes called FC1, FC2, FC3 and FC4 that provide support to the pavement equivalent to a semi-infinite half-space of stiffnesses 50, 100, 200 and 400 MPa respectively. The designs for subbase only and subbase on capping structures specified layer thicknesses and layer stiffnesses.
- The design method can be used to produce alternative foundation structures to the examples reported.
- Successful use of the design method is critically dependent on the value of the design layer stiffness adopted for each selected material. These values can be markedly different from laboratory derived element stiffness.
- Two types of foundation designs are given. Performance Related Designs are derived directly from the design process and require testing in-situ during foundation construction. Restricted Designs are based on the Performance Related Designs but are more conservative because they are not subject to the requirements of the Performance Related Specification.
- The designs were considered to be practical from the perspective of construction and use.

6 Acknowledgements

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Appendix A. Foundation design method

A.1 Introduction

The aim of foundation design is to choose the thicknesses of the foundation layers that overlay the subgrade such that subgrade is not excessively deformed by the construction traffic and the foundation provides the support to the pavement as expected for the Foundation Class designated.

A.2 Design method: Representation of subgrade

The design process uses a multi-layer, linear elastic model of the foundation. A problem in this process is caused by the traditional representation of the subgrade as a uniform half space that is infinitely deep. This representation is obviously incorrect. Stiff layers can occur at depth in the subgrade for various reasons that include the following:

- An actual stiff layer: for example, bedrock.
- An apparent stiff layer caused by the non-linear dependency of the elastic behaviour of soil on in situ stress.
- Inertial behaviour of soil to dynamic loads.

Studies by Rhode and Scullion (1990) and Arnold et al (2001) have incorporated stiff materials at depth in the subgrade. Consequently, for this design method, a stiff half-space of stiffness 10,000 MPa was inserted at the bottom of the subgrade. To determine the depth (H) of this stiff material, a foundation of 225 mm of good quality, unbound granular subbase on a subgrade of CBR 5 per cent shown in the schematic diagram of Figure A1 was structurally analysed for different depths of the stiff half-space. Values of subgrade vertical strain (ε_z) and foundation deflection (D_z) were calculated when the foundation was subjected to a 40kN surface load over a circular area of 0.151m. The results plotted in Figure A2 showed that the surface deflection decreased and the subgrade strain increased as the position of the stiff subgrade half-space was raised. The depth of the half-space was taken to be 1.5m below the top of subgrade. For this structure, the subgrade strain was increased by 0.7 per cent and the deflection reduced by 12 per cent when compared to a uniform half space of subgrade soil of CBR 5 per cent.

Adoption of the subgrade strain criterion of Powell et al (1984) predicts that the traffic carrying capacity of the foundation would only be decreased by about 3 per cent by this representation of the subgrade. More significantly, the foundation stiffness of an equivalent half-space was increased markedly from 88 MPa to 100 MPa by substituting the semi-infinite, uniform subgrade by the selected layered subgrade.

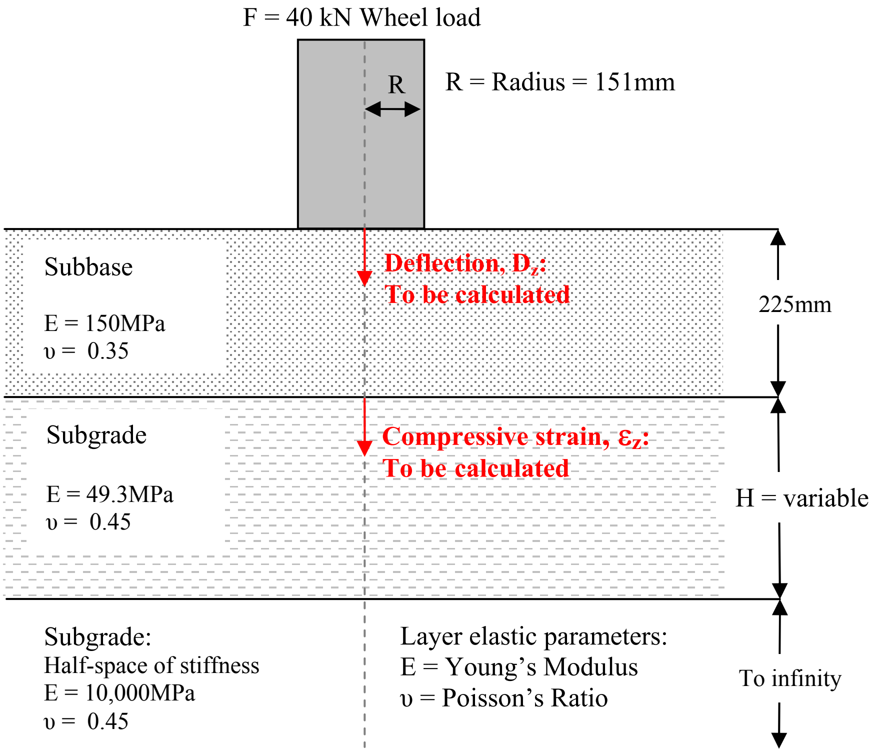


Figure A1. Analysis to determine the depth of the stiff subgrade half-space

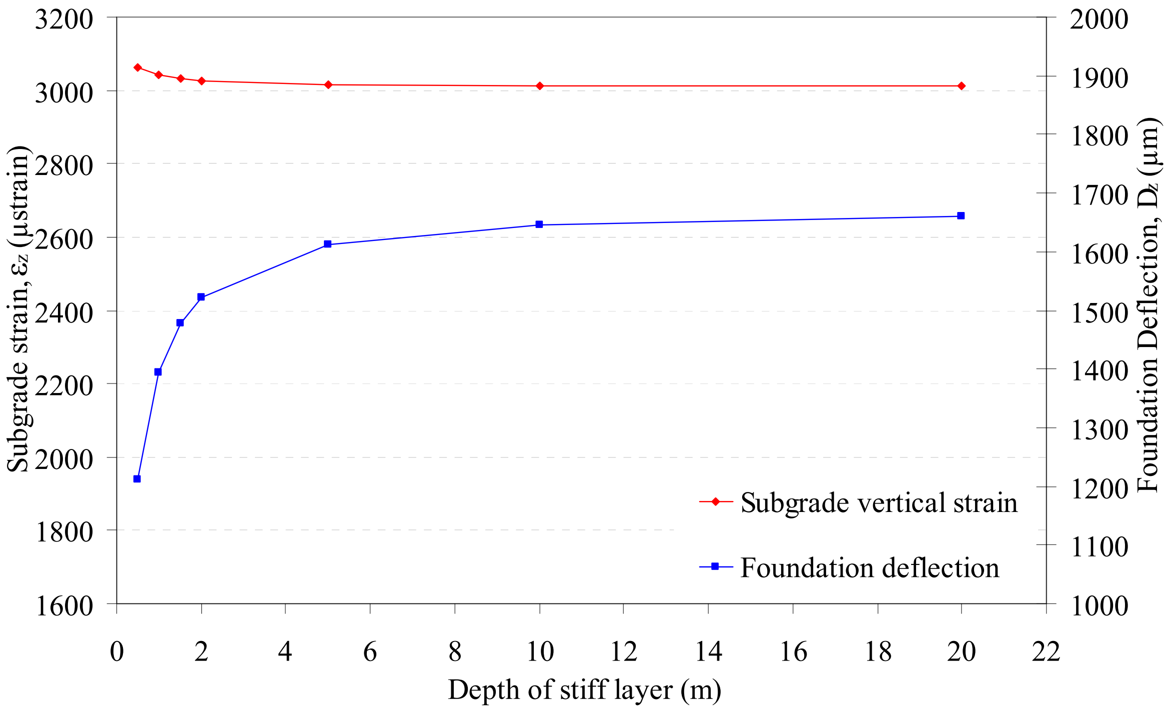


Figure A2. Dependence of subgrade strain and foundation deflection on depth of stiff subgrade half-space

A.3 Calibration of design method

Powell et al (1984) investigated the ability of a foundation to carry construction traffic where the foundation was comprised of a good quality, unbound granular subbase laid directly on soil subgrades. Their study included the analysis of results from trafficking trials to produce designs for a stable foundation that would not rut excessively under construction traffic, either at its surfacing or at formation level. The method was applicable to soils of CBR strength in the range of 2 to 7 per cent. For construction traffic of 1000 sa, values of the deduced subbase thickness for various subgrade CBR strengths are shown in Figure A3 along with the HD 25 (1994) subbase only designs. The HD 25 (1994) designs were based on Powell et al (1984) and therefore, as expected, can be seen to closely follow these authors' designs. The designs for HD 25 (1994) are always of the same thickness as, or marginally thicker than, the designs by trafficking trials of Powell et al (1984).

