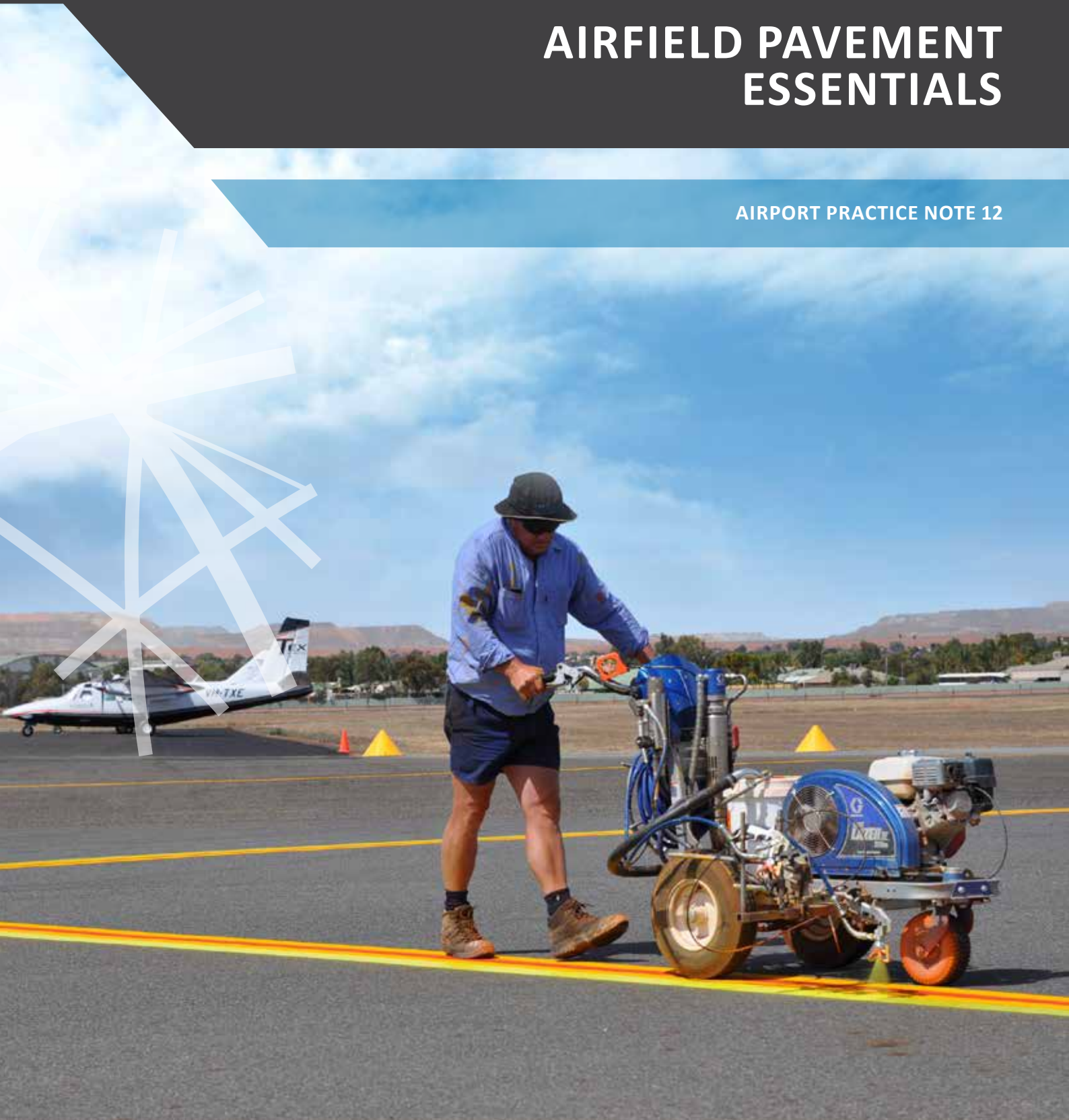




AUSTRALIAN
AIRPORTS
ASSOCIATION

AIRFIELD PAVEMENT ESSENTIALS

AIRPORT PRACTICE NOTE 12



This airport practice note is intended as an information document for airport members, providing useful information regarding airfield pavements at Australian aerodromes. The airport practice note is for general information purposes only and is not intended to be prescriptive or be an exhaustive set of information on matters that should be taken into account regarding airfield pavements at airports. Before making any commitment of a financial nature or otherwise, airports should consider their own specific needs and circumstances and seek advice from appropriately qualified advisers. No material contained within this guideline should be construed or relied upon as providing recommendations in relation to any particular development or planning outcome or decision.

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If you have any questions regarding this document please contact the AAA on 02 6230 1110.

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PREFACE

This practice note has been prepared for the Australian Airports Association. The aim of the practice note is to provide general guidance and information to airport managers and operators regarding airport pavement design, materials, construction, maintenance and rehabilitation. It is not intended to be relied upon for project-specific solutions and does not aim to provide a thorough treatment of all airport pavement engineering technology and practice in Australia. Importantly, most of the practice note addresses ‘airfield pavements’. That is, pavements that are designed using recognised airfield pavement methods and practices. Many rural and remote airports use alternate design methods, because the aircraft loads are less critical than the ground support vehicle loads. Only general guidance is provided for these ‘pavements used by small aircraft’ which fall outside of the definition of ‘airfield pavements’ in many regards.

Following the general divestment of Australia airport ownership by the Commonwealth Government, there has been no centralised or government-endorsed organisation responsible for the design, specification or construction of airfield pavements in Australia. This responsibility is now vested in the private organisations and local government authorities responsible for the management and operation of airports, as well as their consultants and contractors. It follows that the information presented in this practice note reflects the views, opinions and experience of the author, rather than being based on official policies or guidance materials. However, where appropriate, International Civil Aviation Organisation (ICAO) and Federal Aviation Administration (FAA) of the USA policies are referred to, as well as guidance documents published by other organisations.

The preparation of this practice note utilised, in part, training notes and documents prepared over many years by Mr. Bruce Rodway. Bruce’s indirect contribution, advice and comments, are gratefully acknowledged and greatly appreciated.

This practice note is not intended to be specific or authoritative and is not intended to replace the project-specific advice of a qualified professional airport pavement engineer. Neither the Australian Airports Association, nor the author, will be responsible for reliance on the information contained in this practice note by airport owners, their managers, consultants or contractors.

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LIST OF ABBREVIATIONS

AAA	Australian Airports Association
ACN	aircraft classification number
APSDS	Aircraft Pavement Structural Design System
ATI	aerodrome technical inspection
BBI	Boeing Bump Index
CASA	Civil Aviation Safety Authority (of Australia)
CBR	California bearing ratio
CFME	continuous friction measuring equipment
CTCR	cement treated crushed rock
GA	general aviation
FAA	Federal Aviation Administration (of the USA)
FBB	foamed bitumen base
FCR	fine crushed rock
FOD	foreign object debris
FWD	falling weight deflectometer
ICAO	International Civil Aviation Organisation
MOS	Manual of Standards
MPa	megapascals
NASA	National Aeronautics and Space Administration (of the USA)
OGFC	open graded friction course
OMC	optimum moisture content
PCI	Pavement Condition Index
PCN	pavement classification number
PCR	pass-to-coverage ratio
PI	Plasticity Index
PME	polymer-modified (bitumen) emulsion
RPT	regular public transport
SEST	surface enrichment sprayed treatment
SMA	stone mastic asphalt
UK	United Kingdom (of Great Britain and Northern Ireland)
USA	United States of America
USCS	Unified Soil Classification System
WMA	warm mixed asphalt

INTRODUCTION

CHAPTER 1



1.0 INTRODUCTION

1.1 What is a pavement?

A pavement is a durable structure or surfacing placed over existing materials to improve its performance under traffic. The most abundant and well-known pavements in the world are roads. However, there are also car parks, footpaths, sidewalks, driveways, port facilities, runways and more.

Pavements generally comprise a number of layers of engineered or imported materials with physical properties exceeding those of the existing material. The most highly engineered materials are usually located closer to the pavement surface, where the stresses are greatest.

1.1.1 Airport pavements

Pavements for airports are not fundamentally different to those for roads or other applications. The principles for design, construction and maintenance are essentially identical. However, as detailed later (1.4 Roads versus airports) aircraft place particular demands on airport pavements that are not experienced by roads and as such, airport pavements have more stringent requirements than road and other pavements.

The key differences between road and airport pavements relate to aircraft. Aircraft are heavier, have higher tyre pressures, are less stable and are less tolerant of slippery, weak, bumpy or defective pavements, than cars. It follows that airport pavements are generally thicker and stronger than road pavements. Airport pavements also need to be maintained in a condition that protects the relatively fragile engines from damage caused by ingestion of loose stones and debris on the surface.

1.1.2 Pavement types and structures

Pavements can be constructed in many compositions and arrangements and can comprise a number of materials. However, there are essentially two 'categories' of pavement (Huang 1993):

- » **Flexible pavements** – Constructed primarily of granular (quarried and crushed rock or crushed river gravel) materials, usually with a bituminous surface layer (Figure 1) over the subgrade. These pavements are termed 'flexible' because they are intended to deform vertically under load and then rebound to their original shape and level when the load is removed.

All the layers in the pavement contribute to the strength of the pavement. Flexible pavements are most commonly identifiable by their asphalt or bitumen surface, which is black or near-black in appearance.

- » **Rigid pavements** – Constructed primarily of slabs of Portland cement concrete, usually with a relatively thin sub-base (sometimes referred to as base) layer to support the slabs (Figure 2). These pavements are termed 'rigid' because they are not intended to deform significantly during loading. Rather, the concrete slab resists the majority of the stress internally by bending rather than deforming vertically and transferring it to the underlying material. The concrete slabs provide the majority of the pavement strength.

Figure 1: Typical flexible pavement structure

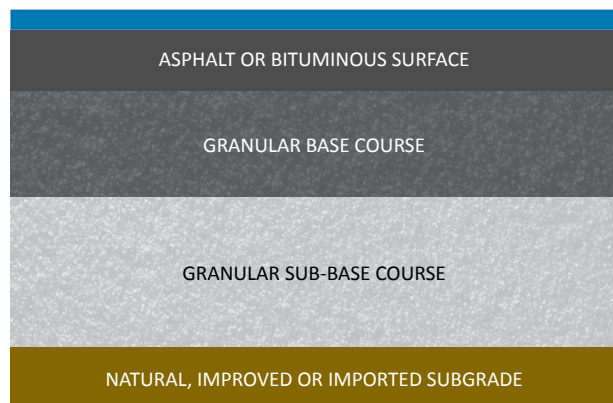
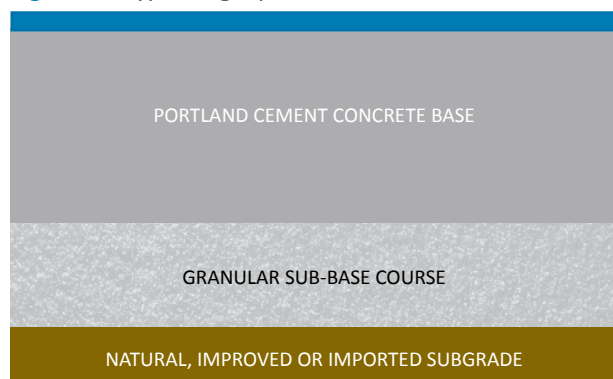


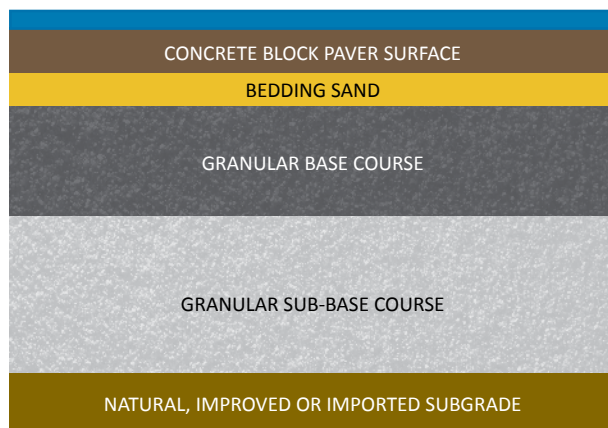
Figure 2: Typical rigid pavement structure



Some pavements are not clearly rigid or flexible. Examples include an old rigid pavement with a thick asphalt overlay as well as a flexible pavement that contains a highly cement-stabilised layer to improve its structural strength. Another example is a flexible pavement with concrete block pavers used as the surface or wearing layer (Figure 3). These hybrid or composite pavements can be more difficult to categorise, although the rule-of-thumb is that any pavement that contains high-strength Portland cement concrete is considered to be a rigid pavement while all other pavements, even those containing cement stabilised granular layers or concrete block pavers, are considered to be flexible. Pavement types and materials are detailed later (2.0 Pavement basics and 3.0 Pavement design).

One aspect common to all pavements types is that the higher strength (most engineered) materials are generally placed at the top of the pavement where the stresses from aircraft loads are greatest. As the stress reduces deeper in the pavement, less strong (and usually therefore less expensive) materials are commonly used.

Figure 3: Typical concrete paver surfaced flexible pavement structure



1.1.3 Airfield pavement ‘failure’

Airfield pavements must be maintained in a condition that allows for the safe operation of the aircraft that use them. The structural (strength) and functional (condition) requirements of pavements are described later (3.0 Pavement design). An airfield pavement is considered to have failed if:

- » the surface produces, or appears likely to produce, excessive loose stones, concrete spalls, or asphalt fragments that could be ingested by jet engines or damage propellers
- » the surface ponds water in wheel paths which could lead to loss of braking capability in wet weather
- » the runway becomes slippery and affects the braking of aircraft. The loss of surface texture is typically due to rubber buildup in touchdown zones, or to flushing of bitumen to the surface, or
- » the runway surface becomes unacceptably rough and so makes control of the aircraft difficult.

Cracking of the surface does not itself constitute a pavement ‘failure’ but, unless attended to, can lead to a failure condition. For example, cracking may lead to spalling and loose material generation. Also, if the ingress of water through cracks causes a loss of pavement strength or de-bonding at pavement layer interfaces.

1.2 Historical perspectives

The design, construction and maintenance practices for Australian airport pavements date back to the Commonwealth Department of Works in the years following World War II. At that time, the majority of airports were Commonwealth-owned and -managed assets and airport pavement works were usually designed and specified by a team of Commonwealth employees. Following disbandment of what had by then become the Department of Housing and Construction in 1982, and the cessation of direct airport management by the Commonwealth in 1998 (Eames 1998) private corporations, mining companies and local government bodies (councils) became the primary operators of airports in Australia.

The responsibility for managing, maintaining and developing airport infrastructure then rested with these private airport owners and councils, as remains the case today. The 28 airfields managed by the Department of Defence, on behalf of the Commonwealth, are an exception. Another exception is a small number of remote offshore airports that fall under the control of the Department of Regional Australia as a service to isolated communities.

Since the privatisation of the major airports in Australia, engineering consultants have become the primary specifiers and designers of Australian airport pavements. The specifications, however, are still largely based on the models developed by the various Commonwealth departments, with only minor changes to reflect challenges encountered and some new technologies.

In summary, Australian airports were developed and owned by the Commonwealth Government until the 1990s. The departments that maintained best-practice, undertook research and development and controlled standardised specifications was lost when the larger airports were privatised and the regional airports were transferred to council ownership. Since that time, no single organisation has been responsible for the up-keep of airport pavement practice and technology in Australia.

1.3 Evolution of aircraft

The Wright brothers achieved the first 'sustained and controlled, powered, heavier-than-air' airplane flight in 1903. By 1905 they had developed their flying machine into the first practical fixed-wing aircraft. The military immediately saw the benefits of airplanes and introduced its first heavier-than-air aircraft in 1909. By 1914 aircraft had played a minor part in World War I. The minor contribution reflected the limited range and payload of aircraft available at that time, such as the example in Figure 4. At that time airfield pavements were not an issue as the aircraft were light enough and robust enough to operate from any relatively flat and cleared paddock.

Between the two world wars, incremental improvements in engines, aerodynamics and weapons, provided a basis for the rapid evolution of aircraft capability in World War II. As a result, aircraft played a more significant part in military operations during

World War II, including long-range surveillance in the Pacific, aircraft carrier-based fighter operations and long-range bombing raids. Well-known World War II aircraft include the P-51 Mustang (Figure 5), Lancaster Bomber (Figure 6) and the B-29 Superfortress (Figure 7). By the end of World War II aircraft had become too heavy to continue to operate on unprepared ground. This prompted the first significant interest in airport pavement design. Interestingly, during World War II the US Army Corps of Engineers (or simply the Corps) constructed a network of airfields in Australia, particularly in the north. Many of these airfields remain in regular use today and some remain essentially in their World War II configuration.

Figure 4: Typical WWI aircraft



Figure 5: P-51 Mustang circa 1941



Figure 6: Lancaster bomber circa 1942



Figure 7: B-29 Superfortress circa 1944



Figure 8: DC-8-50 circa 1958 (NASA 2015)



The aircraft technology developed during World War II also formed the basis for the significant advances in commercial aircraft since that time. Subsequent aircraft technology development was also fueled by the cold war between the United States of America and the Union of Soviet Socialist Republics. For example, between the early 1940s and the early 1950s, military aircraft tyre pressures doubled from around 0.6 MPa to around 1.2 MPa (White 1985).

One significant step in commercial aircraft growth was the DC-8-50, first introduced in 1958 (Figure 8). At the time, this was the most damaging of all commercial aircraft with 19 tonnes of wheel load on 1.35 MPa tyre pressure, and closely spaced wheels. Tyre pressures and wheel loads increased incrementally as new aircraft were developed and entered service (Fabre et al. 2009; Roginski 2007). Other significant aircraft included the B737-800 (1997), which remains a workhorse of the Australian domestic aviation industry and the B747 (1966 for the -100 series and 1989 for the well-known -400 series).

In recent years, the main advances and developments in aircraft technology have come from the commercial aircraft industry, rather than the military aviation sector. It is now common for some military aircraft to be based on existing commercial aircraft. The Royal Australian Air force's airborne communications aircraft (based on a B737) and in-flight jet aircraft refuelers (based on an A330), are examples.

In 2001 Airbus introduced its extended body A340-600 commercial passenger jet. This modern and technologically-advanced aircraft remains one of the most demanding on pavements and its tyre pressure of 1.61 MPa and wheel load of 30.8 tonnes (Airbus 2014).

The A380-800 (Figure 9) became the largest passenger aircraft in the world when it was introduced in 2005. Although heavier than other aircraft, its wheel load is less severe at 26.8 tonnes with a tyre pressure of 1.40 MPa (Airbus 2014). The combined 20-wheel main landing gear allowed for a less critical pavement loading. The B787-8, introduced in 2009, was a smaller aircraft with 1.60 MPa tyre pressure and 27-tonne wheel loads (Boeing 2013). The most recent large aircraft advancement by Boeing is the B747-8, introduced in 2010. With new gull-shaped wings, this aircraft joined the A380 as the only Code F (wingspan exceeding 65 m) commercial jets in the world. Based on a B747-400, the landing gear remains relatively modest at 1.55 MPa tyre pressure and 26.5 tonnes (Boeing 2013).

In contrast, the newest aircraft from Airbus, the A350, first flew in 2013. Its variants enter service in 2015 (A350-900) and 2016 (A350-800). At 1.66 MPa and 31.8 tonnes the A350-900 (Figure 10) is the most demanding commercial aircraft in the world based on tyre pressure and individual wheel load.

In summary, aircraft have changed substantially, particularly since World War II. Modern aircraft manufacturers are driven to achieve the ‘lowest fuel burn per passenger per kilometer flown’ as this is a significant factor for airlines purchasing new aircraft. Reducing the number of landing gear wheels supports the aims of the aircraft manufacturers and necessitates higher aircraft tyre pressures. In combination with aircraft that require stronger, longer and wider pavements, the evolution of commercial aircraft has a significant impact on airport pavement design and technology requirements.

1.4 Roads versus airports

The methods of design, construction and maintenance of aircraft pavements are generally similar to those appropriate for roads. However, there are important differences which must be taken into account in order to provide pavements that are satisfactory for aircraft loadings and operations. Key differences between roads and airfield pavements are summarised in Table 1.

Figure 9: Airbus A380-800 (Airbus 2016)



Figure 10: Airbus A350-900 (Airbus 2016)



Table 1: Comparison of aircraft and road pavements

Characteristic	Aircraft Pavement	Road Pavement
Load repetitions	Low. Often 100,000 or less.	High. Often 1,000,000 or more.
Traffic wander	High. Wide spread of aircraft across pavement width.	Low. Very channelised traffic in designated lanes.
Wheel load	High. Up to 25 tonnes per wheel.	Low. Generally only up to 3 tonnes per wheel.
Tyre pressure	High. Typically up to 1,7 MPa and sometimes up to 2.5 MPa for military jets.	Moderate. Generally not more than 0.8 MPa.
Water tightness	High. Especially for granular pavements.	High. Especially for granular pavements.
Surface texture/flushing	Moderate. Low traffic volumes do not generally flush seals.	High. Especially for maintaining skid resistance.
Resistance to polishing	Low. With low traffic volumes, even aggregates prone to polishing do not typically polish.	High. Especially for high-speed roads, especially at corners and intersections.
Loose aggregate	Extreme. Loose aggregate can cause catastrophic failure of aircraft engines.	Low. Constituting only an inconvenience to road users.
Durability	High. Especially in the touchdown zones where tyre ‘run-up’ occurs.	Moderate. Particularly at turns and intersections, less so on straight runs.

Aircraft are designed for flying but are much less stable and controllable than cars when travelling at high speed along the ground. Landing speeds of modern aircraft are typically 260–280 kilometres per hour in all conditions. Unlike car drivers, pilots cannot increase their safety margin by slowing down to take into account wet and uneven pavements, high crosswinds and poor visibility. A pilot cannot choose to land more slowly. Furthermore, aircraft land on multi-tyred undercarriages which are located close to their centre of gravity, not at each corner like road vehicles, and so are inherently less stable.

Aquaplaning is a serious hazard which is easily avoided on the road by slowing down. In contrast, surface water on aircraft pavements, either present as sheet flow or ponding in wheel-path depressions, is a major concern for runways. Drainage of water is more difficult than for roads due to the lower allowable transverse slope (or cross fall) of 2.0 per cent and the larger pavement widths (typically 30–75 m). As well as providing an adequately textured surface (to allow good wet-weather braking) to tighten initial level tolerances, very high degrees of compaction to large depths must be achieved if surface flatness is not to be lost due to subsequent compaction under the heavy aircraft wheel loads. At the flat grades used on runways, traffic compaction – which would be acceptable in the road situation where cross falls of 3 per cent are typical – would cause water to pond along wheel paths on runways.

Further, aircraft tyres are smooth and have no transverse tread pattern. This contrasts with car and truck tyres. The smoothness of aircraft tyres, in combination with large tyre widths, inhibits the escape of water from beneath the tyres during high speed landings. To reduce the risk of aquaplaning, many runways now have 6 mm by 6 mm grooves sawn transversely, at approximately 40 mm spacing. In effect, the runway, rather than the tyres, has the tread pattern. Runway grooving and friction management are discussed in detail later (3.3 Functional requirements).

Loose stones on a road surface cause only chipped paintwork and perhaps broken windscreens, but the ingestion of stones or pavement fragments by jet engines can have catastrophic consequences. Therefore, it is vital that aircraft pavements be maintained in a condition where the surface will not produce loose material.

Highway wheel loads are generally limited to 2 tonnes per tyre. Many aircraft wheel loads are approximately 10 times the legal highway maximum and some aircraft are now 35 tonnes per wheel. The tyre pressures are also approximately double that of trucks. Some military aircraft have small tyres with pressures of around 3.1 MPa or even higher, but such pressures are invariably associated with small wheel loads and do not usually cause significant pavement damage.

Unlike roads, the mass of the aircraft is not generally reflected in the wheel loads. As the load increases, more wheels are usually added so that the load per wheel might not increase. For many years, new aircraft were designed ‘for existing pavements’ in that the severity of loading did not generally increase with increases in aircraft size. But for some years now airplane manufacturers have focused on designing aircraft landing gears to optimise aircraft flying efficiency (fuel burn per passenger per kilometer flown) so aircraft pavements must now be designed to withstand the higher wheel loads, tighter wheel spacings and higher tyre pressures.

In addition to large pressures and high vertical loads, modern jet aircraft subject pavements to large horizontal braking and cornering forces. These have produced some asphalt surface failures in Australia and overseas.

Impact loads during landing do not constitute a significant problem for pavements except for the rubber buildup that reduces runway surface texture and skid resistance. The puff of smoke seen at touchdown is spectacular, but damage to the pavement is usually not significant.

A further difference between the highway and airfield situations is that aircraft wheel loads are more distributed across the pavement. This is because aircraft traffic flow is less channelised and because of the large variety of aircraft wheel arrangements. Field observations of aircraft movements have shown that successive passes of aircraft along a pavement are statistically normally distributed around the pavement centreline (HoSang 1975). This spreading of aircraft wheel loads across the pavement width is significantly different for runways, taxiways and parking bays and these differences affect the pavement thickness required for different parts of the airfield. Landing aircraft also far lighter than during take-off due to the fuel used in flight.

In summary, higher wheel loads require thicker pavements. Higher tyre pressures and braking forces require more shear resistance surfaces. Therefore, airfield pavements are generally thicker and comprise higher quality materials than road pavements. Further, aircraft are less tolerant of uneven surfaces, low surface friction in wet weather conditions and loose materials on pavement surfaces. It follows that aircraft pavements are flatter than road pavements, require special surface treatments to improve wet weather skid resistance and must be durable enough to avoid cracking, spalling or erosion that results in loose material on the pavement surface. Where these important differences between road vehicles and aircraft are not considered during the design, construction and maintenance of pavements, unsuitable or inappropriate aircraft pavements can result.

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PAVEMENT BASICS

CHAPTER 2



2.0 PAVEMENT BASICS

2.1 Deflections, stresses and strains

Real pavements respond to real loads in a highly complex manner. In fact, the response of a real pavement is far too complex to be accurately replicated in pavement design tools (Huang 1993). Rather, a simplified load-pavement interaction model is developed and then calibrated against full-scale testing of real pavements under real loads (Wardle & Rodway 2010). Despite the limitations, the simplified approach has proven to be effective over many decades and remains the normal approach to all pavement design, including airfield pavements, around the world.

2.1.1 Role of a Pavement

The role of any pavement is to protect the underlying ground from the load, as well as to provide a safe and effective surface for the aircraft or vehicles utilising the pavement. Protection of the subgrade is a 'structural requirement' while the provision of a safe and effective running surface is a 'functional requirement'. Both structural and functional requirements are discussed later (refer to 3 Pavement Design).

The pavement protects the natural ground (known as subgrade) by spreading the load so that the subgrade is not overstressed. Further, the upper layers spread the load to protect the lower layers in the pavement. Depending upon whether the pavement is flexible or rigid in nature (refer to 1.1.2 Pavement types and structures), the load is spread in a different manner.

2.2 Pavement responses to load

Aircraft wheel loads applied at the surface produce deflections, stresses and strains. These are called the pavement responses and are explained below.

- » **Deflection** – Deflection is the easiest to comprehend and is the absolute amount by which a given point in the pavement moves in response to the load. Deflection is usually in the order of 1–2 mm.
- » **Stress** – Stress is a load spread across an area and it equivalent to pressure inside a tyre. Stress due to loading by an aircraft or vehicle tyre changes relatively smoothly with depth because it is not significantly affected by the material in the pavement layer. Stress in an aircraft pavement is usually in the order of 0.01 MPa, to 2 MPa.

