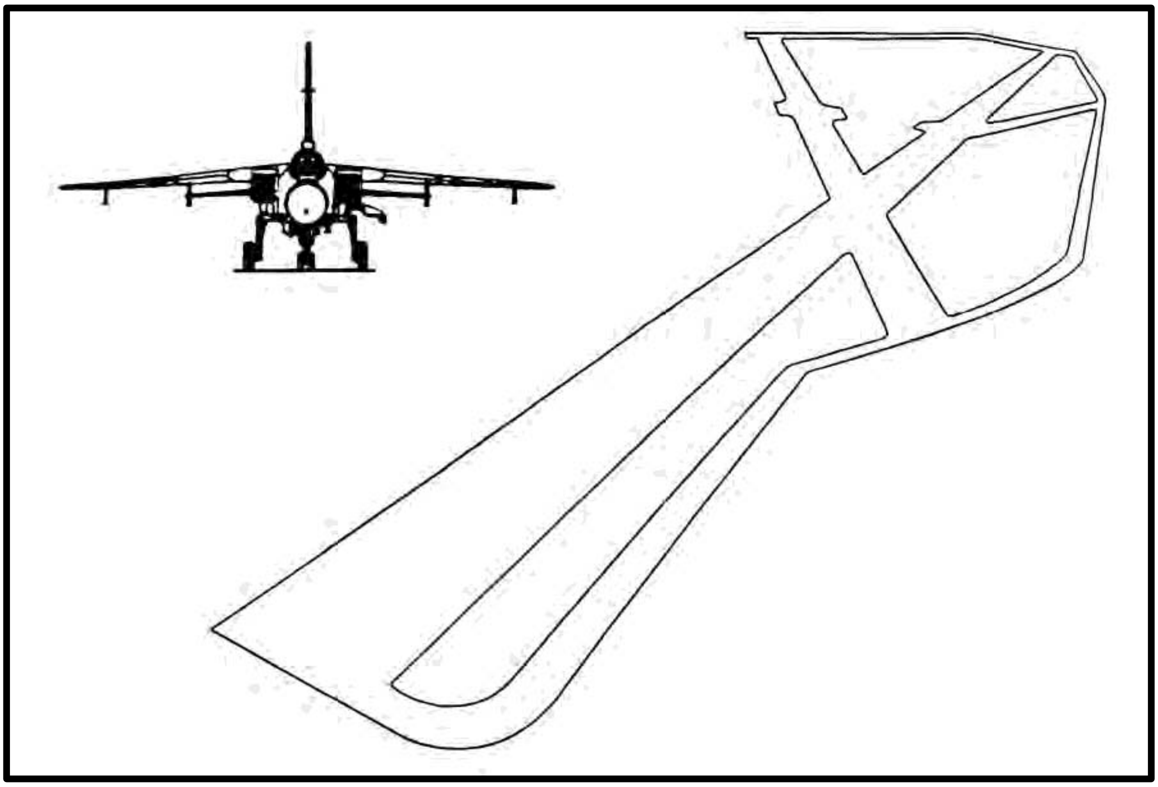
Design & Maintenance Guide 27

# A Guide to Airfield Pavement Design and Evaluation



**DEFENCE ESTATES**
MINISTRY OF DEFENCE

## Design and Maintenance Guide 27

# A Guide to Airfield Pavement Design and Evaluation

**3RD EDITION – FEBRUARY 2011**

CONSTRUCTION SUPPORT TEAM
DEFENCE ESTATES
MINISTRY OF DEFENCE

# Foreword

This guide has been prepared under the patronage of the Construction Support Team, Defence Estates, Ministry of Defence to provide guidance on the structural design and evaluation of airfield pavements. It supersedes the previous edition published in 1989.

The design and evaluation methods presented in this guide are developments of previous methods, incorporating the benefits of additional experience and research.

The aircraft/pavement classification system incorporated in this guide is the ICAO ACN-PCN method. Methods for approximating the relationship with the previously used LCN/LCG system are included.

Further technical assistance regarding the contents of this document can be obtained from Defence Estates. Enquiries regarding this guide should be made to the airfield pavement technical Authority:

Head of Airfield Pavements
Construction Support Team
Kingston Road
Sutton Coldfield
West Midlands
B75 7RL

Tel: 0121 311 2119 or Sutton Coldfield MI 2119

This guide has been devised for the use of the Crown and of its Contractors in the execution of contacts for the Crown and, subject to the Unfair Contracts Terms Act 1977, the Crown will not be liable in any way whatever (including but without limitation negligence on the part of the Crown, its servants or agents) where the guide is used for other purposes.

# Acknowledgements

The guidance in this document has been prepared by TRL Limited and WSP Group in conjunction with and under commission to the Construction Support Team, Defence Estates, Ministry of Defence

# Contents

# Figures

# Charts

# Tables

**Page No**

# Glossary

| *Term* | *Abbreviation* | *Definition* |
|---|---|---|
| Aircraft Classification Number | ACN | A number expressing the relative effect of an aircraft on a pavement for a specified standard subgrade strength. A component of the ICAO ACN-PCN method. |
| All-up Mass/Weight | | A term meaning the total mass/weight of the aircraft under defined conditions, or at a specific time during flight. (Not to be confused with MTOW). |
| Blast Pad | | A length of pavement adjoining the runway end, designed to resist jet blast from aircraft standing on the runway before take off. Generally part of a stopway. |
| Bound Base Material | BBM | Any material equivalent to a granular sub-base or better, which uses a cement or bituminous binder. |
| British Standard | BS | A publication of the British Standards Institution. |
| California Bearing Ratio | CBR | An indication of the bearing capacity of a soil. It is determined by comparing the penetration load of a soil to that of a standard material. |
| Cement-Stabilised Soil | | A relatively low quality cement-bound material produced by the addition of the cement to a natural soil. Mixing can take place in situ or in a mixing plant. |
| Cohesive Soil | | A soil which contains clay; forms a coherent mass. For determining relative compaction requirement, cohesive soils are taken as those with a Plasticity Index greater than or equal to 6%. |
| Composite Pavements | | Pavements consisting of mixed rigid and flexible layers. |
| Coverage | | The application of a maximum stress on a point in the pavement surface. |
| Design Aircraft | | The aircraft which imposes the most severe loading on the pavement. |
| Drylean Concrete | DLC | A low-strength Portland cement concrete generally used as a sub-base and/or base course under PQC or bituminous surfacing (see Rolled Drylean Concrete) or as a working course. Water content and strength requirements are specified. |
| Equilibrium Moisture Content | | The moisture content at any point in a soil after moisture movements have ceased. |
| Equivalent Coverages | | The number of Coverages by one aircraft which has the same damaging effect on the pavement as a given number of Coverages by another aircraft. |

| *Term* | *Abbreviation* | *Definition* |
|---|---|---|
| Flexible Pavement | | A pavement which distributes the load primarily through the sheer strength of the materials. |
| Formation | | The surface of the subgrade in its final shape after completion of the earthworks. |
| Frequency of Trafficking | | The level of Coverages for which the pavement is designed. There are three categories. High, Medium and Low. |
| International Civil Aviation Organisation | ICAO | |
| Load Classification Group | LCG | A range of LCN values. |
| Load Classification Number | LCN | A number expressing the relative effect of an aircraft on a pavement or the bearing strength of a pavement. The original LCN classification system was developed in the UK in the late 1940s but in 1971 the method of calculating LCNs was altered and the LCN/LCG system introduced. LCN values from the two systems are not compatible. |
| Main Wheel Gear | | The undercarriage leg used in ACN calculation. |
| Marshall Asphalt | MA | An asphalt designed by the Marshall method to meet strict specification requirements in order to provide a durable, high stability flexible surfacing material. |
| Maximum All-Up Weight | MAUW | The higher of MTOW and MRW. |
| Maximum Ramp Weight | MRW | Maximum Take Off Weight plus any taxi/runup fuel load. |
| Maximum Take Off Weight | MTOW | The maximum aircraft weight allowable at take off. |
| Mixed Traffic | | A mixture of aircraft types using a pavement, all of which produce a calculable effect on the fatigue life of a pavement. |
| Mixed Traffic Factor | RMTF or FMTF | A figure used in converting Coverages by an aircraft with one ACN to equivalent Coverages by an aircraft with a different ACN. There are different MTF systems for Rigid (RMTF) and Flexible (FMTF) pavements. |
| Modulus of Subgrade Reaction | k | A measurement of the bearing strength of a soil obtained from a loading test with a 762mm (30 inch) diameter plate. |
| Movement Area | | Pavements intended for use by aircraft, including runways, taxiways, aprons and other areas provided for the operation or maintenance of aircraft. |
| Multiple Slab Pavements | | Pavements consisting of two or more concrete layers, with or without separating layers. |
| Non-cohesive soil | | A granular soil; does not form a coherent mass. For determining relative compaction requirements, non-cohesive soils are taken as those with a Plasticity Index less than 6%. |

| *Term* | *Abbreviation* | *Definition* |
|---|---|---|
| Overlay | | An additional layer or layers of structural pavements materials on an existing pavement. |
| Overload | | Use of a pavement by aircraft with a classification (ACN) greater than the pavement classification (PCN). |
| Overslab | | A concrete overlay. |
| Pass | | An aircraft movement over a particular section of the pavement. Under certain conditions a pass may be taken as a movement by departing aircraft only. |
| Pass-to-Coverage Ratio | | The number of passes of an aircraft on a pavement which produces one Coverage at a point in the pavement. |
| Pavement | | A structure consisting of a layer or superimposed layers of selected materials, whose primary purpose is to distribute the applied loads to the subgrade. |
| Pavement Classification | PCN | A number expressing the bearing strength of a pavement for unrestricted operations by an aircraft with a classification (ACN) of the same number. A component of the ICAO ACN-PCN method. |
| Pavement Quality Concrete | PQC | A Portland cement concrete designed within strict limits to give a durable material in pavement applications. |
| Reflective Crack | | A crack in a pavement layer induced by a crack in the underlying layer. |
| Relative Compaction | | The percentage ratio of the dry density of the soil to the maximum dry density of that soil as determined in a compaction test. |
| Rigid Pavement | | A pavement which distributes the load by means of its high flexural stiffness. |
| Rolled Drylean Concrete | | A drylean concrete which is compacted by rolling to give a dense material. |
| Shoulder | | A strip adjacent to the edge of a movement area prepared to provide a transition in strength and , if necessary, in grade between the movement area and the adjacent ground, to provide for use by aircraft in an accident or emergency. |
| Stopway | | A defined rectangular area at the end of runway, designated and prepared as a suitable area in which an aircraft can be stopped if the take off is aborted. |
| Subgrade | | The natural or made-up ground supporting the pavement. |
| Temperature Warping Stresses | | Stresses due to a temperature gradient through the depth of the concrete slab. |
| Transport Road Research Laboratory | TRRL | |

| *Term* | *Abbreviation* | *Definition* |
|---|---|---|
| Twin Slab Pavement | | A multiple slab pavement consisting of two slabs laid at the same time to obtain a thicker equivalent single slab thickness without compaction problems. |
| Wander | | The width over which movements of an aircraft centre-line are distributed 75% of the time. |
| Westergaard's Constant | k | See Modulus of Subgrade Reaction. |
| Unrestricted Operations | | A term meaning that the operator does not have to apply any limitations on use by an aircraft at a particular ACN. |

# 1 Introduction to Airfield Pavement Design in the United Kingdom

## 1.1 GENERAL

1.1.1. The design of an airfield pavement requires realistic methods of assessing the loading characteristics of aircraft and the structural response of the pavement. It has long been recognised that the severity of load-induced stresses in a pavement and subgrade depends on the gross weights of the aircraft using the pavement and the configuration, spacing and tyre pressures of their undercarriage wheels. The response of the pavement in resisting these stresses depends on its thickness, composition, the properties of materials used in its construction and the strength of the subgrade on which the pavement is built.

1.1.2. Through the years, these basic concepts have been developed and extended to include the effects of fatigue, environmental factors, mixed traffic, overload operations etc. Major developments in aircraft designs have required a continuing review of existing pavement designs and the trend up to now has been that new generations of aircraft demand pavements designs well ahead of any practical experience of previous aircraft use.

1.1.3. The design methods for airfield pavements have largely grown out of the experience of pavement performance. For rigid pavements, which rely on the flexural stiffness of concrete to distribute the loads from aircraft wheels to the subgrade, use has been made since the early 1940s of theoretical approaches developed by Westergaard and others. Because of difficulties encountered in developing a realistic mathematical model for flexible pavements, which depend on the mechanical strength of compacted aggregates, empirical design methods (e.g. the CBR method) are still commonly used.

## 1.2 DEVELOPMENT OF PAVEMENT DESIGN IN THE UNITED KINGDOM

1.2.1. In the UK, the history of airfield pavement design really began in 1937 when the first paved runways were constructed, using road experience as a guide. Flexible pavements were comprised of layers of brick or stone topped with two courses of tarmacadam and a sealing coat of mastic asphalt. Concrete pavements were either 150mm or 200mm thick slabs generally laid directly on to the ground after the removal of the topsoil. These early pavements soon failed under the increasing weight of new aircraft and were overlaid with 65mm thickness of tarmacadam and a 20mm thick sealing course of rolled asphalt. The overlays were remarkably successful on concrete and were the first composite pavements. The flexible pavements on the other hand, kept failing and were either replaced by concrete pavements or strengthened with further overlays of tarmacadam.

1.2.2. The Air Ministry Works Directorate, which was responsible for design, construction and maintenance of all airfields for the UK Government, constructed some 450 airfields between 1937 and 1945 without having the benefit of proven design methods. Nevertheless, extensive data on pavement performance, construction details and subgrade characteristics was collected and during the last stages of World War Two attention was being given to developing proper methods of design for airfield pavements.

1.2.3. The first design method[1], published by the Department* in 1945, used Westergaard's equations for calculating the stresses induced in a concrete pavement by aircraft loads and Bradbury's equations for calculating warping stresses induced by thermal effects. The cracking of the slaps was controlled by limiting the allowable flexural stresses in concrete.

1.2.4. As aircraft increased in all-up weight and a wider range of tyre pressures was introduced it became obvious that a system of classifying aircraft, according to the severity of stresses produced in the pavement, was necessary. A series of plate-bearing tests was put in hand to investigate the relationship between the load necessary to produce the failure of a pavement and the contact area over which the load was applied. The results of these tests led to the development of an empirical relationship expressed in the following form:

$$\frac{W_1}{W_2} = \left[\frac{A_1}{A_2}\right]^{0.44} \qquad (1)$$

$W_1$ and $W_2$ are the failure loads and $A_1$ and $A_2$ are the contact areas for two combinations with the same damaging effect.

1.2.5. In 1948, the Department published a load classification system[2] which assigned a Load Classification Number (LCN) to aircraft whose loads and contact areas (derived from tyre pressures) were linked by Equation 1. The LCN represented the relative damaging effect of wheel loads and tyre pressures of aircraft within a practical numerical scale ranging from 1 to 100. The LCN system is still used in some countries and at many military airfields.

1.2.6. During the early 1950s, a method of using plate-bearing tests was developed for evaluation of airfields. Publication TP104/51[3], issued in 1952, included a formal description of the LCN system which had by then been extended to cater for multiple wheel undercarriages, evaluation techniques using plate bearing tests and advice on overload operations. A year later, the Department published a paper[4] describing its latest thinking on the design concepts. Since good compaction of slabs thicker than 300mm was difficult to achieve with techniques available at that time, a twin slab with the corners of the upper slab supported at the centre of the lower slab was used to provide an equivalent construction. To deal with the corner case more accurately the Teller and Sutherland modification to the Westergaard corner case was incorporated into the design procedure. For the design of flexible pavements two methods were introduced – a method based on the CBR equation and the 'Search Plate' method which was abandoned later.

1.2.7. During the construction of flexible pavements including unbound granular materials, problems had sometimes been experienced in uniformly compacting the high quality materials to the levels required. These pavements produced poor performance in the short and long term. Experiments were therefore carried out using full-depth bound constructions by placing weak cement-bound layers beneath bituminous layers. These were very successful and full-depth bound constructions have been adopted as standard construction by the Department since 1954.

1.2.8. The cumulative developments in design methods and the associated construction practices were brought together in the Department's publication entitled 'Airfield Design and Evaluation'[5] produced in 1959. It included design charts for rigid and flexible pavements which used LCNs as the parameter for aircraft loading. For rigid pavements a procedure for allowing two levels of trafficking – channelised and non-channelised – was introduced. The possibility of using reverse design for evaluating the strength of airfield pavements was mentioned. As the compaction of concrete thicknesses greater than 300mm had become possible, the use of twin slabs was discontinued. Charts for the design of overlays on existing pavements were included.

* Throughout the guide 'the Department' refers to Defence Estates and its predecessors in the Directorate of Civil Engineering Services (Airfields Branch), the Ministry of Public Building and Works and Air Ministry Works Directorate.

1.2.9. Experience during the 1960s showed that the plate-bearing tests developed for flexible pavements gave over-optimistic results when such pavements had cement-bound bases. An alternative heavy rolling test was therefore introduced. It was also discovered that the strength of twin slabs and overlays on rigid construction was being overestimated. A new design technique, assuming a high subgrade strength on the surface of the underlying slab, was therefore developed.

1.2.10. At a symposium organised by the Institution of Civil Engineers in London on 12 November 1970, the Department summarised its state-of-the-art on design, evaluation and strengthening of airfield pavements. Three papers[6,7,8] presented at the symposium discussed the effects of multiple wheel undercarriages, limiting criteria for failure of rigid and flexible pavements, types of pavement which had proven to be most satisfactory and design of strengthening.

1.2.11. The Department's last guide, entitled 'The Design and Evaluation of Aircraft Pavements 1971[9], introduced the concept of Load Classification Groups (LCG) which categorised aircraft LCN valued into seven groups. Aircraft imposing similar stress levels on particular pavement thicknesses normally used in construction were placed in one group. This simplified the design and evaluation of pavements and was thought to be sufficiently accurate.

1.2.12. The Load/Contact area relationship used to develop the original LCN scale of relative loading severity was also modified as follows:

$$\frac{W_1}{W_2} = \left[\frac{A_1}{A_2}\right]^{0.27} \qquad (2)$$

This relationship was considered to be more appropriate for the aircraft which were in service at that time. The new LCN values derived from Equation 2 were different and unrelated to those derived in the original LCN system[†].

1.2.13. Although the LCG system was included in the 1977 edition of the ICAO* Aerodrome Design Manual[10] as one of the recommended methods for reporting pavement strength, it did not become popular outside the Department. The LCGs embraced too wide a range for practical use and the new LCNs were often confused with the previous LCN values.

1.2.14. Probably the most radical change in the 1971 publication was the formal recognition of the Department's construction practices, which had for some years discarded the conventional rigid and flexible pavement constructions by adopting cement- and bitumen-bound bases for flexible pavements and lean concrete bases for rigid ones. The design methodology for new pavement construction was modified to reflect these practices.

1.2.15. The 1971 design guide was substantially revised and updated and a new guide published in 1989[11]. The 1989 guide continued to build upon the development of previous concepts with the emphasis fixed firmly on the use of proven design techniques developed from past experience of pavement performance. Evaluation of concrete pavements nearing the end of their design life in the late 1970s indicated that the more frequent failure criterion was longitudinal halving cracking and this led to a more comprehensive fatigue model for calculating the allowable stress in rigid pavements.

1.2.16. The analysis was still based on Westergaard's theories but the design model was refined to include factors such as fatigue, growth in concrete strength with age and temperature warping stresses. The structural contribution of lean concrete bases was also re-appraised.

* ICAO – International Civil Aviation Organisation.

[†] All subsequent references to LCN are in terms of the 1971 LCN/LCG system.

1.2.17. The 1989 guide incorporated improvements to the CBR method based on full scale testing by the US Army Corps of Engineers[12] and introduced Equivalency factors for cement and bitumen bound base courses. Methods of equating multi-layer mixed constructions to model rigid or flexible constructions based on pavement performance experience were included.

1.2.18. The major change in the 1989 guide was the move from the previous LCN/LCG classification system to the ICAO Aircraft Classification Number - Pavement Classification Number (ACN-PCN) method linked to the design and evaluation methods.

## 1.3 CURRENT DESIGN PRACTICE

1.3.1. In 2006 a 2nd Edition of the guide was published, incorporating a number of developments in aircraft and airfield pavement construction and site investigations that had taken place since 1989. The 1989 guide was updated to cover:

(i) More damaging aircraft.
(ii) Tridem (6 wheel) main wheel gears.
(iii) Higher concrete strengths.
(iv) Increases in strength for Drylean Concrete in flexible pavements.
(v) Site investigation practice.

1.3.2. The basic design models were the same as those used for the 1989 guide. Detailed consideration was given to the adoption of a design methodology based on Multi-Layer Elastic Analysis. However, it was decided to maintain the traditional design methodologies because of the problems of dealing with joints in rigid pavements, material behaviour that changes significantly with trafficking, such as cement-bound bases in flexible pavements, and major aspects of pavement evaluation including multiple slab pavements and Type 2 and 3 composite pavements.

1.3.3. The use of high strength Drylean Concrete in flexible pavements was dealt with by the use of modified Equivalency Factors developed from full-scale testing of Drylean Concrete undertaken by Defence Estates and analysis by multi-layer elastic theory.

1.3.4. For tridem main wheel gear an additional rigid pavement design chart and new main wheel gear lines on the flexible pavement design charts were necessary because of the differences in the variation of the damaging effect with subgrade strength and coverages when compared to other main wheel gears. The use of the ACN for tridems on flexible pavements was complicated by the fact that at the time of writing ICAO had not formalised the calculation method. The flexible pavement design charts were based on ACNs for tridem main wheel gears calculated using the "interim" Alpha Factor promulgated by ICAO.

1.3.5. The key change in the 3rd Edition is the modification of flexible pavement ACNs following revisions to the ACN-PCN method promulgated by ICAO in September 2007. The revised ACNs have necessitated major changes to Charts 5, 6 and 8, which cannot be used with flexible pavement ACNs calculated using the original ACN-PCN method. In addition changes have been made to recommendations for longitudinal joint design and minimum top slab thicknesses for multiple slab pavements.

## 1.4 THE GUIDE

1.4.1. This guide supersedes all airfield pavements design and evaluation documents previously published by the Department. It is a development of the previous guide incorporating the latest pavement performance considerations, latest design thinking and advances in construction materials and aviation technology.

1.4.2. Many of the charts, figures and tables have been revised to accommodate recent developments such as the use of high strength drylean concrete, the emergence of larger, heavy aircraft with more complex main wheel gears, and changes to the ICAO ACN-PCN method. An additional Appendix on pavement structural investigation techniques has been included.

# 2 Classification of Aircraft and Airfield Pavements

## 2.1 GENERAL

2.1.1. Several methods of classifying the load ratings of aircraft and bearing strengths of airfield pavements have been in use for many years. The 1977 edition of the Aerodrome Design Manual, Part 3 published by the ICAO described four different methods which included the LCN and LCN/LCG systems originally developed in the UK. However, for safe and efficient use of airfield pavements, the ICAO has been striving to formulate a single universally accepted method of classification which would:

(i) enable aircraft operators to determine the permissible operating weights for their aircraft;

(ii) assist aircraft manufacturers to ensure compatibility between airfield pavements and the aircraft under development;

(iii) permit airport authorities to report on the aircraft they can accept and allow them to use any evaluation procedure of their choice to ascertain the loading the pavements can accept.

2.1.2. On 26 November 1981, the ICAO promulgated an internationally accepted reporting method known as the Aircraft Classification Number – Pavement Classification Number (ACN-PCN) method. Like the LCN and LCN/LCG systems the emphasis is on the evaluation of the load rating of aircraft, for which a standard procedure is specified, rather than evaluation of the pavement. The strength of the pavement is reported in terms of the load rating of aircraft which the pavement can accept on an unrestricted basis.

2.1.3. Following Defence Estates' tradition of using the aircraft classification as the load parameter for pavement design and evaluation, the ACN has been directly linked to the design and evaluation methods described in this guide. For pavements previously designed or classified in accordance with the LCN/LCG system, a procedure for conversion to PCNs is included in Appendix G. Since there is no precise relationship between LCN/LCG and PCN classifications, the conversions are only approximate.

## 2.2 DESCRIPTION OF THE ACN-PCN METHOD

2.2.1. A detailed description of the ACN-PCN method is given in the 1983 edition of the Aerodrome Design Manual, Part 3 published by the ICAO[11]. However, a brief description of the method and its application is given here.

## 2.3 AIRCRAFT CLASSIFICATION NUMBER (ACN)

2.3.1. The ACN of an aircraft expresses its relative loading severity on a pavement supported by a specified subgrade. ACNs are calculated using two mathematical models, one for rigid and the other for flexible pavements. The ACN of an aircraft is numerically defined as twice the single wheel load (expressed in thousands of kilograms) at a standard tyre pressure of 1.25MPa, which requires the same pavement thickness as the actual main wheel gear of the aircraft for a given limiting stress or number of load repetitions. The pavement thickness is known as the reference thickness.

2.3.2. The ACNs are reported separately for rigid and flexible pavements, four standard categories of subgrade (representing ranges of subgrade strength and characterised by a standard value at the middle of the range) and at Maximum Ramp Weight and a representative operating empty weight.

2.3.3. The method of calculating ACNs for aircraft on rigid pavements is set out below with reference to Figure 1:

(i) Calculate the reference thickness ($t_c$), the thickness of concrete slab which when loaded at the centre by one main wheel gear of the actual aircraft gives a maximum flexural stress of 2.75 N/mm$^2$ ($f_{ct}$)* on a subgrade whose Modulus of Subgrade Reaction (k) is one of the standard values (see (iv)). The mathematical model for the stress calculation is the Westergaard solution for an elastic slab on a dense liquid subgrade (Winkler Foundation). The modulus of elasticity for concrete is taken as 27.6 x 10$^3$ MN/m$^2$ and Poisson's ratio as 0.15.

(ii) Calculate the single wheel load ($W_R$) which at a tyre pressure of 1.25MPa induces a flexural stress of 2.75N/mm$^2$, in slab of thickness $t_c$.

(iii) The ACN=2x $\frac{W_R}{1000} = \frac{W_R}{500}$ where $W_R$ is in kgs.

(iv) Calculate ACNs for each aircraft for the following four categories of subgrade characterised in terms of a standard k.

| **Subgrade Category** | **k** |
|---|---|
| High | 150 MN/m$^2$/m |
| Medium | 80 MN/m$^2$/m |
| Low | 40 MN/m$^2$/m |
| Ultra Low | 20 MN/m$^2$/m |

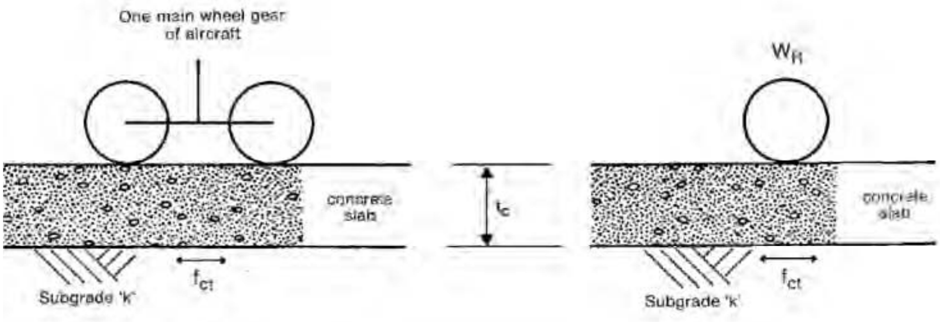



**Figure 1** ACN Rigid pavement model

* ($f_{ct}$) - the flexural stress of 2.75 N/mm$^2$ for centre-case loading was selected by the ICAO to provide a realistic assessment of the relative loading severity of different aircraft in relation to thicknesses of rigid pavement construction on which they are likely to be operating. This may not necessarily be the allowable wheel load stress used in this guide, which varies depending on the flexural strength of the concrete and the load repetitions.

2.3.4. The method of calculating ACNs for aircraft on flexible pavements is set out below with reference to Figure 2:

(i) Calculate the reference thickness ($t_f$), the thickness of conventional flexible pavement which allows 10,000* load repetitions by one main wheel gear of the actual aircraft on a subgrade whose CBR is one of the standard values (see (iv)). The method of calculation is based on the CBR Equation and Boussinesq deflection factors.

(ii) Calculate the single wheel load ($W_F$) which at a tyre pressure of 1.25 MPa allows the same 10,000 load repetitions on a flexible pavement of total thickness $t_f$. The calculation is carried out using the following formula:

$$W_F = \frac{\frac{t_f^2}{200}}{\frac{0.878 - 0.01249}{CBR}}$$

(iii) The ACN=2x $\frac{W_F}{1000} = \frac{W_F}{500}$ where $W_R$ is in kgs.

(iv) Calculate ACNs for each aircraft for the following four categories of subgrade characterised in terms of a standard CBR.

| Subgrade Category | CBR |
|---|---|
| High | 15% |
| Medium | 10% |
| Low | 6% |
| Ultra Low | 3% |

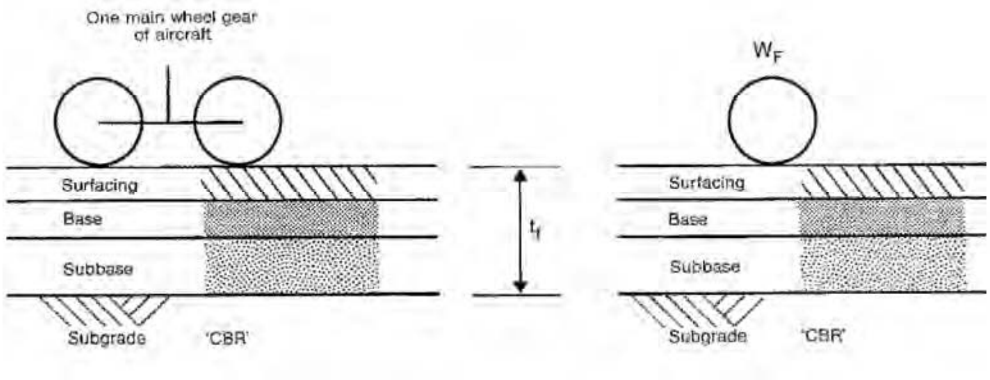



**Figure 2** ACN Flexible pavement model

2.3.5. The ICAO has published ACNs for most civil aircraft[13]. For other aircraft, ACNs may be obtained from the manufacturers. A list of aircraft ACNs with main wheel gear types is given in Appendix B to this guide.

## 2.4 PAVEMENT CLASSIFICATION NUMBER (PCN)

2.4.1. By the definition of the ACN-PCN method, the PCN is the ACN of the aircraft which imposes a severity of loading equal to the maximum permitted on the pavement of unrestricted use.

2.4.2. PCNs are reported as a five part code as follows:

Part i — The PCN Number: The highest permitted ACN at the appropriate subgrade category.

Part ii — The type of pavement: R=rigid, F=flexible. If the actual pavement is of mixed construction the engineer will need to decide whether the behaviour and mode of failure of the pavement are likely to be those of a rigid or flexible one, then classify accordingly. For guidance on the classification of such pavements, see Chapter 7.

Part iii The pavement subgrade category:
A = High
B = Medium
C = Low
D = Ultra Low
The ranges of subgrade strength covered by these categories are shown in Table 1. Note that these strength ranges are not equivalent for rigid and flexible pavements.

**Table 1** PCN Subgrade Categories

| Subgrade Category | Pavement Type | Characteristic Subgrade Strength | Range of Subgrade Strengths |
|---|---|---|---|
| A – High | Rigid<br>Flexible | 150 $MN/m^2/m$<br>CBR 15% | All k values above 120 $MN/m^2/m$<br>All CBR values above 13% |
| B – Medium | Rigid<br>Flexible | 80 $MN/m^2/m$<br>CBR 10% | 60 - 120 $MN/m^2/m$ CBR 8% to CBR 13% |
| C – Low | Rigid<br>Flexible | 40 $MN/m^2/m$<br>CBR 6% | 25 to 60 $MN/m^2/m$<br>CBR 4% to CBR 8% |
| D – Ultra Low | Rigid<br>Flexible | 20 $MN/m^2/m$<br>CBR 3% | All k value below<br>25 $MN/m^2/m$<br>All CBR values below 4% |

Part iv The maximum tyre pressure authorised for the pavement:
W = High, no limit.
X = Medium, limited to 1.5 MPa (217 psi)
Y = Low, limited to 1.0 MPa (145 psi)
Z = Very low, limited to 0.5 MPa (73 psi)
Refer to Chapter 8 for guidance on high tyre pressure operations.

Part v Pavement design/evaluation method:
T = Technical design or evaluation (see Chapters 5, 6 and 7 for detailed guidance).
U = By experience of aircraft actually using the pavement (see Appendix H for guidance

## 2.5 PAVEMENT CLASSIFICATION FOR LIGHT AIRCRAFT

2.5.1. The ACN-PCN method is not intended for reporting the strength of pavements meant for light aircraft, i.e. those with a weight less than 5700kg.

2.5.2. The bearing strength of a pavement intended for use by light aircraft should be classified in terms of the following data:

(i) Maximum allowable aircraft weight.
(ii) Maximum allowable tyre pressure.

## 2.6 THE DESIGN ACN

2.6.1. The design ACN, as used in this guide, is based on the Design Aircraft; which is normally the aircraft with the highest ACN on the actual subgrade.

2.6.2. The actual weight of aircraft when using the pavement must be considered in determining the design ACN. The Maximum All-Up Weight figure will normally be used, but lighter weights are appropriate (see also Section 4.8) where:

(i) the runway length imposes restrictions on the operating weights,
(ii) the pavement is only used by landing aircraft (e.g. fast turn offs) and
(iii) the pavement is only used by unladen aircraft (e.g. the accesses to maintenance hangars).

To compute an ACN at a weight between the published values it is assumed that ACNs vary linearly with weight.

2.6.3. The design ACN should also relate the actual value of the subgrade under a pavement. The ACNs listed in B are for four standard subgrade categories. If the value of actual subgrade is not the same as that of a standard subgrade, the design ACNs are to be calculated by linear interpolation or extrapolation of ACNs for the standard subgrades. The procedure is illustrated in Examples 2.1, 2.2 and 2.3.

2.6.4. The high category subgrade for flexible pavements is for CBR 15%. When designing pavements for subgrades with CBR greater than 15% the following rules may be applied:

(i) Single and Dual Main Wheel Gears

Take the ACN for CBR >15% to be the same as the ACN for CBR 15%.

(ii) Dual-Tandem Main Wheel Gears

Take the ACN for CBR ≥20% as equal to 0.95 x the ACN for CBR 15%.

Values for CBRs between 15% and 20% can be obtained by linear interpolation e.g.

ACN for CBR 17% = 0.98 x the ACN for CBR 15%.

(iii) Tridem Main Wheel Gears

Take the ACN for CBR ≥20% as equal to 0.97 x the ACN for CBR 15%.

Values for CBRs between 15% and 20% can be obtained by linear interpolation.

2.6.5. For rigid pavements, the effect of the higher subgrade values is less significant and it is therefore acceptable to assume that:
ACN for k>150 $MN/m^2/m$ = ACN for k of 150 $MN/m^2/m$.

2.6.6. For pavements which would subsequently be difficult to strengthen, it may be appropriate to design for a higher ACN e.g. for aprons adjacent to hangars and terminal buildings. Hangar floors designed in accordance with Chapter 5 will have an inbuilt element of over-design (see also para. 7.11).

2.6.7. Where a design ACN of less than 10 is being considered a check should be made to ensure that the pavement is strong enough for the expected use by aircraft servicing vehicles.

## 2.7 OVERLOAD OPERATIONS

2.7.1. Provided the PCN for a pavement is equal to or greater than the ACN of the aircraft and the operating tyre pressure does not exceed the PCN limitation, unrestricted use of the pavement by that aircraft (or those with lower ACNs) is permitted. The term 'unrestricted use' of a pavement is not specifically defined. However, it is a pavement design parameter which should reflect current and forecast use over an appropriate design life before major maintenance is required. See Chapter 4 for further guidance on pavement use and design life.

2.7.2. Unless a pavement is subject to extreme overloading it is unlikely to fail suddenly or catastrophically. Nevertheless regular overload operations can substantially reduce the design life of the pavement. The Aerodrome Authority may wish to carry out an assessment of the financial implications of increase maintenance or premature failure. Each aerodrome authority in the UK is free to decide on its own criteria for permitting overload operations as long as pavements remain safe for use by aircraft. See Chapter 8 for more detailed guidance on overload operations.

### EXAMPLES ILLUSTRATING THE ASSESSMENT OF ACNs AND THE REPORTING OF PCNs

#### Example 1

Given a rigid pavement on a subgrade of k = 30 $MN/m^2/m$. The Design Aircraft for the pavement has been identified as the Boeing 747-400.

Determine the design ACN and the PCN for the pavement.