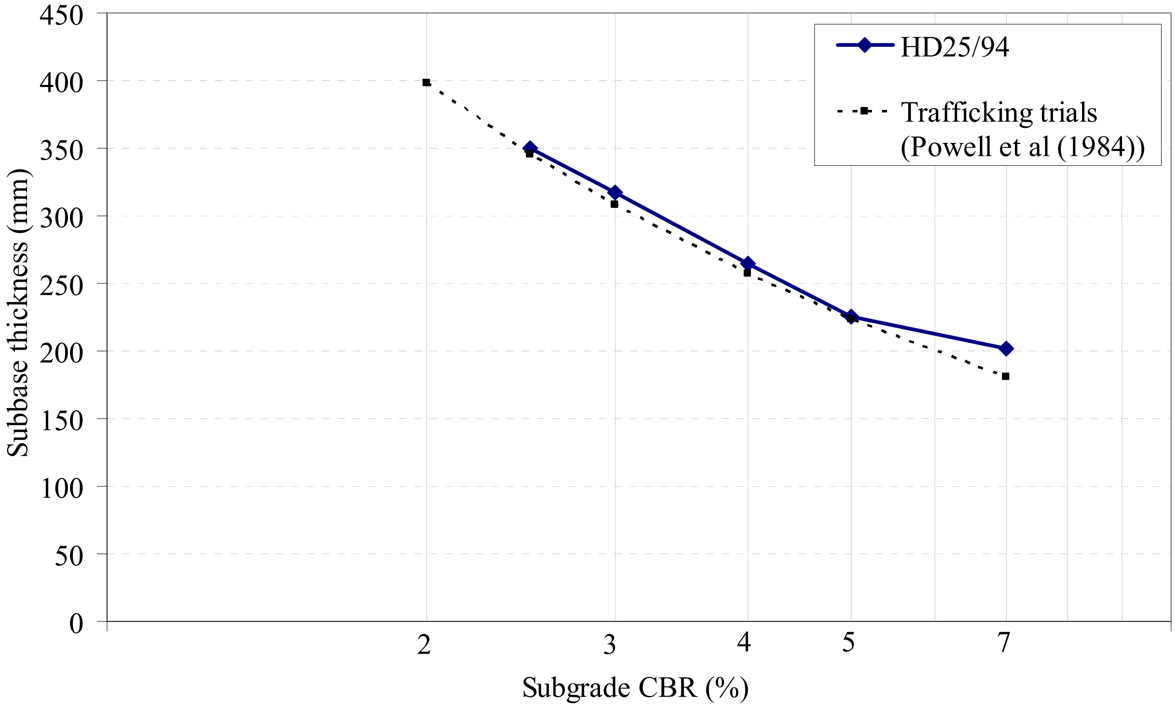
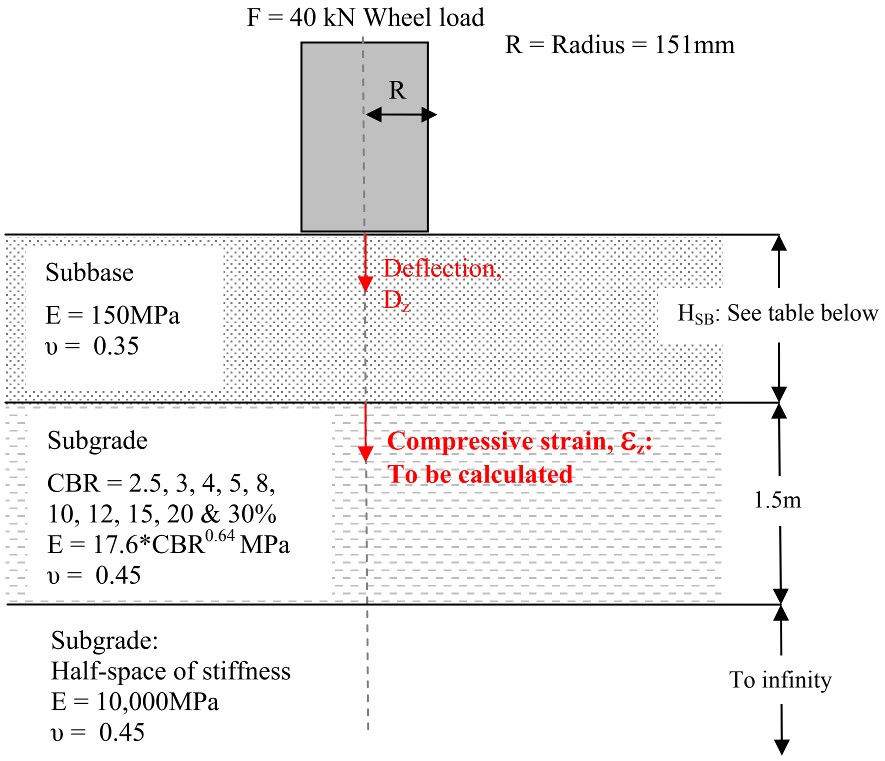


Figure A3. Comparison of subbase only thickness designs

To maintain consistency with earlier designs, which have generally proved acceptable, the design method in this report has been calibrated to the designs of HD 25 (1994). This requirement was achieved in the theoretical analysis summarised in Figure A4 by selecting the subgrade strain criteria in the theoretical model to reproduce the HD 25 (1994) designs.



Subgrade CBR (%)	2.5	3	4	5	8	10	12	15	20	30
Subbase thickness, Hsb (mm)	350	317	265	225	193	178	165	150	150	150

Figure A4. Theoretical analysis for subgrade strain to reproduce HD 25 (1994) designs

In the analysis, the stiffness of the subbase is taken to be 150 MPa for all subgrade strengths. This approach differs from that adopted by Powell et al (1984) in that, in their work, the subbase for soil subgrades of CBR less than 5 per cent was layered with the bottom layer taken to be of stiffness three times that of the stiffness of the soil; that is, 95 MPa to 150 MPa for soil of CBR 2.5 to 5 per cent respectively. However, the approach adopted in this analysis is consistent with the characterisation of other unbound granular materials; for example, as with capping that is not layered and whose stiffness is not reduced when placed on weak soils. Compensation for this change is made through the choice of subgrade strain criteria.

The maximum permissible subgrade vertical compressive strains, or subgrade strain criteria, calculated for the foundation structures of Figure A4 are given in Table A1.

Table A1. Subgrade strain criteria

Subgrade CBR (%)	2.5	3	4	5	8	10	12	15	20	30
Standard subgrade vertical compressive strain (με) for 1000sa* of traffic	2601									
Subgrade factor {K_{sg}}	0.778	0.860	1.020	1.166	1.145	1.120	1.095	1.047	0.902	0.727
Maximum permissible subgrade vertical compressive strain (με)	2024	2238	2654	3032	2979	2914	2849	2724	2345	1892

*{After deformation criteria of Powell et al (1984)}

The subgrade strain criteria are related by a factor K_{sg} to a standard subgrade vertical compressive strain value, which is derived from the following deformation criteria of Powell et al (1984):

$$Log_{10}N = -7.21 - 3.95Log_{10}\varepsilon_Z$$

where: N = Amount of construction traffic in standard axles (sa)
ε_Z = Subgrade vertical compressive strain (μstrain)

Using this equation, the subgrade vertical compressive strain is 2601 (με) for 1000 sa of construction traffic. The factor K_{sg} therefore varies from 0.727 to 1.166. That is, the subgrade strain varies from about 23 per cent below to 17 per cent above the standard subgrade strain value. This approach readily permits a future re-calibration of the foundation design process and clarifies the relationship of the design process of this report with the previous design process given by Powell et al (1984).

The greatest foundation deflection (Dz) for the structures of Figure A4 estimated from the structural analysis was 1480 microns and occurred when 225 mm of subbase with a layer stiffness of 150 MPa was constructed on a layered subgrade soil whose upper layer has a CBR strength of 5 per cent. Apart from the stiff subgrade half-space, this foundation is equivalent to the “Standard Foundation” adopted by Powell et al (1984). The half-space structure, which produces the same deflection under load, was found to have a stiffness of 100 MPa. The “Standard Foundation” of Powell et al (1984) and consequently the derived foundation designs of HD 25 (1994), which use good quality unbound granular subbase, are therefore expected to classify as foundation class FC2.

A.4 Application of design method

The criteria associated with the structural design method that are summarised in Table 1 are listed for convenience in Table A2.

Table A2. Compliance criteria

Subgrade strain criteria (με)

Subgrade CBR (%)	2.5	3	4	5	8	10	12	15	20*	30*
Maximum permissible subgrade vertical compressive strain (με)	2024	2238	2654	3032	2979	2914	2894	2724	2345	1892

* Subbase only designs

Deflection criteria

Foundation Class	1	2	3	4
Half-space stiffness (MPa) {Poisson’s ratio 0.35}	50	100	200	400
Maximum foundation deflection (μm)	2960	1480	740	370

Thickness criteria

Foundation class	Minimum capping/subbase thickness (mm)
FC1 and FC2	150
FC3	175
FC4	200

{40 kN applied to top of foundation over a circular area of radius 0.151m}

A.5 Capping/subbase only Performance Related Designs

The single-stage design method was applied to a three-layer structure of subbase on a layered subgrade shown in Figure A5. The subgrade stiffness was calculated from subgrade CBR using the equation given by Powell et al (1984) and, for the CBR values from 2.5 to 30 per cent, varied from about 30 to 150 MPa. Selected layer stiffnesses appropriate for each foundation class ranged from 50 to 100, 150 to 250, 500 to 2000 and 1000 to 5000 MPa for the foundation classes FC1, FC2, FC3 and FC4 respectively. All layer stiffnesses are taken to be constant throughout their depth. The aim of the analysis process using the model illustrated in Figure A5 was to determine the minimum thicknesses of the subbase layer that satisfied the criteria listed in Table A2 and thereby produce the required foundation class. The minimum values of subbase thickness were 150 mm for foundation classes FC1 and FC2 and 175 mm and 200 mm for foundation classes FC3 and FC4 respectively.

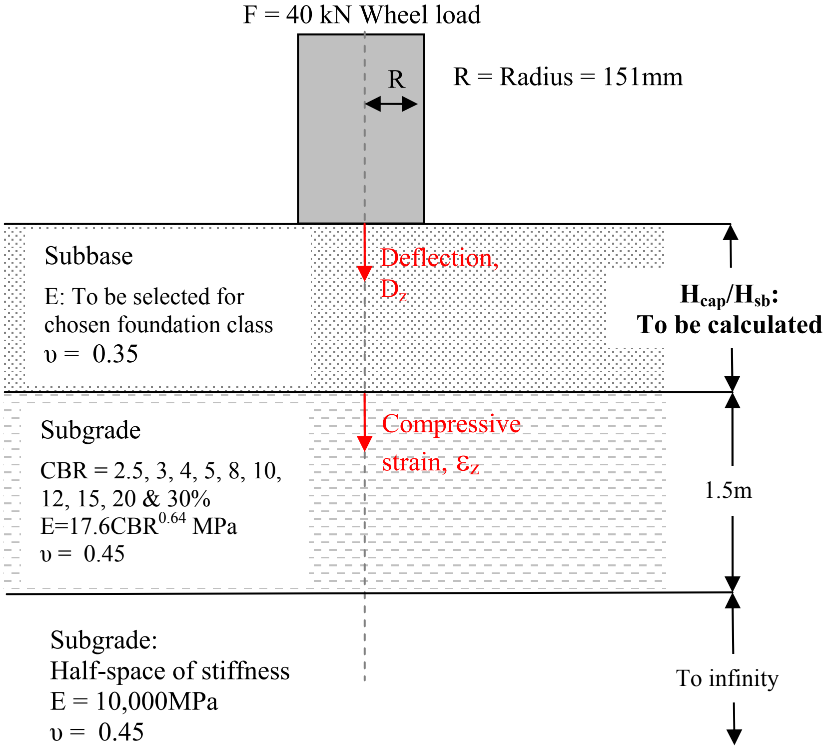


Figure A5. Capping/subbase only foundation structures analysed

The values of capping/subbase thickness calculated are listed in Table A3 together with the dominant criterion.