- » **Strain** – Strain is the most difficult pavement response to conceptualise. Strain is the change in dimension of a material or layer, expressed as a portion of the length over which the change occurred. Strains in an aircraft pavement commonly range from tens of microstrain ($\mu\epsilon$) to 1000-2000 microstrain.

Different responses are used to analyse different pavement-related issues. For example, deflection is the primary basis for comparing the impact of different aircraft wheel configurations on the impact of pavement life. Stress is commonly used to determine proof rolling regimes (refer to 4.9 Proof rolling) for different aircraft during pavement construction and for rigid pavement thickness design. Strain is the basis for relating the damage caused by one aircraft load to the structural life of the pavement in layered elastic flexible pavement design tools.

Each pavement response occurs in three dimensions and changes with the location within the pavement relative to the load, as well as with depth (Huang 1993). Importantly, pavement life cannot be determined solely by theoretical pavement response. As detailed later (3.0 Pavement design) the theoretical responses must be compared to a pavement life, determined from large- or full-scale pavement testing.

2.2.1 Flexible pavement response to load

The simplest way to characterise the response of a pavement to load is to consider the pavement to be a homogenous material of infinite extent and thickness. Prior to more complex, layered elastic theory, being developed in the 1940s, this simple approach to flexible pavement response was the only option available. With this approach, a uniform contact stress (tyre pressure) applied over a circular contact area is assumed between the tyre and the pavement surface. The stress in the pavement spreads out and reduces with depth. The stress at a given location and depth within the pavement is a function of the contact stress, radius of the contact area, as well as the radial distance from the centre of contact area and the depth below the pavement surface.

Multi-layered solutions were then developed where the ability to spread the material changes with depth. Originally based on charts, multiple layers of finite thickness, but infinite horizontal extent, remain the basis of layered elastic flexible pavement design. Even more complex, finite element models, are now available but these are generally reserved for research purposes.

As the stress (or strain) reduces deeper in a flexible pavement, the quality of material required to resist the load reduces. This continues to the subgrade, where the (usually) weakest material is located (Figure 11). Deeper in the pavement, the load is spread over the larger area, reducing the stress. Significant stress is still experienced by the subgrade. A weaker subgrade requires more pavement to protect it from a given load applied at the pavement surface.

2.2.2 Rigid pavement response to load

Unlike flexible pavements, rigid pavements are commonly constructed in slabs. These slabs are generally small (5–6 m square) in relation to the area of the pavement. Joints are provided to relieve environmental stresses from thermal and moisture changes. However, the joints create stress concentrations at slab corners where these are critical for rigid pavement performance (Huang 1993). Rigid pavement slabs also experience curling due to temperature differentials between the top and bottom of the concrete slab. During the day, the top of the slab is warmed by the sun and expands, making the top of the slab longer than the bottom and curling the slab downwards. During the night, the top of the slab cools and shortens, resulting in upward curling (Figure 12). Estimating curling (upward and downward) stresses is difficult and pavement thickness design does not directly account for them.

In contrast to flexible pavement design, the subgrade under a rigid pavement supports the rigid slab so that it can accommodate the internal stress itself (Figure 13). Stronger subgrades provide additional support and allow thinner concrete slabs to be designed. However, the subgrade itself experiences a relatively low level of stress compared to flexible pavement subgrade.

2.2.3 Comparing flexible and rigid pavement response

Flexible and rigid pavements respond to loads to protect the subgrade in different ways. Flexible pavements spread the load until the stress is reduced to a level that the subgrade material can accommodate. In contrast, rigid pavements protect the subgrade by essentially dissipating the stress internally within the concrete slab. This explains why the top of a flexible pavement cannot simply be replaced by a concrete slab. Certainly, the stiffer and stronger concrete could spread the load better than the flexible pavement. This would suggest that the subgrade would be more protected. However, the slab would be insufficient to internally resist the stresses and the concrete would rapidly fail.

Figure 11: Flexible pavement response to load

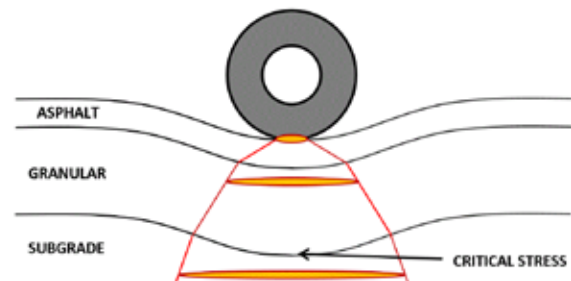


Figure 12: Concrete slab curling due to temperature changes (Huang 1993)

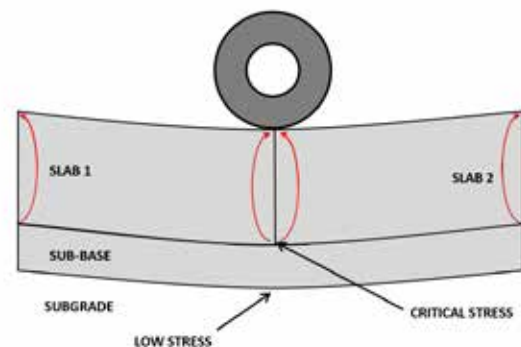
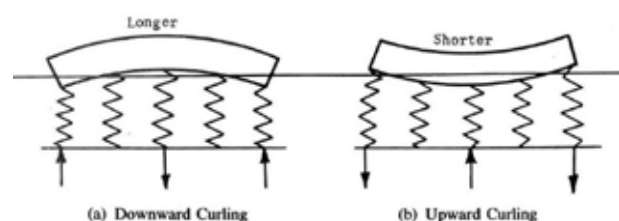


Figure 13: Rigid pavement response to load



2.3 Subgrades

As shown in Figures 1 and 3, the subgrade of a pavement can be naturally-occurring, improved or imported material. Insitu improvement is often provided where the naturally-occurring material is poor. When the naturally-occurring material cannot be adequately improved, a significant layer of imported subgrade may be introduced. Further, when the existing natural surface is significantly lower than the required level, imported material will be utilised to ‘fill’ the subgrade prior to constructing the pavement. In some cases, the fill becomes the effective subgrade. For example, if 10 m of fill is placed over the naturally-occurring material, then the fill would be treated as the subgrade for design purposes. In contrast, if just 100 mm of fill is required, the natural material must still be considered as the subgrade for pavement design. At in-between depths, it is often necessary to perform two pavements designs. The first thing in considering the fill as the subgrade, is to ensure it is adequately protected by the overlying pavements. The second design considers the fill as a part of the pavement structure and ensures the combined fill and pavement adequately protect the naturally-occurring subgrade.

Technically, all granular materials are categorised by the size of the particles, according to the Unified Soil Classification System (USCS) which is based on the majority of the particles in the material being (Holtz & Kovacs 1981):

- » **Clay** – Passing 0.075 mm sieve with significant plasticity.
- » **Silt** – Passing 0.075 mm sieve with insignificant plasticity.
- » **Sand** – Falling between 4.75 mm and 0.075 mm sieves.
- » **Gravel** – Between 75 mm and 4.75 mm in size.
- » **Cobbles** – Between 300 mm and 75 mm in size.
- » **Boulders** – Greater than 300 mm in size.

Plasticity is an important concept for subgrade and pavement materials. Plasticity is the ability for a material to be moulded and formed into shapes. The plasticity of subgrades provides a good indication of the engineering properties of the material over a range of moisture contents (Holtz & Kovacs 1981). Generally, low plasticity is preferred.

In practice, subgrade materials are categorised as sand, gravel, silt or clay. However, a combination of particle sizes is commonly encountered, such as a sandy-clay or a silty-gravel.

Different subgrade material types require different consideration. Further, the treatment and characterisation of the subgrade is often the most complex and difficult part of an airport pavement design. The calculation of the pavement thickness and composition required to protect a certain subgrade material is relatively quick, easy and follows established processes. In contrast, the assignment of subgrade material deformation properties and subgrade treatment is less straight forward and almost always requires an amount of engineering judgment. This reflects the highly variable nature of naturally-occurring materials in different climates and geographical locations.

Subgrades are usually characterised by their resistance to deformation under a controlled load. The most common test is known as the California bearing ratio (CBR) which expresses the deformation resistance of the material as a percentage of that measured on a standard sample of crushed limestone base in California, United States of America (USA). So a CBR of 100 per cent indicates a material that is equally resistant to deformation as the reference limestone and a CBR of 10 per cent indicates a material that has 10 per cent of the reference material’s resistance (Holtz & Kovacs 1981). Because pavement subgrades may become saturated after rain events, the CBR test is usually performed on the subgrade sample after it is soaked in water for four days (Huang 1993).

2.3.1 Characterising subgrades

Subgrades are usually characterised by their bearing capacity, of deformation resistance, and their reaction of moisture content changes. Subgrade deformation resistance for flexible pavements is usually characterised by CBR (refer to 3.4 Flexible pavement design). In contrast, rigid pavement subgrade support is characterised by a parameter known as the coefficient of subgrade reaction, or ‘K’ value (refer to 3.5 Rigid pavement design). The CBR is far simpler and less expensive to measure than K-values, and in practice, rigid airfield pavements are usually designed based on a subgrade K-value derived by correlation to CBR test results (refer to 3.2.5 Subgrade CBR).

Many engineers question the appropriateness of the CBR test, which is not reflective of the stress conditions experienced in the pavement. However, airport pavement design is reliant on empirically derived relationships between subgrade CBR, pavement thickness, aircraft load and pavement structural life. Until an alternate empirical relationship is developed and design tools are recalibrated, subgrade CBR will continue to be essential to airport pavement design.

In assessing moisture sensitivity, the fine particles within any particular subgrade are usually assessed based on their reaction to moisture changes. In the case of clays and silt, this is the majority of the material. A material containing predominantly fine particles changes from a semi-solid to a plastic state at a moisture content called its 'plastic limit', and then to a liquid flowing state as its moisture content is increased to what is called its 'liquid limit'. These limits are determined by standard laboratory tests called the Atterberg limits, carried out on the particles that are smaller than 0.4 mm in diameter. The Plasticity Index (PI) – the difference between the liquid limit and the plastic limit – is the moisture content range over which these soil fines behave in a plastic manner.

A plastic material is one that can be moulded without cracking, but which does not deform or flow under its own weight. The Atterberg limits provide a useful indication of shrink/swell potential (reactivity), permeability, strength, cohesion and compressibility. The PI is often used to consider options for the treatment of subgrades prior to pavement construction, as well for specifying granular pavement materials, such as base and sub-base. For example, a PI limit of 6 per cent is often specified for the fine particles contained in base course materials to limit the strength loss that occurs with increase in moisture content. A PI in excess of around 25 per cent for a clay subgrade warns that it is likely to swell and shrink significantly with moisture change and some treatment may be appropriate.

2.3.2 Sand

Sand is an excellent subgrade material. Clean sands are generally not plastic, so are less affected by moisture. They also generally drain well. The challenge with sand subgrades is performing compaction during construction. It is often necessary to fully saturate the sand, by bunding an area and flooding it, during the compaction process. This allows the friction between the sand particles to be overcome and the sand to be compacted. Once compacted, the excess moisture rapidly drains from the material.

2.3.3 Silt

Silts and clays both consist of very fine particles but clays are plastic and silts are not. Silt is usually hard and strong when dry but loses significant strength when wet. Unlike clays, silts usually do not shrink or swell excessively with changes in moisture content. That is, they have low to moderate reactivity. However, the loss of strength can be significant. It follows that effective drainage is critical for pavements constructed on predominantly silt subgrades.

2.3.4 Clay

Clay consists of fine soil particles and is cohesive, plastic and slippery when wet. Clay is hard when dry but has low strength at high moisture content. If the insitu moisture content of a clay subgrade is at or below the plastic limit, this indicates that it is in a reasonably well-drained situation and will have significant strength. But a moisture content of around the liquid limit warns that the subgrade is likely to have negligible strength when disturbed by construction equipment.

2.3.5 Gravel

Naturally-occurring gravels vary widely in their particle size, plasticity and grading. As a result, the engineering properties of gravel subgrades vary significantly. A well-graded gravel with little or no fine particles drains readily and is not significantly affected by moisture. A 'clayey' or silty gravel presents a more significant challenge. In general, gravel subgrades require little preparation other than compaction by rolling, but gravels containing highly plastic fines may require some improvement to reduce their moisture sensitivity.

2.4 Pavement materials

In contrast to naturally-occurring subgrade materials, pavement materials are more controlled and are often engineered. At a minimum they are selected from the locally available materials to maximise the benefit provided to pavement design, in a cost effect manner. However, in some locations, no suitable materials are locally available and all pavement materials must be imported, usually at significant expense. In other cases, the only economically viable materials are below the standard that would normally be required and special treatment to improve their engineering properties is required.

2.4.1 Fill material

Fill is used over the naturally-occurring subgrade to provide an appropriately shaped area on which to construct the pavement proper. It follows that the amount of fill required is a function of the thickness of the pavement as well as the level and shape of the pavement surface. Further, naturally-occurring subgrades are often undulating and therefore the thickness of fill required is often variable often the length and width of the pavement being constructed.

Because the role of fill is to bring the subgrade to an appropriate level and shape, the engineering properties of fill vary significantly. However, it should be no worse than the material it is covering. Fill materials should also be easily moved, placed, compacted and finished, using the available plant and equipment.

In some cases, the amount of fill required is significant. Sand fill over natural marine clays of 5–10 m thickness is not uncommon. Where land is reclaimed, significant thickness is required to bring the platform out of the ocean. In these cases, the fill effectively becomes the subgrade and the naturally-occurring material becomes irrelevant to pavement design. However, depending on the nature of the naturally-occurring material and thickness of fill, the naturally-occurring subgrade often remains important to overall pavement design.

Common fill materials include dredged sand and naturally-occurring gravels. These materials are often economically available as they are not processed or crushed in a quarry operation. However, their engineering properties vary significantly and material selection is important. Typical fill materials will have a soaked CBR in the range 20–40 per cent. Where the fill becomes the effective pavement subgrade, a maximum design subgrade CBR of 15 per cent is common (refer to 3.2.5 Subgrade CBR).

2.4.2 Processed gravel

Many naturally-occurring gravel deposits comprise materials that are worthy of inclusion in airport pavements. Natural gravels usually come from borrow pits or from river beds. Pit gravels often contain significant amount of fine material. Where the fines are plastic or active, special treatment may be required. In contrast, river gravels are usually clean and free of fine materials. However, they are usually round and must therefore be crushed to produce fractured faces for inter-article friction, as well as reasonable size and grading.

Processed gravels are commonly utilised for sub-base materials. In some circumstances, where crushed rock is not readily available, processed gravels have been used as base course material and even as asphalt aggregate. This has been less common in recent years. Processed gravels may commonly return soaked CBR values anywhere from 20–80 per cent.

2.4.3 Crushed rock

Crushed rock is manufactured in a quarry from hard rock deposits. It is usually produced by first blasting mass rock, followed by a series of crushing and screening processes. Where excessive fines are created, washing may also be required, although this is usually expensive.

Changing the crushing and screening processes changes the size of the crushed particles produced, which is tailored to meet the demands of the local industry. Crushing is considered to be ‘in-balance’ when the process produces a mix of products that matches the demand for those products, resulting in no accumulation of certain products or deficiency in other products. In reality, true ‘balance’ is rarely achieved in most quarry operations. Rather, quarry operators aim to find new opportunities to sell the products they produce in excess of the natural demand.

Crushed rock is a premium granular material for pavement construction. It is usually reserved for the upper pavement layers and for heavy-duty pavements. Typical applications include the base course layers, usually referred to as fine crushed rock (FCR), aggregates for the production of asphalt, aggregate for sprayed sealing and coarse aggregate for concrete production.

Crushed rock for airport pavements is similar to that for roads and highways although airport pavements typically have tighter limits on the processing. Road materials will be similar and more abundantly available, but will often not meet all the requirements of airport quality crushed rock.

The quality of crushed rock is evaluated by a combination of:

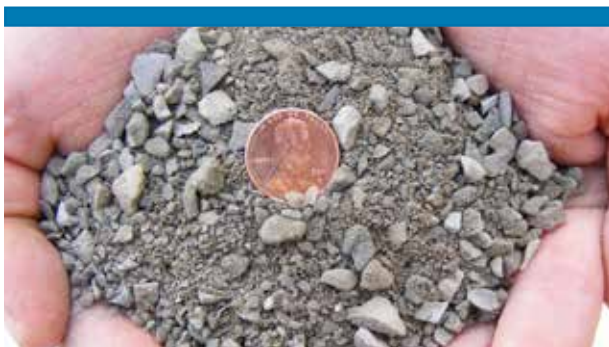
- » **Source properties** – relating to the natural rock from which the crushed rock was produced. For example, abrasion resistance, strength, deleterious material content and chemical composition.

- » **Consensus properties** – relating to the crushing and screening processes used to produce the crushed rock. For example, angularity, size and shape.

Some properties are measured on the crushed rock sample as a whole, while others are measured on a representative portion. For example, plasticity is measured only on the fine particles and some shape parameters are usually measured on particles between 10 mm and 14 mm in diameter. Further, different crushed rock, for different applications, usually have different specification requirements:

- » **Base course** (such as the example in Figure 14):
 - usually 20 mm or 40 mm maximum particle size
 - densely graded
 - minimal fine materials
 - high strength
 - moderate resistance to weathering.
- » **Asphalt aggregate:**
 - supplied in separate sizes (or fractions) usually 14 mm, 10 mm, 7 mm and fines (or dust)
 - densely graded when combined
 - non-plastic fine material
 - high strength
 - high resistance to weathering
- » **Concrete aggregate:**
 - uniform size, crushed, usually 10 mm, 20 mm or 40 mm
 - high strength
- » **Sprayed sealing aggregate:**
 - uniform size, crushed, usually 14 mm, 10 mm and 7 mm
 - moderate to high strength
 - crushed to a cubic shape

Figure 14: FCR for pavement base course



2.4.4 Bitumen

Bitumen is a black and sticky material produced as a by-product of the production of petroleum gas, fuels and oils from the refining of crude oil. Bitumen for pavement surfacing is liquid at high temperature (>100°C) and a brittle solid at low temperature (<10°C). At the intermittent temperatures, experienced in pavements in the field, bitumen properties are complex because of the time and temperature dependence of bitumen, leading to it being described as a visco-elastic material (Shell 2015). For example, conventional (C170 and C320) bitumen typically 'softens' at 45–60°C. In contrast, some highly polymer modified bitumen grades generally soften at 80–100°C.

Further, bitumen properties change over time. A new bituminous surface is often described as being 'green' or 'tender'. After one-to-three years, the lighter fractions within the bitumen (commonly referred to as volatiles) evaporate out of the surface and the bitumen hardens. In addition, the bitumen will harden and age due to oxidation. The rate of oxidation depends on the level of exposure of the bitumen film to the atmosphere, the ultraviolet radiation levels and the temperature of the surface (Airey 2003). As the bitumen oxidises, it becomes more brittle, eroded, and the ability of the bitumen to adhere to aggregate particles is reduced. Eventually the surface starts to lose coarse aggregate particles, which present as surface-generated foreign object debris (FOD) and the surface requires treatment or replacement.

Since 2010 significant changes have occurred in the Australian bitumen supply chain. In 2014 Shell Australia was sold to global bitumen trader Vitol (Shell 2014). Following the announcement of the closure of its Bulwer (Queensland) refinery in 2014, BP Bitumen sold its Australian assets to fuel and energy trader Puma Energy (BP 2015). Puma Energy also purchased the Caltex Australia bitumen business (Caltex 2013). With a transition in bitumen supply from 'oil refiners' to 'energy traders' the sources of crude oil are likely to become more diverse.

Further, the quality of oil has declined on a global scale and the demand for fuel has driven oil refineries to extract more from the oil sources (White 2016). This impacts the residue available for bitumen production. As a result, increased variability, likely to also impact reliability, of bitumen has been reported in Australia and other parts of the world (White 2016). More highly modified, or engineered with polymers and other additives, bitumen has been adopted to reduce the risk associated with increased bitumen variability. The selection of bitumen for airport asphalt and sprayed sealing is described below.

Bitumen can be supplied and delivered in a number of forms. For asphalt production and sprayed sealing, hot bitumen is normal. The heating reduces the viscosity and allows the bitumen to flow and coat the aggregates. Some sealing applications, maintenance treatments and tack coat for asphalt surfacing utilises bitumen emulsion.

Bitumen emulsion is a suspension of very small bitumen particles in water. The Bitumen emulsion is 'water-like' allowing it to coat the aggregate and then the water evaporates, leaving the bitumen film behind. Stabilising agents are often added to the emulsion to prevent the bitumen particles from coagulating in storage or during transportation. Also, the emulsion can be negatively or positively charged, depending on the aggregate type, and fast- or slow-setting, depending on the application. Cutback bitumen is common for priming base-course layers and for some asphalt preservation treatments. It is bitumen 'thinned' or diluted in lighter petroleum products, such as kerosene. The lighter petroleum product evaporates, leaving the bitumen behind. Fluxed bitumen is similar but the thinner is slower to evaporate, meaning the bitumen stays soft for longer. In all cases, the remaining bitumen in the bitumen emulsion, or the cutback bitumen, is referred to as the 'residual' bitumen.

Each delivery method has advantages and disadvantages that make it more or less well suited to different applications. For example, bitumen emulsion and cutback bitumen can be applied at or near ambient temperature, which is of significant benefit for worker safety. However, they are slower to set than hot bitumen and this can leave a 'tender' surface for a period of time, which remains sticky and not suited to short-work windows and immediate trafficking. Similarly, fluxed bitumen has a longer 'shelf-life' than cutback bitumen, but will remain soft and sticky longer after it is used in pavement construction or maintenance.

2.4.5 Asphalt

Asphalt is a conglomerate mixture of coarse aggregate, fine aggregate, bitumen, fillers and air voids (Figure 15). Additives may also be included. The properties of each of the constituent ingredients is important for asphalt performance, as is the portion and distribution of each component in the mixture. Typically, airport surface asphalt comprises (Emery 2005):

- » **Course aggregate**, around 40–50 per cent. Supplied in various sizes to produce a dense graded mixture when combined.
- » **Fine aggregate**, around 40–50 per cent. Usually including a combination of manufactured (from crushed rock) and natural (from a pit) sands.
- » **Added filler**, around 1–2 per cent. Usually hydrated lime.
- » **Bitumen**, around 5–6 per cent. Usually a premium (modified) bitumen.
- » **Air voids**, around 4 per cent. Required to give the bitumen room to expand with temperature increases without filling the voids, which would make the asphalt unstable under traffic.

The above composition is commonly referred to as 'Marshall-designed dense graded airport asphalt' (White 1985). Other types of asphalt have been trialled in Australia in the past (Rodway 2016). Some are common in road applications and others have been utilised extensively overseas. The primary objective of these alternate asphalt mixtures is to achieve a similar level of service and quality without the need to groove the surface for aircraft skid resistance.

Figure 15: Typical dense graded airport asphalt



This requires a minimum 1 mm surface texture (refer to 3.9 Surface texture, friction and skid resistance) which is not possible with ungrooved dense graded asphalt. Of the alternate asphalt surfaces, stone mastic asphalt (SMA) and open graded friction course (OGFC) (also known as popcorn mix) are the most viable and have been used successfully on overseas airports (EAPA 2003).

Regardless the mixture type, it is generally accepted that the selection and control of bitumen is the most challenging element of the asphalt mixture. Australian bitumens are developed for road applications and significant change in supply chains and raw material supplies has occurred over the last 10–20 years. Ongoing effort is required to produce the best-performing asphalt surfaces possible and to reduce the risk of surface distress, particularly in high stress areas such as the aircraft turning, braking and parking zones.

2.4.6 Sprayed seals

Sprayed seals are bituminous surfaces constructed by the application of a sprayed film of bitumen, followed by rolling in cover aggregate. The aggregate is intended to be single-sized (rather than graded) and is usually 7 mm, 10 mm or 14 mm in diameter (White 2010). Sprayed sealing of runways is common in Australia’s regional airports for the following benefits:

- » relatively cheap compared to asphalt (around 20 per cent of the cost)
- » relatively fast to construction compared to asphalt (around six times faster)
- » not requiring an asphalt production plant, making small quantities of work viable in remote locations, and
- » when well-designed and -constructed, providing a surface texture exceeding 1 mm without grooving (sprayed seals cannot be grooved).

Sprayed seals have generally performed well at Australian airports servicing aircraft up to B737 in size. Larger aircraft are harsh on sprayed seals due to the rigid spacing and alignment of dual-tandem (e.g. B767) wheels dragging across the surface when turning. Interestingly, outside of Australia, sprayed sealing of airfield pavements, particularly runways, is rare. Despite the generally good performance, sprayed sealing of airports does introduce the following challenges:

- » surface life is 6–8 years, compared with asphalt which is 10–12 years.

- » the surface is ‘tender’ for 3–6 months after construction, meaning aircraft turning sharply dislodge the aggregate and potentially create a maintenance liability to manage FOD risk
- » construction quality is highly reliant on good weather conditions and sealing operations are less tolerant of cold and/or wet weather than asphalt construction, and
- » sprayed seal surfaces inherently generate more loose stones (FOD) than asphalt surfaces.

Airport sprayed seals have a number of particular requirements to ensure their suitability to aircraft. These requirements are not always well known and some contradict established good road pavement sealing practice. Particulars, compared to road pavements, include (White 2010):

- » higher bitumen content
- » lighter application of cover aggregate
- » significantly higher roller effort, and
- » steel drum rolling of the finished surface.

For maximum durability and performance, larger aggregate sizes are commonly used for airport sprayed sealing. This also assists achieving and maintaining a minimum 1 mm surface texture. Combinations of 14/10 and 14/7 are common. Provision of a ‘lock-down’ treatment, such as a sanded-emulsion seal or an asphalt preservation material (refer to 5.6.2 Asphalt preservation), is also common to reduce stone loss (Figure 16). An on-site trial of the specified bitumen application rate and aggregate spread rate is also essential, as the design rates can only be considered indicative of the optimal solution.

Figure 16: Example sprayed seal surface suited to a runway



2.4.7 Slurry sealing and microsurfacing

Slurry sealing is a mixture of graded fine aggregate, bitumen emulsion and fillers (Hein et al. 2002). The slurry is manufactured and applied by specialised equipment, similar to paving of hot asphalt.

Microsurfacing is similar to a slurry seal with two significant differences. Firstly, the Microsurfacing usually contains a larger (7–10 mm) maximum aggregate size and secondly, a polymer modified bitumen emulsion is used to promote stability (Jamion et al. 2014). Further, the mineral filler is often cement to promote early strength gain (Robati 2014).

Microsurfacing is a variable thickness treatment that is similar slurry sealing but allows for a moderately variable layer thickness (Jamion et al. 2014). As a result, microsurfacing is commonly used to fill wheel ruts in an otherwise sound pavement (Broughton et al. 2012). However, it has limitations. Microsurfacing is intolerant of cracks in the existing pavement and contamination of the existing surface (Broughton et al. 2012). As a result, microsurfacing is only suited to treatment of pavements in generally sound condition. Traditional slurry surfacing was prone to embrittlement and delamination. Failure often occurred in plate-sized pieces, presenting a significant FOD hazard. The polymer-modified bitumen emulsion and a modified tack coat, often known as a ‘bond coat’, reduces this risk with microsurfacing.

Only limited use of microsurfacing of airport pavements has been documented. In Australia, some regional airports, primarily in New South Wales and Queensland, have been treated with microsurfacing since 2010 (Ioakim 2014). The results have been variable and it remains too early to understand the long-term performance.