From Appendix B:

| | Subgrade Category | |
|---|---|---|
| | Low<br>(k 40 $MN/m^2/m$) | Ultra Low<br>(k 20 $MN/m^2/m$) |
| B747-400 | ACN 74.4 | ACN 84.1 |

$$84.1-(84.1-74.4)\times\frac{(30-20)}{(40-20)}=79.75 \qquad (1)$$

(i) By interpolation, the design ACN for k = 30 $MN/m^2/m$ is:

(ii) Having designed or evaluated the pavement for ACN 70 at k = 30 the PCN is reported as follows:

From Table 1 the subgrade category is Low (i.e. k is between 25 and 60 $MN/m^2/m$) for which the code is ‘C’. The PCN is reported as the ACN of the aircraft on the standard subgrade category, therefore assuming there is no tyre pressure limit for the concrete pavement, the PCN is *75/R/C/W/T*.

#### Example 2

Given a flexible pavement on a subgrade whose actual CBR is 5%. The Design Aircraft for the pavement has been identified as the Boeing 747-400.

Determine the design ACN and the PCN for the pavement.

From Appendix B:

| | Subgrade Category | |
|---|---|---|
| | Low<br>(CBR 6%) | Ultra Low<br>(CBR 3%) |
| B747-400 | ACN 72.5 | ACN 94.1 |

(i) By interpolation, the design ACN at CBR 5% is:

$$94.1-(94.1-72.5)\times\frac{(5-3)}{(6-3)}=79.7 \qquad (2)$$

(ii) Having designed or evaluated the pavement for ACN 79 at CBR 5%, the PCN is reported as follows:

From Table 1 the subgrade category is Low (i.e. CBR is between 4% and 8%) for which the code is C. Assuming there is no tyre pressure limit the PCN is 73*/F/C/W/T*.

#### Example 3

Given an existing flexible pavement on subgrade which is known to be in the ‘Low’ category. Experience of aircraft use shows that B737-200s have regularly used the pavement without causing any apparent damage to it.

Determine the classification of that pavement.

From Appendix B, B737-200 on a Flexible Pavement Low subgrade has an ACN of 30.9.

If tyre pressure limit is 1.5MPa then the PCN is 31/F/C/X/U.

NB See Appendix H for advice on the reliability of classifications based on aircraft use.

# 3 The Subgrade

## 3.1 GENERAL

3.1.1. The subgrade is the natural soil or made-up ground which supports the pavement and the wheel loads imposed on it. The pavement spreads and thus reduces the high pressures immediately under the loaded areas to pressures which the subgrade can tolerate without unacceptable deformation. Thorough evaluation of the subgrade is very important, especially for flexible pavements where the required thickness depends greatly on the sheer strength of the soil. This evaluation of the subgrade includes the determination of subgrade strength and the assessment of factors which can affect the uniformity of the subgrade with time: e.g. shrinkage and swelling, frost action and mud pumping. It is also important to ascertain the vertical profile of the soil types, densities and moisture contents.

## 3.2 SOIL CLASSIFICATION AND EVALUATION OF SUBGRADE STRENGTH

3.2.1. Several soil classification systems have been developed in order to relate solid description to engineering properties. The most common is the extended Casagrande Soil Classification shown in Appendix A. The group symbols used for coarse-grained soils are derived from particle size distribution, and those for fine-grained soils are mainly derived from the plasticity index and liquid limit. The tests to assess these parameters are fully described in BS 1377-2: 1990,[15] while the Casagrande system is described in Reference 17. The Casagrande system enables the soil to be assessed for its likely behaviour as a subgrade, including its sheer strength, shrinkage, drainage properties and susceptibility to frost heave. Although an experienced engineer can often estimate the sheer strength and load/deflection values for a subgrade from the classification tests, it is often necessary to carry out further tests specifically to measure these characteristics.

3.2.2. The subgrade strength characteristics required for pavement design are the Modulus of Subgrade Reaction (k) and the California Bearing Ratio (CBR) for rigid and flexible pavements respectively. The design values chosen must be representative of the soil under the pavement after construction. Therefore, they should be based upon a relevant moisture content and density.

3.2.3. In selecting a design moisture content, consideration must be given to seasonal variations and the likelihood of the post-construction moisture content being higher than the pre-construction in situ value. There are some useful guidelines for certain conditions:

(i) A method of ascertaining the post-construction moisture content is to examine the subgrade under an existing adjacent pavement. The accuracy of the assessment will depend upon the similarity of pavement widths, subsoil drainage and permeability of the surface layers.

(ii) In very dry climates, if no water is present, the in situ value of the natural subgrade is likely to be representative.

(iii) In cohesive soils which are homogeneous with depth the moisture content at 1m down may be representative[17].

(iv) In the absence of any other information the moisture content of cohesive UK soils, except those containing a high proportion of montmorillonite, seldom exceeds the plastic limit plus 3%.

3.2.4. Selection of a representative density will depend on the in situ density, and the degree of compaction likely during construction (see Section 3.6).

3.2.5. The test for k is a large scale in situ test, which measures the behaviour of the subgrade as a whole and therefore tends to compensate for variations of density and moisture content with depth. The CBR test only measures the properties of a very small volume of the subgrade and it is more difficult to find a representative design value. However, in practice the Modulus of Subgrade Reaction test is difficult to carry out and in some situations it may be sufficient to assess k from the CBR value. Appendix A includes an approximate relationship between CBR and k. Use this with caution, particularly when considering soils uncommon in the UK (e.g. Laterites, corals and volcanic clinker/ash).

### 3.3 THE MODULUS OF SUBGRADE REACTION (K)

3.3.1. The Modulus of Subgrade Reaction k is determined from loading tests carried out on the subgrade using a standard 762mm (30in.) diameter plate. The plate is loaded to give increments of deflection of 0.25mm (0.01 in.). The pressure on the plate is plotted against settlement and the k value is taken as the slope of the line passing though the origin and the point on the curve corresponding to 1.27mm (0.05 in.) deflection. See Reference 17 for a full description of the test method.

3.3.2. As the 762 mm plate test is an in situ test it is difficult to ensure that the density and moisture content of the soils are appropriate to the post-construction conditions. It is best to do this test on a section prepared to the appropriate density (e.g. during compaction trails). An adjustment for moisture content is described in Reference 17.

### 3.4 THE CALIFORNIA BEARING RATIO (CBR)

3.4.1. The strength of the subgrade for flexible pavement s is measured in terms of the California Bearing Ratio (CBR) of the soil. The CBR test compares the force required to drive a plunger into the test material to a set penetration at a given rate, with the force required to cause the same penetration in a standard crushed limestone. A full description of the test is given in BS 1377-4: 1990. It is also possible to do field (in situ) CBR tests (BS 1377-9: 1990).

3.4.2. The laboratory CBR test should be carried out at a range of densities and, for each density, at a range of moisture contents. This gives a series of curves of CBR against moisture content from which a value applicable to the required condition can be obtained.

3.4.3. In conditions where it is difficult to choose a design moisture content, the test can be done on 4-day soaked samples in order to give a reasonably conservative value[18,19] These conditions could include:

(i) Subgrades where there is a considerable variation of moisture content with depth, in an otherwise homogeneous soil. This is likely when the water table lies near to or within the depth of soil being considered (i.e. the recommended depth of boreholes as shown in Table 4).
(ii) Areas where there is a large annual variation in moisture content due to a fluctuating water table, or possibly a spring thaw.
(iii) Tropical monsoon climates.

3.4.4. A surcharge should be applied in the CBR test to allow for the weight of the overlying soils and pavement construction. Defence Estates has adopted 6 kg as a standard surcharge weight.

3.4.5. When carrying out in situ CBR tests care should be taken to ensure that the density and moisture content are appropriate, as with the 762mm plate test. In situ tests are most useful for testing soils under existing pavements, but two points should still be considered:

(i) Stones close to the plunger area may produce unrealistically high results;
(ii) Because the test only affects a limited volume of the subgrade it will not include the presence of weaker underlying layers. It is therefore essential to know the soil profile at depth.

3.4.6. Laboratory tests on granular materials can give unrealistically high results because of the confining effect of the test mould. In situ tests may give lower figures but are often inappropriate because of the difficulty in testing at the relevant density and moisture content. The Casagrande Soil Classification can be used as a guide to selecting a design CBR value. It is recommended that the maximum design CBR values for flexible pavements are 20% for full-depth bound construction and 30% for unbound constructions (see para. 6.4.5).

3.4.7. Selecting a representative design CBR value can be difficult if the CBR varies considerably with depth. There is no problem if the CBR increases with depth as the critical value is the lowest one, i.e. at the formation. If the CBR decreases with depth (e.g. a layer of sand or gravel overlying a clay), designing on a high CBR value representative of the top layer could overstress the weaker underlying layer, but designing for the CBR of the lower layer will lead to an uneconomic pavement. In this situation Figure 7, Figure 8 and Figure 9 can be used to obtain an equivalent CBR for the two layer system. (See para. 3.8.3 and Example 3.2).

## 3.5 SUBSOIL DRAINAGE

3.5.1. Providing subsoil drainage may be desirable for several reasons:

(i) To increase subgrade strength by reducing the moisture content of the soils.
(ii) To reduce the chances of the moisture content increasing above that assumed in the selection of a design subgrade strength.
(iii) To drain the formation and pavement layers during construction.
(iv) To drain any unpaved shoulders after construction.
(v) To drain granular layers in an unbound pavement structure after construction. In this case the drainage is more likely to be essential rather than desirable as explained in para. 3.5.5.

3.5.2. There are a number of reasons for changes in the moisture content of subgrades, including:

(i) seepage flow from higher ground adjacent to the pavement.
(ii) changes in the water table level.
(iii) transfer of moisture to and from soil adjacent to the pavement.
(iv) percolation of moisture through the pavement.

3.5.3. Maximum benefit can be obtained from subsoil drainage if it is designed to reduce the moisture content of the soils prior to and during construction (e.g. by stopping seepage flow or lowering the water table). After construction the drainage should work to maintain the moisture content at or below that achieved during construction (e.g. by continuing to stop seepage flow, by preventing a rise in the water table or by removing water entering through the pavement or from the adjacent soil.)

3.5.4. It is possible to drain the formation and pavement layers during construction by shaping and by protecting the formation and installing subsoil drains before construction starts.

3.5.5. The large width of runways and other airfield pavements often makes it uneconomic to lower or control the water table because the shape of the draw-down curve would require drains to be installed at impracticable depths. In this case the pavement should be designed for a higher water table. However, it is important that the water table is kept at least 300mm below granular pavement layers to prevent them becoming saturated and to minimise the pumping of fines into the layers by repetitive aircraft loading. A geotextile fabric can also be used as a separator to control the latter problem. Ideally the same control of the water table level should be applied to other pavements to prevent undue deterioration of their materials. If necessary the formation should be elevated to raise the pavement far enough above the highest likely water table.

3.5.6. In assessing whether to install subsoil drainage, careful consideration should be given to the economic gains from potential benefits as compared to the cost of the system. Factors to be considered include the actual effectiveness of the system (which will partly depend on the permeability of the soil), the availability of a convenient outfall and the problems of installing drainage before the min construction starts.

### 3.6 COMPACTION OF THE SUBGRADE

3.6.1. With the exception of those soils listed in 3.6.4 (i) and (ii) the subgrade should be compacted to increase its density and sheer strength, and to prevent excessive settlement under traffic.

3.6.2. Control of settlement due to repetitive loading by traffic is achieved by obtaining specific relative compaction levels in the subgrade. (See Table 2 and Figure 3, Figure 4, Figure 5 and Figure 6). As the subgrade under a rigid pavement is less highly stressed than under a flexible one the relative compaction requirements are less stringent under rigid pavements. Figure 3, Figure 4, Figure 5 and Figure 6 were developed from various compaction trials.[20,21,22]

3.6.3. If the relative compaction requirement cannot be met, the subgrade should be removed and replaced with fill or overlaid with an additional layer of fill, sub-base or base material. The aim is that the uncompacted subgrade should be at a depth beneath the formation where the in situ relative compaction is equal to or greater than that required. This additional material can be taken as enhancing the subgrade, as long as the relative compactions still comply with those required at the new subgrade strength.

3.6.4. The amount of compaction possible in a soil will largely depend on the natural density and moisture content, but certain soils raise particular problems. These are:

(i) High and medium plasticity clays;
(ii) silts and very fine sands with a moisture content at or approaching saturation level;
(iii) uniformly graded non-cohesive materials.

3.6.5. High plasticity and some medium plasticity clays (see the Casagrande Soil Classification) are liable to show a serious decrease in strength when compacted at high moisture contents, especially when over consolidated. In the UK the natural moisture content of these soils is normally well above the optimum for heavy compaction so their undisturbed densities and strengths can rarely be improved by further compaction. In their undisturbed state, these soils give relative compactions ranging from 85-92% and CBRs ranging from 2-5% at typical moisture contents. From Table 2 and Figure 3, Figure 4, Figure 5 and Figure 6, these relative compactions are similar to or slightly lower than those required immediately under the pavement. However, experience in the UK has shown that rigid pavement with lean concrete bases constructed on medium and high plasticity clays provide good long-term performance without excessive settlement. It is therefore Defence Estates’ practice to cause the least possible disturbance when constructing on these soils. Once exposed, the subgrade is usually covered as soon as possible to protect it from the weather and to provide a working area for further construction operations.

3.6.6. In tropical monsoon climates the compaction of high and some medium plasticity soils can present different problems (see also Section 3.10). In the dry season these soils will generally have a natural moisture content well below the optimum for heavy compaction, and thus if too highly compacted they are likely to swell in a later wet season. But if compacted at too high a moisture content, a low dry density will be achieved and the soil is likely to shrink during a dry period. Special care is therefore needed to achieve a moisture content and degree of compaction which reduces subsequent swelling or shrinkage to acceptable levels. In general the appropriate moisture content for compaction will be just above the optimum moisture content.

3.6.7. Silts and very fine sands with moisture contents at or approaching saturation level cannot be compacted. If it is not practical to drain these areas or remove and backfill them, the pavement design should be based on a very poor subgrade strength which reflects a saturated condition. With the pavement designs being based on a low CBR the density requirement is unlikely to be critical. To reduce the effect of poor and variable subgrade support however, a flexible or a rigid pavement design should incorporate a lean concrete base (See Chapters 5 and 6).

3.6.8. It is difficult to achieve compaction of uniformly-graded non-cohesive materials. One method of overcoming this is to compact through a thin layer (75-100mm) of a well-graded material. This layer will have no significant effect on the subgrade strength (CBR or k), which should be taken as that of the compacted underlying material.

3.6.9. To determine relative compaction requirements under flexible pavements using Figure 3, Figure 4, Figure 5 and Figure 6.

(i) select the relevant Figure for the soil type;
(ii) select the relevant main wheel gear type;
(iii) enter the design subgrade CBR on the left hand vertical axis;
(iv) make a horizontal projection to meet the relative compaction line;
(v) make a vertical projection to meet the design ACN;
(vi) make a horizontal projection to the right hand vertical axis and read off the depth requirement.

See Example 3.1 for an application of this procedure.

## 3.7 VERY WEAK SUBGRADES (EXCEPT PEAT)

3.7.1. Subgrades with CBRs less than 3% of k less than 20 $MN/m^2/m$ include saturated or nearly saturated high plasticity clays and silts. The support to the pavement provided by these soils is non-uniform. In the long-term the performance of the pavements will therefore be unpredictable and likely to be subject to premature localised failure.

3.7.2. Wherever practical these soils should be removed and backfilled with suitable fill material. As a lesser alternative Section 3.8 sets out a procedure for improving subgrade support by overlaying with suitable fill material. A thick layer of fill will provide a more uniform support to the pavement, although high plasticity clays may suffer long-term consolidation and loss of pavement shape.

## 3.8 SUBGRADE IMPROVEMENT

3.8.1. On poor subgrades an economic option may be to use suitable fill material which is available locally to improve the effective subgrade support to the pavement and thereby reduce the thickness of pavement required.

3.8.2. For flexible pavement design Figure 7, Figure 8 and Figure 9 set out a method of assessing the subgrade improvement provided by suitable fill material. Figure 8 and Figure 9 relate ACNs, existing subgrade CBRs, and thickness of fill material to an enhanced CBR design value at the top of the fill. The fill material must have a CBR value of not less than 15% at its anticipated equilibrium moisture content and must be compacted to the requirements of Table 2.

3.8.3. To determine the design CBR for a two layer subgrade where the CBR of the upper layer is greater than the CBR of the lower one:

(i) Select the relevant main wheel gear type.
(ii) On Figure 7 enter the CBR of the lower layer on the horizontal axis, make a vertical projection to meet the curve for the CBR of the upper layer ad then a horizontal projection to the vertical axis. Read off an Equivalency Factor from the vertical axis. This represents the load-spreading ability of the soil in the upper layer compared with that of a granular sub-base material.
(iii) Divide the thickness of the upper layer by the Equivalency Factor to obtain ‘t’. Calculate $t^2$/ACN on the vertical axis where ACN represents the loading severity of the Design Aircraft on the CBR of the lower layer.

(iv) On Figure 8 and Figure 9 enter the CBR of the lower layer on the horizontal axis and the value of $t^2$/ACN on the vertical axis. Make horizontal and vertical projections until they intersect. The design CBR on the subgrade is shown by the curve closest to the intersection.

See Example 3.2 for an application of this procedure.

3.8.4. For rigid pavement design, Figure 10 sets out a method for assessing subgrade improvement provided by a granular sub-base.

3.8.5. The pavement on the improved subgrade should then be designed for the ACN of the Design Aircraft corresponding to the uprated CBR or k value.

## 3.9 CONSTRUCTION PRACTICE

3.9.1. Experience has shown that if the moisture content of the subgrade is allowed to increase during construction the final equilibrium strength will be lower than if it had not. It is therefore important that the specification requirements for protecting the formation are compiled with, or the design CBR value should be reduced accordingly.

3.9.2. Construction traffic can damage or reduce the natural strength of the subgrade. The use of the formation in areas of cut should be restricted to the minimum plant and equipment essential for the overlying construction. For subgrades particularly prone to damage (e.g. high plasticity clays and silts) a working course of drylean concrete or granular sub-base/capping layer should be placed on the subgrade before construction continues. In fill areas construction traffic should be restricted to prevent damage to compacted layers and the subgrade. To allow reshaping and recompaction, rut depths in granular layers should not exceed about 40mm.[23]

**Table 2** Relative Compaction Requirements for Subgrades

| PAVEMENT TYPE | FILL/EMBANKMENT AREAS | | CUT AREAS | |
|---|---|---|---|---|
| | COHESIVE | NON-COHESIVE | COHESIVE | NON-COHESIVE |
| Rigid incorporating a strong cement-bound base | 90% | 95% | The top 150mm<br>If k ≥ 40 – 90%<br>k < 40 – 85% | The top 600mm<br>If k ≥ 50 – 95%<br>If k < 50 – 90% |
| Rigid without strong cement-bound base | 90% | The top 150mm – 98%<br>The remainder – 95% | The top 150mm<br>If k ≥ 40 – 85%<br>If k < 40 – 80% | The top 150mm<br>If k ≥ 50 – 98%<br>If k < 50 – 95%<br>Between 150mm and 600mm<br>If k ≥ 50 – 95%<br>If k < 50 – 90% |
| Flexible | The top 225mm – 95%<br>The remainder – 90% | The top 225mm – 98%<br>The remainder – 95% | Refer to Figure 3 and Figure 4 | Refer to Figure 5 and Figure 6 |

Notes to Table 2 and Figure 3, Figure 4, Figure 5 and Figure 6

(i) For the purpose of determining relative compaction requirements non-cohesive soils are those for which the fraction passing the 425 micron sieve size has a plasticity index (P1) of less than 6.

(ii) The density requirements are expressed as a percentage of the maximum dry density given by BS 1377-4: 1990, Section 3.5 or 3.6.

(iii) The compaction requirements in Figure 3, Figure 4, Figure 5 and Figure 6 apply to natural subgrades below flexible pavements. The relative compaction required at a particular depth in the subgrade is a function of the vertical stress induced at that depth by the aircraft wheel loads and the number of load repetitions over the life of the pavement.

(iv) See Section 3.7 for subgrades less than CBR 2%.

(v) Subgrades which cannot realistically be compacted to the requirements in Table 2 and Figure 3, Figure 4, Figure 5 and Figure 6 should be removed and replaced with fill or overlaid with an additional depth of fill, sub-base or base material. This additional depth of construction should be sufficient to ensure that the requirements for relative compaction with depth beneath the pavement are achieved.

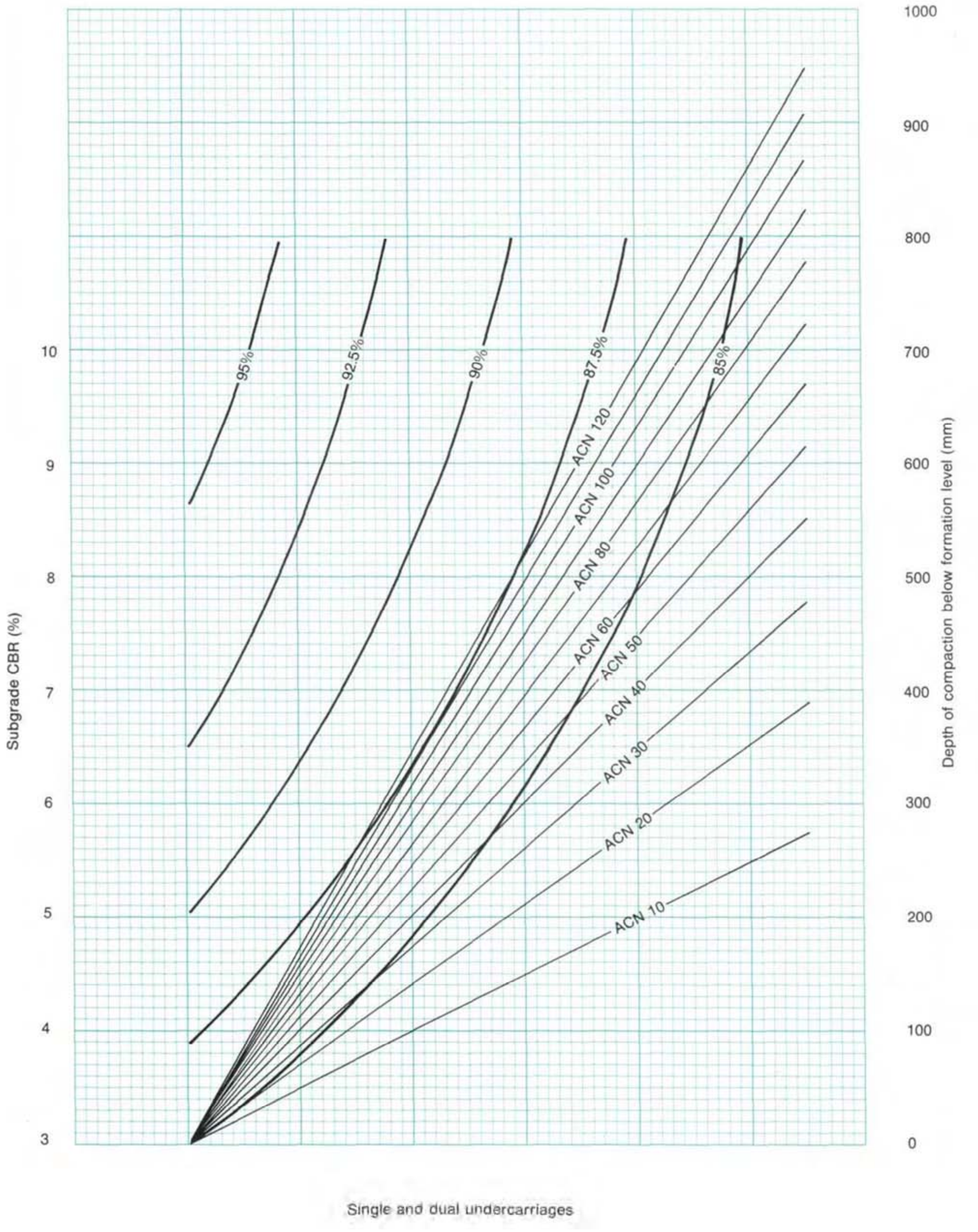



**Figure 3** Relative compaction requirements for subgrades under flexible pavements - Single and dual main wheel gears - Cohesive soils

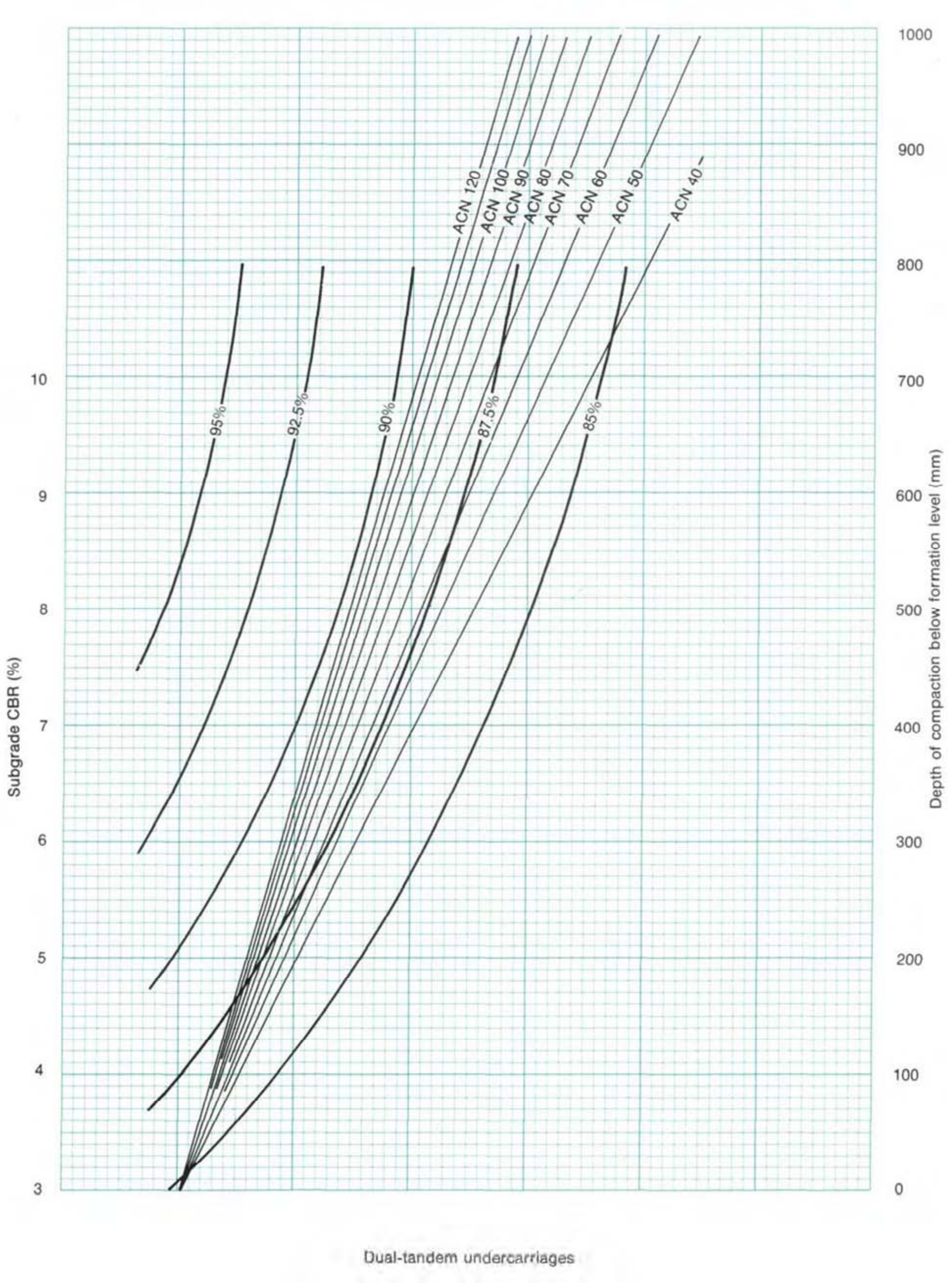



**Figure 4** Relative compaction requirements for subgrades under flexible pavements - Dual-tandem and tridem main wheel gears - Cohesive soils

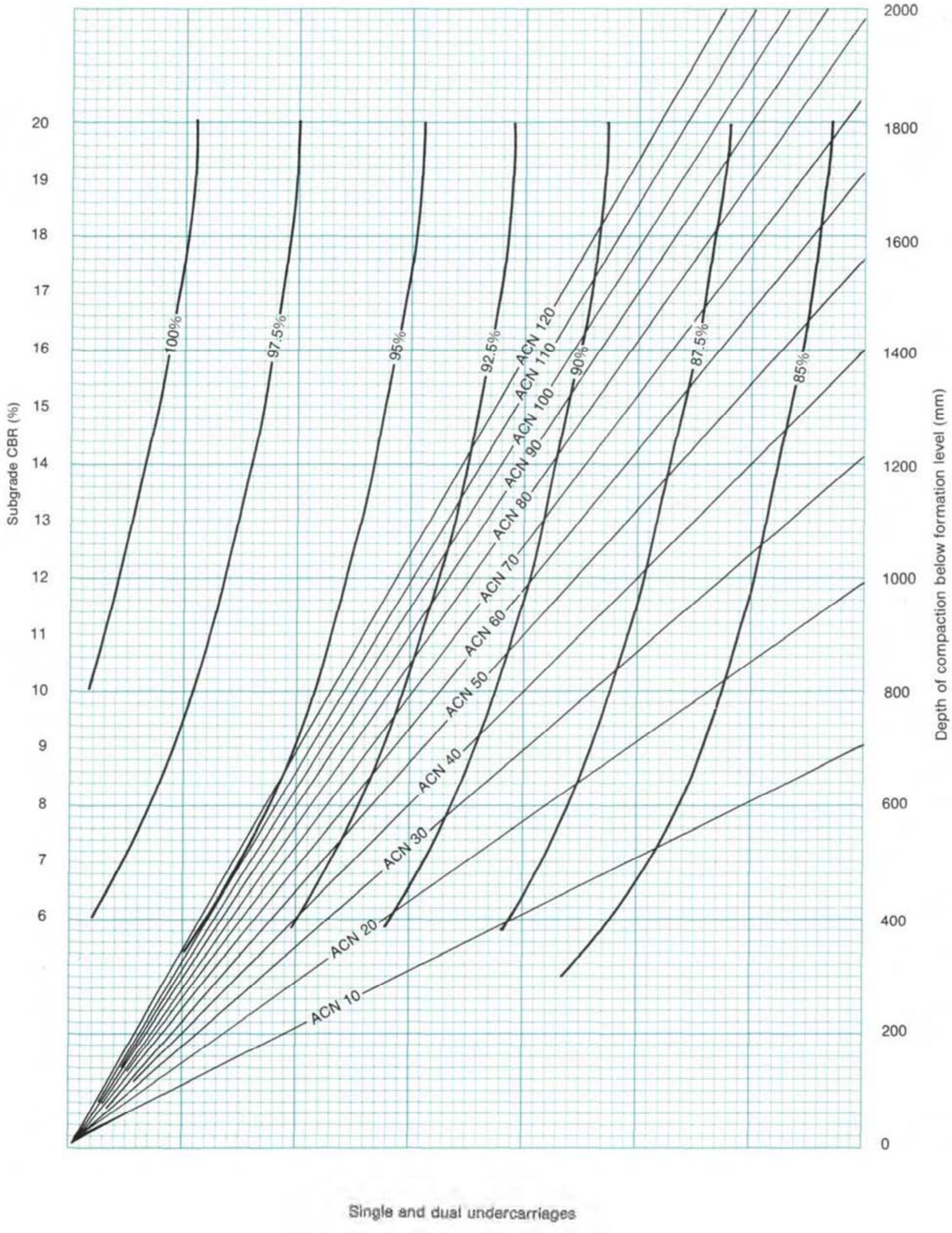



**Figure 5** Relative compaction requirements for subgrades under flexible pavements – Single and dual main wheel gears - Non-cohesive soils

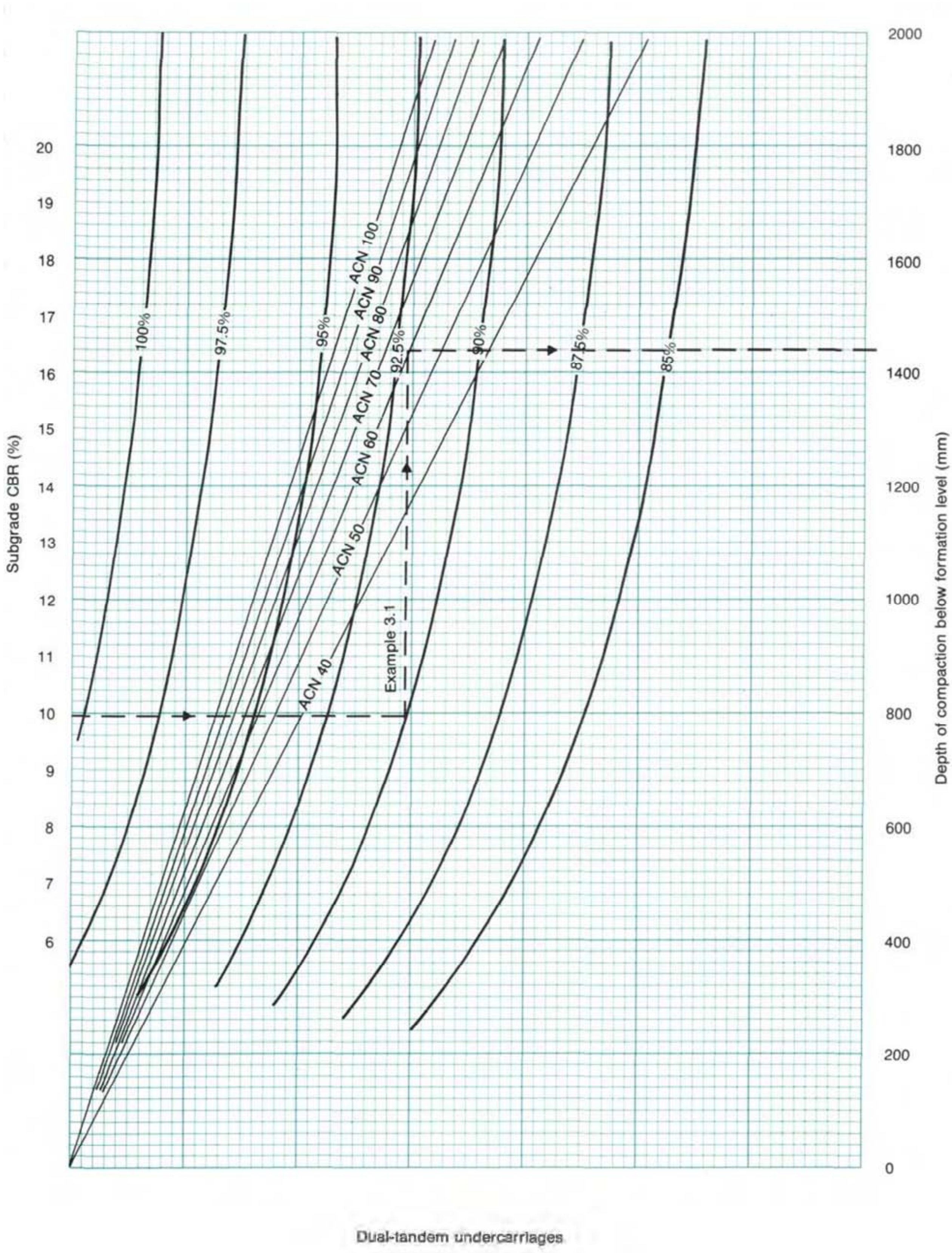



**Figure 6** Relative compaction requirements for subgrades under flexible pavements – Dual-tandem and tridem main wheel gears - Non-cohesive soils

### 3.10 EXPANSIVE SOILS

3.10.1. Some soils can show large volume changes when the moisture content changes. This can lead to loss of uniform support to the pavement, a reduction of bearing capacity of the soil, and bumps, hollows and cracks in the pavement. Generally the problem is only severe in climates where a long hot dry period is followed by a rainy season; the subgrade dries and shrinks during the hot season, but then expands rapidly as the rainy season increases the moisture content. As an appropriate the Plasticity index gives a good indication of the expansive nature of a soil; values less than 20 are non-expansive; between 20 and 40 are moderately expansive; and above 40 can be highly expansive. For more accurate assessment a technique related to the shrinkage limit and expected range of moisture content is described in Reference 18. Problems can also occur if an expansive soil is compacted in too dry a condition or allowed to dry out during construction.

3.10.2. The effect of expansive soils can be much reduced by careful control of moisture content during construction and the degree of compaction achieved (see para 3.6.6). If future expansion is still likely to be excessive, soil swell can be limited by, for example, providing sufficient fill/overburden.

### 3.11 FROST ACTION

3.11.1. For the UK and similar climates, material within 450mm of the pavement surface should not be susceptible to frost. Where the subgrade is frost susceptible the thickness of the base/sub-base must be increased if the proposed total thickness of construction is less than 450mm.

3.11.2. Tests for frost susceptibility has been carried out by TRL on a variety of materials used as subgrades, sub-bases and bases both in research and during routine testing for motorway and trunk road projects. Test results and other aspects of frost susceptibility are contained in TRL Report No LR90.[24] The Frost Test method described in LR90 was latter updated by TRL[26]. The current test method is given in BS 812-124:1989.

