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THE USE OF PAVERS FOR AIRCRAFT PAVEMENTS

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THE USE OF PAVERS FOR AIRCRAFT PAVEMENTS

Professor J Knapton
J A Emery

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Preface

This Report has been written following growth in the use of concrete block paving ('Pavers') on many types of aircraft pavements in the UK and abroad. It was commissioned by the Civil Aviation Authority Safety Regulations Group (CAA) following reports of pavers having been displaced during aircraft manoeuvring and following an incident in which an aircraft was damaged by pavers during take-off.

The information set out in this Report is intended to be applied only by those with experience in the design of aircraft pavements. The designer should have experience of the particular type of pavement being designed or reviewed. The designer should consult those source documents referred to in this Report, particularly to ensure that the original charts are used rather than the schematics used in this Report.

The CAA wishes to thank all those who responded to the questionnaire which allowed Section 1.4 Historic usage of pavers in aircraft pavements to be written. The design and construction guidance included in Sections 2 and 3 relies heavily upon pavement guidance developed by the Federal Aviation Administration, the former Property Services Agency and the Department of Transport and in each case, a full reference is included in the text.

THE AUTHORS

John Knapton is Professor of Structural Engineering at The University of Newcastle upon Tyne and is Chairman of the Small Element Pavement Technologists Council. His interest in concrete block paving commenced in 1973 when he developed the world's first paver pavement design method whilst working as a Research Engineer at The Cement & Concrete Association. Since then, he has published over 60 papers and design guides on concrete block paving and has designed over 1000 concrete block pavements throughout the world. He initiated the First International Conference on Concrete Block Paving in 1980 at Newcastle upon Tyne.

John Emery is Chairman and Managing Director of Advanced Construction Materials Ltd. Following six years with consulting engineers, working on the design and supervision of road and airport projects in Nigeria, Belize and in the Caribbean, he spent 18 years with Luton Borough Council mostly working at Luton International Airport. It was here that he introduced the use of pavers on aircraft pavements. He has presented papers on the use of pavers for aircraft pavements at International Conferences and Workshops in The Netherlands, Israel, USA, Norway, Italy and New Zealand.

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Also the Authors acknowledge the valuable comments and advice provided by Sir Alexander Gibb and Partners Ltd in reviewing the Report on behalf of the CAA.

Executive Summary

This Report includes guidance which may be followed in situations where concrete block paving has been used or is being considered as an aircraft pavement surfacing material. Concrete pavers have been in service on aircraft pavements since the early 1980s when small trial areas of rectangular 200mm long by 100mm wide by 80mm deep concrete pavers were installed on aircraft stands at Luton Airport. This Report shows that since then, many aerodrome owners have installed pavers on stands and some have used them to surface taxiways, maintenance areas and parts of runways. In most cases, experience has been satisfactory but in one area, several incidents have caused questions to be raised regarding their suitability for some categories of aircraft pavements. The Report examines the experience of pavers to date and provides design and specification guidance. It contains recommendations for designers, contractors, owners, operators and users of all types of airside pavements surfaced with pavers.

Section 1 reviews the way in which pavers came to be used on aircraft pavements then deals with specific projects both in the UK and abroad. It describes research which showed the effect of jet blast on pavers and deals in detail with events at Luton Airport. Section 2 shows how the Federal Aviation Administration(FAA) pavement design method can be used to select materials and pavement layer thicknesses when the pavement is surfaced with pavers. It explains how pavers can be used in place of conventional flexible pavement construction materials. Section 3 shows how the Property Services Agency (PSA) design method can be used to assess the suitability of pavers as an overlay on pavements originally designed by the PSA method. Section 4 comprises a list of recommendations for future projects. Essentially, those recommendations state that pavers can be used to surface the following categories of aircraft pavements:

(i) Aircraft stands.

(ii) Low speed taxiways not subject to significant jet blast or propeller wash.

(iii) Aircraft maintenance areas not subject to significant jet blast or propeller wash.

(iv) Helicopter pads.

The recommendations state that pavers should not be used to surface the following categories of aircraft pavements:

(i) Runways.

(ii) Areas where aircraft engines are run at high thrust values.

(iii) High speed taxiways.

Present paver design and specification methods can be adopted with a few exceptions. For example, some mechanical installation techniques lead to large joints around laid clusters and such techniques should be avoided. Also, present laying course material specifications are considered to allow too much fine material. Throughout the Report, the emphasis is upon providing guidance which can be followed to ensure that all future aircraft pavements surfaced with pavers should remain safe and serviceable in day to day use.

Contents

1 OVERVIEW OF THE USE OF PAVERS

1.1 History of the use of pavers

One of the most important factors in the growth of all civilisations is the need for effective rapid transport. Paved Minoan roads dating back 5000 years are still in use and the Romans constructed paved roads throughout northern Europe including Britain, Asia and North Africa many of which can still be found underlying modern roads.

Figure 1 Roman road under construction circa 100AD in Northern England. Many of the features incorporated in present day pavement construction are in evidence: a durable paved surface, a structure sufficiently strong to withstand anticipated use, a firm foundation, edge support and drainage were all designed into Roman roads.

The difference between Roman roads and those constructed by preceding civilisations is in their understanding of the need to design roads as load bearing structures not only in their own right but also incorporating the strength of the underlying soil. The Romans realised that the presence of water within the structure of the road governed the strength of the road construction materials and hence their performance in service. The Romans were also the first to introduce edge restraints to confine granular pavement materials.

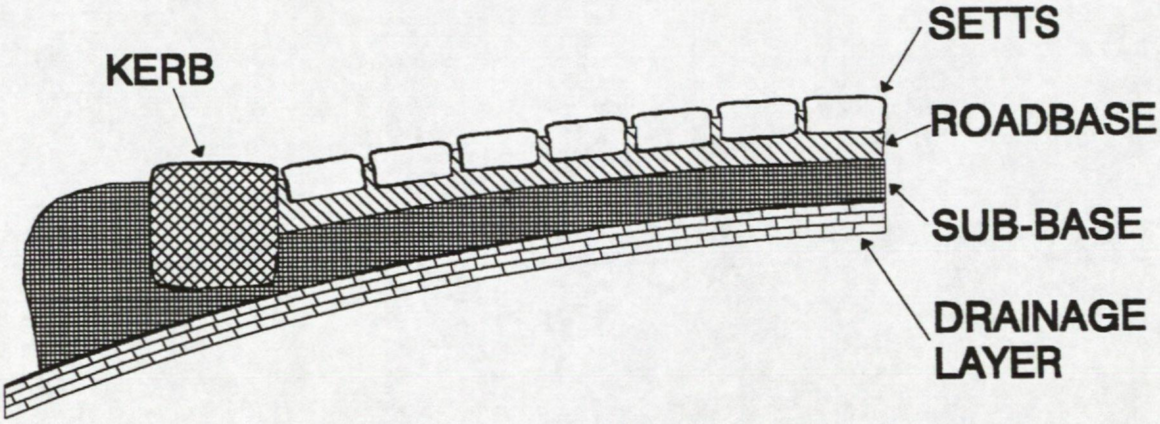


Figure 2 The road edge or kerb was the key to the success of Roman roads[1]

Even the nobility travelled infrequently on arduous medieval roads and transport of essential goods was undertaken mainly by sea or river which led to larger towns developing at coastal and river locations. The provision of hard wearing paving was essential at quay sides and market squares in these towns. Stone cobbles – usually brought to Britain as ship's ballast – were the only freely available material of sufficient strength and durability for pavement surfacing and were used throughout northern Europe into the 20th century. Many medieval pavements are intact today often serving as the foundation to present day urban streets.

The Industrial Revolution brought the need for a greater efficiency in the transport systems of many countries. Communication between previously isolated regions became essential in order to generate wealth. In addition to the growth of road networks, canals and railways resulted in a concentration of traffic at their terminals, increasing the need for hard-wearing pavements[2].

The growth in the complexity of public services, mainly water supply, gas distribution and sewage disposal, coincided with the construction of urban roads in the nineteenth century. It seemed sensible for services to be placed beneath the public roads. Additionally electricity and communications services have been laid beneath many roads during the last 100 years. The wisdom of including services beneath roads became less certain when the need for maintenance of those services arose.

Traditional pavers were limited to stone units (wood and rubber were used less commonly in the past mainly for the reduction of noise associated with horses hooves and metal rims on cart wheels) except in the Low Countries where clay pavers were developed to surface roads constructed over peat and other low strength subgrades. The choice between stone and clay was based upon price and local availability. Concrete products were introduced by the firm of Fielding and Platt in the 1890s who developed the 'wet-press' process, allowing high speed, high quality units to be manufactured to high levels of dimensional stability. The ability to produce concrete units in this way led to a low cost product and their manufacture in a mould allowed different forms to be produced e.g. kerbing, drainage channels and different interlocking designs. The restricting factor on this production process was the high cost of the mould and its susceptibility to wear in the high pressure pressing process.

Concrete paving was first used for road construction in Germany 1936, but the first major use of paving came in post war Germany when the country was being reconstructed. In 1980 Meyer[3] gave four reasons for the development of pavers in post war Germany:

(i) They are durable, skid-resistant, dimensionally accurate and provide great variety with regard to shape, surface structure (pattern) and colour.

(ii) Their unit cost had increased very little with time.

(iii) They can be laid by untrained labour, even in poor weather.

(iv) They can be taken up without any noise nuisance and re-used on the same site or elsewhere.

In parallel with developments in Germany, concrete pavers began to be used to surface urban streets in The Netherlands in the late 1940s, initially as a temporary expedient measure as a substitute for clay pavers. Clay pavers had been used on Dutch streets for over 200 years but a shortage of coal following the war reduced the production of Dutch brick to a level whereby all of the production was needed for reconstruction, especially in housing. Concrete pavers of similar dimensions to clay pavers were introduced and were found to have enhanced properties in terms of durability, dimensional stability and skidding resistance. The recognition of these benefits led to the progressive replacement of many areas of clay pavers with concrete ones so that by 1970, a usage of 15 million m^2/annum had developed, similar on a per capita basis to the German usage and significantly greater than that of any other country, except Denmark whose usage of 4 million m^2/annum equated with Dutch per capita usage.

Paving quickly spread throughout Northern Europe and the rest of the world, mainly due to two identifiable reasons:

(i) As in Germany, other parts of Europe needed to repair and renovate war damaged inner city areas.

(ii) In the United States a depression in the construction industry led to building block manufacturers seeking alternative uses for their products.

1.2 Introduction of pavers to the UK

Pavers were introduced into UK in the late 1960s and were first used in road construction following research and promotional activities at the Cement and Concrete Association including visits to Belgium, Holland, W. Germany and Denmark undertaken by Knapton and Lilley[4,5] to gain an understanding into the design and construction of pavements surfaced with pavers.

A visit was undertaken by Knapton and Lilley[4] to Belgium and The Netherlands in 1973 in order *'..to assess the performance of concrete block roads in these countries with a view to their potential use on British housing estates.'* Discussion with municipal engineers and paver producers together with an examination of many applications of pavers in the low countries revealed that pavers proved highly satisfactory and economical. Their report was the first to describe pavers and their behaviour and performance in use. In particular they reported *'In both Belgium and The Netherlands it was observed that where blocks had been laid correctly they had survived periods of up to 40 years without fault.'*

The following information was reported in Knapton and Lilley's original paper[4]. The minimum paver flexural strength required in Belgium and The Netherlands was 6N/mm^2, but strengths of up to 8N/mm^2 were commonly achieved by using a water/cement ratio of 0.3 with a cement content of approximately 300kg/m^3 and 12mm maximum size aggregate (12mm aggregate would be considered too large in most regions today since although it leads to high strength pavers, it creates an open textured surface which may not be durable). Dimensional tolerances to which manufacturers in Belgium were required to produce pavers were set at ±5% in height and ±3% in length and width. Contemporaneous production processes were able to achieve tolerances of ±2% and ±1% in height and length respectively.

Durability was found to be of prime concern to manufacturers and specifiers: scaling of the top surface of the pavers was a common problem. Scaling had been overcome in one of two ways: firstly by pressing the blocks upside down ensuring the well sealed surface in the base of the mould became the upper wearing surface of the paver and secondly by employing a richer wetter concrete for the uppermost 10mm of the paver. Belgian and Dutch pavers incorporated chamfered perimeters which reduced high intensity local stresses. The probability of damage during handling was also found to be reduced by the introduction of chamfers.

Belgian and Dutch pavers were required to comply with the following requirements:

(i) Wear and skid resistance was measured using a pendulum test and Dutch results showed pavers to have adequate skid resistance.

(ii) Resistance to wear was determined by a blast technique in which a sample was weighed both before and after sand blasting. Even those pavers incorporating a soft limestone aggregate passed the sand blast test.

(iii) The pavers were subjected to 25 freeze-thaw cycles. Results showed that no correlation existed between frost resistance and flexural strength or absorption.

Knapton and Lilley[4] were the first to describe the structural behaviour of pavers. They described the articulated nature of pavers bedded in sand and contrasted that behaviour with the way in which conventional flexible and rigid pavements worked. They introduced four terms which were considered to characterise the behaviour of pavers: *interlock, deformation, sucking and creep.*

Interlock was defined as the ability of pavers to transfer shear, bending and thrust by direct and intimate contact (see Section 1.6). *Horizontal interlock* was understood to be achieved by using pavers with a complex plan shape or by laying rectangular pavers in an interlocking pattern such as herringbone as in Figure 3. In Belgium vertical and horizontal interlock was thought to be enhanced by using complex paver shapes although these did not appear to give a finish to the same standard as the Dutch pavers. Dutch and Belgian experience showed that vertical interlock was necessary to reduce local deformation and that edge restraint, usually in the form of kerbing, was required to maintain full interlock.

The type of deformation which occurred on conventional flexible roads was observed similarly on paved roads in both Belgium and The Netherlands. Roads without a sub-base showed severe longitudinal rutting when trafficked by commercial vehicles. An example was reported in Brussels where several heavily trafficked roads comprising 200mm thickness asphalt over 200mm thickness lean concrete had deformed up to 150mm. Rather than replacing the whole 400mm deep pavement, it was considered more logical to use pavers as an inlay, and it was found that the paver surfaced streets performed better. One of the advantages of paved surfaces was that in the event of deformation it was a simple matter to remove a few pavers, fill the depression, relay and re-pack the deformed pavers.

Figure 3 Herringbone laying pattern has been found to enhance the structural performance of paver projects by enhancing the interlocking nature of the pavers.

Sucking was the term used to describe the removal of sand and detritus from paver joints by tyre suction. This phenomenon caused problems on normally trafficked roads when joint widths were of the order of 5mm or greater, which was reported to lead to total loss of jointing sand and subsequent removal of bedding sand, thereby causing structural failure.

Creep, shown in Figure 4 was defined as the migration of pavers along a road. Creep occurred when rectangular pavers were laid in a non-interlocking pattern, which resulted in the pavers shifting in the direction of the traffic. At that time the cause of creep was not fully understood, although it was believed to be associated with the horizontal braking and accelerating forces of vehicles. Two types of creep were identified at a government research station in Delft, single creep and double creep. Both types of creep were found to be accentuated by one way travel, higher vehicle speed and higher axle load. It was found that the bedding layer of sand often crept with the pavers, although one experiment showed only the pavers moving. Laying pavers in a herringbone pattern was found to minimise the magnitude of creep and also to hide the creep since there was no continuous straight line to draw the eye to the creep.

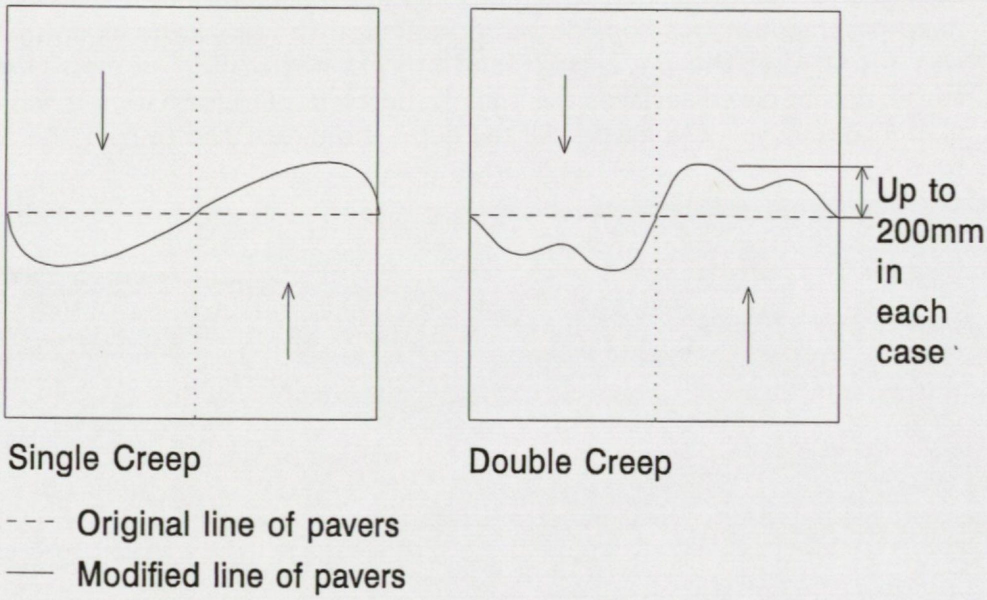


Figure 4 Single and double creep as reported by Knapton and Lilley following their investigations in the low countries in 1973. Several factors were identified as causing the phenomenon, including one way traffic, braking and heavy vehicles. It could be eliminated by appropriate design and construction procedures.

The conclusions of the report compiled by Knapton and Lilley stated that paved roads were an accepted form of construction, particularly in The Netherlands, and that the reasons for their existence were complex but included tradition, aesthetics, soil conditions and economics. It was concluded that Dutch roads serve similar requirements to those in Britain, and that other similarities, both social and geographical, existed between the two countries, i.e. distances travelled, social behaviour, size of towns and traffic characteristics. For these reasons they reported *'..there is no fundamental objection to the use of pavers in Britain.'*[4]

At that time it was considered that all failures occurring in paver streets were attributable to poor construction. It was stated that if pavers were to be introduced into Britain then *'..it is imperative that adequate attention be paid to laying techniques.'*[4] Where good laying had been undertaken, problems such as long and short wave undulation, cracking of blocks, excessive sucking and severe creep rarely occurred. Good laying was reported to ensure *'good interlock, a smooth surface and adequate edge restraint.'*[4]

Emphasis was placed on the fact that failure of a road was no cause for concern: reinstatement was *'simply a matter of removing pavers, re-packing sand and relaying the same blocks'* and could be applied to repairs of both subgrade and sub-base. The advantages of pavers were stated to include:

(i) no special plant is required,

(ii) a repair can be carried out in less than a day,

(iii) the road can be reopened immediately to traffic,

(iv) any further settlement can be rectified in the same manner.

UK developments were based upon Dutch rather than German experience. In particular, by 1970, most German usage comprised 'dentated' or non-rectangular pavers whereas the Dutch concrete pavers, having their origin in clay materials were rectangular so it was the rectangular paver which came to dominate the UK market during the 1970s. It is interesting to note that in the early 1970s, four concrete paver sources existed in the UK and each source comprised either a proprietary shape licensed from Germany, or a near copy of a German product but the growing highway and industrial pavement market moved the UK bias towards rectangular pavers to the extent that approximately 90% of all UK commercial paver usage now comprises rectangular pavers.

By the mid 1970s the use of pavers, for both roads and other pavements was widespread throughout Europe, whilst remaining relatively low in the UK and in the rest of the world. The Cement and Concrete Association visits to Belgium and The Netherlands were supported by laboratory load testing which eventually led to the development of the theories of interlock described in this Report. This in turn led to the publication in 1976 of the world's first paver structural design guide[6]: the most surprising fact to emerge from the mid 1970s was the lack of rigorous design information available in Europe for paver pavement design and how little was published regarding the nature and behaviour of paver pavements. It was reported that *'...the flexibility is provided by the articulation of rigid blocks rather than by uniform elasticity'*[4], and that *'...concrete block roads show characteristics which neither rigid nor flexible roads display.'*[4] These characteristics were fully researched during the 1970s and the 1980s in the UK, Australia, South Africa and, curiously, later in The Netherlands and Germany.

In BS6717 (1986) Part 1 : *Precast concrete block paving. Specification for paving blocks*[7] the size of rectangular pavers (then 80% of UK usage) was standardised as 100mm x 200mm, in order to remove incompatibility between pavers from different manufactures, to simplify maintenance and to reduce the number of types of paver held in reserve by specifying authorities. In the late 1970s the practice of introducing spacer nibs was introduced in the UK as a means of eliminating spalling in pavers manufactured and laid to particularly good dimensional tolerances and virtually all UK rectangular pavers now incorporate spacers, although there is no British Standard requirement for this. Spacers prevent individual pavers from remaining in continuous contact with their neighbours and so ensure joints are filled with jointing sand such that full interlock is developed in the pavement.

1.3 World wide usage of pavers

The following list illustrates the range of principal paver applications:

(i) Bus stations, lay-bys and terminals.

(ii) Aircraft paving.

(iii) Storage areas.

(iv) Ports.

(v) At grade car parks.

(vi) Petrol stations.

(vii) Industrial areas.

(viii) Residential roads.

(ix) Pedestrianisation projects.

(x) Domestic areas.

Table 1 World wide usage of pavers by region

Major Markets	*Million m^2/annum*
Germany	75
Rest of Europe	55
United Kingdom	12
US and Canada	18
Central America	40
South America	25
Australasia	8
Africa	25
Middle East	30
Other Regions	62
World-wide	350

Table 1 is based upon data collected by the Authors in their correspondence with representatives of paver industries world-wide. A feature in the development in the use of pavers in most regions has been an industry led rapid growth as capital intensive production equipment has been commissioned. For this reason, the figures in Table 1 may represent an underestimate.

1.4 Historic usage of pavers in aircraft pavements

Pavers have been used for many categories of aircraft pavements. Currently the existing pavements have been designed structurally using one of the equivalence methods described in this Report and in most cases they have performed satisfactorily. The principal examples where pavers have entered service are now described. It is estimated that 700,000 m^2 of pavers are in service on aircraft pavements in the following proportions:

Apron stands	84%
Helicopter pads	6%
Taxiways	4%
Runway ends	3%
Fuelling areas	3%

Historic usage is now reviewed according to three distinct end uses:

(a) United Kingdom civil use of pavers – 217,500m^2
(b) World-wide civil use of pavers – 290,500m^2
(c) World-wide military use of pavers – 183,000m^2

Each end use is summarised in Tables 2, 3 and 4.

Each of the aerodromes listed in the tables was asked to complete the following questionnaire:

(a) Name of Airport.
(b) Size of paved area(s).
(c) Type of Air Traffic.
(d) Give an indication of performance of pavers.
(e) Estimate number of movements of each type of aircraft over pavers.
(f) Indicate pavement construction details.
(g) Provide plan of airport indicating location of pavers.

A summary of the information so obtained is now provided. Comments on the performance of the pavers varied from 'satisfactory' to 'excellent'.

N.B. For security reasons, UK Defence Works Services felt unable to provide specific information regarding the military airfields for which they are responsible. Therefore it has not been possible to provide comprehensive details concerning their pavements. They did however, confirm that they were generally satisfied with the performance of paver surfaces and would continue to use them where appropriate.

1.4.1 *United Kingdom use of pavers on civil aerodromes*

1.4.1.1 Blackpool Airport

This aerodrome was one of the earliest to make use of pavers following the Luton trials and in 1982 surfaced two helicopter pads with a third being surfaced in 1992. Each helicopter pad was approximately 17.5m x 17.5m, i.e. an area of $920m^2$. In 1987 the 10 and 28 ends of the runway were constructed with a paver surfacing. The pavements were of flexible construction, comprising:

80mm rectangular pavers
50mm sand
150mm lean mix concrete base course
granular sub-base (thickness unknown)

The mix of aircraft using Blackpool is typically light general STOL transports and BAC 1-11s. The number of aircraft movements using the runway where the pavers are in use was given as approximately 10,000 per year. The aerodrome has experienced no problems with the pavers. As a matter of precaution, following the Luton experience, they replaced 40–50 pavers on the runway ends.

1.4.1.2 Coventry Airport

In 1987 the 23 threshold/turning area ($3000m^2$) was constructed as follows:

80mm thick rectangular pavers
50mm sand
300mm cement stabilised soil
regulating layer of lean mix concrete

The mix of aircraft using the aerodrome compromises Boeing B-707, Viscount, Vanguard and Lockheed Electra. It has been noted that the B-707 has on occasions landed on the pavers without damage to them. There are up to 25 aircraft movements per day at the aerodrome. The performance of the paver surface was rated as good but there has been some loss of jointing sand and growth of weeds noted in some joints.

1.4.1.3 Dunsfold Aerodrome

This aerodrome is operated by British Aerospace (Military Aircraft) Ltd. and is used mainly by Harrier VSTOL aircraft with between 12 and 20 aircraft movements per week. Two areas have been surfaced using pavers, the eastern runway overrun/turning area ($750m^2$) and an aircraft handling area ($1780m^2$). The overrun/turning area is thought to have been laid over 250mm pavement quality (PQ) concrete and the aircraft handling area over lean mix concrete. Some jointing sand loss was encountered which has been remedied by sealing the joints with a polymer sealer.

1.4.1.4 London Gatwick Airport.

During 1989 and 1990 Apron Stands 49 – 52 and Stand 54 were constructed. Half the area was new pavement construction as follows:

80mm rectangular pavers
40mm sand
525mm lean mix concrete
300mm granular sub-base (GSB) Type 1 on a drainage layer

The remaining area comprised an overlay to a General Aviation apron and comprises:

80mm rectangular pavers
40mm sand
50mm hot rolled asphalt
225mm dry lean concrete

The aircraft using the stands are mainly Boeing B747 and B737. On average each stand has 2 wide body and 3 narrow body jet aircraft movements per day. A representative of British Airports Authority (BAA), who are responsible for this airport, has given the following comments based on experience at Gatwick:

'....it is not now BAA's policy to utilise blocks (pavers) for new construction. We may consider them for overlay of existing stands but they are not cost effective for new construction and have long term maintenance deficiencies. We do however use blocks on occasions for small scale bay repairs in areas where access for long term repairs is difficult.'

In one trial at Gatwick, fuel entering bedding sand through paver joints softened underlying bituminous material which had been installed to regulate levels prior to installing pavers.

1.4.1.5 Glasgow Airport

Between 1989 and 1991 Stands 14 – 26 at the Domestic Pier were overlain using 80mm thick rectangular pavers in four separate phases. Before laying the pavers the existing PQ concrete construction was regulated using bituminous material. Aircraft using the area range between twin turbo prop and Boeing B757, with approximately 600 aircraft movements per week using the 14 stands. No problems have been encountered with the pavers apart from some minor settlement generally occurring at some of the underlying expansion joints in the PQ concrete.

1.4.1.6 London Heathrow Airport

During the summer of 1992 Apron Stands 74 to 88, (21000m^2), at the North side of the airport were resurfaced using 80mm thick rectangular pavers on 35mm sand after regulating part of the area with Marshall asphalt. Aircraft using these stands are Boeing B767, B757, and McDonnell Douglas DC-9 and the number of aircraft using each stand is 8–10 per day. It is understood that local settlement has occurred in areas of pavers beneath main aircraft undercarriage gear and this appears associated with saturation of the laying course sand. A further area of 26000m^2 of rectangular pavers was to be laid in 1994 on the Eastern Apron Development.

Prior to paving the stands, a 150m length of taxiway was paved in 1986. Pavers were laid on a bed of bitumen coated sand and were overlain with bituminous material. Engineers at the Airport had been concerned to reduce the propagation of cracks to the surface of the pavement and wondered whether their paver sandwich would prevent the phenomenon. The experiment was removed after 18 months.

1.4.1.7 Humberside Airport

During 1986 an apron of $4400m^2$ was constructed as detailed below:

80mm rectangular pavers
50mm sand
200mm lean mix concrete on a subgrade having a California Bearing Ratio(CBR) of 6%.

Aircraft using the stands are mainly helicopters and Boeing B737-400. There are approximately 30 helicopter movements per day and two B737s per week. No problems have been encountered with the pavers, apart from the growth of some weeds in joints and the area is said to have been maintenance free.

1.4.1.8 Luton Airport

The use of pavers at Luton is discussed fully in Sections 1.9 to 1.11.

Table 2 United Kingdom use of pavers on aircraft pavements

Airport	*Area of pavers (m^2)*	*Year installed*	*Pavement use*	*Aircraft using pavement*
Blackpool	5,260	1982,1987 & 1992	Runway end Helicopter pads	BAC1-11, General aviation & helicopters
Coventry	3,000	1989	Runway end	Electra, Viscount Vanguard, B707
Gatwick	30,600	1989 & 1990	Aprons	B747 & B737
Glasgow	42,000	1989 – 1990	Aprons	Twin turbos up to B757s
Heathrow	20,000 26,000	1992 1994	Aprons	B767, B757 & B767
Humberside	4,400	1986	Apron	Helicopters B737
Isles of Scilly	2,000	1992	Apron	Helicopters BN Islander
Luton	24,200	1982 – 1993	Runway ends Aprons	B767, B757, B737 & General Aviation
Southampton	30,000	1991 & 1992	Aprons	Light aircraft
Stansted	30,000		Apron Run-up area	B747

1.4.1.9 Southampton Airport

In 1991 and 1992 two apron areas were built in two separate phases, each area having the following construction:

80mm rectangular pavers
40mm sand
2 x 150mm lean mix concrete on a 'Geotextile' layer.

The mix of aircraft using the stands is typically: British Aerospace 146, BN Trislander, Fokker F27 and Saab 340. There are about 60 aircraft movements per day. Phase 1 was found to be *'Generally OK'* and Phase 2 to be *'Excellent – some problems with lean mix thermal movement and jointing'*.

1.4.1.10 London Stansted Airport

During 1988/1989 as part of the 'Diamond' Hangar construction a 30,000m^2 apron parking and engine run-up area was constructed. Aircraft using the hangar are usually Boeing B747 with typically 4 movements per week.

1.4.2 World-wide use of pavers on civil aerodromes

1.4.2.1 Ben Gurion International Airport – Tel-Aviv, Israel

In 1990 and in 1992 an apron area of 13,300m^2 was constructed in two phases. Phase 1 comprised 6,300m^2 and Phase 2 comprised 27,000m^2. The construction was similar for both areas, i.e.:

80mm pavers – sealed with polymer sealer
40mm sand
'geotextile' layer
230mm stabilised base
950mm sub-base layer
elastomeric bitumen waterproofing membrane on compacted clay

The mix of aircraft using the area comprises Boeing B747, B707, B727 and McDonnell Douglas DC 10. Performance of the pavers was stated to be; 'Very good, with no settlement or any other defects'.

1.4.2.2 Cairns Airport – Queensland, Australia

The first application of pavers occurred in 1988 when a trial was made on a distressed section of the domestic apron. Following the trial about 15,000m^2 of 80mm thick pavers were installed on three aircraft parking bays on the International apron during August and September 1990. The construction of the aircraft pavement, which has a design life of 15 years, is:

80mm non-rectangular pavers – treated with 'Supersand'
20mm sand
5–7mm prime and seal coat
250mm cement bound (2%) fine crushed rock (20mm)
250mm crushed rock sub-base
subgrade CBR stated to be 20%

The mix of aircraft using the apron stands comprises Boeing B747-400, McDonnell Douglas DC10, Airbus A300 and Boeing B767. The forecast number of B747 movements over the design life is 8000. Performance of the pavement is said to be 'excellent'. A major fuel spill of 7500 litres occurred on one section of pavers about six weeks after construction with no visible effect. No loss of shape in wheel tracks or standing positions has been noted to date.

1.4.2.3 Cayman Brac Airport – British West Indies

A small apron/turning area of approximately 1,000m^2 was constructed in 1987/1988 having the following construction:

80mm rectangular pavers
25mm sand
225 – 300mm crushed rock base on a prepared natural limestone formation

The area is used by light aircraft and a Boeing B727 once a week. The performance of the pavers is stated to be satisfactory apart from some chipping of a few pavers. This is considered by the aerodrome operator to be due to the fact that the pavers did not have spacer nibs.

1.4.2.4 Owen Roberts Airport – Grand Cayman, British West Indies

In November 1992 an apron area of 9,800m^2 was constructed as follows:

800mm rectangular pavers – sealed with a proprietary sealer
25 – 50mm sand
150 – 230mm asphaltic base course
175mm crushed rock base

The mix of aircraft using the apron area comprises Boeing B737, B727 and miscellaneous twin engine aircraft. Normally each stand has 1 or 2 aircraft movements per day. Performance of the pavers is stated to be 'very good' although there has been some rutting and cracked blocks which have been replaced. It was further stated that the sealer has not performed satisfactorily.