2.4.8 Cement

Cement is a powder that is produced from calcareous materials including limestone and chalk, combined with alumina and silica found in clays and shales (Neville 1994). The raw materials are ground and then sintered at 1400°C. The resulting ‘balls’, known as clinker, are ground to a fine powder and gypsum is added to produce unblended cement, known as Portland cement.

Traditionally, Portland cement was the only cement used in concrete production, including for airfield pavements. However, a number of blended cements are now available, some of which provide beneficial properties in certain construction applications.

When mixed with water, cement hydrates, which includes a chemical reaction between the cement compounds, producing a firm mass. In time the cement ‘sets’ to a solid. Ongoing reaction and strength gain, known as ‘curing’ continues after the initial setting. Typically cement setting occurs within a few hours. Most curing occurs within a few weeks, but continues (slowly) for years. The rate of cement hydration, setting and curing depend on (among other factors) the chemical composition of the cement.

Importantly, the hydration process consumes water. Hydration also generates heat, expanding the concrete mass. Once set, the concrete cools and shrinks, which can lead to cracking. Different cement types shrink differently. Common cement types (chemical compositions) include (Neville 1994):

- » **Rapid hardening cement**, with finer grinding of the cement and specialised chemical composition, strength gain is accelerated. However, the time to set and the long term strength achieved are similar to that of Portland cement.
- » **General blended**, containing around 25 per cent fly ash and/or slag (from steel production) which slows the hydration process, providing more working time, reduced shrinkage and other benefits.
- » **Low heat cement**, where lower shrinkage is required, low heat cement is used to reduce the rate of hydration without impacting the final strength achieved.
- » **Sulphate resistant**, While many cement types are susceptible to chemical attack by sulphates salts, a sulphate resistant cement, with different chemical composition, is required in situations where sulphate exposure is likely.

2.4.9 Concrete

Concrete is the agglomeration of aggregate, cement and water (Neville 1994). Air is also important, as are chemical additives. Concrete comes in many forms, depending on the application. However, concrete for airfield paving is generally:

- » **40 mm maximum aggregate size**, to enable aggregate-based load transfer across sawn joints.
- » **Low workability**, to ensure true surface shape is not compromised by plastic (un-set) concrete flowing downhill during construction.
- » **High strength**, minimum 4.5 MPa flexural strength is normally specified, which correlates to an unconfined compressive strength of 40–50 MPa.
- » **Cement type**, Portland, blended with 20–25 per cent fly ash.

An airfield pavement concrete mixture (Figure 17) often referred to as pavement-quality concrete, typically comprises (by mass):

- » **40 mm aggregate**, 50–60 per cent
- » **sand aggregate**, 20–30 per cent
- » **cement**, 15–20 per cent
- » **water**, 5–10 per cent
- » **air content**, 3–5 per cent entrained air, and
- » **additives**, less than 2 per cent.

Airfield pavement concrete is not typical of concrete mixtures used for road pavement construction, general building, and construction works. The aggregate is larger (40 mm) and the strength is characterised by flexural beam testing. However, more typical concretes are also used in airfield pavement works. For example, low strength concrete is utilised for backfill of excavations, trench filling and drainage structures.

2.4.10 Cement treated crushed rock

In some applications, crushed rock for base course is treated with cement, or other cementitious material, to produce a cement treated crushed rock (CTCR). This is also referred to as cement-stabilised crushed rock, modified crushed rock or cement-treated base course.

CTCR is intended to function in the pavement as an improved crushed rock base course rather than as a rigid, concrete-like layer that would crack severely. The cement binds the fine matrix in-between the larger stones and reduces its plasticity, but produces only a limited tensile strength so that only fine cracks form when the CTCR shrinks. At typical cement contents (2–4 per cent) a modulus of 1,500 MPa or more is possible. However, like concrete, cement-treated crushed rock shrinks during setting and curing. A treatment is required to reduce the risk of cracks reflecting into overlying layers, including bituminous surfaces.

2.4.11 Concrete block pavers

Concrete block pavers for airport pavements (Figure 18) provide a fuel- and temperature-resistant surface without the expense of a rigid (concrete) pavement. This is highly suited to upgrading of existing flexible pavements in aircraft parking areas as well as the construction of apron surfaces in remote areas where concrete is not viable in relatively small quantities. In some cases, concrete block pavers have also been utilised over existing rigid pavements. However, the blocks have often ‘rocked’ over the joints between the concrete slabs and failed rapidly.

Also, concrete blocks are not used on runways due to the risk that jet blast and suction may dislodge blocks from the surface and damage aircraft.

Concrete blocks for airport pavements are similar to those utilised in roads, car parks and in domestic use. However, they are stronger and more engineered, including:

- » 200 mm by 100 mm surface dimensions
- » shaped to lay in a herringbone pattern (Figure 18)
- » 80 mm-thick blocks for increased strength
- » 3 mm nibs to provide a consistent joint spacing, and
- » chamfered surface edges.

Block pavers are placed on a layer of clean bedding sand and must be restrained to prevent the joints opening. The bedding sand layer must also be well drained to prevent pumping under aircraft loading. After laying, the spaces between the blocks are filled with a specially designed jointing sand. Once the joints are full, the surface is often sealed to reduce the loss of sand over time.

Figure 17: Typical aircraft pavement concrete



Figure 18: Concrete block pavers on a flexible airport pavement



2.5 Other materials

A number of other materials are often encountered in airport pavement works. These include grassing materials for flank works, maintenance products and expedient construction materials.

2.5.1 Grass and turf

Flanks of airfield pavements are often grassed for increased resistance to surface erosion. This is particularly important where runway work is performed at night and the runway is returned to service each morning.

Grassing can include seeding for slow grass growth or turfing. Seeding is usually performed by the application of a bitumen emulsion with seeds mixed in, referred to as hydro-mulch. The bitumen emulsion stabilises the un-grassed flank until significant rainfall initiates seed growth. The bitumen emulsion also assists existing grass to grow rapidly. Turfing includes a layer of topsoil followed by placement of turf. Turf is fragile until established and must be staked or otherwise fixed to avoid disturbance by jet blast. Turfing is more expensive than seeding, but provides a more immediate solution.

Regardless of whether seeding or turfing is adopted, maintenance is required until the grass is established. This generally requires an ongoing watering regime. Further, grass-type selection can impact bird hazard management, as some grasses are more or less attractive than others. Specialist environmental advice is required to ensure the most appropriate grass is selected for the local airport environment.

In many arid regions of Australia, grass will not survive without significant long-term maintenance and watering. At such airfields, the flanks are often stabilised with natural fill material. In such cases, grassing is less appropriate.

2.5.2 Maintenance materials

A broad range of materials are utilised for the performance of airfield pavement maintenance. The selection of materials best suited to the pavement type, condition and local environmental is essential. Commonly encountered materials include (Defence 2015):

- » **Linemarking paint**, special paints selected to minimise flaking paint becoming FOD.

- » **Crack sealer**, usually a rubberised bitumen that is poured into cracks.
- » **Asphalt preservation treatments**, usually cutback bitumen or bitumen emulsion, either with or without polymer modification and with or without fine aggregate to fill in some excess surface texture (refer to 5.6.2 Asphalt preservation).
- » **Concrete joint sealants**, either silicon or urethane 'poured-in-place' materials.
- » **Concrete spall repair**, a number of semi-rigid materials that adhere well to concrete, can be poured and cured to any shape, have enough ductility and flexibility to resist fracturing or sharding, but hard enough to resist aircraft loads.

Many maintenance treatments are proprietary products. Some appear similar but perform differently in the field. In many cases, one product has proven better in one airport, but another has been preferred at other locations. Further, at the same airport different products have performed differently despite seemingly similar conditions. Local conditions, experience and availability have a significant impact on the selection of maintenance treatments and materials (White & Thompson 2016).

2.5.3 Expedient construction materials

Australia's existing airfield pavement inventory was significantly developed during the 1940 and 1950s in preparation for World War II and in response to the cold war period that followed. Many of these airfields have been further developed since. It follows that a significant portion of airfield pavement construction work is associated with the extension, strengthening or replacement of existing pavements, rather than new pavement construction in a green-field area. Where existing pavements are being upgraded or extended, the work is often performed at night and the pavement returned to service during the days. Traditional and conventional construction materials are not conducive to such work as they require multiple layers to be provided, drying back of granular materials prior to covering, or curing of concrete. Expediently-constructible materials are essential to pavement upgrades in short night work periods. Examples include:

- » **Foamed bitumen stabilised base.** An injection of cold water into a stream of hot bitumen causes the bitumen to foam. In this form, the bitumen is workable due to microbubbles that become trapped within the bitumen film for some hours. If mixed into a processed gravel or crushed rock material, the result is a stiff, durable, rapidly constructible bitumen stabilised base course produced at ambient temperature (White 2014). The foaming may be performed insitu or in a pug mill. Insitu is appropriate for improving existing materials while a pug mill is appropriate for new construction using new quarried, crushed rock. Successful use of foamed bitumen stabilised base at Australian airports includes Sydney, Darwin, Brisbane, Darwin, Melbourne, Barimunya (WA) and St George (QLD) (White 2017).
- » **Rapid setting concrete.** Conventional concrete is designed to achieve the specified strength at 28 days. A minimum curing period of 7-14 days is normally required prior to trafficking. However, new cement technologies allow adequate strength gain within just a few hours (Hampton 2016). This provides the only currently viable means of reconstructing failed and aged concrete slabs without closing the pavements for extended periods. Rapid setting concrete has been used to replace old concrete slabs at Sydney, Melbourne and Townsville airports.
- » **Warm mixed asphalt.** Asphalt is normally produced at around 160°C. When constructed in a single 50–70 mm thick, hot asphalt usually cools adequately to resist aircraft loading in just a few hours. However, when three or more layers are required, the increased thickness of hot asphalt remains hot and may deform when trafficked (White 2015). By either foaming the bitumen or adding special chemicals, the production temperature of asphalt is reduced by up to 40°C. In some cases, this has been the difference between rutting under traffic or not (White 2017).

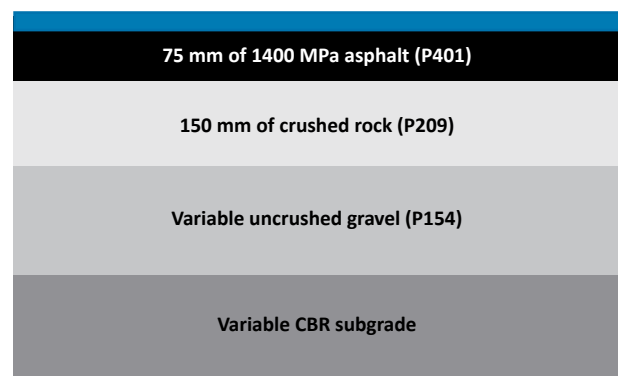
2.6 Material equivalencies

2.6.1 Importance

As discussed later, flexible aircraft pavement thicknesses are often calculated using the Federal Aviation Administration (FAA) computer program COMFAA (refer to 3.4.3 FAA computerised representation of S77-1). The program utilises the US Army Corps of Engineers' pavement thickness design procedure known as S77-1 (Pereira 1977). The pavement thicknesses obtained when using COMFAA refer to pavements that have structures that are the same as those used in the full-scale test pavements that were used to develop the S77-1 design method. The full-scale test pavements consisted of 75 mm of asphalt over 150 mm of crushed rock base course over varying thicknesses of uncrushed gravel sub-base and variable subgrades (Figure 19).

In order to assess the adequacy of an actual pavement to accommodate the design aircraft, it is necessary to take account of the actual materials contained in the pavement. This is done by using material equivalencies to transform the actual thickness of the pavement into an S77-1 structure of equivalent thickness. 'Equivalent' means that the S77-1 pavement of the equivalent thickness will spread aircraft loads to the same degree as the actual pavement at its actual thickness. If the actual pavement contains materials that are better than those of the S77-1 test pavements, then the thickness of an equivalent S77-1 pavement would have to be thicker than that of the actual pavement to have the same load-spreading capability. But if the actual pavement consists of weaker materials than those in the test pavements it has to be thicker than the COMFAA-calculated S77-1 thickness needed by the aircraft.

Figure 19: Standard S77-1 Pavement Composition (White 2006)



2.6.2 Definition

By definition, the layer equivalency factor of material A relative to material B is the thickness of B/thickness of A, where each thickness has the same effect on pavement life.

2.6.3 Material equivalence guidance

A useful starting point for selecting layer equivalencies is provided in a superseded (version 6D) FAA advisory circular (FAA 1995). Note that the current (6F) version of the advisory circular does not contain equivalency recommendations because 6F utilises the layered elastic method for pavement thickness design). The 6D version suggests ranges of equivalencies for a number of 'standard' materials described by FAA specifications. Common equivalencies are summarised in Table 2. P-401 (asphalt), P-209 (crushed rock) and P-154 (uncrushed gravel) are standard aircraft pavement materials specified by the FAA.

The FAA ranges are fairly wide and judgment is required by the pavement designer when selecting equivalency factors. For example, high-quality sound asphalt might be given a top of the range factor of 1.6 if the FCR is of minimum quality (ie CBR 80), but only 1.2 if the asphalt is unsound or thin (and is therefore warmed throughout by the sun) and the FCR is a premium material with a CBR greater than 100. A mid-range equivalency of 1.4 might be appropriate if a typical asphalt replaces a typical FCR. Thicker asphalt surfacing layers (say greater than 100 mm) should be given a higher equivalency than thinner layers because the average temperatures of thick asphalt layers tend to be lower, so the asphalt is stiffer and distributes wheel loads to a greater degree.

2.6.4 Comparison with layered elastic analysis

'Layered elastic' pavement thickness design structures the pavement as a system of horizontal elastic layers. Each layer has an elastic modulus. However, the difficult task of describing the load-spreading characteristics of the various pavement materials still remains. The problem of selecting layer equivalencies has simply been replaced by the equally difficult problem of selecting elastic moduli.

White (2006) determined the Aircraft Pavement Structural Design System (APSDS) (refer to 3.4.4.1 Aircraft pavement structural design system) implied material equivalence factors for common Australian airport pavement materials. The recommended equivalence factors were at the lower end of the FAA ranges (Table 2) as summarised in Table 3. These factors are important in pavement thickness determination for flexible airfield pavements.

Table 2: FAA Material Equivalence Guidance (FAA 1995).

1 mm of this material	Is equivalent to the following thickness (mm)	Of this material
Asphalt (P-401)	1.2 to 1.6	Crushed rock (P-209)
Crushed rock (P-209)	1.2 to 1.8	Uncrushed gravel (P-154)
Asphalt (P-401)	1.7 to 2.3	Uncrushed gravel (P-154)

Table 3: Recommended Materials Equivalencies (White 2006).

1 mm of this material	Is equivalent to the following thickness (mm)	Of this material
Asphalt (P-401)	1.3	Crushed rock (P-209)
Crushed rock (P-209)	1.2	Uncrushed gravel (P-154)
Asphalt (P-401)	1.6	Uncrushed gravel (P-154)

2.6.5 Equivalencies and the CBR

Material strengths are often provided in terms of CBR. But there is no known relationship that allows material equivalencies to be directly calculated from CBR data. For unbound materials, one approach in estimating the equivalency of a material of known CBR is to consider where it lies between the two FAA standard unbound materials i.e. P-154 which has a minimum CBR of 20 and P-209 which has a minimum CBR of 80. As previously noted, FAA guidelines indicate that when P-209 is substituted for P-154, it is equivalent to 1.2 to 1.8 times the thickness of the P-154 layer it replaces. This is a very wide range but knowledge of the CBRs of the materials allows the designer to choose a reasonable equivalency within the range.

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PAVEMENT DESIGN

CHAPTER 3



3.0 PAVEMENT DESIGN

3.1 General principles

Pavements are designed to resist the 'damage' caused by aircraft and other traffic. For full-strength pavements at major airports, the aircraft are significantly heavier than any non-aircraft traffic and the aircraft dominate the pavement thickness requirements. However, some pavements are not designed for regular aircraft traffic (e.g. shoulders) with the non-aircraft traffic (e.g. fire tenders and refuelers) dominating. However, the surface levels, grades and materials are usually still determined for aircraft traffic requirements, such as FOD minimisation.

In many rural and remote airports, pavements are not designed using any analytical method. Rather, the truly empirical approach is based on what has been successfully trialed and used at the same airport in the past. Such pavements are not true 'airfield pavements'. Rather, they are 'pavements used by aircraft' and general guidance is provided later (6 Pavements for Rural and Remote Airfields).

As previously detailed (1.1.3 Airfield pavement 'failure') aircraft pavements are designed and maintained in a condition to allow safe operation of the aircraft that utilise the pavement. The design process varies but generally follows a similar set of steps, some performed in parallel and some performed in sequence.

- » **Determine the existing ground conditions.** This includes the subgrade strength as well as the existing terrain, drainage and ground levels.
- » **Determine the approximate level of the new pavement surface.** Influenced by airspace requirements, obstructions and existing pavement, terminal and associated infrastructure.
- » **Forecast the aircraft traffic.** Based on expected growth in passengers, freight and flights over the pavement design life, usually 20 years (flexible pavements) or 40 years (rigid pavements).
- » **Select the pavement type.** Rigid, flexible, hybrid or a combination of all three.
- » **Pavement thickness design.** Analytical determination of the pavement structure (layers and materials) to support the forecast aircraft traffic over the pavement design life.
- » **Pavement geometric design.** Overall pavement surface shape and finished pavement levels determined on a closely spaced grid.

- » **Design details.** A broad and important element determining all the pavement requirements that are not related to structure and thickness. Examples include the transition from an existing pavement to a new pavement and the concrete slab joints in rigid pavements.
- » **Drawings and specifications.** Preparation of documentation to set the minimum requirements for construction of the pavements.

Pavement design, like all infrastructure design processes, is iterative. That is, the process will be repeated multiple times, with greater sophistication and precision adopted each time. This allows for client and stakeholder issues to be considered, as well as recognising the interaction between the various steps in the process. For a significant development at a major airport, four main stages of design iteration might be expected, including:

- » **concept design** – initial approvals and budget setting
- » **preliminary design** – budget refinement and client input
- » **detailed design** – development of all details for client review
- » **final design** – for tendering and construction purposes.

3.2 Strength requirements

Before flexible and rigid pavement design is described, a number of related concepts must first be introduced. Understanding these concepts is essential to appreciating the complexities and limitations of airport pavement structural design methods.

3.2.1 Pavement damage and life

Pavement 'damage' does not imply any sudden breaking of the pavement surface. In the case of flexible pavements, it refers to the depressions that gradually develop along wheel paths as many aircraft wheels pass along the pavement. The design method assumes that the depressions are due to deformation of the underlying subgrade. After 15 to 20 years the surface may become too rough and rutted for use by aircraft. Also, ponding of water in wheel-path depressions leads to loss of braking capability in wet weather. At this stage the pavement's life is over. Typically, the runway is then resurfaced with asphalt, which fills the wheel-path depressions, so its life begins again.

In the case of rigid pavements, 'damage' is defined as fatigue cracking at the surface of the concrete. The design method assumes that all cracking results from aircraft loading. Other cracking, from shrinkage, curling and warping are not considered. The cracks lead to spalls that may become too severe for use by aircraft. At this stage the pavement's life is over. Cracks and spalls can be repaired (refer to 5.5.3 Concrete maintenance) however, the pavement's design life is not reset.

In other words, 'damage' refers to the gradual consumption of the runway's design life. Importantly, flexible pavement life is typically reset by asphalt resurfacing to correct the accumulated wheel-path depressions. In contrast, the cracks in a rigid pavement can be maintained, but only full depth replacement can reset a rigid pavement's design life.

Also, many defects and distresses other impact aircraft pavement performance and life. These other distresses are not necessarily reflected by pavement strength requirements or design.

Typically, rigid pavements are designed for a 40-year life while flexible pavements are design for a 15 or 20-year life. This reflects the durability of the concrete and asphalt at the surface of the pavement. There is little benefit in designing a pavement that is structurally predicted to last longer than the surface is expected to be durable. In the case of a rigid pavement, concrete surface replacement is not practical unless the full structure is reconstructed. In the case of flexible pavements, resurfacing due to asphalt durability resets the design life, negating any need for full depth reconstruction. In both cases, setting the design life to be slightly longer than the expected surface material durability is a logical and cost-effective approach.

3.2.2 Factors of safety and design reliability

The term 'factor of safety', as commonly understood and used in engineering, means that if, for example, sudden failure occurs under a single application of a load that is three times greater than the design load, the 'factor of safety' is three. But because aircraft pavements fail by the accumulation of incremental damage (i.e. fatigue) the factor of safety concept is less meaningful.

In the case of flexible pavements, the thickness design methods assume that failure involves the gradual accumulation of permanent deformations of the underlying subgrade. This causes the runway surface to gradually deform (rut) in the wheel paths during its intended design life. If the pavement performs exactly as designed, then when all the expected aircraft at their expected weights have actually used the runway, the surface will have deformed to an extent that is just unacceptable. That is, there is no well-defined failure point of the kind that occurs if the load on a structural steel beam is increased to an ultimate load at which the beam suddenly collapses.

Rigid concrete aircraft pavements 'fail' by developing an unacceptable number of full-depth cracks as a result of many passages of aircraft of various sizes over a design life, usually 40 years. As with flexible pavements, rigid pavement failure is a gradual process so the factor of safety concept is not meaningful.

It might be tempting to try to define a factor of safety in terms of the weight of aircraft or the number of aircraft for which a pavement has been designed. For example, if a design is based on an aircraft weight that is double that of the actual aircraft, the factor of safety might be considered to be two. Similarly, if the pavement is designed for 10,000 passes of an aircraft instead of the expected 5,000 passes, the factor of safety might also be considered to be two. The difficulty is that doubling the number of aircraft increases pavement thickness by only around four per cent, but doubling the aircraft weight gives a much greater increase in thickness of around 60 per cent, depending on the aircraft type. That is, pavement thickness is far more affected by load magnitude than by load repetitions. Thus, the term 'factor of safety' is problematic. The term 'design reliability', rather than 'factor of safety', is more commonly used in pavement design.

It is important to realise that some widely-used aircraft design methods do not contain inherent design reliability factors. If the designer inputs the average or exact parameter values for aircraft traffic and subgrade support, the design method has a 50 per cent reliability. That is, there is an equal chance that the designed pavement will fail before the end of the specified design life as there is that it will last longer than the intended design life. One out of two pavements would be expected to fail before their design life was achieved (Potter 1985).

However, in practice pavements rarely fail anywhere near 50 per cent of the time. Consequently, the true design reliability must be much greater than 50 per cent. The possible sources of the higher design reliability are:

- » the designer chooses a level of subgrade support that is somewhat lower than the true value
- » the aircraft are presumed to operate at weights that are higher than the actual operating weights
- » the number of aircraft predicted to use the pavement during its design life is higher than actual usage.

Other conservatism is also included in some pavement design methods because they superimpose the effect of different aircraft types within the forecast aircraft traffic, despite the wheels being located at different distances from the centre of the aircraft.

As indicated by the example above, it is important to acknowledge that not all inputs to pavement design have the same impact on the predicted life of the pavement. The relative influence a given design parameter has on the life of the pavement indicates how much a conservative selection will increase the reliability of the resulting pavement thickness.

3.2.3 Traffic forecasts

The aircraft traffic forecast is critical to pavement structural design. Aircraft traffic factors impacting aircraft pavement design include:

- » aircraft types (airframes and variants)
- » physical aircraft landing gear configuration, including wheel arrangement and spacing
- » aircraft operating mass and tyre pressure
- » aircraft taxiway routes and take-off/landing directions, and
- » frequency of aircraft operations.

Typically, a few large aircraft in the list of design aircraft dominate the pavement thickness design. These largest aircraft should be focused on for pavement design purposes. The smaller aircraft usually do not affect pavement thickness, even at relatively high frequency of operation.

The physical aircraft characteristics are well documented by aircraft manufacturers, including landing gear configurations, maximum and minimum operating masses and standard tyre pressures. The Airbus, Boeing and Embraer aircraft websites all contain aircraft technical manuals. The details for older aircraft types, some produced by now non-existent companies, are harder to find. However, the operating airlines always holds the relevant information.

Other factors, including the range of aircraft operating masses, must be determined by the pavement designer. Similarly, the aircraft frequency of operations and taxi routes must be estimated from information provided by the airport.

Importantly, aircraft operating mass has a significant impact on aircraft pavement thickness design (refer to 3.5.6 Inputs and sensitivities). For example, depending on subgrade CBR, a flexible pavement designed for a B737-800 may range from 650 mm to more than 800 mm as the aircraft operating mass increases from the minimum to maximum operational range. Aircraft frequency affects pavement thickness to a far smaller extent than aircraft operating mass and the aircraft type.

3.2.4 Pass-to-coverage ratio

Pavement thickness design is concerned with the number of load repetitions at a point on the pavement experiences, not the number of times an aircraft passes along the pavement. The airfield situation differs from highways in that wheel loads are much more evenly distributed across the width of the pavement (refer Table 1 and 1.4 Roads versus airports). This is because traffic flow is far less channelised and because of the large variety of aircraft wheel layouts relative to those associated with cars and trucks. Field observations of aircraft movements have shown that successive passes of aircraft along a pavement are statistically normally distributed about the pavement centreline (HoSang 1975). The degree of so-called 'aircraft wander' can therefore be characterised by a standard deviation and is found to be significantly different for runways, taxiways and aircraft parking bays.

The degree of spread of aircraft wheel loads across the pavement width affects the amount of pavement damage caused. Therefore, it was necessary to introduce the concept of a pass-to-coverage ratio (PCR) to account, in an approximate way, for the effect of aircraft wander upon pavement damage. In developing the S77-1 design method, the Corps defined the PCD as follows. A point on the pavement is said to receive a 'coverage' when any part of a tyre's contact area passes over it. The PCR is defined as the number of passes of a wandering aircraft that is statistically required for the most frequently covered point to receive one coverage. The PCR depends upon wheel arrangement, tyre width, and the degree of aircraft wander. PCR remains an important concept in current airport pavement design methods and is retained in the FAA's tool COMFAA. Note, however, that the PCR used in the FAA's design tool, FAARFIELD, is defined differently.

3.2.5 Subgrade CBR

Subgrade bearing capacity is usually the most influential factor impacting aircraft pavement thickness design. The impact of subgrade support on rigid pavement thickness is less significant than for flexible pavement thickness. Importantly, subgrade support changes with subgrade moisture content and density. It follows that significant effort is invested in estimating the subgrade support at the long-term insitu subgrade condition. That is significantly simpler when pavements already exist at the same airport.

Within about one-to-three years of construction, moisture contents reach equilibrium values that are largely independent of the compaction moisture content. Materials further than 5 m from the runway or apron edge then show no significant moisture content variation laterally and tend not to vary seasonally or with rainfall, provided an impermeable pavement surface is maintained.

Most flexible aircraft pavement design methods characterise subgrade support or strength by CBR (refer to 2.3 Subgrades). Rigid pavement design characterise subgrade support by the 'modulus of subgrade reaction', or K-value. K-values for aircraft pavement design are ideally based on 30-inch diameter plate load tests performed on the actual subgrade or constructed fill. This testing is often impractical so a number of suggested relationships between CBR and 'K' have been published and are commonly utilised. Table 4 provides indicative values of 'K' often used for subgrades of known CBR.

Table 4: Indicative correlation between CBR and K-value

CBR (%)	K (kPa/mm)
2	20
3	27
4	34
5	40
6	43
8	48
10	54
15	60

As previously discussed (3.2.2 Factors of safety and design reliability) there are no design reliability factors built into many of the common pavement thickness design methods or software programs. Because of its relatively high variability and significant influence on pavement thickness, the subgrade CBR is typically selected conservatively to introduce greater design reliability.