### 3.12 PEAT

3.12.1. Subgrades of peat are highly compressible and have very little bearing capacity. Pavements constructed on them can suffer from serious differential settlement, so peat should usually be removed and replaced with a suitable fill. A possible option is to surcharge the peat with fill for a long time to reduce the short term consolidation substantially. But this makes a long and phased construction necessary and in the long term the performance of the pavement will be unpredictable; there will probably be localised failures and general loss of shape. This alternative should not be used for pavements whose longitudinal and transverse profiles are critical; e.g. runways and major taxiways. Consider it, however, for stopways.

### 3.13 SPRING THAW AND PERMAFROST

3.13.1. In certain parts of the world where frost conditions are severe, pavements must be designed for the effects of spring thaw and permafrost. Both the spring thaw and intermittent or partial melting of a permafrost layer can considerably reduce the load-carrying capacity of the pavement.

### 3.14 GROUND INVESTIGATION

3.14.1. It is essential that an adequate ground investigation is carried out to obtain the necessary soils information. Recommendations for the spacing and depth of trial pits or boreholes are given in Table 3 and Table 4 Groundwater movements should be monitored over a suitable period, preferably at least one year.

**Table 3** Frequency of Trial Pits/Boreholes

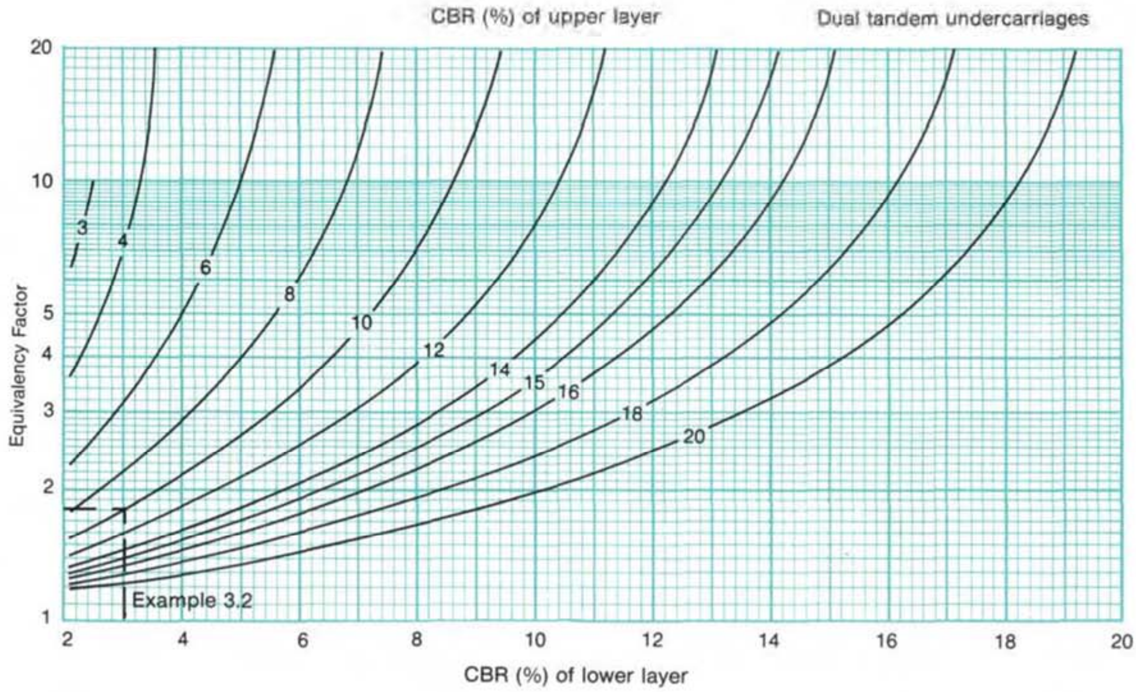
| Location | Frequency |
|---|---|
| Runways/Taxiways | 1 every 50m staggered across centre line |
| Aprons and other areas | To be positioned on a 30m square grid. |

**Table 4** Depth of Trial Pits/Boreholes (mm)

(Below proposed formation in areas of cut and existing ground level in areas of fill)

| ACN of the Design Aircraft on a Flexible Ultra Low Subgrade | Subgrade Category (as ACN-PCN method) | | | |
|---|---|---|---|---|
| | Ultra Low | Low | Medium | High |
| 20 | 600 | 800 | 1000 | 1000 |
| 40 | 800 | 1200 | 1400 | 1400 |
| 80 | 1500 | 2000 | 2200 | 2400 |
| 120 | 1800 | 2400 | 2600 | 3000 |

NB: If it is certain that the construction will be a rigid pavement then the depth can be reduced to 50% of these figures, subject to a minimum of 600mm.



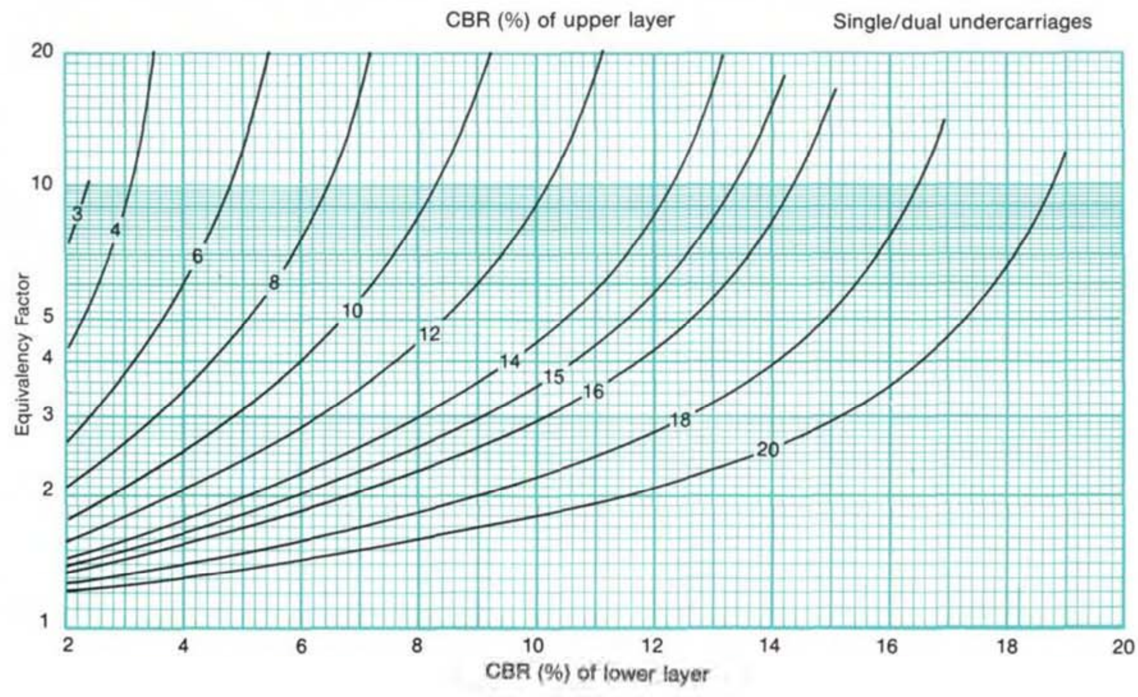




**Figure 7** Equivalency factors for the estimation of a design CBR on a layered subgrade

**Figure 8** Estimation of a design CBR on a layered subgrade – Single and dual main wheel gears

**Figure 9** Estimation of a design CBR on a layered subgrade - Dual-tandem and tridem main wheel gears

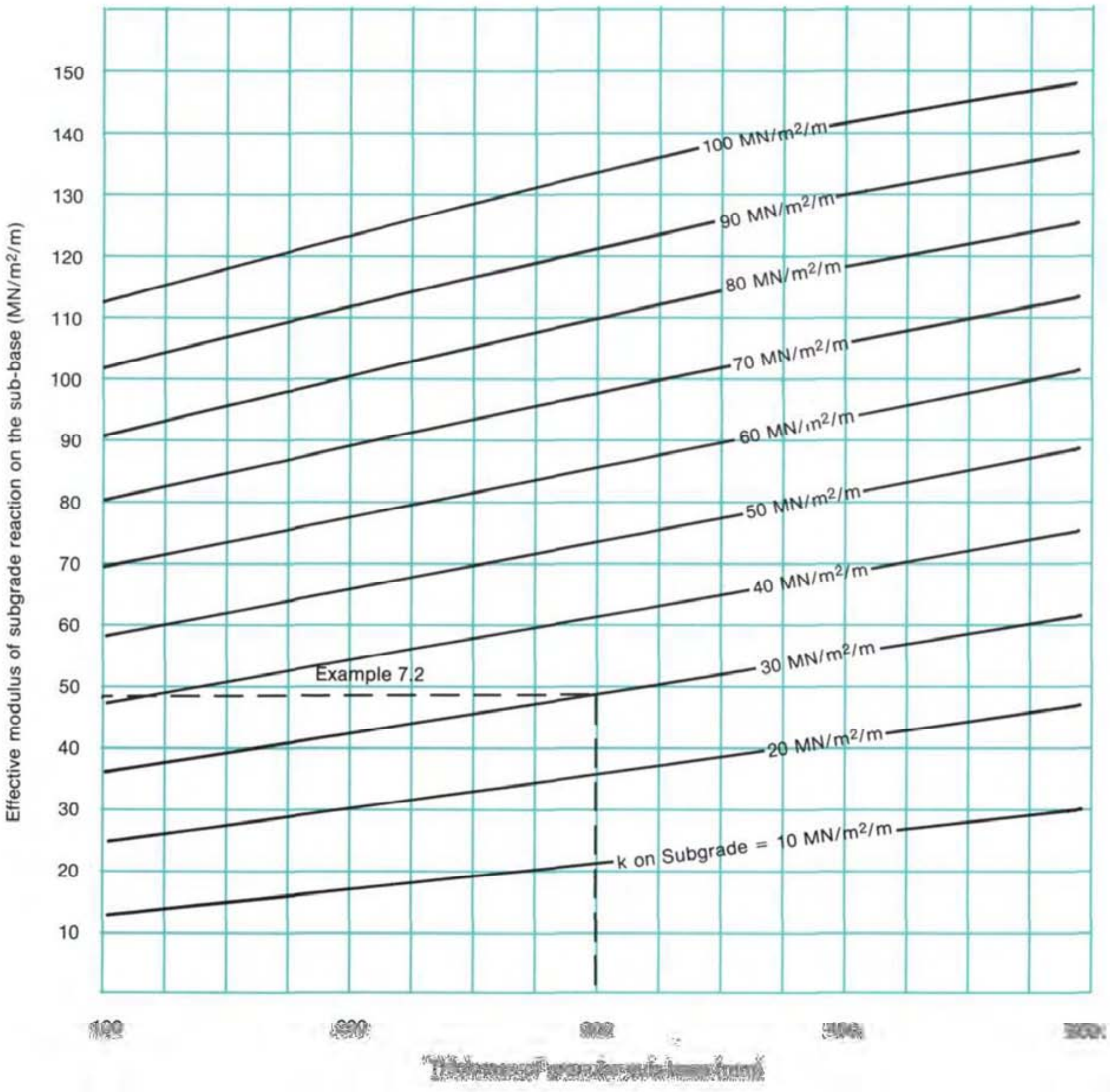



**Figure 10** Effect of granular sub-base on the modulus of subgrade reaction (k) for rigid pavements

## SUBGRADE EXAMPLES

### Example 3.1

A flexible pavement is to be constructed on a sand subgrade with a design CBR of 10%. The Design Aircraft has an ACN of 60, and a dual-tandem main wheel gear. Assess the Relative Compaction requirements.

Using Figure 6

| Relative Compaction | Depth below formation (mm) | |
|---|---|---|
| 100% | 0-100 | |
| 95% | 100-800 | |
| 90% | 800-1450 | (see Example Lines on Figure 6) |
| 85% | 1450-2000 | |

### Example 3.2

A subgrade consists of 500mm sand, CBR 10%, overlying a CBR 3% clay. Using Figure 7 and Figure 9 find a design CBR for a flexible pavement for an aircraft with an ACN of 60 on CBR 3% and a dual-tandem main wheel gear. (See para 3.8.3 for a description of the method).

(i) Equivalency Factor = 1.8
(ii) $t = 500/1.8 = 278$
(iii) $t^2/ACN = 278^2/60 = 1286$
(iv) Design CBR for the subgrade is 4%.

# 4 Design Considerations

## 4.1 DESIGN PARAMETERS

4.1.1. The design of a new pavement requires information on the following parameters:

(i) Pavement type – rigid or flexible
(ii) Quality of the pavement materials including the flexural strength of concrete
(iii) Subgrade strength
(iv) Design ACN
(v) Frequency of Trafficking. This is derived from a number of factors including

  a. The Design Life
  b. The pattern of trafficking and assessment of passes.
  c. Coverages and Pass-to-Coverage ratio.
  d. Mixed Traffic Analysis if there is more than one significant aircraft.

## 4.2 TYPES OF PAVEMENT

4.2.1. The design and classification method presented in this document requires a distinction between rigid and flexible pavements as described below.

4.2.2. A rigid pavement comprises either wholly or partly concrete construction which can be plain, reinforced or prestressed and which distributes the aircraft loading to the subgrade by means of its high flexural stiffness. Chapter 5 gives a design method for the preferred new rigid pavement constructions.

4.2.3. A flexible pavement is composed of bound or unbound granular materials. It distributes the aircraft load primarily through the shear strength of the paving material. Cement-bound granular bases beneath bituminous surfacings make pavements quite rigid in their early years. However, for reasons discussed in para 6.3.7 this type of construction is treated as a flexible pavement for design and evaluation purposes. Chapter 6 gives a design method for the preferred new flexible pavement constructions.

4.2.4. Chapter 7 includes procedures for the design or evaluation of the following pavement constructions:

(i) Traditional flexible constructions incorporating unbound granular bases and sub-bases.
(ii) Traditional concrete pavements laid directly on the subgrade or on a granular sub-base.
(iii) Composite pavements – these comprise flexible-on-rigid construction and are generally the result of various strengthening and maintenance overlays.
(iv) Multiple concrete slab construction – like composite pavements they have generally evolved through strengthening overlays.
(v) Overlays and overslabs required for strengthening existing pavements.

4.2.5. The choice of pavement type depends on performance requirements and cost.

4.2.5.1 Performance requirements: In general, concrete is preferred where there is likely to be venting of fuel, spillage of lubricating oils and hydraulic fluids, jet efflux gases from slow moving high performance jet engines, or areas subject to locked wheel turns. Concrete should therefore be used for the following pavement areas:

(i) Runway ends (typically for a distance of at least 150m).
(ii) Sections of taxiways adjacent to runway ends.
(iii) Holding areas.
(iv) Aprons and hard standings.
(v) Hangar floors.
(vi) Engine run-up platforms.
(vii) Compass calibration bases.

4.2.5.2 Cost: For many pavements this will be the main consideration and will depend on such diverse factors as the availability of materials in the locality and the bearing capacity of the natural subgrade on which the pavements are to be constructed. For rigid pavements there is a minimum thickness of concrete below which its use is impractical, and a maximum subgrade strength beyond which further increases in strength result in little saving of construction depth. On soils of good bearing value, flexible construction is likely to be more economical. The opposite is true for weak subgrades.

4.2.5.3 Other considerations:

(i) The absence of joints in flexible pavements gives them better riding qualities for high speed operations than most types of rigid pavement.
(ii) If the only realistic option is to construct a pavement on an unpredictable subgrade which is liable to long-term shrinkage or heave, a flexible pavement will generally be the best option. This is because a flexible pavement can cope with greater movement and remain serviceable; it can also be more cheaply and expediently overlaid to rectify the loss of shape.

## 4.3 MATERIAL SPECIFICATION

4.3.1. The use of the semi-empirical design methods demands that the quality of material in a pavement is at least as good as those in the pavements upon which the design methods are based. This applies to the material specification and the level of quality control.

4.3.2. Relevant details of the necessary material specification are given in Chapter 5, 6 and 7, and Appendix C.

## 4.4 SUBGRADE STRENGTH

4.4.1. The determination of subgrade strength, and the other subgrade properties to which consideration should be given during design, is described in Chapter 3. Some specific considerations with respect to rigid and flexible pavements are discussed in Sections 5.5 and 6.4 respectively.

## 4.5 THE DESIGN ACN

4.5.1. The method of determining the design ACN for a pavement is given in Chapter 2.

## 4.6 FREQUENCY OF TRAFFICKING

4.6.1. While the magnitude and configuration of the wheel loads are the dominant factors in the design of airfield pavements, the effect of fatigue caused by load repetition is an important secondary consideration for both rigid and flexible pavements. Laboratory and full-scale tests clearly show that pavements subject to high frequencies of trafficking need to be significantly thicker than those subject to low frequencies.[12,27]

4.6.2. The design methods given in this guide cater for 3 frequencies of trafficking: Low, Medium and High, as shown in Table 5.

**Table 5** Design Frequency of Trafficking

| Frequency of Trafficking | Nominal Number of Coverages* over Design Life of Pavement |
|---|---|
| Low | 10,000 |
| Medium | 100,000 |
| High | 250,000 |

*The definition of 'Coverages' is given in Section 4.9

4.6.3. To determine the appropriate frequency of the trafficking, the total number of Coverages during the design life is calculated. This involves consideration of the design life, pattern of trafficking and mixed traffic use.

## 4.7 DESIGN LIFE

4.7.1. The design method and the frequencies of trafficking in Table 5 assume the aircraft movements are spread fairly evenly over the life of the pavement

4.7.2. In normal circumstances pavement deterioration is gradual, becoming noticeable over a period of a few years. This deterioration can be due to surface weathering or structural fatigue or both. In deciding on an appropriate structural design life, the following considerations should be kept in mind:

(i) The need to keep major maintenance work on airfield pavements to a long term cycle.
(ii) The likelihood of a change in aircraft use after a number of years.
(iii) Durability of pavement construction. Concrete pavements are more durable than blacktop pavements assuming both are constructed in accordance with Defence Estates' Specification. The surface serviceability of concrete should, with the aid of minor maintenance work, be adequate for 25-35 years. On the other hand bituminous surfacings, as a result of surface weathering, generally require maintenance work in the form of slurry sealing, the first coat being required after 7-10 years, and more substantial restoration work after 20-25 years. In the case of friction case resurfacing may be required after approximately 15 years.
(iv) The cost of rehabilitation. Concrete pavements generally cost more to rehabilitate than flexible pavements.

4.7.3. With these factors in mind it is recommended that the structural design life be 20-30 years. The upper end of this range being for concrete pavements and the lower end for flexible pavements.

4.7.4. The design method assumes an increasing degree of minor maintenance (e.g. crack sealing) in the last few years of a pavement's life. Where such maintenance cannot be tolerated, the engineer may wish to project a structural design life beyond the expected life of the surfacing.

## 4.8 PATTERN OF TRAFFICKING AND ASSESSMENT OF PASSES

4.8.1. An aircraft movement over a particular section of the pavement normally constitutes a pass. The total number of passes should be taken as the total number of movements and Mixed Traffic Analysis used to consider the effect of aircraft operations at different weights. It is conservative to consider all movements at Maximum Ramp Weight. If it is certain that actual operations (e.g. landings) will always be at weights lower than this figure a more accurate weight can be used (e.g. for fast turn offs, accesses to maintenance areas and where runway length restricts Maximum Take Off Weight).

4.8.2. Runways and main taxiways leading to runway ends are the most heavily loaded pavements as they carry the aircraft at their heaviest, when fuelled for take off. For these pavements the number of passes can be taken as the number of departure movements only; landing movements being accounted for by assuming that all passes are at Maximum Ramp Weight.

4.8.3. Aircraft parking aprons in rigid pavement construction should be designed for the same design ACN and frequency of trafficking as the main taxitrack exit from the apron. This is because it is difficult to predict movement patterns and to construct areas of concrete in varying thicknesses.

4.8.4. The outer portions of runways can be designed to a reduced loading regime as shown in Figure 11. However, where an airfield does not have a parallel or perimeter taxiway, the assessment of the loading regime should include the additional use of the runway for taxiing operations. 'Backtracking' (taxiing) down the runway by departing aircraft will approximately double the Coverages (as defined in Section 4.9) on the runway. In addition, the length of runway used by backtracking aircraft should be provided with the same full depth construction across the width of the pavement to allow for taxiing being offset from the centreline.

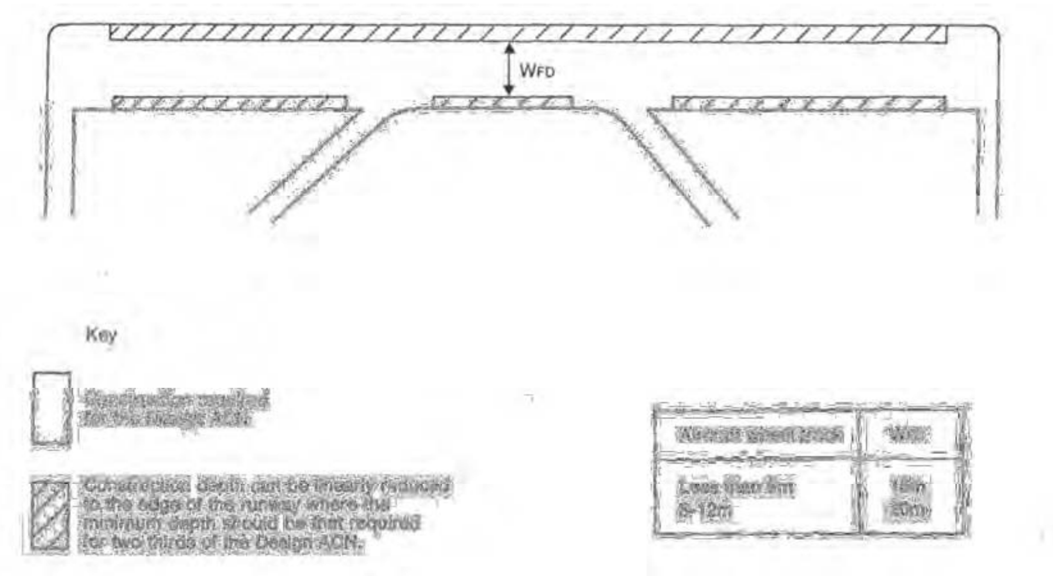



**Figure 11** Reductions in runway thickness requirement

4.8.5. Reduction in construction thickness on the outer strips of runways, is particularly beneficial when strengthening existing runways which have an inadequate camber. The reduced thickness at the edge will allow improved transverse gradients and surface water drainage.

4.8.6. On helicopter pads and Harrier VTOL pads the dynamic effects of landing aircraft increase the loading factor. For these pavements the passes should be taken as the number of take offs plus the number of landings at the ACN appropriate to the maximum weight; the Pass-to-Coverage Ratio listed in Table 6 and Table 7 should also be adopted.

### 4.9 COVERAGES AND PASS-TO-COVERAGE RATIO

4.9.1. Coverages represent the number of times a particular point on the pavement is expected to receive a maximum stress as a result of a given number of aircraft passes. The relationship between passes and Coverages depends on several factors, including the number and spacing of wheels on the aircraft's main wheel gear, the width of the tyre contact area and the lateral distribution of aircraft wheel paths relative to the pavement centre-line or guideline markings. The number of Coverages is calculated using the Pass-to-Coverage Ratio:

$$\text{Coverages} = \frac{\text{Passes}}{\text{Pass-to Coverage Ratio}}$$

4.9.2. Table 6 and Table 7 give Pass-to-Coverage Ratios for various main wheel gear arrangements on runways, taxiways and stands. These ratios assume channelised trafficking consistent with the initial stage of a take off run on runways, very channelised trafficking about a centreline on taxiways, and operations on stands with designated stand centrelines, especially when controlled by docking guidance systems. For aprons without stand centrelines where the actual parking position varies the Pass-to-Coverage Ratios for taxiways should be used.

4.9.3. For the background to the derivation of the Pass-to-Coverage Ratios see Appendix E which also sets out a procedure for calculating Pass-to-Coverage Ratios for non-standard wheel gear arrangements.

**Table 6** Pass to Coverage Ratios

| Main Wheel Gear Type* | Pass-to-Coverage Ratio | | |
|---|---|---|---|
| | Runway | Taxiway | Stand |
| Single | See Table 7 | | |
| Dual | 3.2 | 2.1 | 1 |
| Dual-Tandem | 1.8 | 1.31 | 0.5 |
| Tridem | 1.44 | 1 | 0.33 |

* Refer to Appendix D for definition of landing gear arrangements.

**Table 7** Pass-to-Coverage Ratios for Aircraft with Single Main Wheel Gears

| Tyre Pressure MPa | ACN of Aircraft | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | Up to 10 | | 11-20 | | 21-40 | | Over 40 | | All |
| | Runway | Taxiway | Runway | Taxiway | Runway | Taxiway | Runway | Taxiway | Stands |
| Up to 1.0 | 8 | 4 | 6 | 3 | 5 | 2.5 | 4 | 2 | 1 |
| 1.0 to 1.5 | 10 | 5 | 8 | 4 | 6 | 3 | 5 | 2.5 | 1 |
| >1.5 | 12 | 6 | 10 | 5 | 7 | 3.5 | 6 | 3 | 1 |

## 4.10 MIXED TRAFFIC USE

4.10.1. At a military airfield the pavements are often designed for operations by a specific type of aircraft, so the calculation of the loading regime is relatively straightforward. However, where traffic forecasts indicate operations by a variety of aircraft, the loading criteria will not be so readily assessed. In allowing for a variety of aircraft types it is necessary to be able to relate the loading severity of each type of aircraft to that of the Design Aircraft and thereby to calculate the number of Equivalent Coverages by the Design Aircraft.

4.10.2. The calculation of the loading regime for pavements subject to mixed traffic is explained with reference to Examples 4.1 and 4.2:

(i) Decide on the required design life of the pavement (see Section 4.7).
(ii) Establish the aircraft types likely to use the pavement.
(iii) Establish the ACNs for each aircraft at the actual subgrade value and the appropriate weight.
(iv) Use Appendix B to identify the main wheel gear type for each aircraft and establish their Pass-to-Coverage Ratios from Table 6 and Table 7 (see Section 4.9).
(v) Establish the number of passes by each aircraft.
(vi) Establish the Design Aircraft.
(vii) For setting out the information refer to Table 8 and Table 9 of Examples 4.1 and 4.2 respectively. The tables show the aircraft (col 1), their ACNs (col 2), Pass to Coverage Ratios (col 3) and annual passes (col 4).

(viii) Calculate the number of Coverages by each aircraft during the design life of the pavement (col 5).

(ix) Calculate the ratio of the ACN of each aircraft to that of the Design Aircraft (col 6).

(x) For rigid pavements, use Figure 12 to obtain rigid mixed traffic factors (RMTF) from the ACN ratios found in step (ix). For each aircraft, select the ACN of the Design Aircraft on the left-hand ordinate and make a horizontal projection until it intersects the curve with the appropriate ACN ratio. Make a vertical projection down the graph and read off the RMTF. See Table 8 col 7. Having established the RMTF for each aircraft the number of Equivalent Coverages by the Design Aircraft is equal to the number of Coverages made by each aircraft divided by its respective RMTF (Table 8 col 8) Hence:

$$\text{Equivalent Coverages by Design Aircraft} = \frac{\text{Coverages by aircraft at less than the design ACN*}}{\text{RMTF}}$$

(xi) For flexible pavements, use Figure 13 to obtain flexible mixed traffic factors (FMTF) from the coverages found in step (viii). For each aircraft, select its respective number of Coverages (Table 9 col 5) on the abscissa of Figure 13. Then make a vertical projection until it intersects the curve. Make a horizontal projection and read off the FMTF from the left-hand ordinate. See Table 9 col 7. Modify the FMTF for each aircraft by multiplying it by the respective ACN ratio (Table 9 col 8). Select the Modified FMTF on the left-hand ordinate of Figure 13. Using the graph in reverse, read off the number of Equivalent Coverages by the Design Aircraft (Table 9 col 9).

(xii) Column 8 in Table 8 and column 9 in Table 9 give the mixed traffic loading in terms of Equivalent Coverages by the Design Aircraft. Calculate the total Coverages at the design ACN from:

Total Coverages at = Coverages by the Design Aircraft at the design ACN
the design ACN plus the Equivalent Coverages

(xiii) From Table 5, select a frequency of trafficking to use as an input to the design charts.

---

* This could include the Design Aircraft at weights other than the maximum considered.

**Figure 12** Mixed traffic analysis – rigid pavements

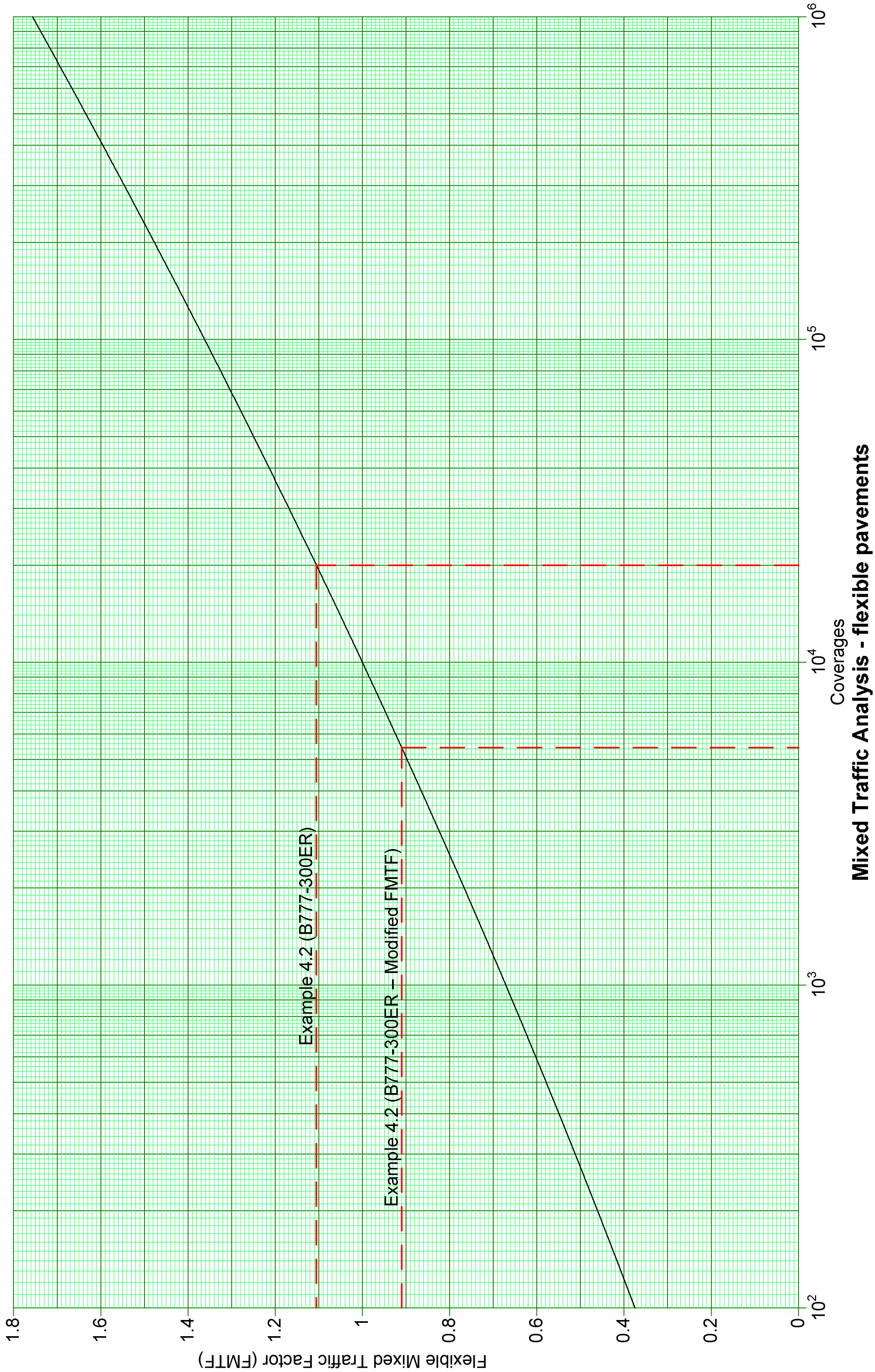



**Figure 13** Mixed traffic analysis – flexible pavements

## TRAFFIC ANALYSIS EXAMPLES

**Example 4.1**
Design a new rigid pavement for the main taxiway at an international airport used by a wide range of aircraft.

1. Design Life 30 years (see Section 4.7).

2. Expected Departures:

| Aircraft | Departures/Year |
|---|---|
| A321-200 | 28600 |
| A340-500 | 2000 |
| A330-200 | 1200 |
| B737-800 | 5000 |
| B747-400 | 1000 |
| B767-300 | 3800 |
| B777-300ER | 1600 |

3. Aircraft Data:

| Aircraft type | All Up Mass (kg) | RIGID PAVEMENT SUBGRADES - MN//m$^2$/m | | | | Main Wheel Gear Type for Pavement Design | Pass-to-Coverage Ratio (Table 6) |
|---|---|---|---|---|---|---|---|
| | | High 150 | Medium 80 | Low 40 | Ultra Low 20 | | |
| | | ACN | | | | | |
| A321-200 | 89,400 | 56.5 | 59.4 | 62.1 | 64.3 | Dual | 2.1 |
| A340-500 | 369,200 | 72.8 | 84.7 | 100 | 115.3 | Dual Tandem | 1.3 |
| A330-200 | 233,900 | 53.7 | 62.4 | 74.3 | 86.9 | Dual Tandem | 1.3 |
| B737-800 | 79,243 | 49.3 | 51.8 | 54.2 | 56.1 | Dual | 2.1 |
| B747-400 | 397,800 | 52.4 | 62.7 | 74.4 | 85.1 | Dual Tandem | 1.3 |
| B767-300 | 159,665 | 38.3 | 45.4 | 54.1 | 62.5 | Dual Tandem | 1.3 |
| B777-300ER | 352,441 | 65.8 | 85.3 | 109.3 | 131.5 | Tridem | 1 |

4. Soil Survey: k = 50 MN/m$^2$/m.

5. Aircraft ACNs at the requisite subgrade value (k = 50) interpolated from Step 3:

| Aircraft | ACN @ k = 50 MN/m$^2$/m |
|---|---|
| A321-200 | 61.4 |
| A340-500 | 96.2 |
| A330-200 | 71.3 |
| B737-800 | 53.6 |
| B747-400 | 71.5 |
| B767-300 | 51.9 |
| B777-300ER | 103.3 |

The Design Aircraft is the B777-300ER with ACN 103.3.

6. Design Aircraft: Boeing 777-300ER.

7. Total Coverages (see Table 8): 76,775.

**Table 8** Rigid Mixed Traffic Analysis Example

| 1<br>Aircraft | 2<br>ACN | 3<br>ACN Ratio | 4<br>Passes (Departures / Year x Design Life) | 5<br>Pass-to-Coverage Ratio | 6<br>Coverages (Col 4 / Col 5) | 7<br>Rigid Mixed Traffic Factor (From Figure 12) | 8<br>Equivalent Coverages (Col 6 / Col 7) |
|---|---|---|---|---|---|---|---|
| A321-200 | 61.4 | 0.59 | 858000 | 2.1 | 408571 | 148.39 | 2753 |
| A340-500 | 96.2 | 0.93 | 60000 | 1.3 | 45802 | 1.89 | 24290 |
| A330-200 | 71.3 | 0.69 | 36000 | 1.3 | 27481 | 33.17 | 828 |
| B737-800 | 53.6 | 0.52 | 150000 | 2.1 | 71429 | 682.42 | 105 |
| B747-400 | 71.5 | 0.69 | 30000 | 1.3 | 22901 | 32.45 | 706 |
| B767-300 | 51.9 | 0.50 | 114000 | 1.3 | 87023 | 939.6 | 93 |
| B777-300ER | 103.3 | 1 | 48000 | 1 | 48000 | 1 | 48000 |
| TOTAL COVERAGES | | | | | | | 76775 |

8. Design for Medium Frequency Trafficking (i.e. 100,000 Coverages) by Boeing 777-300ER.

**Example 4.2**
Design a new flexible pavement for the runway at an international airport used by a wide range of aircraft.

1. Design Life 20 years,

2. Expected Departures:

| Aircraft | Departures/Year |
|---|---|
| A321-200 | 28600 |
| A340-500 | 1000 |
| A330-200 | 2750 |
| B737-800 | 5000 |
| B747-400 | 3500 |
| B767-300 | 3800 |
| B777-300ER | 1000 |

3. Aircraft Data:

| Aircraft type | All Up Mass (kg) | FLEXIBLE PAVEMENT SUBGRADES - CBR | | | | Main Wheel Gear Type for Pavement Design | Pass-to-Coverage Ratio (Table 6) |
|---|---|---|---|---|---|---|---|
| | | High 15 | Medium 10 | Low 6 | Ultra Low 3 | | |
| | | ACN | | | | | |
| A321-200 | 89,400 | 49.4 | 52 | 57.6 | 63.2 | Dual | 3.2 |
| A340-500 | 369,200 | 75.3 | 82.2 | 97.8 | 129.8 | Dual Tandem | 1.8 |
| A330-200 | 233,900 | 58.5 | 63.5 | 73.8 | 99.8 | Dual Tandem | 1.8 |
| B737-800 | 79,243 | 42.9 | 45.4 | 50.4 | 55.3 | Dual | 3.2 |
| B747-400 | 397,800 | 53 | 59 | 72.5 | 94.1 | Dual Tandem | 1.8 |
| B767-300 | 159,665 | 39.5 | 43.3 | 51.1 | 69.9 | Dual Tandem | 1.8 |
| B777-300ER | 352,441 | 63.6 | 71.1 | 89.1 | 120.1 | Tridem | 1.4 |

4. Soil survey shows CBR 10%.

5. The actual subgrade value is one of the standard values. Therefore ACNs can be taken directly from Step 3 above. The Design Aircraft is the A340-500 with ACN 82.2.