1.4.2.5 Dallas/ Fort Worth International Airport – Texas, U.S.A.

During the period September to November 1990 four independent lengths of taxiway having a total area of 24,000m^2 were constructed adjacent to the 18R/36I runway. Details of the construction are:

80mm rectangular pavers – sealed with proprietary polymer sealer
38mm sand
685mm cement treated base
lime/ flyash stabilised clay subgrade

The design life of the taxiway is 20 years. A wide range of aircraft up to Boeing B747 use the taxiways.

1.4.2.6 Fujairah Airport – United Arab Emirates

Between 1988 and the present time 30,000m^2 of pavers have been laid on:

80mm thick shaped pavers
30mm sand
300mm natural aggregate screened to remove fractions greater than 75mm
The subgrade strength varied widely between 23% and 160% CBR

The areas are trafficked by light aircraft and military helicopters.

1.4.2.7 Nairobi International Airport – Kenya

Between 1991 and 1992 a 56,000m^2 apron area was constructed. The limited information obtained suggested that the pavement construction comprises:

80mm rectangular pavers
50mm sand
2 layers of lean mix concrete (depth not stated)

The apron is being used by aircraft up to B747.

1.4.2.8 Subang Airport – Kuala Lumpur, Malaysia

Between September and December 1992 an apron area of 68,000m^2 was constructed as follows:
80mm rectangular pavers – treated with 'Supersand'
38mm sand
100mm lean mix concrete
650mm crushed rock

1.4.2.9 Kristiansand Airport – Norway

During 1990 the existing asphaltic apron stands at this airport were provided with an inlay of 80mm thick shaped pavers. The total area of pavers installed was 6,800m^2 and the joints were treated with a polymer sealer. Aircraft using the stands are mainly Boeing B737-400s.

1.4.2.10 Stavanger/Sola Airport – Norway

As part of the ongoing maintenance scheme the military part of the airport apronage is being reconstructed. Up to the beginning of 1994 approximately 13,000m^2 had been completed. The new pavement construction comprises:

80mm thick shaped pavers – sealed with polymer sealer
30mm sand
140mm crushed stone on a prepared crushed stone formation with a 12% CBR

Part of the area is used for helicopter parking and the remainder is used by F-16 military transport aircraft. Additionally, a hangar apron has been constructed at this airport with the following construction:

80mm thick shaped pavers – sealed with a polymer sealer
30mm sand
60–240mm crushed stone base on a sandy peat subgrade

The apron stand is used by aircraft up to B737-400.

1.4.2.11 Trondheim Airport – Norway

A 26,000m^2 new apron area is currently under construction. Details of the pavement are:

80mm thick UniColoc pavers – sealed with a polymer sealer
30mm sand
400–1200mm crushed stone base

Aircraft using the stands will be up to Boeing B737-400.

1.4.2.12 St. Augustine Airport – Florida, U.S.A.

During September 1992 an aircraft parking area was built having the following construction:

80mm rectangular pavers
25 – 37mm sand
150mm crushed aggregate base
300mm stabilised soil sub-base

The pavement is used by single and twin-engined General Aviation aircraft and executive jets. The performance of the pavers is stated to be 'excellent'.

Table 3 World-wide use of pavers on aircraft pavements

Airport	*Area of pavers (m^2)*	*Year installed*	*Pavement use*	*Aircraft using pavement*
Ben Gurion Israel	13,000	1990 & 1992	Apron	B747, B707, B727 & DC10
Cairns Australia	15,000	1990	Apron	B747, DC10, B767 & A300
Cayman Brac B.W.I.	900	1987/ 1988	Apron	Light aircraft & B727
Grand Cayman B.W.I	9,800	1992	Apron	B727, B737 & Light aircraft
Dallas/ Fort Worth U.S.A.	24,000	1990	Taxiways	Up to B747s
Fujairah U.A.E.	30,000	1988 – present	Apron, Taxiway Fuel Area	Light aircraft Helicopters. 3 new stands for B747s
Jomo Kenyatta Kenya	56,000	1991/1992	Apron	Up to B747s
Subang Malaysia	68,000	1992	Apron	B747 & A300
Kristiansand Norway	6,800	1990	Apron	B737
Stavanger/ Sola Norway	13,000	1990 – present	Apron	F-16 military B737
Trondheim Norway	26,000	1993/ 1994	Apron	B737
St. Augustine FL U.S.A.	5,000	1992	Apron	Twin engine General aviation
Wellington New Zealand	1,500	1989 – 1991	Apron	B767, B737 BAe 146

1.4.2.13 Wellington Airport – New Zealand

Between 1989 and 1991 an apron area of approximately 1,500m^2 was constructed incrementally. The construction is stated to be 80mm pavers on sand on a 60mm base course. Aircraft using the area comprise Boeing B767, B737 and BAe 146. The number of aircraft movements is given as approximately 6,000 per year. Comments have been unfavourable and this may be due to inadequate pavement thickness.

Table 4 Military use of pavers at airfields in the United Kingdom

Airfield	*Area (m^2)*	*Pavement use*
Abingdon	14,000	Aircraft fuelling area
Brize Norton	37,000	Apron
Dishforth	19,000	Helicopter pads
Dunsfold	2,500	Runway end Aircraft servicing area
Lyneham	6,500	Apron
Northolt	63,000	Apron
Scampton	3,300	Apron
Stornoway	14,000	Apron
Valley	19,000	Helicopter pads
Woodvale	4,600	Apron

1.5 Specification for pavers and bedding sand

Figure 5 illustrates the courses which comprise a paver pavement. The design of pavements using both clay and concrete pavers is covered by BS7533 (1992) Structural Design of Pavements Constructed with Clay or Concrete Block Pavers. London, 15pp.[8], and is dealt with later in this report.

The specifications for clay and concrete pavers are dealt with separately by the British Standards, the relevant documents being;

BS 6717 (1993) Part 1 : Precast Concrete paving blocks. Specifications for paving blocks. BSI, London, 8pp.[7]

BS 6717 (1989) Part 3 : Precast concrete paving blocks. Code of practice for laying. BSI, London,13pp.[9]

BS 6677 (1986) Part 1 : Clay and Calcium Silicate Pavers for Flexible Pavements. Specification for pavers. BSI, London, 8pp.[10]

BS 6677 (1986) Part 2 : Clay and calcium silicate pavers for flexible pavements. Code of practice for design of lightly trafficked pavements. BSI, London,12pp.[11]

BS 6677 (1986) Part 3 : Clay and calcium silicate pavers for flexible pavements. Method for construction of pavements. BSI, London, 12pp.[12]

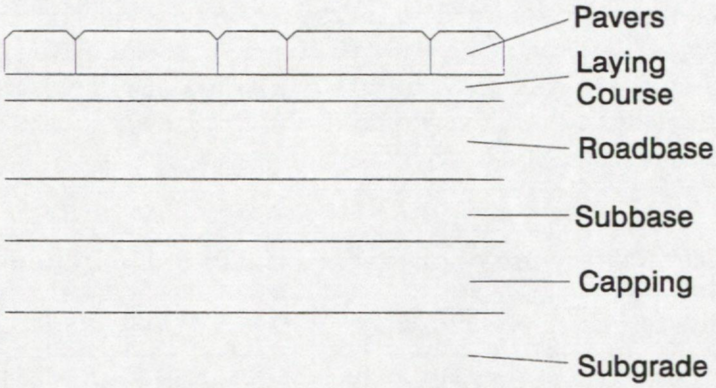


Figure 5 Cross section of Paver Pavement. Some of the courses may be absent – the capping is provided on poor subgrades only.

BS 6717 Part 1[7] specifies that '..*the preferred work size thicknesses are 60mm, 65mm, 80mm and 100mm*'. Manufacturers in the UK produce two different thicknesses of paver : 60mm and 80mm. It is generally accepted that pedestrian areas and lightly trafficked areas require only the 60mm paver, whilst all other pavements require the 80mm paver. Knapton and Cook[13] state that *'Pavers need to be at least 65mm thick to accept traffic. Thickness greater than 80mm is unnecessary.'*

This Section examines the materials used in the pavement surface; the laying course material, pavers and jointing sand. Specification and design of the remaining pavement formation is laid out in Sections 2.6 to 2.8.

Following the failure of some paver pavements attention was focused on the quality of the laying course material used in the construction of the pavement. Until 1990 the main criterion for selection of the laying course material was *'naturally occurring sand or crushed rock fines'* graded in accordance with BS 6717 : Part 3 : 1989[9] shown in Table 5.

Table 5 BS6717:Part 3 grading requirements for laying course sand and jointing sand [9]

Nominal aperture of sieve size	*% by mass passing*	
	Laying course sand	*Jointing sand*
10.00mm	100	100
5.00mm	90–100	100
2.36mm	75–100	95–100
1.18mm	55–90	90–100
600μm	35–70	55–100
300μm	8–35	15–50
150μm	0–10	0–15
75μm	0–3	0–3

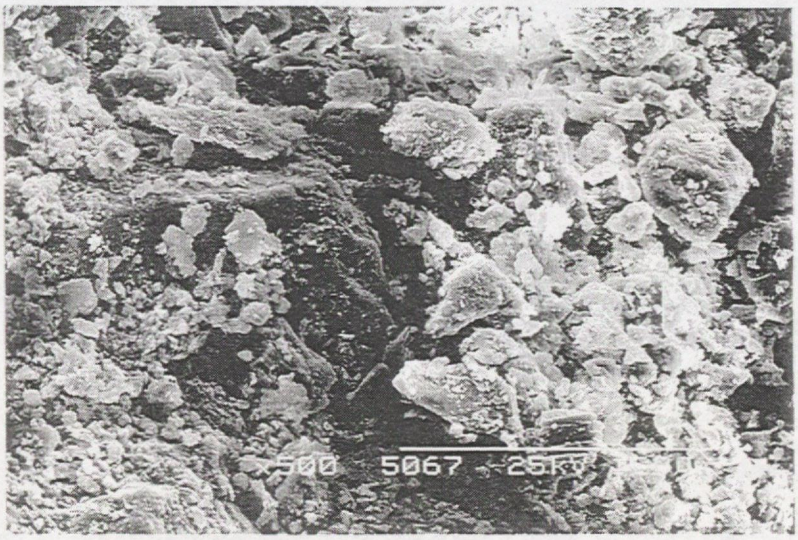


Figure 6 Micrographs illustrate the difference in the structure of naturally occurring sand grains and those obtained by crushing rock. The upper format micrograph shows a naturally occurring particle magnified X500 and the lower micrograph shows crushed rock fine material at the same level of magnification. The particles adhering together loosely in the crushed material may degrade to produce a lubricating slurry capable of collapsing the bedding sand.

Research by Cook and Knapton[13] has shown that properties other than grading are important. They conclude that naturally occurring silica sand of almost single sized grading has significantly enhanced stability over crushed rock materials which have been associated with failures e.g. Pine Street, Seattle[13]. The reason for this is the structure of the sand. Micrographs reproduced in this Report, Figure 6, show the difference between naturally occurring alluvial sand deposits and manufactured crushed rock sand. Although having been sieved to the required grading, BS 6717: 1989: Part 3[9] crushed rock sand may be made up of very angular grains which comprise an agglomeration of microscopic particles. These microscopic particles can become dislodged under the action of water and traffic to form a de-stabilising fine slurry. Under loading crushed rock sand grains abrade against one another and break down into smaller particles. It has been shown that the use of natural silica sand, which comprises very hard wearing uniformly rounded particles eliminates this problem and can thereby remove the possibility of failure.

Following investigations into several laying course failures a Bedding Sand Guide[14] has been published which defines laying course materials in terms of both grading and geological origin. Four categories of laying course material are defined in the Guide according to the pavement end use :

Category 1 Severely channelled traffic
Industrial pavements
Bus stations
Loading bays

Category 2 Adopted Highways
Petrol station forecourts
Regular heavy traffic
Aircraft pavements

Category 3 Occasional heavy traffic
Car parks
Driveways
Overridden footpaths

Category 4 Footways

The grading limits for each of these four categories are as follows:

Category	*% of sand passing 75 micron sieve*	*% of sand passing 600 micron sieve*
1	Less than 0.1%	Less than 60%
2	0.1% to 1.0%	Less than 60%
3	1.0% to 3.0%	Less than 70%
4	3.0% and above	Less than 70%

The most significant distinction between the laying course specifications of BS6717 : Part 3[9] and the Sand Guide[14] is in the fraction permitted to pass a 75 micron sieve. For all categories, BS 6717 : Part 3[9] allows 3% 75 micron material to pass whereas the Sand Guide limits the fraction to the values set out above. One further point to note is that the British Standard permits the use of crushed rock fine material whereas the Sand Guide recommends only naturally occurring sands quarried from geologically recent quaternary beds i.e. materials quarried from loose beds. The recommendations in the Blockleys Sand Guide have been incorporated into the County Surveyors' Society *Pavement Design Manual* ENG/6-94.

It is recommended that County Surveyors' Society Pavement Design Manual ENG/6-94 Category 2 sands be specified for aircraft pavements, other than those in which a hydrostatic pressure head of 1m or more can develop, in which case a Category 1 sand should be specified. This will prevent the water fluidising the sand so that sand instability will be prevented.

1.6 Interlock

Interlock is an important property of pavers. It can be defined as the inability of an individual paver to move independently of its neighbours. It allows pavers to be used as a structural substitute for conventional flexible pavement construction materials. It can be divided into its three components:

1 *Vertical interlock* – the inability of a paver to slide vertically down its neighbours. It is introduced during the vibration of the pavers into the laying course material. The laying course material compacts and is forced upwards into the paver joints so as to allow the transfer of shear forces across paver joints (See Figure 7).

2 *Rotational interlock* – the inability of a paver loaded asymmetrically to rotate independently of its neighbours. It is created by the provision of edge restraint and is completed by the filling of the paver joints by fine jointing material and can be enhanced by the introduction of a joint stabiliser (See Figure 7).

3 *Horizontal interlock* – the inability of a paver to move horizontally along the pavement. It is developed either by the laying of rectangular pavers in a herringbone pattern or by the use of proprietary shaped pavers.

Sometimes, the presence of detritus, dust, oil and rubber form a seal which can stabilise the jointing material but failure of some pavements has shown that natural sealing of the pavement cannot always be relied upon. Indeed, work by Smith and Hade[35] has shown that a pavement so sealed can become unsealed by the action of traffic. Should unsealing occur, then several problems can result: the jointing sand may be lost which can allow water to enter the lower paving layers and in extreme circumstances the strength of the subgrade can be reduced.

1.7 Erosion of jointing sand

Owing to its critical role in the development of interlock it is important to ensure that the jointing sand retains its integrity within the pavement and is not eroded. Five possible causes of erosion of jointing material have been identified:

(i) *Jet or propeller intake suction*

There is some evidence to suggest that pavers on areas subject to aircraft engines under significant load can be displaced as a result of suction in the vicinity of engines.

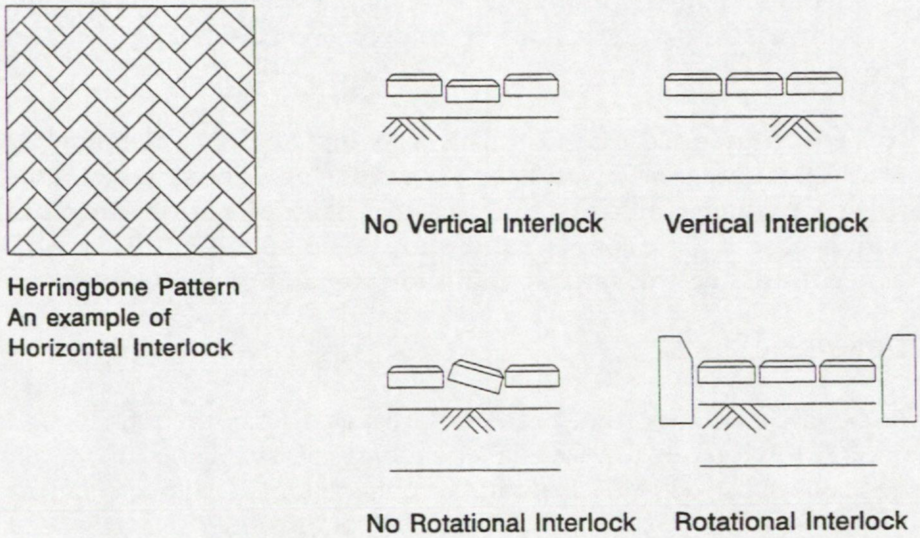


Figure 7 The creation of horizontal, vertical and rotational interlock is essential in the performance of pavers. Interlock is developed during the construction process and may be enhanced in time.

(ii) *Action of jet exhaust or propeller wash from aircraft engines*

Very high velocities and temperatures may be encountered which may have eroded unsealed jointing material. Loose sand can become a source of Foreign Object Damage (FOD) so establishing a potential source of danger on airside paving.

(iii) *Use of vacuum sweepers and high pressure cleaning equipment*

Although the forces involved in pavement cleaning are much less than those associated with aircraft engines, loss of jointing sand is still possible when vacuum cleaning is used on unsealed pavers.

(iv) *Turbulent water flow over pavements*

In areas where high water velocities and turbulence are established, e.g. around drains and gullies, loss of the jointing sand has been experienced, leading to water ingress in the lower layers and stability problems.

(v) *Degradation and liquefaction of laying course material resulting from the ingress of water through joints*

As discussed in Section 1.5, degradation of crushed rock bedding sand may occur. Although it has been accepted that construction of new pavements should avoid the use of crushed rock fines and other very fine grained materials, many existing pavements have been constructed incorporating such materials. Removal and replacement of laying course material is a costly process and one method of reducing the possibility of this problem is to reduce water ingress to a minimum since the presence of water has been found to aid the degradation of many categories of laying course material so encouraging the formation of a destabilising slurry. Various methods and materials have been tested by Emery[15] including lime dust, cement, Pulverised Fuel Ash (PFA), bentonite and commercially available polymers. In the mid 1980s, Emery found none of the then commercially available materials to be satisfactory owing to their inability to form an effective bond or in the case of the polymers a very rigid high strength matrix within the joints was formed which eventually shrank away from the pavers leaving a gap for the ingress of water. A polymer was required specifically for this purpose and four parameters for its formulation were identified by Emery[15]:

(i) an acceptable level of flexibility upon polymerisation

(ii) ability to form a bond with the jointing sand and the sides of the pavers while at the same time reducing the permeability of the joints

(iii) not shrinking or creeping away from the neighbouring pavers

(iv) ease of application.

Emery's trials[15] led to the development of a range of low viscosity flexible polymers which are now used commonly on aircraft pavements and on other categories of pavement when either moisture ingress is to be minimised or alternatively erosion of the jointing sand is feared.

1.8 British Aerospace erosion trials

(Discussion of British Aerospace Report No. BAe-WWT-EN-GEN-000131 *Results of Tests In The Wind Tunnel Department Hot Gas Laboratory To Investigate The Effects Of Direct Impingement On Pavers Treated With ACM Pavseel*)

The British Aerospace trials represent the state of the art regarding the important issue of paver joint erosion. Section 1.9 shows that joint erosion has been a crucial factor in paver failures in an aircraft pavement. A ground erosion study to investigate the effects of direct jet impingement on pavers treated with a proprietary low viscosity moisture cure polymer was carried out at the British Aerospace, Military Aircraft Limited (MAL) Hot Gas Laboratory (HGL), at Warton, England. Although only a small number of samples was tested, results showed considerable erosion resistance for treated joints when subjected to ambient or very low temperature jets. At higher jet temperatures, resistance was found to be evident but minimal.

The tests were conducted on 200mm x 100mm x 80mm thick pavers laid herringbone pattern into trays of dimensions 600mm x 600mm x 100mm. The pavers were laid on a 20mm thick screeded sharp sand into which they were vibrated so that edge restraint was provided by the edges of the steel sample tray and jointing sand was brushed into the paver joints. All joints were well filled with clean jointing sand a polymer joint stabilisation material was applied directly from the container evenly into the paver joints. The polymer was worked into the untreated joints ensuring that the jointing sand had been inundated to a depth of 15mm. Excess or unabsorbed sealant was removed. Twenty four hours minimum curing time was allowed before any testing commenced.

Prior to testing each sample tray was mounted into the static test trolley which was held in place by two clamps and two end stops to prevent the sample moving during testing. The combustion chamber was mounted vertically and the sample secured firmly beneath the nozzle as shown in Figures 8 and 9. The height of the nozzle above the sample was three nozzle diameters (approximately a *wheels on ground* case). This set up is considered the optimum for simulating a VSTOL aircraft. A heat shield was placed between the nozzle and sample to provide protection to the sample whilst the jet was brought up to test conditions. As test conditions were reached the heat shield was rapidly removed by a linear motor powered trolley. This activated an electronic timer and the sample was exposed to the jet blast for the required time. After testing the jet was shut down allowing the equipment to cool.

The criterion for determining the onset of conventional concrete erosion is the explosive removal of surface fragments spalling. This is primarily dependent upon the temperature and resulting heat transfer from the impinging jet creating severe temperature gradients within the concrete. This sets up large internal stresses which induce failure at the sample surface. Pavers are effectively 95% concrete but the loss of surface integrity resulting from the removal of the jointing sand at relatively mild jet conditions means an alternative criterion is required for the area as a whole rather than relying on spalling of individual pavers. The erosion criterion adopted for pavers is generally taken as the removal of jointing sand. The extent of this removal is variable dependent upon the final application. During testing two distinct modes of failure became evident:

1 Erosion of polymer from the surface of pavers only

2 Erosion of polymer from the surface of pavers and jointing sand leading to significant sand loss.

The first mode is not a serious risk to aircraft operation but does create a discontinuity in the material surface appearance. Mode 2 may cause a loss of integrity of the pavers dependent upon the extent and depth of sand removal. From the tests, it was concluded that erosion of sealed jointing sand occurs at a residence time of 9 seconds and a jet temperature of 500°C or at a residence time 3 seconds at a jet temperature of 800°C. Whilst these tests do not simulate the true conditions obtaining on aircraft pavements subjected to normal usage by fixed wing aircraft, they do demonstrate a weakness in pavers with untreated sand joints and they demonstrate how that weakness can be ameliorated by the use of a polymer joint stabilisation material.

1.9 Experience at Luton Airport

The first use of pavers on aircraft pavements was at Luton Airport in October 1981. Initial trials comprised two rectangular panels each of dimensions 9m x 2m constructed on aircraft stands directly beneath undercarriage gear positions. The pavers were used as an inlay in place of bituminous material and were found to remain stable under aircraft loads. Propeller wash and jet blast occurred from time to time on these initial trial areas and some loss of jointing sand was observed.

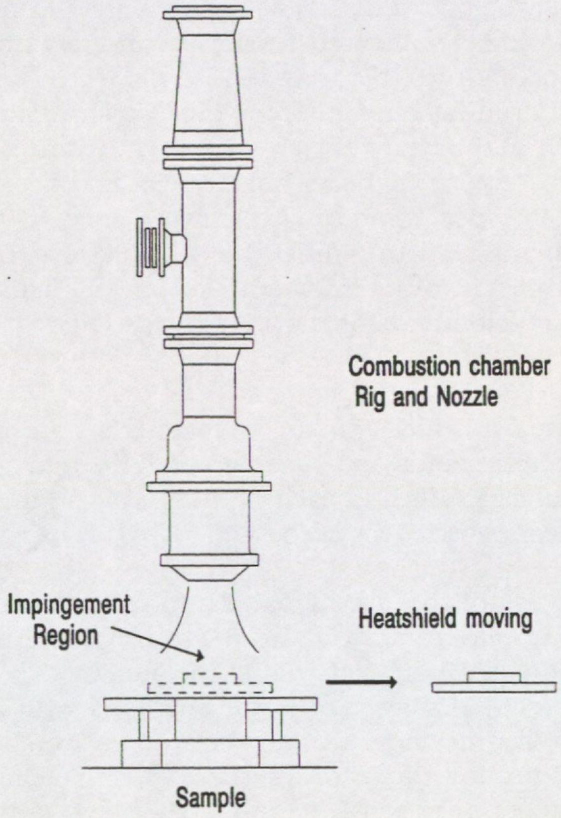


Figure 8 Hot Gas Facility test rig

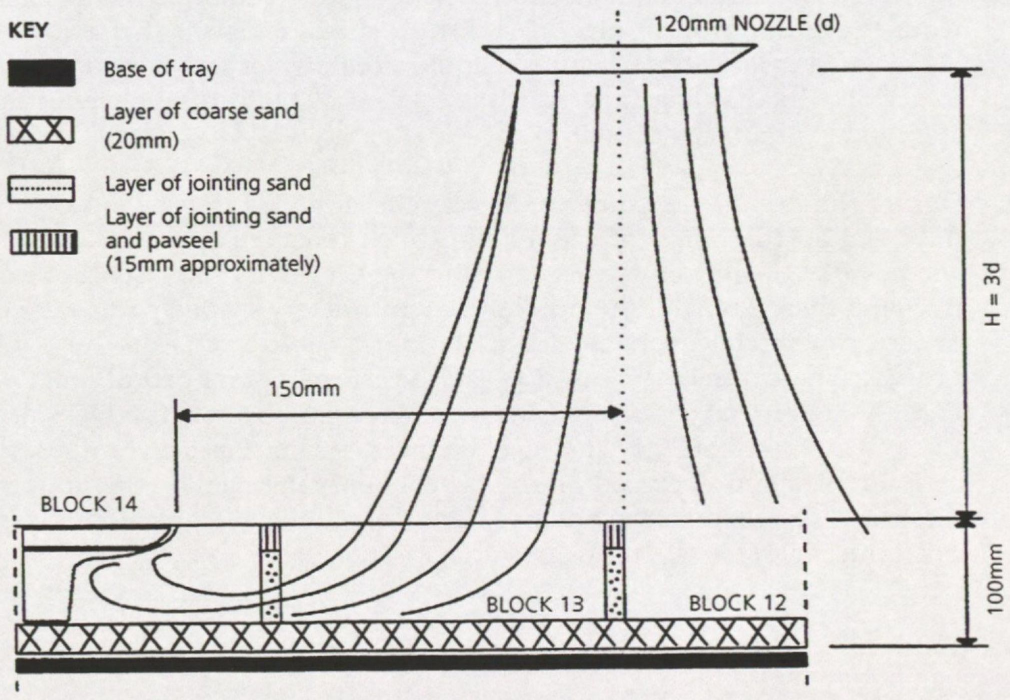


Figure 9 Details of Hot Gas Facility nozzle

In May 1982, a second trial area of 10m x 2m was installed using a proprietary shaped paver on the Eastern Turning Circle in order to assess the suitability of pavers in areas subjected to the turning action and jet blast associated with aircraft taking off. This trial area remained in service until it was overlain as a result of a runway strengthening project which commenced in November 1983. It has been estimated that this Eastern Turning Circle trial was subjected to approximately 25,000 heavy commercial aircraft movements during its 18 months service. Because some of the jointing sand had been eroded by jet blast and propeller wash on the initial trial, the Eastern Turning Circle trial incorporated lime stabilised joints between the pavers. This form of stabilisation did not prevent erosion and some concern was felt regarding the effect of the lime on aircraft.

In January 1983, nine 13m x 23m rectangular areas of pavers were installed on the main aircraft stands and these areas have remained in service with little or no maintenance to 1995. In each of these nine areas, 200mm x 100mm x 80mm thick rectangular pavers were used.

The success of the use of pavers on the main Luton stands together with the positive results from the Eastern Turning Circle trial led to the use of pavers on the turning circles at each end of the runway as part of the strengthening project. The Eastern Turning Circle was surfaced with 5000m^2 of 200mm x 100mm x 100mm thick rectangular pavers between November 1983 and March 1984 and the Western Turning Circle was surfaced with 5000m^2 of 200mm x 100mm x 80mm thick pavers between December 1984 and February 1985. On both of these turning circles, periodic inspections revealed progressive erosion of jointing sand (the joints comprised sand stabilised with either lime, cement or bentonite, none of which proved effective). An incident occurred in July 1987 in which an area of 2m^2 bulged upwards to a height of approximately 100mm when one of the 100mm thick rectangular pavers on the Eastern Turning Circle was discovered beneath its neighbours, presumably having been forced there by the exhaust blast from the engine of an aircraft taking off. As a result of the joint erosion culminating in the above failure, a liquid pre-polymer was developed specifically to stabilise the jointing sand and was applied to both turning circles in October 1987 and joint erosion ceased.

During the period November 1988 to February 1989, reprofiling of the runway necessitated the burial of the 100mm thick rectangular pavers laid during the winter of 1983–1984 on the Eastern Turning Circle and the installation of 5500m^2 of 80mm thick pavers at the new level. A proprietary shaped paver was selected in order to facilitate mechanical installation so as to speed up the construction process. The contractor elected to lay the pavers onto a bed of 6mm grit rather than the more conventionally graded sand. Those pavers on the Western Turning Circle were unaffected by the level changes to the runway. From March 1989, a series of incidents occurred on the pavers newly installed on the Eastern Turning Circle and several repairs were made until all of the pavers were removed in 1992. The principal events at Luton are summarised in Table 6.

Table 6 Summary of principal events in the use of pavers at Luton Airport

Date	*Event*	*Area*	*Paver Type*
October 1981	Initial stand trials	36m^2	65mm & 80mm thick rectangles
May 1982	Turning Circle trial	20m^2	80mm thick 'SF' shaped pavers
January 1983	Nine stands paved	2,700m^2	80mm thick rectangles
November 1983	Eastern Turning Circle paved	5,000m^2	100mm thick rectangles
December 1984	Western Turning Circle paved	5,000m^2	80mm thick rectangles
May 1987	Trial area laid on taxiway	20m^2	75mm thick 'G-Block' paver
July 1987	Single paver displaced on Eastern Turning Circle		100mm thick rectangular paver
February 1989	Eastern Turning Circle re-paved	5,500m^2	80mm thick 'Coloc' shape
March 1989	Pavers displaced on Eastern Turning Circle	100m^2	80mm thick 'Coloc' shape
November 1990	Pavers displaced on Eastern Turning Circle, replaced with rectangles	150m^2	80mm thick 'Coloc' shape
March 1991	Remainder of Eastern Turning Circle repaved	5,300m^2	80mm thick rectangles
September 1992	Pavers displaced on Eastern Turning Circle	200m^2	80mm thick rectangles
November 1992	All pavers removed from turning circles	10,500m^2	80mm thick rectangles
June 1993	Pavers used on New Freight Facility	6,000m^2	80mm thick rectangles

1.10 Analysis of Luton Airport events

From Table 6, it can be seen that the events at Luton fall into three periods, viz.:

(1) *October 1981 to May 1982*
Trials undertaken to establish the suitability of pavers for aircraft pavements.

(2) *November 1983 to August 1986*
A period of nearly three years during which rectangular pavers performed satisfactorily on stands and on the Eastern turning circle.

(3) *July 1987 to November 1992*
The failure of rectangular pavers in July 1987 was followed by the failure of 'Coloc' pavers laid on Eastern Turning Circle on two occasions. They were

replaced with an initial rectangular paver inlay, followed by complete replacement with rectangular pavers. A final failure of the replacement rectangular pavers led to the removal of all turning circle pavers

The following conclusions can be drawn from the experience at Luton.

In each of the Eastern Turning Circle failures, there has been reason to question the stability of the paver joints. An assessment of the pressures which can be developed by jet engines indicates that it is likely that the pavers were removed either by suction in the vicinity of engines or by pressure in the laying course developed by exhaust gases entering the paver joints until the net positive pressure beneath a paver became sufficient to counter the weight of the paver plus the interlocking effect. It is possible that the surface had been lifted on previous occasions but the interlocking nature of the pavers had prevented an individual paver from becoming displaced. The fatigue effect of regular lifting of the pavers eventually reduced the interlocking effect to zero so that the jet pressure variation needed only to counter the weight of a paver to lift it from the pavement. In the case of the failures of 'Coloc' pavers, the unusual grading of the laying course material may have contributed to the failure since its open textured nature may have exacerbated the development of positive pressure beneath the pavers.

The regular turning and braking (not accelerating) of aircraft would apply large horizontal forces to the pavers such that the horizontal interlock generated by the jointing material would eventually fail. For example, a Boeing 737-300, the most common aircraft using the turning circles, has a maximum takeoff weight of over 56,000kg and one main gear wheel applies 13,000kg vertically to the pavement. It would seem reasonable to assume that turning and braking could lead to lateral or longitudinal accelerations of 0.3g so that lateral forces of over 4000kgf(40kN) can be applied and may have been present. A Boeing 757-200 would apply approximately the same horizontal force and a dual tandem gear wide body aircraft would apply approximately twice this load. Experience in the use of pavers on highways suggests that a lateral force of 40kN applied to pavers repetitively would be sufficient to disturb even an elastomeric polymer stabilised joint so significantly increasing the possibility of jet effects disturbing pavers. Once pavers have been displaced laterally the likelihood of jet effects disturbing pavers becomes greater.