Historically in Australia, the 'design' CBR value assigned to the subgrade for pavement strengthening work was generally based on the 75-percentile value of determinations made beneath an existing pavement. That is, 75 per cent of the test results were higher than the adopted design CBR. CBR results were obtained either by insitu CBR testing, or from laboratory CBR tests on recompacted samples, or from insitu penetrometer readings using a dynamic cone penetrometer (DCP) correlated with CBR values (Table 5).

Table 5: Indicative correlation between CBR and DCP penetrate rate

CBR (%)	DCP penetrate rate (mm/blow)
3	60
4	45
5	38
6	35
8	32
10	20
15	12
20	10
30	8
40	6
50	5

Where field measurements of subgrade CBR were not available, laboratory CBR tests were carried out on re-moulded samples of subgrade material at various densities and moisture contents. An estimate of likely in-service subgrade moisture content was then made in order to select relevant CBR values for design. In practice, a combination of field measurements by DCP and laboratory CBR testing of re-moulded subgrade samples is usually performed.

There is no current authoritative guide to the selection of subgrade CBR for Australian airport pavements. Different statistical methods used by various authorities and designers to select a design CBR will produce different degrees of design reliability. Some designers have even selected the lowest value of all the test results, which is unreasonably conservative. Other designers recommend an 85-percentile value based on FAA guidance (FAA 2016).

Pavement designs are typically performed between subgrade CBR 3 and CBR 15. Designs based on CBR values outside of this range are less reliable and should be avoided. However, it is not uncommon to encounter CBR test results that fall outside this range. For example sand subgrades can achieve soaked CBR values of 20–30 while highly reactive clays and marine clays may fall below CBR 1.

In the case of subgrade CBRs exceeding 15, the additional design reliability is generally accepted and subgrade CBR 15 is adopted for design purposes. In the case of low subgrade CBR values, such materials generally will not be trafficable by construction equipment and necessitate some treatment. Either a ‘working platform’ is provided and the top of the working platform is assigned a design subgrade support of CBR 3, or the subgrade is treated to improve the CBR to minimum CBR 3, as discussed later (4.2 Subgrade).

3.3 Functional requirements

Functional requirements for aircraft pavements generally affect the safe operation of aircraft. This contrasts to structural or strength requirements for aircraft pavements, which generally affects only the life of the pavement. However, structural distress impacts functional performance. For example, flexible pavement wheel-path depressions, or ruts, often hold water, which affects ride quality and skid resistance. Further, rigid pavement fatigue cracking leads to pavement-generated FOD. Table 6 summarises aircraft pavement functional requirements, the factors affecting each and the impact on aircraft operations, which are also discussed in more detail below.

Table 6: Aircraft pavement functional requirements

Functional requirement	Factors affecting	Operational impacts
Ride quality	Construction quality	Aircraft skid resistance
	Design surface levels	Passenger comfort at speed
	Subgrade shrink/swell	Aircraft wear and tear
	Pavement/subgrade subsidence	
	Wheel-path depressions	
Skid resistance	Surface treatments	Wet weather aircraft skidding
	Surface materials	
	Surface shape	
	Surface age	
	Rubber contamination	
Freedom from FOD	Surface treatments	Aircraft engine, tyre and structural damage
	Surface materials	
	Construction quality	
	Sweeping frequency	
Visual distinction	Line markings	Aircraft operational safety
	Contrasting flanks	

3.3.1 Ride quality

A runway surface is ideally flat in the longitudinal direction, with consistent 1.5 per cent cross-fall in the transverse direction. The cross-fall allows water to be shed rapidly from the surface and the flatness promotes site distance along the runway length. However, the ideals are often not achieved in practice due to slope requirements of intersection pavements and for reasons of economy.

In practice, runways often have non-zero longitudinal slopes that also change over the length of the runway. Cross-falls are often close to ideal when initially constructed but change over time due to aircraft loading, differential subgrade settlement and reactive subgrade shrink/swell. Resurfacing by asphalt overlay usually increases the cross-falls by putting greater thickness on the central trafficked area and less on outer areas and shoulders. However, economics and physical constraints often prevent ideal cross-falls being reinstated. Rather, the tolerances recommended by ICAO (2013) and permitted by MOS 139 (CASA 2016) are targeted.

Importantly, there are instances where even meeting the Civil Aviation Safety Authority (CASA) tolerances for longitudinal slope are impractical for existing aircraft pavements. These imperfect slopes create 'bumps' in aircraft pavements that affect ride quality. Pavement 'bumps' that occur over different wavelengths impact on aircraft ride quality differently. CASA requirements limit bumps of critical wavelength by placing limits on immediate changes in level (steps), short wavelength changes in level (deviation under a 3.5 m-long straight edge) and the radius of curvature for designed changes in slope.

Importantly, not all bumps are introduced by pavement design and construction. Subgrade shrinkage and swelling with changes in moisture content significantly affect surface shape and ride quality. As do subgrade subsidence or differential settlement and wheel-path depressions or rutting.

There are many tools for the measurement of ride quality in road and highway pavements (Sayers et al. 1986). However, these tools generally focus on bump wavelengths that are important for cars and trucks. The different wheel configurations and operating conditions of aircraft means the critical bump wavelengths are different for runways (Roginski 2012). The Boeing Bump Index (BBI) developed by the Boeing and formalised by FAA, provides a rational approach to evaluating the impact of surface smoothness on aircraft ride quality (Roginski 2012). The BBI determines the criticality of bumps of all wavelengths from 0.5 m to 60 m at intervals along the runway as close as 0.25 m (FAA 2009). The BBI is not typically determined for airport pavement in Australia at this time.

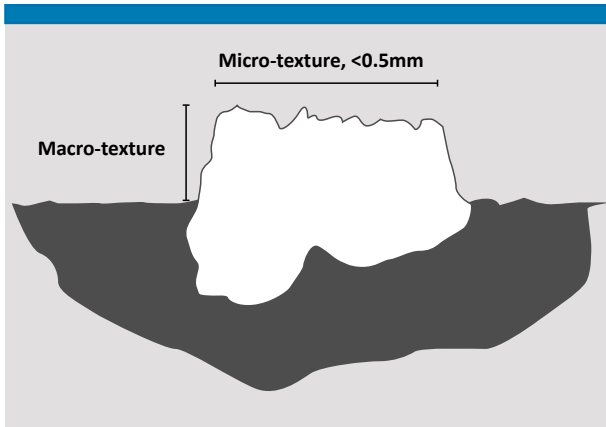
3.3.2 Aircraft skid resistance

As previously discussed (1.4 Roads versus airports) pilots do not have the luxury to simply operate the aircraft more slowly during take-offs and landings during wet weather. It follows that aircraft skid resistance is an important functional requirement of aircraft pavements. Furthermore, skid resistance is most important for runways. Skid resistance is influenced by (Zuzelo 2014):

- » **Micro-texture** – determined by the properties of the individual aggregate particles in the surface asphalt/sprayed seal surface (Figure 20) or the concrete mortar (fine aggregate and cement) at the surface of a rigid pavement. Micro-texture significantly influences the friction offered to the aircraft tyre by the pavement surface.
- » **Macro-texture** – determined by the overall asphalt or concrete mixture design and any treatments applied to the pavement surface (Figure 20). Macro-texture determines the reduction in friction available to the aircraft tyre as a consequence of the film of water between the aircraft tyre and the pavement surface during wet weather.

Typically, airport pavement surfaces provide adequate aircraft skid resistance during dry weather conditions (Emery et al. 2011). However, in wet conditions, additional measures are required to ensure adequate skid resistance is achieved. It is important to understand that during high-speed aircraft braking, there is a rainfall intensity above which no practical aircraft pavement surface will continue to provide adequate skid resistance. However, at such high rainfall intensities, aircraft are unlikely to operate due to low visibility and wind restrictions.

Figure 20: Surface micro-texture and macro-texture



Aircraft skid resistance is not constant over the life of a pavement surface. The following factors change over the life of the surface and impact skid resistance:

- » **Grooving** – grooving a runway surface immediately increased the ability of surface water to escape from between the pavement surface and an aircraft tyre, significantly increasing aircraft skid resistance in wet weather.
- » **Rubber contamination** – as rubber is deposited on the pavement surface during landing aircraft wheel spin-up, surface texture is reduced and eventually aircraft land on the accumulated rubber, reducing skid resistance.
- » **Surface erosion** – with age, pavement surfaces erode. Erosion increases the negative macro-texture of asphalt surfaces but reduces the positive macro-texture of broom-finished concrete surfaces. Further, erosion of a grooved surface reduces the effective groove depth and may reduce skid resistance.
- » **Surface treatments** – as will be further discussed (5.6.2 Asphalt preservation), preservation treatments provide significant life extension to sprayed seal and asphalt surfaces. However, these treatments can adversely affect micro-texture, macro-texture and aircraft skid resistance. Balancing the benefits of surface treatments with management of aircraft skid resistance is discussed later (5.6.2.5 Impact on surface texture and friction).

Because the provision of aircraft skid resistance is such a complex but important element of airport pavement design and management, a detailed discussion of methods to provide, measure and maintain skid resistance follows (3.9 Surface texture, friction and skid resistance).

3.3.3 Freedom from foreign object debris

Complete freedom from pavement generated FOD is likely to be unrealistic, however it is an appropriate goal for pavement designers and managers. Sources of pavement-generated FOD include spalled concrete, spalled concrete block pavers, loose stones from sprayed seals, and ravelled aggregate from asphalt surfaces. As previously noted (1.4 Roads versus airports), intolerance of FOD is a significant difference between road and airport pavements. It follows that FOD reduction is one factor necessitating different materials for airport pavements than are typical for road pavements.

3.3.4 Visual distinction

Runway pavements provide visual cues to pilots during their approach, landing and braking operations. To ensure all pilots are provided with consistent cues at all airports, consistent linemarking and lighting requirements are recommended by ICAO (2013) and required by CASA (2016).

Linemarking requirements are detailed in Manual of Standards Part 139 (MOS-139) so are not considered further here. Aeronautical ground lighting is also detailed in MOS-139, as well as Australian Airports Association *Practice Note 11* (AAA 2016) and is not considered further. Suffice to say that both pavement linemarking and lighting are important for visual distinction of aircraft pavements and must be maintained in a condition consistent with MOS-139 requirements applicable to the airport in question.

3.4 Flexible pavement design

3.4.1 Empirical ties to full-scale testing

Modern flexible aircraft pavement design tools are based on analytical (or mechanistic) processes for calculating the response of the pavement to load (refer to 3.4.4 Advanced mechanistic-empirical design methods). The magnitude of each critical response is then related to the number of loads cycles to failure, via an empirically derived performance relationship. These tools are described as being ‘mechanistic-empirical’ in nature. Different mechanistic tools use different methods to represent the pavement structure and to calculate the pavement responses, with the ‘layered elastic’ method the most common.

The layered elastic method of analysis represents the pavement structure as a system of uniform horizontal elastic layers. Each pavement material is assigned an elastic modulus (similar to stiffness) that reflects its load-spreading ability. The moduli are constant within each layer. By representing the pavement structure in this relatively simple way, an estimate of the load intensity that reaches the subgrade can be calculated using computer software.

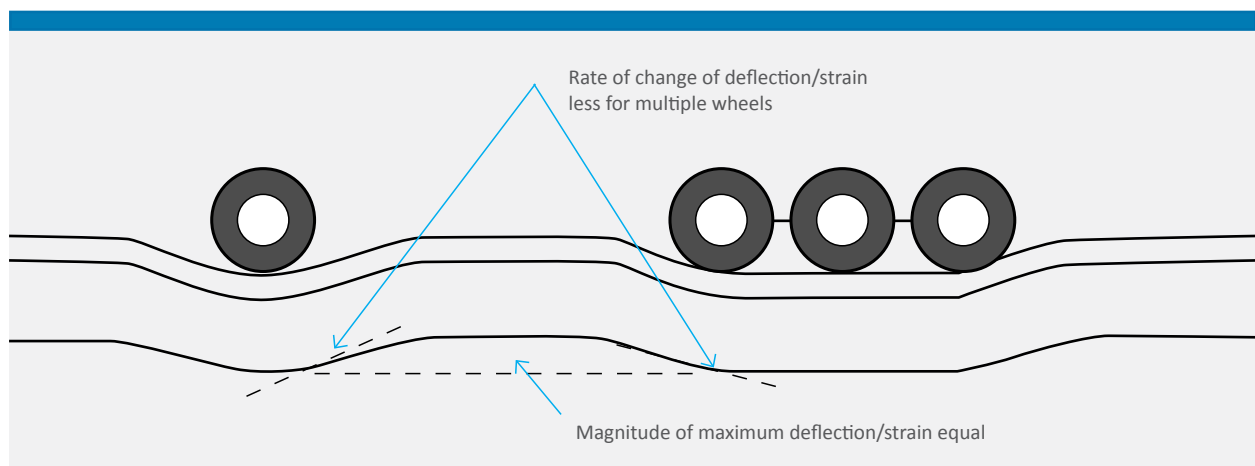
Subgrade vertical strain, stress and deflection have all been used as measures of load intensity, but vertical strain is now favoured. For example, the Corps’ S77-1 methods, computerised by the FAA as COMFAA (3.4.2 US Army Corps of Engineers design method) uses deflection but both APSDS (3.4.4.1 Aircraft Pavement Structural Design System and FAARFIELD (3.4.4.2 FAARFIELD) use vertical strain.

The theoretically-calculated subgrade strain is the primary pavement ‘response’ to load for design purposes. Calculating the pavement response is only the first part of the pavement design process because it says nothing about pavement life. In flexible pavement design, the calculated vertical subgrade strain is referred to as a ‘pavement performance indicator’ because it is used to indicate how quickly wheel-path depressions will develop at the pavement surface when the pavement is subjected to repeated applications of the calculated strain level.

To produce a pavement thickness design method, an equation is needed that relates strain to the number of repetitions of that strain that will cause wheel path depression failure. The equation cannot be derived from theory. It must be obtained empirically by calibrating against full-scale test results. ‘Calibration’ entails adjusting the equation until agreement is obtained with the actual rutting behaviour that was observed during full-scale tests. General agreement over a range of pavement and load conditions is required. The equation must adequately predict the rutting that occurs under different aircraft loadings, with different subgrade CBRs and in pavement of different thicknesses and compositions.

Not surprisingly, tests showed that pavement rutting life does not simply depend on the magnitude of the subgrade deflection/strain. For the same subgrade deflection/strain, pavement life was found to be longer if the deflection was caused by aircraft undercarriages that had larger numbers of wheels. The more gradual, flatter distribution of deflection/strain (Figure 21) gave a longer life than the sharper distribution at subgrade level caused by fewer number of wheels.

Figure 21: Number of wheels and deflection/strain distribution



An adjusting factor, called an alpha factor in the Corps' S77-1, is therefore needed. The alpha factor depends upon the number of wheels that produced the deflection and was introduced to adjust calculated design thicknesses to agree with the rutting performances observed in full-scale tests. Further, to allow the tests to be completed within a reasonable time, thicknesses of the test pavements were limited. That is, the test pavements were not truly full-scale. This introduced an uncertainty because design of thicker airport pavements required extrapolation of the test results. Consequently, some design methods are calibrated taking into account both the test pavement data and also the observed performance of full-depth pavements under actual service conditions at airports.

3.4.2 US Army Corps of Engineers design method

The design procedure for flexible aircraft pavements was initially adapted from the empirical CBR highways method in 1942, and extrapolated to cater for higher, single-wheel aircraft loads. At the time, mathematical solutions were limited to stress, strain and deflection directly under the load (tyre) centre. Solutions were then developed for the deflection beneath and at lateral offsets from a uniformly loaded circular area that represented the tyre contact area.

The thickness design methods were extrapolated as larger aircraft with multi-wheel landing gears appeared. They were calibrated using trafficking tests conducted on large-scale (i.e. not full-scale) pavements by the US Army Corps of Engineers (example in Figure 22).

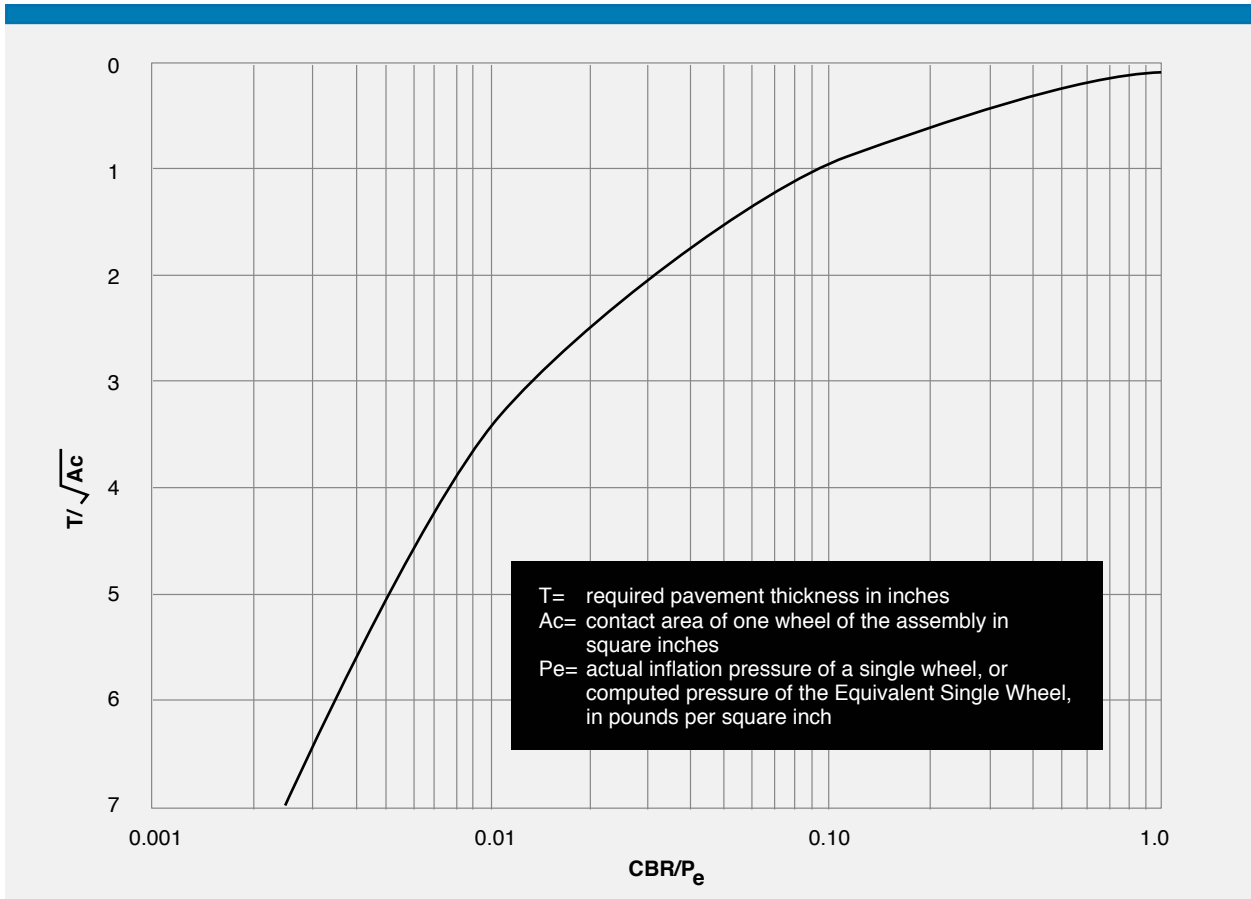
The US Army Corps of Engineers developed an empirical relationship between aircraft loads, subgrade CBR and the required pavement thickness to cater for 5,000 'coverages' (Figure 23). The curve was developed from the full-scale tests in which pavements were trafficked until they failed. Some 37 tests had been completed by 1971 at around the time that the Boeing 747 came into service. The resulting empirical design method was known as S77-1 (Pereira 1977).

The aircraft loads used in the Corps' tests were full-scale. But as explained above, the thicknesses of the test pavements were limited in order to complete tests within a reasonable time. Because S77-1 is an empirical design method, its use to design much thicker pavements for larger aircraft and greater load repetitions than those used in the full-scale tests introduces a degree of uncertainty. The 'golden rule' of empiricism is that empirically-derived methods cannot be applied with full confidence beyond the empirical database. Consequently, recent FAA design methods attempt to take into account both the test pavement data and also the observed performance of full-depth pavements under actual service conditions at US airports.

Figure 22: Example of US Army Corps pavement test section



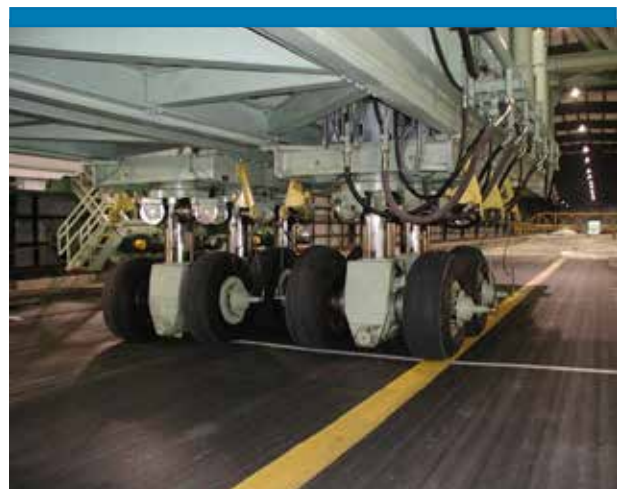
Figure 23: US Corps of Engineers original design curve



The empirical large-scale testing focused on wheel-path depressions. Asphalt cracking, sub-base rutting and other failure modes were not considered. This reflects pavement 'damage' and pavement 'failure' being determined primarily by wheel-path depressions. Failure was generally taken to be the development of 25 mm deep wheel-path depressions. However, assessment of failure was difficult and open to interpretation (Ahlvin 1991).

Further tests have since been carried out by the FAA to quantify the pavement damage caused by newer large aircraft such as the B777 and A380. These tests have resulted in adjustments to the S77-1 method. The test program commenced in 1998 and is continuing at a modern indoor facility constructed by the FAA in Atlantic City, New Jersey, USA in 1999 (Figure 24) (Garg 2016).

Figure 24: Example of recent FAA pavement test section



3.4.3 FAA computerised representation of S77-1

The evolution of the US Army Corps of Engineers design method S77-1, has been described. COMFAA, a free computer program produced by FAA, performs S77-1 aircraft pavement designs and evaluations. COMFAA can be downloaded from the FAA website. COMFAA has been maintained by the FAA to incorporate adjustments to S77-1 from recent large-scale and testing.

In one mode COMFAA calculates aircraft classification numbers (ACN). As part of the ACN definition, they must be calculated using S77-1. Together with the Pavement Classification Number (PCN), they form part of ICAO's ACN-PCN system for strength rating of runways (refer to 3.6 Expedient Pavement Design

Expedient pavement design relies on the same processes and principles as 'normal' pavement design. However, materials suited to expedient construction (2.5.3 Expedient construction materials) are selected and appropriate material equivalencies are assigned (2.6 Material Equivalencies). Expedient pavement design must aim to maximise productivity, generally achieved by selecting materials:

- » with high modulus for maximum structural contribution
- » that are rapidly constructible
- » without the need to cool or cure for long periods of time, and
- » that are immediately trafficable.

When designing expedient pavements solutions, some designers are tempted to increase the thickness of the layer(s) above that required by pavement thickness design. This aims to add some conservatism to account for the expedient nature of the construction and the impact this may have on construction quality. For example, a 250 mm-layer of warm asphalt may be increased to 300 mm of 450 mm of rapid setting concrete may be increased to 500 mm. However, each additional layer, required by the additional thickness, further adversely impacts construction quality. Unnecessarily adding thickness is likely to have a negative impact on overall pavement construction quality (White 2017) despite the opposite intention.

ICAO Pavement Strength Rating System). Consequently, an advantage in using S77-1 for pavement thickness design is that the results are then easily related to the chosen PCN for the designed runway. In contrast, the FAA's FAARFIELD software produces larger flexible pavement thickness than S77-1 which is inconsistent with the ACN-PCN system.

3.4.4 Advanced mechanistic-empirical design methods

As explained earlier, the Corps' flexible pavement thickness design method, S77-1, is computerised as COMFAA, which also includes the Corps' rigid pavement design method (refer to 3.5.2 Thickness design tools). COMFAA-calculated pavement thicknesses reflect the results from the Corps test pavements and remain the truest representation of the relationship between full scale aircraft loads, airport pavement structures and pavement life. Consequently, COMFAA is commonly used by pavement designers around the world. However, it has a number of limitations, including:

- » **Single aircraft design** – early versions considered only one aircraft at a time. This required designs for multiple aircraft to be performed separately and then manually combined. It is noted that the latest version (COMFAA 3) allows multiple aircraft to be considered simultaneously.
- » **Superposition of aircraft wheels** – when combining different aircraft, the wheels are assumed to be located the same distance from the aircraft's centreline. This overestimates pavement damage and results in thicker pavements when combining the effects of multiple aircraft types into one pavement design. It is noted that this is different to accounting for aircraft wander, which COMFAA does by the PCR concept (refer to 3.2.4 Pass-to-coverage ratio).
- » **Standard materials** – COMFAA thicknesses are based on the standard pavement structures adopted by the US Army Corps of Engineers large-scale testing. The standard S77-1 structure comprised 75 mm of asphalt, 150 mm of crushed rock base and variable thicknesses of natural gravel sub-base (Figure 19). Actual aircraft pavement structures are typically different to this. As discussed, (2.6 Material Equivalencies) conversion from the S77-1 pavement thickness to an equivalent thickness of a realistic pavement structure requires the manual application of material equivalencies, such as the examples provided in Table 3.

More advanced mechanistic-empirical design tools were developed to overcome some of these limitations. Researchers also aspire to a truly mechanistic tool for pavement design. However, airport pavement design is expected to remain reliant on empirical relationships between aircraft loads, pavement structures and pavement life, for the foreseeable future.

In Australia, the most common advanced mechanistic-empirical flexible pavement design tools are APSDS and FAARFIELD. Both are layered elastic in nature.

Aircraft Pavement Structural Design System

APSDS is an Australian computer program developed by Leigh Wardle, Bruce Rodway and Ian Rickards (Wardle & Rodway 1998). It is based on the layered elastic program CIRCLY (Wardle 1977). APSDS is now widely recognised as an advanced layered elastic pavement design software. It is both transparent to the user and offers greater flexibility to the pavement designers than is permitted by other design tools.

One important feature is that subgrade strains, the indicators of the rate at which wheel-path depressions develop, are computed for all points across the pavement in order to capture all damage contributions from all the aircraft wheels in all their wandering positions. This contrasts with other methods that compute only single maximum values of subgrade strain and empirically relate these to rutting performance. This feature eliminates the need for the pass-to-coverage concept (refer to 3.2.4 Pass-to-coverage ratio) and allows the designer to specify any degree of aircraft wander.

APSDS has been calibrated against the Corps' S77-1, as computerised and updated in COMFAA (Wardle & Rodway 2010). APSDS enables designers to access the full advantages of the layered elastic method, including treatment of wander to quickly produce designs for complex aircraft mixes and layered structures that are consistent with the S77-1 method.

FAARFIELD

FAARFIELD is the FAA's pavement thickness design computer program for both rigid and flexible aircraft pavements. It can be freely downloaded from the FAA website. FAA now mandates the use of FAARFIELD for the design of pavements for US airports that receive FAA funding. It replaced the FAA's rigid and flexible 'manual' pavement thickness design charts contained in earlier versions of the FAA pavement design advisory circular.