Table A3. Capping/subbase only foundation designs for the four foundation classes

Foundation class	Capping /subbase stiffness (MPa)	Thickness required (mm) for subgrade CBR (%):									
		2.5	3	4	5	8	10	12	15	20	30
FC1	50	604	438	350	297	250	229	212	193		
FC1	*75*[1]	*428*	*386*	*322*	*274*	*233*	*214*	*198*	*181*		
FC1	100	397	359	300	255	218	201	186	170		
FC2	*150*[1]	*350*	*317*	*265*	*225*	*193*	*178*	*165*	*150*	*150*	*150*
FC2	200	318	288	241	203	175	161	150	150	150	150
FC2	250	292	265	221	186	160	150	150	150	150	150
FC3	500	336	316	285	261	210	186	175	175	175	175
FC3	*660*[1]	*290*	*273*	*246*	*226*	*182*	*175*	*175*	*175*	*175*	*175*
FC3	750	265	249	225	207	175	175	175	175	175	175
FC3	1000	230	217	197	180	175	175	175	175	175	175
FC3	2000	175	175	175	175	175	175	175	175	175	175
FC4	1000	458	434	403	379	328	303	284	259	228	200
FC4	2000	310	296	275	259	225	209	200	200	200	200
FC4	*2900*[1]	*268*	*256*	*238*	*225*	*200*	*200*	*200*	*200*	*200*	*200*
FC4	3000	259	248	231	217	200	200	200	200	200	200
FC4	4000	231	221	205	200	200	200	200	200	200	200
FC4	5000	212	202	200	200	200	200	200	200	200	200

[1] Refer to Section 4.1.1.

🟦 Deflection controlled 🟩 Subgrade strain controlled ☐ Minimum thickness reached

The dominant criterion for foundation class FC1 is primarily subgrade strain with deflection taking over for the 50 MPa stiff capping on the weaker soils. For foundation class FC2, subgrade strain is dominant for all subbase materials and subgrade strengths examined except where the minimum thickness of 150 mm is invoked for stiffer subgrades. With regard to the superior foundation classes FC3 and FC4, the dominant criterion is confined to deflection except where the minimum subbase layer thicknesses of 175 mm and 200 mm respectively are invoked for the stiffer subgrades. The designs are shown for each foundation class FC1 to FC4 in Figures A6 to A9 respectively for selected values of layer stiffness that provide practical foundations.