From the above and from an assessment of the particular site and construction conditions, it can be concluded that the Luton Airport Eastern Turning Circle incidents occurred as a result of the use of pavers in a critical location where the combination of large horizontal forces and severe jet effects applied over long periods (the aircraft would be travelling slowly) led to the gradual reduction of interlock so that ultimately little more than the weight of individual unconnected pavers prevented failure. The unusual bedding material (predominantly 6mm single sized grit), the presence of water in the bedding sand, the laying of the pavers by mechanical means in clusters and the lack of joint stabilisation may have each contributed to the failures. Effectively, the following factors may have contributed to conditions which were conducive to the loss of pavers:

(a) Severe lateral loads on a turning circle.

(b) Full thrust engines when aircraft are lined up for takeoff.

(c) Trafficking by Boeing 737-300,-400 aircraft with low slung engines.

(d) Abnormal paver joint widths around clusters in the case of the mechanically laid 'Coloc' system.

(e) The inclusion of a rigid concrete section within the area of pavers.

1.11 Conclusions from Luton Airport events

Some or all of the following factors need to be addressed on a case by case basis for all areas of paving.

(a) Structural design of the pavement structure.

(b) Detailing of the surfacing to ensure full interlock is developed throughout the pavement.

(c) Construction to be to a high standard, including supervision. Mechanical laying of pavers to be permitted only when cluster effects are absent.

(d) Particular attention to be paid to all aspects of laying course.

(e) Joints to be resistant to erosion and ingress of liquids.

(f) Regular inspection system including abnormality recording.

(g) Maintenance to be carried out expeditiously.

(h) Surface and sub-surface drainage.

(i) Edge restraint in relation to horizontal loading.

1.12 Structural comparison of pavers and asphalt

Since the early 1970s, research has been undertaken in the UK to understand better the contribution that pavers make to the structural performance of pavements. Much of the research has concluded that when loaded, pavers behave in a manner which allows them to be equated with asphalt on a thickness for thickness basis[16]. Researchers have concluded a wide variation in the thickness of asphalt to which pavers should be equated[17,18,19]. For example, Lilley & Walker concluded that pavers behaved in a similar manner to 225mm thickness of lean concrete[17] whilst Woodman showed that in some circumstances, pavers added negative value to the strength of a pavement[18]. However, during recent years, a consensus has emerged whereby pavers are considered to equate to asphalt on an equal thickness basis, i.e. 80mm pavers bedded on 30mm sand perform in a similar manner to 110mm thickness asphalt[19]. This consensus is used in the FAA design method adaptation and in the PSA design method adaptation set out in Sections 2 and 3 of this Report. One particularly relevant piece of research was reported at The Third International Conference on Concrete Block Paving by **J. A. Emery**, *('An evaluation of the performance of concrete blocks on aircraft pavements at Luton Airport')*[15]. The work is important because it represents the first reported attempt to measure the contribution of pavers to the structural performance of an aircraft pavement.

Tests were performed to find the contribution pavers make to the overall strength of an aircraft pavement in terms of its Load Classification Number(LCN). The tests were undertaken by the Department of Civil Engineering Services (Airfields branch) of the Property Services Agency for Luton Airport at the Western Turning Circle. A section of pavement was to have its bituminous surface removed so the airport took the opportunity to measure the strength of the pavement before removal of the surface, when the surface had been removed and after pavers had been installed in place of the bituminous material. A seventy ton mobile plate bearing test rig was used as follows:

(1) on original bituminous overlay which comprised 40mm grouted open macadam on 85mm Marshall asphalt,

(2) on the underlying 250mm thick PQC, i.e. after removal of bituminous overlay,

(3) on the 80mm thick pavers on 50mm thick laying course sand.

Pavement Construction	Stage 1 Bit. surface 250mm PQC 100mm DLC	Stage 2 250mm PQC 100mm DLC	Stage 3 80mm pavers Sand 250mm PQC 100mm DLC
Mean of safe loads(x), based on 10 tests	240.25kN	223.25kN	255.58kN
Standard Deviation(SD)	26.89kN	28.18kN	14.28kN
Working Load, x-SD/2	226.81kN	209.20kN	248.44kN
Coeff. of variation	11%	13%	6%
LCN	64	60	73

Figure 10 Luton Airport plate bearing test results

Ten plate bearing tests were carried out at each of the three stages. The basic test method used was the rigid centre test which uses a 457mm diameter plate. Each test was carried out on an individual 5 metre square concrete bay to ensure that results were not influenced by cracks caused by tests at a previous stage. The ten locations for stages two and three were adjacent to the earlier stage. This minimised the effect of variations in subgrade strength, concrete strength and layer thickness. As far as possible the load was applied to the centres of underlying concrete bays to avoid interference from the joints. The LCN values were obtained from plate bearing tests. Figure 10 indicates the results obtained.

A comparison of the results indicates that the paver surface shows a 14% increase in the value of the LCN as compared with that of the original bituminous surfacing, and a 21.7% increase over that of the original 250mm thick rigid pavement. The LCN value obtained during the stage one tests is less than expected from a 100mm Marshall asphalt overlay on a PQC base. This may be accounted for by the fact that the top 40mm of the bituminous surface was a grouted macadam, which has a lower strength than the underlying Marshall asphalt. From these trials it was concluded that 80mm pavers on 50mm bedding sand are equivalent to approximately 100mm bituminous materials. This conclusion has been used to develop the Material Conversion Factor for pavers included in Table 18 (Section 2.10)

1.13 Maintenance of paver pavements

The comments made by owners of aerodromes where pavers have been in service for several years indicate that on correctly designed, specified and constructed paver pavements, maintenance has been minimal. The principal concern lies in those projects where pavers have been laid on runways or on areas subjected to loading similar to that experienced by runways. For example, the experience on the Luton Eastern Turning Circle shows that paver pavements in such areas can fail in a dramatic way with little advance warning. Because of the experience at Luton, it is recommended that pavers should not be installed on runways or areas where engines are run at high thrusts but in cases where pavers already have been installed on runways, engine test bays or on similar high speed areas they should be subjected to an inspection regime as follows.

It is recommended that pavers should be inspected regularly. A typical suggested regime for pavers installed on runways, areas where aircraft engines are run at high thrust values and high speed taxiways should include regular inspections at intervals of between one week and one month according to the level of loading. During those inspections, attention should be focused on bedding sand erosion and tapping the surface to detect separation of pavers from bedding sand. Because each $1m^2$ of paving contains approximately 14m length of joint, examining all of the area exhaustively would be impractical. It is recommended that at least five representative locations be chosen and an exhaustive examination of $1m^2$ be undertaken at each location. The degree of joint erosion should be assessed by probing the joint with a calibrated gauge. Where 5mm or more erosion is measured, remedial work should be undertaken on the eroded area. This will involve lifting the pavers, rescreeding the bedding material and relaying either new pavers or those recovered. The joints should be refilled and stabilised.

The frequency of inspection of other paver areas should depend upon several factors. Areas subjected to jet blast or propeller wash should be inspected more frequently than areas subjected to rolling aircraft. Areas trafficked by heavy aircraft should be inspected more frequently than those trafficked by light aircraft. Areas including lighting or other features where pavers have been cut to obstructions should be inspected particularly thoroughly.

There should be no reason to question the slipperiness of pavers. After initial installation, pavers maintain a level of skidding resistance which cycles through high and low values on an annual basis in common with traditional surfacing materials. It is recommended that pavers should be dealt with in exactly the same way as bituminous surfacing materials.

The results of each inspection should be recorded even when no adverse comments are made. A standard recording system should be introduced and the following items should be incorporated in the recording system:

(a) Date, time, location, inspector.

(b) Number of $1m^2$ areas inspected.

(c) Representative erosion depth.

(d) Any paver spalling, cracking or surface defect.

(e) Surface irregularity including steps between pavers.

(f) Ponding or evidence of recent standing water.

(g) Pavement surface draining fully.

1.14 Detailing of paver pavements

Experience in the construction and use of pavements surfaced with pavers both in aircraft pavements and in other types of pavements indicates that the following areas require particularly careful consideration:

1.14.1 *Drainage, falls and laying tolerances*

The falls which are normally recommended in highways applications are often too steep to permit the efficient operation of aircraft and maximum falls of 1 in 100 are commonly specified in aircraft pavements. In such flat pavements, high quality installation is required to avoid ponding. This can usually be achieved only by precompacting the bedding sand and by ensuring that the pavers and installation conform in all respects with BS6717:1988:Part 1 *'Precast Concrete Paving Blocks. Part 1 Specification for Paving Blocks. Part 3 Code of Practice for Laying'* [7].

1.14.2 *Edge Restraint*

Edge restraint is a crucial component of the stability of pavers. In many aircraft applications, standard highway practice will be insufficient and edge restraint will need to be designed from first principles taking into account the horizontal forces transmitted by aircraft wheels and the internal forces generated by thermal expansion of the pavers where they have been installed in large contiguous areas. For example, buckling took place on a $63,000m^2$ area during warm weather as a result of the edge restraint rotating on an overlay project where the edge restraint had been fixed to the underlying course by adhesive and not by dowel bars. Particular care in this respect needs to be taken for pavers laid in cold conditions. It may be that expansion joints can be incorporated to reduce internal forces but care must be taken to avoid losing restraint.

1.14.3 *Edge Detailing*

Poor workmanship in forming edging not only looks unattractive but can lead to pavement failure. In general, BS6717:1988:Part 3 *'Precast Concrete Paving Blocks. Part 3 Code of Practice for Laying'* [9] should be followed. Where special edge units are available, consideration should be given to their use and where cutting cannot be avoided, units should be sawn and not split. A higher quality edge can often be achieved by installing an end to end stretcher course around the perimeter of the project so that cut blocks adjoin other blocks rather than other material. If at all possible, special fittings should be used to avoid cutting, especially at edges abutting other paving materials where traffic passes directly over the edge.

1.14.4 *Drainage of bedding sand*

Several failures in highway pavements have occurred as a result of the bedding sand losing stability in wet conditions. As a result, there has been a move towards creating positive drainage in the bedding sand and in some cases, failure has occurred because of migrating water transporting the finer fractions of the bedding sand. Section 1.5 provides guidance in the specification of bedding sand. Positive sand drainage should be provided only where there would otherwise be the opportunity for a significant pressure head to develop within the bedding sand. This will depend upon the difference in levels between areas of paving. In cases where levels across a paved area vary by more than one metre, consideration should be given to specifying bedding sand drainage. This is true even when joint stabilising materials are used since they do not fully prevent the ingress of water. However, experience indicates that the provision of joint stabilisation material inhibits the ingress of water.

1.14.5 *Intermediate restraint*

There has been experience in large areas of aircraft pavements (e.g. several adjacent stands) of thermally induced creep leading to the opening of joints subsequent to installation. Consideration should be given to the subdivision of such areas by intermediate restraint. Also, the construction of restraint within an area is sometimes necessary in phased construction and has been used to avoid the build up of internal forces generated by thermal expansion. The introduction of intermediate restraint can generate significantly increased costs, particularly in relation to paver cutting and can lead to differential settlement and ponding. There have been cases where the weakening of the pavement at the intermediate restraint has resulted in relatively high levels of maintenance.

1.14.6 *Joint tightness*

A fundamental feature of pavers is their simplicity of laying whereby a paver is placed 'hand tight' against its neighbours. Where attempts have been made to lay pavers tighter than usual, spalling and surface buckling has occurred. Where pavers have been laid deliberately loose, the surface has remained loose and failed to develop interlock. Experience indicates that rectangular pavers take up the 'hand tight' spacing more reliably than do pavers of dentated shaped: indeed, all of the commercially available pavers in the UK include spacers or nibs to help to regulate the joint width and to thereby prevent spalling and ensure that interlock is developed. In larger projects, care should be taken to ensure that pavers manufactured at similar mould wear rates are laid together: there can be a significant growth in paver plan dimensions during the wearing of a mould so much so that trying to integrate the two extremes is virtually impossible.

1.14.7 *Regulating courses in overlay work*

It is frequently the case that new surface levels will not follow the profile of the original surface and a regulating course will be needed. Whilst some variation can to achieved by deliberately adjusting laying course thickness, the minimum thickness should be 20mm and the maximum should be 50mm. Even then, precompaction should be carried out and an initial layer of constant thickness should be pre-compacted followed by the tapering layer. In cases where a greater make up is required, Cement Bound Material or Dense Bitumen Macadam protected with a fuel resistant slurry seal in areas where fuel ingress might otherwise damage the bitumen has been found to be suitable. Often, the material can be laid directly over the existing surface but it may be necessary to treat the surface. For example, cracks and joints in the pavement below should first be sealed and a bituminous tack coat may be required to ensure waterproofing and to assist in adhesion. Unless a significant proportion of the regulating course is of constant thickness, it should not be considered to contribute to the strength of the pavement.

1.14.8 *Paver types*

Rectangular pavers of nominal plan dimensions 100mm x 200mm and of thickness 80mm and incorporating a chamfer around their upper perimeter have been found to be suitable. In some applications, dentated units have been preferred usually in conjunction with mechanical laying systems to increase the rate of working. The great majority of pavers used in the UK comprise rectangular units and unless there are compelling reasons to the contrary, rectangular units are suggested. The pavers should comply with BS6717:1988:Part 1 *'Precast Concrete Paving Blocks. Part 1 Specification for Paving Blocks'*. [7]

1.14.9 *Additional Specification Guidance*

Ministry of Defence has produced 'Concrete Block Paving for Airfields' which gives guidance on specifying and detailing pavers for military airfields. The document was prepared by Defence Estate Organisation (Works) and was published in March 1996 by HMSO.

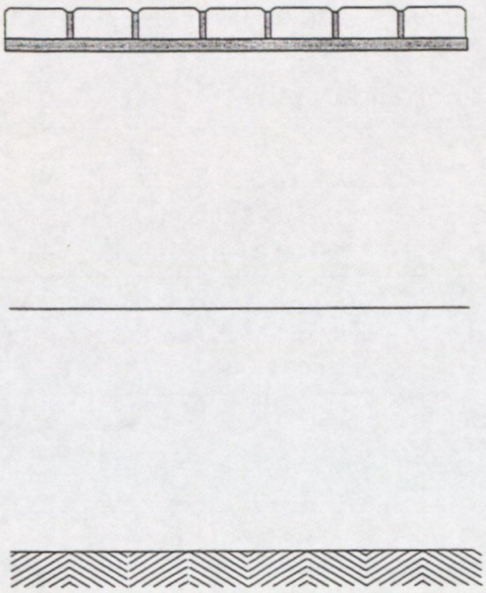
2 DESIGN OF AIRCRAFT PAVEMENTS SURFACED WITH PAVERS

One of the principal purposes of an aircraft pavement is to dissipate high stresses applied to its surface so that much lower stress levels are transmitted into the supporting subgrade. Subgrade stresses must be maintained at levels which will prevent undue deflexion or deformation of any part of the pavement or the subgrade. A design method is a procedure which provides thicknesses and properties for each layer comprising the pavement such that the subgrade maintains its support and each of the pavement layers is not overstressed.

The Federal Aviation Administration (FAA) flexible pavement design method[20] has been modified to allow aircraft pavements surfaced with pavers to be designed. The modifications comprise firstly the substitution of pavers for bituminous material as the surfacing and secondly the transformation of the FAA design charts from imperial units to SI units. This Section describes how the modified FAA method can be applied to the design of pavements surfaced with pavers. In cases where an existing pavement is to be overlain or inlaid with pavers and the existing pavement has been designed according to the Property Services Agency (PSA) aircraft pavement design method[21], then the PSA method should be used instead as described in Section 3.

2.1 Elements of a paver pavement

An aircraft pavement consists of three main parts, the *surface*, the *structure* and the *foundation* as shown in Figure 11. Design is concerned with specification of material quality and thickness for the three parts.



Surface Specification requirement set out in Section 1.5.

Structure To ensure the pavement can sustain a prescribed loading regime without undue distress.

Foundation To ensure the ground is sufficiently protected from applied load regime and to ensure sufficient support for the pavement is provided.

Subgrade Existing ground above which the pavement is constructed.

Figure 11 Typical design section indicating the principal pavement components

Essentially, the specification of the pavement structure is a function of the loading regime and the specification of the foundation is a function of ground conditions, although there is some interaction between the two. The safe performance of any aircraft pavement will be achieved only if the engineering properties of the ground beneath the pavement are fully understood and accounted for. For this reason, those soil properties relevant to pavement design are described in Section 2.2 Soil properties.

2.2 Soil properties

An accurate assessment of the strength of the pavement foundation is critical to the safety of aircraft pavements. An assessment of the strength of the subgrade material is required in order to establish its bearing capacity. The pavement distributes the loads imposed onto its surface into the subgrade. It is necessary for the pavement engineer to classify the subgrade material in order to be able to proportion the thickness of the lower courses of the pavement structure. With some soils, it is necessary to assess the variation of strength with depth. A site investigation should be carried out to determine the properties of each type of material encountered beneath the proposed pavement. Samples of soils should be taken in order to test and determine the physical properties and characteristics of the various soil materials with respect to subgrade support.

2.3 **Surveying and sampling**

The initial step in an investigation of soil conditions is a soil survey to determine the quantity and extent of the different types of soil, the arrangement of soil layers, and the depth of subsurface water. A soil auger or similar device is used to obtain a profile of the underlying soils and the extent of each layer. A suggested number of borings is given in Table 7. The locations, depths, and number of borings must be such that all important soil variations can be determined and mapped.

Table 7 Suggested Soil Boring Spacings and Depths

Area	*Spacing*	*Depth*
Runways and taxiways	Along centreline, 68m on centres.	Cut areas 3.5m below finished grade. Fill areas 3.5m below existing ground level①.
Other paved areas	1 Boring per 930 square metres of area.	Cut areas 3.5m below finished grade. Fill areas 3.5m below existing ground level①.
Borrow areas	Sufficient tests to clearly define the borrow material.	To depth of proposed excavation of borrow.

① For deep fills, boring depths should be used as necessary to determine the extent of consolidation and slippage, which the fill to be placed may cause.

2.4 **Unified classification system**

The standard method of classifying soils in the US for engineering purposes is the Unified System. It is important to review the US soil classification method because the FAA design method which this Report recommends for pavements surfaced with pavers is based upon it. The Unified System classifies soils on the basis of grain size and plasticity. The initial division of soils is based on the separation of coarse (sand) and fine (clay) grained soils and highly organic soils (peat). The distinction between coarse and fine grained is determined by the amount of material retained on the No. 200 (75 micron) sieve. Coarse grained soils are subdivided into sands and gravels on the basis of the amount of material retained on the No. 4 (6mm) sieve. Gravels and sands are then classed according to whether fine material is present. Fine grained soils are subdivided into two groups on the basis of Liquid Limit (LL) and Plasticity Index (PI). The classification system subdivides soil types into different groupings according to the following system:

GW Well graded gravels and gravel – sand mixtures, little or no fines.
GP Poorly graded gravels and gravel – sand mixtures, little or no fine.
GM Silty gravels, gravels – sand mixtures.
GC Clayey gravels, gravel – sand – silt mixtures.
SW Well graded sands and gravely sands, little or no fines.
SP Poorly graded sands and gravely sands, little or no fines.
SM Silty sands, sand – silt mixtures.
SC Clayey sands, sand – clay mixtures.
ML Inorganic silts, very fine sands, rock flour, silty or fine sands.
CL Inorganic clays of low to medium plasticity, gravely clays, silty clays, lean clays.
OL Organic silts and organic silty clays of low plasticity.
MH Inorganic silts, micaceous or diatomaceous fine sands or silts, plastic silts.

CH inorganic clays of medium to high plasticity.
PT Peat, mud and other highly organic soils.

The Unified System allows soils to be classified from any geographic location into categories to which engineering properties can be assigned e.g. particle size distribution, Liquid Limit (LL) and Plasticity Index (PI). The various groupings of this classification system have been devised to correlate in a general way with the engineering behaviour of soils. This procedure provides a useful step in any field or laboratory investigation for geotechnical engineering purposes. Once the soil has been classified, its California Bearing Ratio (CBR) can be read from Table 8. Sections 2.9 to 2.12 describe the modified FAA design procedure and the CBR is needed in order to use the modified FAA design charts. Note that when a rigid pavement is to be overlain with pavers, a design check has to be carried out on the existing concrete pavement using the PSA design method as described in Section 3 of this Report. In such cases, another property of the subgrade is required, the Modulus of Subgrade Reaction. Table 9 gives Modulus of Subgrade Reaction values for different ground conditions. Note that rigid pavements are less sensitive to changing ground conditions than flexible ones and the 4 values in Table 9 will cover all design situations.

It will frequently be the case that Table 8 will suffice and design can proceed using the CBR value in Table 8. On most projects, it will be necessary to confirm the assumed design CBR value and Section 2.5 describes the CBR measurement test. Table 8 was originally included in the UK highway flexible pavement design guide LR1132[22] and has been used in BS7533[8] the UK paver design guide.

Table 8 Relationship between California Bearing Ratio, soil description, construction conditions and location of water table.

The CBR values in this table may be used in design but it may be necessary to confirm the design values by test as described in Section 2.5. Note how the CBR of a given type of soil can vary significantly according to the conditions prevailing during construction. If the CBR falls to a low value during construction, it may remain at that low value throughout the life of the pavement.

Type of Soil	Plasticity Index	High Water Table						Low Water Table					
		Construction conditions:						Construction conditions:					
		Poor		Average		Good		Poor		Average		Good	
		Thin	Thick	Thin	Thick	Thin	Thick	Thin	Thick	Thin	Thick	Thin	Thick
Heavy clay	70	1.5	2.0	2.0	2.0	2.0	2.0	1.5	2.0	2.0	2.0	2.0	2.5
	60	1.5	2.0	2.0	2.0	2.0	2.5	1.5	2.0	2.0	2.0	2.0	2.5
	50	1.5	2.0	2.0	2.5	2.0	2.5	2.0	2.0	2.0	2.5	2.0	2.5
	40	2.0	2.5	2.5	3.0	2.5	3.0	2.5	2.5	3.0	3.0	3.0	3.5
Silty clay	30	2.5	3.5	3.0	4.0	3.5	5.0	3.0	3.5	4.0	4.0	4.0	6.0
Sandy clay	20	2.5	4.0	4.0	5.0	4.5	7.0	3.0	4.0	5.0	6.0	6.0	8.0
	10	1.5	3.5	3.0	6.0	3.5	7.0	2.5	4.0	4.5	7.0	6.0	>8.0
Silt		1.0	1.0	1.0	1.0	2.0	2.0	1.0	1.0	2.0	2.0	2.0	2.0
Sand p		← 20 →											
Sand w		← 40 →											
Sandy gravel		← 60 →											

p = poorly graded w = well graded

2.5 Soil strength assessment

2.5.1 *California Bearing Ratio & Modulus of Subgrade Reaction*

When using the FAA pavement design method, soil strength is expressed in terms of its California Bearing Ratio (CBR) which can be obtained either by direct measurement or from a knowledge of other soil information as in Table 8. When using the PSA pavement design method as described in Section 3 for assessing the suitability of existing pavements for a paver overlay or inlay, it will commonly be the case that the pavement to be overlain comprises pavement quality concrete. In that case, the Modulus of Subgrade Reaction of the subgrade is required. Table 9 gives values of both California Bearing Ratio and Modulus of Subgrade Reaction for four categories of subgrade.

Table 9 Modulus of Subgrade Reaction and California Bearing Ratio values for four strengths of soil as defined by ICAO. A Modulus of Subgrade Reaction value is needed when the procedure described in Section 3 is used to check the suitability of an existing rigid pavement for a paver overlay.

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

The CBR of a soil is determined by a penetration test which measures the force required to produce a given penetration in the material. This force is compared with the force required to produce the same penetration in a standard crushed limestone. The result is expressed in percentage terms as a ratio of the two penetration forces. Thus a material with a CBR value of 4% offers 4% of the resistance to penetration as compared with that which standard crushed limestone offers. The laboratory test should be carried out in accordance with BS1377[23]. Different subgrade materials will have different CBR values, and a conservative value is used for each category of soil. It is unusual for CBR to be measured directly since it can usually be determined with sufficient accuracy from LL and PI values. If the CBR is to be measured directly, it should be done so at the most adverse moisture content which the soil can reasonably be predicted to sustain. BS1377[23] includes a 72 hour soaking procedure which will be appropriate in some design situations.

Table 10 Subgrade characteristics pertinent to pavement foundations

Major	*Division*	*Letter*	*Name*	*Compaction Equipment*	*Field CBR*
Coarse grained	Gravel and gravely soils	GW	Gravel or sandy gravel, well graded	Crawler-type tractor, rubber-tyred equipment, steel-wheeled roller	60–80
		GP	Gravel or sandy gravel, poorly graded	Crawler-type tractor, rubber-tyred equipment, steel-wheeled roller	35–60
		GU	Gravel or sandy gravel, uniformly graded	Crawler-type tractor, rubber-tyred equipment	25–50
		GM	Silty gravel or silty sandy gravel	Rubber-tyred equipment, sheepsfoot roller, close control of moisture	40–80
		GC	Clayey gravel or clayey sandy gravel	Rubber-tyred equipment, sheepsfoot roller	20–40
	Sand and sandy soils	SW	Sand or gravely sand, well graded	Crawler-type tractor, rubber-tyred equipment	20–40
		SP	Sand or gravely sand, poorly graded	Crawler-type tractor, rubber-tyred equipment	15–25
		SU	sand or gravely sand, uniformly graded	Crawler-type tractor, rubber-tyred equipment	10–20
		SM	Silty sand or silty gravely sand	Rubber-tyred equipment, sheepsfoot roller, close control of moisture	20–40
		SC	Clayey sand or clayey gravely sand	Rubber-tyred equipment, sheepsfoot roller	10–20
Fine grained	Low compressibility LL<50	ML	Silts, sandy silts, gravely silts, or diatomaceous soils	Rubber-tyred equipment, sheepsfoot roller, close control of moisture	5–15
		CL	Lean clays, sandy clays, or gravely clays	Rubber-tyred equipment, sheepsfoot roller	5–15
		OL	Organic silts or lean organic clays	Rubber-tyred equipment, sheepsfoot roller	4–8
	High compressibility LL>50	MH	Micacceous clays or diatomaceous soils	Rubber-tyred equipment, sheepsfoot roller	4–8
		CH	Fat clays	Rubber-tyred equipment, sheepsfoot roller	3–5
		OH	Fat organic clays	Rubber-tyred equipment, sheepsfoot roller	3–5
	Peat and other fibrous organic soils	Pt	Peat, humus, and other	Compaction not practical	

2.5.2 *Protection of Subgrade from Frost Damage*

The design of aircraft pavements must accommodate the climatic conditions which will act on the pavement during its construction phase and during its service life. Pavements constructed in areas subjected to frost action require special attention. The detrimental effect of frost action has a direct bearing on the design of aircraft pavements and is treated separately from the structural design for aircraft loadings. The degree of frost protection required is dictated by the soil conditions and climate. In the UK, fine grained soils require a pavement of thickness 450mm or greater to provide protection to the subgrade against frost damage.

2.5.3 *Subgrade Compaction*

Subgrade soils are subjected to lower stresses than the concrete pavers, base and sub-base courses. On sites with varying ground levels, cutting and filling of subgrade material is inevitable. Fills which will later support aircraft loadings should be placed and compacted to provide a stable grade. Compaction is the process of packing together soil particles by expelling air from the voids, thus increasing its dry density. Compaction increases the density, hence the strength of the soil and reduces subsequent settlement and permeability. By using modern compacting equipment, high stability levels can be achieved. There are two main types of compaction equipment used and the choice between them depends on the type of subgrade material being compacted, see Table 10.

The sheepsfoot roller is most suitable for cohesive soils and consists of hollow steel drums with numerous tapered or club-shaped feet protruding from the drum surface. Compaction of cohesionless soils can be accomplished using Smooth Wheeled Rollers, commonly with a vibratory device inside so the compaction is achieved by a combination of both pressure and vibration. Depths of up to 2m can be compacted at any one time with this type of equipment.

Subgrade stabilisation should be considered if one or more of the following conditions exist in the subgrade material: poor drainage, adverse surface drainage, frost, or a need for a stable working platform. Different soil types require different stabilising agents such as portland cement, bitumen and lime.

2.5.4 *Subgrade Strength Profile*

It is frequently the case that the critical subgrade position is at its surface where stresses generated by imposed pavement loads are greatest. However, several situations arise where the strength of the soil at depth needs to be checked. For example, a weak layer of soil beneath otherwise strong material at grade, fill material compacted to different densities or variations in moisture content or in-situ density may result in the critical position being below grade. The site investigation should include density testing at increments of depth beneath proposed grade so that a check can be made that there is no possibility of the subgrade failing at depth. The following example which is based upon an example set out in FAA Advisory Circular AC 150/5320-6C *'Airport Pavement Design & Evaluation'* [20] illustrates how a density profile check can be undertaken.

Consider an aircraft pavement designed to withstand a 154,000kg dual tandem geared aircraft over noncohesive subgrade. The site investigation revealed the data shown in Table 11.

Table 11 Variation of soil density with fill as used in example

Depth below finished subgrade (mm)	*In-situ measured % of theoretical dry density*
50	70
350	84
660	86
970	90
1270	93

In the Figure, project a line downwards from 154,000kg on the dual tandem scale and where it meets each of the four density curves (100%, 95%, 90% and 85%), project a line horizontally to the noncohesive compacted subgrade depth scale (dashed line). Each of the four horizontal projections represents the depth to which the corresponding relative density needs to to achieved. In this case, Figure 12 shows that 500mm depth of the subgrade needs to achieve 100% relative density; the next 350mm (i.e. from a depth of 500mm to a depth of 850mm) needs to achieve 95% relative density, a further 400mm needs to achieve 90% relative density (from 850mm depth to 1250mm) and 375mm needs to achieve 85% (from 1250mm to 1625mm).

Comparing the above requirements with the results of the site investigation shows that compaction must be applied to increase the density to a depth of approximately one metre. At a depth of one metre, the in-situ density has been measured to be approximately 90%. The compacted density needs to exceed 90% only at depths of less than 850mm. The compaction regime set out in Table 11 should be capable of achieving the additional density required. Otherwise, it would have been necessary to undertake in-situ stabilisation or replace the unsuitable material with imported fill compacted to achieve the requisite density profile.

2.6 Concrete and cement bound materials

The information provided in this section is based upon *'Specification for Highway works, Series 1000, Road Pavements – Concrete and Cement Bound Materials'*[24] and upon *'A Guide to Airfield Pavement Design and Evaluation'* [21] written by Property Services Agency and available from Building Research Establishment Publications Sales Office.