Based on its assessment of US aircraft pavement performance at airports, the FAA has calibrated FAARFIELD to give significantly larger flexible pavement thicknesses than those obtained using S77-1 (COMFAA). The key FAA belief is that the past use of FAA's now-retired 'manual' design charts has, over many years, produced 'reasonable and conservative' designs for flexible aircraft pavements. FAARFIELD has therefore been calibrated to give thicknesses for aircraft mixes that are, on average, 'reasonably similar' to those given by the old 'manual' or chart-based method.

Although the FAA's 'manual' design charts were generally calculated using S77-1, the thicknesses were greater than those that would be obtained using COMFAA. This is in part due to the FAA's requirement for thicker asphalt surfacing and thicker base courses than those used in the earlier full-scale tests from which the S77-1 method was derived.

As noted earlier (refer to 3.4.3 FAA computerised representation of S77-1) the ICAO's ACN-PCN system of strength rating of runways requires, by definition, that S77-1 (via COMFAA) be used to calculate ACNs. Because FAARFIELD gives larger pavement thicknesses than COMFAA, the thicknesses are inconsistent with the ICAO pavement strength rating system. This causes confusion, particularly when an airport asks their designer to design their runway to a particular PCN, rather than detailing the expected aircraft type, weights and frequency.

This is not to say that the FAARFIELD thicknesses are incorrect. Rather, they reflect the FAA's assessment of US airport pavement performance and the degree of conservatism that the FAA has decided is appropriate. In Australia, where pavement construction is funded by individual airport operators and freeze-thaw cycles do not occur in pavements, the additional conservatism is not necessarily appropriate.

3.4.5 Accounting for non-asphalt surfaces

In some flexible airport pavements, non-asphalt surfaces are utilised, including sprayed seals (refer to 2.4.6 Sprayed seals) and concrete block pavers (refer to 2.4.11 Concrete block pavers). These alternate surfaces are accounted for in the structural design by:

- » **Sprayed seals** – the seal is omitted from structural pavement design. The thickness of the seal and its high level of flexibility are assumed to provide no structural contribution.

- » **Concrete block pavers** – the structural design is performed treating the 80 mm thick concrete block and 20 mm thick bedding sand as a single 100 mm thick layer of asphalt. Each block has a much higher modulus (stiffness) than asphalt but the articulated nature of the jointed block surface is assumed to reduce the effective modulus to a level similar to an asphalt surface.

3.4.6 Inputs and sensitivities

Mechanistic-empirical, layered elastic, flexible aircraft pavement thickness design typically requires the following input parameters:

- » subgrade CBR
- » aircraft type, mass and tyre pressure
- » number of aircraft passes during the design life
- » degree of aircraft wander or PCR (depending on the design tool used), and
- » the thickness and modulus of all layers except the one to be designed.

The required thickness of the layer to be designed is calculated using the appropriate performance relationship. For a particular aircraft type and typical pavement materials, flexible aircraft pavement thickness is most sensitive to subgrade CBR and aircraft mass. Flexible pavement thickness is least sensitive to aircraft tyre pressure and the number of passes over the design life (White 2005). Designers should align the effort expended during pavement design with the impact of the various input parameters. That is, more effort should be made to test the subgrade CBR and expected operating mass of the aircraft than on the frequency of aircraft operations.

3.5 Rigid pavement design

Rigid airfield pavement design evolved similarly to that for flexible pavements. A series of accelerated traffic tests for aircraft loads were conducted by the Corps from World War II through to 1974. This consisted of 60 full-scale pavements tested under aircraft loadings up to B747 and C5A aircraft. Further testing has since been undertaken by the FAA and adjustments to COMFAA and FAARFIELD have resulted.

3.5.1 Empirical basis

It is important to realise that the so-called ‘full-scale’ rigid test pavements are ‘large-scale’, not truly ‘full-scale’. The applied loads were full-scale but the test pavements, both rigid and flexible, were of reduced thickness so that tests to failure can be completed within a reasonable time. The significance is that extrapolations are necessary to design thicker, real life pavements. This introduces uncertainty and is of particular concern with rigid pavements because important thermal and moisture stresses depend greatly on concrete thickness. Realising this limitation, the FAA plans to construct 400 mm-thick concrete test pavements and load them over five years by applying 100,000 coverages. To date, test pavement thicknesses have been limited to only 280 mm. Results of from the more realistic concrete thicknesses tests are not expected until 2021.

The FAA considers that the many years of past use of the now-retired thickness design charts has produced ‘reasonable and conservative’ designs for rigid aircraft pavements. Consequently, rigid pavement thicknesses produced by FAARFIELD are based on both the performance of in-service pavements as well as the performance of test pavements of limited thickness.

3.5.2 Thickness design tools

Both COMFAA and FAARFIELD are used in Australia to determine rigid pavement thicknesses. COMFAA is based on stress calculated using Westergaard’s bending slab theory while FAARFIELD uses a combination of layered elastic and finite element analyses to calculate edge stresses. APSDS does not have a rigid pavement capability.

Direct comparisons between COMFAA and FAARFIELD thicknesses are not straightforward because, when using COMFAA the designer must make an allowance for the effect of the sub-base on the concrete thickness. In contrast, the sub-base effect is dictated by FAARFIELD. Further, recent large-scale testing and more advanced analysis of historical results have led to changes in the FAARFIELD performance criterion. Generally, these changes have resulted in somewhat thicker rigid pavements but thicknesses for the six-wheeled gears (e.g. B777 and A380) have substantially increased. This is a current cause for concern and remains under investigation.

3.5.3 Concrete strength

Concrete strength is critically important to airfield pavement design and is specified in terms of flexural tensile strength. This contrasts to compressive strength which is typically used in road pavement and structural building design.

Flexural concrete strength is measured by bending 500 mm-long test beams that have a 150 mm by 150 mm square section. The characteristic concrete flexural strength is the strength used by the pavement designer when calculating the required pavement thickness. In Australia, the characteristic strength is defined statistically as the strength that is exceeded by 95 per cent of the test beams (i.e. 19 out of 20). A moderate characteristic strength of 4.5 MPa is usually specified in Australia. Concrete suppliers can usually design a concrete that achieves this strength and which has good workability and low shrinkage, without using a high cement content.

To take account of production and testing variations, the concrete producer must target strengths that are higher than the required characteristic strength. Typically, a target average strength of 5.2–5.4 MPa is needed to achieve a characteristic of 4.5 MPa.

Flexible beams are heavy and cumbersome to test. Therefore, concrete producers sometime propose to test concrete cylinders in compression, rather than beams in flexure. However, there is no clear relationship between flexural strength and compressive strength. Rather, the relationship varies from mixture to mixture. A 4.5 MPa flexural strength concrete generally achieves a compressive strength between 40 MPa and 50 MPa.

Some designers have also specified higher strengths in order to reduce slab thickness. But this has sometimes led to concrete mixtures that are hard to place, compact and finish, or which have high shrinkage. The result is spalling, cracking and slab warping. In addition, the airfield pavement thickness design methods are based on the observed cracking performance of pavements constructed using concretes of moderate strength. Consequently, it is of concern that higher strength concrete might behave differently, for example they might be more brittle, and the thickness reductions might not be justified.

Although concrete strength is important, poor performance of concrete pavements is more commonly due to poor workmanship and the use of difficult to place concrete mixtures and high shrinkage mixtures. During rigid pavement construction, these factors must be given as much attention as concrete strength.

3.5.4 Sub-base materials

Rigid pavement concrete base is generally constructed on a sub-base. The sub-base is intended to provide a working platform over the subgrade material and to provide uniform support to the concrete slabs, thereby reducing rocking.

In Australia, rigid pavement sub-bases have most commonly consisted of 150–200 mm of FCR (refer to 2.4.3 Crushed rock). The aggregate grading is such that the material it is not susceptible to pumping up through joints.

Lean mix concrete sub-bases, called ‘econcrete’ in the USA, have rarely been used in Australia but are often preferred overseas. Asphalt sub-bases are also used overseas. Sub-base materials called ‘dry lean concrete’ in the United Kingdom and cement treated crushed rock (CTCR) (refer to 2.4.10 Cement treated crushed rock) in the USA is also commonly used overseas but had not been used in Australia until 2012. CTCR and lean mix concrete are intended to provide increased support to the concrete slabs, particularly at the joints. Despite some FAA testing indicating a longer life for rigid pavements with bound sub-bases, Australian experience has generally seen good performance from rigid pavements containing FCR sub-base across a wide range of subgrade types and environmental conditions.

CTCR differs from lean mix concrete in that it is compacted by rolling, not by vibration. The achievement of a sufficiently flat surface at the correct level during rolling can be difficult. Correction by grinding high spots and filling the roughened surface with mortar is commonly needed. Some designers have also required CTCR to be proof rolled (refer to 4.9 Proof Rolling) using a large pneumatic-tyred roller. As discussed later (4.9 Proof rolling) proof rolling is not appropriate for bound materials such as CTCR and further increases the risk of not achieving a sufficiently flat surface.

Both lean mix concrete and CTCR are intended to have a relatively low compressive strength, typically 5 MPa after seven days, so that they will exhibit low shrinkage cracking and need not be jointed.

3.5.5 Edge thickening and joints

Rigid aircraft pavements consist of unreinforced, jointed concrete slabs, usually with joint spacing of 5–6 m. Reinforced concrete (with larger joint spacing), continuously reinforced concrete (free of joints) and pre-stressed concrete are not typically used in Australian airport pavements.

The concrete pavement thickness calculated by COMFAA or FAARFIELD applies to internal slabs that are supported by adjacent slabs by partial transfer of load across the joints.

A number of methods are available to transfer the load. Where contiguously placed concrete is sawn to create a 'contraction' joint, the large 40 mm-sized aggregate located below the depth of the saw cut (typically 25 per cent of the slab thickness) sufficiently transfers the load across the joint. Where adjacent slabs are constructed separately, steel dowels are used to provide vertical load transfer without tying the slabs laterally together. This is achieved by casting one end of the dowel rigidly within one concrete slab and de-bonding the dowel within the other slab. The de-bonded portion of the dowel allows the slab to slide along it as the slabs contracts due to shrinkage, and expands and contracts due to variations in temperature and moisture.

Unsupported edges of rigid pavements must be thickened by 25 per cent if they are to be subjected to frequent aircraft traffic. Thickening is not needed in cases such as an apron edge, or immediately adjacent to a building where aircraft wheels will not traffic the edge. Similarly, the outer longitudinal edges of concrete runways and taxiways are not thickened because they are very rarely trafficked. However, rigid pavement edges are thickened where a rigid pavement meets a flexible pavement or where future extension of the rigid pavement is likely.

Rigid structures such as grated drains, service pits, high light mast footings and refueling outlets are protected from pavement expansion by compressible isolation joints. Since there is no load transfer across these joints the pavement edges are thickened (by the same 25 per cent).

3.5.6 Inputs and sensitivities

Rigid aircraft pavement thickness design requires the following input parameters:

- » subgrade K-value (usually converted from CBR)
- » aircraft type, mass and tyre pressure
- » number of aircraft passes, coverages or departures over the design life
- » the sub-base material modulus and thickness, and
- » flexural (bending) tensile strength of the concrete.

The internal slab concrete thickness is calculated. For a particular aircraft type and typical pavement materials, rigid aircraft pavement thickness is most sensitive to concrete strength and aircraft mass. Rigid pavement thickness is least sensitive to the number of passes over the design life. Designers should align the effort expended during pavement design with the impact of the various input parameters. That is, more effort should be made to evaluate the expected concrete flexural strength and aircraft operating masses, than on the frequency of aircraft operations.

3.6 Expedient pavement design

Expedient pavement design relies on the same processes and principles as 'normal' pavement design. However, materials suited to expedient construction (2.5.3 Expedient construction materials) are selected and appropriate material equivalencies are assigned (2.6 Material Equivalencies). Expedient pavement design must aim to maximise productivity, generally achieved by selecting materials:

- » with high modulus for maximum structural contribution
- » that are rapidly constructible
- » without the need to cool or cure for long periods of time, and
- » that are immediately trafficable.

When designing expedient pavements solutions, some designers are tempted to increase the thickness of the layer(s) above that required by pavement thickness design. This aims to add some conservatism to account for the expedient nature of the construction and the impact this may have on construction quality. For example, a 250 mm-layer of warm asphalt may be increased to 300 mm of 450 mm of rapid setting concrete may be increased to 500 mm. However, each additional layer, required by the additional thickness, further adversely impacts construction quality. Unnecessarily adding thickness is likely to have a negative impact on overall pavement construction quality (White 2017) despite the opposite intention.

3.7 ICAO Pavement Strength Rating System

The ICAO developed an international system for the rating of aircraft pavement strength and to ensure an airport operator is aware when more damaging aircraft are utilising the pavement systems (ICAO 2013). The ICAO strength rating system is well known as ACN-PCN. ACN-PCN is generally applied only to runways. However, some airport operators extend its use to taxiways and aprons.

3.7.1 Aircraft classification and pavement classification

An aircraft classification number (ACN) is a number that indicates the amount of damage to a particular aircraft pavement that is caused by an aircraft, relative to that caused by other aircraft. In general, aircraft that have the same ACN are considered to cause the same pavement damage. A pavement classification number (PCN) is a number that indicates the strength of a particular aircraft pavement.

An airport owner selects and publishes a PCN. This is an invitation to all aircraft that have ACNs less-than or equal-to the PCN to use the runway as often as they wish. Aircraft with ACNs that are higher than the PCN must seek the permission of the airport owner to use the pavement. The owner might grant a 'concession' to use the runway, but might limit the aircraft's weight and/or the frequency of usage. In this way the runway owner controls the usage of the runway and thereby controls the rate at which the pavement structurally deteriorates. Most airport operators will grant pavement concessions based on a balance of the ACN-PCN ratio, the condition of the pavement, previous overload history and the revenue to be generated by permitting the aircraft to operate.

The ACN is defined as twice the wheel load (in tonnes) which on a single wheel, inflated to 1.25 MPa tyre pressure, causes pavement damage equal to that caused by the actual multi-wheel gear at the actual gear load and the actual tyre pressure of the aircraft. In this case, the measure of pavement 'damage' is the maximum vertical deflection calculated at the top of the subgrade.

3.7.2 Subgrade categories

The interaction between multiple wheels on a specific landing gear changes with pavement depth. This means that two aircraft with different landing gear configurations, but the same ACN, will cause relatively different damage depending on the pavement thickness. Pavement thickness is significantly affected by subgrade strength, usually expressed as the CBR. The application of ACN-PCN therefore changes with subgrade CBR. Rather than a continually varying ACN, across all possible subgrade CBR values, subgrades are categories and a representative CBR adopted (Table 7).

3.7.3 Tyre pressure limits

The ACN-PCN also includes a limit based on tyre pressure. The tyre pressure limits are categorical in nature and are somewhat arbitrary. Aircraft manufacturers proposed an increase in the categorical tyre pressure limits in 2008 (Rodway 2009). There were approved in 2013 following full-scale testing efforts (Roginski 2013). However, the revised tyre pressure limits (Table 8) merely reflect aircraft that are already in common use, or are scheduled to be introduced imminently.

Table 7: ACN-PCN subgrade categories

Category	Representative CBR	CBR Range
A	15	Greater than 13
B	10	8–13
C	6	4–8
D	3	Less than 4

Table 8: Tyre pressure category limits

Category	Original tyre pressure limits	Revised tyre pressure limits
W	Unlimited	Unlimited
X	1.50 MPa	1.75 MPa
Y	1.10 MPa	1.25 MPa
Z	0.50 MPa	0.50 MPa

Aircraft with tyre pressures less than the assigned category limit are permitted to operate without specific approval. Aircraft with higher tyre pressures require a pavement concession. Some countries, such as Australia, have adopted airport-specific tyre pressure limits rather than tyre pressures categories and category limits.

3.7.4 The PCN expression

The full PCN expression is best explained by example. As an example, the PCN for Brisbane Airport is: **PCN 108/F/D/1750/T**.

- Where:
- 108 is the numerical element against which the ACN is compared.
 - F is to indicate a Flexible pavement, rather than R for Rigid.
 - D is the category of subgrade from Table 7.
 - 1,750 is the tyre pressure limit, which would fall into an X (from Table 8) if Australia adopted ICAO's tyre pressure categories.
 - T is to indicate a Technical assessment rather than U for a Usage based assessment.

3.7.5 Impact of new aircraft

Aircraft have become larger, with greater mass per landing gear wheel, which in turn requires higher tyre inflation pressures. This impacts both pavement structures and surfaces. Regional airports are not expected to ever have to consider the impact of the B777 or A350 aircraft. However, the principles associated with the introduction of new aircraft at major airports equally apply to regional airports preparing for the introduction of larger and more demanding aircraft in the future, as well as for the granting of Pavement Concessions.

Larger aircraft, such as the A380, also trigger runway and taxiway widening. However, this is more an airport planning issues and is not considered further.

Impact on structures

The ACN-PCN system was developed to protect pavement structures from more damaging aircraft. As already discussed (3.2.1 Pavement damage and life) the definition of 'damage' is wheel-path depressions (usually due to subgrade rutting) in flexible pavements and fatigue cracking in rigid pavements. It follows that the ACN of an aircraft is related to the relative damage that the aircraft does to the pavement. This allows an analytical approach to evaluating the impact of new aircraft on pavement structures.

It is important to understand that ACN is not linearly related to pavement damage. That is to say that an aircraft with an ACN 50 per cent higher than another aircraft will not do 50 per cent more damage. In fact, the damage caused by the aircraft with 50 per cent higher ACN will be equivalent to 10–30 coverages by the reference aircraft. The actual damage caused by the more damaging aircraft is dependent on the pavement thickness and the wheel configuration of the aircraft (Figure 25).

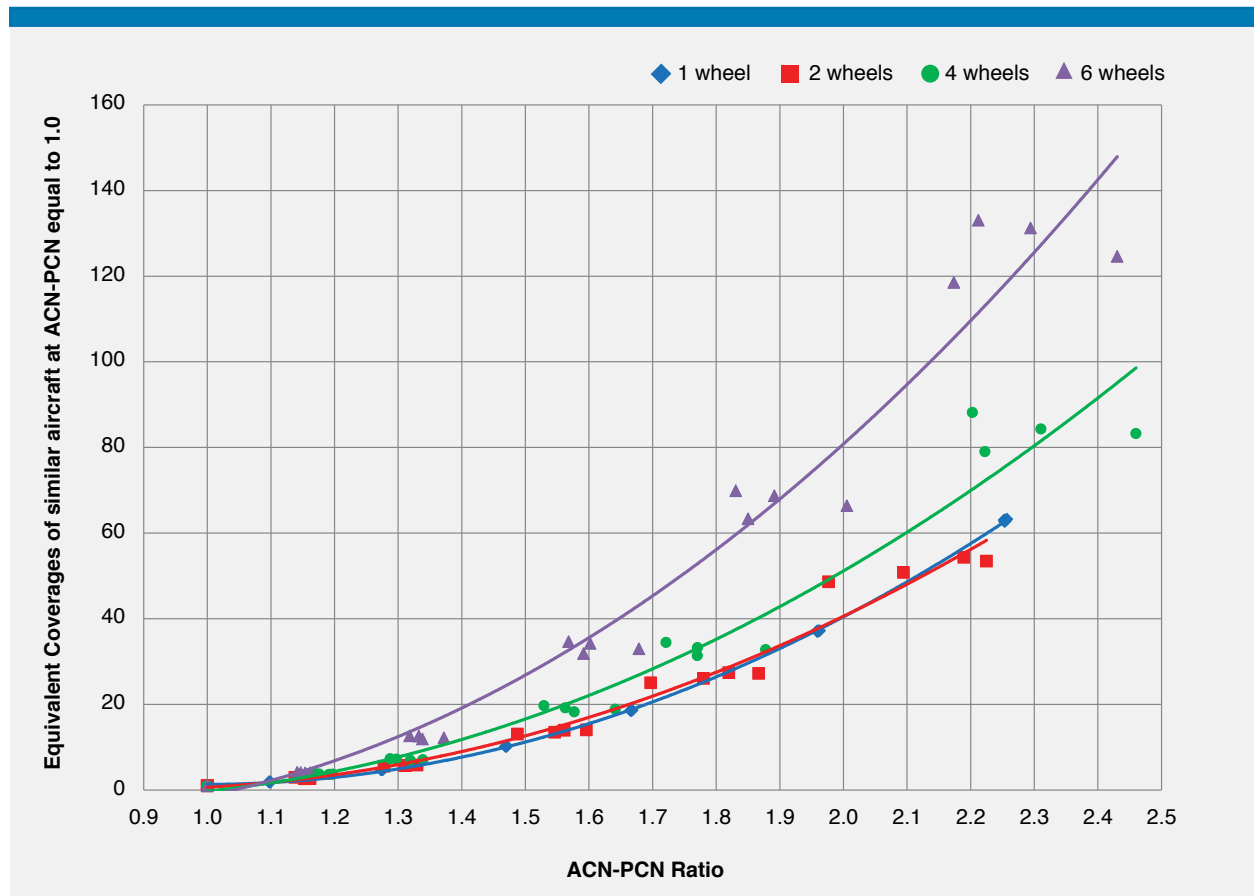
Because ‘damage’ is the gradual consumption of pavement life, the ‘equivalent’ damage can be expressed in the equivalent number of coverages of the reference aircraft. This can be converted to a reduction in the pavement’s expected structural life.

Impact on surfaces

The tyre pressure limit contained in the ACN-PCN system (refer to Table 8) was intended to protect marginal surfaces from aircraft with higher tyre pressures. The tyre pressure limits do not provide an analytical approach to determine the relative impact of new aircraft (White 2016). In fact, the shear stresses induced by an aircraft are a product not only of the tyre pressure, but also of the individual wheel load. Because the ACN-PCN system was developed to protect pavement structures from ‘damage’, surface distress was not considered. At the time the ACN-PCN system was developed, surface distress was less concerning to airport operators that is now the case.

There is growing concern that new aircraft with higher individual wheel loads and tyre pressures are damaging the asphalt surfaces of flexible pavements. Rigid pavements do not suffer the same distresses due to the rigid nature of the concrete surface.

Figure 25: Example of relative damage for aircraft of different ACN



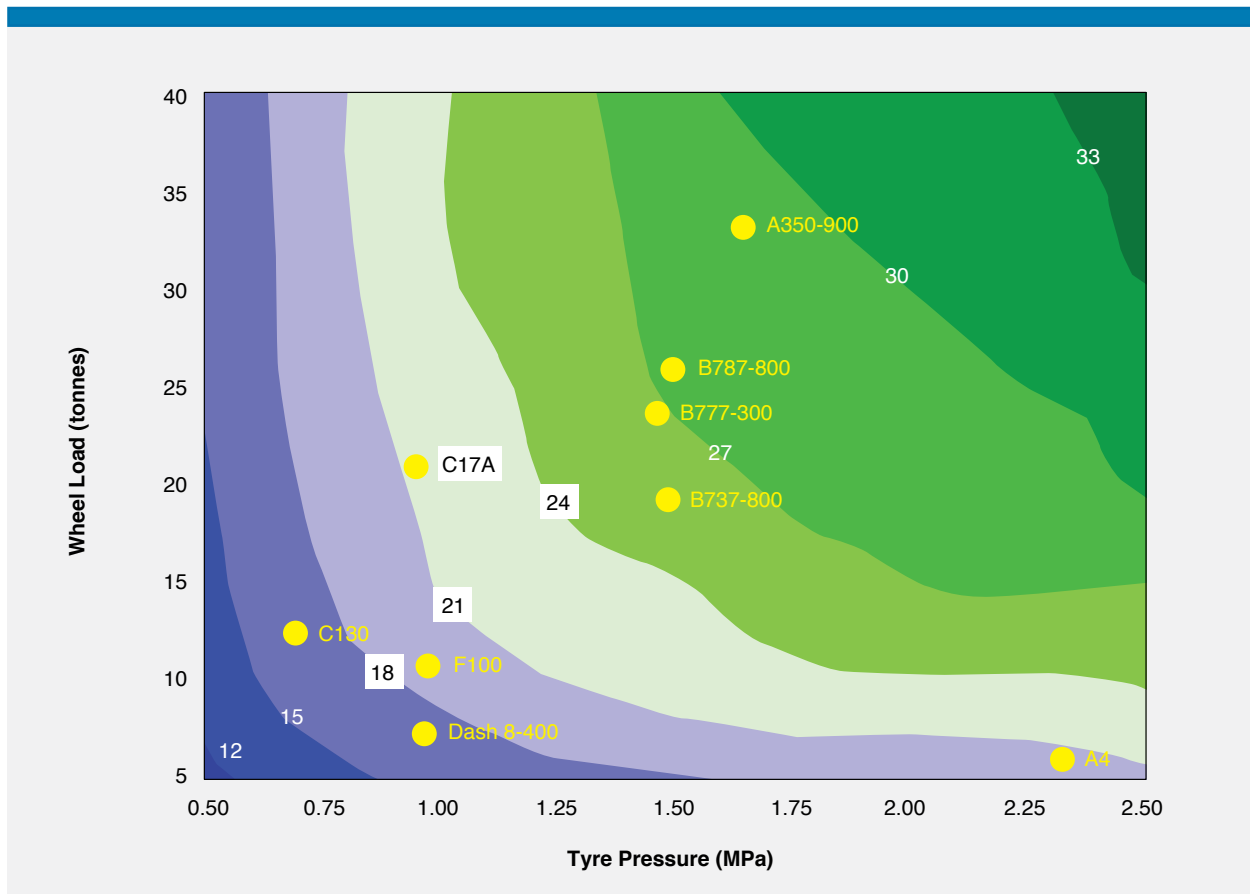
A critical condition is experienced in asphalt surfaced pavements when a landing aircraft brakes heavily to make an early taxiway to vacate the runway area (White 2016b). Aircraft turning can also result in surface distress (Mooren et al. 2014). A modification to the ACN-PCN system to better reflect the increase stress applied to pavements caused by new aircraft (White 2016a). As an example of the impact of new aircraft, Figure 26 shows wheel loads and tyre pressure of various aircraft. The various colour bands indicate the relative shear stress in the asphalt surface layer caused by the aircraft.

3.8 Existing pavement evaluation

Most airport pavement projects are not related to new pavement design and construction. Rather, they involve the evaluation and upgrade of existing pavements. In this case, the term ‘evaluation’ refers to evaluation of the pavement’s structural capacity. This should not be confused with evaluation of surface condition and maintenance requirements, which is addressed later (5.4 Periodic evaluation).

Structural pavement evaluation is closely related to pavement design and relies on ‘reverse design’ principles. For new pavement design, the aircraft traffic and subgrade conditions are estimated and then a suitable pavement structure is determined. In contrast, pavement evaluation takes an existing pavement and subgrade condition, and determines its structural suitability under the existing and/or projected future aircraft traffic. Where the aircraft types, weights and frequencies have been determined, the existing pavement’s capacity is best expressed in terms of ‘remaining life’.

Figure 26: Example aircraft wheel loads and tyre pressures



When the existing pavement is determined to be inadequate, upgrade options are considered (refer to 5.7 Rehabilitation and upgrade options). For example, where a structural asphalt overlay is selected to increase the strength of an existing pavement, the additional asphalt thickness required in addition to the existing pavement structure (including the subgrade) is determined for the projected aircraft traffic.