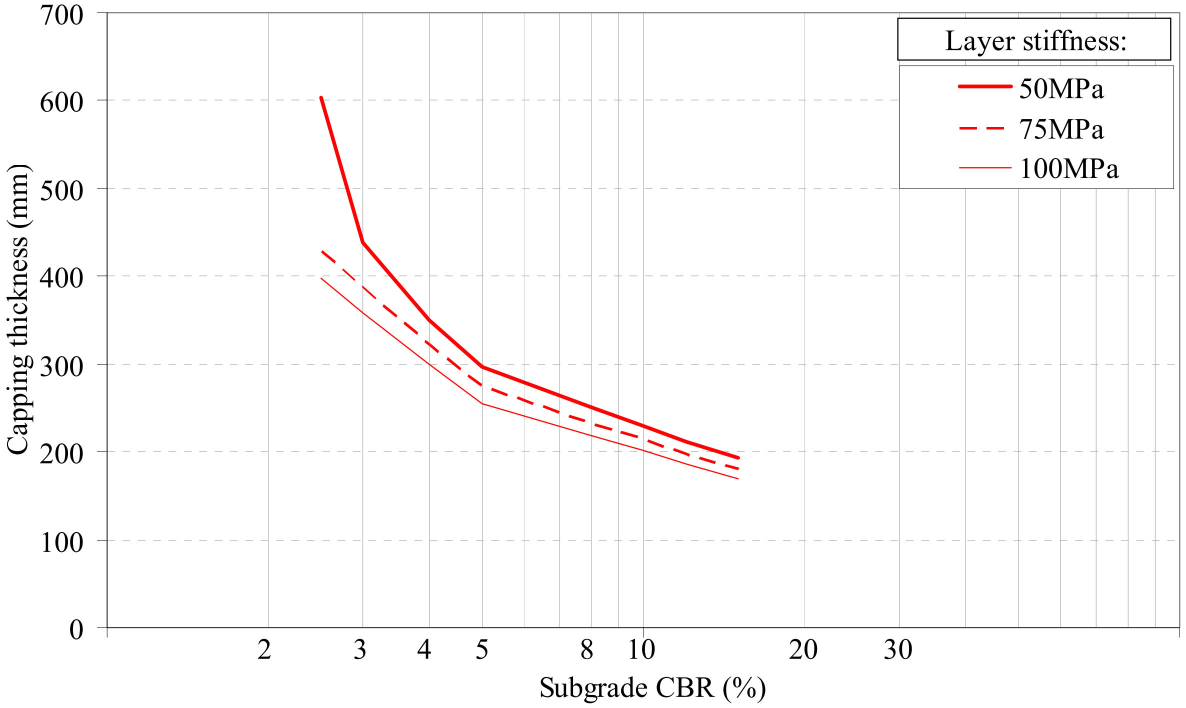


Figure A6. Capping only Performance Related Designs for foundation class FC1

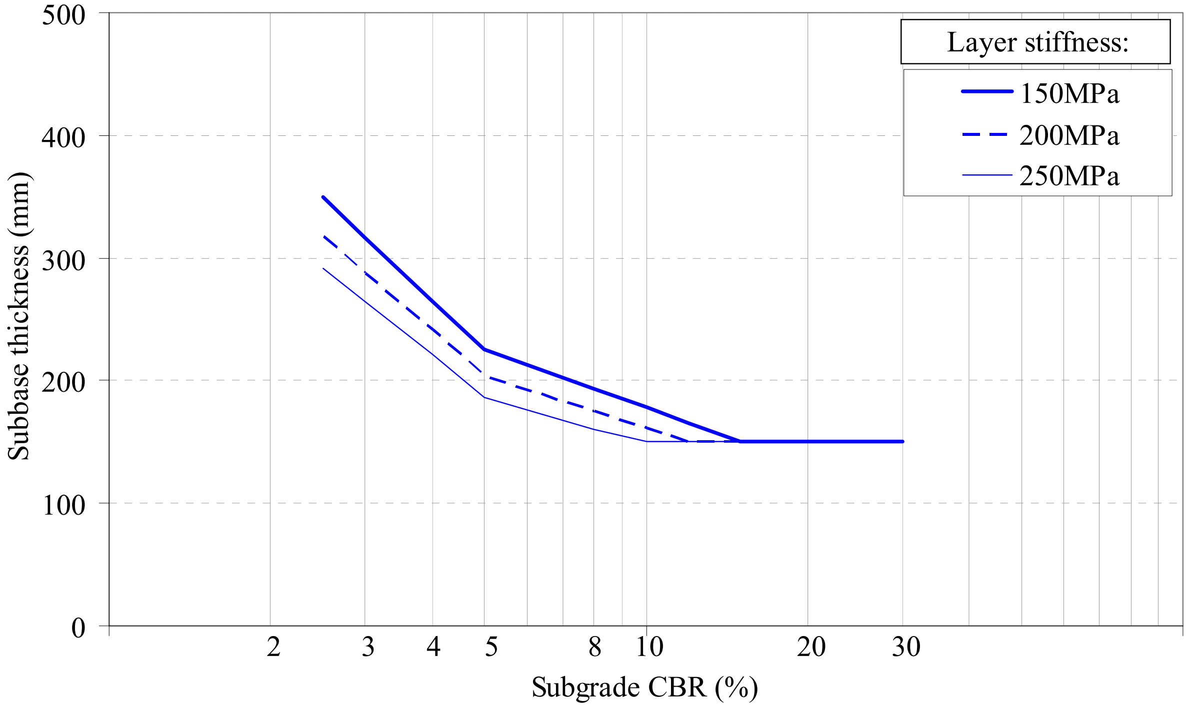


Figure A7. Subbase only Performance Related Designs for foundation class FC2

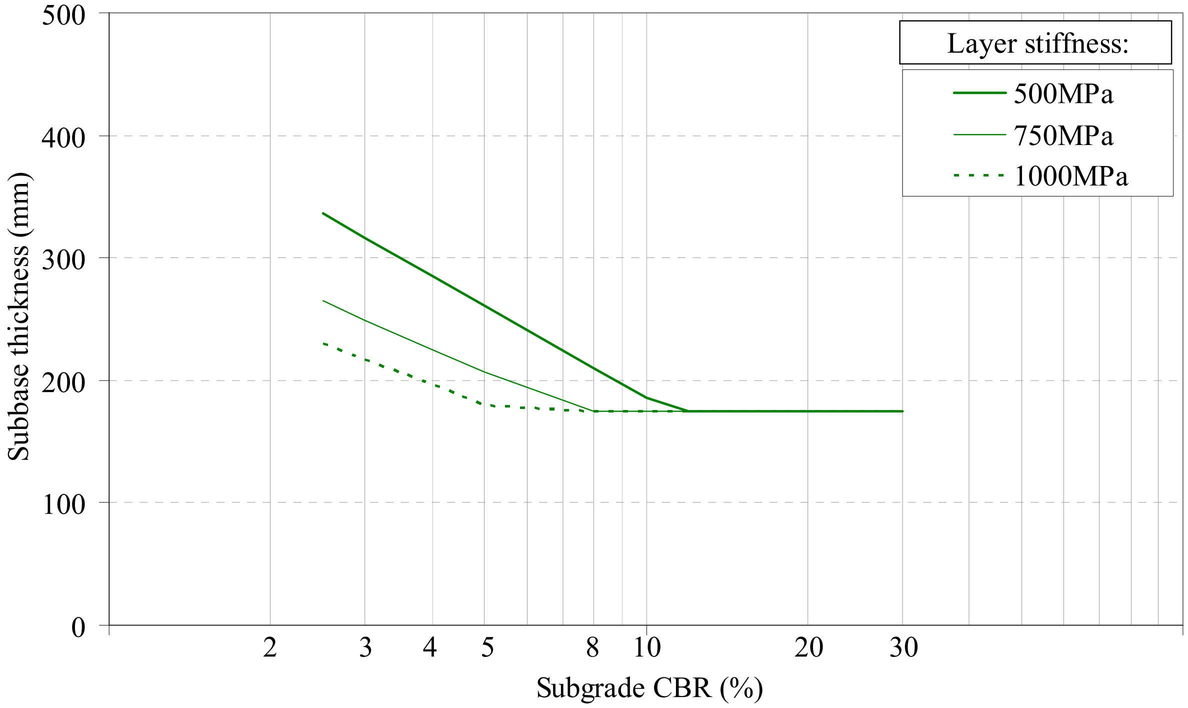


Figure A8. Subbase only Performance Related Designs for foundation class FC3

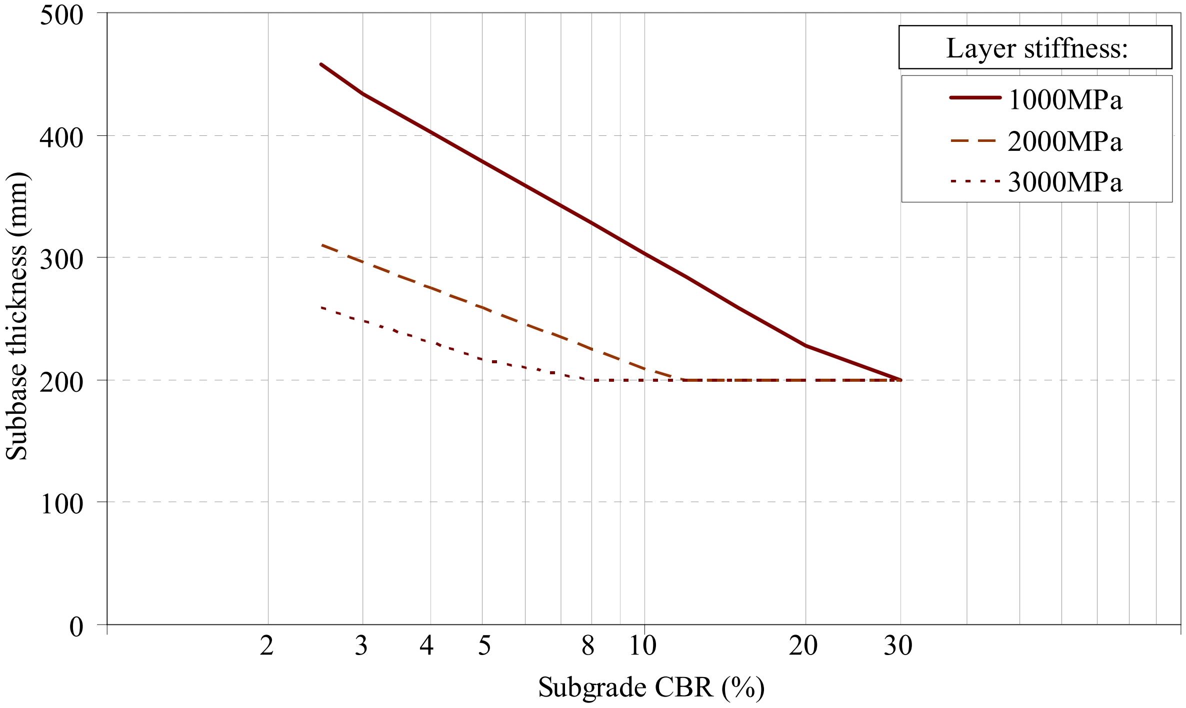


Figure A9. Subbase only Performance Related Designs for foundation class FC4

The values of capping/subbase thickness required to achieve a designated foundation class reduce with increase in layer stiffness and subgrade CBR strength until, for foundation classes FC2 to FC4, these thicknesses coincide with the assigned minimum thicknesses. As shown in Table A3, for subbases of thickness 225 mm, layer stiffnesses of at least 150, 660 and 2900 MPa are required for foundation classes FC2 to FC4 respectively when laid on a subgrade of CBR strength of 5 per cent.

The thicknesses determined using the Performance Related Design examples in this section are minimum thickness values. Allowance for permitted level tolerances must be added when specifying construction thicknesses. For each specific material and site, pragmatic construction procedures need to be developed especially for subbases laid on weak subgrades.

The following equations that describe the designs have been developed for foundation classes FC1 to FC4:

- Foundation class FC1 (Capping only):

For subgrade CBR >2.5% and ≤ 5%, the greater of the thicknesses given by the following two equations:

$$H_{cap}(S) = 1.845 \times 10^3.E_{cap}^{-0.25}(1 - 0.395.E_{cap}^{-0.025}Ln(CBR))$$

$$H_{cap}(D) = 2.00 \times 10^2.E_{cap}(Ln(CBR) - 1.540) - 10.918 \times 10^3.(Ln(CBR) - 1.541)$$

For subgrade CBR > 5% and ≤ 15%

$$H_{cap}(S) = 1.016 \times 10^3.E_{cap}^{-0.214}(1 - 0.23.E_{cap}^{-0.026}Ln(CBR))$$

where, the minimum value of H_{cap} permissible is 150 mm and these relationships are valid for capping material with a layer stiffness of between 50 and 100 MPa.

- Foundation class FC2 (Subbase only):

For subgrade CBR > 2.5% and ≤ 5%, subbase thickness (mm) is given by:

$$H_{sb}(S) = 2.85 \times 10^3 . E_{sb}^{-0.341}(1 - 0.316 . E_{sb}^{0.021} Ln(CBR))$$

For subgrade CBR > 5% and ≤ 30%, subbase thickness (mm) is given by:

$$H_{sb}(S) = 9.25 \times 10^2 . E_{sb}^{-0.202} - 69. Ln(CBR))$$

where, the minimum value of H_{sb} permissible is 150 mm and these relationships are valid for subbase material with a layer stiffness of between 150 and 250 MPa.

- Foundation class FC3 (Subbase only):

For subgrade CBR > 5% and ≤ 30%, subbase thickness (mm) is given by:

$$H_{sb}(D) = 8.44 \times 10^3 . E_{sb}^{-0.48}(1.0 - 0.261 . E_{sb}^{-0.008} . Ln(CBR))$$

where, the minimum value of H_{sb} permissible is 175 mm and these relationships are valid for subbase material with a layer stiffness of between 500 and 2,000 MPa.

- Foundation class FC4 (Subbase only):

For subgrade CBR > 5% and ≤ 30% subbase thickness (mm) is given by:

$$H_{sb}(D) = 1.53 \times 10^4 . E_{sb}^{-0.4833}(1.0 - 0.234 E_{sb}^{-0.025} . Ln(CBR))$$

where, the minimum value of H_{sb} permissible is 200 mm and these relationships are valid for subbase material with a layer stiffness of between 1,000 and 5,000 MPa.

In the above equations:

H_{cap} (mm) is capping layer thickness,
H_{sb} (mm) is subbase layer thickness,
E_{cap} is capping layer stiffness (MPa),
E_{sb} is subbase layer stiffness (MPa) and,
CBR is the California bearing ratio of the subgrade (%).
(S) and (D) denotes whether the thicknesses were determined using the subgrade strain criterion (S) or the deflection criterion (D).

Table A4 gives the percentage differences between the capping/subbase thicknesses calculated from the equations and thicknesses derived from the theoretical analysis.

Table A4. Performance Related Design equation errors for capping/subbase only designs

Foundation class	Capping /subbase stiffness (MPa)	Difference[2] (%) between thickness by equations and theoretically modelled thickness for subgrade CBR (%)									
		2.5	3	4	5	8	10	12	15	20	30
FC1	50	0.0	-0.3	-0.2	-1.4	-0.1	0.2	0.4	-0.3		
FC1	*75*[1]	*-1.1*	*-0.9*	*-1.0*	*-1.8*	*-0.9*	*-0.8*	*-0.4*	*-1.2*		
FC1	100	-0.4	-0.3	-0.4	-0.8	0.1	0.0	0.5	-0.2		
FC2	*150*[1]	*0.0*	*0.0*	*0.0*	*-0.2*	*-0.2*	*-0.4*	*-0.2*	*-0.5*	n/a	n/a
FC2	200	-0.5	-0.6	-0.9	-0.5	-0.7	-1.7	n/a	n/a	n/a	n/a
FC2	250	0.2	-0.2	-0.3	0.0	-0.2	n/a	n/a	n/a	n/a	n/a
FC3	500	-1.7	-1.6	-1.7	-1.7	-1.6	-1.6	n/a	n/a	n/a	n/a
FC3	*660*[1]	*2.2*	*2.0*	*1.9*	*1.8*	*1.3*	n/a	n/a	n/a	n/a	n/a
FC3	750	2.6	2.9	2.7	2.2	n/a	n/a	n/a	n/a	n/a	n/a
FC3	1000	3.1	2.9	2.3	2.6	n/a	n/a	n/a	n/a	n/a	n/a
FC3	2000	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
FC4	1000	-2.8	-1.9	-2.0	-2.1	-2.2	-2.0	-2.3	-2.1	-2.3	n/a
FC4	2000	3.1	3.3	3.4	3.3	3.2	3.0	n/a	n/a	n/a	n/a
FC4	*2900*[1]	*1.7*	*2.1*	*1.8*	*2.0*	n/a	n/a	n/a	n/a	n/a	n/a
FC4	3000	1.6	1.7	1.5	1.8	n/a	n/a	n/a	n/a	n/a	n/a
FC4	4000	-0.7	-0.5	-0.2	n/a	n/a	n/a	n/a	n/a	n/a	n/a
FC4	5000	-2.7	-1.0	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

[1] Refer to Section 4.1.1.