2.6.1 *Constituents*

The cement in cement-bound materials must comply with the materials in Table 12 or the combinations in Table 13

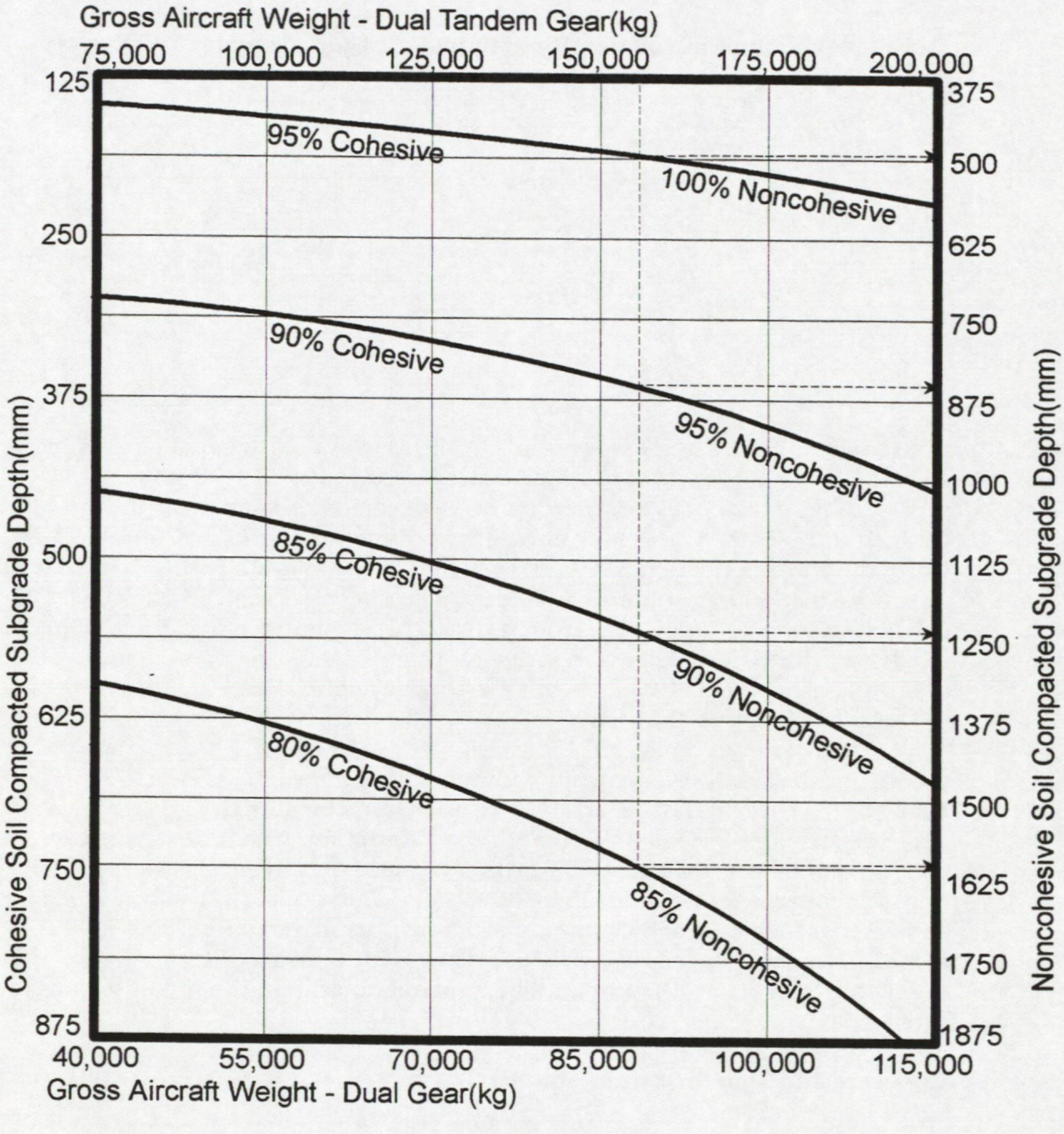


Figure 12 Modified FAA subgrade profile chart

Table 12 Cementitous Material Specifications

Cement	*Complying with*
Portland Cement (PC)	BS 12
Portland Blast furnace cement (PBC)	BS 146
Portland pulverised-fuel ash(PFA) cement	BS 6588
Pozzolanic cement (Grades C20 or below	BS 6610

Table 13 Cementitous Material Combination Specifications

Combination	*Complying with*
Portland cement with ground granulated blast furnace slag	BS 12
Portland cement with pulverised-fuel ash (PFA) for use as a cementious component	BS 3892: Part 1
Portland cement with micro silica having a current BBA certificate	BS 12

The maximum proportions of ground granulated blast furnace slag (ggbs) with Portland cement should not be greater than 65% of the total cement content for cement-bound materials. The water content should be the minimum amount required to provide suitable workability to give full compaction and the required density.

2.6.2 *Cement Bound Material Category 1 (CBM1)*

CBM1 is typically made from a material which has a grading finer than the limits in Table 14. It may be used as a sub-base but should be avoided as a base.

Table 14 Grading of aggregate materials used in the four categories of cement bound materials. The DTp specification for CBM3 relates closely to FAA base course material P-304 and is appropriate when used in conjunction with the FAA design charts.

BS Sieve Size	*Percentage by mass passing Nominal Maximum size:*			
	–	–	*40 mm*	*20 mm*
	CBM1	*CBM2*	*CBM3 & CBM4*	
50 mm	100	100	100	–
37.5 mm	95	95–100	95–100	100
20 mm	45	45–100	45–80	95–100
10 mm	35	35–100	N/A	N/A
5 mm	25	25–100	25–50	35–55
2.36 mm	N/A	15–90	N/A	N/A
600 micron	8	8–65	8–30	10–35
300 micron	5	5–40	0–8	0–8
75 micron	0	0–10	0–5	0–5

2.6.3 *Cement Bound Material Category 2 (CBM2)*

CBM2 is typically made from gravel-sand, a washed or processed granular material, crushed rock, all-in aggregate, blast furnace slag or any combination of these. The constituents of the material must fall within the grading limits shown in Table 14 Range of grading. The material must have a 10% fines value of 50 kN or more when tested in accordance with BS 812: Part 111 with samples in a soaked condition. It may be used as a sub-base but should be avoided as a base.

2.6.4 *Cement Bound Material Category 3 (CBM3)*

CBM3 is made from natural aggregate material complying with BS 882. It may be used as a sub-base or as a base.

2.6.5 *Cement Bound Material Category 4 (CBM4)*

CBM4 is made from natural aggregate material complying with BS 882. It may be used as a sub-base or as a base.

If blast furnace slag aggregate is to be used, it must comply with BS 1047: 1983. Cement for use in all cement-bound material and aggregate for use in CBM3 and CBM4 should be kept dry and used in the order in which it is delivered to the site. Different types of Cementious material must be stored separately.

2.6.6 *Drylean concrete*

Drylean concrete is a lean concrete with a low water content. Under rigid pavements the maximum aggregate to cement ratio is 15 to 1. In flexible pavements the maximum strength is $15N/mm^2$. The water content should be between 5 and 7% by weight of dry materials, the final value being selected to give the maximum dry density. The material should be rolled to give the maximum possible density.

2.6.7 *Batching and mixing*

Cement bound materials should be made and constructed as in Table 15.

Batching and mixing should be carried out in the appropriate manner described in Table 15. Where the mix-in-plant method is used and materials are batched by mass, materials should be batched and mixed in compliance with BS 5328: Part 3[25].

Table 15 Batching and Mixing of Cement Bound Materials

Field Requirements					*Specimen requirements*	
Category	*Mixing Plant*	*Methods of Batching*	*Moisture content*	*Minimum Compaction*	*Minimum 7 day Cube compressive strength (N/mm^2)*	
					Average	*Individual*
CBM1	Mix-in-Place or Mix-in-plant	Volume or mass	To suit requirements for strength, surface level, regularity and finish	95% of cube density	4.5	2.5
CBM2	"	"	"	"	7.0	4.5
CBM3	Mix-in-plant	Mass	"	"	10.0	6.5
CMB4	"	"	"	"	15.0	10.0
Drylean Concrete	"	"	Between 5% & 7% of dry weight	Maximum possible	15.0 (Maximum) (No single cube below 12)	

2.6.8 *Transporting*

Plant-mixed cement-bound material when mixed should be removed from the mixer immediately and transported directly to the point in consideration.

2.6.9 *Laying*

All cement-bound material should be placed and spread evenly in such a manner as to prevent segregation and drying. Spreading the material is undertaken concurrently with placing or without delay. Base cement-bound material is often spread using a paving machine or a spreader box and operated with a mechanism which levels off the cement-bound material to an even depth. Cement-bound material is always spread in one layer so that after compaction, the total thickness is as specified. Compaction is carried out immediately or within 2 hours of the addition of the cement. The surface of any layer of cement bound material on completion of compaction and immediately before overlaying, should be well closed, free from movement under compaction plant and from ridges, cracks, loose material, pot holes, ruts or other defects.

2.6.10 *Compaction*

Compaction should be carried out immediately after the cement-bound material has been spread and in such a manner to prevent segregation. Compaction must be completed within 2 hours of the addition of the cement. The surface of any one layer of cement-bound material on completion of compaction and before overlaying should be well closed, free from movement, compaction plant and from ridges, cracks, loose material, pot holes, ruts or other defects.

2.6.11 *Curing*

Immediately on completion of compaction, the surface of the cement-bound base or sub-base is cured for a minimum period of 7 days.

2.7 **Unbound materials for sub-bases**

The information provided in this section is based upon *'Specification for Highway works, Series 800, Road Pavements – Unbound Materials'*[24] and upon *'A Guide to Airfield Pavement Design and Evaluation'* [21] written by Property Services Agency and available from Building Research Establishment Publications Sales Office. The material should comprise an approved durable granular material such as gravel, hard clinker, crushed rock or well burnt colliery shale, blended if necessary with sand or other fine screenings.

Blast furnace slag for use of sub-base materials should comply with BS 1047[26]. Steel slag may be used provided it has been weathered and conforms to the requirements of BS 4987 Part 1[27]. Materials other than slag when placed within 500mm of cement bound materials or concrete products should have a water soluble sulphate content not exceeding 1.9g of sulphate (expressed as weight of SO_3 per litre) when tested in accordance to BS 1377: Part 3[23].

2.7.1 *Granular Sub-base Material Type 1*

Unless evidence suggests that Type 2 materials will be suitable, all granular sub-bases should be constructed from Type 1 materials which can comprise crushed rock, crushed slag, crushed concrete or well burnt non-plastic shale. The material must lie within the grading envelope of Table 16 and not be gap graded. The sub-base material is transported, laid and compacted without drying out or segregation. The material must have a ten percent fines value of 50 kN or more when tested to BS 812: Part 111[28] and an Aggregate Crushing Value of less than 30 when tested to BS 812:Part 111[28]. Additionally, the material should have a CBR of 80% or more.

2.7.2 *Granular Sub-base Material Type 2*

Type 2 granular materials are made up of natural sands, gravels, crushed rock, crushed slag, crushed concrete or well burnt non-plastic shale. The specification states that the material must lie within the grading envelope of Table 16 and not be gap graded. The material is transported, laid and compacted at a moisture content within the range 1% above and 2% below the optimum moisture content and without drying out or segregation. The material must have a ten percent fines value of 50 kN or more when tested to BS 812: Part 111[28]. Additionally, the material should have a CBR of 20% or more.

Table 16 Grading requirements for granular materials

	Percentage by mass passing	
BS Sieve Size	*Granular Sub-base Material Type 1*	*Granular Sub-base Material Type 2*
75 mm	100	100
37.5 mm	85–100	85–100
10 mm	40–70	40–100
5 mm	25–45	25–85
600 micron	8–22	8–45
75 micron	0–10	0–10

2.7.3 *Compaction of Granular Materials*

Unbound material up to 225mm compacted thickness is spread and compacted in one layer so that after compaction the total thickness is as specified. The minimum compacted thickness shall not be less than 110mm. Where the layers of unbound material are of unequal thickness the lowest layer should be the thickest layer. Compaction of unbound materials is carried out by a method shown in Table 17. The surface of any one layer of material on completion of compaction and immediately before overlaying should be well closed, free from movement under compaction plant and from ridges, cracks, loose material, pot holes, ruts or other defects. All loose, segregated or otherwise defective areas should be removed to the full thickness of the layer, and new material laid and compacted.

Table 17 Compaction Requirements for Granular Sub-base Material Types 1 and 2

Type of Compaction Plant	*Category*	*Number of passes for layers not exceeding following compacted thicknesses:*		
		110 mm	*150 mm*	*225 mm*
Smooth-wheeled roller (or vibratory roller operating without vibration)	Mass per metre width or roll:			
	over 2700kg up to 5400kg	16	Unsuitable	Unsuitable
	over 5400kg	8	16	Unsuitable
Pneumatic-tyred roller	Mass per wheel:			
	over 4000kg up to 6000kg	12	Unsuitable	Unsuitable
	over 6000kg up to 8000kg	12	Unsuitable	Unsuitable
	over 8000kg up to 12000kg	10	16	Unsuitable
	over 12000kg	8	12	Unsuitable
Vibratory roller	Mass per metre width of vibrating roll:			
	over 700kg up to 1300kg	16	Unsuitable	Unsuitable
	over 1300kg up to 1800kg	6	16	Unsuitable
	over 1800kg up to 2300kg	4	6	10
	over 2300kg up to 2900kg	3	5	9
	over 2900kg up to 3600kg	3	5	8
	over 3600kg up to 4300kg	2	4	7
	over 4300kg up to 5000kg	2	4	6
	over 5000kg	2	3	5
Vibrating-plate compactor	Mass per square metre of base plate:			
	over 1400kg/m^2 –1800 kg/m^2	8	Unsuitable	Unsuitable
	over 1800kg/m^2 –2100 kg/m^2	5	8	Unsuitable
	over 2100kg/m^2	3	6	10
Vibro-tamper	Mass:			
	over 50kg up to 65kg	4	8	Unsuitable
	over 65kg up to 75kg	3	6	10
	over 75kg	2	4	8
Power rammer	Mass:			
	100kg up to 500 kg	5	8	Unsuitable
	over 500kg	5	8	12

Notes to Table 17

- The number of passes is the number of times that each point on the surface of the layer being compacted is traversed by the item of compaction plant in its operating mode (or struck, in the case of power rammers). The compaction plant in Table 17 is categorised in terms of static mass. The mass per metre width of roll is the total mass on the roll divided by the total roll width. Where a smooth-wheeled roller has more than one axle, the category of the machine is determined on the basis of the axle giving the highest value of mass per metre width.
- For pneumatic-tyred rollers the mass per wheel is the total mass of the roller divided by the number of wheels. In assessing the number of passes of pneumatic-tyred rollers the effective width is the sum of the widths of the individual wheel tracks together with the sum of the spacings between the wheel tracks providing that each spacing does not exceed 230mm. Where the spacings exceed 230mm the effective width is taken as the sum of the widths of the individual wheel tracks only.

- Vibratory rollers are self-propelled or towed smooth-wheeled rollers having means of applying mechanical vibration to one or more rolls. The requirements for vibratory rollers are based on the use of the lowest gear on a self-propelled machine with mechanical transmission and a speed of 1.5–2.5 km/h for a towed machine. Vibratory rollers operating without vibration are classified as smooth-wheeled rollers.
- Vibrating-plate compactors are machines having a base plate to which is attached a source of vibration consisting of one or two eccentrically-weighed shafts. They normally travel at speeds of less than 1 km/h.
- Vibro-tampers are machines in which an engine driven reciprocating mechanism acts on a spring system, through which oscillations are set up in a base-plate.
- Power Rammers are machines which are actuated by explosions in an internal combustion cylinder; each explosion being controlled manually by the operator. One pass of a power rammer is considered to have been made when the compacting shoe has made one strike on the area in question.

2.8 Bituminous base materials

The information provided in this section is based upon *'Specification for Highway works, Series 900, Road Pavements – Bituminous bound Materials'*[24] and upon *'A Guide to Airfield Pavement Design and Evaluation'*[21] written by Property Services Agency and available from Building Research Establishment Publications Sales Office.

2.8.1 *General*

The aggregates used for pavement bases should be clean, hard and durable. Coarse aggregates for bituminous materials should have the following properties; a ten per cent fines value not less than 140 kN for natural crushed and uncrushed aggregates and not less than 85 kN for blast furnace slag when tested in a dry condition in accordance with BS 812:Part 111[28], an aggregate impact value not greater than 30% for natural crushed and uncrushed aggregates and not greater than 35% for blast furnace slag when tested in a dry condition in accordance with BS 812:Part 112[29].

Wherever practicable, bituminous materials should be spread, levelled and tamped by a self-propelled paving machine. The rate of the paver machine, and its method of operation, should be adjusted to ensure a uniform flow of bituminous material, thus preventing tearing and segregation of the material.

2.8.2 *Compaction*

Compaction is carried out using a large dead-weight smooth roller (8–10 tonnes) which should have a width not less than 450mm, or by a multiwheeled pneumatic-tyred roller of equivalent mass. Compaction of bituminous material should commence as soon as the uncompacted material arrives on site and should terminate when the temperatures falls below the rolling temperature of the material or when the roller marks have been removed from the surface.

2.8.3 *Macadam Base Course*

Macadam base courses should comply with BS 4987: Part 1[27]. The aggregate must be in a surface dry condition prior to mixing. When the aggregate used is gravel, 2% by mass of total aggregate of Portland cement or hydrated lime should be added. Cement or lime is not required when the gravel is limestone. The binding materials which can be used are petroleum bitumen which complies to BS 3690: Part 130, or tar bitumen complying with BS 3690: Part 3[30], or tar complying with BS 76[31].

2.8.4 *Hot Rolled Asphalt Base Course*

Hot rolled asphalt base courses must comply with BS 594: Part 1:1985[32]. The aggregate must be in a surface dry condition prior to mixing. When the aggregate used is gravel, 2% by mass of total aggregate of Portland cement or hydrated lime should be added. Cement or lime is not required when the gravel is limestone. The binding material must comply with BS 3690: Part 1[33].

2.9 Modified FAA method for flexible pavement design using pavers

It is suggested that the FAA flexible pavement design method[20] is adopted using the material specifications set out in Sections 2.6 to 2.8. The FAA method is modified by the use of materials to UK specifications and by the replacement of the asphalt surface with pavers. Section 1.11 describes research which shows this modification to be valid.

2.9.1 *Concrete Pavers*

In most parts of the world, standards have been developed for concrete pavers and these should be applied. In the UK, BS 6717 Parts 1[7] and 3[9] should be used, with restrictions in laying method and bedding sand specification. Pavers are manufactured from portland cement, and coarse and fine aggregate. Admixtures may be used to increase strength, density, and to reduce the likelihood of efflorescence. Experience indicates that 80mm thick rectangular pavers laid in a herringbone pattern are suitable for all categories of aircraft pavements (see Section 1.5).

2.9.2 *Laying Course*

The laying course material resists the compressive forces associated with high load and tyre pressure aircraft, and must be a high quality bedding sand. Laying course information is given in Section 1.5. It is important to note that highway laying course specifications may be inadequate for aircraft pavements.

2.9.3 *Base*

The base is the principal structural component of a flexible pavement and has the major function of distributing the imposed wheel loads to the sub-base and the subgrade. Concrete pavers cannot be assumed to be impervious, therefore base material selection is critical. It is recommended that CBM3, CBM4 or drylean concrete as defined in Section 2.6 should be used. Should an alternative base material be required, Material Conversion Factors can be used to determine the thickness of the alternative material. Section 2.10 explains the use of Material Conversion Factors.

2.9.4 *Sub-base*

The sub-base is an integral part of a flexible pavement in all pavements except those on subgrades classified as GW or GP. The sub-base can be constructed of either a granular or a stabilised material and it is recommended that Type 1 or Type 2 as defined in Section 2.7 should be used.

2.9.5 *Capping*

The concept of using a capping layer over low strength soils is becoming increasingly widely used in many parts of the world. The capping layer comprises locally available low cost material having a CBR value of at least 15%. It frequently comprises hardcore, crushed concrete or crushed stone of lesser quality than would be used as a sub-base.

2.9.6 *Aircraft Considerations*

The FAA pavement design method[20] requires as input the gross weight of the mix of aircraft using the pavement. The design procedure assumes 95% of the gross weight is carried by the main landing gear and 5% is carried by the nose gear. The maximum takeoff weight should be used in calculating the pavement thickness required. Use of maximum takeoff weight provides some degree of conservatism in the design, and is justified by the fact that changes in operational use can often occur. Forcast traffic is approximate at best. By ignoring relatively light arriving traffic some of the conservatism is offset.

The gear type and configuration dictate how the aircraft weight is distributed to the pavement. They also determine pavement response to aircraft loadings. It would have been impractical to develop design curves for each type of aircraft. However, since the pavement thickness is dependent upon the gear dimensions and the type of gear, separate design curves would be necessary unless some valid assumptions could be made to reduce the number of variables. Examination of gear configurations, tyre contact area, and tyre pressure in common use indicates that these follow a definite trend related to aircraft gross weight. Reasonable assumptions can therefore be made and design curves constructed from the assumed data. These assumed data are as follows:

Single Gear Aircraft — No special assumptions needed.

Dual Gear Aircraft — Spacing between dual wheels indicates that a dimension of 0.51m between the centreline of the tyres appears reasonable for the lighter aircraft and a dimension of 0.86m between the centreline of the tyres appears reasonable for the heavier aircraft.

Dual Tandem Gear Aircraft — A dual wheel spacing of 0.51m and a tandem spacing of 1.14m for lighter aircraft, and a dual wheel spacing of 0.76m and a tandem spacing of 1.40m for the heavier aircraft are assumed.

Wide Body Aircraft — Wide body aircraft, i.e., B-747, DC-10 and L-1011 represent a radical departure from the geometry assumed for dual tandem aircraft described above. Because of large differences in gross weights and gear geometries, separate design curves have been prepared by FAA for each type of wide body aircraft.

Tyre pressure varies between $0.516 N/mm^2$ and $1.380 N/mm^2$ depending on gear configuration and gross weight. It should be noted that tyre pressure exerts less influence on pavement stresses as gross weight increases, and the assumed maximum of $1.38 N/mm^2$ may be safely exceeded if other parameters are not exceeded.

The forecast of annual departures by aircraft type results in a list of a number of different aircraft. The design aircraft should be selected on the basis of the one requiring the greatest pavement thickness even though it may not necessarily be the heaviest aircraft. Each aircraft type in the forecast should be checked to determine the pavement thickness required by using the appropriate design curve with the forecast number of annual departures for that aircraft. The aircraft type which produces the greatest pavement thickness is the design aircraft. The design aircraft is not necessarily the heaviest aircraft in the forecast. Since the traffic forecast is a mixture of a variety of aircraft having different landing gear types and different weights, the effects of all traffic must be accounted for in terms of the design aircraft. First all aircraft must be converted to the same landing gear type as the design aircraft. The following conversion factors should be used to convert from one landing gear type to another:

To Convert From	*To*	*Multiply Departures By*
Single Wheel	Dual Wheel	0.8
Single Wheel	Dual Tandem	0.5
Dual Wheel	Dual Tandem	0.6
Double Dual Tandem	Dual Tandem	1.0
Dual Tandem	Single Wheel	2.0
Dual Tandem	Dual Wheel	1.7
Dual Wheel	Single Wheel	1.3
Double Dual Tandem	Dual Wheel	1.7

Secondly, after the aircraft have been grouped into the same landing gear configuration, the conversion to equivalent annual departures of the design aircraft should be determined by the following formula:

$$\log R_1 = \log R_2 \times \left(\frac{W_2}{W_1}\right)^{1/2} \qquad \text{Equation 1}$$

Where: R_1 Equivalent annual departures by the design aircraft
R_2 Annual departures expressed in design aircraft landing gear
W_1 Wheel load of the design aircraft
W_2 Wheel load of the aircraft in question

For this computation, 95% of the gross weight of the aircraft is assumed to be carried by the main landing gears. Wide body aircraft require special attention in this calculation. The procedure discussed above is based upon a relative rating which compares different aircraft to a common design aircraft. Since wide body aircraft have radically different landing gear assemblies than other aircraft, special considerations are needed to maintain the relative effects. This can be calculated by treating each wide body as a 136,100 kg dual tandem aircraft when computing equivalent annual departures. After the number of equivalent annual departures has been determined, the design should proceed using the appropriate design curve for the design aircraft. For example if a wide body is the design aircraft, all equivalent departures should be calculated as described above; then the design curve for the wide body should be used with the calculated equivalent annual departures.

A pavement thickness is determined for each aircraft in the forecast using the appropriate design curves. The aircraft that gives the greatest pavement thickness is known as the design aircraft. Once the design aircraft and its landing gear configuration is known, all the other aircraft have to be grouped into the same configuration. The equivalent annual departures can be calculated using Equation 1 for each individual aircraft trafficking on the particular pavement in question.

2.10 Material conversion factors

Material Conversion factors can be used in two ways. Firstly, the modified FAA design method described in Section 2.9 produces design sections incorporating CBM3 as the base and Type 2 granular material as the sub-base. Material Conversion Factors permit alternative materials to be substituted for those produced by the design method. In this way, they greatly extend the range of design solutions which can be produced by the modified FAA design method. Secondly, they can be used in the assessment of an existing pavement when a paver overlay is being contemplated as described in Section 3. Material Conversion Factors should be used with caution and in the conversion from CBM3 to other materials. Where there is any doubt that the transformed pavement will be as strong as the original CBM3 pavement a full structural analysis should be undertaken.

Stabilised materials offer some structural benefit to a flexible pavement as compared with granular materials of equal thickness. The benefit can be expressed in the form of Material Conversion Factors which indicate the substitution thickness ratios applicable to various materials. The equivalent thickness of a material can be computed by multiplying the pavement course thickness in question by its Material Conversion Factor, giving the thickness in terms of that of the standard material CBM3. An example of the use of Material Conversion Factors is demonstrated in Section 2.12. A range of Factors is presented in Table 18.

Material Conversion Factors were first proposed as a means of extending the range of design solutions by The Asphalt Institute, Maryland, US and have been incorporated in several highway and industrial pavement design guides e.g. the British Ports Association *'The Structural Design of Heavy Duty Pavements for Ports & Other Industries'*[34]. The values shown in Table 18 are similar to those used in the British Ports Association publication. They are essentially empirical: it is difficult to identify an absolute figure because some materials are chosen according to limiting stresses whereas others need to include a strain criterion. The figures are based upon limiting stresses in the case of cement bound materials and upon limiting strains in the case of granular materials. Values are given to bitumen bound materials based upon empirical assessment of how different thicknesses of cement based materials perform in relation to bitumen bound materials.

Table 18 Suggested Material Conversion factor ranges. The suggested values relate to standard material. Where the material is considered to be superior or inferior to normal specification, the Material Conversion Factor may be varied within the range shown.

Material	*Suggested value*	*Range*
80mm pavers on 30mm sand	1.2	1.0 to 1.4
Cement bound material (CBM1)	0.6	0.4 to 0.8
Cement bound material (CBM2)	0.7	0.5 to 0.9
Cement bound material (CBM3)	1.0	0.7 to 1.3
Cement bound material (CBM4)	1.0	0.7 to 1.3
Drylean concrete	1.0	0.7 to 1.3
Pavement quality concrete	2.4	2.0 to 2.8
Dense Bitumen macadam	1.4	1.1 to 1.7
Marshall asphalt	1.8	1.6 to 2.0
Grouted open graded macadam	1.4	1.1 to 1.7
Open textured macadam	1.0	0.7 to 1.3
Wet-mix or dry bound macadam	0.6	0.4 to 0.8
Type 1 granular sub-base material over material with a CBR of >5%	0.4	0.2 to 0.6
Type 1 granular sub-base material over material with a CBR of ≤5%	0.3	0.2 to 0.4
Type 2 granular sub-base material over material with a CBR of >5%	0.3	0.2 to 0.4
Type 2 granular sub-base material over material with a CBR of ≤5%	0.1	0.05 to 0.15
Subgrade improvement material	0.1	0.05 to 0.15

Note

The suggested values in this table relate to materials in their common situations. In unusual situations, alternative values may be substituted but will generally not depart from the Range.

2.11 FAA modified design charts

The design charts in FAA Advisory Circular 150/5320-6C[20] have been modified to accommodate concrete pavers. The pavement design method allows the thickness of the pavement courses to be proportioned and assumes that the pavement will be surfaced with 80mm rectangular concrete pavers bedded on 30mm sand. Owing to the variations in stress distribution of single, dual tandem, and wide body landing gear configurations, separate flexible pavement design curves have been prepared and are represented in Figures 13 to 19.

The pavement design charts can be used as shown in the example in Section 2.12 to determine the total pavement thickness required including pavers. Figure 20 allows the minimum required thickness of cement bound base material to be determined for a given total pavement thicknesses and CBR value.

The use of the design charts requires:

CBR value for the subgrade material.
Gross weight of the aircraft.
Total number of annual departures of the design aircraft.

The design charts are used as follows. First, select one of the charts according to the aircraft gear configuration (Figures 13 to 19). Determine the pavement thickness by projecting a line down from the upper horizontal axis to the appropriate gross aircraft weight curve. From there, project a line horizontally to the appropriate annual departures line, then project a line down to the lower horizontal axis and read the total thickness of the pavement in millimetres.

The base thickness is determined using the base chart (Figure 20). The thickness is determined by starting with the overall pavement thickness (just obtained) and projecting a line horizontally to meet the appropriate subgrade CBR curve. From this point, project a line vertically down and read the base thickness.

2.12 Modified FAA method design example

As an example of the use of the design curves, assume a paver pavement is to be designed for the mix of aircraft shown in Table 19.

Table 19 Assumed mix of aircraft

Aircraft	*Gear Type*	*Annual Departures*	*Maximum Takeoff weight (kg)*
B737-200	Dual Wheel	6000	52,390
B747-100	Double Dual Tandem	3000	272,155
L-1011-100	Dual Tandem	1200	211,374
DC-10-30	Dual Tandem	1200	267,619
Airbus A-300-B2	Dual Tandem	3000	142,000

The subgrade was found to be a cohesive material which gave a CBR value of 5% and the sub-base to be used is Type 2 granular sub-base material. First, the design aircraft has to be determined. This is the one requiring the thickest pavement for the appropriate number of departures of the aircraft. Using Figures 13 to 19, the overall pavement thicknesses shown in Table 20 are obtained.