It is important to acknowledge the practical limitations associated with existing pavement upgrade works. As discussed later (5.2 Operational constraints) upgrade works are often performed during short night shifts and required to be returned to a serviceable condition each morning. The design must be consistent with these operational constraints. For example, an existing runway cannot be provided with a granular (FCR) overlay at night and returned to service in the morning. Designs and materials that are cost effective for new pavement construction are often impractical for overnight upgrade works.

One advantage of existing pavement evaluation is the ability to test the existing pavement and in-service subgrade conditions and to consider the existing pavement's observed performance under the historical aircraft traffic. Existing pavement structural assessment generally includes three sources of existing pavement information:

- » **Documentation** – previous construction design documents and as-constructed documentation often provide an indication of the existing pavement structure and materials. The airport's PCN also provides at least some indication of the subgrade CBR, based on the published subgrade category (refer to 3.7.2 Subgrade categories).
- » **Non-destructive testing** – A range of non-destructive test methods are available and the falling weight deflectometer (FWD) is the most common. The FWD applies a dynamic (i.e. falling) load to the pavement surface and measures pavement surface deflection at various distances from the point of load impact, typically up to 1,500 mm away. The deflection results provide an indication of the stiffness (i.e. strength) of the pavement, which can be empirically related to expected pavement performance.

- » **Intrusive testing** – usually by coring or excavating the existing pavement structure to determine the various layers, materials and thicknesses. Excavated materials are often retained for laboratory evaluation, typically focused on the plasticity of the FCR and uncrushed gravels, as well as subgrade moisture content and CBR.

Some airports have commissioned existing pavement evaluations for 'current pavement PCN' relying primarily on analysis of deflection results from FWD surveys. This approach relies on the analysis of the FWD results, in particular the conversion of deflection results to pavement layer modulus values. There are concerns relating to the reliability and repeatability of these conversions. Further, the FWD analysis relies on assigned pavement layer thicknesses and aircraft frequency.

The determination of PCN based primarily on FWD results is concerningly unreliable. That is not to say the FWD is not a valuable tool. In fact, the FWD provides a cost-effective and rapid evaluation of the relative stiffness of the whole of the pavement that is not practical with intrusive testing, which is generally limited to only a few 'representative' locations. However, FWD must be utilised in combination with intrusive testing and the experience of an experienced airport pavement designer.

A reliable existing pavement structural evaluation includes:

- » assessment of existing pavement structures and materials
- » analysis of FWD results to determine 'consistent' areas of pavement response
- » intrusive testing to confirm representative pavement layer materials and thickness including laboratory testing of recovered materials
- » visual assessment of the pavement's structural performance under the historical aircraft traffic, and
- » analytical reverse engineering of the pavement structure, using design methods such as those identified above.

3.9 Surface texture, friction and skid resistance

As previously discussed (3.3.2 Aircraft skid resistance), aircraft skid resistance is an important function requirements of airport pavements and a critical factor for safe aircraft operations. The interactions between aircraft tyres and pavement surfaces are also complex, as are the associated ICAO recommendations (ICAO 2013) and CASA requirements (CASA 2016).

3.9.1 ICAO recommendations

ICAO's Annex 14 clause 3.1.23 (ICAO 2013) recommends that *measurements of the friction characteristics of a new or resurfaced runway should be made with a continuous friction measuring device using self-wetting features*. Annex 14 also provides guidance to ICAO member countries, such as Australia, to decide what measured friction values to adopt:

- » as their design objective for a new runway surface
- » to trigger planning for improvement of runway friction, and
- » to initiate immediate remedial measures and prompt warnings to be issued regarding possible runway slipperiness.

ICAO's Annex 14 guidance table of friction values closely follows the FAA's table from its advisory circular entitled *Measurement, Construction, and Maintenance of Skid-resistant Airport Pavement Surfaces* (FAA 1997). The FAA table lists friction values for several different continuous friction measurement equipment (CFME) devices that might be used. Each machine has been evaluated by the USA's National Aeronautics and Space Administration (NASA) at its runway friction research facility. A USA standards committee recommended to the FAA in 2011 a revision to include additional CFME devices as, well as separate grooved and ungrooved friction targets for new surface construction.

With regard to texture depths, ICAO's Annex 14 also recommends that a 1 mm surface texture (by sand patch test) be maintained on runways. However, clause 3.22 of Section 4 of the FAA circular states, with to regard to measured friction values, that "when friction values meet the criteria, no texture depth measurements are necessary".

3.9.2 CASA regulations

Although ICAO deals with friction largely by providing recommendations and guidance material, some countries have made ICAO's recommendations mandatory. Others use the ICAO guidance material and the friction values obtained using CFME devices only to assist them in judging when slippery rubber build-up should be removed from their runways. This latter approach is in accord with the following FAA advice that accompanies their table of friction values (FAA 1997).

Mu numbers (friction values) measured by CFME can be used as guidelines for evaluating the surface friction deterioration of runway pavements and for identifying appropriate corrective actions required for safe aircraft operations.

The general reticence of some aviation authorities and airports to mandate and publish measured friction values recognises the practical difficulty in reliably measuring absolute values of friction. Also, there remains considerable uncertainty as to the relationship between the measured friction values and the stopping distance of aircraft on wet runways.

Despite these concerns, Australia's CASA has mandated (note that ICAO only recommends) a minimum texture depth of 1 mm, but drops the requirement if an adequate friction number is obtained by CFME (CASA 2016). CASA also acknowledges the equivalent (or greater) benefit of grooving the full width and length of a runway, as an alternate to achieving 1 mm surface texture. It is important to note that ungrooved dense-graded 10 mm or 14 mm asphalt will not achieve a 1 mm texture depth. This effectively requires all Australian airports, regardless of their size, to either:

- » achieve a 1 mm surface texture in the runway surface, by using a highly textured sprayed seal or an open graded friction course, or
- » groove the length and width of the runway, or
- » achieve the ICAO recommended design objective levels of surface friction when tested by ICAO recommended CFME.

All airports are also required to demonstrate ongoing achievement of adequate surface texture and/or friction as part of the technical inspection process (CASA 2016). This requires either periodic CFME surveys, or periodic verification of the condition of the grooves by visual inspection, as well as surface texture verification, either by visual inspection or sand patch testing.

International airports with Code 4 jet operations are required to periodically measurement runway surface friction by CFME to determine the requirement for rubber contamination removal. The frequency of CFME surveys is to be determined by the airport operator based on aircraft operations and the historical rate of rubber contamination accumulation.

3.9.2 Practical implications

The majority of sealed runway pavement in Australia is constructed with either an airport-quality sprayed seal or dense-graded asphalt. The asphalt may be grooved or ungrooved. At major airports, the runway ends, each typically 80 m long, are often concrete. The similarity across most Australian airports leads to a small number of practical implications and solutions regarding aircraft skid resistance.

Sprayed seal surfaces

A well-designed and constructed airport sprayed seal (refer to 2.4.6 Sprayed seals) provides a surface texture around 1.5 mm. This exceeds the CASA requirements for 1 mm surface texture. However, as the seal wears or flushes with bitumen (refer to 5.5.5 Sprayed seal maintenance) the surface texture is reduced. Further, some use has been made of smaller (5 mm and 7 mm) aggregate in the top layer of an airport seal. The surface texture achieved by smaller aggregate sizes is less than by larger aggregates sizes and may not achieve the 1 mm surface texture. Even when the 1 mm is achieved with a smaller sized sprayed seal aggregate, the amount of wear or flushing required to drop to surface texture below 1 mm is significantly reduced.

Once constructed, the opportunity to increase the surface texture or skid resistance of a sprayed seal is limited. Sprayed seals cannot be grooved. A flushed sprayed seal can be watercut to remove the free bitumen (refer to 5.5.5 Sprayed seal maintenance) however this is expensive.

Due to their typically remote location and lower operating budget, runways with sprayed seal surface are rarely tested for surface friction using CFME. Rather, visual assessment or sand patch testing of the surface is more common.

Asphalt surfaces

A new, dense-graded airport asphalt will not achieve CASA's 1 mm surface texture. A sand patch surface texture of 0.4 to 0.6 mm is typical for a new surface. Erosion of the surface asphalt's mastic over time will increase the surface texture and pavement preservation treatments (refer to 5.6.2 Asphalt preservation) will reduce surface texture. Further, testing of a new (ungrooved) asphalt surface by CFME will typically return a result less than the ICAO recommended design objective level. However, the results are typically well above the maintenance planning level.

Limited tests results indicate that grooving the surface typically increases the CFME results by 10–15 per cent at 65 km/hr test speed and by 20–30 per cent at 95 km/hr test speed. This is often adequate to achieve the ICAO-recommended design objective level of friction. However, as discussed below many regional airports continue not to groove their asphalt surface surfaces. Where the runway is grooved, MOS-139 requires the full length and width to be grooved. The FAA advisory circular (FAA 1997) provides guidance regarding the amount of groove loss, by erosion, closure or surface patching, before the grooves are deemed to be of reduced effectiveness.

Concrete surfaces

No Australian airport currently has a concrete runway. However, concrete runways are commonplace in parts of Europe, and the Middle East. Also, a number of regional and major Australian airports have concrete runway ends, typically 60–80 m in length.

New airfield concrete pavement will not typically achieve 1 mm surface texture, with 0.4–0.7 mm more likely. Most texture can be introduced by more aggressive finishing of the surface during construction. However, this is likely to be eroded more rapidly under traffic. Therefore, to meet CASA's requirements, the concrete runway ends must usually be grooved. Some major Australian airports do in fact groove the concrete ends of the runway. Other airports leave the concrete ends ungrooved. The concrete slab joints complicate grooving concrete pavements and the short length of the concrete runway ends, compared with the overall runway length, suggests the risk of not grooving the ends is reduced. In the USA, concrete runways are usually grooved over their full length and width.

Alternate runway surfaces

As discussed further below, grooving a runway is expensive and introduces a number of risks, including groove closure and groove erosion (White & Rodway 2014). It is not surprising that a number of overseas airport authorities have developed alternate asphalt surfaces. These alternative mixtures aim to provide adequate surface texture and skid resistance, without necessitating grooving of the surface (White 2017). The most commonly reported alternate runway asphalt types are summarised in Table 9.

Australia has made only limited use of alternate asphalt mixtures for runway surfaces. OGFC was first trialled in Australia at Sydney Airport in 1973 and a 50 m length was then placed on the main runway in 1975. It was placed during light rain, rapidly failed and was removed. However, subsequent experience at other Australian airports showed that the material lasted well. For example, material placed on Townsville’s main runway in 1987 was replaced after 18 years.

Cairns airport has SMA on a number of apron areas and Sydney airport performed a small production and construction trial in 1999. Variable success during apron and taxiway trials, as well as perceived ravelling risk, has prevented any significant use of SMA on Australian airport runways.

These alternate asphalt surfaces appear attractive. However, each has disadvantages that must also be considered:

- » **OGFC** – lower (typically 6–8 years) life expectancy due to the open structure of the course aggregate skeleton and is prone to clogging by detritus.

- » **SMA** – Australian experience has indicated variable performance and SMA is acknowledged to be less tolerant of production and handling variability.
- » **BBA** – limited use outside of France and examples in the UK have not yet achieved their full expected service life.

Of the alternate runway asphalt surface options, SMA appears to be the most viable. Based on the solutions developed by Chinese airports, SMA is expected to provide a durable, low FOD and shear-resistant runway surface without the need to groove. This is a particularly attractive solution for regional airports that have not traditionally grooved their runway surfaces.

Grooving

Grooving was first trialled in Australia at Sydney Airport in 1975. In addition to a lower cost than OGFC, the preference for grooving was based on the greater perceived durability of the surface when compared to OGFC. That is, the surface was considered to be less likely to produce FOD and was not susceptible to debonding from the underlying asphalt. Various groove configurations were trialed and adopted at different Australian airports over the years.

There is currently no authoritative standard for grooving runways in Australia. MOS 139 states that grooving is an acceptable surface friction treatment but does not state the detailed requirements of grooves. However, the practices developed over time provide for grooves to be:

- » aligned transversely to the runway alignment
- » square cut 6 mm deep and 6 mm wide
- » spaced 38 mm from centre to centre, and
- » ceased 100–300 mm from AGL fitting, cable slots and similar services.

Table 9: Alternate airport asphalt types

Asphalt type	Basis	Usage	Reference(s)
Open graded friction course (OGFC)	Porous mixture that allows water to drain through the thin surface and exit at a free edge	UK (various) Townsville (1980s) Richmond (1980s)	EAPA (2003) White (2017)
Stone mastic asphalt (SMA)	Open grading filled with additional mastic to create a coarse surface texture of 1.1 to 1.3 mm	Europe (various) Mexico (various) China (many)	EAPA (2003) NCAT (2009) Campbell (1999) Xin (2015)
Beton Bitumeux Aeronautique (BBA)	Coarse gap graded aggregate to increase surface texture to 1.2-1.3 mm	France (various) Manchester (UK)	Hakim et al. (2014) Widyatmoko et al. (2013)

The sawing head of grooving machines is often located between the vehicle's front and rear wheels. The machines are also heavy and require a strong pavement to support their weight. Consequently, where shoulder strength is marginal, the machines cannot transverse far enough to groove right to the runway edge. Therefore, the grooves are often terminated 0.5–1 m from the runway edge line.

Grooving asphalt surfaces also introduced the risk of groove closure. Groove closure in runway surfaces is one of the most challenging modes of airport pavement surface distress. Grooves often close when slow moving aircraft deform the grooves, usually in hot weather. The risk of groove closure is greatest:

- » in hot environments
- » during summer, especially after consecutive days of unrelieved very hot weather that cause high pavement temperatures
- » on asphalt surfaces that have been constructed relatively recently
- » in locations where aircraft travel slowly
- » in locations subjected to aircraft with high wheel loads and high tyre pressures
- » in areas where aircraft track parallel to the grooves, and
- » in asphalts produces with binders that soften excessively at elevated pavement temperatures.

A number of Australian airports have experienced groove closure. The severity and extent have ranged from 'minor and isolated' to 'severe and widespread'. In some cases, groove closure has required the removal and replacement of large impacted areas. Closed grooves cannot be opened and cannot be re-sawn. As a result, some airports have decided not to groove their runways, or to cease grooving near the runway end, where the risk of groove closure is greatest. The basis of these decisions are usually a combination of:

- » heavy rain events (particularly in tropical locations) that prevent aircraft landings, meaning that aircraft only land in the dry, when grooves are of limited value
- » infrequent rain (in arid locations) meaning the risk of groove closure is high compared to the risk of aircraft skidding incident
- » ungrooved areas at the runway end (typically 80 m long) not being significant in comparison to the length of the runway.

Grooving runway surfaces also complicates pavement maintenance activities such as pavement preservation (refer to 5.6.2.3 Treatment products). Pavement preservation treatments require special consideration and rubber contamination from landing aircraft is greater for grooved surfaces. Rubber removal is also made more complicated (White and Rodway 2014). Further, when resurfacing a runway by asphalt overlay, the grooves must be removed prior to construction of the new surface (refer to 4.5 Asphalt).

As discussed later, trapezoidal grooves are gaining favour in the USA and some Australian airports have expressed interest in this relatively new technology. Trapezoidal grooves have the same 6 mm base width but the sides are sawn at 45 degrees, resulting in a groove width of 12 mm at the surface. The grooves are spaced at 57 mm, centre to centre, to result in the same average 'groove volume per surface area' (Zuzelo 2014). Preliminary research by the FAA indicates that trapezoidal grooves provide (Patterson 2012):

- » improved water evacuation from between the aircraft tyre and surface
- » reduced groove breakage and closure, and
- » reduced rubber contamination.

Surface friction survey

It is important to understand that ICAO and FAA intend for survey friction surveys by CFME to be tools for pavement management. This is reflected in the FAA advisory circular (FAA 1997) which states that CFME results "can be used as guidelines for evaluating the surface friction deterioration of runway pavements and for identifying appropriate corrective actions required for safe aircraft operations". The mandatory achievement of the ICAO recommended values published in MOS-139 (CASA 2016) is not consistent with this intent.

Further complicating the Australian situation is the absence of guidance or protocols for the performance of a runway friction survey and the subsequent interpretation of results. By definition, CFME devices measure runway friction on a continuous basis and record it as often as every 10 m. One value below the MOS-139 limits should not result in the runway being considered 'slippery'. Fortunately, the FAA advisory circular (FAA 1997) includes runway friction survey protocols.

The New Zealand Civil Aviation Authority publishes similar guidelines (CAA 2015). These documents generally require a runway friction survey to include:

- » applying a target 1 mm thick film of water to the surface immediately in front of the test wheel
- » test runs performed at both 65 km/hr and 95 km/hr
- » test runs at 3 m and 6 m offsets on both side of the runway centreline
- » test runs extending the full length of both runway directions
- » adjustment of results for pavement surface temperature.

This protocol results in eight runs of the full runway length, which is usually achieved in one work period (e.g. one night shift) depending on the length of the runway and operational constraints. Rolling 100 m average results are compared to the ICAO-recommended (CASA-mandated) limits for new surface design objective, maintenance planning and considering the runway slippery when wet (for example Figure 27).

Expected changes

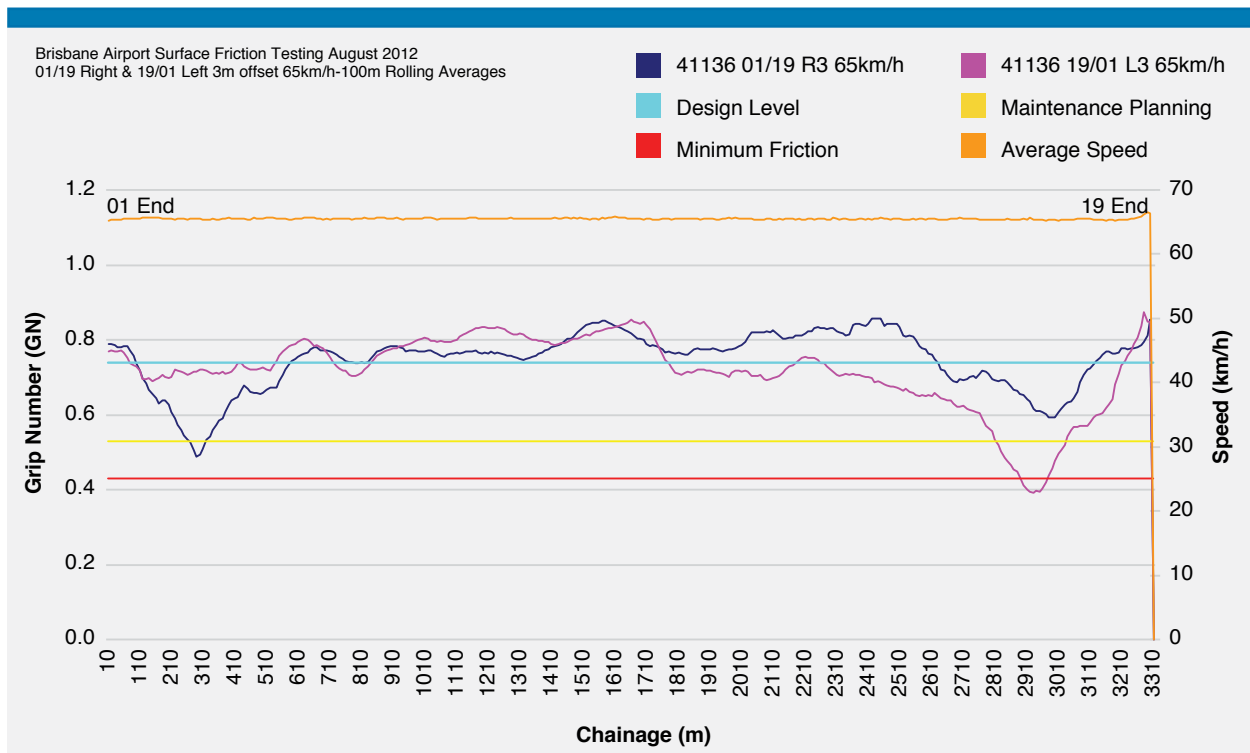
The 2017 revision of MOS 139 is expected to include significant changes relating to runway friction, surface texture and aircraft skid resistance requirements. The intent is not expected to change significantly, however, the processes are expected to be more clearly defined and consistent with current practice.

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Figure 27: Example CFME (Griptester) 100 m rolling average results



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PAVEMENT CONSTRUCTION

CHAPTER 4



4.0 PAVEMENT CONSTRUCTION

4.1 General

In general, airport pavements are constructed using the same plant, equipment and techniques as roads, highways and other pavements. Therefore, only general construction requirements for the most commonly encountered materials are described. However, where airport-specific requirements are typically different to roads and highways, more detail is provided.

Proof rolling is one issue that is particular to airport pavements. Proof rolling is therefore addressed separately (4.9 Proof rolling).

4.2 Subgrade

As previously described (2.3 Subgrades) airport pavement subgrades can comprise a range of materials from sands to gravels to clays. The construction techniques required vary with the material type, as well as whether the pavement construction is in 'cut or fill'. When in cut, the level of the finished subgrade surface is below the natural ground's surface level. Excess material is excavated and removed. When in fill, material is required to be imported to raise the level of the finished subgrade surface such that when the pavement is constructed, the finished surface level meets the geometric requirements of the design.

It is typical for a design to 'balance' the cut and fill requirements. A balanced cut and fill means that the volume of excavated material from construction in cut is approximately equal to the volume of material required in areas of fill. In practice, some residual cut material is preferred. This reflects the likelihood of some material being deemed 'unsuitable' and excess cut material can readily be utilised for unclassified fill in flanks or other non-critical areas. It is also more economical to dispose of excess cut material than to import additional fill material.

The basic processes involved in subgrade construction are:

- » remove vegetation and top-soil
- » shape the subgrade level by cutting and filling, above the design level
- » moisten or treat the subgrade and compact
- » remove and replace any unsuitable material
- » allow the subgrade to dry-back and trim to the final level

- » proof roll (refer to 4.9 Proof rolling), and
- » protect from traffic and rain until pavement construction.

Material-specific construction processes are specified by designers and typically include:

- » **Sand subgrades** – bunding and flooding during compaction (Figure 28). Sand can only be effectively compacted when completely saturated and when completely dry. Completely drying insitu sand subgrades and fills is not practical. It follows that sand compaction is performed in a saturated condition.
- » **Gravel subgrades** – no special treatment required.
- » **Clay subgrades** – insitu lime stabilisation (Figure 29). Lime flocculates the clay particles, reducing the potential for shrink/swell and improving the material's wet strength.

Figure 28: Flooded sand compaction



Figure 29: Insitu lime stabilisation



4.3 Fine crushed rock

FCR is typically constructed in layers. For example, a design requiring a 600 mm thickness of FCR will typically be constructed in three or four layers of approximately equal thickness. This allows each layer to be compacted adequately. Even large compaction rollers are limited to around 200 mm effective compaction depth.

Traditionally, FCR was tipped directly from a delivery truck, spread and levelled with a mechanical grading machine. However, this typically resulted in segregation of the surface which required subsequent treatment prior to the next layer being constructed. Since the 1980s, some specifications have mandated the use of mechanical pavers, similar to those used for asphalt paving (Figure 30), for FCR construction. Paved FCR has a more uniform surface finish and its level and thickness can be better controlled.

Like other granular (or unbound) materials, FCR has an optimum moisture content (OMC) for a particular compactive effort. At OMC, a particular compaction effort will result in the highest density and lowest air voids. At higher moisture contents, the moisture will prevent the aggregate particles from being pushed closer together, while at lower moisture content, the friction between the particles will prevent the aggregate particles from being pushed closer together. At OMC, the moisture provides an optimum level of lubrication of the particles during compaction.

Moisture is usually added to FCR to achieve the OMC. Because airport pavement FCR is designed to be porous, it does not hold moisture for long periods of time. Therefore, conditioning to OMC must be performed immediately prior to paving and compaction. This is typically undertaken with an on-site pug mill (Figure 31). The pug mill also re-mixes the FCR to remedy any segregation of the particles during transportation.

Compaction is performed by a combination of pneumatic tyred and steel drum rollers. The steel drums vibrate and efficiently increase the density of the FCR layer. The pneumatic-tyred rollers assist by closing and tightening-up the surface of the FCR layer.

Once paved and compacted, FCR is typically proof rolled. As discussed later, (4.9 Proof rolling) proof rolling the upper FCR layers in a flexible pavement with thin asphalt surfacing requires a rolling with high tyre pressure. The current proof rollers are no longer adequate to fully prove the upper FCR layers. This is a current concern and work is continues to establish new solutions. To be effective, proof rolling must be performed before the FCR dries back to a moisture content significantly below OMC, by which time, the FCR is less compactable than when at OMC.

Following placement, compaction and proof rolling, FCR is ideally allowed to dry back to well below OMC prior to construction of the subsequent layer(s). However, airport pavement FCR includes a low fines content and the fines are often non-plastic in nature. As a result, the compacted surface quickly loosens and ravels unless it is promptly covered by the subsequent layer. The upper layer is typically sealed, by priming, to prevent ravelling.

Figure 30: Mechanical paving of FCR



Figure 31: FCR moisture addition in an on-site pug mill



FCR is also susceptible to damage by construction vehicles and wet weather. Consequently, airfield pavement practice is to promptly prime or seal the compacted FCR.

The advantages of drying back the FCR prior to surfacing with asphalt are well-recognised. However, having proof rolled the compacted FCR pavement with wheel loads and pressures comparable to those of the design aircraft, it is assumed that even at OMC, the FCR will have adequate initial resistance to rutting under aircraft and the resistance will gradually increase as the FCR dries out in service. This is why airfield pavement FCR is not typically allowed to dry back, as would be expected for a road pavement.

This practice has normally proven to be satisfactory. However, recent exceptions, where base course rutting occurred shortly after opening the pavements to traffic, suggests that success can only be expected in particular circumstances. If the FCR is near the upper limit of plasticity (typically PI = 5 per cent) and if the compaction water that is sealed in does not drain promptly, failures might occur early in the life of the pavement. This is a particular issue where pavement and subgrade drainage is poor and where the FCR fines content is near the specified maximum.

The risks associated with FCR in poor draining environments is also reflected in the FAA's advisory circular (FAA 2016) which states that "Pavements should not be configured such that a pervious granular layer is located between two impervious layers. This type of section is often called sandwich construction. Problems are often encountered in sandwich construction when water becomes trapped in the granular layer causing a dramatic loss of strength and results in poor performance."

4.4 Cement treated crushed rock

CTCR is similar to FCR except for the inclusion of cement to provide a bound or semi-bound material capable of withstanding tensile stresses. The cementitious material is typically introduced in the pug mill with the compaction moisture. The OMC of CTCR is higher than for FCR as some moisture is absorbed by the fine cement particles. Although CTCR is paved and compacted similar to FCR, the inclusion of cement creates a number of complications.

Firstly, cement hydrates to create bonds between the aggregate particles. The setting rate determines the time available between mixing and the completion of placement and compaction.

Secondly, CTCR does not bond well to overlying layers once set. The bond between layers is often poor, as is the bond across construction joints. For this reason, many designers limit the thickness of CTCR to that which can be constructed in a single layer, typically 200 mm. Where two or more layers are required, all layers are often required to be constructed within the same work period. However, this creates significant additional construction joints which is not ideal. Further, even when multiple layers are constructed within the same work period, the bond between layers is still less than ideal.

Thirdly, CTCR shrinks as part of the curing process. The shrinkage usually results in cracking of the CTCR layer. Generally, the higher the cement content, the more shrinkage and the more cracking will result. When CTCR is placed directly below an asphalt or sprayed seal surface, the cracks can reflect up through the surface and this is known as 'reflective cracking'. To retard reflective cracking, it is typical to provide a minimum asphalt thickness of 100 mm above any CTCR layer or to provide a layer of FCR between the CTCR and the asphalt surface. But as discussed previously (4.3 Fine crushed rock) sandwiching FCR between two bound layers is not recommended by the FAA.