[2] [Difference (%) = (Thickness by equation – Modelled thickness)*100/Modelled thickness]

It can be seen that the maximum errors introduced by using the equations vary with foundation class and are greatest for FC4 at about ±3 per cent.

These equations can be used to deduce quickly capping/subbase thickness for a designated foundation class, given subgrade CBR strength and specific layer stiffness other than those presented in Figures A6 to A9.

A.6 Subbase on capping Performance Related Designs

The single-stage design method was applied to a four-layer structure of subbase on capping on layered subgrade shown in Figure A10. The capping thickness was varied with subgrade CBR as given in Table A5. The subgrade stiffness was calculated from subgrade CBR using the equation given by Powell et al (1984) and, for the CBR values from 2.5 to 15 per cent, varied from about 30 to 100 MPa respectively. The capping stiffness was varied in the range originally studied by Powell et al (1984) by selection of the values 50, 75 and 100 MPa. The subbase layer stiffness was selected in the range of 150 to 250 MPa. All layer stiffnesses are taken to be constant throughout their depth. The aim of the analysis process using the model illustrated in Figure A10 was to determine the minimum thicknesses of the subbase layer that satisfied the criteria listed in Table A2 and thereby produce the required foundation class of FC2. The minimum subbase thickness was taken to be 150 mm.

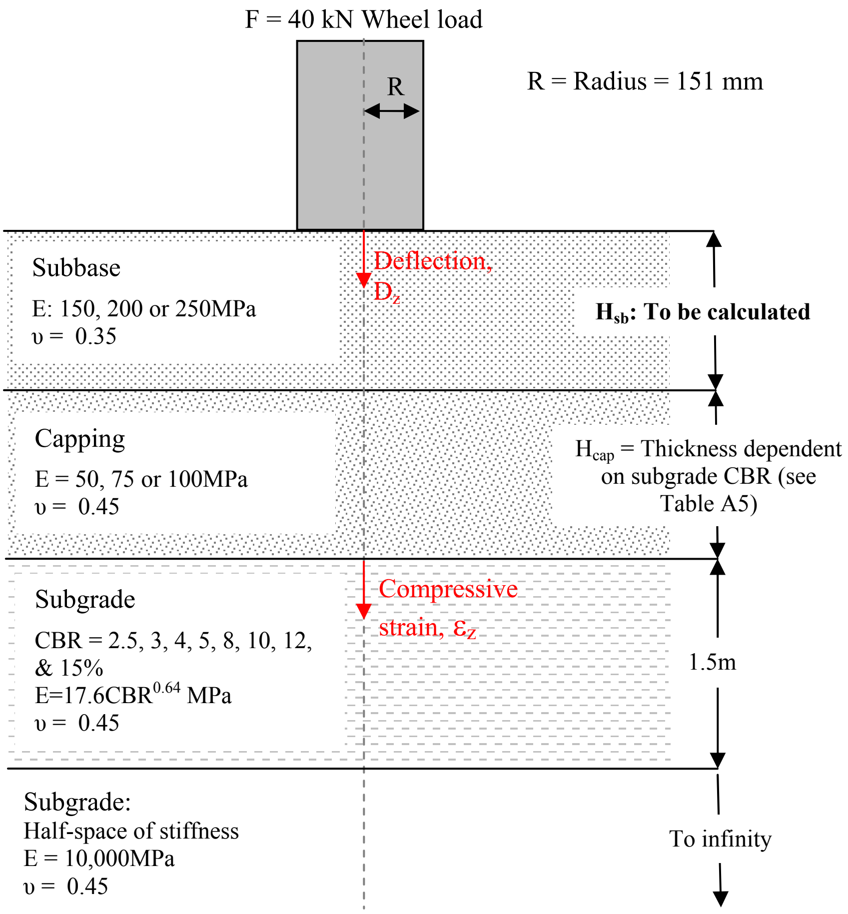


Figure A10. Subbase on capping foundation structures analysed

Table A5. Capping thickness

Subgrade CBR (%)	Capping thickness, H_{cap} (mm)
2.5	250
3	240
4	224
5	211
8	185
10	173
12	162
15	150

The values of subbase thickness calculated are listed in Table A6 together with the dominant criterion.

Table A6. Subbase thickness requirements of subbase on capping foundation designs for foundation class FC2

Foundation class	Subbase stiffness (MPa)	Capping stiffness (MPa)	Foundation structures for subgrade CBR (%):							
			2.5	3	4	5	8	10	12	15
			Capping thickness (mm)							
			250	240	224	211	185	173	162	150
			Subbase thickness (mm)							
FC2	150	50	312	289	256	231	183	161	150	150
		75	253	231	199	175	150	150	150	150
		100	202	181	150	150	150	150	150	150
FC2	200	50	227	212	189	172	150	150	150	150
		75	182	167	150	150	150	150	150	150
		100	150	150	150	150	150	150	150	150
FC2	250	50	192	180	161	150	150	150	150	150
		75	153	150	150	150	150	150	150	150
		100	150	150	150	150	150	150	150	150

🟦 Deflection controlled 🟩 Subgrade strain controlled ☐ Minimum thickness reached

For the given values of subbase and capping stiffness, the dominant criteria is often deflection controlled for the weaker soils with the minimum thickness criteria invoked for the stronger soils. As the subbase and capping stiffnesses increase, the range in soil strengths with deflection controlled design reduces until all soils within the range studied require only minimum thickness design of 150 mm. The designs are shown in Figures A11 to A13 for subbases of layer stiffness 150, 200 and 250 MPa respectively, where each subbase is built on capping of stiffnesses of 50, 75 and 100 MPa. The capping thickness is shown along with the combined thickness of subbase on capping plotted against subgrade CBR.

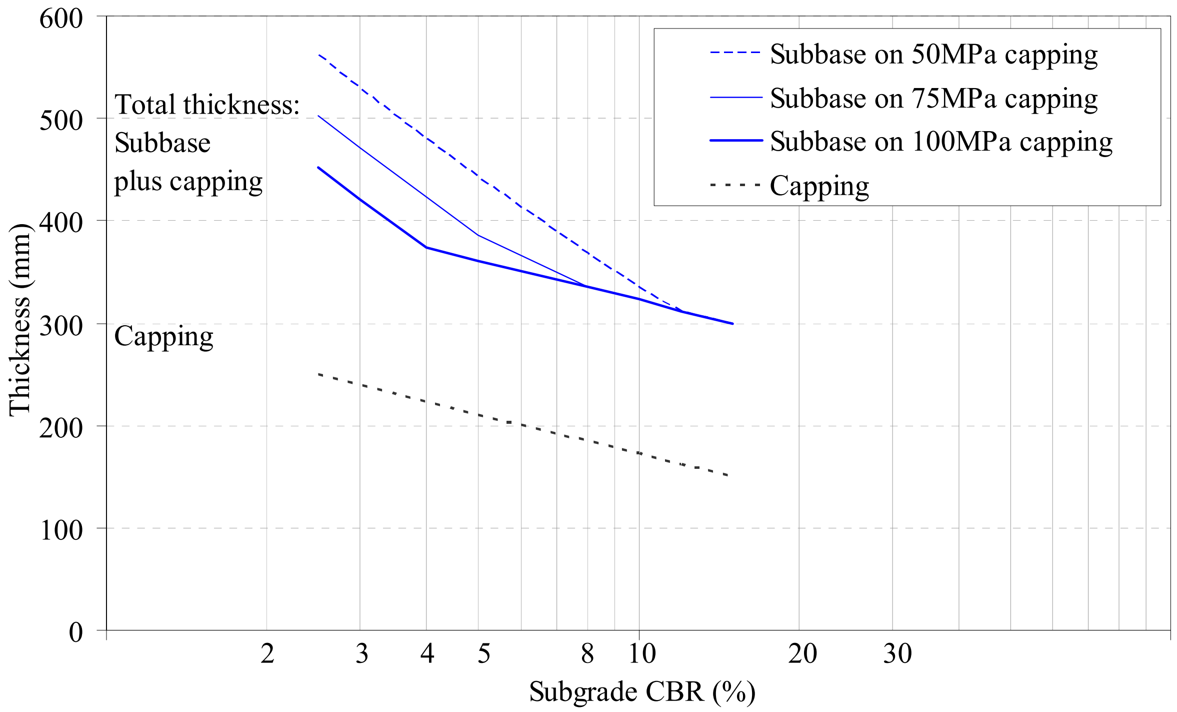


Figure A11. Subbase on capping Performance Related Designs for foundation class FC2: Subbase stiffness 150 MPa