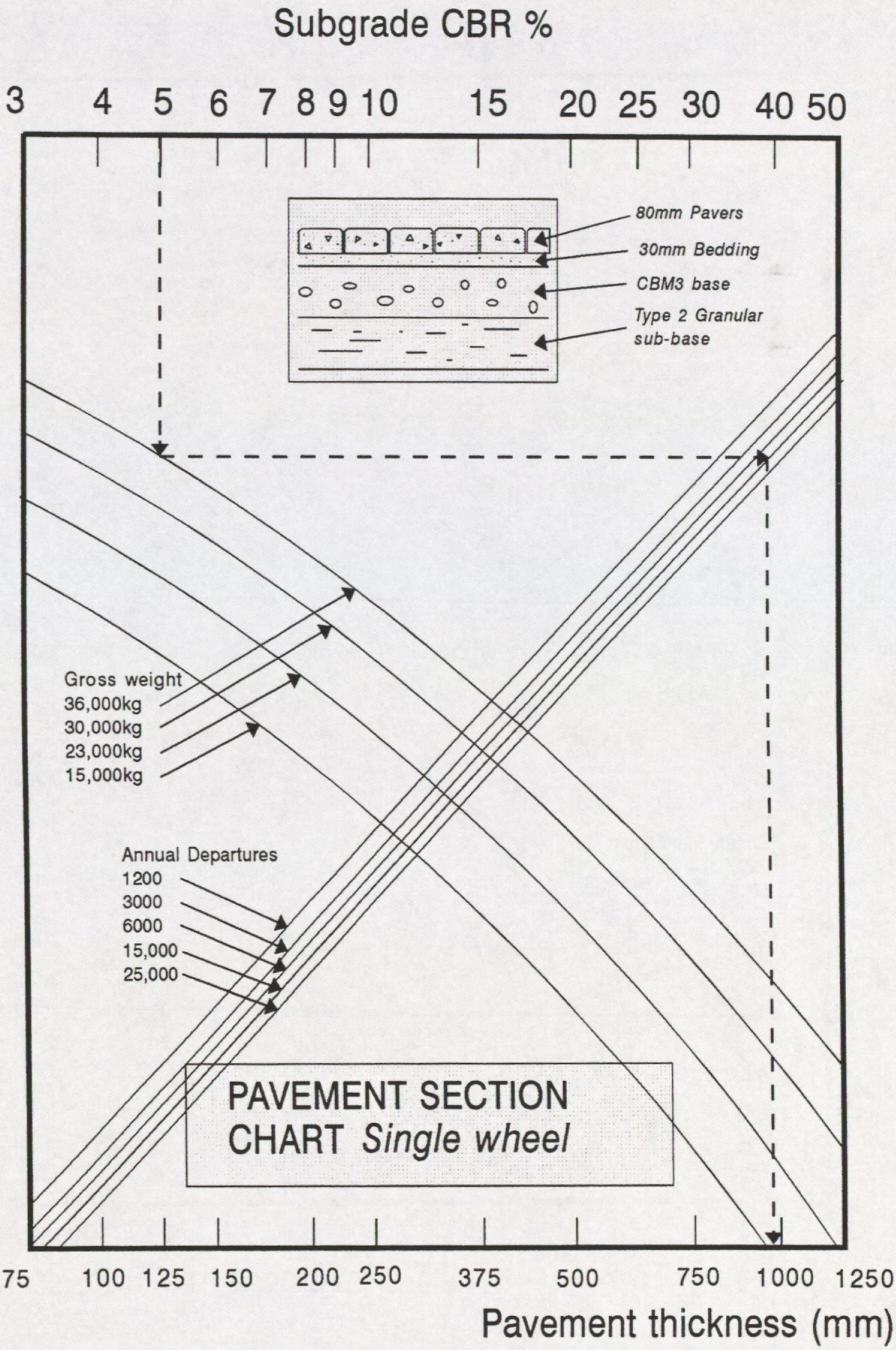


Figure 13 Modified FAA Flexible Pavement Design Chart for Single Wheel Gear

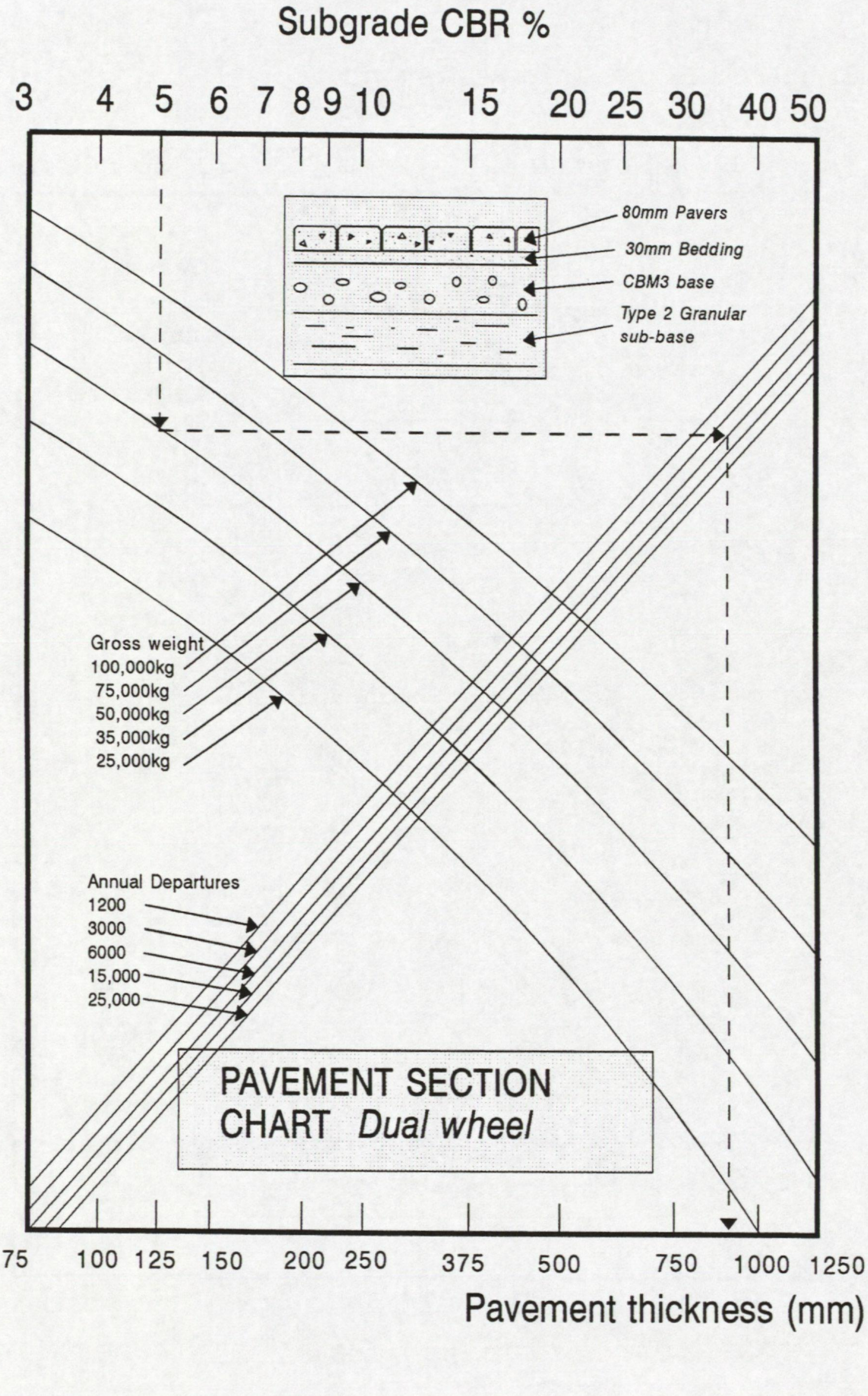


Figure 14 Modified FAA Flexible Pavement Design Chart for Dual Wheel Gear

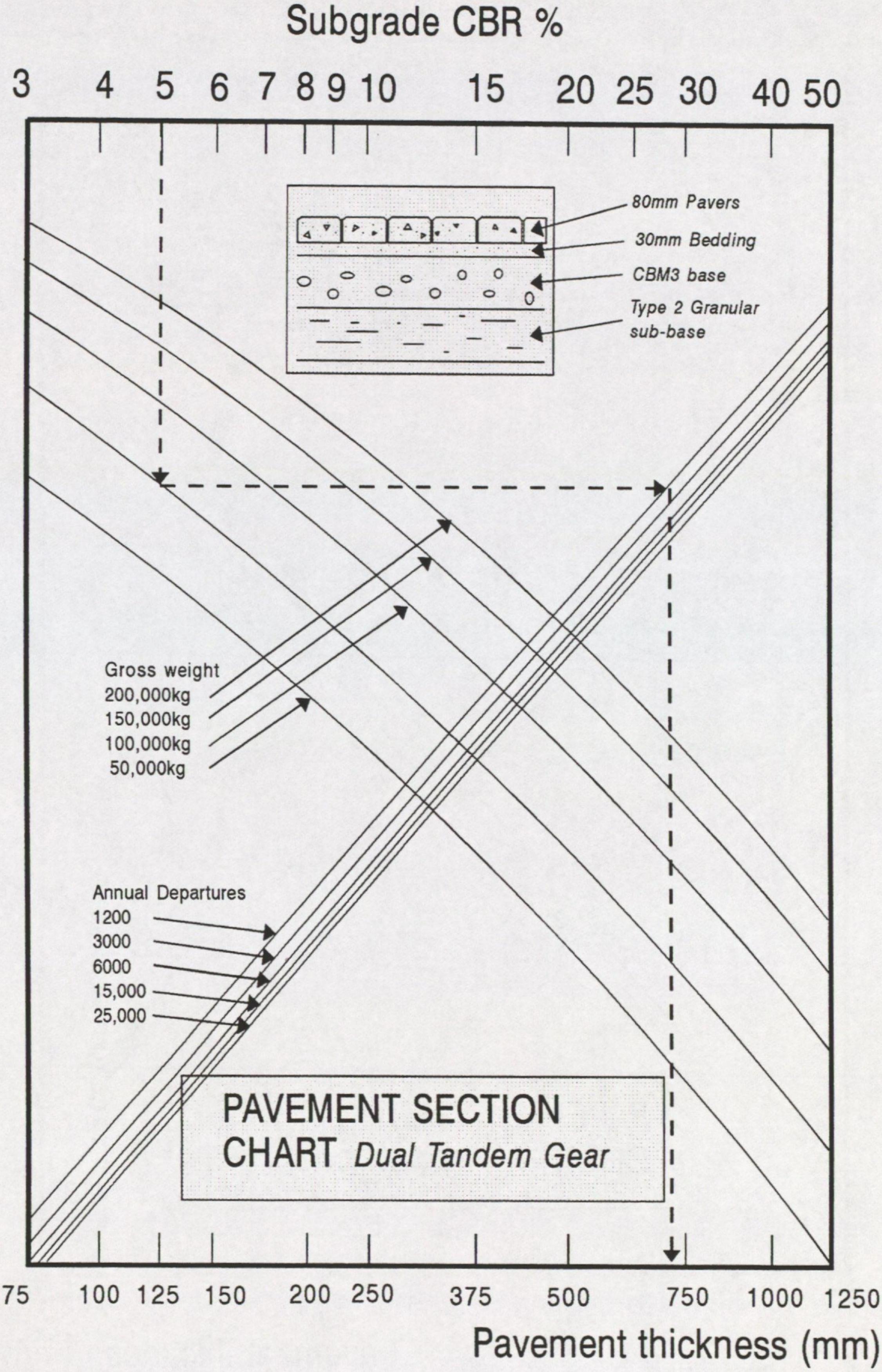


Figure 15 Modified FAA Flexible Pavement Design Chart for Dual Tandem Gear

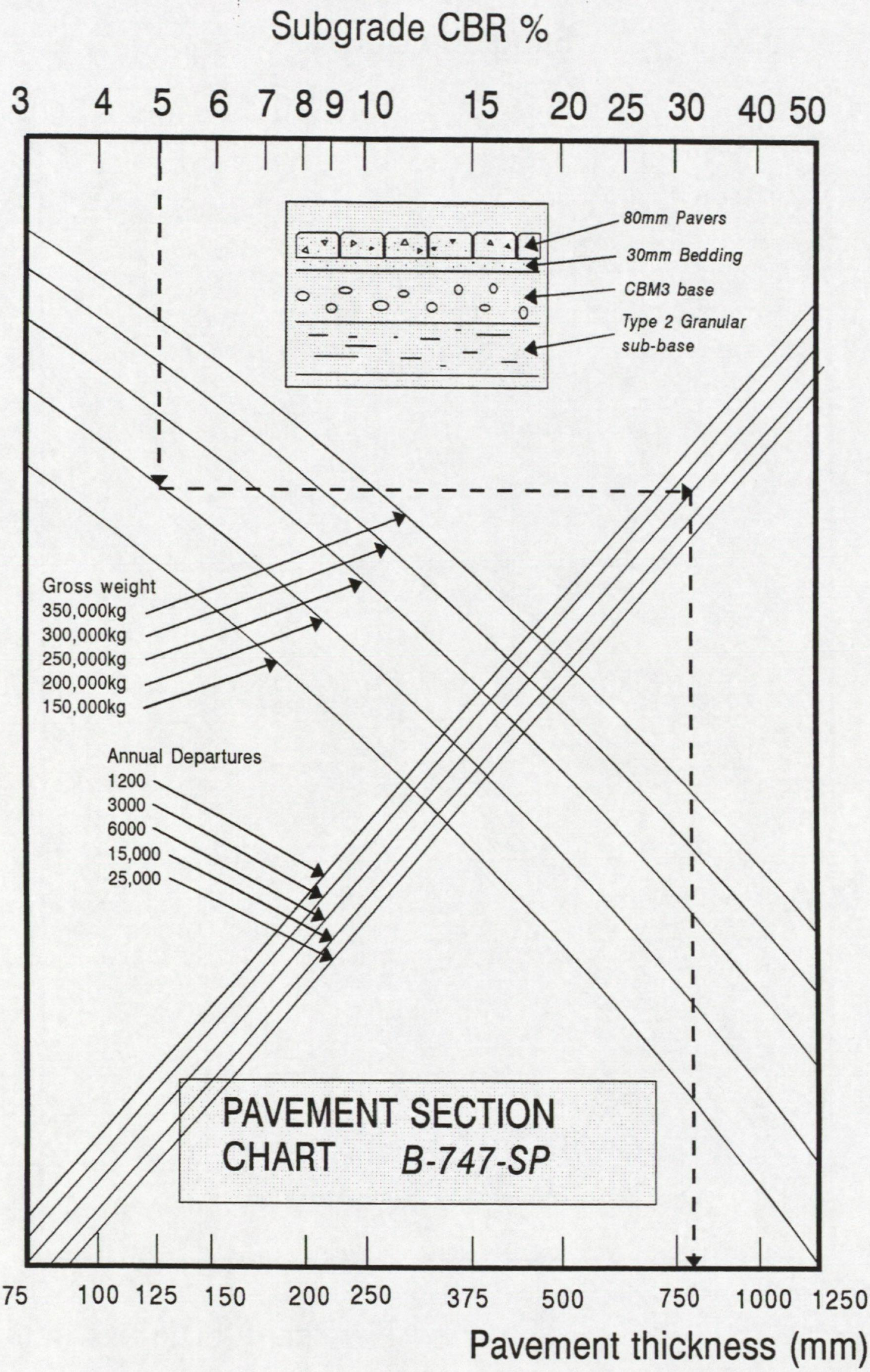


Figure 16 Modified FAA Flexible Pavement Design Chart for B-747-SP Aircraft

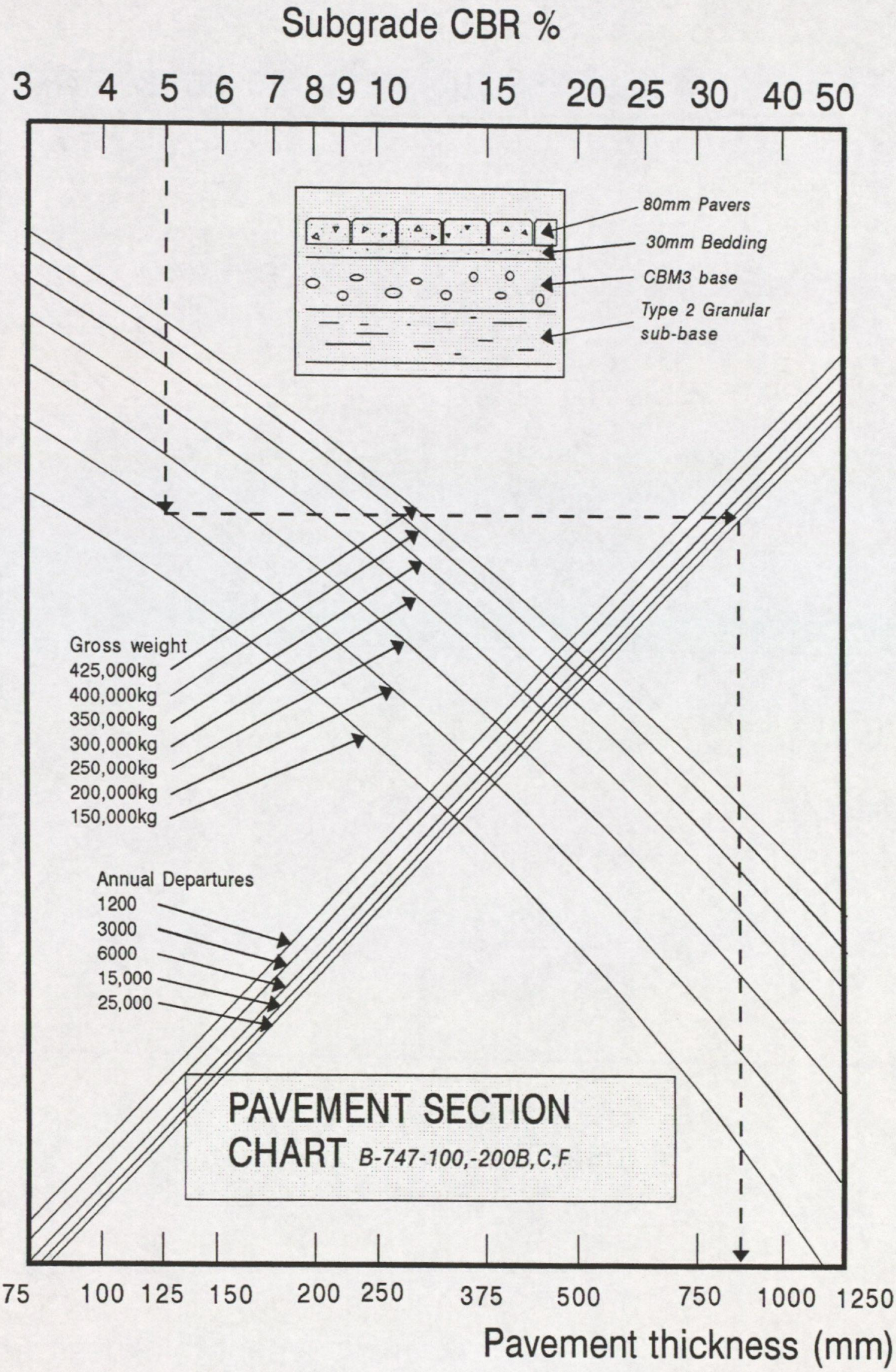


Figure 17 Modified FAA Flexible Pavement Design Chart for B-747-100, -200B,C,F Aircraft

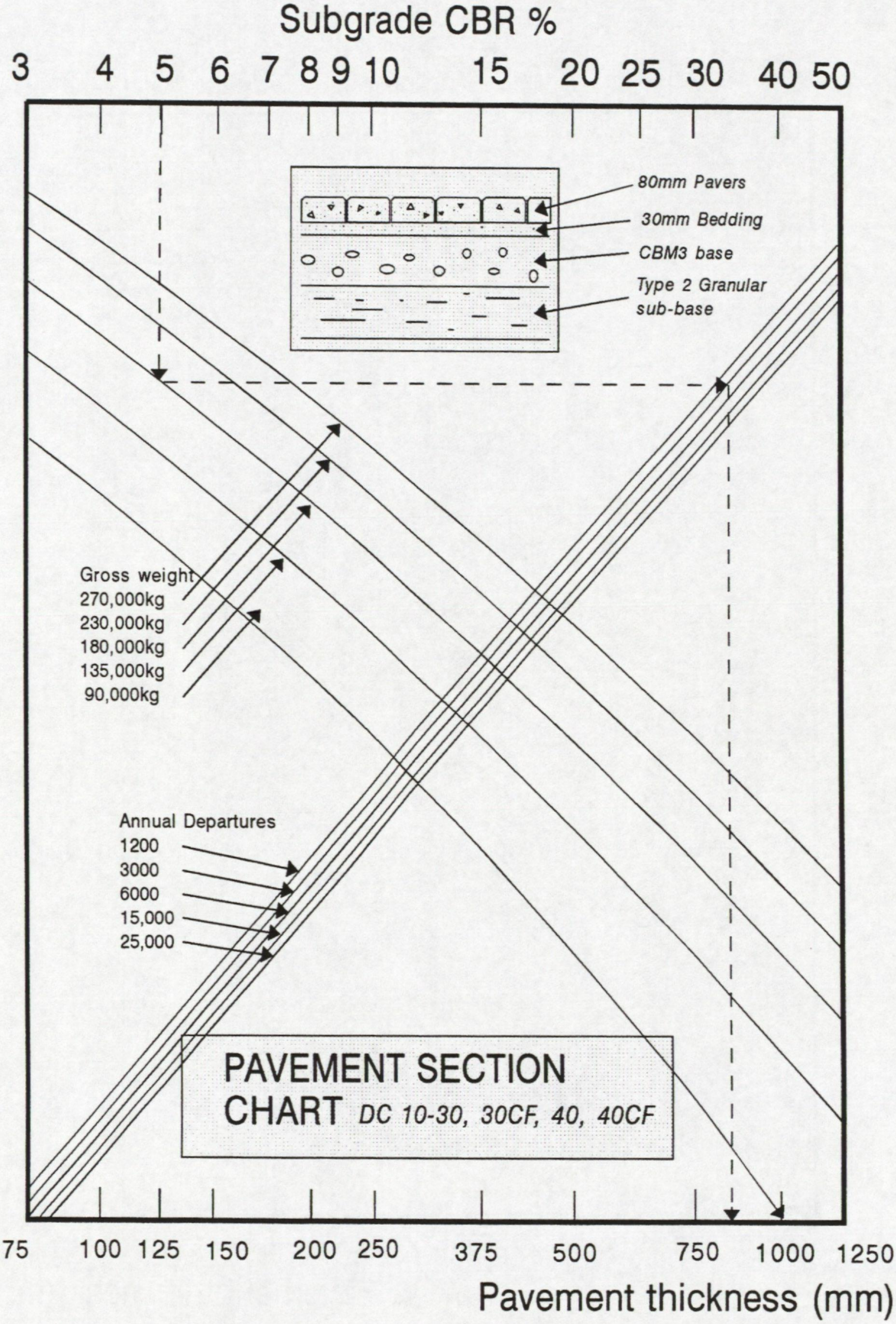


Figure 18 Modified FAA Flexible Pavement Design Chart for DC 10-30, 30CF, 40, 40CF Aircraft

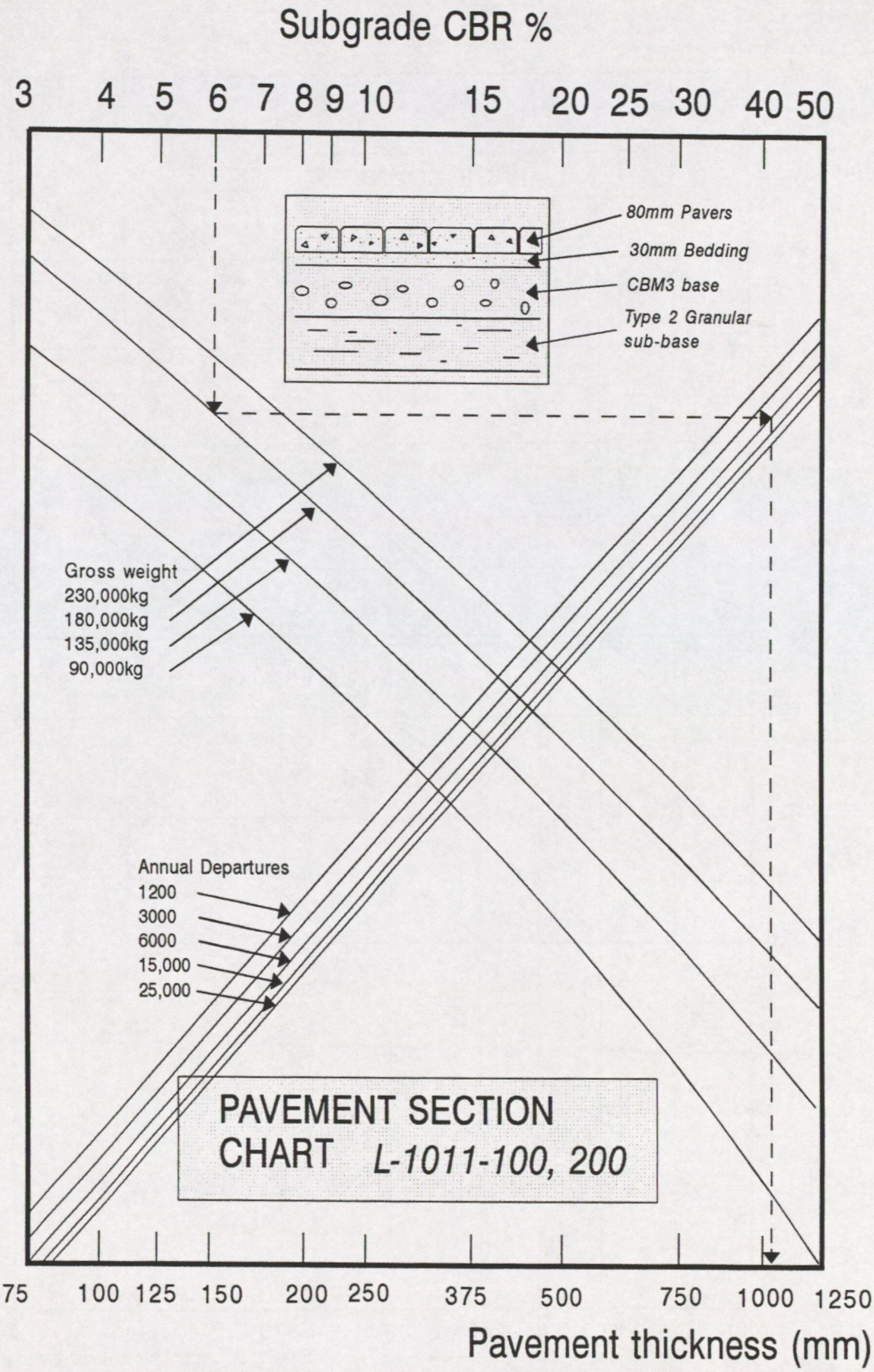


Figure 19 Modified FAA Flexible Pavement Design Chart for L-1011-100, 200 Aircraft

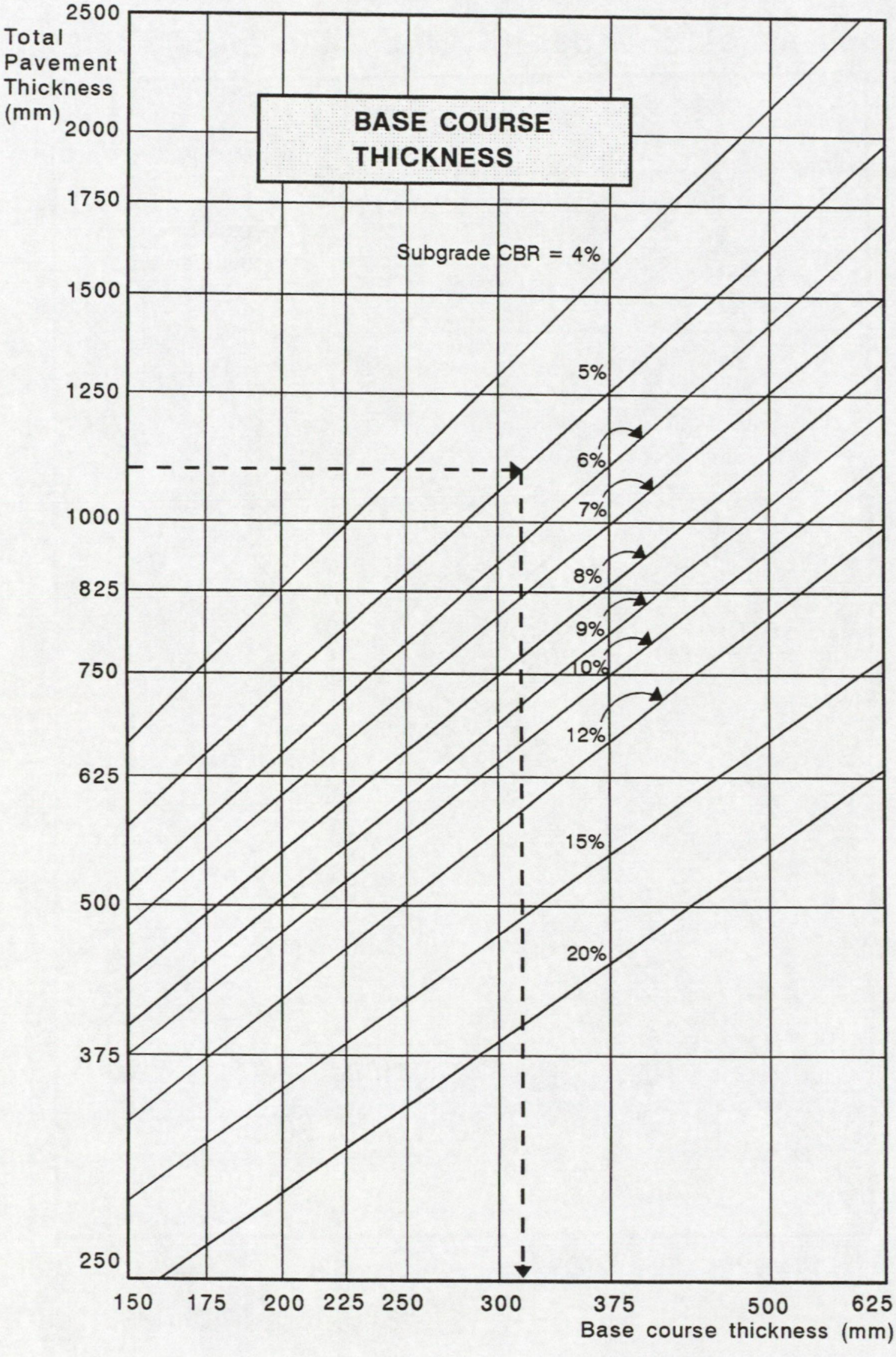


Figure 20 Modified FAA Base Course Thickness Design Chart

Table 20 Pavement Thicknesses Required

Aircraft	*Overall pavement thickness (mm)*
B737-200	950
B747-100	975
L-1011-100	1125
DC-10-30	1175
Airbus A-300-B2	1100

The DC10-30 requires the greatest pavement thickness and is therefore the design aircraft. This aircraft has dual tandem wheel landing gear, so all traffic must be grouped into the dual tandem wheel configuration. The equivalent number of annual departures is calculated as in Table 21, taking into account Equation 1 which equivalences departures for aircraft of different weights.

Table 21 Equivalent Annual Departures

Aircraft	Equivalent Dual Tandem Gear Departures	Maximum Wheel load (kg)	Maximum design aircraft wheel load (kg)	Equivalent Annual Departures Design Aircraft
B737-200	3,600	12,440♦	16,160	1,319
B747-100	3,000	16,160♦	16,160	3,000
L-1011-100	1,200	16,160♦	16,160	1,200
DC-10-30	1,200	16,160♦	16,160	1,200
Airbus A-320-100	3,000	16,862♦	16,160	4,231
				10,949

♦ Wheel loads for wide body aircraft will be taken as the wheel load for a 136,100 kg aircraft for equivalent annual departure calculations.

Therefore, the pavement would be designed for 11,000 annual departures of a dual tandem gear DC-10-30 aircraft weighing 267,619 kg. The DC-10 aircraft has a special Design Chart shown in Figure 18. The Chart includes a dashed line running from the 5% value on the upper horizontal axis, down to just below the 270,000kg gross weight curve, then to the right to intercept the 15,000 annual departures line (the difference between 11,000 departures and 15,000 departures is negligible in terms of pavement design) and finally down to a pavement thickness of 1080mm. Figure 20, which applies to all aircraft types, is then used to determine the thickness of the base. The dashed line on that figure refers to this example and finishes at a base course thickness of 325mm on the lower horizontal axis. From Figures 18 & 20, the following pavement section can be concluded (all of the values refer to course thicknesses):

Pavers	80mm
Laying Course	30mm
Cement Bound Material 3	325mm
Type 2 Granular Material	645mm
	1080mm

If there was a need to reduce the overall pavement construction thickness owing to restricted headroom, e.g. a culvert, this can be achieved by providing additional base material and less sub-base material by the correctly factored amount. Material Conversion Factors are given in Section 2.10, Table 18, which expresses materials in an equivalent thickness of the standard material, CBM3. It is recommended that any pavement course thickness should not be adjusted by more than ±25% of its original thickness. Using Table 18 from Section 2.10 the following conversion factors can be used:

Cement Bound Material 3	1.0
Type 2 granular sub-base	0.3

If the CBM3 base thickness is increased by 100mm, the reduction in Type 2 granular sub-base material thickness is 100/0.3=333mm (say 330mm). Therefore, 100mm of CBM3 is equivalent to 330mm of Type 2 granular material, and this equivalent thickness can be subtracted from the original thickness of granular material.

645mm – 330mm = 315mm

The new section through the pavement is as follows:

Pavers	80mm
Laying Course	30mm
Cement Bound Material 3	425mm
Type 2 Granular Material	315mm
	850mm

Alternatively, the overall pavement thickness can be increased by reducing the thickness of the stronger base material, which will increase the thickness of the weaker granular material. Consider a reduction in base thickness from 325mm to 250mm. The new sub-base thickness is:

645mm + 250mm = 895mm

The new pavement section is:

Pavers	80mm
Laying course	30mm
CBM3	250mm
Type 2 granular	895mm
	1255mm

When using the conversion factors, it is also possible to alter the section by substituting different materials for the standard ones to which the design curves apply. For example, if the CBM3 in the above section were to be replaced with dense bitumen macadam (DBM) and the Type 2 granular material with CBM1, the following section can be achieved. Note that the conversion of Type 2 granular material to CBM1 takes place in two steps with an intermediate stage of CBM3:

CBM3 ⇨ DBM	250mm ÷ 1.4 = 180mm
Type 2 Granular Material ⇨ CBM3	895mm x 0.3 = 270mm
CBM3 ⇨ CBM1	270mm ÷ 0.6 = 450mm

The new section through the pavement is as follows:

Pavers	80mm
Laying course	30mm
DBM	180mm
CBM1	450mm
	740mm

It can be seen that by using material conversion factors different sections of similar strength can be developed so that the preferred solution can be selected.

2.13 Paver life cycle cost analysis

The decision between the use of pavers and other materials may be taken on a life cycle cost analysis basis. This section sets out the recommended procedure.

For areas where conventional concrete pavements have been the material of choice, concrete pavers can provide a viable alternative pavement structure. Savings in initial construction cost of 10–15% have been reported when a rectangular concrete paver pavement has replaced a conventional rigid concrete pavement. Some authorities have found pavers to offer no economic benefit in terms of initial construction and consequently use pavers only on overlay projects.

The life cycle cost concept is a means of comparing the total cost of different types of pavement. The components of the life cycle cost analysis comprise:

Initial construction cost,
Periodic maintenance cost,
Time value of money (ie Interest rates),
Salvage cost.

Since some of the components, e.g. periodic maintenance, will be incurred at a future date, these future costs must be discounted to a present value using an appropriate discount rate and added to the initial construction cost in order to compare alternatives. Discount rate can be defined as the minimum attractive rate of return on an investment. It is impossible to predict the year on year discount rate over a design life of say 40 years for a pavement but values of 5%, 10% and 15% are often used in economic comparisons of pavements. By using a discount rate, it is possible to evaluate the present worth of a future cost

2.13.1 *Pavement Design*

Pavement quality concrete and rectangular concrete paver pavements are to be designed and compared using a life cycle costs analysis over a period of 20 years based on the following input conditions:

Subgrade CBR 7%
Pavement quality concrete 45N/mm^2
Concrete flexural strength 4.9N/mm^2
12000 annual departures of dual tandem gear aircraft at 200kN wheel load.