Some designers have specified that CTCR must be proof rolled similar to FCR. Proof rolling CTCR is unnecessary and is not appropriate.

4.5 Asphalt

The production of asphalt requires a large and expensive production plant. In capital cities and major regional areas, fixed or static asphalt plants are available. However, in many regional and remote areas, a transportable or mobile asphalt plant is required (Figure 32). The cost of mobilising an asphalt plant is prohibitive except when only small volumes of asphalt are required.

Figure 32: Mobile asphalt production plant



Asphalt is constructed in layers of thickness dependent on the size of the asphalt mixture. Airport asphalt is typically 14 mm sized and the layer thickness typically varies from 35 mm to 80 mm. Although thicker layers can be constructed and compacted, controlling the smoothness of the surface is more difficult, particularly when a variable layer thickness is required.

Except for small patches performed by hand, asphalt is constructed using a mechanical paver and a combination of pneumatic tyred and steel drum rollers. The steel drums vibrate. A number of roller manufacturers recently introduced vibrating pneumatic-tyred rollers and these are highly efficient, but are generally utilised in combination with steel drums and larger static pneumatic-tyred rollers, rather than replacing them. The level of the mechanical paver is usually automatically controlled by computer software, based on the existing and designed surface levels. This requires a survey team to operate immediately in front of the paver.

Unlike roads, Australian airports have rarely used thick asphalt pavements. It follows that most asphalt on Australian airports is constructed as a surface layer. As a result, significant attention is placed on the level, smoothness and tightness of the finished surface. Further, most airport pavement asphalt is constructed as resurfacing of an existing runway pavement. This work is typically performed at night and the pavement returned to service each morning. As a result, the typical construction processes include:

- » **Milling** – the upper 5 mm (ungrooved) or 10 mm (grooved) of existing asphalt surface is removed to provide mechanical interlock and to prevent detritus or contamination from inhibiting the bond between the existing and the new surface layer (Figure 33).
- » **Cleaning** – the milled surface must be thoroughly cleaned to promote bond between the existing and new surface layers.

- » **Tack coating** – bituminous ‘glue’ is applied to the existing surface, usually as a bitumen emulsion, and allowed to ‘break’. In recent times, modified tack coats have been favoured for their reduced pick-up on construction vehicle tyres and improved bond strength at elevated temperatures.
- » **Asphalt paving** – either one or two pavers are typically utilised to maximise the productivity within the work period and to optimise the construction joint layout (refer below).
- » **Compaction** – pneumatic-tyred and steel drum rollers increase the density of the asphalt layer and tighten the surface, as well as providing smooth transitions across construction joints.

Asphalt is produced very hot (typically 160–180°C) and constructed while still hot (typically 90–130°C). Once below approximately 90°C, rolling asphalt is largely ineffective. Asphalt working time is reduced when:

- » the temperature of the asphalt at the time of paving is reduced
- » the asphalt layer thickness is reduced, and
- » the air and existing pavement temperatures are reduced.

For a typical asphalt pavement surface, the joints are the most likely location of distress. The hotter the asphalt when the joints are constructed, the less likely the joints will open and require maintenance through the life of the surface (5.5.4 Asphalt maintenance). As a result, asphalt paving is planned to minimise the cold joints as much as possible.

Figure 33: Milled and cleaned asphalt surface



Ideally, all asphalt joints would be constructed hot. However, asphalt productivity is determined by the capacity of the production plant, not the paving operation. Doubling or tripling the number of pavers will not make any significant difference to the condition of the asphalt joints and doubling the asphalt production capacity is usually not cost effective or practical. There are two main types of joints in asphalt surface construction:

- » **Longitudinal joints** – between adjacent runs of the paver(s), usually parallel to the runway centreline. Can be hot, warm or cold constructed joints.
- » **Transverse joints** – aligned transversely to the direction of paving. Located between subsequent shifts of works and therefore always cold constructed.

A long, single paving run would minimise cold transverse joints but every longitudinal joint would be cold. In contrast, very short paving runs would allow the longitudinal joints to be hot, but the transverse cold joints would be closely spaced. Experience indicates that a paving run 80–100 m in length allows the full width of 45 m-wide runway to be resurfaced in a single night shift. Where day works are performed, 100–120 m long runs provide a reasonable balance between transverse and longitudinal joint conditions. Where multiple layers of asphalt are constructed, it is preferable to fully complete the first layer before starting the next layer and joints should be offset from underlying joints to reduce pavement permeability.

4.6 Concrete

Concrete is generally produced in large and expensive production plants. The production plants are generally fixed in permanent locations but some producers also provide mobile plants, which are cost effective for large projects. Once produced, concrete has a limited working time and it is typical for designers to specify that concrete be paved, compacted and finished within 45–60 minutes of production.

Concrete is self-levelling and flows with only minor vibration. Therefore, concrete is vibrated by ‘pokers’ rather than rolled, to achieve the required density (Figure 34). In Australia, airfield concrete has been placed between fixed forms. That is, it has not been slip-formed. The fixed forms are removed once the concrete has set, typically 12–24 hours after placement.

The formwork defines the location of construction joints and the finished level of the concrete slabs. Typically, alternate rows are constructed and then infill rows are placed, using the already constructed slabs as the formwork on either one or both sides (Figure 35).

In the USA and Europe, an alternate approach to concrete construction has been commonly used for airfield pavements. A stiffer and dryer concrete mixture is paved by large paving machines with forms that move with the paver (Figure 36). This approach is referred to as 'slip-form paving' and is commonly used for highway construction in Australia. However, largely due to the perceived difficulty associated with slumping of unsupported thick concrete edges, no airfield pavements have been slip-formed in Australia.

Special measures are sometimes necessary when concreting during hot weather, especially if dry winds are expected. Chilled water, ice or night-time construction are often required in summer. Concrete construction also ceases when temperatures approach freezing, to prevent the mixing water from becoming solid, although this is not common in Australia.

Rigid aircraft pavements consist of unreinforced, jointed concrete slabs, usually with joint spacing around 5 m. Historically, 7.5 m-square slabs were used, as this is convenient for 15 m-wide taxiways, as well as 30 m and 45 m-wide runways. However, many of these slabs have cracked and the trend has been to smaller slab sizes. Reinforced concrete (with larger joint spacing), continuously reinforced concrete (free of joints) and pre-stressed concrete are not used in Australian airports, but are common in road and building construction.

Once constructed, the individual concrete slabs must be free to shrink and expand independently of each other, with daily and seasonal temperature fluctuations. Therefore, the dowels that transfer the load between adjacent slabs must be parallel to each other, and at right angles to the joint. Also, the surface of the sub-base layer must be flat to prevent the slabs being 'anchored'. The surface of the sub-base layer is typically treated with a bituminous de-bonding layer to reduce friction between the sub-base and concrete slabs.

Figure 34: Internal poker vibrators and vibrating screed



Figure 35: Infill paving of concrete with single-sided form



Figure 36: Slip form paving rigid airfield pavement (Hodgkinson 2016)



The joints between concrete slabs are critically important to rigid pavement performance. There are a number of joint types and arrangements but the primary joints are:

- » **Transverse shrinkage joints** – aligned transversely to the direction of concrete paving, these joints break the otherwise continuous concrete mass. The joints are sawn to a depth 25 per cent of the slab thickness. As the concrete shrinks, a crack forms from the bottom of the saw cut to the bottom of the slab. The ‘jagged’ shape of the crack continues to transfer the load across the joint but the saw cut at the slab surface minimises the risk of spalling.
- » **Longitudinal construction joints** – formed parallel to the direction of paving by the formwork. The smooth interface prevents interlock across the joints so dowels are incorporated to provide load transfer.
- » **Isolation joints** – constructed to protect rigid structures from expanding pavements. Dowels are not incorporated and a smooth interface is necessary to prevent interlock.

Curing is also critical to concrete construction. Concrete continues to harden for years following its production. However, it is accepted that the majority of hardening, and therefore shrinkage, occurs during the first seven days. Preventing the concrete surface from drying out is essential for avoiding drying shrinkage cracks. It is typical to cover the concrete in hessian or otherwise maintain the surface in a wet condition for 48 hours (as can be seen in Figure 35) followed by the application of a chemical membrane to prevent moisture loss by evaporation.

4.7 Concrete block pavers

Concrete block paver construction includes the spread and preparing of the bedding sand layer, laying the blocks, filling the joints with sand and finishing off. Although relatively simple, concrete blocks are routinely not constructed well. It often requires 10,000 m² of more for the processes to be established and refined. Therefore, a large quantity is required to justify the time taken to achieve a quality product.

Particular requirements that must be considered for high quality airport pavement concrete block paver construction include:

- » **Sound base** – to prevent blocks from rocking and cracking, a sound and consistent base is required. FCR has been used on many projects, although recent projects have favoured CTCR or asphalt.
- » **Bedding sand drainage** – bedding sand drainage must be effective to prevent pumping of the sand resulting in unsupported blocks.
- » **Edge restraint** – usually a concrete plinth around the full extent of the blocks (Figure 37) prevents the blocks near the edge migrating and the joints’ opening.
- » **Randomised location** – all the blocks for a particular project are usually cast from one set of moulds. The moulds wear with repeated use and as a result, the last blocks produced are slightly larger than the first blocks. If all the smaller blocks are placed at one end of an apron and the larger blocks at the other end, the apron will not be rectangular. A randomly distributed location of blocks over time is required.
- » **Soldier course** – A single row of full or near-full-sized blocks immediately adjacent to the edge restraint, aligned perpendicular to the edge restraint (Figure 38). This provides a sound transition between the blocks and the restraint and avoids small part-blocks.
- » **Part-blocks** – in some locations, part-blocks will be required to complete the surface or match to services. Part-blocks should always exceed 50 per cent of a full block (Figure 39). When 20 per cent of a block is required to finish an area, two part-blocks, 60 per cent each, are preferred to one full block and one 20 per cent part-block.
- » **Block alignment** – on completion, visual inspection across the surface should easily allow the corners of all blocks to be aligned (Figure 37).
- » **Joint filling** – joints must be fully filled with jointing sand to prevent voids.

Blocks can be placed individually by hand or by machine in approximately 1 m square ‘sections’. The latter is faster but more expensive.

Figure 37: Edge restraint at concrete block paver perimeter



Figure 38: Soldier course at edge of pavers



Figure 39: Multiple large part-blocks to avoid small part-blocks and slithers



4.8 Sprayed Sealing

Sprayed sealing generally includes the spraying of a film of hot bitumen over the surface of a pavement and then spreading and rolling in cover aggregate. Excess aggregate is then swept free from the surface.

Sprayed sealing of airport pavements generally follows road construction practices. However, sprayed sealing is more prone to loose stone generation following construction and particular processes are required to minimise the risk of FOD. The particular requirements for sprayed sealing a runway include (White 2015):

- » **Spray run length** – to increase control and to minimise delays to aggregate spreading and rolling, spray run lengths are generally restricted to 350 m.
- » **Rolling** – the very low traffic volumes and high degree of aircraft wander across the pavement width result in negligible post-construction rolling. Therefore, all the effective rolling that the seal will receive must be performed at the time of construction. One hour of rolling is typically required for every 800 L of binder sprayed. That is around four times more than road sealing requires. In general, six rollers, each rolling continuously for 10 hours, can adequately roll 50,000 L of sprayed binder per day.
- » **Steel drum rolling** – to prevent excessive tyre wear, airport spray sealing requires the uppermost hot bitumen seal layer to be steel drum rolled. The steel drum breaks the sharp edges and tops off the aggregate particles, creating a flatter and smoother surface. Steel drum rolling is not routine for road seal construction and unfamiliar contractors may resist it, citing aggregate crushing concerns. However, when operated in non-vibrating mode on quarried crushed rock (i.e. not natural gravel) two or three passes of the steel drum roller does not normally crush the aggregate.
- » **Sweeping** – constructing multiple seal layers requires many sequential steps and the pavement surface must be thoroughly swept between each of these. Sweeping is therefore a significant requirement for airports.

4.9 Proof rolling

4.9.1 Importance to aircraft pavement construction

Perhaps the most important factor contributing to the historically good performance of flexible aircraft pavements in Australia is the long-established practice of ‘proving’ the pavements during construction by using heavy pneumatic rollers to simulate aircraft effects. The intention of proof rolling is to subject all parts of the pavement and subgrade to stresses and deflections that exceed those expected in service and to check that the structure behaves satisfactorily under these imposed loadings.

Historically, proof rolling requirements were included by the Corps when developing their flexible pavement thickness design curves. The Corps’ pavement thickness design curves for unbound pavements were strictly intended to apply only to unbound pavements that had been proven during construction by appropriate proof rolling. Australia adopted the Corps’ approach. While this design intention has not generally been adhered to in the USA and elsewhere, it is still followed in Australia.

4.9.2 Timing

It is important that all proof rolling be carried out while the pavement materials are at their most compactable moisture content (e.g. at saturation for clean sands and OMC for FCR). At these high moisture contents, the materials are weaker (i.e. more deformable) than they will be in service once the pavement surface is sealed, the drainage works are complete, and the moisture contents reduce. If the pavement layers remain stable under sufficient repetitions of appropriate proof rollers during construction, the expectation is that they will also be stable in service and will not compact further under aircraft loadings.

4.9.3 Selection of proof rollers

Layered elastic analysis is used to select appropriate proof rollers. Firstly, the proposed pavement and subgrade structure is analysed under the aircraft loads to be applied to the finished pavement to estimate the stress caused at various depths below the surface. Then the available proof rollers are applied to the various pavement layers and the resulting stresses are computed.

Rollers, wheel loads, tyre pressures and the levels at which rollers operate are then chosen to produce stresses throughout the pavement and subgrade that are larger than those produced by the aircraft. Unfortunately, for many projects, proof rolling regimes are not customised in this way. Rather, designs simply replicate previously specified proof rolling regimes, which may either be inadequate or excessive for the pavement being constructed.

Figure 40 shows an example proof rolling regime to cater for a B747. The scheme is based on using a Marco roller (refer 4.9.4) operated at different weights at appropriate levels during construction.

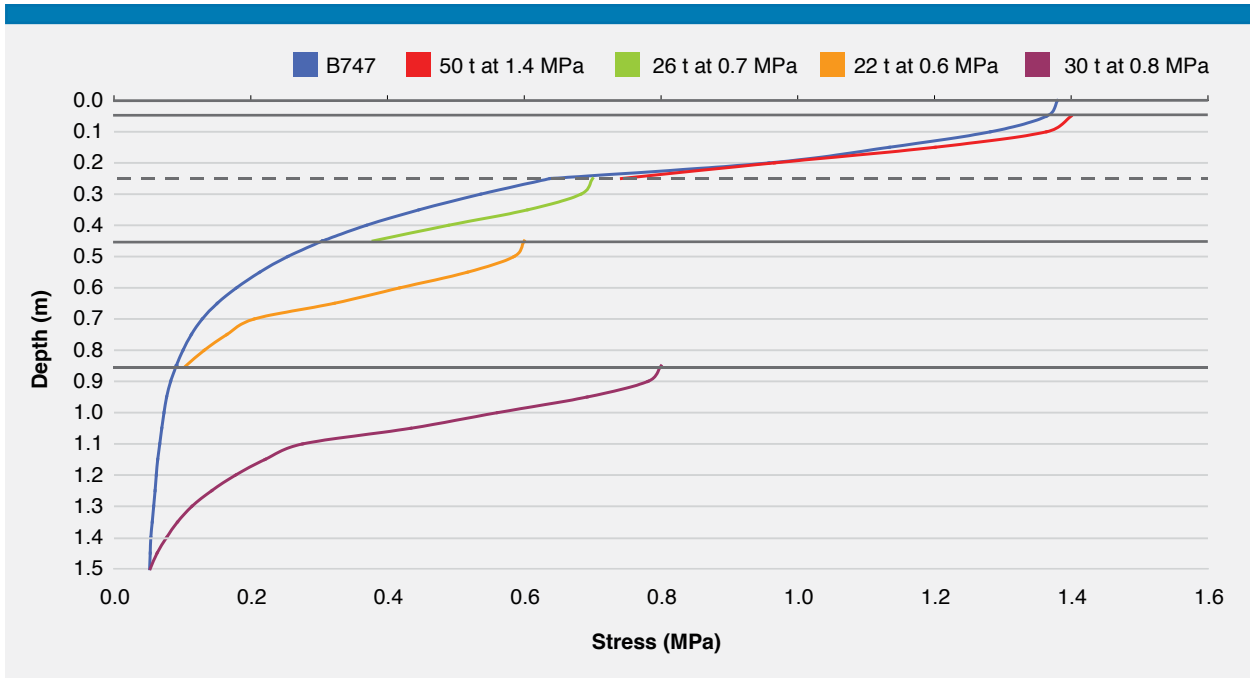
4.9.4 Proof rollers

A number of purpose-built, large, pneumatic-tyred rollers were procured by the Commonwealth Government prior to the privatisation of Australia airports:

- » **Supercompactor** – up to 200 tonnes carried on four wheel with tyres inflated up to 1.05 MPa. Designed to produce high densities to depths of 1,500 mm in sand fills that had been placed in very thick layers, typically by dredging. Subsequently replaced by more efficient large vibrating rollers designed for highways.
- » **Marco (or Macro) roller** – up to 50 tonnes carried on four wheels with tyres inflated up to 1.4 MPa (see details below) (Figure 41). Designed specifically for proving the upper layers of FCR in flexible pavements with thin asphalt surfaces.
- » **Test rig** – up to 50 tonnes carried on two wheels with tyres inflated up to 1.65 MPa. A one-off modification to a Marco roller to allow full-depth pavements to be proven for B727 operations.

When the airports were privatised, the rollers were transferred to the Department of Defence and in 2016 were sold to private organisations. A number of airports and constructors also designed and built their own proof rollers, generally based on the requirements of the Marco roller. However, in some circumstances, highway rollers adequately prove airport pavement layers.

Figure 40: Marco proof rolling regime for B747 (White 2007)



Large highway rollers can apply a load up to five tonnes through each of seven or nine pneumatic tyres at inflation pressures up to 0.9 MPa. This is adequate to prove most granular layers within a light duty aircraft pavement and the sub-base under a rigid pavement’s concrete slab. However, for the FCR layers within a heavy duty aircraft pavement, significantly higher tyre pressures and wheel loads are required.

Figure 41: 50 tonne Marco roller



4.9.5 Marco roller limitations

The Marco rollers are fitted with earthmoving tyres with a standard inflation pressure rating of 1.0 MPa. However, the Marco rollers were historically operated at 1.4 MPa tyre pressure to achieve the necessary level of stress in the upper FCR layer. For many years, the tyre manufacturers conditionally allowed over-inflation of earthmoving tyres subject to a number of operating constraints, including limiting roller speed and part-filling roller tyres with water. Around the year 2000, the conditional over-inflation permission was revoked by all earthmoving tyre manufacturers, citing safety concerns. Since that time, 1.0 MPa has typically been adopted to reflect the rated maximum inflation pressure of earthmoving tyres fitted to the proof rollers.

The 1.0 MPa tyre pressure limit has left a proving ‘gap’ at the top of the pavement. The uppermost 100 mm of base course is often exposed to stresses exceeding 1.0 MPa when modern aircraft, including the common B737-800, are operated on pavements with thin asphalt or spray sealed surfaces (White 2008). As aircraft wheel loads and tyre pressures increase (refer to 1.3 Evolution of aircraft) the gap between aircraft-induced stress and proof roller capability broadens.

The only viable options for breaching the proof rolling gap are:

- » **Thicker asphalt surfaces** – a thicker asphalt surface reduces the stress experienced by the upper FCR. However, asphalt is significantly more expensive than FCR.
- » **Bound upper base layers** – this is the FAA’s approach and options include CTCR, base course asphalt or bitumen treated base. All these materials are more expensive than FCR.
- » **Alternate proof rollers** – a 60-tonne roller with tyre pressure around 1.6 MPa would be sufficient. This is possible based on use of second-grade aircraft tyres but has not been attempted in Australia to date.

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PAVEMENT MAINTENANCE

CHAPTER 5



5.0 PAVEMENT MAINTENANCE

5.1 General

Pavements are typically constructed within a one or two-year period. The design life is usually 20 (flexible pavements) or 40 years (rigid pavements). With appropriate maintenance and rehabilitation, actual service lives often exceed the design life. It follows that through-life maintenance is arguably as important as design and construction of airport pavements.

Like pavement construction, airport pavement maintenance is generally similar to road and highway pavement maintenance. However, the intolerance to FOD and to ponding water justifies an increase in condition monitoring and maintenance effort.

5.2 Operational constraints

As outlined previously (3.8 Existing pavement evaluation), the majority of airport pavement projects relate to maintaining or upgrading existing pavement, rather than the construction of new pavements. Where existing pavements are maintained or rehabilitated, the operational constraints must be determined and accounted for in the selection, specification and execution of maintenance and upgrade activities.

Operational constraints vary substantially between airports. Further, many airports are able to relax some constraints with significant notice to airlines, usually 12 months ahead of time. Prevailing operational constraints typically include:

- » **Continuous closure** – usually only possible at regional airports without regular public transport (RPT) flights and with alternate airports located closely for emergency and medical evacuation operations. Day works can be performed without the need to return the runway to a serviceable condition.

- » **Single or multi-day closures** – some regional airports have RPT flights on only one or a few days each week. This allows the pavements to be temporarily closed between the scheduled RPT flights. Day works and double shifts are appropriate to maximise productivity but general aviation (GA) aircraft, emergency and medical flights require alternate arrangements.
- » **Weekend closure** – similar to multi-day closures, some regional airports have no RPT flights on weekends. When GA, emergency, and medical flights are catered for, closures can extent from Friday afternoon to Monday morning.
- » **Night closures** – many larger regional airports and major airports have RPT operations seven days a week and significant day works are not possible. Nightly closures are required with pavements returned to service each morning. The duration of the nightly closure has significant impact on the works and typically varies from twelve hours at regional airports to just five hours at major airports.
- » **Time-limited works** – simple maintenance activities at regional airports can often be performed between aircraft operations, as time limited works. However, at major airports, time limited works are unlikely to be productive.

5.3 Lifecycle expectations

Airport pavement maintenance is performed to improve the pavement lifecycle and thereby reduce the whole of life cost associated with airport infrastructure. As previously discussed (3.2.1 Pavement damage and life), the expected service life of airport pavements varies with pavement type. Also, flexible pavement life is routinely 're-set' by resurfacing while rigid pavement life is not. The typical life expectancy of well-maintained airport pavements is summarised in Table 10. Upgrades triggered by more damaging aircraft are separate and are not considered in these expectations.

Table 10: Typical airport pavement life expectancy

Pavement type	Design life	Surfacing life	Structural life
Flexible with sprayed seal surface	15 years	8–10 years	15–20 years (unless reset by asphalt overlay)
Flexible with asphalt surface	20 years	10–12 years	Unlimited (periodically reset by asphalt overlay)
Rigid (concrete)	40 years	N/A	40–60 years

5.4 Periodic evaluation

Periodic evaluation of airport pavement condition is an important element of pavement maintenance and management. In this case, 'evaluation' primarily refers to the visual assessment of the pavement surface for confirming operational serviceability and for determining current and future maintenance requirements. This is distinctly separate to structural evaluation (refer to 3.8 Existing pavement evaluation) although some visually detectable distresses may be indicative of structural deficiency.

Operational serviceability includes freedom from FOD and other distresses immediately impacting the safe operation of aircraft. This is more an 'operational' activity. In contrast, determining future maintenance requirements aims to maximise the pavement and surface lifecycle by optimising the type and timing of maintenance treatments. This is not an operational activity.

Regional airports typically include periodic pavement condition evaluation as part of the aerodrome technical inspection (ATI) process required by MOS-139 (CASA 2016). The ATI is often undertaken by general airport engineers or technicians. This is appropriate for the operational serviceability element of the inspection, but is less appropriate for the prediction of future maintenance requirements. Specialist aircraft pavements engineers have the expertise and experience to better interpret the pavement's condition and predict future maintenance requirements.

5.5 Airport pavement maintenance

5.5.1 Guides to distress and maintenance

A number of comprehensive guides to airport pavement distress and maintenance treatments already exist (Table 11) and are freely accessible. Rather than repeating significant amounts of existing information, only the most common and important maintenance activities are included for the different pavement and surface types.

These guidance documents provide information and recommendations covering:

- » airport pavement inspection processes
- » example forms and templates for inspection reports
- » airport pavement condition index (PCI) calculation
- » airport pavement management systems
- » identification of defects and distresses for rigid and flexible pavements
- » common treatment types and products for the various distresses, and
- » references to other guides and documents particular to certain distresses.

Table 11: Guides to airport pavement inspection and maintenance

Publisher	Title	Reference
Transportation Research Board (of the USA)	Common Airport Pavement Maintenance Practices	TRB (2011)
Department of Defence (Australia)	Airport Pavement Maintenance Manual	Defence (2015)
FAA (USA)	Guidelines and Procedures for Maintenance of Airport Pavements	FAA (2014)
US Army Corps of Engineers	Airfield Pavement Condition Survey Procedures	DOD (2004)
Ministry of Defence (of the UK)	Inspections of Airfield Pavements	MOD (2011)
Ministry of Defence (of the UK)	Guide to Airfield Pavement Maintenance	MOD (1994)

5.5.2 General maintenance

Some airport pavement maintenance activities are common to all pavement types. Examples include:

- » **Removal of FOD** – using a FOD-boss, vacuum sweeper or mechanical broom to remove FOD and detritus.
- » **Linemarking** – typically two coats for fresh markings and one coat for re-marking. Usually applied by walk behind or self-propelled purpose-built spraying equipment (Figure 42).
- » **Rubber removal** – removal of rubber contamination, usually constrained to the aircraft touchdown zone, is an element of aircraft skid resistance management (refer to 3.9 Surface texture, friction and skid resistance). Available methods include chemical, mechanical and water removal methods (5.6.1 Rubber removal) of which ultra-high pressure ‘water cutting’ has been favoured in recent years (White 2012) (Figure 43).
- » **Crack sealing** – typically using a hot-applied elastomeric bitumen bandage. Important for preventing spalling of cracks leading to FOD and for maintaining an impervious pavement surface (Figure 44).

5.5.3 Concrete maintenance

The most common concrete distresses and maintenance activities include:

- » **Severe crack repairs** – when beyond-normal crack sealing, concrete cracks may be routed-out and sealed, usually with a joint sealant material. In severe cases, a shallow trench is cut into the concrete slab to remove all the cracks and the trench is filled with asphalt or other repair material (Figure 45).
- » **Repairing spalls** – when beyond treatment with a hot bitumen bandage, spalls are cut out and the void patched with asphalt or a semi-rigid (flexible) epoxy material (Figure 46).
- » **Reinstatement of joint sealants** – failed joints sealants are removed and replaced, usually with special-purpose polyurethane or silicone materials (Figure 47).
- » **Partial and full slab replacement** – slabs or partial slabs beyond normal maintenance are reconstructed in isolation, including the provision of new dowels (to adjacent slabs) and/or ties (when part of a slab).

Figure 42: Walk-behind linemarking applicator



Figure 43: Water cutter for rubber removal



Figure 44: Hot bitumen crack bandage application



Figure 45: Severe crack trenched and filled with asphalt



Figure 46: Semi-rigid epoxy spall repair



Figure 47: Joint sealant replacement



Typical maintenance expectations for appropriately designed and constructed rigid (concrete) airport pavements are:

- » **Severe crack repairs** – minor after 20 years, increasing for the remainder of the pavement’s life
- » **Repairing spalls** – minor after five years, increasing after 20 years.
- » **Reinstatement of joint sealants** – Every 10–15 years.
- » **Partial and full slab replacement** – minor after 30 years, increasing for the remainder of the pavement’s life.