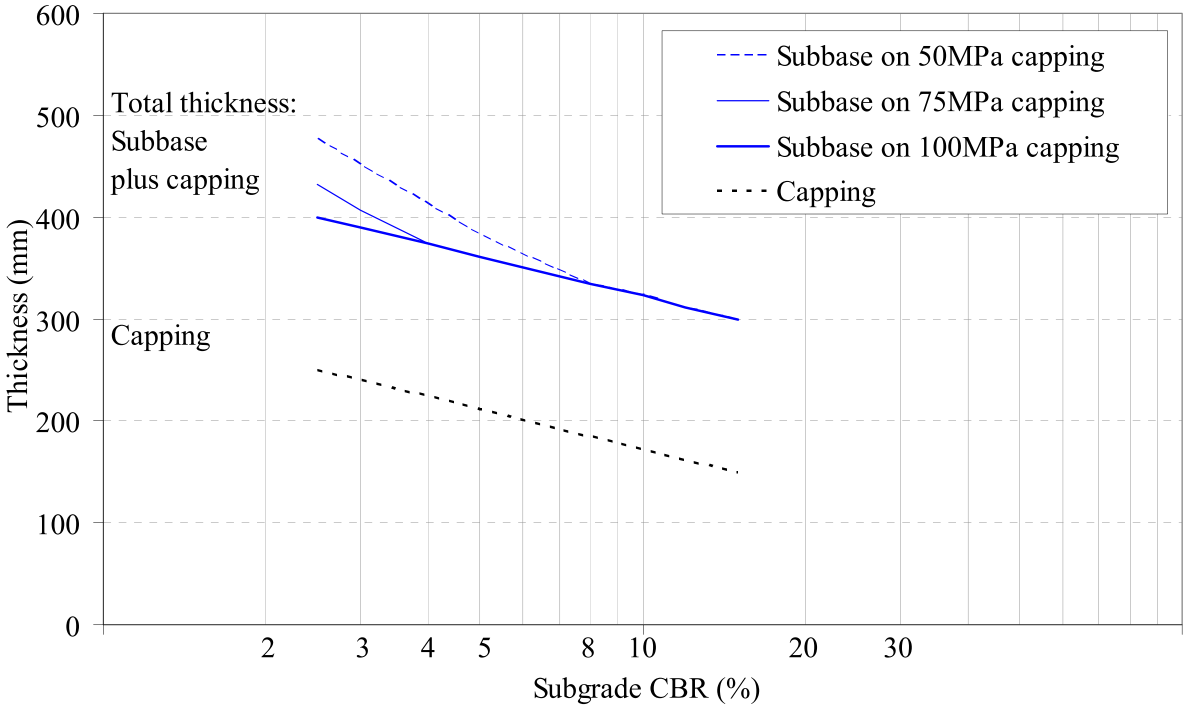


Figure A12. Subbase on capping Performance Related Designs for foundation class FC2: Subbase stiffness 200 MPa

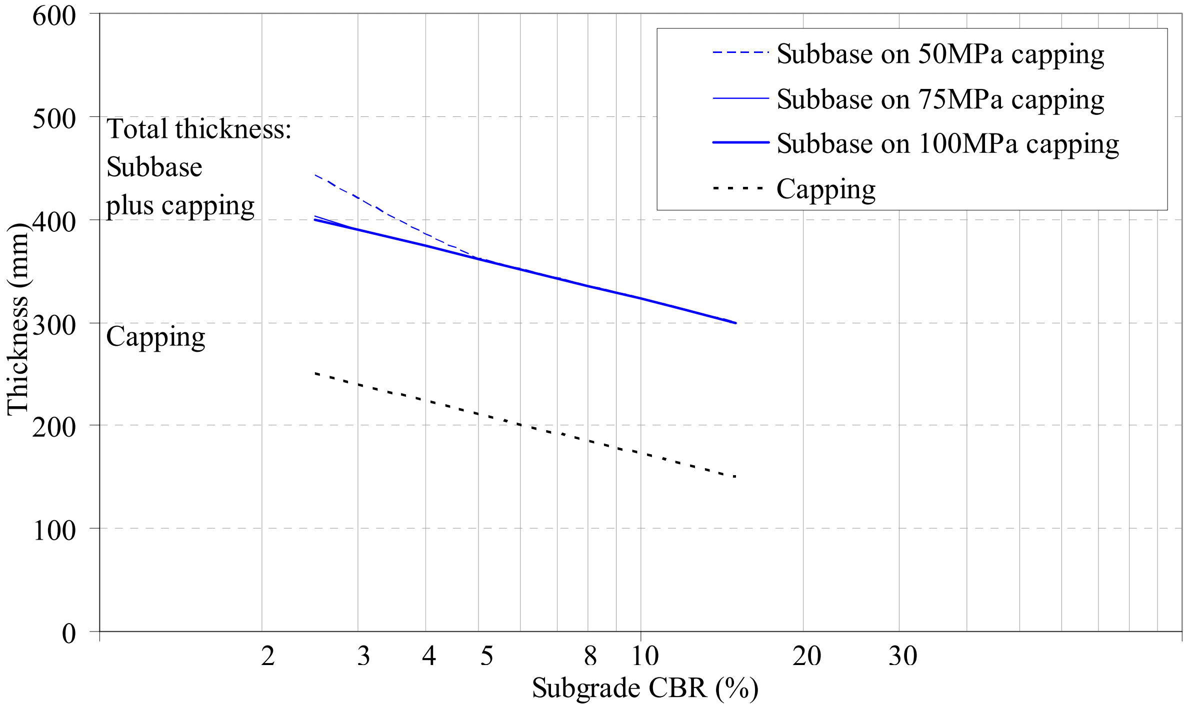


Figure A13. Subbase on capping Performance Related Designs for foundation class FC2: Subbase stiffness 250 MPa

The subbase thickness required to achieve the foundation class FC2 reduces with increasing strength of the subgrade and layer stiffness of the capping and/or subbase. Minimum thicknesses of subbase of 150 mm are invoked for all subbase materials studied, which implies that a thinner, but not necessarily cheaper, foundation structure could be designed incorporating subbase only.

The thicknesses determined using the Performance Related Design examples in this section are minimum values. Allowance for permitted level tolerances must be added when specifying construction thicknesses.

The following equations that describe the designs have been developed for subbase on capping foundation class FC2 and subgrade CBR in the range >2.5% and ≤ 15%:

The subbase thickness (mm) is given by:

$$H_{sb}(D) = 8.27\times10^{4}.(0.4123Ln(E_{cap}) - 1)E_{sb}^{-(0.2075+0.1933Ln(E_{cap}))} - 21.39.E_{cap}^{1.745}.E_{sb}^{(0.271-0.335Ln(E_{cap}))}Ln(CBR)$$

The capping thickness (mm) is given by:

$$H_{cap} = 3.01\times10^{2} - 56.Ln(CBR))$$

where, the minimum value of H_{sb} and H_{cap} permissible is 150 mm and these relationships are valid for capping material with a layer stiffness of between 50 and 100 MPa and subbase material with a layer stiffness of between 150 and 250 MPa.

Also, in the above equations:

H_{cap} (mm) is capping layer thickness,
H_{sb} (mm) is subbase layer thickness,
E_{cap} is capping layer stiffness (MPa),
E_{sb} is subbase layer stiffness (MPa) and,
CBR is the California bearing ratio of the subgrade (%).
(D) denotes that the thicknesses where determined using the foundation deflection criterion.

Table A7 gives the percentage differences between the subbase thicknesses calculated from the equations and the thicknesses derived from the theoretical analysis.

Table A7. Performance Related Design equation errors for subbase on capping designs

Foundation class	Subbase stiffness (MPa)	Capping stiffness (MPa)	Difference[1] (%) between thickness by equations and theoretically modelled thickness for subgrade CBR (%)							
			2.5	3	4	5	8	10	12	15
FC2	150	50	-1.7	-0.7	0.0	0.4	-1.0	-2.4	n/a	n/a
		75	-2.4	-1.9	-2.1	-2.8	n/a	n/a	n/a	n/a
		100	-0.8	-0.7	n/a	n/a	n/a	n/a	n/a	n/a
FC2	200	50	3.1	3.5	3.9	3.8	n/a	n/a	n/a	n/a
		75	2.1	2.6	n/a	n/a	n/a	n/a	n/a	n/a
		100	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
FC2	250	50	-1.2	-1.0	-0.7	n/a	n/a	n/a	n/a	n/a
		75	-2.7	n/a	n/a	n/a	n/a	n/a	n/a	n/a
		100	n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a

[1] Difference (%) = (Thickness by equation – Modelled thickness)*100 / Modelled thickness

It can be seen that the maximum errors introduced by using the equations vary with the foundation structure being within about -3 to +4 per cent of the theoretically modelled thicknesses.

These equations can be used to deduce quickly subbase thicknesses on pre-selected capping thicknesses, which are required for the designated foundation class FC2, from knowledge of subgrade CBR strength, capping stiffness and subbase stiffness.

In this report, capping is limited to material that is not very much stronger and stiffer than the subgrade soil that needs to be improved. However, composite subbase structures of far more superior material can be developed using the principles described.

A.7 Restricted Designs

Restricted Design foundations are based on selected Performance Related Design foundations but are more conservative to allow for construction level tolerance and, as the foundations are not subject to the requirements of the Performance Related Specification, uncertainty in material performance. Conservatism is attained by a combination of increased design thicknesses and specification of selected materials, whose performance is not only reasonably predictable but also likely to be more than adequate for the requirements of the selected foundation classes.

A.7.1 Materials

The permissible materials are specified in the Specification (MCHW 1) as follows:

- Any Series 600 capping.
- Unbound granular subbase Types 1, 2*, 3 and Category B of the Series 800. {* Restrictions are placed on the use of this material in a Restricted Design foundation}.
- Cement bound granular materials Types CBGM A or CBGM B of strength classifications C3/4, C5/6 and C8/10 of the Series 800.

The assumed layer stiffnesses of these materials in relation to those values adopted for reference Performance Related Designs for a particular foundation class are given in Table A8.

Table A8. Material quality

Material		**Assumed layer stiffness (MPa)**	**Layer stiffness (MPa) of reference Performance Related Design required for foundation class:**		
			FC1	**FC2**	**FC3**
Any Series 600 MCHW1 Capping		75	75	-	-
Subbase Type 1		150	-	150	-
Subbase Type 2		130	-	150	-
Subbase Type 3		140	-	150	-
Subbase Category B		180	-	150	-
CBGM A or CBGM B	C3/4	3500	-	150	660
	C5/6	4200	-	150	660
	C8/10	6000	-	150	660

Except for some capping and unbound granular subbase, the estimated layer stiffnesses of all materials equal or exceed the minimum layer stiffness assumed for the reference Performance Related Designs. Where this is not the case, increased thickness of the Restricted Design over the Performance Related Design reduces the risk of using these materials.

A.7.2 Designs

The thicknesses of the Restricted Design foundations in relation to selected Performance Related Designs are shown in Figures A14 to A16 and Figures A17 and A18 for capping/subbase only and subbase on capping foundations respectively.

Any capping material specified in the Specification (MCHW 1, Series 600) can be used on its own to produce a foundation class FC1. Figure A14 shows the thickness of the Restricted Design foundation to be greater than the Performance Related Design foundation for a capping of layer stiffness of 75

MPa by between about 120 mm and about 20 mm. The greatest thickness difference is specified for subgrades weaker than a CBR strength of 5 per cent. This Restricted Design foundation is not permitted in IAN 73 (2006) for use on Trunk roads, including motorways.