6. Design Aircraft: Airbus A340-500.

7. Total Coverages (See Table 9): 33,442.

**Table 9** Flexible Mixed Traffic Analysis Example

| 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 |
|---|---|---|---|---|---|---|---|---|
| Aircraft | ACN | ACN Ratio | Passes (Departures / Year x Design Life) | Pass-to-Coverage Ratio | Coverages (Col 4 / Col 5) | Flexible Mixed Traffic Factor (from Figure 13) | Modified Mixed Traffic Factor (Col 3 x Col 7) | Equivalent Coverages (from Figure 13) |
| A321-200 | 52 | 0.63 | 572000 | 3.2 | 178750 | 1.46 | 0.92 | 5933 |
| A340-500 | 82.2 | 1 | 20000 | 1.8 | 11111 | 1 | 0 | 11111 |
| A330-200 | 63.5 | 0.77 | 55000 | 1.8 | 30556 | 1.17 | 0.9 | 5261 |
| B737-800 | 45.4 | 0.55 | 100000 | 3.2 | 31250 | 1.17 | 0.65 | 849 |
| B747-400 | 59 | 0.72 | 70000 | 1.8 | 38889 | 1.21 | 0.87 | 4082 |
| B767-300 | 43.3 | 0.53 | 76000 | 1.8 | 42222 | 1.22 | 0.64 | 818 |
| B777-300ER | 71.1 | 0.86 | 20000 | 1.4 | 13889 | 1.05 | 0.91 | 5368 |
| TOTAL COVERAGES | | | | | | | | 33442 |

8. Design for Medium Frequency Trafficking (i.e. 100,000 Coverages) by Airbus A340-500.

# 5 Rigid Pavement Design

## 5.1 GENERAL

5.1.1. For over 50 years Defence Estates' preferred choice of new rigid construction has comprised unreinforced pavement quality concrete (PQC) without dowels, tie bars or keys, on a rolled drylean concrete (DLC) base. Defence Estates does not consider necessary the use of traditional mechanical load transfer devices; experience has shown that with good base support provided by drylean concrete together with aggregate interlock at the transverse (contraction) joints of the PQC and the omission of regular expansion joints (see para 5.3.1), an adequate level of load transfer is maintained for a considerable number of load repetitions. Furthermore standard unreinforced, undowelled rigid pavement design simplifies construction and gives reliable performance.

5.1.2. Longitudinal joints are simple butt joints without load transfer. In general the absence of load transfer has not caused problems. However, where aircraft regularly traffic across longitudinal joints, e.g. on some aircraft stands where the concrete is laid normal to the stand centre-line, early failures have occurred. In these situations the load transfer should be provided at the longitudinal joint, by dowels or a profiled joint, or the concrete slab thickness should be increased as described in 5.6.3.

5.1.3. Apart from the preferred choice the following types of rigid construction are also considered in this Chapter:

(i) Fully dowelled (unreinforced) – see Section 5.7
(ii) Jointed reinforced (with dowelled expansion, construction and contraction joints) – see Section 5.8.
(iii) Continuously reinforced concrete – see Section 5.9.

5.1.4. In climates with a high seasonal temperature variation, omitting the dowels and regular expansion joints must be considered with caution. Pavements constructed without expansion joints at low temperatures in these climates may be subject to 'blow-ups'. Conversely, those constructed without dowels at the high end of the temperature range would have poor load transfer properties at open transverse joints in winter. Figure 14 gives three zones of annual temperature variation, moderate, high and extreme. The preferred constructions with undowelled PQC slabs without regular expansion joints (see para 5.3.1) on drylean concrete bases apply without restrictions in the zone of moderate temperature variation. For the zone of high annual temperature variation PQC slabs constructed within the centre 80% band of annual temperature do not need dowels or regular expansion joints. However, PQC slabs constructed outside this temperature range and those constructed in the zones of extreme temperature variation, should be fully dowelled; when constructed at low temperatures, regular expansion joints should also be provided.

5.1.5. Also to be considered are the excessive temperature differentials which can develop between the top and bottom of a slab, causing high warping stresses. Figure 15 shows the regions where temperature warping stresses are likely to be significantly greater than allowed for in the rigid pavement design model (see Appendix F). In these regions the PQC thickness requirements obtained from the design charts should be increased by 10% to allow for excessive warping stresses.

**Figure 14** Zones of annual temperature variations applicable to rigid pavements

**Figure 15** Regions where high temperature warping stresses are likely to occur in rigid pavements

## 5.2 PAVEMENT QUALITY CONCRETE SLAB

5.2.1. Pavement Quality Concrete (PQC) must be strong enough to provide an economical pavement thickness. The PQC must also provide a durable, hard wearing, weather resistant surface so that the expense and disruption of major maintenance is seldom required. Air entrainment should be used to provide resistance to frost and the action of de-icing chemicals.

5.2.2. The design flexural strength referred to on Charts 1, 2, 3 and 4 is the in situ mean flexural strength of the PQC at 28 days (28 days is assumed to be the minimum time before the pavement is brought into use). The in situ mean flexural strength parameter relates directly to the failure criteria assumed in the design method i.e. 50% of the bays in the trafficked area have developed cracks; as halving cracks initially develop at the underside of the slabs this does not necessarily mean that 50% of bays will be exhibiting surface cracks at failure (see Appendix F). The design flexural strength relates to the concrete in the pavement. Quality control during construction should be based on strength tests on samples with the same degree of compaction and cured in the same regime as the in situ concrete e.g. by using cores from the slab, provided the flexural to compressive strength ratio is known.

5.2.3. Figure 16 provides guidance on relationships between 28 day in situ and laboratory mean flexural strengths, 7 day laboratory mean and characteristic compressive strengths from cubes and 28 day in situ characteristic compressive strengths from cores. The characteristic strength is based on a 5% defective rate. The relationship between 7 day cube strengths and 28 day core strengths is based on the Defence Estate's experience, modified for the method of determining compressive strength described in BS EN 13877-2:2004. It takes into account the differences in both the curing regime and degree of compaction for cast cubes and cores extracted from the pavement. The estimated laboratory mean flexural strength is based on a 20% gain in strength from 7 to 28 days. If evidence suggests that the actual gain in strength is different, the strengths on the axis should be adjusted by the ratio of the actual gain in strength to the assumed 20%.

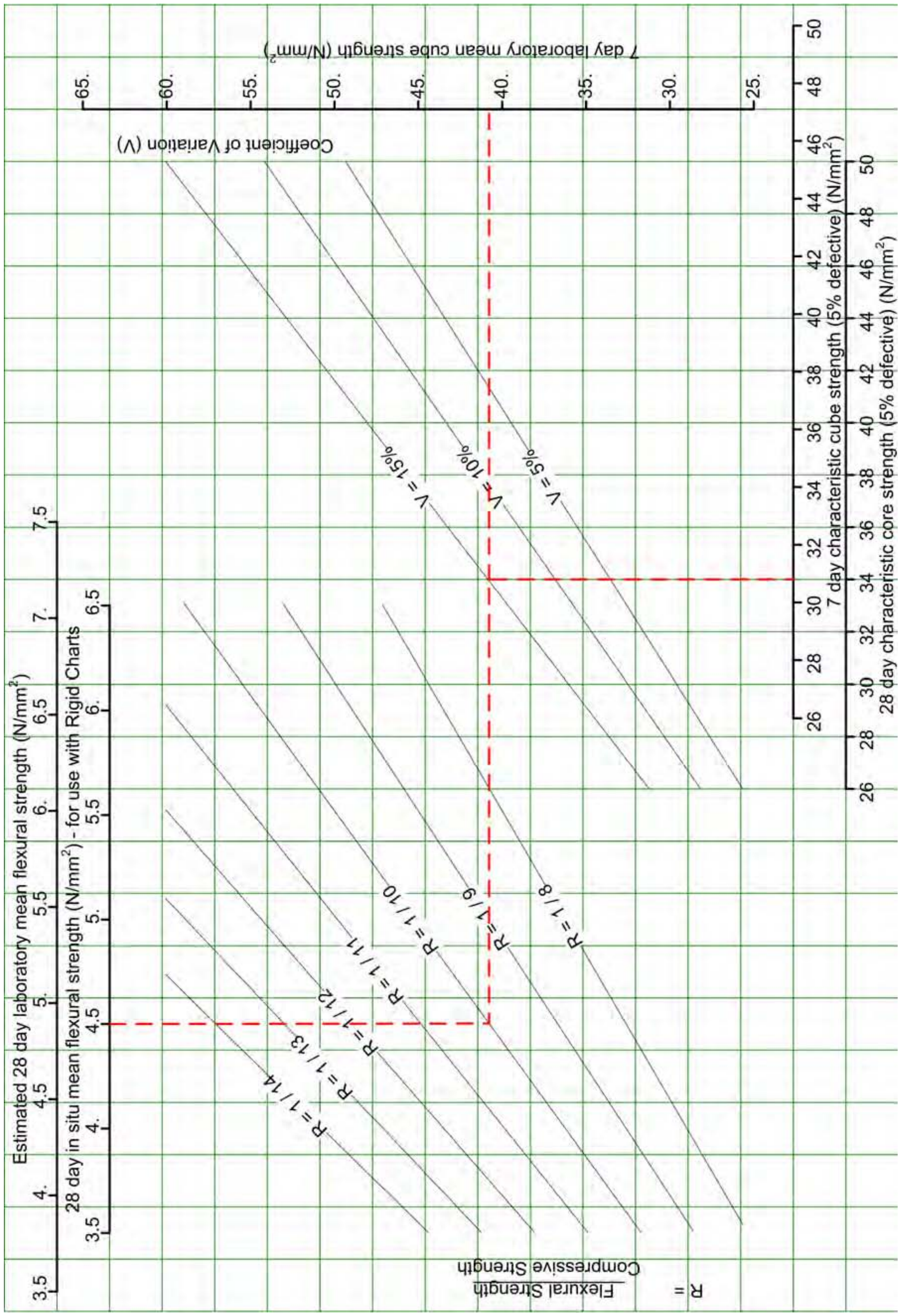



**Figure 16** Concrete flexural strengths

## 5.3 JOINTS IN PAVEMENT QUALITY CONCRETE SLABS

5.3.1. Recommendations on the frequency of expansion joints and the maximum spacing of contraction and construction joints are given in Table 10 for unreinforced PQC. Joint spacings are fundamental to the pavement design so these recommendations should not be exceeded, except as modified in para 5.3.2.

5.3.2. Expansion joints. For PQC slabs 250mm or more in thickness regular expansion joints are not usually required. However, for some situations it is advisable to provide them to limit movement of the pavement, at maximum intervals such that expansion will not cause unacceptable extrusion of the sealant from the joint. For pavements constructed at low temperatures in climates with high or extreme annual variations in temperature as defined by Figure 14 it is wise to provide regular expansion joints for all PQC slab thicknesses. The spacing of expansion joints in these circumstances for slabs 250mm or more in thickness should be similar to that required for 225mm thick slabs (Table 10). The actual spacing will depend on the type of coarse aggregate, the annual range of temperature and the movement accommodation factor of the joint filler and the sealing compounds. For slabs less than 250mm thick the spacing of expansion joints depends on the slab thickness and the type of coarse aggregate used in the PQC. For all PQC thickness expansion joints should be formed between new and existing pavements, at junctions, at tangent points of bends, around box gutters and around other obstructions to the continuity of the slabs. Figure 17 and Figure 18 show details of dowelled and undowelled expansion joints. When constructing undowelled unreinforced PQC, Defence Estates does not normally include any specific design provisions (i.e. dowels or thickened slab edges) for expansion joints. This practice has not led to premature maintenance problems primarily because of the stiff DLC base and the dearth of expansion joints. If dowels are to be provided at expansion joints in an otherwise undowelled pavement, care should be taken in the joint detailing to ensure that the overall movement of the slabs as a result of moisture and temperature changes is not locally impeded in the direction transverse to the dowelled joints.

5.3.3. Contraction grooves. Contraction grooves initially control the development of cracks caused by drying shrinkage or a drop in temperature shortly after laying. Initial cracking due to these factors rarely occurs at every contraction joint. In the long-term the spacing of these grooves together with the construction joints is fundamental to the pavement design as it controls the warping stresses caused by temperature differences between the top and bottom of the slab. An undowelled contraction groove, which is standard Defence Estates practice, relies on aggregate interlock to provide load transfer. Load transfer from aggregate interlock decreases as the crack width increases. For thin slabs with regular expansion joints the effect of joint opening is built into the design, but for thick slabs the assumption is that there are no expansion joints. In situations where there induced cracks in slabs greater then 250 mm thick may open more than expected, e.g. where it is necessary to provide expansion joints, consideration should be given to dowelling the contraction groove. Figure 19, Figure 20 and Figure 21 show typical details for unsealed contraction grooves, sealed contraction grooves, and dowelled and sealed contraction grooves. The grooves can be sawn or wet formed, but Defence Estates prefers the former in conjunction with the use of limestone coarse aggregate which can be easily sawn. This is because wet forming grooves can cause the adjacent concrete to become overworked leading to poor durability and long-term maintenance problems. In arid regions where wind blown sand and dust are prevalent, the engineer may prefer to provide wider contraction grooves which can be sealed to prevent abrasion and ‘jamming’ of joints (see Figure 20 and Figure 21). For reinforced concrete pavements the spacing of joints can be increased as explained in Section 5.8.

5.3.4 Day work joints. Day work joints are usually simple butt joints. In most circumstances they are infrequent and have little effect on the failure rate of the pavement. In some situations frequent daywork joints become necessary, e.g. laying in winter with short days. In these situations consideration should be given to dowelling the day work joints.

5.3.4. Construction joints. The spacing of these joints in unreinforced PQC should be the same as the contraction groove spacing. This is because experience has shown that the effects of wheel load and warping stresses are much reduced in square bays. Figure 22 shows the standard construction joint detail used by Defence Estates. Figure 23 details a sealed joint which may be considered more appropriate in certain circumstances for the same reason as described in para 5.3.3. Where load transfer is required at construction joints (para 5.1.2) it should be provided by dowels (para. 5.3.5) or a profiled joint (para 5.3.6). Both dowels and profiled joints give greater quality problems than butt joints.

5.3.5. Dowelled Construction joints. The use of dowels, including the diameter and spacing and the potential problems associated with them, is described in Section 5.7. Figure 24 details a dowelled and sealed construction joint.

5.3.6. Profiled Construction joints. An alternative to dowelling construction joints to provide load transfer is a keyed joint. In addition to traditional keys various curved profiles for the faces of construction joints have also been tried, not necessarily for load transfer. The dimensions of keys have been based on the slab thickness rather than a design for the specific loading. Historically keyed joints have not performed well, often suffering premature failure. due to factors such inadequate shear capacity in the key and very high stresses at sharp angles. In addition the geometry of some key designs means that if the joint opens due to shrinkage or movement caused by temperature changes, the faces do not come into contact when loaded and the load transfer is lost.

5.3.7. Figure 25 shows a profiled joint specifically designed to provide load transfer to meet the design requirement while avoiding high stresses at angles and being practicable to construct with a shaped form. A profiled joint may be considered when:

(i) The slab thickness is greater than 250 mm.
(ii) It can be demonstrated that the capacity of the joint, based on its dimensions and the concrete strength, is adequate for the proposed loading.
(iii) The detail can be offered as an option to dowels so that the contractor can confirm that fixed forms and side-forms for slip-form pavers can be formed to the correct dimensions, that the concrete mix allows formation of the profile and will have a standard deviation less than or equal to the design assumption, and that any increase in slab thickness is more economic than dowelling the standard design thickness.

5.3.8. To design a profiled joint:

(i) Design the pavement in accordance with Section 5.6.
(ii) Check the capacity of a profiled joint for the Design Aircraft, using the equation below.
(iii) If an increase the slab thickness is considered a viable option increase the thickness until the Joint Capacity Factor is 1.
(iv) Check the Joint Capacity Factor for any aircraft in the design mix that may have an individual wheel load greater than that of the design aircraft. (NB. Unlike overload of a concrete slab which is unlikely to result in failure under a single load, overload of a profiled joint may result in an immediate failure in shear. If significant overload is foreseeable the Joint Capacity Factor should be checked for likely aircraft.)
(v) Detail the joint in accordance with Figure 25.

The capacity of a profiled joint within a given slab thickness is given by:

(i) $$JCF = \frac{11.199P}{h\sqrt{f_{cm}(1-2.33CV)}\sqrt{\frac{P}{p}}}$$

where:
**JCF** = Joint Capacity Factor (must be ≥ 1).
**h** = slab depth (mm)
**P** = wheel load (kg)
**p** = tyre pressure (MPa)
$\mathbf{f_{cm}}$ = mean 28 day in situ compressive strength of concrete (N/mm$^2$)
**CV** = Coefficient of Variation of concrete (%)

The profiled joint is adequate for the load if the Joint Capacity Factor is greater than or equal to one.

5.3.9. Profiled joints can be formed by manufacturing shaped side forms for fixed-form or slip-form paving. It is vital that the profiled joint is formed without sharp angles or steps. For instance forming the joint by welding a shaped plate to an existing steel shutter, leaving a step along the top of the profile, is guaranteed to cause deep spalling along the joint. When slip-form paving the concrete miz, and the mixing, delivery and laying processes, are critical to accurately forming the profile.

5.3.10. Joint Rotation. When construction joints are loaded by wheels trafficking directly along joint the deflection causes the bay edge to rotate towards the adjacent bay. Contact between the two faces can cause deep spalling. Providing load transfer does not mitigate the problem as transferring the load to the adjacent bay results in the same total rotation. Figure 25 shows a solution to the problem, eliminating the contact between the faces. This solution may be applied to any of the other construction joint details. It may also be applied to daywork joints where the same problem can occur.

**Table 10** Maximum Joint Spacing for Unreinforced PQC

| Type of joint or groove | Coarse aggregate | Nominal thickness of slab (mm) | | | | |
|---|---|---|---|---|---|---|
| | | 150 | 200 | 225 | 250 | 275 or over |
| Expansion | Limestone | 36 m | 48 m | 54.0 m | None | None |
| | Other rocks and gravels | 18 m | 22.5 m | 31.5 m | None | None |
| Contraction or Construction | Limestone | 4 m | 4 m | 6.75 m | 6.75 m | 7.5 m |
| | Other rocks and gravels | 3 m | 3 m | 5.25 m | 5.26 m | 6 m |

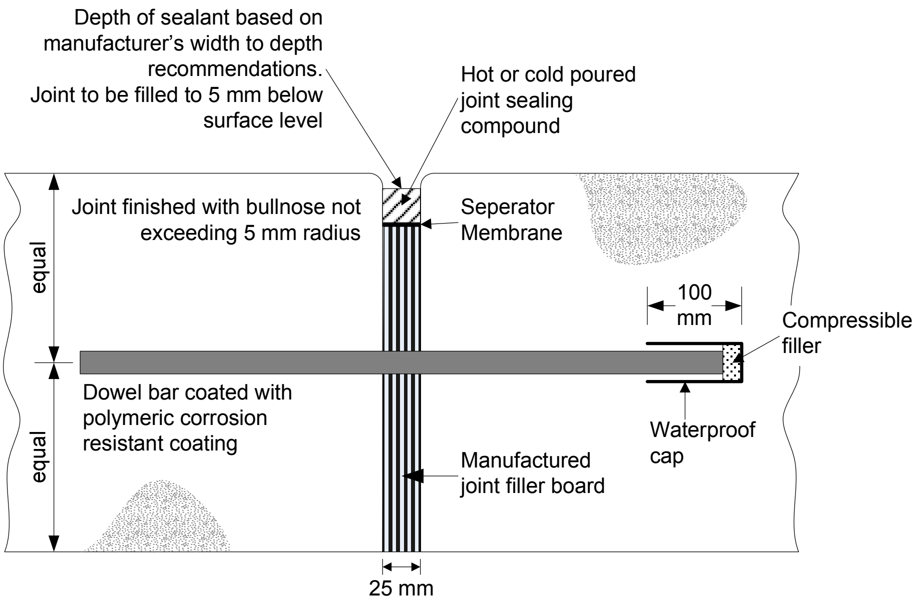



**Figure 17** Dowelled expansion joint

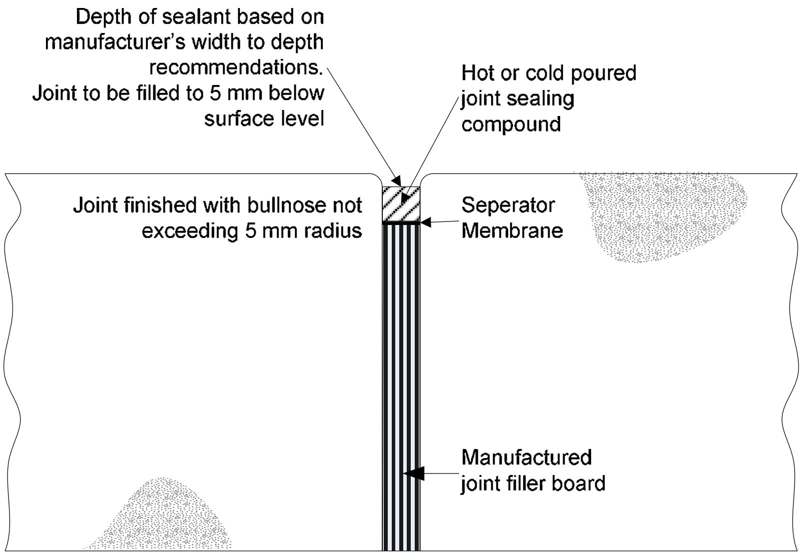



**Figure 18** Undowelled expansion joint with hot or cold poured sealant

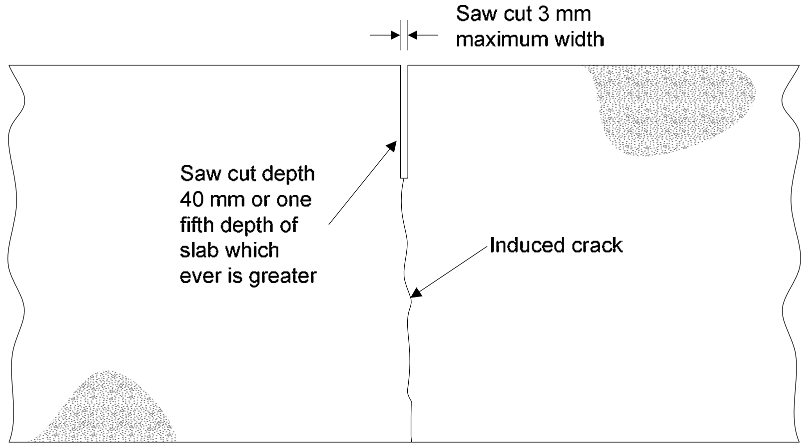



**Figure 19** Sawn contraction groove (not to be used for flint gravel aggregates)

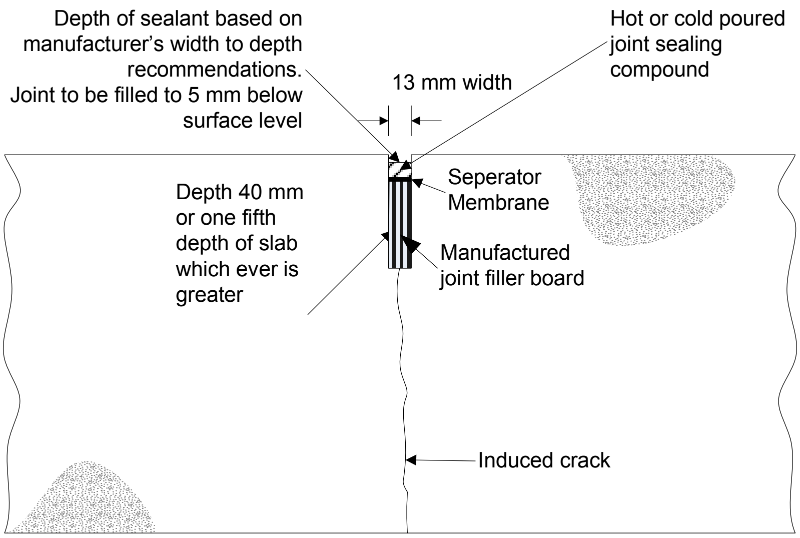



**Figure 20** Formed contraction groove

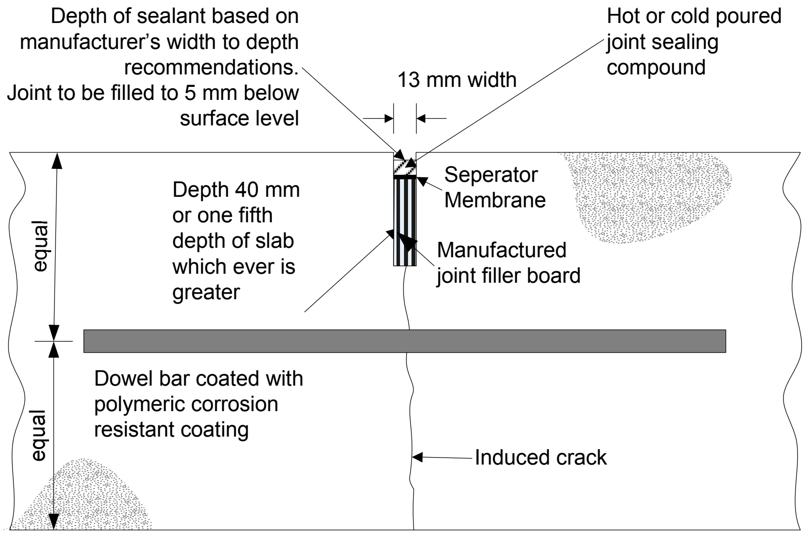



**Figure 21** Dowelled contraction joint with formed groove

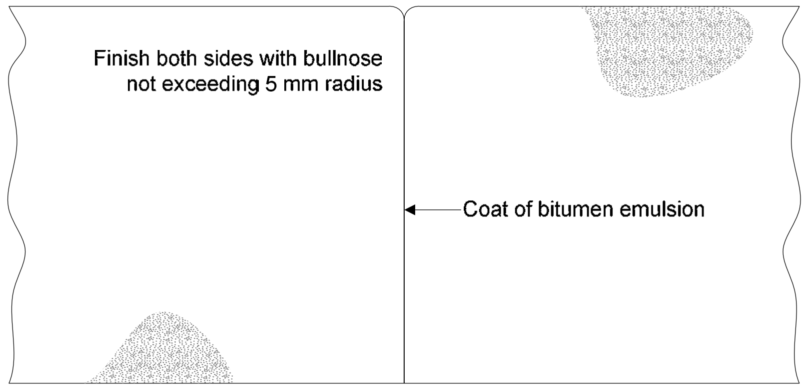



**Figure 22** Undowelled construction joint

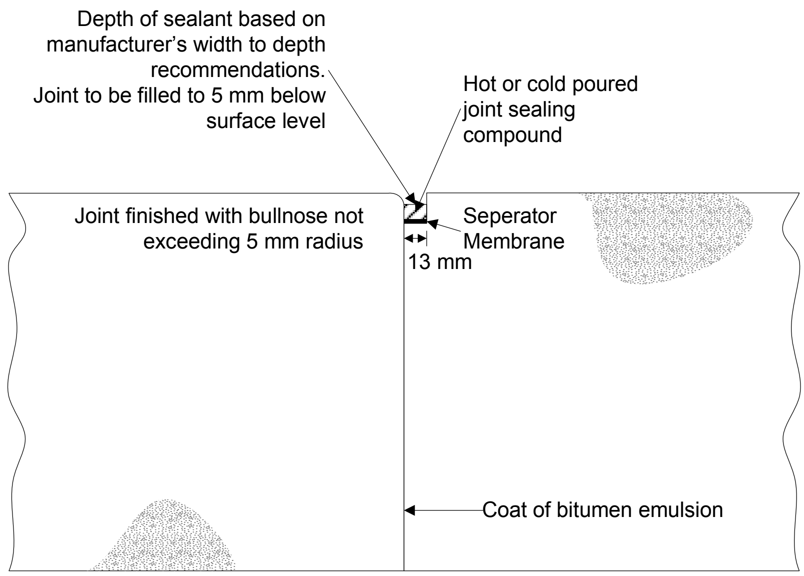



**Figure 23** Undowelled sealed construction joint

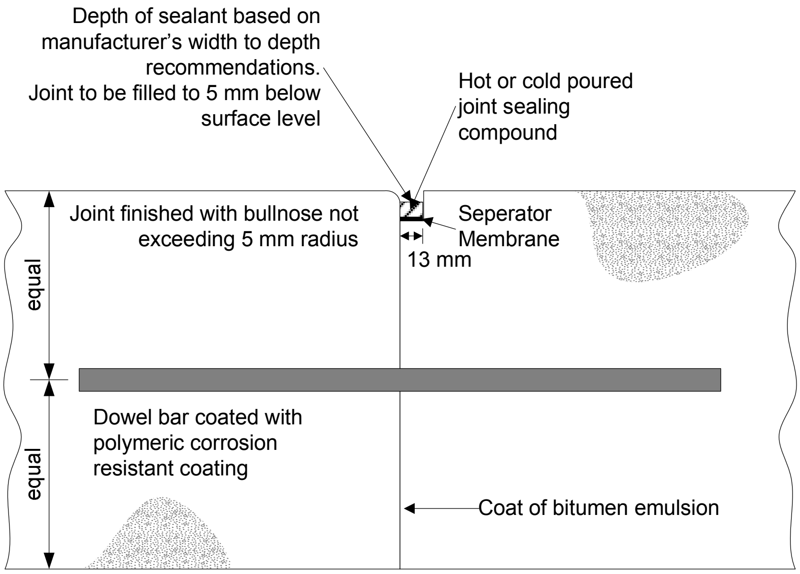



**Figure 24** Dowelled sealed construction joint

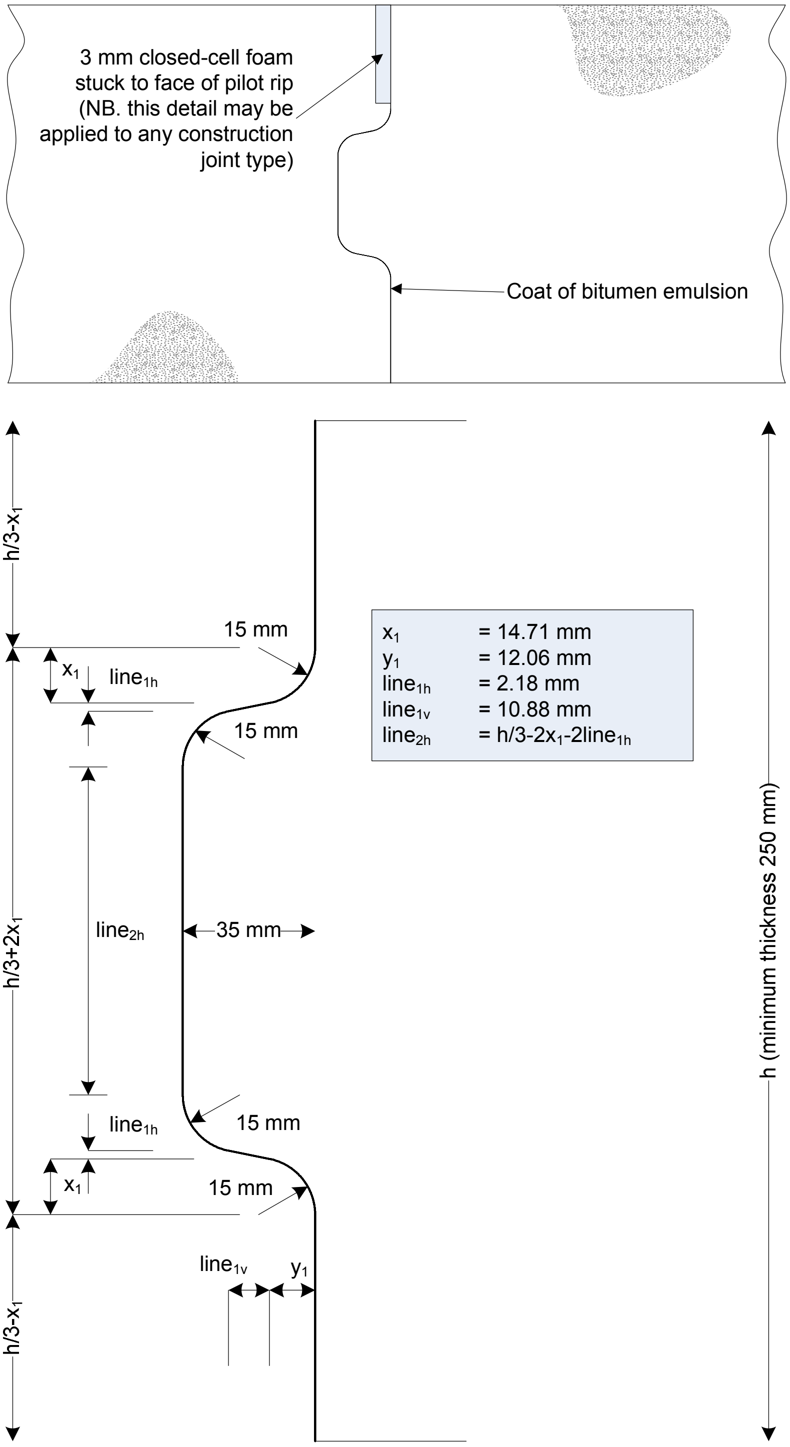



**Figure 25** Profiled construction joint, with former to mitigate joint rotation

## 5.4 BASE

5.4.1. The standard base material used by Defence Estates is drylean concrete (see Appendix C).

5.4.2. The purpose of the DLC base is:

(i) to provide a uniform and substantially improved support to the PQC, particularly at slab joints,

(ii) to reduce the deflection at slab joints, caused by wheel loading, and thereby help to preserve aggregate interlock at transverse joints so that a high level of load transfer is maintained,

(iii) to act as a protective layer to moisture sensitive soils while PQC works is in hand and also to form a level and firm working course on which to lay the PQC,

(iv) to prevent mud pumping,

(v) to reduce the rate of deterioration if cracking of the PQC occurs,

(vi) in the case of PQC pavements for high ACN values on poor subgrades, to reduce the required PQC thickness.

5.4.3. Chart 3 gives an increased thickness of DLC for pavements on poor subgrades subjected to heavy multiple wheel loads. This is to allow for the additional wheel load interaction at depth and to prevent over-stressing or poor subgrades.

5.4.4. The DLC thickness shown on Charts 1-3 is the minimum thickness required under the PQC slab. On poor subgrades it may not be possible to achieve adequate compaction and the necessary finished level tolerances if this thickness is laid on one layer directly on the natural formation. In this case the DLC should be place in two layers, the first one forming a working course on which the second can be compacted. The working course should be laid by hand with only very light compaction. As a guide, the working course thickness should be 100mm for k = 20-30MN/$m^2$/m and 75mm for k = 30-40 MN/$m^2$/m. As the top layer should not be less than 75 mm thick the minimum total thickness of DLC which can be practically laid directly on a poor natural formation will be 175mm for k = 20-30 MN/$m^2$/m and 150mm for k = 30-40 MN/$m^2$/m. Alternatively the subgrade may be improved by using a granular sub-base (see para 3.8.4).

5.4.5. The use of a cement-stabilised material may be considered instead of drylean concrete. Figure 26 gives equivalency factors for cement-stabilised material in relation to drylean concrete which depends on the 7-day characteristic cube strength (5% defective). Note that Figure 26 gives reduced equivalency factors for cement-stabilised fine-grained materials. This is because of the greater reduction in stability that occurs in fine-grained materials after cracks eventually propagate in the cement-bound layer; there being substantially less aggregate interlock. Cement-stabilised material may be produced by plant mixing or in situ stabilisation as long as the required strengths are met. In other respects, such as surface tolerances and densities, the specification for cement-stabilised material should be the same as that for drylean concrete.

5.4.6. Rigid pavement designs for PQC slabs on granular sub-bases, or for PQC slabs laid directly on the subgrade are not included in this Chapter. Chapter 7 includes a procedure using Chart 5 for evaluating these types of construction. This procedure can also be used for assessing strengthening requirements (see Chapter 7).

## 5.5 SUBGRADE

5.5.1. For details of subgrade characteristics, the test method for determining k, subsoil drainage and sub-grade compaction requirements, see Chapter 3.