For the input conditions presented above, the design alternatives are:

Pavers	**Pavement quality concrete**
80mm rectangular pavers	400mm Pavement quality concrete
30mm laying coarse sand	150mm CBM3
420mm CBM3	150mm Type 2 granular sub-base
550mm Type 2 granular sub-base	

2.13.2 *Initial Construction Costs*

Using comparative and relative costings (in 1996 pounds), the initial construction cost (per square metre) of two alternative pavement types can be calculated. Pavement costs do not include subgrade grading and compaction, which are considered equal in both cases. The costs presented are believed to be reasonable for the purpose of comparing the relative costs of two alternatives. However, actual costs for pavers, as well as pavement quality concrete pavement may vary depending on many factors such as geographic location, project size and specific site conditions.

Concrete paver pavements	**£/ m^2**	**Pavement quality concrete**	**£/ m^2**
Pavers/ laying material	12.00	Pavement quality concrete	33.00
Pavement sealer	1.40	150mm CBM3	7.15
420mm CBM3	19.90	150mm Type 2 granular material	2.50
550mm Type 2 granular material	9.20		42.65
	42.50		

It is possible to reduce the cost of the paver section by the use of material conversion factors. Therefore, an optimum cost can be achieved by comparing the relative costs of the different materials available and then apply the relevant material conversion factor to derive the new section. This can be demonstrated by using the following examples:

Concrete paver pavement	**£/ m^2**	**Concrete paver pavement**	**£/ m^2**
Pavers/ laying material	12.00	Pavers/ laying material	12.00
Pavement sealer	1.40	Pavement sealer	1.40
320mm CBM3	15.15	520mm CBM3	24.65
900mm Type 2 granular material	15.05	200mm Type 2 granular material	3.70
	43.60		41.75

It can be seen that by reducing the sub-base material thickness and increasing the thickness of base material, the section is approaching £1/m^2 less expensive than the original section.

2.13.3 *Maintenance Costs*

When comparing the two alternatives, the maintenance of the pavement must be taken into consideration. Since pavement maintenance costs are normally included in an airports' overall operations and maintenance budget, it is often difficult to identify specific annual and periodic maintenance costs for airport pavements and some judgement is inherent in estimating these costs. Future pavement maintenance will often depend on the original design and therefore the construction costs must be evaluated in conjunction with future maintenance costs. Maintenance costs should include the cost of maintaining adequate surface integrity (e.g. reapplying sealant on interlocking concrete pavements).

Concrete pavers

Activity	*Frequency*	*Costs / m²*
Reapply sealant	5 years	0.40
Replace pavers	5 years	0.90

Pavement Quality Concrete

Activity	*Frequency*	*Costs / m²*
Reseal joints	10 years	0.60
Patch and crack seal	5 years	0.90

2.13.4 *Salvage Cost*

A residual value in the pavement after 20 years should be expressed as a negative cost in the whole life cycle cost analysis. It is considered that any salvage cost in a concrete pavement would be very small, say 10% of its original value. However, pavers are likely to remain sound and indeed might have enhanced antique value, as has been the case with many reclaimed building bricks in the UK. Therefore, it is assumed in this example that the future worth of the pavers will be 50% of the original price. This figure takes into account the damage which will be sustained by some of the pavers during their removal and the labour required to prepare them for reuse. Not all authorities have found pavers to have salvage value. In some cases, there has been a cost associated with removing old pavers.

Concrete Pavers	0.5x £7.00/ m^2 = £3.50/ m^2
Pavement Quality Concrete	0.1x £33.00/ m^2 = £3.30/ m^2

2.13.5 *Present Worth*

The choice of pavement design is made on the comparison of the total present worth costs, i.e. costs discounted to the time of the analysis of the original construction, subsequent maintenance and the salvage value. The 20 year analysis period is the period adopted for the economic analysis of the two alternative pavement types, and is also considered the design life of the pavement.

The basic equation for determining present worth is:

$$PW = C + M_1\left(\frac{1}{1+r}\right)^{n_1} + \ldots\ldots + M_i\left(\frac{1}{1+r}\right)^{n_i} - s\left(\frac{1}{1+r}\right)^{z}$$

Where:

PW	Present Worth
C	Present cost of initial design or rehabilitation activity

M_i	Cost of the i^{th} maintenance or rehabilitation alternative in terms of present cost, i.e., constant pounds.
r	Discount rate (5% suggested)
n_i	Number of years from the present to the i^{th} maintenance or rehabilitation activity
s	Salvage value at the end of the analysis period
z	Length of the analysis period in years (20 years suggested)

The term $\left(\frac{1}{1+r}\right)^{n_i}$

is commonly called the single payment present worth factor. From a practical standpoint, if the difference in the present worth of costs between two designs or rehabilitation alternatives is 10% or less, it is normally assumed to be insignificant and the present worth of the two alternatives can be assumed to be the same.

The present value of the above examples can now be determined using the present worth formula and an analysis can be made over a period of 20 years to determine the most cost effective alternative.

	Pavers		**Pavement Quality Concrete**	
@ 0 years	Initial cost	£42.50	Initial cost	£42.65
@ 5 years	Replace paver	£0.71	Patch/crack seal	£0.71
@ 5 years	Reapply sealant	£0.31		
@ 10 years	Replace paver	£0.55	Patch/crack seal	£0.55
@ 10 years	Reapply sealant	£0.24	Reseal joints	£0.36
@ 15 years	Replace paver	£0.43	Patch/crack seal	£0.43
@ 15 years	Reapply sealant	£0.19		
@ 20 years	Salvage cost	£–3.50	Salvage cost	£–3.30
	PW / m^2	£41.43	PW / m^2	£41.40

The present worth analysis of the two alternative pavements shows that they are of similar total cost.

2.13.6 *Other factors to be considered in choosing between alternative types of pavement*

In addition to the economic analysis, a number of other factors should be considered when a decision is being made between different pavement types.

- The availability of funds for maintenance. Pavements are often allowed to deteriorate below the terminal level of serviceability without the economic consequences being properly taken into account. Planned budgeting for maintenance over a number of years should solve this problem.

- The diversion of aircraft traffic to alternative routes could increase pavement loadings elsewhere. This can become a problem if the existing pavement is not designed to accomodate the diverted aircraft.

3 ASSESSMENT OF PAVEMENTS FOR PAVER OVERLAY

3.1 Property Service Agency (PSA) pavement design method

In the UK, the PSA design method[21] has been the principal means by which most aircraft pavements have been designed for many years. Frequently, pavers will be used as an overlay or as an inlay at locations where the remainder of the pavement will have been designed by the PSA method. Therefore, it is important to understand how to use the PSA design method to check whether pavers can be used to overlay or inlay an existing rigid or flexible pavement. The following Sections describe the PSA method and show how it can be used in this way.

When a paver overlay or inlay is proposed, a pavement should be designed for the expected traffic and ground conditions according to the PSA method. The proposed overlain or inlaid pavement can then be compared with the designed pavement using the Material Conversion Factors shown in Table 18 so that the suitability of the existing pavement for overlay or inlay can be assessed.

In fact, the FAA design method[20] could be applied equally in this way but it is considered that where the original pavement has been designed according to the PSA method, it is more appropriate to undertake the evaluation using the design method by which it was originally designed.

In the PSA design method the following parameters need to be considered in the design of a paver pavement:

(a) Quality of pavement construction materials

(b) Subgrade strength

(c) Design Aircraft Classification Number (ACN)(See Section 3.1.1)

(d) Trafficking in the following terms:

- (i) Design life,
- (ii) Pattern of trafficking / assessment of passes,
- (iii) Coverages / pass to coverage ratio,
- (iv) Mixed traffic analysis.

3.1.1 *Aircraft Classification Number (ACN)*

The ACN of an aircraft defines its relative loading severity on a pavement supported by a specified subgrade. Any given aircraft has a variety of ACNs depending upon whether it is trafficking a rigid or a flexible pavement and depending upon the strength of the subgrade. The ACN of an aircraft is defined as twice the equivalent single wheel load (in tonnes) at a standard tyre pressure, i.e. twice that single wheel load which requires the same pavement thickness as the actual main wheel gear of the aircraft for a given limiting stress and number of load repetitions. ACN values are given in the Appendix for common aircraft.

The procedure for calculating ACNs in the case of rigid pavements is as follows (see Figure 21):

(i) Calculate 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 on a subgrade of a standard value. The mathematical model for the stress calculation is the Westergaard solution for an elastic slab on a Winkler foundation with $E_{conc.}$ = 27600 N/mm^2 and $\nu = 0.15$.

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

(iii) ACN = 2 x (W_R / 1000) where W_R is in kg.

(iv) Calculate ACNs for each aircraft for subgrade categories having the following Modulus of Subgrade Reaction values:

High	150MN/m^2/m
Medium	80MN/m^2/m
Low	40MN/m^2/m
Ultra Low	20MN/m^2/m

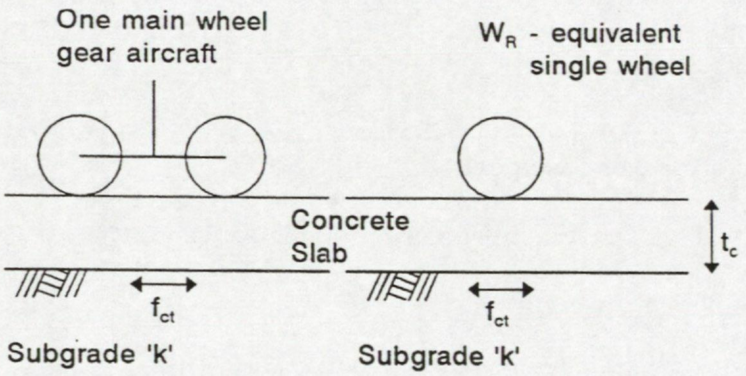


Figure 21 Location of maximum flexural stress f_{ct} when calculating Aircraft Classification Number(ACN) in the case of rigid pavement design

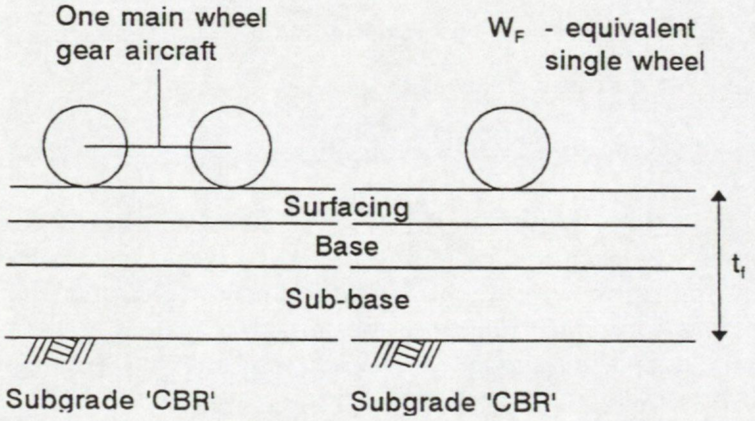


Figure 22 Reference thickness t_f used in the calculation of Aircraft Classification Number(ACN) in the case of flexible pavement design

The procedure for calculating ACN in the case of flexible pavements is as follows.

(i) Calculate 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 with a standard CBR. The method of calculation is based on the Boussinesq deflection factors and the CBR equation.

(ii) Calculate the single wheel load WF which at a tyre pressure of 2.75N/mm^2 allows the same 10,000 load repetitions, using the following formula:

$$W_F = (t_f^2 / 200) / ((0.878 / CBR) - 0.01249)$$

(iii) ACN = 2 x (W_F / 1000) where W_F is in kg.

(iv) Calculate ACNs for each aircraft for subgrades having the following California Bearing Ratio values:

High	15%
Medium	10%
Low	6%
Ultra Low	3%

3.1.2 *Pavement Classification Number (PCN)*

The PSA method uses the Pavement Classification Number system to describe pavements. The PCN system classifies the type of pavement being considered as a five part code an example being PCN 76/F/C/W/T. The PCN is the ACN of the aircraft which imposes a severity of loading equal to the maximum permitted on the pavement for unrestricted use. Each part of the PCN code has the following meaning:

Part 1 – The PCN:
The highest permitted ACN at the appropriate subgrade category.

Part 2 – The type of pavement:
R = Rigid F = Flexible

If the pavement is of mixed construction the pavement type is that with the most likely method of failure. Because pavements surfaced with pavers behave structurally in a similar manner to traditional flexible pavements, they should be considered to fall within type F.

Part 3 – The pavement subgrade category:
A = High
B = Medium
C = Low
D = Ultra Low

Table 9 (Section 2.5.1) defines these four terms.

Part 4 – The maximum tyre pressure authorised for the pavement:
W = High, no limit
X = Medium, limited to 1.5 N/mm^2
Y = Low, limited to 1.0 N/mm^2
Z = Very Low, limited to 0.5 N/mm^2

Part 5 – Pavement design/evaluation method:
T = technical design / evaluation
U = By experience of aircraft actually using the pavement.

The design ACN is based on the Design Aircraft which is normally the aircraft with the highest ACN on the actual subgrade.

3.1.3 *Frequency of trafficking*

A factor in the design of a paver pavement is the magnitude and configuration of the wheel loads. Most aircraft have a tricycle type undercarriage arrangement comprising two main wheel gears near the centre of gravity of the aircraft and a nose wheel gear. The nose wheel gear is usually ignored as it contributes only 5 to 10% of the load of the aircraft to the pavement. The number of wheels on the main gear varies with type and weight of the aircraft. Tandem wheel gears are not common and are therefore treated as dual wheel gears. Other combinations of four wheels are treated as dual tandems.

Calculations to obtain the ACN of an aircraft are based on one main wheel gear only. Wheels from an adjacent gear may be close enough to result in load interaction and so increase the level of stress induced in the pavement. This is not a problem in rigid pavements but it may affect flexible pavements. Only the Boeing 747 needs an amendment to the ACN for this reason.

The effect of fatigue caused by load repetition is an important secondary consideration for rigid and flexible pavements. When the frequency of trafficking is higher a thicker pavement is required. The PSA design method uses three levels of trafficking; low, medium and high. To determine the frequency the total number of coverages during the design life is calculated. This involves the design life, pattern of trafficking and mixed traffic use. An example of frequency of trafficking is shown in Section 3.3.

3.1.4 *Design life*

In the PSA design method the frequency of trafficking is assumed to be spread evenly over the design life. Pavement deterioration is gradual under normal circumstances, owing to surface weathering and or structural fatigue. The following considerations are used to determine the design life:

(i) Major maintenance work should be kept on a long term cycle.
(ii) The likelihood of a change of aircraft use after a period of time.
(iii) The durability of pavement construction.
(iv) Cost of rehabilitation.

Considering the above factors the structural design life is recommended to be 20 years for flexible pavements and 30 years for rigid pavements. The PSA design method includes an increasing degree of minor maintenance (crack sealing) during the last few years of the pavement's life. If maintenance cannot be tolerated the structural design life can be projected beyond the expected life of the surfacing. A pass is an aircraft movement over a particular section of the pavement. The total number of passes is the total number of movements. Mixed traffic analysis is used to consider the effect of aircraft operations at different weights. It is conservative to consider all movements at the maximum ramp weight (maximum take off weight plus any taxi/run-up fuel load). If actual operations will be at a lower weight the more accurate weight can be used in the design.

Runways and taxiways are usually the most heavily loaded aircraft pavements. For these pavements the number of passes can be equated to the number of departure movements only. The landing movements are accounted for by assuming all passes are at maximum ramp weight. Aircraft parking aprons for rigid pavements are designed for the same design ACN and frequency of trafficking as the main taxi track exit from the apron.

Construction depth can be reduced linearly to the edge of the runway where the minimum depth should be that for 2/3 of the design ACN. If the airfield has no parallel or perimeter taxiway, the runway may be used as a taxiway. In this situation the aircraft may not use the centre line of the runway and therefore the maximum depth should be used across the whole runway width. Reduction in runway thickness is beneficial when strengthening existing runways which have an inadequate camber. Reduced thickness at the edge will allow improved transverse gradients and surface water drainage. The dynamic effects of landing induced on helicopter pads and Harrier VTOL's increase the loading factor and therefore the number of passes equals the number of take offs plus the number of landings at an ACN of appropriate weight.

3.1.5 *Coverage and Pass-to-Coverage Ratio*

Coverage is the number of times that a particular point on the pavement (i.e. the surface of flexible pavements and the underside of the slab in rigid pavements) 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 the number and spacing of wheels on the main gear, width of the contact area and lateral displacement of aircraft wheel paths relative to the centre line of the pavement.

Coverages were developed by the US Army Corps of Engineers in which the distribution of the aircraft on runways and taxiways are represented by a general normal distribution (GND). The Pass-to-Coverage ratio is found from:

$P/C = 1/\gamma W_t$ where γ is a function of the GND curve
W_t is the tyre width in m.

If there is more than one wheel the Pass-to-Coverage ratio is found by summing the distribution curves. If the wheels are far enough apart the distribution curves will not overlap and the Pass-to-Coverage ratio is that for one wheel. The design requires the number of coverages by an aircraft on the pavemenet, this can be found from:

Number of coverages = Passes/Pass to coverage ratio.

Table 22 indicates pass to coverage ratios for dual and dual tandem gear and Table 23 indicates pass to coverage ratios for aircraft with single main wheel gears.

Table 22 Pass-to-Coverage Ratios

Main Wheel Gear Type	*Pass-to-coverage Ratio*
Single	See Table 23
Dual	3.2
Dual Tandem	1.6

Table 23 Pass-to-Coverage Ratios for Aircraft with Single Main Wheel Gears

Tyre Pressure N/mm²	*ACN of Aircraft*			
	Up to 10	*11 – 20*	*21 – 40*	*Over 40*
Up to 1.0	8	6	5	4
1.0 to 1.5	10	8	6	5
Greater than 1.5	12	10	7	6

3.1.6 *Mixed traffic use*

Most airfields have varied aircraft making the calculation of the loading regime more complex as the load severity of each aircraft needs to be related to the load severity of the design aircraft. The equivalent number of coverages by the design aircraft can then be calculated as set out below.

(i) Decide on required design life.

(ii) Establish the aircraft types likely to use the pavement.

(iii) Establish the ACNs for each aircraft at the actual subgrade value and appropriate weight.

(iv) Identify the main wheel gear and establish a pass to coverage ratio.

(v) Establish the number of passes by each aircraft.

(vi) Establish the design aircraft.

(vii) Calculate the number of coverages by each aircraft during the design life of the pavement.

(viii) Calculate the ratio of ACN of each aircraft to the design aircraft.

(ix) Rigid pavements:

Use Figure 23 to obtain Rigid Mixed Traffic Factors (RMTFs) from ACN values. For each aircraft select the ACN of the design aircraft, then project a line horizontally until the appropriate ACN ratio is intersected. At this intersection read off the RMTF from the horizontal scale. The number of equivalent coverages by the design aircraft can be found:

Equivalent coverages=Coverages by aircraft at less than the design ACN/RMTF

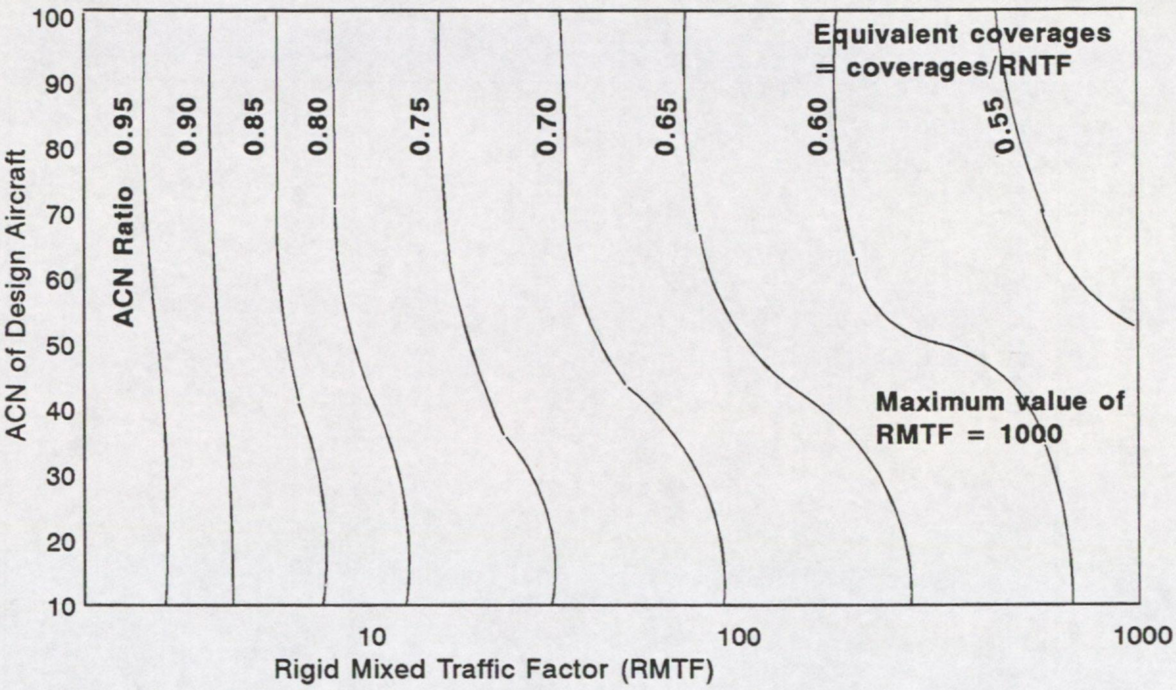


Figure 23 Chart to determine Rigid Mixed Traffic Factor which is needed to express the number of coverages of an aircraft in terms of equivalent coverages of the design aircraft. Each curve represents a different ACN ratio which is the ACN of the aircraft being considered divided by the ACN of the design aircraft.

(x) Flexible pavements:

Use Figure 24 to obtain Flexible Mixed Traffic Factors (FMTFs). For each aircraft select the respective number of coverages. Project a vertical line until it intersects the curve. The FMTF can be read off the vertical scale. Modify the FMTF by multiplying the FMTF for each aircraft by that aircraft's ACN ratio. Select modified FMTF on Figure 24 and work back to find the number of equivalent coverages by the design aircraft.

(xi) The total coverages at the design ACN can be found from:

Total coverages at design ACN = Coverages by the design aircraft at the design ACN + Equivalent coverages

(xii) Using Table 24 a frequency of trafficking can be obtained.

Table 24 Design Frequency of Trafficking. Depending on the nominal number of coverages calculated over the design life of the pavement, the frequency of traffic will be Low, Medium or High. One of these three categories is selected and subsequently used in a PSA design chart.

Frequency of trafficking	*Nominal Number of Coverages Over Design Life of Pavement*
Low	10,000
Medium	100,000
High	250,000

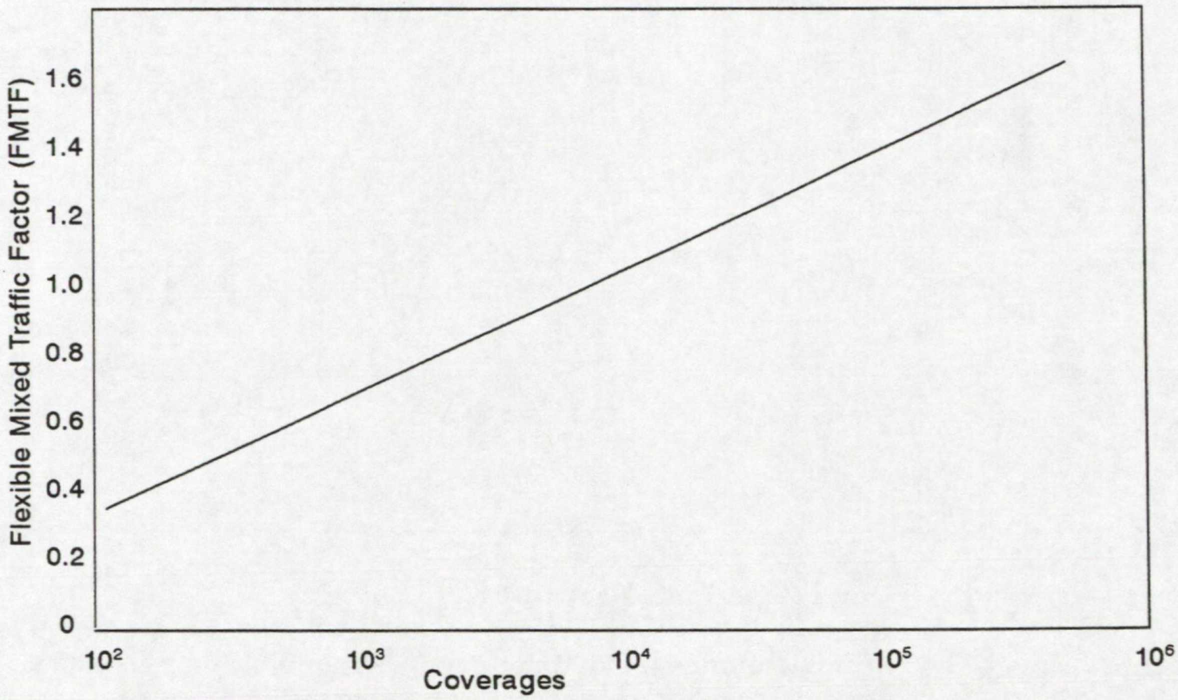


Figure 24 Chart to determine Flexible Mixed Traffic Factors

3.2 Rigid pavement design to the PSA method

Historically in the UK the preferred method of rigid aircraft pavement construction has been unreinforced Pavement Quality Concrete without dowels, tie bars or keys, on rolled Dry Lean Concrete. This Section is included because it is common for rigid pavements to be overlain with pavers. The following issues are relevant in the consideration of overlaying rigid pavements:

(a) Pavement Quality Concrete Slab.

(b) Joints in Pavement Quality Concrete Slabs.

(c) Base.

(d) Subgrade.

(e) Design of Undowelled and Unreinforced Concrete Pavements.

(f) Doweled Concrete Pavements.

(g) Jointed Reinforced Concrete Pavements with Dowels.

(h) Continuously Reinforced Concrete Pavements.

3.2.1 *Pavement Quality Concrete (PQC) Slab*

The PQC slab must be strong enough to provide an economical pavement thickness. The PQC also forms the surface which must be durable, hard wearing and weather resistant. The design flexural strength is the mean flexural strength of the PQC at 28 days. During construction strength tests should be carried out on samples with the same degree of compaction and curing as the in-situ concrete. Figure 25 indicates the relationship between 28 day mean flexural strengths and 7 day/28 day characteristic compressive strengths. (Characteristic strength is defined as that strength below which 5% of samples are allowed to fall.)

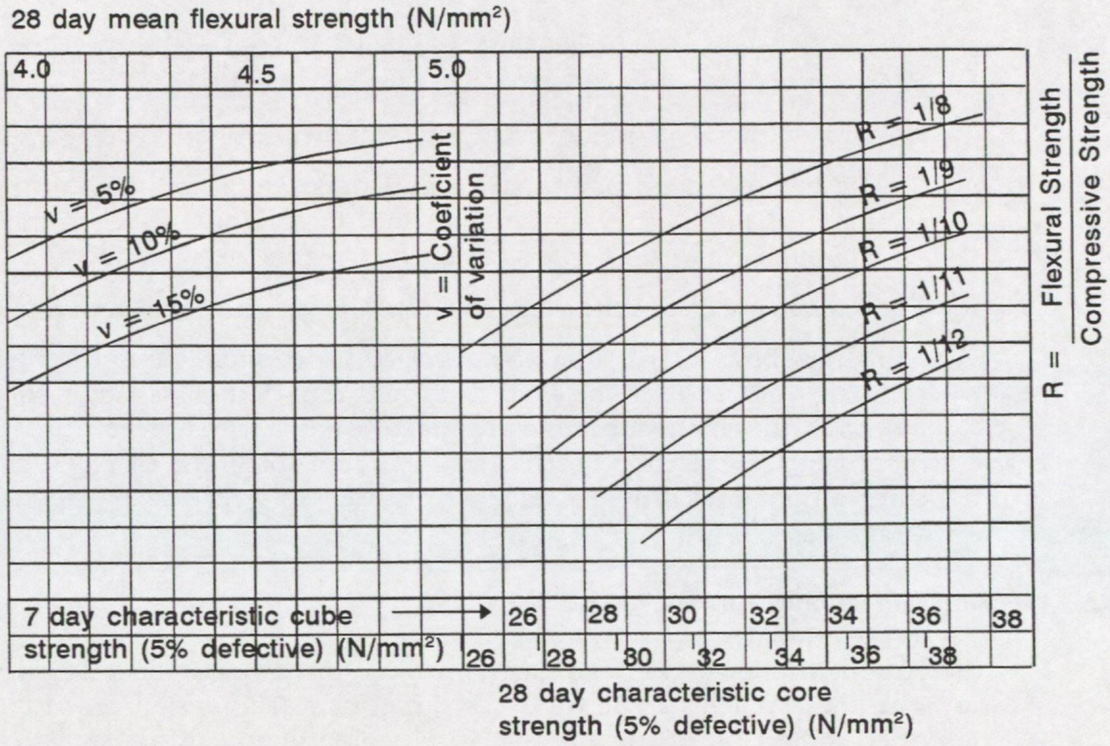


Figure 25 Relationship between compressive and flexural strengths for concrete

3.2.2 *Base*

The material specifications for pavement bases are set out in Section 2.6 of this Report. The PSA design method's standard base is drylean concrete, a lean concrete with a low water content. Under rigid pavements a maximum aggregate to cement ratio of 15:1 must be achieved and a water content between 5 to 7% of the weight of the dry materials. The drylean concrete should be rolled during construction to achieve maximum density.

3.3 PSA design procedure for rigid pavements

The basic PSA design procedure is that for an undoweled, unreinforced concrete pavement. The design of doweled and/or reinforced concrete pavements follows the same basic procedure; the differences in the design procedure are set out in Sections 3.3.1 and 3.3.2. Figures 26, 27 and 28 comprise Design Charts for single, dual and dual-tandem wheel gears, respectively. The use of the Design Charts requires four parameters:

(1) Flexural strength of the concrete.

(2) Modulus of subgrade reaction, k.

(3) Design ACN.

(4) Frequency of trafficking.

The design charts shown in Figures 26, 27 & 28 can be used to determine the thickness of construction required as follows:

(i) Select the frequency of trafficking and make a horizontal projection until it intersects with the appropriate design flexural strength.

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

(iii) From this intersection point make a horizontal projection to the right hand section of the chart (the k = 20 line) and trace a line parallel to the curves until it intersects with a vertical projection from the design value of k.

(iv) The drylean concrete thickness can be found from this intersection point.

(v) Using the above intersection point project a horizontal line to the right hand ordinate and read off the PQC thickness required. This value should be rounded up to the nearest practical construction increment (25mm increments are usually used). The minimum thickness of PQC is 150mm since a thinner slab might crack prematurely as a result of warping effects within the slab.

3.3.1 *Doweled Unreinforced Concrete Pavements*

The PSA method does not recommend the use of doweled concrete pavements owing to the problems associated with dowel bars. The design procedure is as described in Section 3.3 except that if the construction thickness is less than 250mm it can be reduced using Table 25.

Table 25 Thickness reduction for Doweled Pavements

PQC slab thickness (mm)	*Allowable reduction in thickness for doweled pavements (mm)*
equal to or greater than 250	0
225	15
200	25
175	25

The minimum slab thickness is 150mm.

Dowels should be provided at all construction, contraction and expansion joints to the specifications of Table 26.