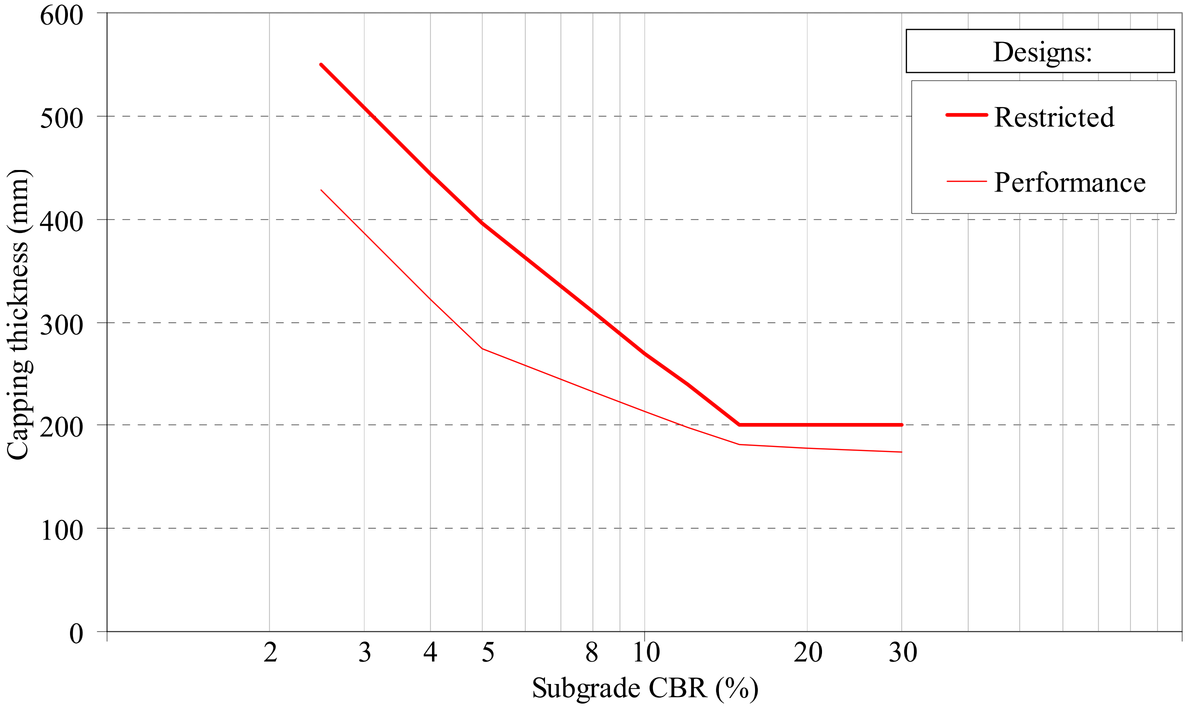


Figure A14. Capping only Restricted Design for foundation class FC1 – Comparison with Performance Related Design

Unbound granular subbase of Types 1, 2, 3 and Category B can be used on their own to produce a foundation class FC2. Figure A15 shows the thickness of this Restricted Design foundation in comparison with the relevant Performance Related Design foundation.

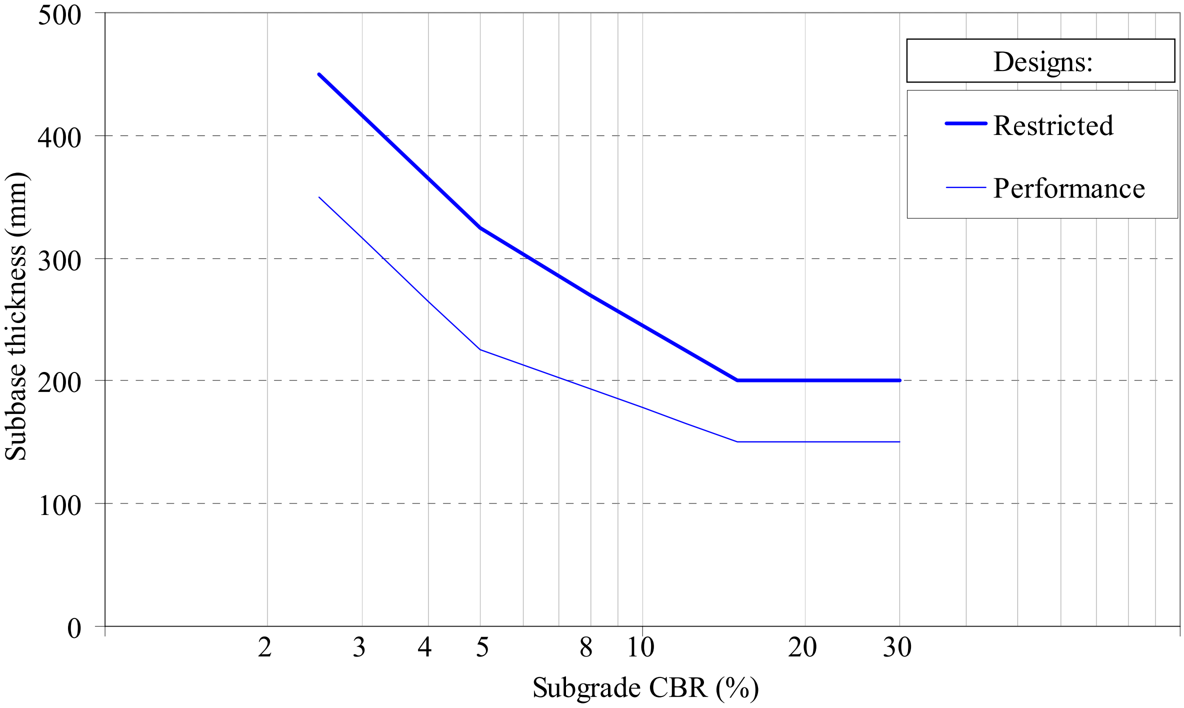


Figure A15. Subbase only Restricted Design for foundation class FC2 (Unbound granular material) – Comparison with Performance Related Design

The Restricted Design foundation is between 100 mm and 50 mm thicker than the Performance Related Design foundation built with a 150 MPa layer stiffness subbase. The greatest thickness difference is specified for soil subgrades weaker than a CBR strength of 5 per cent. Type 2 subbase is restricted in IAN 73 (2006) to designs for traffic below 5 msa.

Bound subbases can be used on their own to produce both foundation class FC3 and FC2. Subbase Types CBGM A or CBGM B of strength classification C8/10 are specified for foundation class FC3, whilst subbase Types CBGM A or CBGM B of strength classification C3/4 or C5/6 are specified for foundation class FC2. Figure A16 shows the thickness of the Restricted Design foundation to be greater by between 50 mm and 25 mm than the thickness of the foundation class FC3 Performance Related Design foundation built with a bound subbase of layer stiffness 660 MPa. The greatest thickness difference is specified for soil subgrades weaker than a CBR strength of 8 per cent.

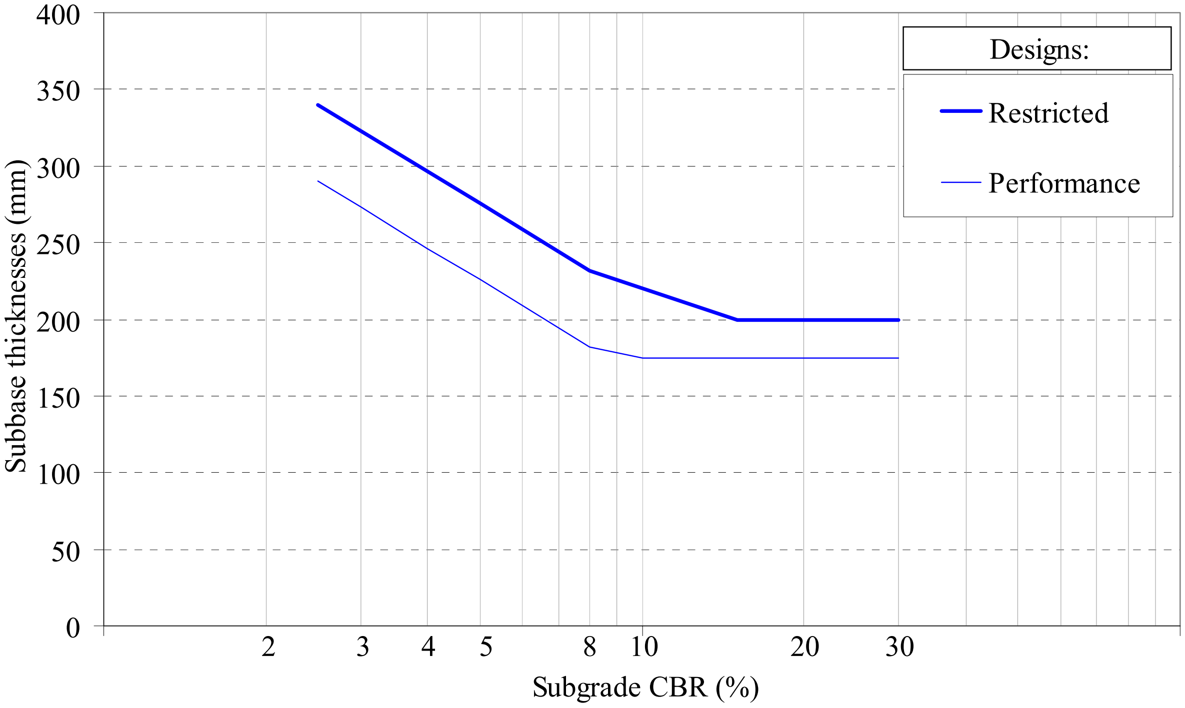


Figure A16. Subbase only Restricted Design for foundation class FC2 and FC3 (Bound material) - Comparison with Performance Related Design

Unbound granular subbase of Types 1, 2, 3 and Category B can be used in combination with capping composed of any material specified in the Specification (MCHW 1, Series 600) to form a foundation class FC2. Figure A17 shows the Restricted Design foundation in comparison with the Performance Related Design foundation that are both built with a 150 MPa layer stiffness subbase on capping of layer stiffness 75 MPa.