5.5.2. In assessing k, the presence of work underlying layers in the soil must be carefully considered. Heavy multiple wheel loads induce large deflection basins in a rigid pavement giving rise to significant stress levels in the subsoil at depth. Therefore pavements for aircraft with heavy multiple wheel gears should be designed for a conservative k which reflects the strength of the underlying weak soils.

5.5.3. Figure 10 sets out a method of assessing subgrade improvement provided by a granular sub-base (see para 3.8.4).

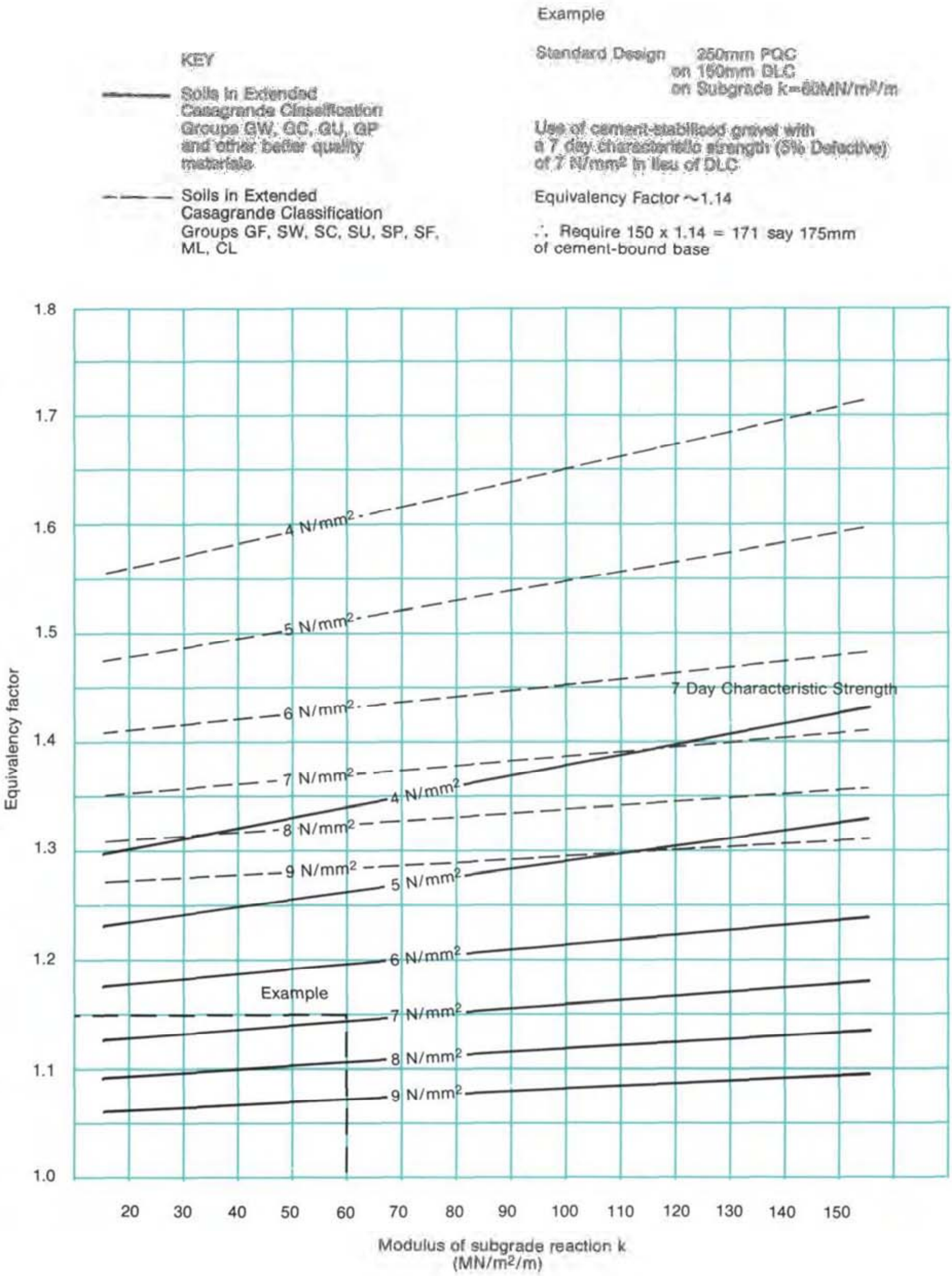



**Figure 26** Cement-bound sub-bases for rigid construction

## 5.6 DESIGN OF UNDOWELLED AND UNREINFORCED CONCRETE PAVEMENTS

5.6.1. Separate design charts have been prepared for single, dual dual-tandem and tridem main wheel gears, Charts 1, 2, 3 and 4 respectively; see Appendix D for the definition of these gear types. The use of the charts requires four design parameters:

(i) Flexural strength of the concrete (see section 5.2).

(ii) The Modulus of Subgrade Reaction k. See Section 5.5 and Chapter 3 for details of subgrade characteristics. If subgrade improvement is to be carried out as detailed in Section 3.8 the increased k value will be appropriate for design.

(iii) The design ACN (see Section 2.6).

(iv) The frequency of trafficking – either Low, Medium or High. Chapter 4 defines these traffic levels in terms of Coverages by the Design Aircraft. For calculating the number of Coverages for different areas of pavement and equating the loading effects of different aircraft see Chapter 4.

5.6.2. Having established the above parameters, Charts 1-3 are used as follows:

(i) Select the frequency of trafficking (i.e. Low, Medium, High); for High Frequency Trafficking see Section 5.10.

(ii) Make a horizontal projection until it intersects with the appropriate design flexural strength.

(iii) Make a vertical projection from the intersection point to the design ACN.

(iv) From this intersection point make a horizontal projection to the k = 20 line. Trace a line parallel to the curves until it intersects the vertical projection of the appropriate k. At this stage read off the DLC base thickness required.

(v) From the last intersection point make a horizontal projection to the right hand ordinate. Read off the PQC thickness and round it to the nearest practical construction increment (Defence Estates works in 25mm increments). The minimum PQC slab thickness is 150mm. This is because thinner slabs constructed to the minimum practical by size in the Specification would crack prematurely due to warping effects.

See Examples 5.1 and 5.2.

5.6.3. Where aircraft regularly traffic across the longitudinal joints and load transfer is not provided the slab should be thickened (see paragraph 5.1.2). To provide the equivalent of good load transfer the thickness of the slab should be increased by 25%.

See Examples 5.1 and 5.2.

## 5.7 FULLY DOWELLED CONCRETE PAVEMENTS

5.7.1. Generally Defence Estates does not specify fully dowelled concrete pavements (i.e. with all joints dowelled). If dowelled concrete designs are being considered the following points should be borne in mind.

(i) Dowels induce high localised stresses in the concrete. This can lead to crushing and/or cracking of the concrete around the dowel, particularly if the concrete has not been properly compacted in this area.

(ii) Long-term effectiveness of dowels depends largely on their accurate alignment which reduces their tendency to seize up. If the movement at the joint is impeded this can lead to ‘blow-ups’ in hot weather or the development of cracks parallel to the joints in unreinforced concrete in cold weather. In addition excessive differential shrinkage between newly constructed adjacent lanes of concrete can cause the dowels across the construction joints to become jammed, so that any subsequent contraction of the bays would induce tensile stresses in the concrete.

(iii) Experience has shown that the load transfer effectiveness of dowels lessens with load repetition so in many cases it is considered that to incorporate dowels does not reduce the thickness given by the standard undowelled/unreinforced designs (see para 5.7.2). In climates with high annual variations in temperature it may be necessary to provide a dowelled PQC slab to maintain load transfer effectiveness (see para 5.1.4).

5.7.2. With the following exception, the design procedure for fully dowelled concrete pavements is the same as that set out in Section 5.6 for undowelled/unreinforced concrete using Charts 1,2 and 3. Table 11 gives reductions in PQC slab thickness (determined from Chart 1, 2 and 3) for dowelled concrete pavements less than 250mm thick.

5.7.3. For a fully dowelled concrete pavement dowels should be provided at all construction, contraction and expansion joints to the requirements set out in Table 12. They should be installed at mid-depth of the slab. See Section 5.3 for joint layout requirements and details.

## 5.8 JOINTED REINFORCED CONCRETE PAVEMENTS WITH DOWELS

5.8.1. Generally Defence Estates does not specify this type of construction which provides little or no gain in structural performance and is more likely to present long term maintenance problems than the standard undowelled unreinforced rigid pavement designs.

5.8.2. Jointed reinforced concrete pavement is usually constructed in long bays giving fewer transverse joints. The long bays will tend to develop one or more transverse cracks due to shrinkage and differential temperature stresses. The function of the reinforcement is to hold the cracks tight and minimise deterioration. Failure of jointed reinforced concrete pavement is generally by spalling of the transverse cracks. Monitoring and maintenance of the cracks can be problematic, including increased disruption to aircraft operations. The risk of premature failure is greater in this type of pavement than in jointed unreinforced concrete constructed in square bays.

**Table 11** Design Thicknesses for Dowelled Constructions

| PQC slab thickness requirement from Charts 1, 2 and 3 (mm) | Allowable reduction in PQC slab thickness for dowelled construction (mm) |
|---|---|
| equal to or greater than 250 | 0 |
| 225 | 15 |
| 200 | 25 |
| 175 | 25 |

**Table 12** Dowel Size Requirements

| PQC Slab Thickness (mm) | Dowel Diameter (mm) | Total Dowel Length (mm) | Spacing (mm) |
|---|---|---|---|
| 150 | 20 | 400 | 300 |
| 175-200 | 25 | 450 | 300 |
| 225-275 | 30/32 | 450 | 300 |
| 300-400 | 40 | 500 | 375 |
| 425-450 | 50 | 600 | 450 |

5.8.3. Incorporating light reinforcement into a concrete slab to control shrinkage and warping cracks does allow a considerable increase in the spacing of transverse contraction joints. The quantity of steel required varies from 0.05% to 0.3% of the cross sectional area of the slab and should be placed in the upper part of the slab with at least 50mm cover. This does not improve the flexural strength of the slab and therefore the design thickness requirements are the same as those for dowelled PQC slabs (see para 5.7.2).

5.8.4. The areas of reinforcement required in both the longitudinal and transverse directions should be calculated from the following formula.

$$A_s = \frac{LC_f}{2F_s}\frac{Wh}{}$$

Where $A_s$ = area of steel in $mm^2$/m width of slab

L = distance between contraction joints (longitudinal direction) or construction joints (transverse direction) in metres. The spacing of contraction joints should not exceed 23 metres.

W = weight of concrete in $kN/m^3$

h = slab thickness in mm

$F_s$ = working stress in reinforcement in $N/mm^2$ ($F_s$ = 0.75 yield stress)

$C_f$ = coefficient of subgrade resistance to slab movement. This is dependent on the base material and the slab dimension. For construction with a DLC base and a polythene separation layer a value of 1.5 can be taken.

'$A_s$' should not be less than 0.05% of the cross sectional area of the concrete. Reinforcement is usually in the form of mesh. Longitudinal laps should be at least 30 times the diameter of the wire. Transverse laps should be not less than 150 mm or 20 times the transverse wire diameter, whichever is the greater.

5.8.5. Dowels should be provided at construction, contraction and expansion joints in accordance with the requirements set out in Table 11. Figure 27 shows a typical longitudinal section through a jointed reinforced concrete pavement. See Section 5.3 for joint details.

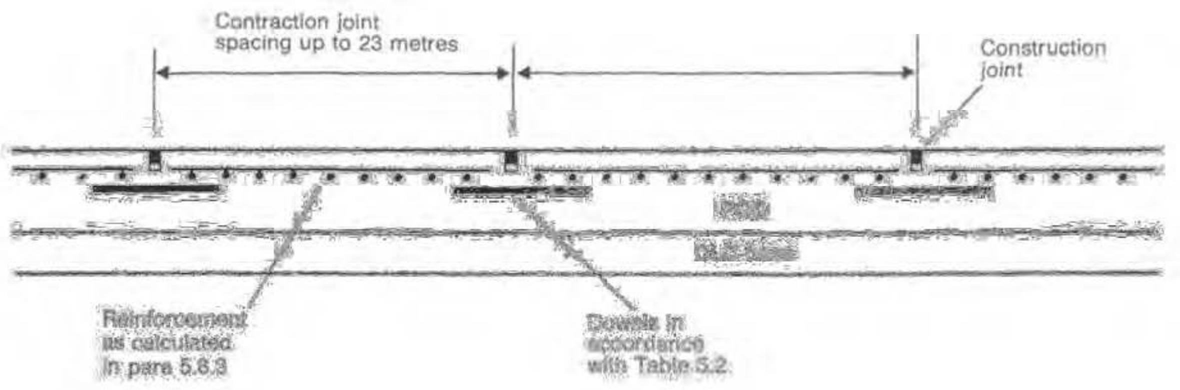



**Figure 27** Typical longitudinal section through jointed reinforced concrete pavement

## 5.9 CONTINUOUSLY REINFORCED CONCRETE PAVEMENTS

5.9.1. In Defence Estates' experience the use of continuously reinforced slabs has not resulted in more cost-effective pavements. Continuously reinforced slabs of reduced thickness generally suffer early spalling at shrinkage/warping cracks. The spalling is caused by a combination of frost damage, excessive working of cracks from repetitive wheel loading, jet blast and high tyre pressure.

5.9.2. Defence Estates does not have an established procedure for this type of construction. However, where it is being considered the following points need to be remembered:

(i) To achieve a consistent and controlled development of cracks the amount of longitudinal reinforcement required is likely to be between 0.5-0.7% of the cross-sectional area of the concrete.

(ii) To avoid excessive deflections and consequent working of cracks due to trafficking by heavy wheel loads, only a modest saving in PQC thickness should be considered. A reduction in excess of 15% on the dowelled concrete designs may be unwise.

(iii) Special attention needs to be given to compaction around and under the reinforcement particularly with the thicker constructions and their correspondingly higher steel contents.

(iv) The advantage of improved ridability is perhaps not significant in relation to unreinforced PQC with sawn contraction grooves.

## 5.10 DESIGN FOR HIGH FREQUENCY OF TRAFFICKING

5.10.1. The High Frequency design level is nominally 250,000 Coverages by the Design Aircraft (see para 4.6.2). As Defence Estates lacks both experience and research data on pavement performance at this level of use, the construction thickness requirements have been extrapolated beyond proven designs. On this basis the PQC slab thickness for the High Frequency design is 10% greater than that required for the Medium Frequency design.

## RIGID DESIGN EXAMPLES

**Example 5.1**

A rigid pavement is required for nre stands at a small municipal airport, used principally for charter traffic. The majority of departures are Boeing 737-800s.

**Guide Reference**

1. SUBGRADE: Soil Survey shows k = 30 MN/m$^2$/m

2. AIRCRAFT DATA:

Appendix B a) ACN

| Aircraft type | All Up Mass (kg) | RIGID PAVEMENT SUBGRADES - MN//m$^2$/m | | | | Main Wheel Gear Type for Pavement Design | Pass-to-Coverage Ratio (Table 6) |
|---|---|---|---|---|---|---|---|
| | | High 150 | Medium 80 | Low 40 | Ultra Low 20 | | |
| | | ACN | | | | | |
| B737-800 | 79,243 | 49.3 | 51.8 | 54.2 | 56.1 | Dual | 1 |

Appendix B — b) Main Wheel Gear: Dual

Section 4.9, Table 6 — c) Pass–to-Coverage Ratio: 3.2

3. AIRCRAFT USE: Expected departures are 3 Boeing 737-200s per day.

Para 4.7.3 — 4. DESIGN LIFE: 30 years.

5. FREQUENCY OF TRAFFICKING

Section 4.9 — No of Coverages = $\frac{(30 \times 365 \times 3)}{1} = 32850$

6. DESIGN CRITERIA

a) ACN: from 2a above, using linear interpolation between subgrade values and rounding to the nearest integer, ACN = 55

Para 4.6.2, Table 5 — b) Frequency of Trafficking: Low

Para 5.2.3 — 7. CONCRETE STRENGTH: 4.5 N/mm$^2$ mean flexural at 28 days

Chart 2 — 8. REQUIRED CONSTRUCTION: 345 mm Pavement Quality Concrete
150 mm Rolled Drylean Concrete

Para. 5.6.3 — Note: if the stands are constructed so that the butt longitudinal joints are normal to the stand centreline, the joints should be provided with load transfer (e.g. dowels) or the slab thickness increased by 25%. i.e.
430 mm Pavement Quality Concrete
150 mm Rolled Drylean Concrete

Para 2.4.2 — 9. CLASSIFICATION:

a) Subgrade Category: Low (C)

b) PCN:ACN of the Boeing 737-800 on a Rigid Low Subgrade =54.2

c) Pavement Type: Rigid (R)

d) Tyre Pressure Limitations: No limitations on a concrete surface (W)

e) PCN 55/R/C/W/T

**Example 5.2**

Design a rigid pavement for a new parallel taxiway at an international airport used by a wide range of aircraft.

**Guide reference**

1. SUBGRADE: Soil Survey shows k = 50 MN/m$^2$/m

2. AIRCRAFT DATA:

Appendix B
Section 4.9 Table 6

a) ACNs, Main Wheel Gears and Pass-to-Coverage Ratios.

| Aircraft type | All Up Mass (kg) | RIGID PAVEMENT SUBGRADES - MN//m$^2$/m | | | | Main Wheel Gear Type for Pavement Design | Pass-to-Coverage Ratio (Table 6) |
|---|---|---|---|---|---|---|---|
| | | High 150 | Medium 80 | Low 40 | Ultra Low 20 | | |
| | | ACN | | | | | |
| A321-200 | 89,400 | 56.5 | 59.4 | 62.1 | 64.3 | Dual | 2.1 |
| A340-500 | 369,200 | 72.8 | 84.7 | 100 | 115.3 | Dual Tandem | 1.3 |
| A330-200 | 233,900 | 53.7 | 62.4 | 74.3 | 86.9 | Dual Tandem | 1.3 |
| B737-800 | 79,243 | 49.3 | 51.8 | 54.2 | 56.1 | Dual | 2.1 |
| B747-400 | 397,800 | 52.4 | 62.7 | 74.4 | 85.1 | Dual Tandem | 1.3 |
| B767-300 | 159,665 | 38.3 | 45.4 | 54.1 | 62.5 | Dual Tandem | 1.3 |
| B777-300ER | 352,441 | 65.8 | 85.3 | 109.3 | 131.5 | Tridem | 1 |

3. AIRCRAFT USE: Proposed aircraft use shown in Table 8 (Page 38).

Para 4.7.3

4. DESIGN LIFE: 30 years.

5. DESIGN CRITERIA:

a) ACNs of user aircraft calculated at k = 50 are shown in Table 8.

Section 2.6

The Design Aircraft is the Boeing 777-300ER. Design ACN = 103.

Para 4.6.2 Table 5

b) The Mixed Traffic Analysis is shown in Table 8. The total coverage is 76,775 and therefore Medium Frequency Trafficking is used.

6. CONCRETE STRENGTH: 5 N/mm$^2$ mean flexural strength at 28 days.

Chart 4

7. REQUIRED CONSTRUCTION: 390 mm Pavement Quality Concrete
175 mm Rolled Drylean Concrete

Para 2.4.2

8. CLASSIFICATION:

a) Subgrade Category: Low (C)

b) PCN is the ACN of the Boeing 777-300ER on a Rigid Low Subgrade = 109.3

c) Pavement Type: Rigid (R)

d) Tyre Pressure Limitations: No limitations on a concrete surface (W).

e) PCN 110/R/C/W/T.

# 6 Flexible Pavement Design

## 6.1 GENERAL

6.1.1. For over 50 years Defence Estates' policy has been to construct 'flexible' pavements with either cement or bitumen-bound bases. While an unbound base or sub-base can provide the desired performance, the strict grading requirement together with the need for a high a consistent level of compaction throughout can result in construction problems and unreliable performance. This is particularly true on wet sub-grades, common in the UK. These disadvantages are worsened in the case of pavements subject to regular trafficking by heavy and high tyre pressure aircraft. On the other hand pavements with bound bases permit the use of less stringent specification and give structural benefits over conventional flexible pavements, allowing a saving in thickness over the granular base and sub-base requirements. The bound base designs provide an economic and practical solution and most significantly give reliable performance.

6.1.2. Sometimes, the availability of good quality materials, with or without self-cementing properties, can make convention granular base and sub-base construction a practical and economic choice. However, this type of construction is only recommended on good dry subgrades, where it is possible to achieve the necessary high level of compaction. As the aircraft weight increases there is an increasing possibility that failure to achieve uniform compaction over the whole pavement area will lead to premature rutting due to consolidation of the granular materials. Thus for heavy aircraft (ACN > 50) the granular materials should have a well proven record of performance an the designer may consider proof rolling the base course before laying the bituminous surfacing. The required subgrade conditions are more likely to be found in certain overseas locations than in the UK. For these reasons flexible constructions with unbound bases/sub-bases are not included on the design chart for this Chapter (Chart 4). Chapter 7 includes a design and evaluation chart for these pavements.

## 6.2 SURFACING

6.2.1. The standard flexible pavement designs to Chart 5 require a minimum surfacing thickness of 100mm. This will usually be made up to a 40mm surface course on a 60mm binder course. A 20mm thick open macadam friction course is not considered to be a structural layer and therefore should not be counted as part of the 100mm surfacing.

6.2.2. The principal bituminous surfacing materials used by Defence Estates are Marshall asphalt surface and base course or hot rolled asphalt surface course on macadam binder course. These materials should meet the specialist performance required of airfield pavements:

(i) High stability to withstand the shear stresses induced by heavy wheel loads and high tyre pressures.
(ii) Good ridability.
(iii) A durable hard-wearing weatherproof surface free from loose material and sharp edges which might endanger aircraft.

6.2.3. To provide good wet weather braking characteristics on a runway an additional surface treatment is usually specified. The standard surface treatments used by Defence Estates are friction course, coarse slurry seal and grooving; the choice of treatment depends on the availability of materials, site geography and performance requirement. A surfacing of porous macadam friction course with cross-falls of 1.5%, gives runways an excellent all-weather friction characteristic. The friction course must have an underlay of at least 100mm of high quality asphalt. A friction course is not recommended in areas where the pores are liable to silt up (e.g. by wind blown sand) or to freeze in extreme winter conditions (e.g. where temperatures of less than -10ºC can be expected to last for periods o greater than 24 hours). Surface dressing should not be use for jet aircraft operations because of its tendency to loose stones which present a FOD (foreign object damage) hazard. High speed taxiways may also need treatment, either with a course slurry seal or by grooving.

6.2.4. For temperate climates, Table 13 gives guidance on the suitability of various surfacing materials. The stability of hot rolled asphalt on a macadam base course is adequate for the frequencies of trafficking and tyre pressures given in Table 13. The frequencies of trafficking assumed in the table apply to a single user aircraft. Where mixed traffic use is envisaged the aircraft with the highest category tyre pressure, not necessarily the Design Aircraft, should be considered at the frequency of trafficking appropriate to that tyre pressure category. For pavements in hot climates the Marshall asphalt specification should be used. For guidance on high tyre pressure aircraft operations on blacktop surfacings see Chapter 8.

**Table 13** Suitability of Surfacing Materials (Temperate Climates)

| Tyre Pressure | Frequency of Trafficking | | |
|---|---|---|---|
| | Low | Medium | High |
| W (> 1.5 Mpa) | MA | MA | MA |
| X (up to 1.5 MPa) | HRA/MB | MA | MA |
| Y (up to 1.0 MPa) | HRA[1]/MB | HRA/MB | MA |
| Z (up to 0.5 MPa) | HRA[1]/MB | HRA/MB | HRA/MB |

MA – Marshall asphalt or alternatively Marshall Dense Tar Surfacing surface course on Marshall asphalt or Marshall DTS binder course.
HRA/MB – Hot rolled asphalt on Macadam binder course.
Note 1 – Dense Tar Surfacing is acceptable as an alternative.

6.2.5. Marshall asphalt is a more highly controlled and consistent material than hot rolled asphalt and is to be preferred wherever a contract is large enough to cover the enhanced level of supervision and testing effort involved. To aid proper control and make sure that the performance criteria will be met, Marshall asphalt should, wherever physically and economically possible, be mixed on site.

6.2.6. If there is a requirement for a fuel resistant pavement surface such as for a runway end or apron a tar-based slurry seal can be used to provide some resistance, although it should be noted that they are susceptible to mechanical damage, especially early in their life, and are not resistant to hydraulic fluid spillage.

6.2.7. Other surfacing materials which have been use to a limited extent by Defence Estates include grouted macadam, concrete blocks and Stone Mastic Asphalt. Grouted macadam and concrete blocks are fuel resistant and can be used on aprons, although fuel can penetrate the joints between blocks to reach lower layers. In many cases grouted macadam has not given good long-term performance, and the performance of Concrete Block Surfacing has been variable. Concrete Block Surfacing should not be used on runways. Research shows that Concrete Block Surfacing has little structural capacity until the blocks rotate sufficiently to come into contact and develop interlock. Because of the surface tolerances required for airfield pavements enough movement to create interlock is unlikely, and a Concrete Block Surfacing will add little to the strength of a pavement. Concrete Block Surfacing should be treated as being equivalent to 50mm of Marshall Asphalt or less. Stone Mastic Asphalt has shown considerable promise, although long-term durability has not been fully proven. Structurally it should be treated as equivalent to Marshall Asphalt.

## 6.3 BASE

6.3.1. The standard designs in Chart 5 require a bound base construction from the underside of the surfacing down to the subgrade or improved subgrade (see Section 3.8). Therefore a conventional unbound sub-base is not needed.

6.3.2. The bound base materials normally specified by Defence Estates are high strength drylean concrete (Type FH DLC), and Marshall Asphalt. The thickness requirements on the design chart can be made up of any one or a combination of these materials. However having regard to stringent compaction and laying requirements for Marshall asphalt, DLC should normally be used as the first layer of bound base material on the formation / subgrade.

6.3.3. The design model for Chart 5 is based on that used in Reference 11 for the design of standard flexible pavements comprising bituminous surfacing materials on bound bases. However, Chart 5 incorporates higher equivalency factors than those used in Reference 11 to take account of experience gained since that time and more recent full scale testing of high strength drylean concrete bases (Type FH DLC). Further details on materials and design rationale are provided in Appendices C and F.

6.3.4. When laid on low strength subgrades (CBR less than 6%) it may be difficult if the initial layers of Type FH DLC are laid directly on the subgrade to compact the layers sufficiently to obtain the required minimum strength and density. In this situation a working course should be provided before laying the initial layer, either an unbound capping or a sacrificial working course of drylean concrete.

6.3.5. Chapter 7 deals with the evaluation and strengthening of existing pavements incorporating DLC bases laid to the Defence Estates' specification prior to 1989 and now designated Type F DLC, and also of pavements incorporating asphalts, including Hot Rolled Asphalt and Macadam Base Course. Details of these materials are provided at Appendix C. Chart 5 does not apply to these materials.

6.3.6. Chapter 7 also deals with pavements incorporating unbound granular base and sub-base layers; Chart 5 does not apply to them.

6.3.7. The use of DLC as the principal base material results in a pavement with a rigid mode of behaviour which gradually changes to a flexible mode as the stiffness of the pavement reduces after cracks form in the cement-bound layer. Experience shows that DLC cracks into irregular shaped bays, and the cracks eventually reflect through the surfacing. Where the DLC is thick the resultant irregular bays tend to be large giving rise to wide cracks subject to considerable movement. A requisite thickness of blacktop overlay should be provided; it will substantially delay reflective cracking in the surfacing and postpone the need for widespread maintenance with consequent loss in rideability, drainage and friction characteristics. For minimisation of reflection cracking the thickness of bituminous material over the DLC should be in accordance with Defence Estates Design & Maintenance Guide 33[52].

6.3.8. The use of cement stabilised material instead of DLC may be considered as follows:

(i) Cement-stabilised fine or medium-grained material is unlikely to provide long-term load-spreading characteristics comparable to DLC. Following the eventual propagation of cracks in a cement-stabilised layer a fine-grained material will provide minimal aggregate interlock with a consequent loss of stability and load distribution properties. Therefore, cement-stabilised fine or medium-grained material of which more than 60% passes the 5mm sieve should only be considered as a sub-base. See Chapter 7, para 7.4.2.3 for cement-stabilised sub-bases.

(ii) To give performance comparable to a DLC base, strength characteristics of the cement-stabilised material should comply with the minimum requirements for either Type FH DLC or Type F DLC , as described in Appendix C, for use with Chart 5 or Chart 7 respectively. Cement-stabilised materials are more likely to meet Type F DLC requirements, in which case para 6.3.6 should be referred to. The strength requirements for DLC are unlikely to be achieved with any degree of consistency with an in situ stabilised soil.

## 6.4 SUBGRADE

6.4.1. For details of subgrade characteristics, the CBR test method, subsoil drainage and subgrade compaction requirements, see Chapter 3.

6.4.2. Flexible pavements are more sensitive to sub-grade characteristics than rigid pavements, making the assessment of a representative design CBR more critical than that of a design k. On most sites the soil types at the formation levels are likely to vary. Where the variation occurs in distinct and large areas of the site it may be feasible to consider separate flexible pavement designs. However, if such variation occurs randomly, then a single design based on the limiting soil type (i.e. lowest CBR) may be the only realistic solution. If the change in subgrade support characteristics is considerable, the possibility of differential settlement and densification, particularly in the transitional areas, may need to be considered.

6.4.3. The presence of weak layers in the subsoil must be carefully considered in assessing the design CBR. This is particularly important when the pavement is to be designed for heavy aircraft with multiple wheel main gears which induce significant stress levels at considerable depths below the pavement surface, as reflected in the ACNs for poor subgrades. Para 3.4.7 sets out a procedure for assessing the design CBR when there is a weak underlying layer in the subsoil.

6.4.4. For assessing the subgrade improvement provided by a granular fill see Section 3.8.

6.4.5. The maximum CBR value on Chart 7 is 20%. This is intended to limit the stresses and strains in the bound base materials by imposing a minimum pavement thickness for a given aircraft loading, i.e. the pavement thickness required for CBR 20%. The same subgrade scale is shown on Chart 8, but in this case it is also possible to design for CBR 30% by using the Y-axis only.

### 6.5 DESIGN OF FLEXIBLE PAVEMENTS WITH BOUND BASES

6.5.1. Chart 5 has been prepared for single, dual, dual-tandem and tridem main wheel gears; see Appendix D for the definition of these gear types. The use of the Chart requires three design parameters:

(iii) The CBR of the subgrade – see Section 6.4 and Chapter 3 for details of subgrade characteristics. If subgrade improvement is to be carried out as detailed in Section 3.8 the increased CBR value will be the appropriate design value.

(iv) The design ACN (see Section 2.6).

(v) The frequency of trafficking – either Low, Medium or High. Chapter 4 defines these traffic levels in terms of Coverages by the Design Aircraft. For calculating the number of Coverages for different areas of pavement and equating the loading effects of different aircraft, see Chapter 4.

6.5.2. Having established the above parameters the Chart is used as follows:

(i) Select the frequency of trafficking (Low, Medium or High); for High Frequency Trafficking see Section 6.6.

(ii) Select the ACN scale appropriate to the Design Aircraft's main wheel gear type. Enter the Chart with the design ACN and make a horizontal projection until it intersects the vertical projection of the appropriate CBR.

(iii) From the intersection, trace a line parallel to the curves until it intersects the right hand ordinate. Read off the thickness of bound base material required. The minimum surfacing thickness required on top of the base is 100mm. See Section 6.2 for details of surfacing and Section 6.3 for details of bound base construction.

See Examples 6.1 and 6.2.

## 6.6 HIGH FREQUENCY OF TRAFFICKING

6.6.1. The High Frequency design level is nominally 250,000 Coverages by the Design Aircraft (see para 4.6.2). As Defence Estates lacks both experience and research data on pavement performance at this level of use, the construction thickness requirements have extrapolated beyond proven designs. On this basis the required thickness of bound base material for the High Frequency design is increased to provide a total pavement thickness which is 8% greater than that required for the Medium Frequency design.

## FLEXIBLE DESIGN EXAMPLES

**Example 6.1**

**Guide reference**

Design a flexible pavement using a Type FH Bound Base Material for a taxiway at small municipal airport used principally for charter traffic. The majority of departures are Boeing 737-800s.

1. SUBGRADE: Soil Survey shows CBR 5%.

2. AIRCRAFT DATA:

Appendix B — a) ACN

| Aircraft type | All Up Mass (kg) | FLEXIBLE PAVEMENT SUBGRADES - CBR | | | | Main Wheel Gear Type for Pavement Design | Pass-to-Coverage Ratio (Table 6) |
|---|---|---|---|---|---|---|---|
| | | High 15 | Medium 10 | Low 6 | Ultra Low 3 | | |
| | | ACN | | | | | |
| B737-800 | 79,243 | 42.9 | 45.4 | 50.4 | 55.3 | Dual | 2.1 |

Appendix B — b) Main Wheel Gear: Dual

Section 4.9 Table 6 — c) Pass-to-Coverage Ratio: 2.1

3. AIRCRAFT USE: Expected Departures are 3 Boeing 737-800s per day.

Para 4.7.3 — 4. DESIGN LIFE: 20 years.

Section 4.9 — 5. FREQUENCY OF TRAFFICKING

No of Coverages = $\frac{(20\times365\times3)}{2.1} = 10429$

6. DESIGN CRITERIA

a) Design ACN: from 2a above, using linear interpolation between subgrade values and rounding to the nearest integer ACN = 52

Para 4.6.2,Table 5 — b) Frequency of Trafficking: Low

Chart 5 — 7. REQUIRED CONSTRUCTION: 100mm Surfacing
375mm High Strength Bound Base Material

Para 6.3.7 — If most of the Bound Base Material is to be Type FH Drylean Concrete, a minimum thickness of bitumonous material should be provided to restrict reflective cracking. Defence Estates Design & Maintenance Guide 33 suggests that 220mm is required for a long-life pavement.

e.g. 40mm Marshall Asphalt Surface Course
60mm Marshall Asphalt Binder Course
60mm Marshall Asphalt Base Course
60mm Marshall Asphalt Base Course
255mm TypeFH Drylean Concrete.

Para 2.4.2 — 8. CLASSIFICATION:

a) Subgrade Category: Low (C).

b) PCN is the ACN of the Boeing 737-200 on a Flexible Low Subgrade =51.

c) Pavement Type: Flexible (F)

Table 13 — d) Tyre Pressure Limitations: No limitations for Marshall Asphalt surfacings (W).

e) PCN 51/F/C/W/T.

**Example 6.2**

Design a flexible pavement using a Type F Bound Base Material for a runway at an international airport used by a wide range of aircraft.

**Guide Reference**

1. SUBGRADE: Soil Survey shows CBR 10%

Appendix B, Section 4.9 Table 6

2. AIRCRAFT DATA:

a) ACNs, Main Wheel Gears and Pass-to-Coverage Ratios

| Aircraft type | All Up Mass (kg) | FLEXIBLE PAVEMENT SUBGRADES - CBR | | | | Main Wheel Gear Type for Pavement Design | Pass-to-Coverage Ratio (Table 6) |
|---|---|---|---|---|---|---|---|
| | | High 15 | Medium 10 | Low 6 | Ultra Low 3 | | |
| | | ACN | | | | | |
| A321-200 | 89,400 | 49.4 | 52 | 57.6 | 63.2 | Dual | 3.2 |
| A340-500 | 369,200 | 75.3 | 82.2 | 97.8 | 129.8 | Dual Tandem | 1.8 |
| A330-200 | 233,900 | 58.5 | 63.5 | 73.8 | 99.8 | Dual Tandem | 1.8 |
| B737-800 | 79,243 | 42.9 | 45.4 | 50.4 | 55.3 | Dual | 3.2 |
| B747-400 | 397,800 | 53 | 59 | 72.5 | 94.1 | Dual Tandem | 1.8 |
| B767-300 | 159,665 | 39.5 | 43.3 | 51.1 | 69.9 | Dual Tandem | 1.8 |
| B777-300ER | 352,441 | 63.6 | 71.1 | 89.1 | 120.1 | Tridem | 1.4 |

3. AIRCRAFT USE: Proposed aircraft use shown in Table 9 (page 40).

Para 4.7.3.

4. DESIGN LIFE: 20 years.

5. DESIGN CRITERIA.

a) ACNs of the user aircraft calculated at CBR 10% are shown in Table 9.

The Design Aircraft is the Airbus 340-500. Design ACN = 82

Para 4.6.2 Table 5

b) The Mixed Traffic Analysis is shown in Table 9. The total coverages are 33,442, therefore Medium Frequency Trafficking is used.

Chart 6

6. REQUIRED CONSTRUCTION: 100mm Surfacing
525mm High Strength Bound Base Material

Para 6.3.7

If most of the Bound Base Material is to be Type F Drylean Concrete, a minimum thickness of bitumonous material should be provided to restrict reflective cracking. Defence Estates Design & Maintenance Guide 33 suggests that 220 mm is required for a long-life pavement, if the Surface Course is grooved.

e.g. 40mm Marshall Asphalt Surface Course
60mm Marshall Asphalt Binder Course
60mm Marshall Asphalt Base Course
60mm Marshall Asphalt Base Course
305mm TypeFH Drylean Concrete.