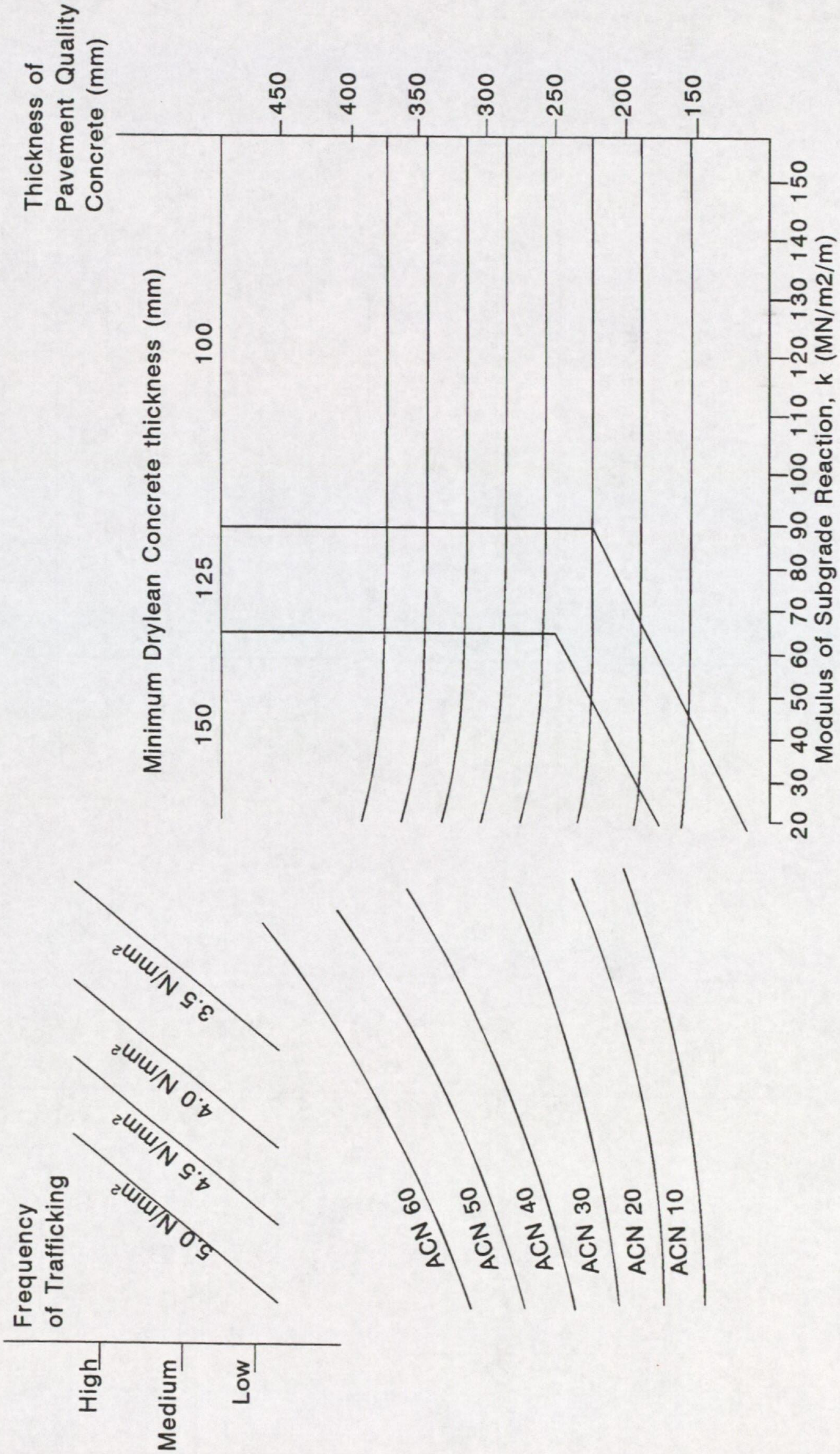


Figure 26 PSA Single Wheel Gear Design Chart for Rigid Pavements

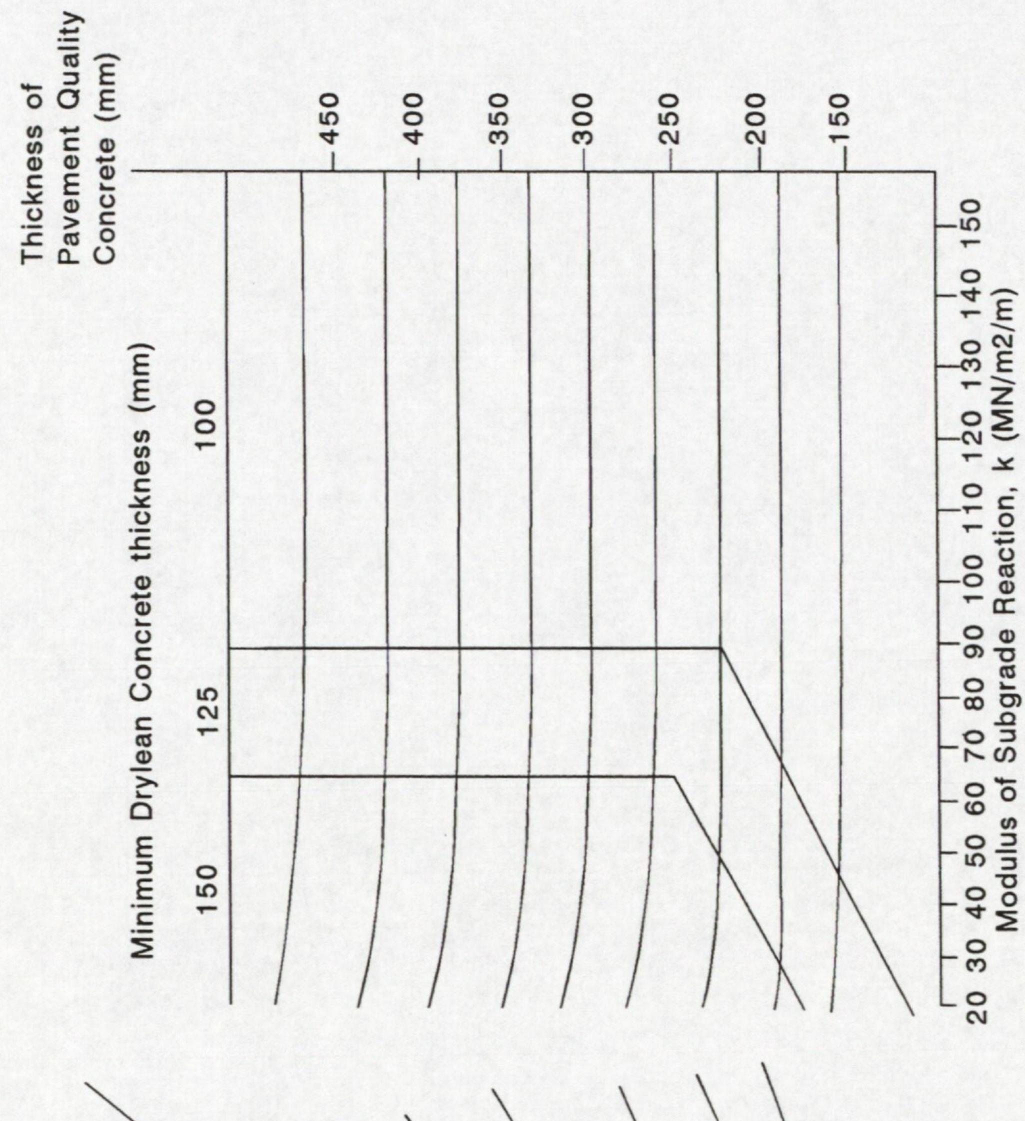


Figure 27 PSA Dual Wheel Gear Design Chart for Rigid Pavements

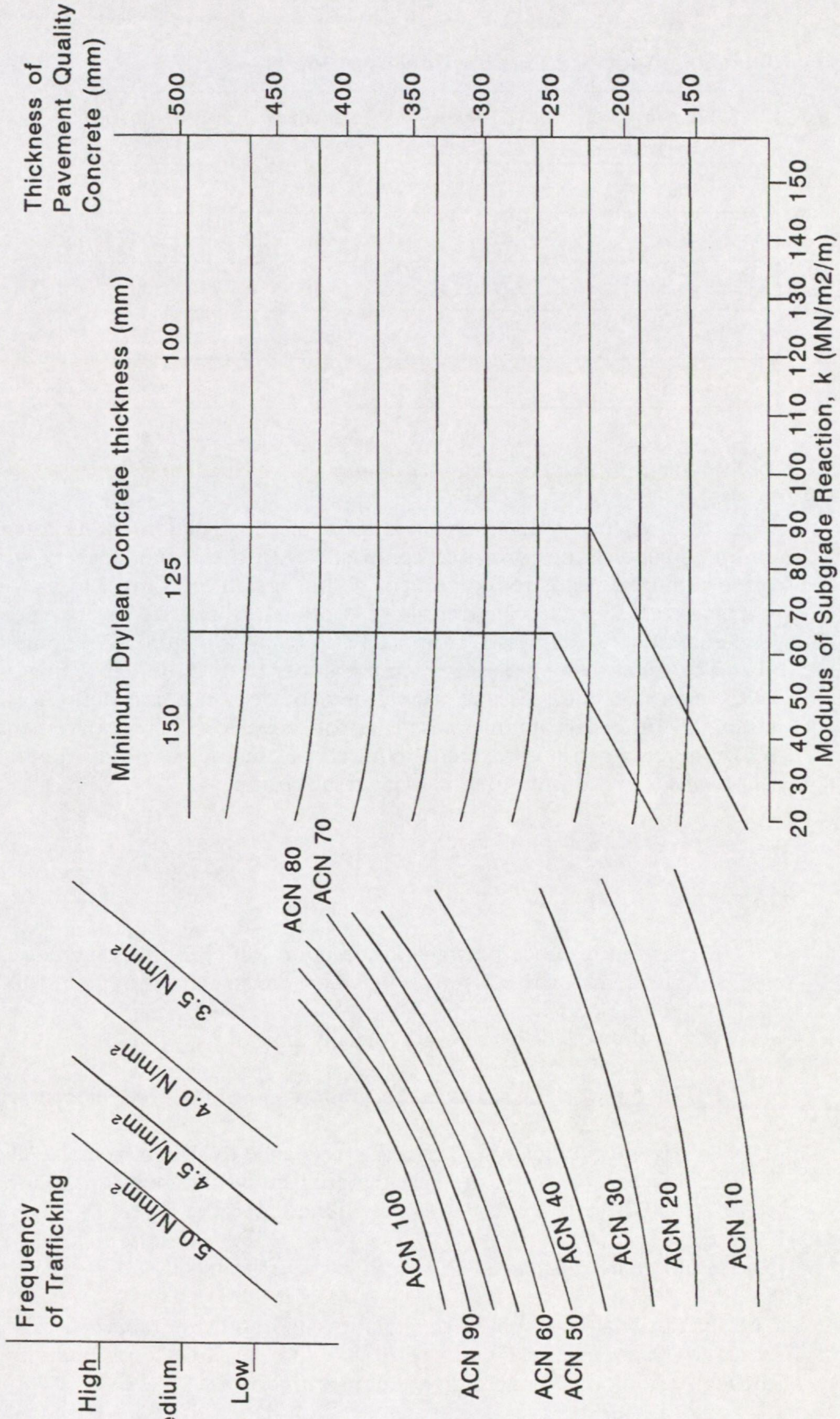


Figure 28 PSA Dual Tandem Wheel Gear Design Chart for Rigid Pavements

Table 26 Specifications for Dowels at Joints

PQC slab thickness (mm)	*Dowel diameter (mm)*	*Total dowel length (mm)*	*Dowel 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

3.3.2 *Doweled Reinforced Concrete Pavements*

The PSA does not recommend this form of construction owing to the minimal gain in structural performance compared with the higher level of maintenance often required. Light reinforcement within a slab to control the shrinkage and warping cracks enables the transverse contraction joints to be at greater spacings. The quantity of steel ranges from 0.05% to 0.3% of the cross sectional area of the slab. The reinforcement is placed in the upper part of the slab with a cover to the outer bars of 50mm. Because reinforcement does not contribute to the flexural strength of the slab, its thickness is as for doweled concrete pavements (Section 3.3). The area of reinforcement required, A_s, in the longitudinal and transverse directions is found from the following relationship.

$$A_s = (L\, C_f\, W\, h) / (2\, F_s)$$

where

- L is the distance between contraction joints in the longitudinal direction (<23m) or the distance between construction joints in the transverse direction (m).
- W is the weight of concrete (usually 24kN/m^3).
- h is the depth of the slab (mm).
- F_s is the working stress in the reinforcement (F_s = 0.75 for the yield stress), N/mm^2.
- C_f is the coefficient of subgrade resistance to slab movement. The value is dependent on the base material and slab dimensions, (C_f = 1.5 where a DLC base exists with a polythene separation layer).

The reinforcement is placed as a mesh in the upper section of the slab.

The longitudinal laps should be equal to 30Ø and the transverse laps should be equal to the greater of 150mm or 20Ø. Figure 29 indicates a longitudinal section through a reinforced concrete pavement with dowels.

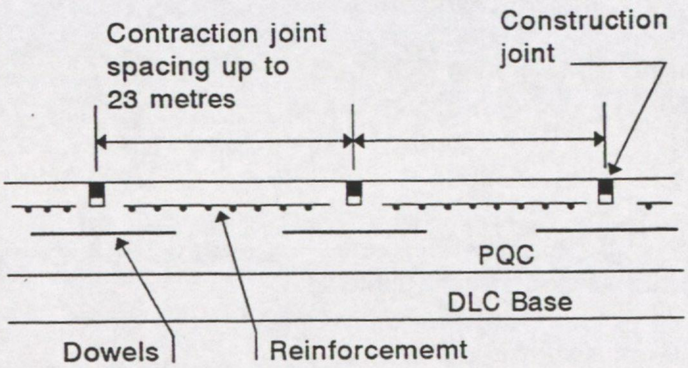


Figure 29 Typical longitudinal section through a jointed reinforced concrete pavement

3.3.3 Continuously Reinforced Concrete Pavements (CRCP)

The PSA has no established procedure for the design of CRCP for two main reasons:

(a) The pavement is no more cost effective than other types of pavement;

(b) Reduced thickness slabs used are prone to early age shrinkage, warping and spalling. Spalling is caused by frost damage and/or excessive working of cracks from repetitive wheel loading, jet blast and high tyre pressure.

The PSA recommends consideration of the following points for the design of CRCP.

(a) For consistent and controlled development of cracks the value of longitudinal reinforcement required is ≈ 0.5 – 0.7% of the cross sectional area of the concrete.

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

(c) Compaction of the concrete must be thorough.

(d) The advantage in rideability using CRCP is not significant.

3.4 PSA method rigid pavement design example

Consider the structural design of a rigid pavement on subgrade with a Modulus of Subgrade Reaction of 40MN/m^2/m for an aerodrome used by a range of aircraft.

Aircraft	*Annual Departures*
B737-200	6000
B747-100	3000
L-1011-100	1200
DC-10-30	1200
Airbus A300-B2	3000

Aircraft ACNs and main wheel gears are found from the Appendix. Pass-to-Coverage Ratios are found from Table 23.

This information is shown in Table 27.

Table 27 Rigid pavement design example Aircraft Classification Numbers for various aircraft on rigid pavements

Aircraft Type	*High k=150 $MN/m^2/m$*	*Medium k=80 $MN/m^2/m$*	*Low k=40 $MN/m^2/m$*	*Ultra Low k=20 $MN/m^2/m$*	*Main Wheel Gear*	*Pass-to-Coverage Ratio*
B737-200	29	30	32	34	D	3.2
B747-100	38	44	53	60	DT	1.6
L-1011-100	46	55	66	78	DT	1.6
DC-10-30	49	59	71	83	DT	1.6
Airbus A-300-B2	37	44	52	60	DT	1.6

The design life of the pavement is 20 years.
Design criteria:
ACNs of each aircraft are calculated for $k = 40\ MN/m^2/m$
Mixed Traffic Analysis for the Aircraft using Figure 23.
The design aircraft is the DC-10-30.
This information is shown in Table 28.

Table 28 Rigid Pavement Design Example. This Table summarises the procedure for equivalencing the number of coverages throughout the design life to coverages of the design aircraft, the DC-10-30.

Aircraft	*ACN*	*Passes to coverage ratio*	*Annual Departures*	*Coverages during design life*	*ACN ratio*	*Rigid Mixed Traffic Factor*	*Equivalent Coverages*
B737	32	3.2	6,000	37,500	0.45	1,000	38
B747	53	1.6	3,000	37,500	0.75	22	1,705
L-1011	66	1.6	1,200	15,000	0.93	2	7,500
DC-10	**71**	**1.6**	**1,200**	**15,000**	**1.00**	**1**	**15,000**
Airbus	52	1.6	3,000	37,500	0.73	25	1,500
					Total Coverages =		25,743

Table 33 indicates the frequency of trafficking to be Medium (up to 100,000 nominal coverages over design life).
Concrete flexural strength = 4.5N/mm^2 at 28 days.
Using Figure 28 the thicknesses of construction can be found:

Required construction is:	320mm Pavement Quality Concrete 150mm Drylean Concrete
PSA classification:	PCN 71/R/C/W/T

3.5 PSA design procedure for flexible pavements

The PSA policy has been to construct flexible pavements with either cement or bitumen bound bases. An unbound base can give the same results but it requires strict grading requirement and a need for a high and consistent level of compaction which in reality is harder to achieve. This is especially true with wet subgrades which are common in the UK. Pavements with bound bases permit the use of a less stringent construction specification and give structural benefits over the conventional unbound base. Thus the bound base design provides an economical and practical solution with reliable performance. Consideration is given to the following factors:

(a) Surfacing.

(b) Base, the standard designs require a bound base construction from the underside of the surfacing down to the subgrade.

(c) Subgrade, Section 2 details the methods used to find the subgrade strength.

3.6 PSA method flexible pavement design example

Design a flexible pavement on a subgrade with a CBR of 7% for an aerodrome used by a range of aircraft.

Aircraft	*Annual Departures*
B737-200/200C Advanced	6000
B747-SP	3000
L-1011-500	1200
DC-10-30/40	1200
Airbus A300	3000

Aircraft ACNs and Main wheel gears are found from the Appendix. Pass to Coverage Ratios are found from Table 24. This information is shown in Table 29.

Table 29 Flexible pavement design example. Aircraft Classification Numbers

Aircraft Type	*High* *CBR15%*	*Medium* *CBR10%*	*Low* *CBR6%*	*Ultra Low* *CBR3%*	*Main Wheel Gear*	*Pass to Coverage Ratio*
B737	29	31	34	39	D	3.2
B747	41	45	54	72	DT	1.6
L-1011	60	65	79	107	DT	1.6
DC-10	59	64	78	106	DT	1.6
Airbus	46	51	62	79	DT	1.6

The Design Life of the pavement is 20 years:

Design Criteria:

ACNs of the aircraft calculated at a CBR of 7%, the ACN of the B747 has to be altered owing to its gear wheel configuration, refer to Table 30.
Mixed Traffic Analysis for the Aircraft using Figure 24.
The Design Aircraft is the L-1011-500.
This information is shown in Table 31.

Table 30 ACN correction for adjacent load interaction on flexible pavements

Standard ACN	*Corrected ACN to allow for adjacent load interaction*
50	55
60	65
70	75
80	90
90	105
100	120

Table 31 Flexible Pavement Design Example. The L1011 is the design aircraft so coverages from the other aircraft have been expressed in equivalent L1011 coverages. Because the total number of equivalent coverages throughout the design life is less than 100,000, the Frequency of Trafficking falls into the Medium category.

Aircraft	*ACN*	*Passes to cover ratio*	*Annual departures design life*	*Coverages during*	*ACN ratio*	*FMTF*	*MFMTF*	*Equivalent Coverages*
B737	33	3.2	6,000	37,500	0.43	1.20	0.52	320
B747	57	1.6	3,000	37,500	0.75	1.20	0.90	5,200
L1011	**76**	**1.6**	**1,200**	**15,000**	**–**	**–**	**–**	**15,000**
DC10	75	1.6	1,200	15,000	0.99	1.06	1.05	13,500
Airbus	59	1.6	3,000	37,500	0.78	1.20	0.94	7,000
						Total Coverages		41,020

Table 31 indicates the frequency of trafficking, Medium (up to 100,000 nominal coverages over design life). Using Figure 30 the thickness of bound base material can be found.

Required construction:	80mm	Concrete Pavers
	30mm	Bedding Material
	625mm	Bound Base Material

Modified PCN Classification: PCN 76/F/C/W/T

3.7 Use of material conversion factors with PSA design method

Consider a situation where an area of aircraft stands is to be overlain with pavers. The ground conditions and aircraft mix are as set out in the example in Section 3.6. The existing pavement comprised 450mm thickness of Pavement Quality Concrete on 150mm D.Tp. Type 1 granular sub-base material. The existing concrete has been assessed to have a Material Conversion Factor of 2.2. The granular sub-base has a Material Conversion Factor of 0.3. The existing pavement is equivalent to the following thickness of CBM3, the standard material to which other materials are converted:

450mm PQC is equivalent to:	450 x 2.4 = 1080mm	CBM3
150mm Type 1 is equivalent to:	150 x 0.4 = 60mm	CBM3
80mm pavers on 30mm sand are equivalent to:	110 x 1.2 = 132mm	CBM3
	Total = 1272mm	CMB3

The above total of 1272mm represents the thickness of CBM3 to which the proposed overlain pavement will equivalence. The PSA design method can now be used to assess whether this thickness is sufficient. The PSA method produced the following design (See example in Section 3.5):

320mm PQC
150mm drylean concrete

Using Material Conversion Factors from Table 18, this design section can be converted into an equivalent thickness of CBM3 as follows:

320mm PQC is equivalent to 320 x 2.4	= 768mm	CBM3
150mm drylean concrete is equivalent to 150 x 1	= 150mm	CBM3
Total	= 918mm	CMB3

This value of 918mm represents the equivalent thickness of CBM3 material required. Because it is less than the thickness of 1272mm which the overlay would produce, the overlay is feasible.

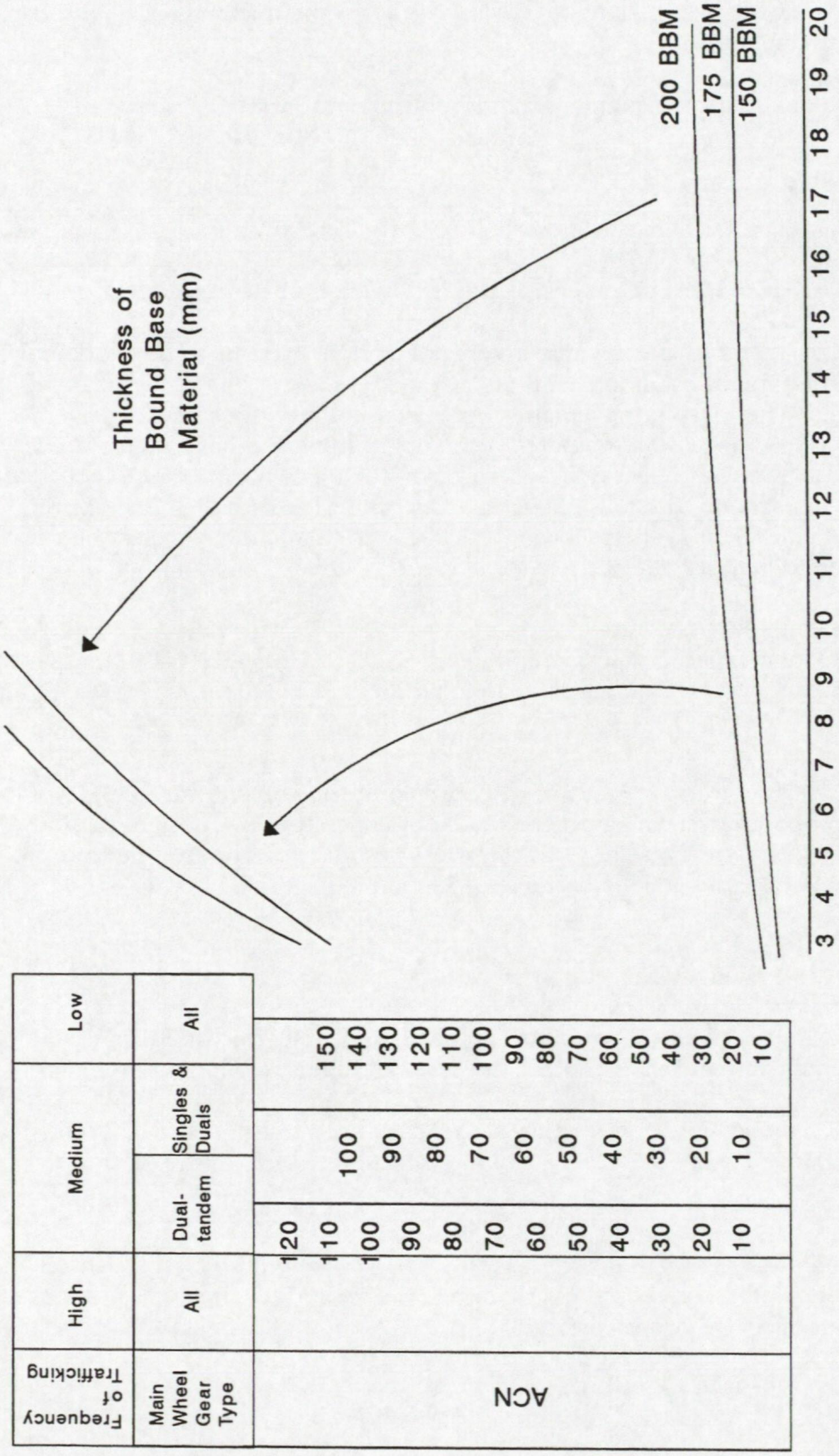


Figure 30 PSA Design Chart for Flexible Pavements

3.8 Assessment of existing pavements

In cases where pavers are being considered as on overlay or inlay, it will be necessary to make an assessment of the existing pavement in order to assign suitable Material Conversion Factors to each existing layer. Pavements can show signs of distress in many forms:

Cracks	a separation of the pavement surface.
Distortion	any change of pavement surface from its original shape.
Disintegration	the breaking up of the pavement into small loose fragments, the disintegration can spread until a complete new pavement will be required.
FOD	(Foreign Object Damage) pavement disintegration leading to damage to aircraft.

3.8.1 *Signs of deterioration of pavements*

The next two Sections discuss typical failures for different pavement constructions. A pavement will very rarely fail exactly as predicted owing to the variations between pavement constructions. The method of construction, the standard of workmanship and the natural variation in the subgrade all affect the pavement and its behaviour. An engineer should use his judgement when deciding whether a pavement can be overlain or inlaid with pavers.

3.8.2 *Rigid pavement deterioration*

Figure 31 shows a rigid pavement with extensive cracks. The Figure shows a multi bay rigid pavement with transverse and corner cracks. Where such a pavement is to be overlain, existing cracks and joints must be sealed and filled to prevent the loss of bedding and jointing material. Also, pavers should not be used as an overlay when existing slabs or parts of slabs are rocking.

(a) **Corner cracks**, a diagonal crack forming a triangle with a longitudinal joint or edge or a transverse joint or crack. This form of crack is caused by traffic loads on unsupported corners or curled or warped slabs. It may also be caused by a load applied over a weak spot in the subgrade beneath the slab. Providing the corner of the slab is not rocking, it will be possible to overlay slabs with corner cracks.

(b) **Diagonal cracks**, diagonal cracks are generally caused by loads on unsupported slab ends. The slab end may be unsupported owing to foundation settlement or the slab curling and then the subgrade pumps out to leave a void. To repair this the slab must be undersealed and the joint repaired. Any voids should be filled with grout prior to overlaying with pavers.

(c) **Longitudinal cracks**, longitudinal cracks run approximately parallel to the centre line of the pavement. These cracks are caused by concrete shrinkage, expansive subgrade or sub-base, combined warping and load stresses or loss of support resulting from edge pumping. If there is evidence that the slab is continuing to move, overlaying with pavers should be avoided.

(d) **Transverse cracks**, transverse cracks run at approximately right angles to the centre line of the pavement. Figure 32 shows a transverse crack in a rigid pavement. This section of pavement occurs at the end of a taxiway and consists of 250mm PQC laid over 150mm of Hoggin, a material with a wide aggregate range and a significant proportion of fines giving a clay like appearance, constructed in 1946. The cracks are caused by various factors; overloading, repeated bending of pumped pavements, failure of soft foundations, frozen joints and shrinkage of concrete. Overlaying with pavers is possible but all of the joints and cracks – which may now be pseudo joints – should be filled and sealed. Transverse and longitudinal cracks may be repaired by sand-blasting the crack faces, cleaning and filling with a rubber asphalt compound. If a void exists under the pavement it should be filled before the cracks are repaired.

(e) **Restraint cracks**, these are caused by foreign matter in the joints which impedes the movement of the joint. If the joint cannot move the slab cannot expand. Restraint cracks develop near the outer edge of the pavement and progress in an irregular path towards a longitudinal joint. Repair consists of ploughing out the old sealer and foreign matter, sand blasting and refilling and sealing. Once repaired, the slab can be overlain. Figure 33 shows a repaired joint, the joint had failed and so was raked out and then the faces of the joint and the pavement surface adjacent to the joint were sand blasted. The joint was resealed and an epoxy mortar applied to the pavement surface. The application of mortar to the pavement surface is only needed when the edge of the pavement has started to break down owing to the failure of the joint.

(f) **Faulting**, a fault is a difference in elevation of two slabs at a joint or a crack, caused by inadequate load transfer between slabs and consolidation or shrinkage of underlying layers or pumping. To repair a fault remove the existing sealer from the joint or crack, sand blast and raise slab to original grade and fully fill crack. Care should be taken when overlaying such faults. If differential slab movement continues, pavers will loosen along the fault line and interlock will be lost which may result in pavers being removed from the surface.

(g) **Pumping**, pumping occurs when there is slab movement under passing loads. A mixture of water, sand, clay or silt is ejected. Pumping occurs at transverse and longitudinal joints and edges, and also along the pavement edges. Pumping is caused by the presence of free water on or in the subgrade or sub-base and a heavy load deflecting the slab. To repair the pavement the voids must be filled and any affected joints resealed. Once the pumping has been remedied, a paver overlay is possible.

(h) **Scaling**, a peeling away of the surface owing to; over finishing, improper mixing, unsuitable aggregates, improper curing or chemical action of de-icing salts. Pavers may constitute a particularly efficient way of dealing with scaling. There should be no need to treat the existing slab surface. The pavers and their bedding sand will protect the scaled surface from further damage.

Figure 31 Extensive cracking in a rigid pavement. Pavers can be used as an overlay providing the cracks and joints are sealed and none of the concrete rocks

Figure 32 Transverse crack in a rigid pavement. A paver overlay is possible providing the joint has been sealed.

(j) **Spalling**, the breaking or chipping of the pavement at a joint, crack or the edge. Spalling can be caused by various factors; hard pieces of gravel lodged in a joint or crack, improperly installed load transfer devices, improper sawing and forming of joints or a weak mortar. Pavers can be used as an overlay in this situation but care must be taken to ensure that bedding sand is prevented from entering existing slab joints.

In all of the above cases, it may be necessary to reduce the concrete slab Material Conversion Factor from its usual value of 2.4 as shown in Table 18. Values of between 2 and 2.2 are recommended. If the condition of the slab is so poor that a value of less than 2 seems appropriate, then the slab is probably too damaged to overlay.

3.8.3 *Flexible pavements*

(a) **Crocodile cracks** form a series of small blocks generally caused by excessive deflection of the surface over an unstable subgrade. The unstable support usually occurs when the base is saturated. Affected areas usually start in small patches. If no action is taken these patches can spread until the whole pavement is affected. Pavers should not be used to overlay pavements in this condition. However, if the crocodile cracking is confined to the upper courses, it may be possible to remove them and construct a paver inlay.

(b) **Edge cracks**, these are longitudinal cracks approximately 0.5m from the edge of the pavement. They are caused where there is a lack of shoulder support from settlement of material under the cracked area resulting from poor drainage, frost heave and shrinkage. A paver overlay is possible and the edge restraint needed by the pavers should extend down to form a restraint to the bituminous material. Prior to installing the pavers, the edge cracks should be filled and sealed.

(c) **Edge-joint cracks**, a separation of the joint between pavement and shoulder owing to alternate wetting and drying beneath the shoulder surface causing settlement, mix shrinkage or differential loading. It is likely that sand will be lost from a paver overlay, leading to the edge joint crack being reflected through to the surface of the pavers.

(d) **Lane joint cracks**, a longitudinal separation along the seam between paving lanes, usually caused by a weak seam. If a volume change occurs in the underlying soil vertical movement is apparent. A paver overlay is possible after the joint has been sealed and providing there is no continuing movement of the subgrade.

(e) **Reflection cracks**, a crack in an asphalt overlay which reflects the crack pattern and movements of the structure beneath. Figure 34 shows an example of a reflection crack. The construction of the pavement consists of 125 – 225mm of concrete overlain with 40mm of Dense Tar Surface wearing course, laid 45 years after the concrete. The cracking reflects the line of the original taxiway around the airfield. Reflection cracks usually occur over existing pavements where the original cracks have not been repaired. These cracks are not detrimental to the pavement except that they form a route for water to enter the pavement. The repair consists of sealing the joints to prevent ingress of water. Once the sealing has been undertaken, a paver overlay is possible but extreme care needs to be taken during sand screeding to hide the line of demarkation between the underground features.

Figure 33 Joint having been repaired with epoxy mortar in rigid concrete

Figure 34 Reflexion crack in flexible pavement

(f) **Shrinkage cracks** comprise interconnected cracks forming large blocks, often caused by a volume change of the asphalt material. A paver overlay will not be possible but an inlay can be constructed if, as is often the case, the shrinkage cracks are confined to the upper courses of the existing pavement.