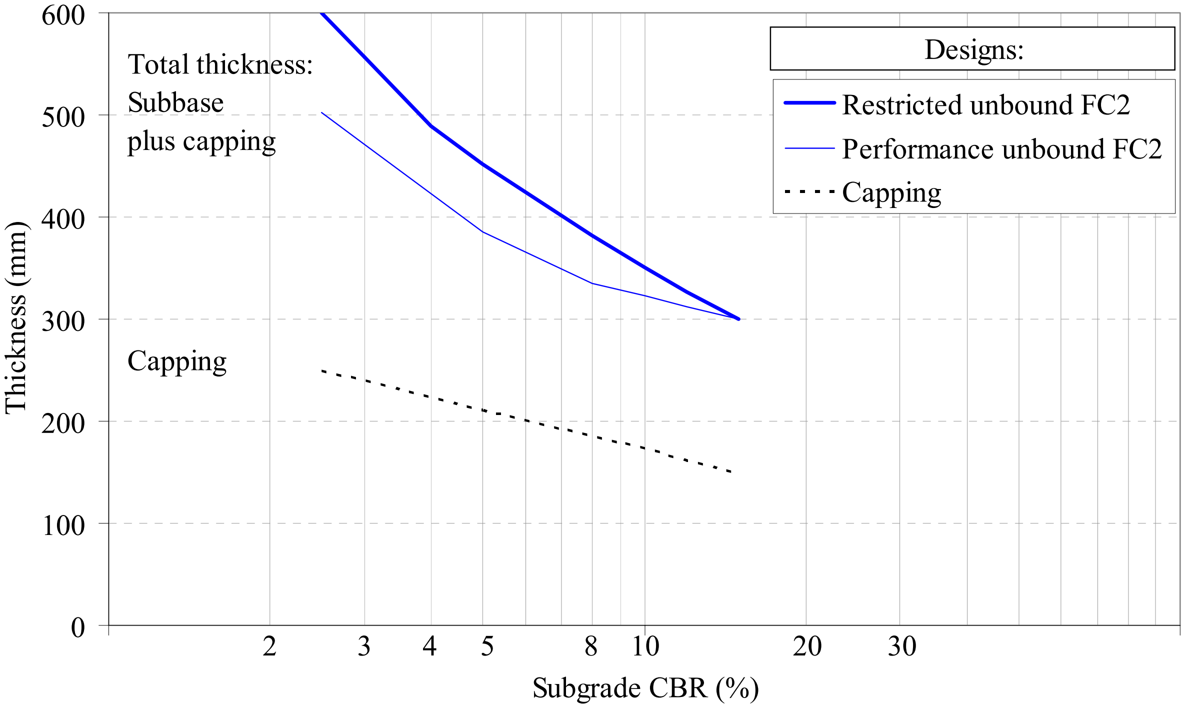


Figure A17. Subbase on capping Restricted Design for foundation class FC2 (Unbound granular subbase) – Comparison with Performance Related Design

The total thickness of the Restricted Design foundation is greater by about 100 mm than the thickness of the subbase on capping Performance Related Design foundation for the foundation design for a subgrade soil whose CBR strength is 2.5 per cent. This thickness difference decreases with increase in soil strength to zero for a soil of CBR strength 15 per cent.

Bound subbase can be used in combination with capping composed of any material specified in the Specification (MCHW 1, Series 600) to form foundation class FC2. Subbase types permitted are CBGM A or CBGM B of strength classification C3/4 or C5/6. Figure A18 shows the total thickness of this Restricted Design foundation in comparison with the relevant Performance Related Design foundation.

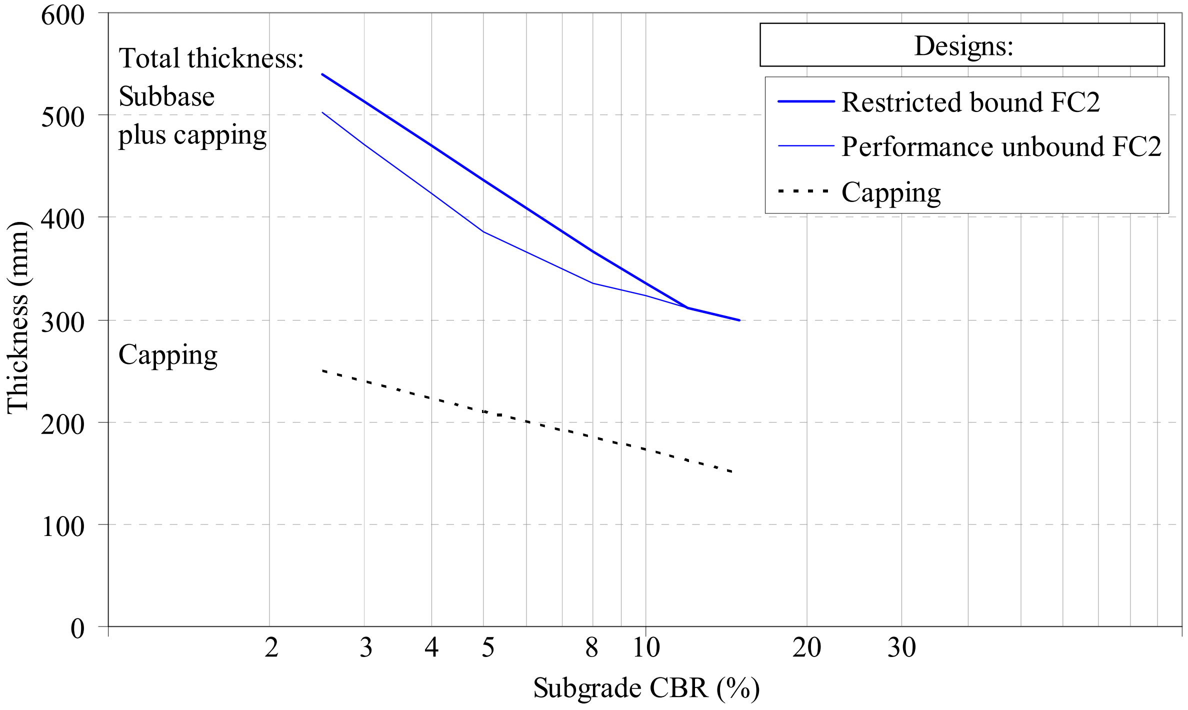


Figure A18. Subbase on capping Restricted Design for foundation class FC2 (Bound subbase) - Comparison with Performance Related Design

The Restricted Design foundation is, at most, 50 mm thicker than the thickness of the reference Performance Related Design foundation comprised of a 150 MPa layer stiffness subbase on capping of layer stiffness 75 MPa. These Restricted and Performance Related Design curves converge at higher subgrade CBR values.

The Restricted Design foundations can therefore often be seen to have material specified that is superior to that required for the designated foundation class. Also, these foundations generally have design thicknesses that are greater than those of the Performance Related Designs. The assigned thicknesses are construction thicknesses and include allowance for the subgrade to be built at most 30 mm high as permitted by tolerances assigned to the level of the formation. It is recommended that the degree of conservatism and permitted materials be reassessed as experience of the use of these Restricted Design foundations and knowledge of material behaviour is gained.

A.8 References

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Appendix B. Stiffness degradation factors

B.1 Introduction

Layers of hydraulic bound material (HBM) in the road foundation develop a natural crack pattern as they cure. The cracks open as the temperature falls and relative movement of slabs caused by traffic loading can abrade material at crack boundaries and, in time, reduce the ability of the HBM to transfer load from one slab to the adjacent slab as vehicles travel along the pavement. The effective layer stiffness of the cracked HBM can therefore be markedly different from the intact layer stiffness that is often estimated from laboratory tests on an HBM specimen. The ratio of the values of cracked to intact layer stiffness is defined as the degradation factor.

B.2 Experimental investigation

This Appendix describes several experimental investigations whose aim was to estimate the magnitude of these degradation factors for various materials. Tests were carried out on foundations during their construction and on pavements needing maintenance to assess degradation factors “shortly after foundation construction” and in the “long-term” design stages respectively.

The experimental approach consisted of the measurement of foundation deflection with the falling weight deflectometer (FWD) at cracks and within the slabs at least 3m from a crack. Averages of these deflections at cracks and within slabs were separately calculated for selected regions of the foundations and pavements studied. Reference was then made to the work of Goddard (1990), who gave relationships between the deflection of a pavement and the stiffness and thickness of the upper bound layers of the structure and the equivalent surface stiffness of the foundation. By assuming unchanged bound layer thickness and formation stiffness, the ratio of the deflections at cracks and in slabs was transformed into a ratio of layer stiffnesses of cracked and uncracked material, or an expression for the degradation factor.

The calculated degradation factors are given in Table B1. The HBM materials studied in the foundations during their construction were strong cement bound materials of Type CBM2A of the Specification, (MCHW1 2003), and a stabilised soil, both used as subbase. For the long-term condition, combined asphalt on a cement bound material layers in cracked flexible composite pavements were studied.

Table B1. Estimated stiffness degradation factors

Construction stage:	Road designation / Region	Bound material	Degradation factor
Shortly after construction	A / 1	CBM2A	0.81
	A / 2		0.73
	B / 1	CBM2A	0.92
	C / 1	Stabilised clay	0.82
	C / 2		0.64
Long-term	A / 1	Asphalt on CBM	0.52
	B / 1	Asphalt on CBM	0.42
	B / 2		0.34
	B / 3		0.22

B.3 Discussion and conclusions

For foundations subjected to limited trafficking during construction, the lowest values of the degradation factor were about 0.7 for strong cement bound materials and approximately 0.6 for stabilised clay. For the long-term, the lowest value of the degradation factor for a cracked asphalt on cement bound structure was about 0.2. This latter factor is consistent with the treatment of this type of pavement in France where the Design Manual of LCPC-SETRA (1997) assigns the cement bound material a value of stiffness equal to 0.2 of its initial uncracked stiffness for the final part of its life. Further studies are required on other HBMs to assess their long-term degradation factors.

B.4 References

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