Para 2.4.2

7. CLASSIFICATION

a) Subgrade Category: Medium (B)

b) PCN is the ACN of the Airbus A340-500 on a Flexible Medium Subgrade = 82

c) Pavement Type: Flexible (F)

Table 13

d) Tyre Pressure Limitations: None (W)

e) PCN 82/F/B/W/T

# 7 Pavement Evaluation and Strengthening

## 7.1 METHODS OF EVALUATION

7.1.1. For various reasons it may be necessary or desirable to reappraise the bearing capacity of a pavement. This would apply in any of the following circumstances:

(i) A mid/end of life reassessment of the pavement to plan future maintenance work and/or rehabilitation.
(ii) The pavement has been disused for some time and is to be rehabilitated.
(iii) The pavement is to be strengthened for regular use by heavier aircraft.
(iv) After several years service it has become apparent that the pavement's strength has been reduced and it is showing signs of premature fatigue.
(v) There has been a change in the classification system.

7.1.2. Evaluation is carried out by 'reverse design', with pavement inputs determined by a site investigation. There are no in situ test methods that directly measure pavement strength.

7.1.3. Reverse design works best when used with a pavement management system which includes periodic maintenance inspections and records of construction, subgrade characteristics and aircraft movements. Defence Estates has used reverse design extensively for over 35 years. The method, as presented in this guide, requires the existing pavement to be structurally equated to one of the standard constructions included in the design and evaluation Charts 1-8. Using the Charts in reverse, the strength of the pavement can be determined.

7.1.4. Any evaluation must be weighted by consideration of factors such as the pavement condition, records of its operational use, future operational requirements and an estimate of the pavement's residual fatigue life which must necessarily be subject to engineering judgement.

7.1.5. If strengthening is required an overlay thickness can be calculated using the procedures set out in Sections 7.5 to 7.10

## 7.2 INVESTIGATIONS FOR EVALUATION AND STRENGTHENING

7.2.1. Reverse design requires details of pavement construction and condition, and possibly a record of its use. Section 7.3 provides an overview on assessment of pavement condition and residual fatigue life. An evaluation is then made using the methods described in Section 7.4.

7.2.2. Construction records are not always reliable and rarely give any indication of material condition. A site investigation to determine the pavement inputs for reverse design is therefore usually necessary. The investigation will:

(i) ascertain the existing construction,
(ii) ascertain the condition of the pavement,
(iii) ascertain material condition.

7.2.3. A detailed description of site investigation and interpretation methods for airfield pavements in given in Appendix I.

## 7.3 PAVEMENT CONDITION AND RESIDUAL LIFE

*7.3.1. Accounting for the Pavement Condition*

7.3.1.1 Structural deterioration of pavement layers will reduce their load bearing capacity and suitable allowances may have to be made in evaluation or overlay design. The formulae for design and evaluation of composite and multiple slab pavements (Sections 7.9 and 7.10) include specific Condition Factors which take account of cracking of underlying concrete slabs. In some other cases the effective pavement thickness can be reduced by an analysis of fatigue consumption (para 7.3.2.2). If the pavement is showing signs of serious structural distress materials may be downgraded to ones of a lower structural value (paras 7.3.1.5 and 7.3.1.6). The following paragraphs describe how to determine Condition Factors and when they should be used; advice on assessing Condition Factors by in situ testing is given in Appendix I.

7.3.1.2 Normal deterioration caused by live loading or climatic effects is built into the methods presented in this document. An airfield operator expects a pavement with a given strength when new, and that the pavement will have the same strength until the end of its life before major maintenance. The operator does not expect to change aircraft use in the middle of the pavement life because normal deterioration has occurred. Unless deterioration is excessive the pavement classification should not be altered during the design life, and future performance must be defined by considering together the initial strength, the residual fatigue life and the expected life of the pavement materials. If a mid/end of life evaluation is being made to obtain a classification or to estimate a pavement's residual fatigue life, condition factors should not be applied to the most recent layers of construction. The condition factors for other layers should not generally be changed from those used in the design of the last strengthening, unless it has been agreed with the operator that excessive deterioration is best expressed by a decrease in PCN rather than by a decreased pavement life.

7.3.1.3 If a pavement is being strengthened, the overlay thickness requirement should be calculated on the basis that it provides a renewed design life (see Section 4.6). The evaluation of the existing pavement should therefore reflect its current condition. This will generally necessitate making due allowance for the deterioration of all layers in the existing construction.

7.3.1.4 If deterioration is excessive the likely causes are overloading, fatigue, poor quality construction or reduction in subgrade strength due to a change in moisture content. The reason for the failure should be established and an evaluation of the various layers of construction made. The pavement should be overlaid or reconstructed to restore serviceability at the current classification. Where adjacent level constraints are critical reconstruction may be the only choice.

7.3.1.5 Structural failure of concrete pavements is indicated by cracking of bays in the wheel path (see Appendix F). The following points should be considered:

(i) Condition Factors related to cracking of concrete are given in Table 18 and should be applied to slabs that are part of a composite construction, or to concrete slabs that are to be overlaid, including all layers of existing multiple slab constructions (see Sections 7.9 and 7.10). The Condition Factors should not be applied to the top layer of an existing multiple slab construction for a mid/end of life evaluation.

(ii) If the state of the pavement is significantly worse than the failure condition described in Appendix F the concrete is down-graded to an equal thickness of drylean concrete. Alternatively localised areas of severe failure could be reconstructed and the pavement as a whole assigned an appropriate condition factor.

7.3.1.6 Structural failure of a flexible pavement is indicated by rutting with associated heaving and/or cracking in the wheel paths (see Appendix F). (Note: Rutting is sometimes due to compaction of the pavement layers or subgrade by aircraft operations which while giving rise to a serviceability problem, does not cause a loss of bearing capacity). Provided a pavement is not showing signs of a severe failure it should still possess enough residual strength to form an integral part of a strengthened construction. In developing a design concept for rehabilitation of a failed flexible pavement the following points need to be considered:

(i) If the failure has occurred suddenly or unexpectedly or there is uncertainty in assessing the condition of the various layers of construction the engineer may consider it wise to do deflection tests to reassess the behaviour of the pavement. Tests in failed areas and in areas adjacent to the wheel tracks may indicate whether pavement strength has been significantly reduced.

(ii) Severe shear failure of a pavement (i.e. rutting and heave in excess of twice that given as the failure criterion in Appendix F) is likely to result in loosening of the pavement construction and/or subgrade. In these circumstances either reconstruction, or recompaction and reappraisal of material strengths should be done.

(iii) If small areas of severe rutting have occurred, the pavement may be reconstructed locally and assigned the same residual strength as the sections which are deteriorating normally.

(iv) A surface showing appreciable cracking but with little or no ravelling of the cracks should not be considered as being any better than a granular base (see para 7.8.3). Again, if the crack pattern along the wheel tracks is extensive and well defined with ravelling along the cracks, the surfacing should not be considered as being any better than a granular sub base (see para 7.8.4), or it should be removed before overlaying.

(v) Structural failure resulting from shear failure within unbound base and sub-base layers or within the subgrade can lead to substantial decreases in the in situ CBR values of the layers. Ideally a failed base should be regraded and recompacted but this will be difficult if there is a thick layer of bituminous materials overlying it. Recompaction of sub-bases and the subgrade will only be possible if the pavement is completely reconstructed. The alternative to recompaction is to do in situ CBR tests in the failed and unfailed areas and then use the lowest results for overlay design. This would normally lead to the downgrading of granular bases and sub-base to sub-base and capping layer respectively and to a reduced CBR value being taken for the subgrade.

(vi) If subgrade shear failure is due to the reduced load bearing characteristics of a degraded bound base the structural value of the bound base will also need to be reconsidered. Depending on its density and grading, an aged and embrittled bituminous bound base will be reassessed as a granular base course or granular sub-base. An extensively cracked drylean concrete base will be worth little more then a granular sub-base.

(vii) When an underlying concrete slab has undergone extensive multiple cracking with subsequent shear failure of the subgrade the broken slabs should be equated to an equivalent thickness of lean concrete base. (See Table 18). As in (vi) above, the subgrade should also be reassessed.

*7.3.2. Estimating Residual Fatigue Life*

7.3.2.1 Records of aircraft use are essential for residual fatigue life calculations, and are very useful when designing pavement overlays where adjustments can be made to existing pavements thicknesses to allow for past fatigue. They are also helpful in assessing the classification of a pavement, since in conjunction with the pavement condition they provide a good indication of the integrity and strength of the pavement. The greater the previous use the more significant this factor becomes in the evaluation. Care should be taken to ensure that too great a reliance is not put on the evidence of a few movements.

7.3.2.2 If a pavement has been regularly used for several years by aircraft at or approaching its PCN it must be considered that a portion of the structural fatigue life has been used up. A mid/end of life appraisal of a pavement will indicate its remaining structural life. The first step is to evaluate the pavement. As explained in paragraph 7.3.1.2 condition factors for the most recent layers of construction need not be incorporated into a reverse design and generally condition factors for other layers should not be altered from those used for the previous strengthening design. The next step is to use the records of aircraft movements to assess the past fatigue, in terms of an aircraft with an ACN equal to the PCN of the pavement. The procedures for mixed traffic analysis detailed in Chapter 4 should be used for this purpose. The residual fatigue life is the difference between the design Coverage level for the evaluation and the equivalent number of Coverages by the aircraft to date (see Example 7.9).

## 7.4 EVALUATION BY REVERSE DESIGN

### *7.4.1. Procedure*

7.4.1.1 Where an existing pavement can be equated to one of the standard constructions in Chapters 5 and 6 reverse design is carried out using the design Charts 1-8. For existing flexible pavements equating to the standard construction described in Chapter 6 but with Type F DLC Chart 7 can be used in the same way as Chart 5 (para 7.4.2.8). In other cases use Charts 5, 7 and 8 as described in Section 7.6 and 7.7. The subgrade strength, pavement thickness, material properties and the relevant frequency of trafficking are determined and then entered on the charts to give the ACN of the Design Aircraft. The ACN is then modified to allow for the difference between the actual subgrade strength and one of the standard subgrade categories in the ACN-PCN method.

7.4.1.2 If the pavement construction is not similar to one of those shown on the relevant Charts then equivalency factors are used to convert materials in the actual pavement to an equivalent thickness of one of the standard materials assumed in the Charts. The methods of equating various types and combinations of construction to an appropriate type covered by the Charts are set out in and, Figure 29 and Figure 30. The procedures for converting composite and multiple slab constructions to equivalent standard ones are set out in Sections 7.9 and 7.10.

7.4.1.3 Pavement condition is dealt with either by using residual life calculations to allow for past fatigue and give an equivalent pavement thickness (see Example 7.9) or, in the case of concrete slabs, by using 'Condition Factors' as set out in Table 18. An explanation of determining Condition Factors and when Condition Factors should be used is given in section 7.3.

### *7.4.2. Pavement Constructions*

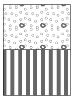
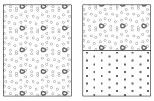
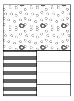
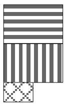
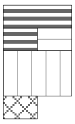
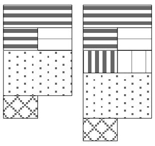
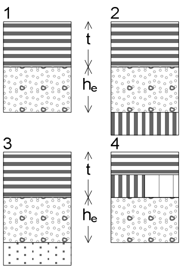
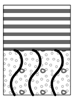
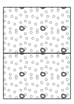
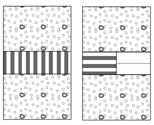
7.4.2.1 Many existing pavements may not directly correspond with the construction assumed for the design charts. Techniques for dealing with them are described below.

7.4.2.2 Subgrade improvement: Capping layers under flexible pavements and granular sub-bases under rigid pavements are allowed for by calculating an effective subgrade strength using the techniques described in Chapter 3. For capping layers, evaluation will be an iterative process as it is first necessary to estimate the ACN of the Design Aircraft from which an effective CBR at the formation is calculated. The effective subgrade strength is the value entered on the charts.

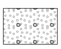
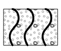
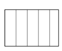
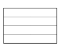
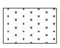
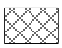
7.4.2.3 Cement-stabilised soils: Cement-stabilised soils under rigid pavements should be converted to an equivalent thickness of drylean concrete (see para 5.4.5 and Figure 26). In flexible pavements cement-stabilised gravels and crushed rock can be treated as a bound base material (see para 6.3.4), otherwise cement-stabilised soils should be converted to an equivalent thickness of granular sub-base, using the equivalency factors given in Table 17, and Chart 8 for the evaluation.

7.4.2.4 Excess or deficiency of Type R DLC under rigid pavements: Reverse design using Charts 1-4 implies that a certain thickness of Type R DLC base exists for a given concrete slab thickness and subgrade strength. If this thickness does not exist in practice the drylean concrete thickness can be altered by converting PQC thickness to drylean concrete thickness or vice versa, using an equivalency factor for PQC to drylean concrete of 3. The maximum deficiency of drylean concrete is 100mm (i.e. not more than 33mm of PQC should be converted to drylean concrete) and the maximum excess is 50mm (i.e. not more than 50mm drylean concrete should be converted to PQC). Any additional thickness of drylean concrete should be ignored. If the PQC-drylean concrete conversion is insufficient to give the required thickness of drylean concrete the existing drylean concrete should be ignored.

**Table 14** Reverse design and overlay design procedures

| **Construction** | **Pavement Type** | **Procedure** | | **Chart (Example)** |
|---|---|---|---|---|
| | | **Reverse Design** | **Overlay Design** | |
|  | Rigid<br>(PQC on Type R DLC) | If base thickness greater or less than the design chart requirement para 7.4.2.4 | See Composite or Multiple Slab | Chart 1, 2, 3, 4<br>(7.1) |
|  | Rigid<br>(PQC on the subgrade or on an unbound sub-base) | Para 7.4.2.2<br>Section 7.6<br>Effective k on a granular sub-base para 3.8.4 | See Composite or Multiple Slab | Chart 6<br>(7.2) |
|  | Rigid<br>(PQC on a bituminous base) | Para 7.4.2.5. | Para 7.5.4 | Chart 1, 2, 3, 4 |
|  | Flexible<br>(100 mm Marshall Asphalt surfacing on Type FH DLC or Marshall Asphalt Bound Base Material, on an optional capping layer) | Para 7.4.1.1<br>*Capping layer* Para 7.4.2.2<br>Effective CBR on a capping layer para 3.8.2 | Para 7.5.2 | Chart 5<br>(7.4, 7.9) |
|  | Flexible<br>(100 mm Marshall Asphalt surfacing on Type F DLC or Bituminous Bound Base Material, on an optional capping layer) | Para 7.4.2.8<br>Section 7.7<br>*Capping layer* Para 7.4.2.2<br>Effective CBR on a capping layer para 3.8.2 | Para 7.5.2<br>Section 7.7 | Chart 7 |
|  | Flexible<br>(100 mm Marshall Asphalt surfacing on unbound granular base and sub-base, or a combination of Bound Base Material and unbound materials, on an optional capping layer) | Para 7.4.2.9,<br>Para 7.4.2.10<br>Section 7.8<br>*Capping layer* Para 7.4.2.2<br>Effective CBR on a capping layer para 3.8.2 | Para 7.5.2<br>Section 7.8 | Chart 8 |
| Case<br><br>$\beta = t / h_e$ | Composite<br>$\beta \leq 0.5$ Type 1<br>$\beta \geq 1$ Type 2<br>$0.5 < \beta < 1$ Type 3 | Para 7.4.2.11<br>Section 7.9 | Para 7.5.3<br>Section 7.9 | *Type 1*<br>Case 1, 3, 4 Chart 6<br>Case 2 Chart 1, 2, 3, 4<br>(7.3)<br>*Type 2*<br>Case 1, 2, 4 Chart 5 or 7<br>Case 3 Chart 8<br>(7.5)<br>*Type 3*<br>Case 1, 4 Chart 6, and 5 or 7<br>Case 2 Chart 1, 2, 3, 4, and 5 or 7<br>Case 3 Chart 6 and 8<br>(7.8) |
|  | Composite<br>(Crack and Seat) | Para 7.4.2.12 | Para 7.5.3.3 | Chart 5 |
|  | Rigid<br>(Multiple Slab) | Para 7.4.2.13<br>Section 7.10 | Para 7.5.5<br>Section 7.10 | Chart 1, 2, 3, 4, 6<br>(7.10) |
|  | Rigid<br>(Multiple Slab with cement-bound or bitumen-bound inter-layer) | Para 7.4.2.13<br>Section 7.10 | Para 7.5.5<br>Section 7.10 | Chart 1, 2, 3, 4, 6<br>(7.2) |

Key

| | | | | | | | |
|---|---|---|---|---|---|---|---|
|  | Pavement Quality Concrete |  | Crack and Seat |  | Type R or FH DLC or equivalent cement-bound base |  | Type F DLC or equivalent cement-bound base |
|  | Marshall Asphalt |  | Bituminous Bound Materials other then Marshall Asphalt |  | Granular base and / or sub-base |  | Granular fill beneath flexible pavements |

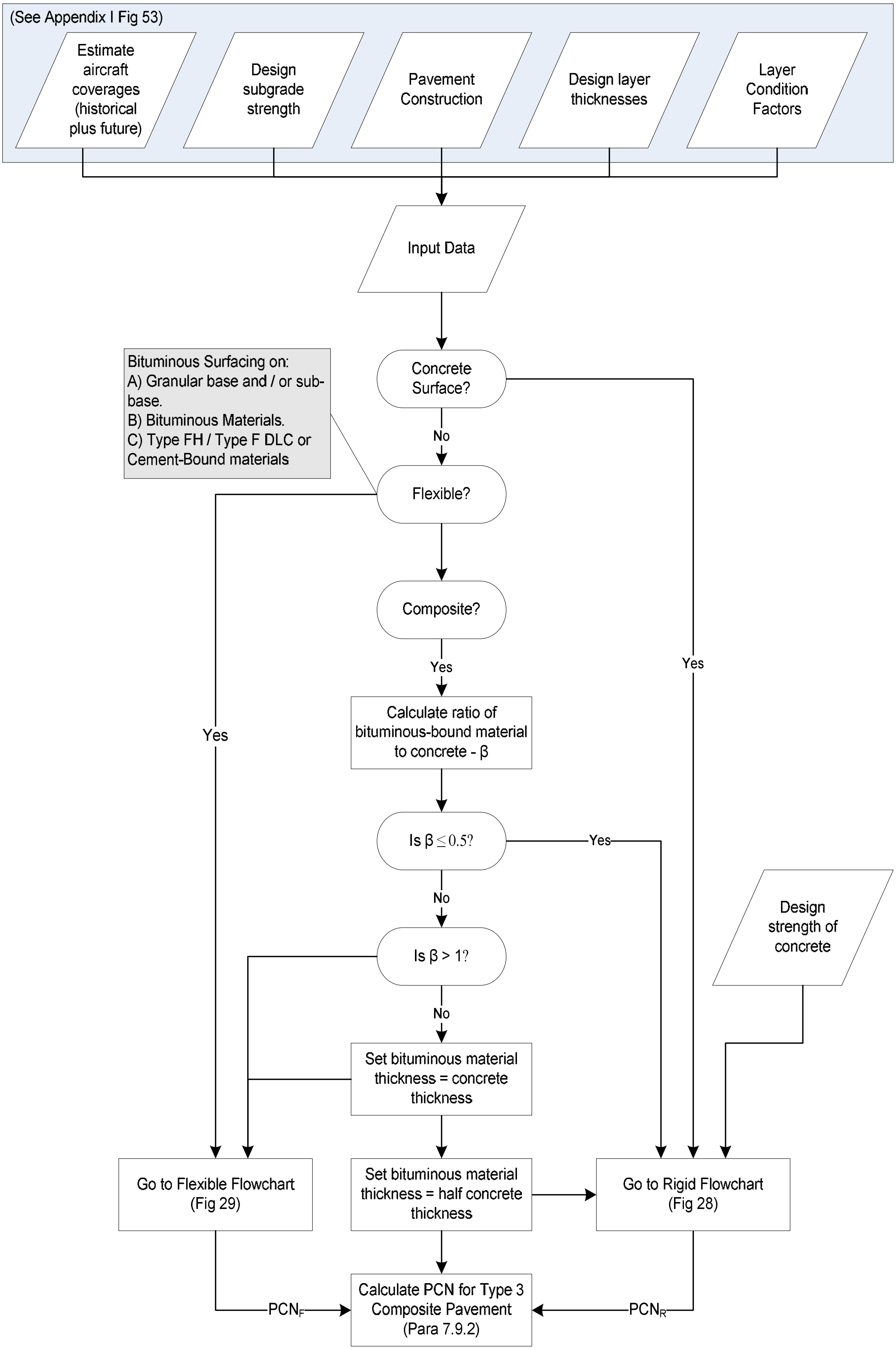



**Figure 28** Flow charts for the evaluation of airfield pavements

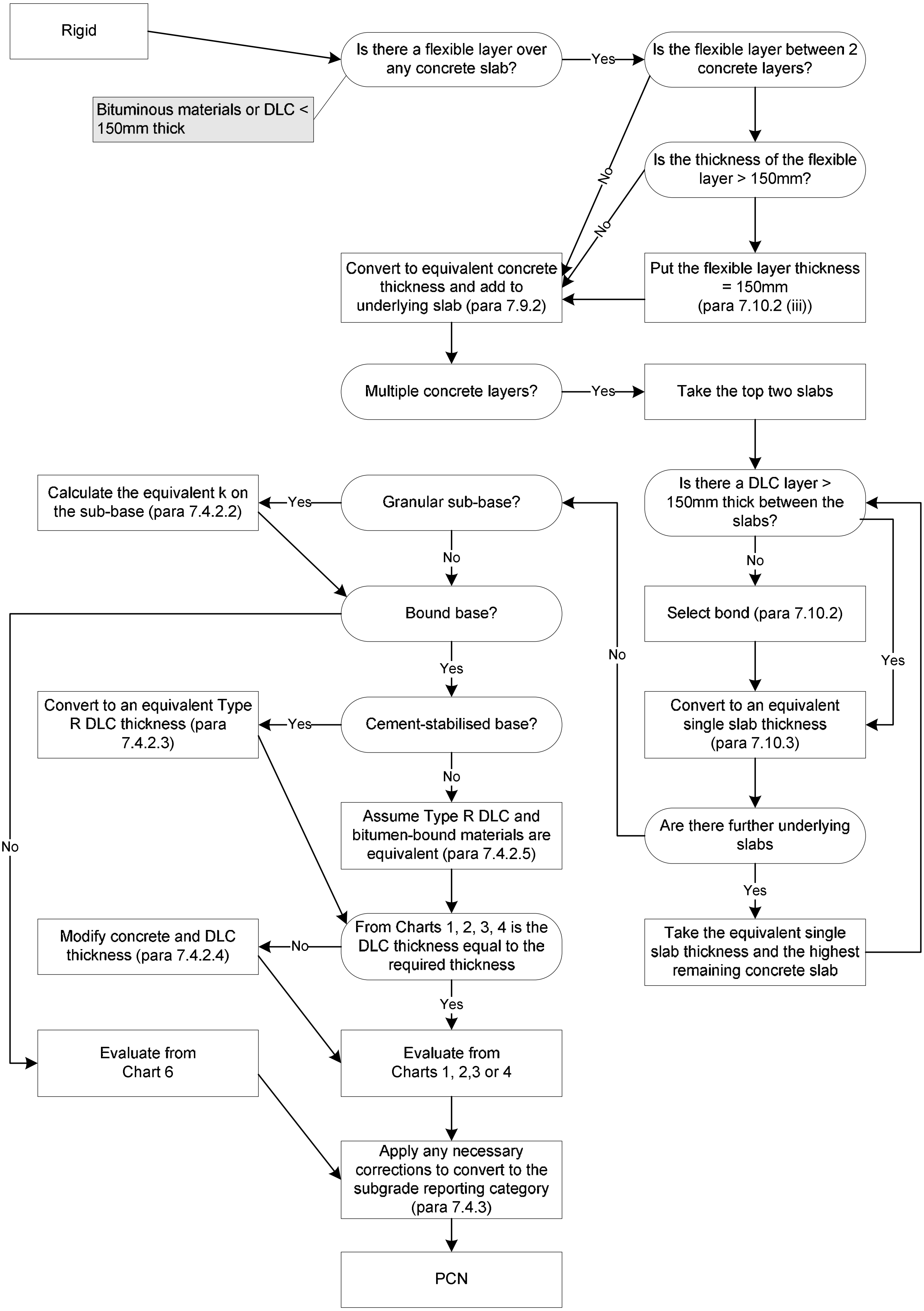



**Figure 29** Reverse design for rigid pavements

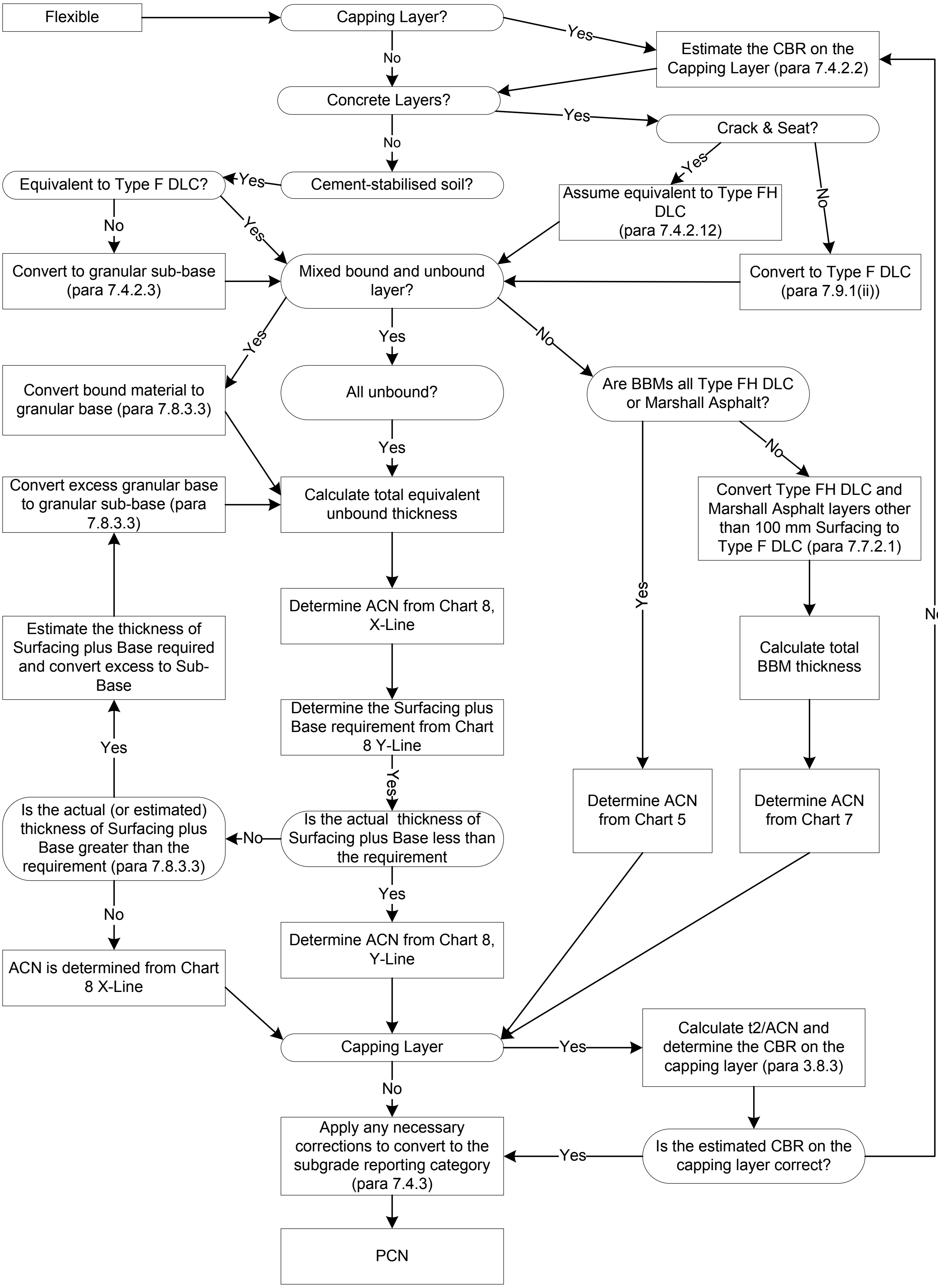



**Figure 30** Reverse design for flexible pavements

7.4.2.5 Rigid pavements with bituminous base layers: The bituminous base layers should be treated as Type R DLC.

7.4.2.6 Rigid pavements without a bound base: These pavements are evaluated using Chart 6, as described in Section 7.6.

7.4.2.7 Dowelled and/or reinforced concrete: For dowelled concrete pavements the slab should be treated as described in Sections 5.7 or 7.6 for rigid pavements with and without bound bases respectively. Jointed reinforced concrete pavements (see Section 5.8) should be taken as plain concrete. Continuously reinforced concrete pavements (see Section 5.9) are outside the scope of this guide and should be evaluated using the method by which they were originally designed.

7.4.2.8 Flexible pavements incorporating Type F DLC, as described in Appendix C: These should be evaluated using Chart 7 as described in Section 7.7.

7.4.2.9 Flexible pavements incorporating unbound granular bases and sub-bases: These pavements are evaluated using Chart 8, as described in Section 7.8.

7.4.2.10Mixed bound and unbound flexible constructions: The procedure for dealing with these constructions is set out in Section 7.8. Bound layers should be converted to unbound layers so that the strength at the top of the unbound layers is properly checked in the evaluation. Converting an unbound layer to a bound layer risks missing the possibility that the surface of the unbound layer is the critical point for the pavement strength.

7.4.2.11 Bituminous layers on concrete (including bituminous layers on thin drylean concrete regulating courses on concrete): These pavements are defined as composite and the techniques for evaluating them are described in Section 7.9. Thin drylean concrete regulating courses will crack and behave as a flexible material; they should therefore be included as part of the bituminous material thickness.

7.4.2.12 When an existing concrete slab has been or is to be treated by Crack and Seat techniques before overlaying the cracked concrete should be treated as Type FH DLC as described in Appendix C, and the pavement designed or evaluated using Chart 5.

7.4.2.13 Multiple slabs: Concrete slab on concrete slab, concrete on bituminous layers on concrete and concrete on drylean concrete on concrete are evaluated using the techniques described in Section 7.10.

7.4.2.14 Concrete Block Surfacing: The structural contribution of Concrete Block Surfacing is discussed in Section 6.2. Concrete Block Surfacing provides very little structural strength, in particular on strong bases, it should be considered as equivalent to no more than 50mm bituminous surfacing.

### *7.4.3. Determination of PCN*

The allowable ACN obtained from the Charts corresponds to the actual subgrade value. To establish a PCN several aircraft should be selected with ACNs at or near this value so that the ACN corresponding to the reported subgrade category can be interpolated. This is the reverse procedure to that described in Section 2.6 and Examples 2.1 and 2.2; it is shown in Example 7.3. If the allowable ACN is greater than that for any existing aircraft the ACN adjustment (to correspond with the reported subgrade category) will have to be based on a percentage increase or decrease determined from the aircraft with the closest ACN. If the subgrade strength is greater than that represented by CBR 15% for flexible pavements or k = 150MN/m$^2$/m for rigid pavements then the allowable ACN should be modified as described in Section 2.6 to give the PCN. The choice of the pavement type, i.e. rigid (R) of flexible (F), should be based on the chart used for the evaluation. If Charts 1 to 3 or 5 are used the pavement is classified as rigid; if Charts 4 or 6 are used the pavement is classified as flexible. Composite Pavements Type 3 (see para 0) should be categorised as flexible (F).

## 7.5 PAVEMENT STRENGTHENING (DESIGN OF OVERLAYS)

### *7.5.1. Procedure*

7.5.1.1 The procedure for establishing the strengthening requirements is as follows:

(i) The existing pavement is evaluated by reverse design (see Section 7.4).

(ii) The likely composition and mode of behaviour (i.e. rigid or flexible pavement incorporating a bound or unbound base) of the strengthened pavement is addressed and the appropriate design/evaluation chart is used to establish the full depth pavement required for the Design Aircraft; Table 14 can be used as a guide for selecting the appropriate design method and chart together with the procedures set out in paras 7.5.2 to 7.5.5.

(iii) The existing pavement evaluated in (i) above is assigned an equivalent structural value in terms of the new construction calculated in (ii) above. For composite pavements this necessitates using the semi-empirical equivalency factors given in Section 7.9. When an existing flexible pavement is to be overslabbed it can only be structurally equated to a rigid pavement base (see para 7.5.4).

(iv) If a flexible overlay is being provided the required thickness is given by the difference between (ii) and (iii) above. For a concrete overslab the thickness can be established using the method set out In para 7.5.4, or in the case of multiple slab construction from the empirical design method set out in para 7.5.5 and Section 7.10.

*7.5.2. Flexible Overlays on Existing Flexible Pavements*

7.5.2.1 The existing pavement is evaluated using the procedures described in Section 7.4.

7.5.2.2 If a renewed design life (see Section 4.5) is to be provided by the strengthening overlay an additional thickness of overlay is needed to allow for the reduced effective value of the existing pavement (see Example 7.9).

7.5.2.3 Where the existing construction is showing signs of impending failure or deterioration of any layer, its structural value is appropriately reduced below its original design value and a strengthening overlay provided to give a renewed design life. See para 7.3.1.6 for assessment of flexible pavement constructions which are showing signs of fatigue.

7.5.2.4 If the pavement is to be used by a Design Aircraft with an ACN greater than the PCN of the pavement the required construction is obtained from Chart 5 (see Chapter 6), Chart 7 or Chart 8 (see Sections 7.7 and 7.8), whichever is appropriate. The overlay requirement is then the shortfall in construction between the new requirement and the existing.

*7.5.3. Flexible Overlays on Existing Rigid Pavements*

7.5.3.1 Unless it is necessary to retain a surface with a high resistance to fuel spillage and jet blast strengthening of a rigid pavement will generally be more expediently and economically achieved by a flexible overlay, in spite of the problems of cracking of bituminous layers laid over unreinforced concrete. The thickness of the bituminous surfacing over existing unreinforced concrete should not in any case be less than 100mm. If the existing concrete is jointed early reflective cracking will occur at the transverse joints. For minimisation of reflection cracking the thickness of bituminous material over the DLC should be in accordance with Defence Estates Design & Maintenance Guide 33[52]. In apron areas, either concrete blocks or grouted macadam will give adequate resistance to fuel spillage and jet blast. However, as stated in Section 6.2 these surfacing materials are not yet fully proven.

7.5.3.2 Flexible overlays on existing rigid pavements are defined as composite pavement and are designed using the methods described in Section 7.9.

7.5.3.3 Numerous methods have been tried in attempts to control reflective cracking of existing joints and cracks in concrete pavements through flexible overlays[52]. The most effective technique has been found to be crack and seat, where the existing concrete slab is cracked at regular intervals to minimise movement and cracks and joints. Overlay design should be based on the recommendations of para 7.4.2.12. The specification and construction of crack and seat overlays is described in Reference 53. The discussion of design in the reference is superceded by this document.

*7.5.4. Overslabbing Existing Flexible Pavements*

7.5.4.1 The overslab design method considers the existing flexible pavement either as a bound base or simply an improved subgrade. When the existing pavement includes a good quality blacktop surfacing and bound base of adequate thickness and is in sound condition, it may be considered equivalent to a drylean concrete base; Chart 1, 2, 3 or 4 (see Chapter 5) may be used to design the overslab. Otherwise, the existing pavement should be equated to a granular sub-base.

7.5.4.2 If there is a difference in thickness between the actual bitumen/cement-bound flexible construction and the base requirements of Charts 1, 2, 3 or 4, the overslab thickness may be modified as described in para 7.4.2.3.

*7.5.5. Overslabbing Existing Rigid Pavements*

7.5.5.1 The basis of the design method is the multiple slab empirical design formula developed by the US Army Corps of Engineers[35] and described in Section 7.10.

7.5.5.2 The joint layout of the overslab should as far as possible correspond with that of existing slab unless the overslab is at least 1.25 x the thickness of the existing slab, or the existing slab is showing multiple cracking.

7.5.5.3 To allow for differential temperature effects the minimum top slab thickness for an unreinforced and undowelled slab should not be less than that given in Table 15.

**Table 15** Minimum Top Slab Thickness for a Multiple Slab Construction

| | Minimum top slab thickness (mm) | |
|---|---|---|
| ACN for k = 150 $MN/m^2/m$ | Low Frequency Trafficking | Medium Frequency Trafficking |
| >50 | 275 | 300 |
| 41-50 | 250 | 275 |
| 31-40 | 225 | 250 |
| 21-30 | 200 | 225 |
| 15-20 | 175 | 200 |
| 15 | 150 | 175 |

## 7.6 CONCRETE SLABS LAID ON THE SUBGRADE OR ON A GRANULAR SUB-BASE (DESIGN, REVERSE DESIGN AND OVERLAY DESIGN)

*7.6.1. General*

7.6.1.1 Chart 6 has been developed for the design or evaluation of PQC slabs founded on either a granular sub-base or directly onto the subgrade.