(g) **Slippage cracks**, crescent shaped cracks pointing in the direction of thrust of wheels, usually caused by the lack of a good bond between the pavement layers. The affected material should be removed and a paver inlay can be provided. However, care should be exercised since this type of defect occurs in those areas where pavers could be removed if all of the recommendations in this Report are not followed.

3.8.4 *Pavements surfaced with pavers*

The maintenance of pavers is dealt with fully in Section 1.19. In general, an existing paver pavement will not be suitable for overlaying with either additional pavers or other materials. An experiment at Heathrow Airport in which pavers were overlain with asphalt as a means of arresting reflective cracking proved unsuccessful. Figure 35 shows an area of asphalt pavement strengthened using pavers. The edge of the pavers has failed owing to the underlying layers moving. Water has seeped into the underlying layers causing paver displacement. Pavers can be repeatedly lifted and relayed with only a few pavers needing replacement, giving easy access to underground services. The level of noise pollution is greatly decreased as no mechanical plant is needed to remove the pavers. Reinstatement is less unsightly than that for other forms of pavement. Once pavers have been lifted the bedding sand should be replaced to the same thickness as that removed to ensure continuity when the pavers are replaced. In cases where bedding sand is rescreeded over concrete joints or cracks, it may be necessary to ensure that the joints or cracks are sealed with bituminous material to avoid the possibility of sand escaping downwards. Woven geotextiles have been used successfully in such applications but sand particles have on several occasions destroyed non-woven materials.

It may be that the surface of the pavement is being raised in which case it may be necessary to include an additional course between the bedding sand and the underlying concrete. The sand bed is normally 30mm thick but this can be increased to 50mm to accomodate minor level changes. If new levels dictate that the sand bed thickness is to vary, a constant thickness of sand should be screeded initially and the constant thickness should then be compacted to a thickness equal to the minimum sand bed thickness required. Additional sand can then be screeded over the compacted sand and a further compaction operation should be undertaken prior to installing pavers. Also, a loose layer of sand should be provided over the compacted sand prior to installation to ensure upwards sand penetration into paver joints.

In cases where new surface levels cannot be achieved by varying sand thickness, it is suggested that a (possibly tapering) course of Dense Bitumen Macadam (DBM) should be laid directly over the concrete. The thickness of the DBM should be specified to ensure that the sand bed thickness is uniform. Where the DBM is laid over poor quality concrete, a bituminous tack coat may be required between the concrete and the DBM.

Figure 35 Paver edge detailing failure

Figure 36 Spalling of edge restraint leads to Foreign Object Damage

3.8.5 *Foreign Object Damage (FOD)*

FOD is of major concern on airfields. Any foreign matter ingested into an engine can have catastrophic consequences. At the very least the aircraft may need extensive repairs. Loose material on the runways or taxiways must be removed. The main causes of foreign matter on the pavement are:

Migration of stones onto the pavement from adjacent areas owing to wind or the action of birds.
Human error – nuts and bolts dropped when maintaining the aircraft.
Nuts and bolts dropped from an aircraft in service.
Pavement breakdown.
Birds flying into oncoming aircraft.

The pavements should be regularly checked for foreign matter dropped from aircraft and blown onto the pavement. Figure 36 shows an example of pavement breakdown leading to FOD. Pavements should be regularly checked for breakdown and any loose material removed. If the pavement is regularly maintained, discussed in Section 3.11.1, there should be no breakdown of the pavement.

There is no reason to believe that a paver pavement will influence the likelihood of FOD. Erosion of the jointing material must be eliminated and the recommendations in Section 1 should ensure that paver joints remain filled.

4 RECOMMENDATIONS

The following recommendations should be followed in all cases where pavers either have already been used or are being contemplated on aircraft pavements at civil aerodromes in the United Kingdom. They are based upon the information detailed in this Report.

4.1 Recommendation 1

The information set out in this Report is intended to be applied only by those with experience in the design of aircraft pavements. The designer should have experience of the particular type of pavement being designed or reviewed. The designer should consult those source documents referred to in this Report.

4.2 Recommendation 2

Pavers may be used to surface the following categories of aircraft pavements:

(a) Aircraft stands.

(b) Low speed taxiways not subject to significant jet blast or propeller wash.

(c) Aircraft maintenance areas not subjected to significant jet blast or propeller wash.

Pavers should not be used on the following categories of aircraft pavements:

(a) Runways.

(b) Areas where aircraft engines are run at high thrust values.

(c) High speed taxiways.

4.3 **Recommendation 3**

All proposed pavements to be surfaced with pavers should be rigorously structurally designed using an appropriate method. Where pavers are to be used to surface an existing pavement, a structural evaluation of that pavement should be undertaken. Recommendation 3 needs to be followed to ensure that the support offered to the pavers by the structure and the foundation of the pavement is sufficient to eliminate the possibility of interlock being lost and to ensure that the pavement retains its structural integrity.

4.4 **Recommendation 4**

In relation to paver and laying course materials, the recommendations presently used for pavers in non-aircraft applications **(British Standards Institution (1988)** *Precast Concrete Paving Blocks. Part 1 Specification for Paving Blocks. Part 3 Code of Practice for Laying.* BS6717:1988, BSI, London) can be applied with the following amendments:

(a) Only those pavers which when laid develop a joint of width of less than 4mm should be used. Normally, this will confine the choice of pavers to rectangular units.

(b) Methods of mechanical installation whereby a 'cluster' of pavers is placed onto a sand bed should be avoided unless cluster effects can be eliminated. Experience indicates that the cluster perimeter joint may be too wide.

(c) The laying course should comprise a Category 1 or a Category 2 material as described in the County Surveyors' Society *Pavement Design Manual* ENG/6-94. Category 2 material will be sufficient in all cases except those where the topographical design of the pavement could induce a 1m or more height pressure head in the laying course in which case a Category 1 material is required.

(d) In all cases, the paver joints should be formed in such a way as to minimise the erosion of the jointing material by jet blast or propeller wash. Frequently, this will involve the use of a joint stabilising material introduced into the jointing sand.

(e) Pavers should be laid to a herringbone pattern. The orientation of the pattern need not be conditioned by the direction of principal trafficking. There should be no discontinuity within the laying pattern and in phased construction pavers laid at different times should always be fully interlocking across construction phase boundaries.

4.5 Recommendation 5

Areas of pavers should be inspected regularly. The frequency of inspection should take into account the volume and character of traffic. Those areas subject to regular movements of heavy aircraft using engines at more than half thrust should be inspected on a monthly basis. Areas subject to zero or minor levels of thrust should be inspected at frequencies up to 6 months. Each inspection should include an examination of the paver joints and any evidence of joint erosion should be recorded. Also, the surface of the pavers should be tapped with a steel bar or similar implement to determine whether the pavers are seated intimately on the laying course material. Any defects should be rectified immediately. Erosion treatment will comprise the removal of jointing material and the refilling and stabilising of the joints.

In cases where pavers have been used to surface runways, areas where aircraft engines are run at high thrust values and high speed taxiways, all areas of pavers should be inspected at intervals of between one week and one month according to the level of loading and particular care should be taken in assessing paver joint erosion and the seating of pavers over the laying course material.

4.6 Recommendation 6

A record should be maintained of each area of pavers. The record should include the construction drawings and the design assumptions and calculations. Each inspection should be recorded and the details of any remedial work should be kept.

4.7 Recommendation 7

Careful attention should be paid to detailing of the pavement. In particular, attention should be focussed upon those items described in Section 1.14.

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Appendix Aircraft Classification Numbers

Aircraft Type	*All up Mass*	*Load on one main gear leg*	*Tyre Pressure*	*Rigid Pavement Subgrades MN/m³*				*Flexible Pavement Subgrades CBR*				*Main gear type for pavement design*
				High 150	*Medium 80*	*Low 40*	*Ultra Low 20*	*High 15*	*Medium 10*	*Low 6*	*Ultra Low 3*	
	kg	*%*	*MPa*	*ACN*				*ACN*				
Airbus A300 Model B2	142,000 85,690	46.5	1.23	37 19	44 22	52 26	60 30	40 21	45 23	55 26	70 35	Dual-Tandem
Airbus A300 Model B4	157,000 87,826	46.5	1.41	44 20	52 23	61 27	69 32	46 22	51 23	62 27	79 35	Dual-Tandem
BAC 1-11 Series 400	39,690 22,498	47.5	0.93	25 13	26 13	28 14	29 15	22 11	24 12	27 13	29 15	Dual
BAC 1-11 Series 475	44,679 23,451	47.5	0.57	22 10	25 11	27 12	28 13	19 9	24 10	28 12	31 15	Dual
BAC 1-11 Series 500	47,400 24,757	47.5	1.08	32 15	34 16	35 16	36 17	29 13	30 13	33 15	35 17	Dual
BAe 146 Series 100	37,308 23,000	46.0	0.80	18 10	20 11	22 12	23 13	17 10	18 10	20 11	24 13	Dual
BAe 146 Series 100	37.308 23,000	46.0	0.52	16 9	18 10	19 11	21 12	13 8	16 9	19 11	23 13	Dual
BAe 146 Series 200	40,600 23,000	47.1	0.88	22 11	23 12	25 13	26 14	19 10	21 10	23 11	27 13	Dual
BAe 146 Series 200	40,600 23,000	47.1	0.61	19 10	21 11	23 12	24 12	16 8	20 10	22 11	27 13	Dual
B707-120B	117,027 57,833	46.7	1.17	28 12	33 13	40 15	46 18	31 13	34 14	41 15	54 20	Dual-Tandem

Aircraft Type	*All up Mass*	*Load on one main gear leg*	*Tyre Pressure*	*Rigid Pavement Subgrades MN/m³*				*Flexible Pavement Subgrades CBR*				*Main gear type for pavement design*
				High 150	*Medium 80*	*Low 40*	*Ultra Low 20*	*High 15*	*Medium 10*	*Low 6*	*Ultra Low 3*	
	kg	*%*	*MPa*	*ACN*				*ACN*				
B707-320B	148,778 64,764	46.0	1.24	39 14	46 15	55 18	63 20	42 15	47 16	57 17	73 23	Dual-Tandem
B707-320C (Freighter)	152,407 61,463	46.7	1.24	41 13	49 14	58 17	66 19	44 14	49 15	60 17	77 21	Dual-Tandem
B707-320C	152,407 67,269	46.7	1.24	41 15	49 16	58 19	66 22	44 16	49 17	60 19	76 24	Dual-Tandem
B-727 (Advanced)	95,254 45,677	46.1	1.15	57 24	60 25	63 27	66 28	51 21	54 22	61 24	66 28	Dual
B737-100	44,361 25,941	46.2	0.92	22 12	24 13	26 14	27 15	20 11	22 12	24 13	29 15	Dual
B737-200	45,722 25,941	46.4	0.95	23 12	25 13	27 14	28 15	21 11	22 12	25 13	30 15	Dual
B737-200	52,616 27,293	45.5	1.10	29 13	30 14	32 15	34 16	26 12	27 13	31 14	35 15	Dual
B737-200	52,616 27,293	45.5	0.63	24 11	26 12	29 13	31 14	21 10	26 11	29 13	34 15	Dual
B737-200/200C (Advanced)	53,297 28,916	46.4	1.16	30 14	31 15	33 16	35 17	27 13	28 14	31 15	35 16	Dual
B737-200/200C (Advanced)	56,699 27,868	46.3	1.23	33 15	34 16	36 17	38 18	28 13	30 14	33 15	37 17	Dual

Aircraft Type	All up Mass	Load on one main gear leg	Tyre Pressure	Rigid Pavement Subgrades MN/m³				Flexible Pavement Subgrades CBR				Main gear type for pavement design
				High 150	Medium 80	Low 40	Ultra Low 20	High 15	Medium 10	Low 6	Ultra Low 3	
	kg	%	MPa	ACN				ACN				
B737-200 (Advanced)	58,332 29,138	46.0	1.26	34 15	36 16	38 17	39 18	29 13	31 14	34 15	39 17	Dual
B707-320/420	143,335 64,682	46.0	1.24	37 14	43 15	52 17	59 20	40 15	44 15	54 17	69 23	Dual-Tandem
B720	104,326 50,258	47.4	1.00	25 10	30 11	37 13	43 16	29 11	31 12	39 14	51 18	Dual-Tandem
B720B	106,594 52,163	46.4	1.00	25 10	30 11	37 14	43 16	29 11	31 12	39 14	51 18	Dual-Tandem
B727-100	77,110 39,778	45.2	1.14	43 20	45 21	48 22	50 23	39 18	40 19	46 20	51 23	Dual
B727-100C	73,028 39,734	45.4	1.09	40 20	43 22	45 23	47 24	37 18	38 19	43 20	48 23	Dual
B727-200 (Standard)	78,471 44,293	46.2	1.15	45 23	48 24	50 26	53 27	40 20	42 21	48 23	53 27	Dual
B727-200 (Advanced)	84,277 44,270	46.7	1.02	48 22	51 24	54 26	57 27	44 20	46 21	53 24	58 28	Dual
B727 (Advanced)	86,636 44,347	46.6	1.02	50 22	53 24	56 25	58 27	46 20	48 21	55 23	60 28	Dual
B727 (Advanced)	89,675 44,470	46.4	1.15	53 23	56 24	59 26	62 28	48 21	51 22	57 24	62 25	Dual

Aircraft Type	All up Mass	Load on one main gear leg	Tyre Pressure	Rigid Pavement Subgrades MN/m³				Flexible Pavement Subgrades CBR				Main gear type for pavement design
				High 150	Medium 80	Low 40	Ultra Low 20	High 15	Medium 10	Low 6	Ultra Low 3	
	kg	%	MPa	ACN				ACN				
B747-100	323,410 162,385	23.4	1.50	41 18	48 19	57 22	65 26	44 19	48 20	58 22	78 28	Dual-Tandem*
B747-100B	334,749 173,036	23.1	1.56	43 19	50 21	59 24	68 28	46 20	50 21	60 24	80 31	Dual-Tandem*
B747-100B	341,553 171,870	23.1	1.32	42 18	49 20	59 23	68 27	46 20	51 21	62 23	82 30	Dual-Tandem*
B747-100B SR	237,228 164,543	24.1	1.04	25 16	29 18	35 21	42 25	30 19	32 20	38 23	52 30	Dual-Tandem*
B747 SP	300,730 147,716	22.9	1.30	36 15	42 17	50 19	58 22	40 16	43 17	52 19	71 25	Dual-Tandem*
B747 SP	381,881 147,996	21.9	1.40	38 15	44 16	53 19	60 20	41 16	45 17	54 18	72 23	Dual-Tandem*
B747-200B	352,893 172,886	23.6	1.37	45 19	54 21	64 24	74 28	50 21	55 22	67 24	88 31	Dual-Tandem*
B747-200C	373,305 166,749	23.1	1.30	47 17	55 19	66 22	76 26	52 19	58 20	71 22	92 29	Dual-Tandem*
B747-200F	379,201 156,642	22.7	1.39	48 18	56 20	67 23	77 27	52 20	58 21	71 23	92 30	Dual-Tandem
B757-200	109,300 57,000	45.2	1.17	27 11	32 13	38 16	44 18	29 13	32 14	39 15	52 20	Dual-Tandem

* On Flexible Pavements there is interaction between the main wheel gear.

Aircraft Type	All up Mass	Load on one main gear leg	Tyre Pressure	Rigid Pavement Subgrades MN/m^3				Flexible Pavement Subgrades CBR				Main gear type for pavement design
				High 150	Medium 80	Low 40	Ultra Low 20	High 15	Medium 10	Low 6	Ultra Low 3	
	kg	%	MPa	ACN				ACN				
B767-200	143,800 79,800	46.3	1.31	34 16	39 17	47 20	54 24	37 18	41 19	50 20	66 26	Dual-Tandem
B767-200-ER	159,700 81,600	46.3	1.21	38 17	45 18	53 21	62 25	42 18	46 19	58 21	76 27	Dual-Tandem
B767-300	159,600 85,700	46.3	1.21	38 18	45 20	53 23	62 27	42 20	46 21	58 23	76 30	Dual-Tandem
Caravelle Series 10	52,000 29,034	46.1	0.75	15 7	17 8	20 9	22 10	15 7	17 7	19 9	23 11	Dual-Tandem
Caravelle Series 12	55,960 31,800	46.0	0.88	16 8	19 9	22 10	25 12	17 8	19 9	21 10	26 12	Dual-Tandem
Concorde	185,066 78,698	48.0	1.26	61 21	71 22	82 25	91 29	65 21	72 22	81 26	98 32	Dual-Tandem
Canadair CL 44	95,708 40,370	47.5	1.12	25 9	30 10	35 11	40 13	27 9	30 10	36 11	47 14	Dual-Tandem
Convair 990	115,666 54,685	48.5	1.28	41 15	48 17	54 19	60 22	40 15	45 16	53 19	64 24	Dual-Tandem
DC-3	11,430 7,767	46.8	0.31	6 4	7 5	7 5	7 5	4 3	6 4	8 5	9 6	Single
DC-4	33,113 22,075	46.75	0.53	13 8	15 9	17 10	18 11	11 7	14 9	16 10	20 12	Dual

Aircraft Type	*All up Mass*	*Load on one main gear leg*	*Tyre Pressure*	*Rigid Pavement Subgrades MN/m³*				*Flexible Pavement Subgrades CBR*				*Main gear type for pavement design*
				High 150	*Medium 80*	*Low 40*	*Ultra Low 20*	*High 15*	*Medium 10*	*Low 6*	*Ultra Low 3*	
	kg	*%*	*MPa*	*ACN*				*ACN*				
DC-8-43	144,242 61,919	46.5	1.22	41 15	49 16	57 18	65 21	43 15	49 16	59 18	74 23	Dual-Tandem
DC-8-55	148,778 62,716	47.0	1.30	45 15	53 16	62 19	69 22	46 15	53 16	63 18	78 24	Dual-Tandem
DC-8-61	148,778 68,992	48.0	1.30	46 17	54 19	63 22	71 25	48 18	54 19	64 21	80 28	Dual-Tandem
DC-8-62	160,121 65,025	46.5	1.29	47 15	56 16	65 19	73 22	49 16	56 16	67 18	83 24	Dual-Tandem
DC-8-63	162,386 72,002	47.0	1.34	50 17	60 19	69 23	78 26	52 18	59 19	71 22	87 29	Dual-Tandem
DC-9-15	41,504 22,300	46.2	0.90	23 11	25 12	26 13	28 14	21 10	22 11	26 12	28 15	Dual
DC-9-21	45,813 23,879	47.15	0.98	27 12	29 13	30 14	32 15	24 11	26 12	29 13	32 15	Dual
DC-9-32	49,442 25,789	46.2	1.05	29 14	31 15	33 15	34 16	26 12	28 13	31 15	34 16	Dual
DC-9-41	52,163 27,821	46.65	1.10	32 15	34 16	35 17	37 18	28 13	30 14	33 15	37 18	Dual
DC-9-51	55,338 29,336	47	1.17	35 17	37 17	39 18	40 19	31 .15	32 15	36 16	39 19	Dual

Aircraft Type	*All up Mass*	*Load on one main gear leg*	*Tyre Pressure*	*Rigid Pavement Subgrades MN/m³*				*Flexible Pavement Subgrades CBR*				*Main gear type for pavement design*
				High 150	*Medium 80*	*Low 40*	*Ultra Low 20*	*High 15*	*Medium 10*	*Low 6*	*Ultra Low 3*	
	kg	*%*	*MPa*	*ACN*				*ACN*				
MD-81	63,957 35,571	47.75	1.17	41 20	43 21	45 23	46 24	36 18	38 19	43 21	46 24	Dual
MD-82	68,266 35,629	47.55	1.27	45 21	47 22	49 24	50 25	39 18	42 19	46 20	50 24	Dual
MD-83	73,023 36,230	47.4	1.34	49 21	51 22	53 24	55 25	42 18	46 19	50 21	54 24	Dual
MD-87	63,957 33,183	47.9	1.17	41 17	43 20	45 21	47 22	36 17	38 17	43 19	47 22	Dual
DC-10-10	196,406 108,940	47.15	1.28	45 23	52 25	63 28	73 33	52 26	57 27	68 30	93 38	Dual-Tandem
DC-10-10	200,942 105,279	46.85	1.31	46 22	54 24	64 27	75 31	54 24	58 25	69 28	96 36	Dual-Tandem
DC-10-15	207,746 105,279	46.65	1.34	48 22	56 24	67 27	74 31	55 24	61 25	72 28	100 36	Dual-Tandem
DC-10-30/40	253,105 120,742	37.7	1.17	44 20	53 21	64 24	75 28	53 22	59 23	70 25	97 32	Dual-Tandem
DC-10-30/40	260,816 124,058	37.6	1.21	46 20	55 21	67 25	78 29	56 23	61 23	74 26	101 33	Dual-Tandem
DC-10-30/40	268,981 124,058	37.9	1.24	49 20	59 21	71 25	83 29	59 23	64 23	78 26	106 33	Dual-Tandem

Aircraft Type	All up Mass	Load on one main gear leg	Tyre Pressure	Rigid Pavement Subgrades MN/m^3				Flexible Pavement Subgrades CBR				Main gear type for pavement design
				High 150	Medium 80	Low 40	Ultra Low 20	High 15	Medium 10	Low 6	Ultra Low 3	
	kg	%	MPa	ACN				ACN				
DCH 7 DASH 7	19,867 11,793	46.75	0.74	11 6	12 6	13 7	13 7	10 5	11 6	12 6	14 8	Dual
FOKKER 27 Mk 500	19,777 11,879	47.5	0.54	10 5	11 6	12 6	12 7	8 4	10 5	12 6	13 7	Dual
Fokker 28 Mk 1000 TP	29,484 15,650	46.3	0.58	14 6	15 7	17 8	18 9	11 5	14 6	16 7	19 9	Dual
Fokker 28 Mk 1000 HTP	29,484 16,550	46.3	0.69	15 8	16 8	18 9	18 10	13 6	15 7	17 8	20 10	Dual
HS125-400	10,600 5,683	45.5	0.77	6 3	6 3	7 3	7 3	5 2	5 3	6 3	7 3	Dual
HS125-600	11,340 5,683	45.5	0.83	7 3	7 3	7 3	8 3	5 2	6 3	7 3	8 3	Dual
HS748	21,092 12,183	43.6	0.59	10 5	11 5	11 6	12 6	8 4	9 5	11 6	13 7	Dual
IL62	162,600 66,400	47.0	1.08	42 14	50 15	60 18	69 20	47 16	54 17	64 18	79 24	Dual-Tandem
IL-62M	168,000 71,400	47.0	1.08	43 16	52 17	62 19	71 22	50 17	57 18	67 20	83 26	Dual-Tandem
IL-76T	171,000 83,800	23.5	0.64	38 11	38 14	38 16	39 16	37 15	40 16	45 18	53 22	Dual-Tandem

Aircraft Type	All up Mass	Load on one main gear leg	Tyre Pressure	Rigid Pavement Subgrades MN/m^3				Flexible Pavement Subgrades CBR				Main gear type for pavement design
				High 150	Medium 80	Low 40	Ultra Low 20	High 15	Medium 10	Low 6	Ultra Low 3	
	kg	%	MPa	ACN				ACN				
IL-86	209,500 111,000	31.2	0.88	25 13	31 14	38 16	46 19	34 16	36 17	43 19	61 23	Dual-Tandem
L-1011-1	195,952 108,862	47.4	1.33	45 24	52 25	62 28	73 33	52 25	56 27	66 29	91 38	Dual-Tandem
L-1011-100/200	212,281 110,986	46.8	1.21	46 23	55 24	66 28	78 32	56 25	61 26	73 30	100 38	Dual-Tandem
L-1011-500	225,889 108,924	46.2	1.27	50 23	59 24	72 27	84 31	60 25	65 26	79 28	107 36	Dual-Tandem
TU-134A	47,600 29,350	45.6	0.83	11 7	13 8	16 9	19 10	12 7	13 8	16 9	21 12	Dual
TU-154B	98,000 53,500	45.1	0.93	19 8	25 10	32 13	38 17	20 10	24 11	30 13	38 18	Dual
Trident 1E	61,160 33,203	46	1.03	32 15	34 16	37 17	39 18	23 10	24 11	27 12	32 15	Dual-Tandem
Trident 2E	65,998 33,980	47	1.07	37 16	39 17	42 18	44 19	26 11	28 12	31 13	36 16	Dual-Tandem
Trident 3	68,266 39,060	45.5	1.14	37 18	40 19	42 21	44 22	26 13	28 14	31 15	36 18	Dual-Tandem
VC10-1150	151,953 71,940	48.25	1.01	38 16	46 17	56 20	65 23	44 17	50 18	61 21	77 27	Dual-Tandem

Aircraft Type	All up Mass	Load on one main gear leg	Tyre Pressure	Rigid Pavement Subgrades MN/m³				Flexible Pavement Subgrades CBR				Main gear type for pavement design
				High 150	Medium 80	Low 40	Ultra Low 20	High 15	Medium 10	Low 6	Ultra Low 3	
	kg	%	MPa	ACN				ACN				
Andover C Mk 1	22,680 13,472	45.6	0.545	10 6	11 6	12 7	13 7	9 6	11 6	12 7	15 8	Dual
Andover CC Mk 2	20,183 11,884	46.2	0.53	10 5	11 6	11 6	12 7	8 5	9 5	11 6	13 7	Dual
Andover CC Mk 2 (TQF)	21,090 11,884	46.2	0.59	11 5	12 6	13 6	13 7	9 5	10 5	12 6	14 7	Dual
Andover E Mk 3	22,680 14,747	45.6	0.545	12 7	13 8	14 8	14 9	9 6	11 6	13 7	15 9	Dual
BAe 146 100 (TQF)	37,535 21,183	46.5	0.93	20 10	21 11	23 12	24 13	18 9	20 10	22 11	25 13	Dual
Buccaneer S Mk 2A	26,935 14,014	46.1	1.79	28 15	28 15	28 15	28 15	28 14	26 14	26 14	25 13	Single
Buccaneer S Mk 2B	26,935 14,286	46.7	1.79	28 15	28 15	28 15	28 15	28 14	27 14	26 14	25 13	Single
Dominie T Mk 1	9,662 5,171	44.5	0.70	5 2	5 2	6 3	6 3	4 2	5 2	5 3	6 3	Dual
Harrier GR Mk 3	11,475 5,700	42.7+	0.83+	9 4	9 4	9 4	9 5	9 4	9 5	10 5	10 5	Single+
Harrier T Mk 4	11,885 5,950	42.4+	0.83+	9 4	9 5	9 5	9 5	9 4	9 5	10 5	10 5	Single+

+ Based on Nose wheel.

Aircraft Type	*All up Mass*	*Load on one main gear leg*	*Tyre Pressure*	*Rigid Pavement Subgrades MN/m³*				*Flexible Pavement Subgrades CBR*				*Main gear type for pavement design*
				High 150	*Medium 80*	*Low 40*	*Ultra Low 20*	*High 15*	*Medium 10*	*Low 6*	*Ultra Low 3*	
	kg	*%*	*MPa*	*ACN*				*ACN*				
Harrier T Mk 4A	11,885 6,240	42.4+	0.83+	9 5	9 5	9 5	9 5	9 5	9 5	10 5	10 5	Single+
Harrier T Mk 4N	11,885 6,170	42.4+	0.83+	9 5	9 5	9 5	9 5	9 5	9 5	10 5	10 5	Single+
Harrier GR Mk 5	13,495 7,196	51.8+	0.86+	9 6	9 6	10 6	10 6	9 6	10 6	10 6	10 6	Single+
Hawk T Mk 1	5,700 3,510	47.0	1.05	5 3	5 3	5 3	5 3	5 3	5 3	5 3	5 3	Single
Hercules C Mk 1	70,760 34,632	48.0	0.76 0.55	31 13	34 13	37 15	39 16	29 11	32 13	34 15	38 16	Tandem
Hercules C Mk 3	73,028 36,623	48.4	0.76 0.55	32 13	35 14	38 16	40 17	30 12	33 14	35 16	39 17	Tandem
Jaguar GR Mk 1	15,700 7,424	45	0.82	9 4	10 4	10 4	11 4	9 5	11 5	12 5	13 6	Dual
Jaguar T Mk 2	15,700 7,424	45	0.82	9 4	10 4	10 4	11 4	9 5	11 5	12 5	13 6	Dual
Jetstream T Mk 1	5,700 4,148	43.8	0.38	3 2	3 3	4 3	4 3	2 2	3 3	4 3	5 4	Single
Jetstream T Mk 2	6,000 4,473	44.3	0.38	3 2	3 3	4 3	4 3	2 2	3 3	4 3	5 4	Single

+ Based on Nose wheel.

Aircraft Type	*All up Mass*	*Load on one main gear leg*	*Tyre Pressure*	*Rigid Pavement Subgrades MN/m³*				*Flexible Pavement Subgrades CBR*				*Main gear type for pavement design*
				High 150	*Medium 80*	*Low 40*	*Ultra Low 20*	*High 15*	*Medium 10*	*Low 6*	*Ultra Low 3*	
	kg	*%*	*MPa*	*ACN*				*ACN*				
Jetstream T Mk 3	6,950 4,241	45.5	0.54	4 3	5 3	5 3	5 3	5 3	5 3	6 3	6 4	Single
Jetstream 31	6,650 4,015	45.6	0.23	3 2	3 3	4 3	4 3	2 2	3 3	4 3	5 4	Single
Nimrod R Mk 1	80,513 42,410	47.6	Up to 1.40	29 12	33 14	38 16	41 18	31 13	32 14	36 16	42 19	Dual-Tandem
Nimrod MR Mk 1	80,513 39,281	47.6	1.31	29 11	33 12	38 15	41 16	31 11	32 12	36 14	42 17	Dual-Tandem
Nimrod MR Mk 2	83,461 41,458	47.6	Up to 1.40	31 12	35 13	39 15	43 17	32 12	34 13	37 15	44 18	Dual-Tandem
Pembroke C Mk 1	6,124 4,616	44	0.38	2 1	2 2	3 2	3 2	1 1	2 2	3 3	3 3	Dual
Pembroke C (PR) Mk 1	6,124 4,637	44	0.38	2 1	2 2	3 2	3 2	1 1	2 2	3 3	3 3	Dual
Phantom FG Mk 1	27,397 14,512	43.8	2.07	28 15	28 15	27 15	27 14	27 14	26 14	25 14	24 13	Single
Phantom FGR Mk 2	27,397 14,603	43.6	2.07	28 15	27 15	27 15	27 14	27 14	26 14	25 14	24 14	Single
Phantom F4J	25,579 14,286	43.8	2.07	26 15	26 15	26 14	25 14	25 14	24 13	23 13	23 13	Single

Aircraft Type	All up Mass	Load on one main gear leg	Tyre Pressure	Rigid Pavement Subgrades MN/m^3				Flexible Pavement Subgrades CBR				Main gear type for pavement design
				High 150	Medium 80	Low 40	Ultra Low 20	High 15	Medium 10	Low 6	Ultra Low 3	
	kg	%	MPa	ACN				ACN				
Sea Harrier FRS Mk 1	11,885 5,940	42.4+	0.83+	9 4	9 5	9 5	9 5	9 4	9 5	10 5	10 5	Single+
Tornado F Mk 2	26,600 14,231	44.5	2.00	27 15	27 14	27 14	27 14	27 14	25 13	25 13	24 13	Single
Tornado GR Mk 1	28,584 13,747	47.3	2.17	32 15	32 15	31 15	31 15	31 14	29 14	28 14	27 13	Single
Tristar K Mk 1/ KC Mk 1	245,850 109,550	46.65	1.43	59 24	69 25	82 28	95 32	68 26	74 27	90 29	120 37	Dual-Tandem
VC 10 C Mk 1	147,417 67,630	47.5	0.97	35 15	43 15	52 18	60 21	44 16	47 17	58 19	73 25	Dual-Tandem
VC 10 K Mk 2	143,334 68,000	45.5	0.952	31 15	38 15	46 18	54 21	39 16	43 17	52 19	67 25	Dual-Tandem
VC 10 K Mk 3	152,860 71,000	46.6	1.02	36 15	44 16	53 19	61 22	45 17	48 18	61 20	76 26	Dual-Tandem
Victor K Mk 2	101,833 51,416	45.5	2.24 2.03	39 13	45 16	50 19	55 22	37 14	44 16	51 19	58 25	Dual-Tandem
Chinook HC Mk 1	22,700 10,411	30.8	0.60	11 4	11 5	12 5	12 5	8 3	10 4	12 4	13 5	Dual
Puma HC Mk 1	7,000 3,700	38	0.60	2 1	2 1	3 2	3 2	2 1	3 1	3 1	3 2	Dual

+ Based on Nose wheel.