7.6.1.2 The same design model as that described in Appendix F for new reinforced, rigid pavement designs was used to produce Chart 6, except that the structural contribution of the lean concrete base was not included (i.e. no enhancement of subgrade support taken) and a reduced value of load transfer at transverse joints is adopted for slabs less than 300mm thick. The pavement designs have been linked directly to ACNs as described in Appendix F. The omission of a cement-bound base layer allows the three standard main wheel gear types (i.e. single, dual and dual-tandem (see Appendix D) to be included on one chart.

7.6.1.3 The improvement in the subgrade support provided by a granular sub-base can be assessed using Figure 10 (see Section 3.8).

*7.6.2. Use of Chart 6*

7.6.2.1 The use of design/evaluation Chart 6 requires the following parameters:

(i) Flexural strength of the concrete. This can either be established from construction records (28 day core strengths) or by tests on samples taken from the pavement (see para I8.5).

(ii) If the Chart is being used for evaluation purposes, the thickness of the concrete slab and granular sub-base (if any).

(iii) If Chart 6 is being used for design purposes the design ACN (see Section 2.6).

(iv) The Modulus of Subgrade Reaction k. Chapter 3 and Section 5.5 give details of subgrade characteristics. If subgrade improvement in accordance with Section 3.8 is to be allowed for, the increased k will be appropriate for design.

(v) The frequency of trafficking; either Low, Medium or High. Chapter 4 defines these traffic levels in terms of Coverages by the Design Aircraft. For equating the loading effects of different aircraft, see Chapter 4.

7.6.2.2 In addition to the above parameters the bay layout and the load transfer effectiveness of transverse joints also have a significant bearing on the future performance of the pavement. If it is suspected that load transfer is substantially below that assumed in the rigid pavement design model (see Appendix F) the evaluation will need to be done conservatively. For details of joints and spacing requirements see Section 5.3.

7.6.2.3 For slabs less than 300mm thick a fully dowelled pavement should provide a significantly greater load transfer than that assumed in the design model for Chart 6. Table 17 gives allowable reductions in the PQC thickness requirements of Chart 6 for fully dowelled slabs (i.e. dowelled expansion, construction and contraction joints).

**Table 16** Dowelled PQC Pavements on the Subgrade or on a Granular Sub-Base

| Chart 6 Design thickness of PQC (mm) | Allowable reduction in PQC thickness for fully dowelled slabs (mm) |
|---|---|
| 300 | 0 |
| 265 | 15 |
| 230 | 30 |
| 185 | 35 |
| The minimum slab thickness is 150mm | |

7.6.2.2 Having established the design parameters, Chart 6 is used in the same way as Charts 1 to 4 for design. The procedure for evaluation is as follows:

(i) Select the appropriate PQC thickness on the right hand ordinate.
(ii) Make a horizontal projection until it intersects the vertical projection of the appropriate k. From this intersection point trace a line parallel to the curves until it intersects the left-hand ordinate which is also the k = 20 line.
(iii) At the k = 20 line make a horizontal projection; this projection must be maintained.
(iv) Select the design frequency of trafficking (i.e. Low, Medium, High); for High Frequency of Trafficking see Section 5.10. Make a horizontal projection until it intersects the appropriate flexural strength.
(v) Make a vertical projection until it intersect the horizontal projection maintained from (iii) above. Read off the design ACN.

## 7.7 FLEXIBLE PAVEMENTS INCORPORATING TYPE F DLC (DESIGN, REVERSE DESIGN AND OVERLAY DESIGN)

### *7.7.1. General*

7.7.1.1 Chart 7 deals with the Department's pre 1989 specification for drylean concrete now designated Type F DLC as well as Hot rolled asphalt and Macadam bases and equivalent materials. Further details on material types is provided at Appendix C. Higher quality materials can be converted to Type F DLC using equivalency factors given in Table 17: this is for the purposes of evaluation of composite pavements (see Section 7.9 ) and multi-layer pavements incorporating combinations bituminous and/or Type F and HF DLC.

7.7.1.2 When used for design, the thickness of bituminous material (including the 100mm surfacing) over the DLC should not be less than one third of the total thickness of the bound pavement materials, as described in para 6.3.7, unless special measures are taken to control reflective cracking, e.g. the use of geotextiles or crack and seat techniques, as described in Defence Estates Design & Maintenance Guide 33[52].

*7.7.2. Use of Chart 7*

7.7.2.1 Chart 7 has been prepared for single, dual, dual-tandem and tridem main wheel gears; see Appendix D for the definition of these gear types. The use of the Chart requires three design parameters:

(i) If Chart 7 is being used for evaluation purposes – the thickness of the surfacing, and BBM. The thickness of BBM entered into the chart should be the total thickness of surfacing plus BBM minus a standard 100 mm allowance for surfacing.

(ii) If Chart 7 is being used for design purposes, the design ACN (see Section 2.6).

(iii) The CBR of the subgrade. See Chapter 3 and Section 6.4 for details of subgrade characteristics. If subgrade improvement in accordance with Section 3.8 is to be allowed for, the increased CBR value will be the appropriate design value.

(iv) The frequency of trafficking – either Low, Medium or High. Chapter 4 defines these traffic levels in terms of Coverages by the Design Aircraft. For equating the loading effects of different aircraft see Chapter 4.

7.7.2.2 Having established the above parameters, the following sets out the procedure for use of Chart 7 for pavement evaluation:

(i) Select the appropriate BBM thickness and trace a line parallel to the curves until it intersects the vertical projection of the appropriate subgrade CBR.

(ii) From the intersection point make a horizontal projection. Read off the design ACN at the relevant trafficking level.

When designing pavements use Chart 7 in the same way as Chart 5

## 7.8 FLEXIBLE PAVEMENTS INCORPORATING A GRANULAR BASE AND/OR SUB-BASE DESIGN, REVERSE DESIGN AND OVERLAY DESIGN)

*7.8.1. General*

7.8.1.1 Chart 8 has been developed for the design or evaluation of flexible pavements incorporating granular bases and/or sub-bases.

7.8.1.2 The same design model as that described in Appendix F for new flexible pavements was used to produce Chart 8, except that the Equivalency Factors for bound base materials were omitted. Figure 31 sets out the pavement construction for use with Chart 8. To enable various other combinations of construction to be considered in the design evaluation, Table 17 sets out Equivalency Factors relating the structural value of a granular base and sub-base as given by Chart 8 to that of cement and bitumen-bound materials; see para 7.8.3.3 for the application of Equivalency Factors. The Equivalency Factors for materials are related to a number of parameters, including the quality of materials, the subgrade strength, the thickness of construction and the magnitude of the loading. Consequently they vary particularly with regard to the sub-base. They have largely developed from studies of full scale tests and are set out in Table 18 in relation to subgrade CBR. For practical design purposes the Equivalency Factors can be linearly interpolated for intermediate subgrade CBRs.

*7.8.2. Bituminous Surfacing*

7.8.2.1 A minimum thickness of 100mm is necessary to comply with the requirements set out in Section 6.2. Pavements designed for regular use by aircraft with an ACN greater than 50 should have a minimum surfacing thickness of 125mm if constructed on a granular base. This is to prevent early fatigue cracking being developed in the surfacing by high wheel load deflections on a granular base. The additional 25mm thickness can, in these circumstances, be subtracted from the granular base requirement.

**Table 17** Equivalency Factors for Base and Sub-base Materials

| Material | Structural Equivalency Factor to apply to Chart 8 requirements | | | |
|---|---|---|---|---|
| | Base | Sub-Base | | |
| | | Subgrade CBR | | |
| | | 3% | 10% | 20% |
| Granular Sub-base | - | 1.0 | 1.0 | 1.0 |
| Granular Base | 1.0 | 2.0 | 1.5 | 1.0 |
| Marshall Asphalt Surface and Base Course | 1.5 | 3.0 | 2.3 | 1.5 |
| Other Bituminous Materials | 1.15 | 2.3 | 1.75 | 1.15 |
| Type FH DLC (see Appendix C) | 1.5 | 3.0 | 2.3 | 1.5 |
| Type F DLC (see Appendix C) | 1.15 | 2.3 | 1.75 | 1.15 |
| Cement stabilised fine grained material with a minimum compressive cube strength of 4 N/mm$^2$ at 7 days | - | 1.0 | 1.0 | 1.0 |

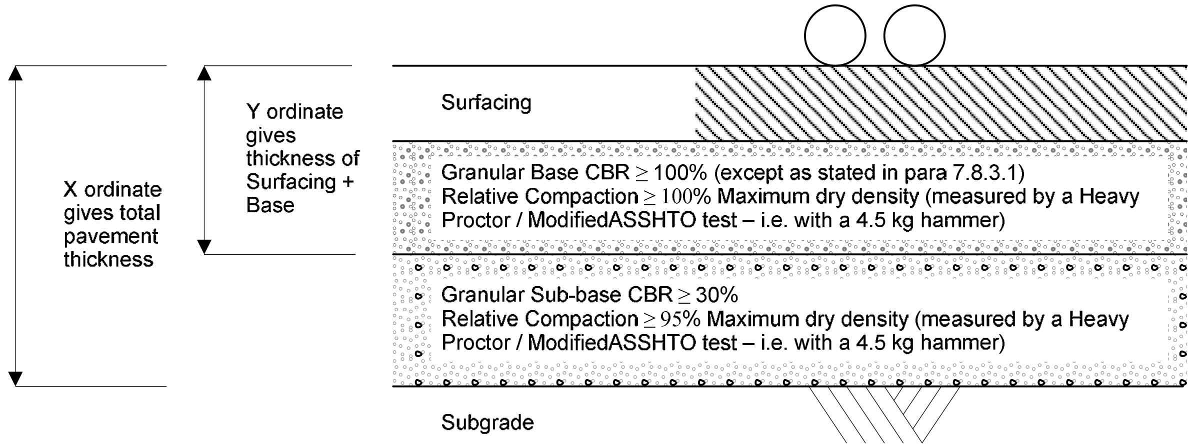



**Figure 31** Pavement design and thickness requirements for Chart 8

### *7.8.3. Granular Base*

7.8.3.1 The base thickness requirement on Chart 8 relates to the granular base material shown in Figure 31. For medium/low severity loading (i.e. nominally less than ACN 30) the granular base requirements can be reduced to CBR 80%.

7.8.3.2 In circumstances where long-term use has shown good performance of a different type of base material to those listed in Table 17, the engineer may assess it as being structurally equivalent to the standard granular base. Some base materials in overseas locations have good self-cementing properties including limestone, coral and certain laterites and may well give adequate performance particularly in respect of medium/low severity loading (i.e. nominally less than ACN 30). Field performance of cement-stabilised fine-grained material may also indicate structural equivalency as a pavement base at this level of loading. However, as explained in Section 6.3 it is unlikely that this type of construction will provide long-term load-spreading characteristics equivalent to the base construction listed in Table 17.

7.8.3.3 If, in addition to granular base and/or sub-base, the pavement contains a bound base material (see Sections 6.3 and 7.7) the material should be converted to an equivalent thickness of granular base using the equivalency factors given in Table 17. If when the first stage of the evaluation is complete there is found to be an excess of granular base, some of the excess can be converted to granular sub-base, using the equivalency factors given in Table 17; this will give a new total thickness and surfacing plus base course thickness. This process is repeated until the surfacing plus base thickness is equal to that required for the critical ACN obtained from the total thickness (see Example 7.7).

*7.8.4. Granular Sub-base*

7.8.4.1 The sub-base thickness requirement on Chart 8 relates to the granular sub-base material shown in Figure 31. For granular sub-bases with CBRs between 20% and 30% see para 7.8.5.2. vi. Materials less than CBR 20% should not be considered as a sub-base.

*7.8.5. Use of Chart 8*

7.8.5.1 Chart 8 has been prepared for the three standard main wheel gear types i.e. single, dual and dual-tandem (see Appendix D) and the constructions are linked directly to ACNs as described in Appendix F. The use of Chart 8 requires the following parameters:

(i) If Chart 8 is being used for evaluation purposes – the thickness of the surfacing, base and sub-base.

(ii) If Chart 8 is being used for design purposes, the design ACN (see Section 2.6).

(iii) The CBR of the subgrade. See Chapter 3 and Section 6.4 for details of subgrade characteristics. If subgrade improvement in accordance with Section 3.8 is to be allowed for, the increased CBR value will be the appropriate design value.

(iv) The frequency of trafficking – either Low, Medium or High. Chapter 4 defines these traffic levels in terms of Coverages by the Design Aircraft. For equating the loading effects of different aircraft see Chapter 4.

7.8.5.2 Having established the above parameters, the following sets out the procedure for use of Chart 8 for pavement evaluation:

(i) Select the appropriate total pavement thickness on the X ordinate and trace a line parallel to the unbroken line curves until it intersects the vertical projection of the appropriate subgrade CBR.

(ii) From the intersection point make a horizontal projection. Read off the design ACN at the relevant trafficking level.

(iii) Check the base thickness required for this classification. Retrace the horizontal projection to the ACN in (ii) until it again intersects the vertical projection of the appropriate subgrade CBR.

(iv) From the intersection point trace a line parallel to the *broken line* curves until it intersects the Y ordinate. The minimum combined thickness of surfacing and base required can then be read off.

(v) If the required thickness of base an surfacing is greater than the actual thickness in the pavement then the PCN will be limited by the thickness of the base. If the actual thickness of the base and surfacing is greater than the required thickness, the excess thickness can be converted to granular sub-base using the equivalency factors given in Table 17. This will give an equivalent total pavement thickness which can be re-entered on the X-Axis.

(vi) If the sub-base is between CBR 20% and 30% the base thickness requirement is greater than that determined in (iv) and can be derived from the Chart by the following method. From (ii) retrace the horizontal projection to the ACN and project it across until it intersects the X ordinate. The X ordinate then represents the combined thickness of surfacing and base required above the sub-base.

7.8.5.3 When designing pavements use Chart 8 in the same way as Chart 5; except that, having drawn a horizontal line through the design ACN to meet the subgrade CBR line, follow both the continuous and dotted curves to obtain the total thickness and surfacing plus base thickness from the X and Y axes respectively. Obtain the sub-base thickness by subtracting one from the other.

## 7.9 COMPOSITE PAVEMENTS – REVERSE DESIGN AND STRENGTHENING

### *7.9.1. General*

7.9.1.1 Pavements comprised of flexible overlays on concrete slabs are termed composite. The methods for designing and evaluating these pavements depend on how they behave, and in particular the form of their failure. When viewed in this way composite pavements, other than those using crack and seat techniques to minimise reflective cracking (para 7.5.3.3), can be divided into three types:

(i) Type 1: Composite pavements with relatively thin flexible overlays.

In this case reflective cracking of structural cracks in the underlying concrete will lead to the failure mechanism described in Appendix F. From long-term performance of pavements, Equivalency Factors have been obtained to convert the thickness of flexible overlay to an equivalent concrete thickness. The pavement is then treated as rigid.

(ii) Type 2: Composite pavements with relatively thick flexible overlays.

In this case reflective cracking is delayed sufficiently for a considerable amount of structural cracking to occur in the concrete slab, leading to a transfer of the load to the subgrade and eventual failure by subgrade shear, as described in Appendix F. From long-term performance of pavements, Equivalency Factors have been obtained to convert the thickness of the concrete slab to an equivalent thickness of bound base material which is added to the thickness of the overlying flexible overlay. The pavement is then treated as flexible and Charts 7 or 8 should be used for reverse design and strengthening.

(iii) Type 3: Composite pavement with overlays which fall between Types 1 and 2 above.

In this situation the pavement cannot be defined as rigid or flexible and there is no clear cut failure criterion. The evaluated strength of these pavements is found by interpolating between rigid and flexible strengths calculated for nominal constructions conforming to Types 1 and 2 above.

7.9.1.2 Type 1 and 3 composite pavements are likely to suffer from reflective cracking from the joints in the concrete slab before structural cracking of the slab occurs. Techniques for controlling reflective cracking when designing flexible overlays of concrete slabs are described in Defence Estates Design & Maintenance Guide 33[52]

7.9.1.3 Reverse design and overlay design for composite pavements using crack and seat techniques to minimise reflective cracking is described in para 7.5.3.3.

*7.9.2. Reverse Design of Composite Pavements*

The following formulae should be used for evaluating composite pavements:

(i) Type 1 If $\beta \leq 0.5$

$$h_c = C_t h_e + \frac{t}{1.8}$$

(ii) Type 2 If $\beta \geq 1$

$$h_f = t + 1.8 C_t h_e + b_e$$

(iii) Type 3 If $0.5 < \beta < 1$

$$PCN = PCN_R + (PCN_F - PCN_R)(2\beta - 1)$$

where $\beta$ = **t/h**$_e$
**h**$_e$ = thickness of existing concrete slab
**h**$_c$ = equivalent concrete thickness
**h**$_f$ = equivalent thickness of flexible pavement (surfacing plus bound base material)
**t** = thickness of bituminous surfacing
**b**$_e$ = thickness of existing bound base, if any
**PCN**$_R$ = PCN of nominal Type 1 Composite pavement with $\beta = 0.5$.
**PCN**$_F$ = PCN of a nominal Type 2 Composite Pavement with $\beta = 1.0$
**C**$_t$ = Condition Factor (see Table 18)

NB: If **C**$_t$<0.85 and $\beta$<1 then reliable performance of the pavement cannot be guaranteed and measures should be taken to increase the overlay thickness.

*7.9.3. Overlay Designs for Composite Pavements*

The following formulae should be used for designing flexible overlays to concrete pavements, producing a composite pavement.

(i) If the overlay thickness is less than or equal to half the concrete thickness

$$t = 1.8(h_c - C_t h_e)$$

(ii) If the overlay thickness is greater than or equal to the concrete thickness

$$t = h_f - 1.8 C_t h_e - b_e$$

(iii) If the overlay thickness is greater than half and less than one times the concrete thickness

$$\beta = \left( \frac{PCN_P - PCN_R}{PCN_F - PCN_R} + 1 \right) \times \frac{1}{2}$$

and $t = h_e \beta$

where **t** = bituminous overlay thickness required

**h**$_e$ = thickness of existing concrete slab

**b**$_e$ = thickness of existing bound base, if any

**h**$_c$ = concrete slab thickness required for the design

**h**$_f$ =total flexible pavement thickness (surfacing plus bound base material) required for the design

**PCN**$_R$ = PCN of a nominal Type 1 composite pavement with an overlay thickness equal to half the concrete thickness

**PCN**$_F$ = PCN of a nominal Type 2 composite pavement with an overlay thickness equal to the concrete thickness

**PCN**$_P$ = Design ACN for the strengthened pavement

**C**$_t$ = Condition Factor (see Table 18)

NB: If the value of $C_t$ is less than 0.85 then the concrete should be converted to an equal thickness of drylean concrete, and an overlay at least equal to the concrete thickness applied to ensure reliable performance.

## 7.10 MULTIPLE SLAB PAVEMENTS – REVERSE DESIGN AND STRENGTHENING

7.10.1. Pavements comprised of two or more successive concrete slabs are termed multiple slab pavements. These pavements are designed or evaluated using the empirical formula developed from full scale testing by the US Army Corps of Engineers[28]. The formula can be expressed in the form

$$h_r = \sqrt[n]{C_1 h_1{}^n + C_2 h_2{}^n}$$

where **$h_r$** is an equivalent single slab thickness
**$h_1$**,**$h_2$** are the component slab thicknesses
**n** is a factor depending upon the bond between the layers
**$C_1$**,**$C_2$** are condition factors

7.10.2. Three conditions of bond are used:

(i) Fully bonded: by very careful preparation of the existing surface the two concrete layers are bonded together and behave as a monolithic slab. This form of construction should only be used if the existing surface is in good condition.

(ii) Partially bonded: the two slabs are place on top of each other with no attempt at producing a bond between layers, although some shear transfer is achieved at the interface through friction and mechanical interlock. The Defence Estates normally places a membrane between the layers; the value of **n** given below for partially bonded slabs is based on analysis of the long-term performance of this type of construction.

(iii) Unbonded: in some situations it may be necessary to use a layer of regulating material between the two slabs. When separated in this way the slabs will act more independently of each other than in the partially bonded case. Regulating courses of bituminous material or bituminous materials on thin cement-bound or drylean concrete layers less than 150mm thick can be accounted for the evaluation by converting them to an equivalent concrete thickness. This thickness should be added to the thickness of the underlying slab using the composite pavement equation shown in para 7.9.2 (I). The maximum amount of material assessed in this way should be 150mm; anything in excess of this is to be ignored. Techniques for dealing with thick drylean concrete regulating courses are given in para 7.10.3. As the thickness of a bituminous regulating course increases, the behaviour of the top slab will be increasingly governed by elastic deflections of the bituminous materials, reducing the effect of the lower slab. Therefore as much as possible of a thick regulating course should be in cement-bound materials.

*7.10.3. Reverse Design of Multiple Slab Pavements*

The following formulae should be used for evaluating multiple slab pavements.

(i) $$h_r = \sqrt[n]{C_1 h_1^{\,n} + C_2 h_2^{n}}$$

(ii) for multiple slab construction containing a drylean concrete regulating course greater than 150mm thick.

$$h_r = \sqrt[1.6]{C_1 h_1^{\,1.6} + \left(\frac{h_d}{1.8}\right)^{1.6} + C_2 h_2^{1.6}}$$

where **$h_r$** = equivalent slab thickness

$h_1$, $h_2$ = top and bottom slab thickness

**$C_1$, $C_2$** are the condition factors (see Table 18)

NB **$C_1$** will only be required if the evaluation is being carried out as part of an overlay design (see para 7.3.1.3)

n = 1.0 for a fully bonded pavement

n = 1.6 for a partially bonded pavement

n = 2.0 for an unbonded pavement

**$h_d$** = thickness of drylean concrete.

*7.10.4. Overlay Design for Multiple Slab Pavements*

The following formulae should be used for the design of an overslab to an existing concrete pavement.

(i) $$h_o = \sqrt[n]{h_c^n - C_2 h_e^n}$$

(ii) for a multiple slab construction containing a drylean concrete regulating course greater than 150mm thick

$$h_o = \sqrt[1.6]{h_c^{1.6} - \left(\frac{h_d}{1.8}\right)^{1.6} - C_2 h_e^{1.6}}$$

where **$h_0$** = thickness of overslab required

**$h_c$** = thickness of a single concrete slab required for the design

**$h_e$** = thickness of the existing concrete slab

**$h_d$** = thickness of a drylean concrete regulating course

**$C_2$** = condition factor (see Table 18)

**n** = 1.0 for a fully bonded pavement

**n** = 1.6 for a partially bonded pavement

**n** = 2.0 for an unbonded pavement.

7.10.5. If the top slab is thicker than the underlying one, the formulae given above may be conservative and evaluations or overlay designs should be checked by assuming k = 150MN/m$^2$/m on the surface of the bottom slab and then using Chart 8.

**Table 18** Condition Factors for Concrete Slabs

| Conditions of concrete bays in the wheel track area | Condition Factors | |
|---|---|---|
| | $C_t$ | $C_i$ |
| a) No more than a few cracks | 1.0 | 1.0 |
| b) 30%-50% contain halving, quartering or delta cracks | 0.85 | 0.75 |
| c) Virtually all cracked with 30%-50% containing corner cracks or having cracked into 5 or more pieces | DLC N/A | DLC N/A |
| d) Many with multiple cracking and some deformation | Gbc N/A | Gbc N/A |

Abbreviations: DLC = equate to drylean concrete
Gbc = equate to granular base course
N/A = formulae in Section 7.9 are not applicable
NB: i = 1, 2 etc see para 7.10.1

## 7.11 EVALUATION OF HANGAR FLOORS

7.11.1.1The rigid design model and the Charts include a factor for the effects of temperature-induced stresses. However, in hangar floors, the full effects of the temperature range are not often experienced, and thus evaluation based on Charts 1, 2, 3, 4 or 6 will underestimate the bearing strength of the floors. For existing hangar floors where the normal daily temperature range is 50% (or less) of that for the external pavements, the PCN obtained from the charts may be factored by:

(i) 1.5 for Low Frequency Trafficking
(ii) 1.2 for Medium Frequency Trafficking

if the aircraft use suggests that the evaluation without these factors is over-conservative.

## EVALUATION EXAMPLES

**Example 7.1** CONCRETE SLAB ON A ROLLED DRYLEAN CONCRETE BASE

**Guide Reference**

1. CONSTRUCTION:

   275mm Pavement Quality Concrete
   150mm Rolled Drylean Concrete.

2. USE: The runway end on a busy military airfield.

   MAIN USER AIRCRAFT: ACN – 16
   Main Wheel Gear – Single
   Tyre Pressure – 1.3 MPa
   Para 4.9.2, Table 7 — Pass-to-Coverage Ratio – 8

   MOVEMENTS: 75 Departures a day for about 350 days of the year.

   Para 4.7.3 — DESIGN LIFE: 30 years.

   FREQUENCY OF TRAFFICKING: Coverages = $\frac{75x30x350}{8} = 98438$

   Para 4.6.2, Table 5 — Take Medium Frequency Trafficking

3. SUBGRADE: A clay with k = 30MN/m$^2$/m, obtained from in situ testing.

Para 5.2.3

4. MATERIAL QUALITY: Concrete produced to Defence Estates' Specification. Assume the concrete flexural strength = 4.5N/mm$^2$ at 28 days

5. PAVEMENT TYPE: Rigid.

Chart 1

6. EVALUATION: PCN 33.

   k = 30 MN/m$^2$/m is not a standard subgrade reporting value and it may therefore be necessary to correct the PCN to an appropriate value for k.

   Para 2.4.2, Table 1 — In this case the reporting category is Low (k = 40MN/m$^2$/m) but the ACN for a single main wheel gear does not change with the subgrade support. (NB. Examination of published ACN data may show a variation of ACN with subgrade support for single wheels, but this is due to the difference between the actual tyre pressure and the standard ACN-PCN tyre pressure).

Para 2.4.2

7. CLASSIFICATION:

   a) Subgrade Category: Low (C).

   b) PCN: 33.

   c) Pavement Type: Rigid (R).

   d) Tyre Pressure Limitations: No limitations on a concrete surface (W).

   e) PCN 33/R/C/W/T.

**Example 7.2** MULTIPLE CONCRETE SLAB CONSTRUCTION

**Guide Reference**

1. CONSTRUCTION:

200mm Pavement Quality Concrete} Twin slab construction
200mm Pavement Quality Concrete} with a building paper separating membrane.
150mm average Rolled Drylean Concrete
150mm Concrete
300mm Granular Fill.

2. USE: A parallel taxiway on a busy military airfield with an expected use of 50,000 Coverages by dual and dual-tandem aircraft during a 30 year life i.e. Medium Frequency Trafficking.

3. SUBGRADE: Clay. k = 30 MN/m$^2$/m obtained from in situ testing.

4. MATERIAL QUALITY: The construction records for the twin slab show that the concrete strength was low. The 150mm concrete slab is wartime construction. Cores show that the mean flexural strength of the top slab is 4.7 N/mm$^2$. There are no visable cracks in the pavement surface.

5. PAVEMENT TYPE: Rigid.

6. EVALUATION:

Para 7.4.2.13 — (i) Convert the twin slab construction to an equivalent single slab.

Para 7.10.4

$$h_r = \sqrt[n]{C_1 h_1^n + C_2 h_2^n}$$

n = 1.6 for a twin slab with a separating membrane.
**C**$_1$ = 1.0 as the surface layer is considered as new.
**C**$_2$ = 1.0 for a slab in good condition.

Table 18

$$\sqrt[1.6]{1.0 \times 200^{1.6} + 1.0 \times 200^{1.6}} = 308\text{mm}$$

(ii) Convert the equivalent single top slab, DLC regulating course and bottom slab to an equivalent single thickness pavement.

From Para 7.10.4

$$h_r = \sqrt[1.6]{C_1 h_1^{1.6} + \left(\frac{h_d}{1.8}\right)^{1.6} + C_2 h_2^{1.6}}$$

It is conservative to assume that the wartime concrete slab has suffered some degree of cracking; take $C_2$ = 0.75.

Table 18

$$\sqrt[1.6]{1.0 \times 308^{1.6} + \left(\frac{150}{1.8}\right)^{1.6} + 0.75 \times 150^{1.6}} = 375\text{mm}$$

Para 7.4.2.2 — (iii) Calculate an effective k on the granular sub-base.

Para 3.8.4, Figure 10 — 300mm granular sub-base on k = 30MN/m$^2$/m gives 48MN/m$^2$/m.

(iv) Equivalent construction 375mm PQC on k = 48MN/m$^2$/m.

Chart 6 — (v) PCN 41.

Para 2.4.2 Table 2.1
Para 7.4.3

The standard subgrade category is Low (k = 40MN/m$^2$/m). Examination of a number of aircraft with an ACN close to 40 on a Rigid Low Subgrade (see below) shows that the change in ACN between k = 48MN/m$^2$/m and k = 40MN/m$^2$/m is less than 1.

| Aircraft type | All Up Mass (kg) | RIGID PAVEMENT SUBGRADES - MN/m$^2$/m | | | |
|---|---|---|---|---|---|
| | | High 150 | Medium 80 | Low 40 | Ultra Low 20 |
| | | ACN | | | |
| A318 | 68,400 | 36 | 38.4 | 40.6 | 42.5 |
| B737-500 | 60,800 | 36.4 | 38.4 | 40.2 | 41.7 |
| B757-200 | 116,100 | 30.7 | 36.8 | 43.4 | 49.3 |
| C130H | 79,379 | 35.8 | 38.6 | 41.6 | 44.5 |
| Embraer 190 | 47,790 | 41.8 | 42.2 | 42.6 | 42.9 |
| Nimrod MR Mk 2 | 83,461 | 31.9 | 36.2 | 40.4 | 44.1 |

Para 2.4.2

7. CLASSIFICATION

a) Subgrade Category: Low (C).

b) PCN: 41.

c) Pavement Type: Rigid (R).

d) Tyre Pressure Limitations: No limitations on a concrete surface (W).

e) PCN 41/R/C/W/T.

**Example 7.3** THIN FLEXIBLE OVERLAY ON A CONCRETE SLAB ON A THIN ROLLED DRYLEAN CONCRETE BASE

**Guide Reference**

1. CONSTRUCTION:

   40mm Hot Rolled Asphalt Surface Course
   60mm Macadam Binder Course
   300mm Pavement Quality Concrete
   100mm Rolled Drylean Concrete.

2. USE: A taxiway for dual-tandem aircraft. Expected use is less than 10,000 Coverages in a 20-year life, i.e. Low Frequency Trafficking.

3. SUBGRADE: Sand. k = 60MN/m$^2$/m from in situ testing.

4. MATERIAL QUALITY: Cores in the Pavement Quality Concrete at 20 years give a mean compressive strength of 56N/mm$^2$, and show a crushed rock aggregate. A conservative estimate of the flexural strength is 56/10 = 5.6N/mm$^2$. Take a 4.5N/mm$^2$ mean flexural strength at 28 days to allow for gain in strength with age. Concrete bay joints have reflected through the surfacing, but there is no sign of structural cracking.

Para 7.4.2.10
Para 7.9.2

5. PAVEMENT TYPE: Composite pavement where the ratio of the flexible overlay to the concrete thickness is less than 0.5 i.e Type 1.

6. EVALUATION:

Para 7.9.2

(i) $$h_c = C_t h_e + \frac{t}{1.8}$$

$$h_c = 1 \times 300 + \frac{100}{1.8} = 355$$

Chart 3

(ii) 355mm PQC on subgrade k = 60 MN/m$^2$/m requires 150mm DLC.

Para 7.4.2.4

(iii) Convert some of the PQC slab to DLC to make up the deficiency.

$$\frac{50}{3} = 17\text{mm}$$

Modified PQC thickness: 355-17 = 338mm.

(iv) Equivalent construction is 340mm PQC
150mm DLC.

Chart 3

PCN 70.

Para 2.4.2, Table 1

(v) Subgrade Category – Medium (k = 80 MN/m$^2$/m). For aircraft with dual-tandem main wheel gears the ACN varied considerably with the sub-grade strength. Consider a range of aircraft with an ACN close to 70 on k = 60.

Appendix B

| Aircraft | k80 (1) | k60 (2) | k40 (3) | $\frac{(1)}{(2)}$ |
|---|---|---|---|---|
| B747-200 | 56 | 61 | 67 | 0.92 |
| Concorde | 71 | 76 | 82 | 0.93 |
| DC10-30 | 53 | 58 | 64 | 0.91 |
| L1011-500 | 59 | 65 | 72 | 0.91 |
| | | | | 0.92 |

The ACN on k = 80 is approximately 0.92 times the ACN on k = 60

70 x 0.92 = 64

Para 2.4.2

7. CLASSIFICATION

Table 2.1

a) Subgrade Category: Medium (B).

b) PCN: 64.

c) Pavement Type: Rigid (R).

Para 6.2.4, Table 13

d) Tyre Pressure Limitations: X.

e) PCN 64/R/B/X/T.

**Example 7.4** ASPHALT ON TYPE F DRYLEAN CONCRETE

**Guide Reference**

1. CONSTRUCTION:

   40mm Marshall Asphalt Surface Course
   60mm Marshall Asphalt Binder Course
   37mm Hot Rolled Asphalt Surface Course
   63mm Macadam Base Course
   450mm Drylean Concrete.

2. USE: The main runway on a busy military airfleld, with the majority of movements by aircraft with single main wheel gears. 200,000 Coverages expected in a 20-year life, i.e. High Frequency Trafficking.

3. SUBGRADE: Clay. CBR 3%.

4. MATERIAL QUALITY: All materials to Defence Estates' Specification or one of its predecessors. Cores show the Drylean Concrete has a compressive strength of 11 N/mm$^2$; therefore take as Type F.

5. PAVEMENT TYPE: FLEXIBLE.

6. EVALUATION:

(i) Correct for High Frequency Trafficking (and use the Medium Frequency Trafficking line on the Chart).

Para 6.6.1

$$\text{Equivalent Thickness} = \frac{TotalThickness}{1.08} = \frac{650}{1.08} = 600$$

(ii) Equivalent Construction 100mm Surfacing
500mm Bound Base Material.

Chart 7

PCN 30.

CBR 3% is a standard subgrade category, so no correction is required to the PCN.

Para 2.4.2, Table 1

7. CLASSIFICATION:

a) Subgrade Category: Ultra Low (D).

b) PCN 30.

c) Pavement Type: Flexible (F).

Para 6.2.4, Table 13

d) Tyre Pressure Limitations: No limitations for Marshall Asphalt (W).

e) PCN 30/F/D/W/T.

**Example 7.5** FLEXIBLE OVERLAY ON A THIN CONCRETE SLAB

**Guide Reference**

1. CONSTRUCTION:
   40mm Hot Rolled Asphalt Surface Course
   60mm Macadam Base Course
   40mm Hot Rolled Asphalt Surface Course
   60mm Macadam Base Course
   25mm Asphalt Surface Course
   65mm Tarmacadam
   20mm Sand Asphalt.
   150mm Concrete

2. USE: Main taxiway of a provincial airport with an expected use of 10,000 Coverages by dual-tandem aircraft in a 20-year life, i.e. Low Frequency Trafficking.

3. SUBGRADE: A dense silty sand. CBR 10%.

4. MATERIAL QUALITY: Cores show that all the materials are in good condition.

   Inspection Reports produced before the first Hot Rolled Asphalt/Macadam Base Course overlay was placed indicate that considerable reflection cracking was present showing longitudinal, quartering and corner cracking in the underlying concrete.

Para 7.4.2.11
Para 7.9.2

5. TYPE: Composite pavement where the ratio of the flexible overlay to the concrete thickness is greater than 1 i.e. Type 2.

6. EVALUATION

Para 7.9.2

   (i) $h_f = t + 1.8 C_t h_e + b_e$

Table 18

   Take $\mathbf{C}_t$ = 0.85 because of evidence of structural cracking in the concrete.

   $h_f = 310 + 1.8 \times 0.85 \times 150 + 0 = 540\text{mm}$

   (ii) Equivalent Construction: 100mm Surfacing
   450mm Bound Base Material.

Chart 7

   PCN 68.

   CBR 10% is a standard subgrade category.

Para 2.4.2

7. CLASSIFICATION:

Table 1

   a) Subgrade Category: Medium (B).

   b) PCN 68.

   c) Pavement Type: Flexible (F).

Para 6.2.4 Table 13

   d) Tyre Pressure Limitations: X.

   e) PCN 68/F/B/X/T.

**Example 7.6** ASPHALT SURFACING ON A GRANULAR BASE AND SUB-BASE

**Guide Reference**

1. CONSTRUCTION:

   40mm Marshall Asphalt Surface Course
   60mm Marshall Asphalt Base Course
   250mm Granular Base
   650mm Granular Sub-base.

2. USE: Taxiway on a provincial airport. Expected use 10,000 Coverages by dual aircraft in a 20-year life, i.e. Low Frequency Trafficking.

3. SUBGRADE: Clay. CBR 4%.

4. MATERIAL QUALITY: Site investigation confirms that the granular materials have a grading and in situ density compatible with Defence Estates' Specifications for base and sub-base materials. There are no signs of rutting.

5. TYPE: FLEXIBLE.

Section 7.7, Chart 8

6. EVALUATION:

(i) Evaluate PCN from the total pavement thickness.
Total Pavement Thickness = 1000mm.
From X-Axis PCN = 48.

(ii) Check thickness of base plus surfacing.
From Y-Axis, PCN48 on CBR 4% requires 275mm of base plus surfacing, which compares with 350mm in the actual pavement.

(iii) Convert excess granular base to granular sub-base.
Estimate base + surfacing requirement as 275mm.
Excess Granular Base = $(250-(275-100)=75\text{mm}$.

Para 7.8.5.2v
Table 17

Equivalency Factor (by interpolation between the published values)

$$= 2.0 - \frac{(2.0-1.5)}{7} \times 1 = 1.93$$

Equivalent Thickness of Granular Sub-Base = $75 \times 1.93 = 145\text{mm}$.

Equivalent Construction
100mm Surfacing
175mm Granular Base
800mm Granular Sub-Base

Chart 8

(iv) If we round up to the nearest 100mm, i.e. total thickness of 1100mm, Chart 6 indicates a PCN greater than 50 and a base plus surfacing requirement of 275mm. However for a PCN greater than 50, 125mm of surfacing is required, therefore

Para 7.8.2.1

the PCN of the actual pavement is restricted to 50.

Para 2.4.2, Table 1

(v) The Standard Subgrade Category is Ultra Low (CBR 3%).
Consider a range of aircraft:

| Aircraft | ACN CBR 6% (1) | CBR 4% (2) | CBR 3% (3) | $\frac{(3)}{(2)}$ |
|---|---|---|---|---|
| A321-200 | 46.8 | 50.7 | 52.6 | 1.038 |
| B727-100 | 49.2 | 52.6 | 54.3 | 1.032 |
| B737-900 | 50.4 | 53.7 | 55.3 | 1.030 |
| MD90-30 | 49.5 | 51.6 | 52.6 | 1.020 |
| | | | | 1.03 |

The PCN on CBR 3% is approximately 1.04 times the PCN on CBR 4%.
50 x 1.03 = 51.

Para 2.4.2

7. CLASSIFICATION:

a) Subgrade Category: Ultra Low (D).

b) PCN: 51.

c) Pavement Type: Flexible (F).

Para 6.2.4, Table 13

d) Tyre Pressure Limitations: W.

e) PCN 51/F/D/W/T.

**Example 7.7** MIXED BOUND AND UNBOUND FLEXIBLE CONSTRUCTION (INCLUDING CAPPING LAYER)

**Guide Reference**

1. CONSTRUCTION:
   20mm Friction Course
   40mm Marshall Asphalt Surface Course
   60mm Marshall Asphalt Base Course
   650mm Type F Rolled Drylean Concrete
   300mm Granular Sub-base
   550mm Capping Layer.

2. AIRCRAFT USE: Main runway for an international airport. Expected use is equivalent to 100,000 Coverages by Boeing 767-200 in 20 years i.e. Medium Frequency Trafficking.

3. SUBGRADE: Silty Clay CBR 2%.

4. MATERIAL QUALITY: Asphalt, Rolled Drylean Concrete and Granular Sub-base are compatible with Defence Estates' Specification. The capping layer is a granular material with a minimum CBR of 15%.

5. PAVEMENT TYPE: FLEXIBLE

6. EVALUATION:

Para 6.2.1 — (i) The Friction Course is ignored.

Figure 7 Dual-Tandems — Determine Equivalency Factor for the Capping Layer. 1.3

Para 7.4.2.2 — (ii)

| | | | 1st Estimate | 2nd Estimate | | | |
|---|---|---|---|---|---|---|---|
| | | **Determine Design ACN** | | | | | |
| | a) | CBR on Capping | Estimate 3% | 3.5 | 3 | 3.5 | |
| Para 7.4.2.9 Para 7.8.1.2, Table 17 | b) | Calculate Equivalency Factor of BBM to Granular Base. | 1.15 | | | | |
| | | Calculate Equivalency Factor of Granular Base Course to Granular Sub-base | 2 | ((2-1.5)/(3-10))*(3.5-3)+2=1.96 | 2 | 1.96 | |
| Para 7.8.2.1 | d) | Surfacing Requirement. | 100 | | | | |
| | | | | | | | |
| Para 7.8.3.3 | e) | Convert BBM to Granular Base. | 650x1.15=750 | | | | |
| | | Convert Excess Granular Base Course to Granular Sub-base | 0 | (750-275)*1.96=930 | (750-375)*2=750 | (750-325)*1.96=830 | |
| | f) | Calculate Total Thickness (X). | 100+750+0+300=1150 | 100+275+930+300 | 100+375+750+300 | 100+325+830+ | |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| | | | | =1605 | =1525 | 300= 1555 | |
| Chart 8 X-line | g) | Determine Design ACN | 32 | 71 | 55 | 67 | |
| Chart 8 Y-line | h) | Determine required Surfacing and Base Thickness required. | 275 | 375 | 325 | | |
| | | **Check CBR on Capping Layer** | | | | | |
| | | Calculate Equivalent Thickness of Capping Layer as Granular Sub-base | 550/1.3=423 | | | | |
| | | Calculate $t^2$/ACN for the Capping Layer | $423^2$/32=5591 | $423^2$/71=2520 | $423^2$/55=3253 | | |
| | | Determine the CBR on the Capping Layer | 3.5 | 3 | 3.5 | | |
| | | | | | | | |
| | i) | Estimate thickness of Surfacing plus Base required | 350 | | | | |
| | | | | | | | |
| | j) | Convert Excess Base to Sub-base. | 1000 | | | | |

Para 7.4.2.9
Para 7.8.1.2, Table 17 — b) Calculate Equivalency Factor of BBM to Granular Base. 1.15

Para 7.8.1.2, Table 17 — c) Calculate Equivalency Factor of Granular Base to Sub-base. 2

Para 7.8.2.1 — d) Surfacing Requirement. 100

Para 7.8.3.3 — e) Convert BBM to Granular Base. 750

| | | 1st Estimate | 2nd Estimate |
|---|---|---|---|
| | f) Calculate Total Thickness. | 1150 | 1650 |
| Chart 8 X-line | g) Determine PCN. | 37 | 70 |
| Chart 8 Y-line | h) Determine Surfacing and Base Thickness required. | 275 | 350 |

i) Estimate thickness of Surfacing plus Base required.350

j) Convert Excess Base to Sub-base. 1000

k) Return to step (f).

(iii)Check the CBR on the Capping Layer.

Calculate Equivalent Thickness of Capping Layer as Granular Sub-base. 423

| | | |
|---|---|---|
| Figure 9 | Calculate $t^2$/ACN for the Capping Layer. | 2557 |
| | Determine the CBR on the Capping Layer. | 3% |

Para 2.4.2

7. CLASSIFICATION:

a) Subgrade Category: Ultra Low (D).

b) PCN: 70.

c) Pavement Type: Flexible (F).

Para 6.2.4, Table 13

d) Tyre Pressure Limitations: W.

e) PCN 70/F/D/W/T

(This pavement is likely to suffer from early and extensive reflection cracking form shrinkage cracks in the DLC base, and is not recommended for a new pavement. Further details are given in Defence Estates Design & Maintenance Guide 33[52])

**Example 7.8** FLEXIBLE OVERLAY ON CONCRETE WITH $0.5<\beta<1$

**Guide Reference**

1. CONSTRUCTION:
   40mm Hot Rolled Asphalt
   60mm Macadam Base Course
   37mm Hot Rolled Asphalt
   63mm Macadam Base Course
   225mm Pavement Quality Concrete.

2. USE: A Taxiway. The use is expected to be less than 10,000 Coverages by dual-tandem aircraft in a 20-year life, i.e. Low Frequency Trafficking.

Figure 32 — 3. SUBGRADE: A silty sand. CBR 10%/k = 50 $MN/m^2/m$.

4. MATERIAL QUALITY: All materials complied with Defence Estates' Specification. Concrete strength is 5.3 $N/mm^2$.

Para 7.4.2.10
Para 7.9.2 — 5. PAVEMENT TYPE: Composite pavement where the ratio of the flexible overlay to concrete thickness lies between 0.5 and 1 i.e. Type 3.

Para 7.9.2 — 6. EVALUATION:

(i) Evaluate an imaginary pavement with $\beta = 1$

Construction is 225mm Asphalt
225mm Concrete.

Para 7.9.2(ii)

$$\mathbf{h_f} = t + 1.8\,\mathbf{C_t h_e} + \mathbf{b_e} \qquad (\mathbf{b_e = 0})$$
$$= 225 + 1.8 \times 225 = 630$$

Equivalent Construction 100mm Surfacing
525mm Bound Base Material.

Chart 7 — $PCN_F = 95$

(ii) Evaluate an imaginary pavement with $\beta = 0.5$

Construction is 112mm Asphalt
225mm Concrete.

Para 7.9.2(i)

$$\mathbf{h_c} = \mathbf{C_t h_e} + \frac{t}{1.8}$$
$$= 1.0 \times 225 + 112/1.8 = 287$$

Equivalent Construction = 285mm PQC

Chart 6 — $PCN_{(R)} = 30$

(iii)Evaluate the final PCN of the actual construction.

Para 7.9.2

$$\beta = \frac{200}{225} = 0.89$$

Para 7.9.2(iii)

$$PCN = PCN_{(R)} + (PCN_f - PCN_{(R)})\,(2\beta-1)$$
$$= 30 + (95-30) \times 0.78$$
$$= 81.$$

Para 2.4.2

7. CLASSIFICATION:

a) Subgrade Category: Medium (B).
b) PCN: 81.
c) Pavement Type: Flexible (F). (Para 2.4.2)
d) Tyre Pressure Limitations: X. (Para 6.2.4, Table 13)
e) PCN 81 /F/B/X/T

(In determining the final overlay requirement the critical factor for the overlay requirement may be reflection cracking rather than structural strength. Further details are given in Defence Estates Design & Maintenance Guide 33[52])

## OVERLAY DESIGN EXAMPLES

**Example 7.9** FLEXIBLE OVERLAY ON AN EXISTING PAVEMENT

**Guide Reference**

1. REQUIREMENT: A taxiway currently carrying Boeing 727-200 and lighter aircraft is to be strengthened to take Boeing 747-100.

2. AIRCRAFT DATA:

Appendix B
Para 4.9.2, Table 6

a) ACN, Undercarriage Type and Pass-to Coverage Ratio.

| Aircraft Type | FLEXIBLE PAVEMENT SUBGRADES | | | | Main Wheel Gear | Pass-to-Coverage Ratio |
|---|---|---|---|---|---|---|
| | High | Medium | Low | Ultra Low | | |
| 747-100 | 44 | 48 | 58 | 78 | D-T | 1.6 |
| 727-200 | 40 | 42 | 48 | 53 | Dual | 3.2 |

3. AIRCRAFT USE: The existing pavement is 15 years old and had had an average use of 1200 departures per year by Boeing 727-200.

Para 4.9.1

Use to date = $\frac{15x1200}{3.2} = 5625$ coverages.

The expected future use is 500 departures a year by Boeing 747-100.

Para 4.7.3

4. DESIGN LIFE: 20 YEARS.

5. FREQUENCY OF TRAFFICKING:

Para 4.6.2, Table 5

a) For the evaluation of the existing pavement use Low Frequency Trafficking based on the use to date.

Para 4.7.3

b) For future use the optional coverages in a 20 year life are

$$\frac{20x500}{1.6} = 6250$$

Para 4.6.2, Table 5

i.e. Low Frequency Trafficking

6. EXISTING CONSTRUCTION:
   40mm Hot Rolled Asphalt Surface Course
   60mm Macadam Base Course
   425mm Type F Rolled Drylean Concrete.

7. SUBGRADE: CBR 6%.

8. MATERIAL QUALITY: The pavement materials are compatible with Defence Estates' Specification. Some rutting is present in small areas.

9. EVALUATION OF THE EXISTING PAVEMENT:
   100mm Surfacing
   425mm Bound Base Material.

Chart 7

PCN 50.

Para 7.3.2.2

The aircraft use to date equates to 5625 coverages by Boeing 727-200, which have an ACN of 48 on CBR 6%. The Equivalent Coverages on the actual pavement can be calculated as follows:

Figure 13

| | ACN/ PCN | ACN Ratio | FMTF | Modified FMTF | Coverages |
|---|---|---|---|---|---|
| Pavement | 50 | | | | |
| Boeing 727-200 | 48 | 0.96 | 0.92 | 0.88 | 4400 |

Since the evaluation is for Low Frequency Trafficking – nominally 10,000 coverages – the remaining life is 10,000-4,400 = 5,600 Coverages. if the pavement is to be overlaid to give a further 20 year life for a heavier aircraft the existing construction should be re-evaluated to find a lighter load which will allow a new 10,000 Coverage life. Therefore find a PCN which will allow a further 10,000 Coverages with an equivalent damaging effect to 5,600 Coverages at ACN 50.

Mixed Traffic Factor 10,000 Coverages = 1.0
Mixed Traffic Factor 5,600 Coverages = 0.91.

$$\text{ACN Ratio} = \frac{0.91}{1.0} = 0.91$$

PCN = 50 x 0.91 = 45

Chart 7

Equivalent Construction is 100mm Surfacing
400mm Bound Base Material

10. DESIGN REQUIREMENT FOR NEW LOADING

The design requirement is for Low Frequency Trafficking by Boeing 747-100.

(see also Example 4.2)

The ACN of the aircraft on a Flexible Low Subgrade is 58.

Chart 7

100mm Surfacing
500mm Bound Base Material

11. OVERLAY DESIGN

(i) The existing pavement is equivalent to a total of 500mm.

(ii) The new design requirement is for a total of 600mm.

Overlay requirement = 600-500 = 100mm.

Overlay with 100mm asphalt or equivalent materials.

(In determining the final overlay requirement the critical factor for the overlay requirement may be reflection cracking rather than structural strength. Further details are given in Defence Estates Design & Maintenance Guide 33[52])

**Example 7.10** RIGID OVERSLAB OF AN EXISTING RIGID PAVEMENT

**Guide Reference**

1. REQUIREMENT: An existing hardstanding is to be uprated to take dual wheel gear short/medium range transport aircraft, of which McDonnell-Douglas DC9-51 will be the most severe loading case.

2. AIRCRAFT DATA:

Appendix B

a) ACN

| Aircraft Type | RIGID PAVEMENT SUBGRADES | | | |
|---|---|---|---|---|
| | High | Medium | Low | Ultra Low |
| DC 9-51 | 35 | 37 | 39 | 40 |

Appendix B

b) Main Wheel Gear: Dual

Para 4.9.2, Table 6

c) Pass-to-Coverage Ratio: 3.2.

3. AIRCRAFT USE: The expected use is less than 10,000 Coverages by DC9-51 in 30 years, i.e. Low Frequency Trafficking.

Para 4.7.3

4. DESIGN LIFE: 30 years.

5. EXISTING CONSTRUCTION:
175mm Pavement Quality Concrete
300mm Granular Sub-base.

6. SUBGRADE: k = 40 $MN/m^{2/}/m$.

7. MATERIAL QUALITY: The concrete is of good quality and from the available information it is thought appropriate to use the 5.3 $N/mm^2$ line on Chart 6. A few of the existing bays have one or more corner cracks and about 30% of the bays have halved. There are no signs of differential settlement or mud-pumping.

8. EVALUATION: Only an estimate of the effect of the granular sub-base is needed.

Para 3.8.4. Figure 10

300mm of granular sub-base on k = 40 $MN/m^2/m$ gives an effective K of 60$MN/m^2/m$.

9. DESIGN REQUIREMENT FOR NEW LOADING:

The design requirement is for Low Frequency Trafficking by DC9-51. Design ACN = 38 (on k = 60$MN/m^2/m$).

Chart 6

325mm Pavement Quality Concrete

10. OVERLAY DESIGN

Para 7.10.4

$$\mathbf{h}_0 = \sqrt[n]{\mathbf{h}_c{}^n - \mathbf{C}_2\mathbf{h}_e{}^n}$$

The overslab will be laid on a polythene separating membrane, directly on the underlying slab; therefore n = 1.6.

Table 18

From the existing degree of cracking $\mathbf{C}_2$ = 0.75.

$$\mathbf{h}_0 = \sqrt[1.6]{325^{1.6} - 0.75x175^{1.6}}$$

$$= 265\text{mm PQC}$$

Overlay with 275mm PQC.

Para 7.10.4

NB.Chart 6 shows that if the existing construction is considered as a sub-base giving an effective k of 150 $MN/m^2/m$, the overlay requirement is also 275mm. If the existing slab was thinner, the method used above to calculate the overslab thickness becomes pessimistic and it is more economic to consider the existing construction as a good sub-base.

# 8 Overload and High Tyre Pressure Operations

## 8.1 OVERLOAD OPERATIONS

8.1.1. Individual aerodrome authorities are generally free to decide on their own criteria for permitting overload operations as long as pavements remain safe for use by aircraft. Unless severely overloaded, (e.g. an aircraft with an ACN four times greater than the PCN) it is most unlikely that a pavement will suddenly or catastrophically fail. Nevertheless regular overload can substantially reduce the design life of a pavement, resulting in high rehabilitation costs and the inconvenience of a main runway or taxiway out of action. The limiting criteria for overload must be somewhat arbitrary, representing a reasonable balance between operational flexibility and the need to avoid undue damage to pavements. On that basis the following guidance has been developed:

(i) A 10% difference in ACN over PCN involves an increase in pavement working stresses which is generally considered acceptable provided the following conditions are satisfied.

a. The pavement is more than 12 months old.
b. The pavement is not already showing signs of structural distress.
c. Overload operations do not exceed 5% of the annual departures and are spread throughout the year.
The 5% must be calculated from the number of departures of aircraft with ACNs at or near the PCN of the pavement (i.e. 5% of the ‘design traffic’). Otherwise if there is a high frequency of use by light aircraft which are well below the PCN, 5% of the *total* movements could represent a substantial proportion of the actual coverage level for the pavement (see para 4.6.2) and lead to an unacceptable rate of deterioration.

The effect of maintaining overload operations at this level and frequency cannot be accurately predicted owing to the number of variables; for example, the type of construction (i.e. rigid and flexible), its condition, the type of aircraft (e.g. pass-to-coverage ratios) and the environmental factors at the time. As an approximate guide the standard rigid and flexible pavement design models were used to establish average results; these gave a 5-15% reduction in the remaining design life.

(ii) Overload operations representing a difference in ACN over PCN from 10% to 25% justify regular inspections of the pavements by a competent person in addition to satisfying the criteria for 10% overload. Overload operations should stop as soon as distress becomes evident; the higher loading should not be reimposed until appropriate pavement strengthening work has been completed.

As for the 10% overload case the standard rigid and flexible design models were used to assess the implications of maintaining 25% overload operations at a frequency of 5% of the ‘design traffic’ The results varied from 25-75% reduction in design life depending on the pavement type and aircraft type. Therefore overload operations at this level and frequency should only be short-term.

(iii) Overload operations representing a difference in ACN over PCN from 25% to 50% should only be permitted very occasionally. They call for scrutiny of available pavement construction records and test data and a thorough pavement inspection by a pavement engineer before and on completion of the movement to assess any signs of pavement distress.

(iv) Overload operations representing a difference in ACN over PCN of more than 50% should only be undertaken in an emergency.

## 8.2 HIGH TYRE PRESSURE OPERATIONS

8.2.1. For practical design purposes the tyre pressure produces the intensity of the load on the pavement. The primary consideration for excess tyre pressure operations is the risk of undue damage to the surfacing. The consequences of pavement damage as a result of overstressing of the surfacing layers are likely to be less serious than a deep seated structural failure. Nevertheless an engineer must carefully weight the problems of carrying out maintenance work in the event of damage before allowing occasional excess tyre pressure operations for the sake of maintaining operational flexibility. The following notes are for guidance:

(i) Occasional movements by aircraft with tyre pressures over the maximum authorised for unrestricted use (see para **Error! Reference source not found.**) of the pavements are unlikely to have significant effect on the performance of the pavement except in circumstances described in (iii). The factors which affect surface stability make it inappropriate to lay down rules.

(ii) Concrete pavements are not subject to surface indentation by high tyre pressure aircraft.

(iii) Bituminous surfacing of other than high stablility Marshall asphalt or with less than 100mm of Marshall asphalt are liable to indentation by high pressure tyres. The amount of indentation depends on the following factors:

   a. The stability of blacktop surfacings is temperature dependant and therefore they are more liable to identation by high pressure tyres on hot days. This is particularly the case for tar-bound surfacings (e.g. dense tar or tar macadam).
   b. Although ready for use within hours of laying, bituminous surfacings continue to harden for some months. This depends on the type of mix and the climatic conditions. The full stability of surfacing is not realised for several months after laying.
   c. Due to creep, indentation is more likely to occur on a bituminous surface when aircraft are parked on it. Metal plates can be used to spread the load beneath the tyres of parked aircraft, they will protect a low stability black-top surfacing.
   d. Shallow pavements comprising less than 100mm of bituminous surfacing on low-grade granular bases (i.e. CBR <80%) are liable to structural damage by high tyre pressure aircraft, particularly where the aircraft are parked. In practice this situation will effectively represent a combination of overload and excess tyre pressure and will therefore need to be carefully considered.

(iv) Use of pavements by aircraft with tyre pressures three categories above the designated PCN should only be considered in an emergency.

# 9 Stopways, Shoulders and Blast Pads

## 9.1 GENERAL

9.1.1. Whether stopways and shoulders should be provided is explained in the ICAO publications Annex 14[13] and the Aerodrome Design Manual Parts 1 and 2[11]. Stopways and shoulders should be strong enough to support any aircraft which the runway is designed for, without introducing structural damage to the aircraft. They should also be able to support rescue and fire fighting vehicles. The definitions of strength and serviceability are open to some interpretation; the following sets out the design concept and method Defence Estates uses for establishing Stopways and shoulder construction

## 9.2 STOPWAYS

9.2.1. A stopway provides a safe 'run out' for an aircraft if take off is aborted. It can be included as part of the Accelerate Stop Distance Available (ASDA) which is one of the four declared runway distances in Annex 14. Note: this distance is referred to as the Emergency Distance Available in the AIP).[14]

9.2.2. A stopway surface can be unpaved or paved. A low-cost unpaved stopway could be designed in accordance with the procedure set out in Section 9.3 for shoulder construction. However, such a stopway would probably require some regrading and reconstruction after each pass of an aircraft. It would also result in a surface with a variable ridability and braking characteristics. The degree of variability will depend on the prevailing moisture contents of the pavements and the subgrade.

9.2.3. The paved stopway designs are intended to provide support to the Design Aircraft for 0.1% of the design frequency of trafficking for the runway, before major maintenance is required. This is achieved by designing for a reduced ACN at the design level of trafficking.

9.2.4. Using Charts 1-6 a paved stopway design can be established by the following procedures:

(i) The design ACN is the ACN of the Design Aircraft divided by 3 for flexible pavements or 2 for rigid pavements. To allow for use by emergency vehicles the design ACN should not be less than 5 with a minimum concrete thickness of 150mm.

(ii) The frequency of trafficking used for the runway design should be selected for the Charts.

(iii) The pavement thickness is obtained form the relevant chart. The actual make-up of the construction should be in accordance with Table 19.

9.2.5. With the exception of blast pads a flexible pavement is preferable to a rigid one to provide easy future rehabilitation. A failed flexible pavement with a granular base and sub-base can be recompacted, regraded and surfaced. A flexible pavement with a cement-bound base can be provided with a thin bituminous overlay, or the existing surfacing can be planed off and replaced. However, a failed rigid pavement requires a thick bituminous overlay or complete replacement.

9.2.6. As the use of a stopway is unpredictable, and it is designed and constructed to a lower standard than the movement areas, some maintenance work should be expected if the stopway is to have the same life as the runway.

## 9.3 SHOULDERS

9.3.1. The shoulders should be able to support an aircraft running off a runway or taxiway. The surface of the shoulders should not be susceptible to erosion and the blowing up of debris. On a runway, grassed surface shoulders will generally suffice provided the climate and topsoil are capable of sustaining them. However, taxiways used by large jets with outboard engines extending beyond the edge of the pavement may need shoulders with a paved surface to prevent erosion and foreign object damage to the aircraft.

9.3.2. Using Chart 6 or Figure 7 and Figure 8 a shoulder construction can be established in accordance with the following procedure:

(i) The ACN design parameter is the ACN of the Design Aircraft divided by 3. To allow for use by rescue vehicles the design ACN should not be less than 5.

(ii) For paved shoulders the frequency of trafficking used for the runway design should be selected. For grassed shoulders the Low frequency of trafficking should be used.

(iii) The pavement construction should accord with Table 20.

9.3.3. On grassed shoulders regrading and some reconstruction would most likely be required after each pass of an aircraft. Wheel penetration is unlikely to exceed 150mm on prepared grassed shoulders and it would be substantially less on paved shoulders. The design concept is based on References 28 and 29. As failure criteria and design methods are not precise, the designs cannot be expected to be accurate and may therefore be a little conservative.

9.3.4. Paved surfaces can give rise to a lack of visual contrast between the runway and the shoulders. This can be overcome either by providing a good visual contrast between the surfacings of the runway and shoulders or by applying a distinctive marking at the edge of the runway.

## 9.4 BLAST PROTECTION

9.4.1. Areas adjacent to movement areas, especially those immediately off the end of runways may be subject to blast from jet engines. In these situations paved shoulders and blast pads should be provided. They should be large enough to prevent surface erosion and migration of foreign materials onto the movement areas. The width of the paved shoulders will depend on the taxiway width and the position of the outboard jet engines of the user aircraft.

9.4.2. Shoulders and blast pads forming part of a stopway should be designed to the recommendations given in Sections 9.2 and 9.3. For aircraft with high velocity turbojet engines (e.g. fighters) a concrete surface is preferable for the blast pad, otherwise the minimum thickness of asphalt surfacing should be 75mm.

**Table 19** Stopway Constructions

| PAVEMENT TYPE | SURFACING | BASE/SUB-BASE | | DESIGN CHART |
|---|---|---|---|---|
| Rigid | Pavement Quality Concrete (PQC) (Section 5.2) | DLC<br>Cement-stabilised base<br>Granular base. | - Section **1.1**<br>- Section **1.1**<br>- Section 3.8 | Chart 1, 2, 3 or 5 as appropriate. |
| Flexible | Marshall asphalt or<br>Hot rolled asphalt or<br>Dense bituminous macadam<br>The thickness of surfacing can be reduced to 50mm with these materials but the total thickness of construction (including surfacing + base/sub-base) should be kept the same as that required by the Chart i.e. increase the base course thickness by 50mm. | DLC<br>Cement-stabilised base<br>Cement–stabilised base<br>Granular base and sub-base<br>If the base is either wholly or partly cement-bound the minimum thickness of surfacing should be not less than 1/5th of the total thickness of bound pavement construction. | - Section 6.3<br>- Section 6.3<br>- Section 6.3<br>- Section 7.7 | Chart 4 or 6 as appropriate. |
| | Proprietary surfacing<br><br>This should be of proven durability.<br>If laid over a cement-bound base it should not be subject to premature reflective cracking.<br>Possibilities are proprietary blacktop materials, concrete blocks and grouted macadam. | DLC<br>Cement-stabilised base<br>Granular base and sub-base. | - Section 6.3<br>- Section 6.3<br>- Section 7.7 | Chart 4 or 6 as appropriate.<br>The total thickness of construction (including surfacing + base/sub-base) should not be less than that required by the Charts. |

**Table 20** Shoulder Construction

| DESIGN AIRCRAFT ACN AND TYRE PRESSURE | SURFACING | BASE/SUB-BASE | CONSTRUCTION THICKNESS CALCULATION |
|---|---|---|---|
| ACN … 30<br>Tyre pressure … 1.5 MPa | Either topsoiled and grassed with a maximum topsoil depth of 100mm or as for Table 19(Flexible). | If the subgrade is equal to or better than CBR 15% no base/sub-base is required. The CBR 15% must still be valid in wet weather.<br>If the subgrade is less than the design requirement this can be improved with granular fill (Section 3.8). | Use Figure 7 and Figure 8 to calculate the thickness of granular fill required to provide a CBR 15% support level or use Chart 6 if the depth of granular subbase required to give CBR 30% proves more economical. |
| ACN > 30<br>and all the aircraft with tyre pressures<br>1.5 MPa<br><br>NB. The ACN is the design Aircraft CAN before dividing by 3. | | If the subgrade is equal to or better than CBR 30% no base/sub-base is required.<br>The CBR 30% must still be valid in wet weather. If the subgrade is less than the design requirement this can be improved with granular sub-base or, for paved shoulders only, the equivalent thickness of cement-bound base (Section 6.3). | Use Chart 6 to calculate the thickness of granular sub-base required; the thickness is the X ordinate minus the Y ordinate. This will provide CBR 30%. The equivalent thickness of cement-bound base can be calculated. (Section **1.1** and 6.3). |

# References

1. Air Ministry Works Department. Design and Construction of Concrete Pavements. Air Publication No. AP3129A. 1945.
2. Air Ministry Works Department. Load Classification of Runways an Aircraft Technical Publication 102. 1948.
3. Air Ministry Works Department. Airfield Evaluation. Technical Publication 104. 1952
4. Air Ministry Works Department. The Fundamentals of Airfield Pavement Design. Technical Publication 107 1953.
5. Air Ministry Works Department. Airfield Design and Evaluation. Technical Publication 109. 1959.
6. J L Dawson and R L Mills. Undercarriage Effects on (a) Rigid Pavements (b) Flexible Pavements. ICE Proceedings of Symposium on Aircraft Pavement Design 1970.
7. F R Martin, A R Macrae. Current British Pavement Design ICE Proceedings of Symposium on Aircraft Pavement Design 1970.
8. H Jennings, F L H Straw. Strengthening of Pavements. ICE Proceedings of Symposium on Aircraft Pavement Design 1970
9. Department of the Environment. Design and Evaluation of Aircraft Pavements 1971. 1971
10. International Civil Aviation Organisation, Aerodrome Design Manual Parts 1-3, First Edition 1977, Second Edition 1983.
11. Property Services Agency. A Guide to Airfield Pavement Design and Evaluation. HMSO. 1989.
12. US Army Engineer Waterways Experiment Station. Procedures for Development of CBR Design Curves – Instruction Report S-77-1. 1977.
13. International Civil Aviation Organisation. Annex 14. Aerodromes – Internationa Standards and Recommended Practices. Eight Edition 1983
14. Civil Aviation Authority. United Kingdom Aeronautical Information Publication. London 1982.
15. BSI. Methods of test for soils for civil engineering purposes - Part 2: Classification tests. BS 1377-2: 1990 incorporating Amendment No. 1 May 1996.
16. Road Research Laboratory. Soil Mechanics for Road Engineers. HMSO 1952.
17. D Croney. The Design and Performance of Road Pavements. HMSO London 1977.
18. US Army Engineer Waterways Experiment Station. Field Moisture Content Investigation, October 1945 – November 1952 Phase. Report No. 2 1955.
19. US Army Engineer Waterways Experiment Station. Field Moisture Content Investigation, November 1952 – May 1956 Phase. Report No. 3. 1961.
20. W A Lewis. Full Scale Compaction Studies at the British Road Research Laboratory. Highways Research Board Bulletin 254. Washington 1960.
21. US Army Engineer Waterways Experiment Station. Compaction Requirements for Soil Components of Flexible Airfield Pavements. Technical Report No 3-529. 1959
22. W J Turnbull and Charles R Foster. Proof Rolling of Subgrades. Highway Research Board Bulletin 254. Washington. 1960.
23. W D Powell, J F Potter, H C Mayhew and M E Nunn. The Structural Design of Bituminous Roads. Report LR 1132. Transport and Road Research Laboratory, Crowthorne, Berks. 1984.
24. D Croney and J C Jacobs. The Frost Susceptibility of Soils and Road Materials. RRL Report LR 90. Transport and Road Research Laboratory, Crowthorne, Berks. 1967.

25. BSI. Testing aggregates - Method for determination of frost-heave. BS 812-124:1989. 1989.
26. P G Roe and D C Webster. Specification for the TRRL Frost Heave Test, Supplementary Report 829. Transport and Road Research Laboratory, Crowthorne, Berks. 1984.
27. R G Packard. Fatigue Concepts for Concrete Aircraft Pavement Design. Transportation Engineering Journal. 1974.
28. R L Hutchinson. Basis for Rigid Pavement Designs for Military Airfields. Miscellaneous Paper No 5-7. US Army Corps of Engineers, Ohio River Institute. Washington DC 1958.
29. US Army Corps of Engineers Waterways Experiment Station. Validation of Soil Strength Criteria for Aircraft Operations on Unprepared Landing Strips. Technical Report No.3-554. July 1960.
30. Military Engineering Experimental Establishment Sinkage of a Dual Aircraft Wheel Assembly. Report No 925. Christchurch. October 1965.
31. D N Brown and O O Thompson. Lateral Distribution of Aircraft Traffic. Miscellaneous Paper S-73-56 July 1973. US Army Engineer Waterways Experimental Station, Vicksburg. 1973.
32. H M Westergaard. Stresses in Concrete Pavements Computed by Theoretical Analysis Public Roads. Vol 7 No 2. 1926.
33. G Pickett, M E Raville, W C Jones, F J McCormick. Deflections, Movements and Reactive Pressures for Concrete pavements. Kansas State College Bulletin 65. October 1951.
34. R G Packard. Computer Programme for Airport Pavement Design, Portland Cement Association. Chicago, Illinois. 1967
35. G Pickett. Concrete Pavement Design, Appendix III: A Study of Stresses in the Corner Region of Concrete Pavement Slabs under Large Corner Loads. Portland Cement Association, Skorkie.1946.
36. US Army Corps of Engineers. Final Report on the Dynamic Loading of Concrete Test Slabs – Wright Field Slab Tests. Ohio River Division Laboratories, Mariemont, Ohio August 1943.
37. R H Ledbetter. Pavement response to Aircraft Dynamic Loads. FAA Report No. FAA-RD-74-39-III. June 1973.
38. Highway Research Board. Joint Spacing in Concrete Pavements: 10 year Reports on Six Experimental Projects. Research Report 17B. 1956.
39. B E Colley and H A Humphrey. Aggregate Interlock in Joints in Concrete Pavements. Highway Research Record Number 189. 1967.
40. L D Childs. Effect of Granular and Soil-Cement Sub-bases on Load Capacity of Concrete Slabs. Journal of the PCA Research and Development Laboratories, Vol 2, No. 2. 1960.
41. L D Childs and J W Kaperick. Tests of Concrete Pavement Slabs on Gravel Sub-bases. Proceedings ASCE, Vol 84 (HW3). October 1958.
42. L D Childs. Tests of Concrete Pavement Slabs on Cement Treated Sub-bases. Highway Research Record 60, Highway Research Board. 1964.
43. L D Childs. Cement Treated Sub-bases for Concrete Pavements. Highway Research Record 189, Highway Research Board 1967.
44. Air Ministry Works Department. Investigation into the Value of Lean Concrete as a Base in Rigid Pavements. Air Ministry Tech Memo No.4. 1955.
45. R D Bradbury. Reingforced Concrete Pavements. Wire Reinforcement Institute. Washington DC. 1938.
46. L W Teller and E C Sutherland. The Structural Design of Concrete Pavements. Public Roads Vol 16, No 8, 9 and 10, 1935; Vol 17 No 7 an 8, 1936; and Vol 23, No. 8 1943.
47. J Thomlinson. Temperature Variations and Consequent Stresses Produced by Daily and Seasonal Temperature Cycles in Concrete Slabs. Road Research Laboratory. June 1940.
48. US Army Corps of Engineers. Lockbourne No 1 Test Track. Final Report. Ohio River Division Laboratories, Mariemont, Ohio. March 1946.
49. Charles R Foster and R G Ahlvin. Notes on the Corps of Engineers CBR Design Procedures. Highways Research Board Bulletin 210, Washington, 1959.
50. F R Martin. A Heavy-Duty Airfield pavement Embodying Soil Stabilisation. ICE. Airport Paper 34.

51. M A Napier. A Report on the Testing of Stabilised Soil Airfield Pavements 1955-60. MEXE Report No 592.
52. Defence Estates. Reflection cracking on airfield pavements – a design guide for assessment, treatment selection and future minimisation. Design & Maintenance Guide 33. Defence Estates. Sutton Coldfield, UK, 2005.
53. Defence Estates. The Use of the Crack and Seat Treatment. Design & Maintenance Guide 21. Defence Estates. Sutton Coldfield, UK, 2003.
54. Defence Estates. Pavement Quality Concrete for Airfields. Specification 33. Ministry of Defence. 2005.
55. Defence Estates. Marshall Asphalt for airfield pavement works. Defence Works Functional Standard 13. Ministry of Defence. 1996.
56. Defence Estates. Hot Rolled Asphalt and Coated Macadam for airfield works. Defence Works Functional Standards.
57. Defence Estates. Porous friction course for airfields. Specification 40. Ministry of Defence. 1996.
58. Defence Estates. Concrete block paving for airfields. Specification 35. Ministry of Defence. 1996.