5.5.4 Asphalt maintenance

The most common asphalt distresses and maintenance activities include:

- » **Joint sealing** – open and longitudinal and transverse paving joints using materials and methods utilised for sealing cracks (Figure 44).
- » **Boney surface filling** – built-in segregation and isolated severe erosion is treated with the proprietary surface filling treatments utilised for severely aged asphalt preservation (refer to 5.6.2 Asphalt preservation) (Figure 48).
- » **Asphalt patching** – isolated surface or pavement failures are treated by small patches, performed by hand or by mechanical paver, usually when larger than 2.5 m wide by 5 m long.
- » **Asphalt preservation** – treatment of aged and eroded asphalt surfaces to extend the period between resurfacing. Uses various materials, as discussed in more detail below (5.6.2 Asphalt preservation).

Figure 48: Isolated segregated asphalt treated by surface filling product



Typical maintenance expectations for appropriately designed and constructed asphalt surfaced flexible airport pavements are:

- » **Joint sealing** – commencing after five years, increasing until resurfacing.
- » **Boney surface filling** – minor requirement immediately following construction and every five years thereafter.
- » **Asphalt patching** – minor after six years, increasing for the remainder of the surface's life.
- » **Asphalt preservation** – typically, after six to eight years and potentially again approximately three years later (refer to 5.6.2 Asphalt preservation).

5.5.5 Sprayed seal maintenance

The most common sprayed seal distresses and maintenance activities include:

- » **Flushed bitumen removal** – when a sprayed seal flushes (Figure 49) it is possible to remove the excess bitumen by water cutting, using the same equipment used for rubber removal (Figure 43).
- » **Surface preservation** – when a sprayed seal is initially designed and constructed without a lock-down treatment (refer to 2.4.6 Sprayed seals) a delayed surface treatment, like that used for preservation of severely aged asphalt surfaces (Figure 48) is appropriate, five-to-eight years into the seal's life.

When it occurs, bitumen flushing usually becomes evident during the first summer after sealing or resealing. Water cutting in the period between the first and second summer is appropriate.

Figure 49: Flushed sprayed seal surface



5.6 Critical maintenance activities

Rubber removal and asphalt preservation are important topics, particularly for regional airports with asphalt surfaces. These activities may only be required once or twice in an asphalt surface's life. Inappropriate treatment has operational implications and re-treatment is often expensive.

5.6.1 Rubber removal

As discussed earlier (3.9 Surface texture, friction and skid resistance), rubber contamination accumulates on runway surfaces during aircraft landing and wheel spin-up. Rubber removal is typically performed:

- » every year or two at major airports
- » every five to six years at larger regional airports, and
- » never required at remote and small regional airports.

Grooved pavements usually require an increased frequency of rubber removal in order to maintain groove effectiveness. Also, the edges of the grooves accumulate rubber faster than ungrooved asphalt (Zuzelo 2014). Rubber removal methods are generally the same whether the surface is grooved or not, and a number of methods are available, including:

- » **Shot-blasting** – relying on physical abrasion of the rubber to remove it from the surface. Shot-blasting is generally avoided on runways due to the risk of unrecovered shot causing damage to aircraft engines.
- » **Chemical treatment** – Relying on chemical agents to soften the rubber allowing it to be scrubbed or washed from the surface. Chemical treatments lost favour due to environmental concerns regarding contamination of storm water by unrecovered chemical run-off.
- » **Water blasting** – Relying on water pressure to physically wear and remove the rubber from the surface. Water blasting (moderate pressure and high water volume) is more likely to excessively erode the asphalt surface and has been largely discontinued on runways in favour of water cutting methods.
- » **Water cutting** – Similar to water-blasting but uses ultra-high pressures and low volumes of water. The result is more controlled removal of rubber with minimal erosion of the underlying asphalt surface. Water cutting is more expensive than water blasting, due to the specialised equipment required.

5.6.2 Asphalt preservation

Preservation of asphalt surfaces, intended to extend the period between asphalt resurfacing, is a long-established practice at airports in Australia and around the world.

Treatment types

Preservation treatments vary but generally include:

- » **Asphalt rejuvenator** – a chemical (non-bituminous) treatment intended to penetrate into the asphalt surface and chemically reverse the ageing of the bitumen binder. There is debate regarding the efficacy of true rejuvenation materials. True rejuvenation is similar in concept to a long-term moisturiser.
- » **Asphalt enrichment** – enrichment is also commonly referred to as ‘surface enrichment sprayed treatment’ (SEST) (refer to 5.6.2.4 Historical changes) or a ‘fog seal’. A sprayed treatment of bitumen applied to the top of the asphalt surface to replace the eroded mastic (fine aggregate binder) and provide a protective barrier against further oxidation and erosion. Enrichment is similar to a sunscreen.
- » **Polymer-modified emulsion (PME)** – PME treatments are sometimes referred to as a ‘seal coats’ (refer to 5.6.2.4 Historical changes) or a ‘fine slurry’. Reference to a ‘slurry’ must not be confused with slurry sealing or microsurfacing (refer to 2.4.7 Slurry sealing and microsurfacing). PME is similar to an enrichment but with added sand-sized filler mixed into the bituminous material. The sand filler is intended to replace the fine aggregate in more eroded asphalt surfaces.

It is important to understand that different engineers and organisations may use different terminology for some preservation treatments. Misunderstanding can result in invalid cost estimates and the consequent use of inappropriate treatments.

In Australia, most airports have embraced enrichment and PME over many years. Rejuvenation has been less common and the true benefit of the rejuvenation products has been questioned.

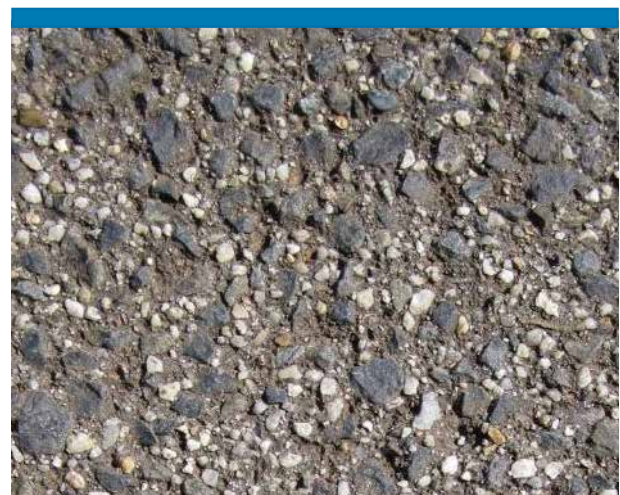
Selection of types of preservation treatment

In selecting a treatment for an existing pavement surface, the most important decision is whether the surface is better suited to a treatment with or without sand filler. In the latter case, the treatment would be called an ‘enrichment’. The decision depends primarily on the level of surface macro-texture and the amount of bituminous mastic erosion that has occurred. Figure 50 shows an asphalt surface suited to an enrichment treatment and Figure 51 shows a more eroded surface that is better suited to a PME product.

Figure 50: Asphalt surface suited to enrichment



Figure 51: Asphalt surface suited to PME



Treatment products

There are multiple proprietary products of both type (Table 12) and all are similar in composition if the residual bitumen content (after the emulsifying water evaporates) is held the same. Both product types have been successfully applied to both grooved and ungrooved runway surfaces, although additional care is required during application to prevent grooves being filled. Some airports have applied the treatment across the runway and the contractors were required to 'sweep' the product out of the grooves, which was inefficient and expensive. More recently, multiple light applications of product, sprayed in opposite directions along the runway, prevented the product flowing to the bottom of the grooves. While care is required not to fill the grooves, the presence of the grooves mitigates the impact the treatment has on the skid resistance offered by the asphalt surface.

Historical changes

Traditionally, coal tar was emulsified in kerosene, or similar, for enrichment without sand filler. This was commonly referred to as coal tar SEST. The material cured rapidly, was very effective, and was also fuel resistant. However, because coal tar is carcinogenic, these products are largely no longer available. Cutback bitumen SEST then replaced the coal tar products for asphalt preservation. Similar cutters were used with conventional bitumen to provide a similarly rapid curing, but the material was not fuel resistant.

In the early 2000s, safety concerns associated with low flash point cutters (like kerosene and turpentine) led the industry to favour bitumen emulsion (water based) treatments, sometimes known as emulsion SEST. However, the bitumen in emulsion is in the form of small globules, whereas cutback is completely dissolved. Consequently, cutback bitumen penetrated and sealed fine cracks, whereas bitumen globules in emulsion were retained on the surface.

However, polymer-modified bitumen emulsions have now been developed that largely overcome this limitation. They are specifically designed for surface enrichment and represent current industry practice for treatment of aged asphalt surfaces where sand filler is not required.

Treatments that incorporated a sand filler were traditionally reserved for isolated areas of stony or coarse and segregated asphalt. The treatment included choking the surface texture with dry and clean sand and then squeegeeing bitumen emulsion into the sand to bind it. When emulsion spray trucks became widely available, this process was then inverted, with sand spread on top of the sprayed bitumen emulsion and rolled in. This treatment was far more efficient, enabling large areas to be rapidly and effectively applied.

In the 1990s, proprietary products, known as PME treatments become common. The composition (bitumen-water-filler) is not significantly different to the combined composition of the traditional sand and emulsion treatment. However, the modified bitumen is intended to improve sand retention and adhesion to the pavement surface, reduce tackiness in hot weather and the combined product is much quicker to apply to the surface, with minimal clean-up required.

Impact on surface texture and friction

The application of surface treatments unavoidably reduces surface texture. There have been reports of aircraft skidding off treated runways where the surface texture and friction have been adversely impacted by surface treatment (Emery et al. 2011). Where a surface has ample texture and friction, the reduction resulting from surface treatment is not concerning in light of the benefits associated with the improved retention of coarse aggregate and the minimisation of FOD. However, if the texture and friction are already marginal, then further reduction by the application of a surface treatment is unacceptable.

Table 12: Current locally available preservation products

Enrichment (non-filled) Products		PME (mineral filled) Products	
Product	Supplier	Product	Supplier
GSB 88	Concrete Roads	JetBlack	Fulton Hogan
SERT	Fulton Hogan	PreserveX	Downer
RejuvineX	Downer	SealCoat	SAMI

A small trial in an un-trafficked area of the pavement is essential to verifying the impact of the treatment on texture and friction. Friction should be tested before and after a trial application, usually by a spot-tester such as the British pendulum (Figure 52). Post-treatment survey of treated runways by an ICAO-approved CFME, such as the Griptester, is recommended (refer to 3.9.3.6 Surface friction survey).

5.7 Rehabilitation and upgrade options

Isolated areas of pavement may perform inadequately compared to the surrounding pavement areas. Further, the introduction of larger and more damaging aircraft may render a pavement structurally inadequate. Finally, without maintenance, a pavement may exceed its design life and structurally fail beyond repair by normal maintenance activities. In all these cases, a rehabilitation or structural upgrade is required.

Rehabilitation and upgrade works are intrusive compared with normal maintenance. As previously highlighted (5.2 Operational constraints), the operational constraints must be reflected in the design solutions. Further, designs are often optimised by reuse of the existing pavement structure and materials where appropriate. These circumstances combine to create a significant challenge for designers. Rehabilitation of upgrade design often comprises structural asphalt overlay, insitu stabilisation and resurfacing, rigid pavement reconstruction and flexible pavement reconstruction.

Figure 52: British pendulum spot friction tester



5.7.1 Asphalt overlay

Asphalt overlays for structural upgrade do not address any material deficiencies within the pavement structure. However, asphalt overlay is effective at adding strength to the pavement. Also, the asphalt is added to the existing surface level. This usually necessitates flank regarding and may impact airfield drainage.

Theoretically, there is no limit to the thickness of an asphalt overlay pavement upgrade. However, in practice asphalt overlays are cost effective up to thicknesses of 100–150 mm, typically constructed in two or three layers. Strength increases requiring greater asphalt overlay thicknesses are usually more cost-effectively provided by improvement of the existing pavement structure.

5.7.2 Insitu stabilisation and surfacing

Insitu stabilisation of existing FCR or uncrushed gravel base layers approximately doubles the modulus of the base layer material. The resulting material provides 60 per cent or more structural capacity compared to the un-stabilised material (refer to 2.6.3 Material equivalence guidance). It follows that insitu stabilisation of the existing base course, followed by construction of a new surface, provides an efficient and effective upgrade or rehabilitation option. This is particularly applicable to regional airports where the existing base courses were often constructed with margin uncrushed gravels.

Insitu stabilisation is readily performed at night and the pavement can be returned to service at the end of each work period. However, this requires that the shape of the finished stabilised base layer is approximately the same level and shape as the existing pavement. While minor correction of isolated bumpiness can be rectified, significant reshaping is not practical. Any significant shape correction must be performed in the surfacing, which necessitates an asphalt surface because no shape correct is possible with a sprayed seal.

The surfacing also provides any further strengthening required. The practical depth of insitu stabilisation is limited by construction equipment. Despite stabilising machines being able to work to depths of 400 mm or more, the current compaction equipment typically available is only effective to around 250–300 mm.

Coincidentally, many regional airports have 200–300 mm thick uncrushed gravel base courses. Therefore, 250 mm is the general maximum practical thickness for insitu stabilisation. Additional depth requires the removal and replacement of the upper material, which is not cost effective and is unlikely to be operationally viable. Any residual deficiency in pavement strength is provided by a thick (i.e. structural) asphalt overlay. For example, a typical regional airport originally designed for F27 aircraft, may be upgraded to B737 capacity by 250 mm insitu stabilisation and 80–120 mm of asphalt. When the insitu stabilisation achieved the required strengthening, a sprayed seal surface is also appropriate.

Traditionally, insitu stabilisation of FCR and uncrushed gravels utilised cement as the stabilising agent. However, cement stabilisation, like CTCR, shrinks and cracks (2.4.10 Cement treated crushed rock). The cracks often ‘reflect’ through the surface, creating an ongoing maintenance liability.

In recent years, foamed bitumen stabilisation has become a popular stabilisation technique for road and airport pavement upgrades in Australia (2.5.3 Expedient construction materials). The foamed bitumen stabilised material does not crack, is highly moisture resistant and provides a structural contribution similar to that of asphalt (White 2014). Foamed bitumen stabilisation also provides a rapidly constructible and immediately trafficable material and some airports have landed small aircraft on the stabilised material surface until the subsequent surfacing is scheduled.

5.7.3 Rigid pavement reconstruction

Rigid pavement reconstruction is extremely challenging within an operational airfield. Conventional rigid pavement reconstruction typically takes 6–12 weeks, during which time the existing pavement is demolished, the sub-base is prepared, formwork is established, the new concrete slabs are constructed, the formwork removed and the concrete cured. Fortunately, most rigid pavement reconstruction can be staged with small areas continuously closed within a larger apron or taxiway system. However, some locations, such as critical taxiways and busy parking stands, can only be accessed at night and must be returned to service each morning.

In locations where pavements must be returned to a serviceable condition each morning, conventional rigid pavement reconstruction is not possible. Recent works at Sydney and Melbourne airports, as well as at Defence airfields, used rapid-setting concrete technology (refer to 2.5.3 Expedient construction materials).

Rapid-setting concrete is similar to conventional airfield concrete except the cement is designed to provide over 65 per cent of the 28-day flexural concrete strength in just four hours, and over 95 per cent of the 28-day flexural strength is achieved in seven days (Hampton 2016). The high rate of cement hydration and strength gain requires volumetric-based mixing of concrete on site, immediately prior to its placement, compaction and finishing. If produced in a conventional concrete production plant and transported to site in a concrete agitator (i.e. a concrete truck) the rapid setting concrete would set during transportation.

Reconstruction of airfield pavements using rapid setting concrete is equipment and labour intensive. As a result, the work is relatively expensive and productivities are relatively low. However, in areas that cannot be closed for extended periods, there are limited alternate options for rigid pavement rehabilitation or strength upgrading (White 2017).

The USA and Europe have made use of alternate rigid pavement rehabilitation and upgrade options, including:

- » **Rigid concrete overlay.** Thin concrete is constructed on top of the existing concrete slabs. However, in apron areas, other infrastructure rarely allows the finished pavement level to be raised and an imperfect bonding results in rapid failure.
- » **Pre-cast concrete slabs.** Slabs are pre-cast off site and essentially ‘dropped and grouted’ into place. Alignment of dowels and inconsistent slab dimensions creates a challenge. Further, achieving a perfectly flat sub-base surface, to prevent rocking, is critical to slab performance.

Australian airports have not made any significant use of these alternate technologies. This reflects the high level of technical risk and lack of local experience.

5.7.4 Flexible pavement reconstruction

Flexible pavement reconstruction is simpler than rigid pavement construction. That is because flexible pavement materials generally do not require extended curing periods or formwork erection. However, the significant thickness of flexible aircraft pavements, typically 600 mm to over 1,500 mm, requires deep excavation and backfilling. Conventional flexible pavement materials, such as FCR (refer to 4.3 Fine crushed rock) and CTCR (refer to 4.4 cement treated crushed rock) are not rapidly constructible due to the need to cure, proof roll and dry back. Also, the relatively low modulus (stiffness) associated with FCR makes it inefficient for overnight reconstruction to significant depth. Similarly, cracking of CTCR creates a challenge in overnight reconstruction as the opportunity to provide a crack retarding treatment under the asphalt surface is reduced.

The overriding criterion for rapid flexible pavement reconstruction is minimisation of the pavement depth required. This reduces the depth of excavation as well as the depth of new pavement construction. As discussed earlier (2.6 Material equivalencies) stiffer materials (i.e. those with higher modulus) reduce the total thickness required and are most suited to flexible pavement reconstruction (White 2017).

Thick asphalt reconstruction has been used for flexible pavement reconstruction at airports. Asphalt is typically viable in two layers within a single work period. Therefore, a patch up to 150 mm (a 90 mm first layer and 60 mm second layer) is a reasonable approach. At greater depths and more layers, asphalt retains significant heat for extended periods and the upper layers cannot be adequately compacted against the underlying hot and soft layers. In one case, 400 mm thick patches of hot asphalt were constructed on an apron in a single work period, resulting in rutting under aircraft traffic.

Warm asphalt (WMA) (refer to 2.5.3 Expedient construction materials) is produced at lower temperatures than hot asphalt but is similarly workable and compactable. Patches of 400 mm total thickness using WMA have been constructed and proved to be quickly trafficable by aircraft (White 2015). However, thick asphalt is relatively expensive and large areas are not readily constructible in short overnight work periods.

A number of airports have rapidly reconstructed airport pavements with multiple layers of CTCR (2.4.10 Cement treated crushed rock). However, the requirement for the CTCR to cure, the risk of inadequate bond between layers and the risk of reflective cracking must be considered.

Foamed bitumen-stabilised base (FBB) (refer to 2.5.3 Expedient construction materials) provides a crack-free alternate. For flexible pavement reconstruction, a new FCR material stabilised in a pug mill is preferred because the new FCR reduced the risk of insitu material variability. Not being constructed insitu also negates any thickness limitations associated with compaction equipment. Multiple thick layers of FBB can be constructed rapidly, do not require curing or dry back and the material is constructed at ambient temperature so retained heat is not an issue.

Rapid flexible pavement reconstruction with FBB has been used at Darwin (taxiway shoulders), Melbourne (taxiway) and Brisbane (taxiways) airports. Thicknesses of up to 300 mm were adequately compacted in a single layer and up to 600 mm total thickness was constructed in a single overnight work period, along with a thin asphalt surface. Structurally, FBB provides modulus values comparable to hot asphalt, making it an efficient and effective flexible pavement reconstruction material.

5.7.5 Practical limitations

When planning for the rehabilitation or upgrade of airport pavements in areas where overnight works are essential and pavements must be returned to a fully operational condition each morning, a pragmatic approach must be taken. It is more appropriate to ask 'what can we actually get done in the work window available and what is the risk associated with pavement performance' rather than designing a pavement that is 'theoretically adequate, but not constructible'.

Some designers have compensated for the expedient nature of rehabilitation construction by increasing the theoretically required pavement thickness. This reflects the belief that quality control will be reduced due to the compressed timeframes and an increased pavement thickness will compensate for this. However, this is often a flawed logic. Rather, increasing overall pavement thickness is detrimental to expedient pavement construction quality. Any theoretical improvement associated with the increased pavement thickness is lost due to the increase in pressure to construct an additional layer, or to produce additional material, within the same time period. Often, acceptance of rutting risk in an understrength pavement is preferred to a theoretically adequate, but not constructible pavement. The ruts can always be corrected, by a subsequent asphalt overlay, if they eventuate.

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PAVEMENTS FOR RURAL AND
REMOTE AIRFIELDS

CHAPTER 6



6.0 PAVEMENTS FOR RURAL AND REMOTE AIRFIELDS

As detailed earlier (3.1 General principles), at some rural and remote airports, the pavements used by GA and other small aircraft are not designed the way larger airfield pavements are designed. In fact, they are often designed by truly empirical experience. That is, a solution that has previously worked for similar aircraft at the same airport, or a similar nearby airport, is adopted without any particular analysis. Although this contrasts with conventional airfield pavement design, it is a valid approach in many circumstances.

In many rural and remote airfields, the fire tender and the refuelling truck are more damaging to the pavement than the light aircraft traffic. In this case, conventional road or airfield pavement design methods are employed, usually based on the ground support vehicle(s) loads, rather than the aircraft loads.

6.1 Defining airfield pavements

Airfield pavements are logically defined to be pavements that are designed to accommodate the aircraft that they support. Much of Chapter 3 (Pavement design) was dedicated to methods used to design both flexible (3.4 Flexible pavement design) and rigid (3.5 Rigid pavement design) airfield pavements. However, these methods do not apply to pavements that are used by aircraft that require less pavement thickness than practical construction method dictate, or that ground support vehicles require.

It follows that airfield pavements should be defined as ‘pavement designed to accommodate the aircraft that use them’. Pavements that are designed based on ground support vehicles or other means are more appropriately referred to as ‘pavements used by aircraft’.

Importantly, the impact of fuel tankers and fire tenders must not be underestimated. These are large vehicles and are much more damaging than most light aircraft. Pavements that perform well under light aircraft loadings often fail rapidly under continuous and often channelised heavy ground support vehicle usage.

6.2 Example solutions

Pavements that are analytically designed for ground vehicles should be designed using methods commonly adopted for road pavements in the local area. Design tools such as CIRCLY (Wardle 1977) and chart-based methods are published by various road authorities, including Austroads (Austroads 2012). Solutions for pavements designed by truly empirical methods vary widely and depend on:

- » local materials
- » local construction capabilities
- » success of similar solutions in the past, and
- » experience of the airport manager and/or ‘designer’.

Some example solutions that have been successfully utilised for pavements used by light aircraft in rural and remote areas, include:

- » **New flexible pavement** – 150–200 mm of local granular material with a sprayed seal.
- » **New rigid pavement** – 200 mm reinforced concrete directly on subgrade.
- » **New asphalt surface** – 25–40 mm heavy duty road asphalt with conventional C320 binder.
- » **Asphalt resurfacing** – 20–40 mm heavy duty road asphalt with conventional C320 binder.
- » **New spray sealed surface** – a 14/7 mm or 10/7 mm two coat seal with conventional C170 or C320 bitumen, at high bitumen application rate, lighter aggregate coverage and significant rolling and sweeping.
- » **Sprayed sealing** – a 7 mm or 10 mm single coat seal with conventional C170 or C320 bitumen, at high bitumen application rate, lighter aggregate coverage and significant rolling and sweeping.

Due to the empirical basis for the design of pavements used by light aircraft, more specific guidance is not able to be provided. Separate guidance material, focused on pavement solutions for rural and remote airports, is required in the future.

6.3 Regulatory requirements

It is important to understand that MOS-139 requirements relating to friction, texture and freedom from FOD, apply almost equally to light aircraft pavements as they do to capital city or even international airports. It is therefore recommended that advice be sought from an experienced airfield pavement engineer, who can work with the local airport manager to understand economically available materials and construction capabilities. This will allow appropriate and economical solutions to be developed, that are also consistent with the intent of MOS-139.

6.4 Chapter references

Austrroads 2012, *Guide to Pavement Technology Part 2: Pavement Structural Design*, AGPT 02-12, Austrroads, 6 March.

Wardle, LJ, 1977, *Program CIRCLY User's Manual*, Commonwealth Scientific and Industrial Research Organisation, Australia, Division of Applied, Geomechanics, Geomechanics Computer Program No 2.

GLOSSARY OF TERMS

Aviation terms

Airside The movement area of an aerodrome, adjacent terrain and buildings or portions thereof, access to which is controlled.

Apron A defined area on a land aerodrome intended to accommodate aircraft for purposes of loading and unloading passengers, mail or cargo, fuelling, parking or maintenance.

Blast protection area A prepared area, usually adjacent to the end of the runway, which has been treated as a protection against erosion from jet or propeller blast.

Continuous Friction Measuring Equipment (CFME)

Various ICAO endorsed devices for the continuous measurement of surface skid resistance or roads and runways, including the Griptestter.

GA (general aviation) All civil aviation operations other than scheduled air services and non-scheduled air transport operations for remuneration or hire.

GSE (ground service equipment) Vehicles and equipment used in the servicing of aircraft.

Holding bay A defined area in the taxiway system where aircraft can be held, or by-passed, to facilitate efficient surface movement of aircraft.

Holding point A specified location on the manoeuvring area of the aerodrome, identified by visual means, at which an aircraft may be held in accordance with instructions issued by an air traffic control unit.

Land side That portion of an aerodrome not designated airside and to which the general public normally has free access.

Movement area That part of an aerodrome to be used for the surface movement of aircraft, including maneuvering areas and aprons.

Primary runway Runway(s) used in preference to others whenever conditions permit.

RET (rapid exit taxiway) See taxiway.

RPT (regular public transport) A service consisting of regular public transport operations.

Runway A defined rectangular area on a land aerodrome, prepared for the take-off and landing of aeroplanes along its length.

RESA (runway end safety area) A cleared and graded area adjacent to the end of a runway or stopway if provided, symmetrical about the extended runway centreline and intended for use in the event of an aeroplane undershooting or overrunning the runway.

Runway number The number allotted to a runway end, being that whole number nearest to one-tenth of the magnetic bearing of the centreline of the runway measured clockwise from magnetic north when viewed from the direction of approach. Single digit numbers so obtained are preceded by '0' and where the final numeral of the bearing is 5 degrees, the number allocated is the next largest number.

Runway strip A defined area including a runway and stopway, if provided, and intended:

- » to reduce the risk of damage to aeroplanes running off the runway, and
- » to protect aeroplanes flying over it during take-off or landing operations.

Runway threshold The beginning of that portion of the runway useable for landing. It should be noted that because the threshold is associated with the landing direction, each runway normally has two thresholds one for landing in one direction, the other for landing in the reciprocal direction.

Shoulder An area adjacent to the edge of a runway, taxiway or apron pavement so prepared as to provide a transition between the pavement and adjacent surfaces for aeroplanes running off the pavement. The shoulder is designed to be strong enough to prevent aircraft damage but may itself be damaged. This is typically achieved by making the shoulder half the pavement thickness.

Taxiway A defined path on a land aerodrome established for the taxiing of aircraft and intended to provide a link between one part of the aerodrome and another, including:

- » **Aircraft stand taxilane.** A portion of an apron designated as a taxiway and intended to provide access to aircraft stands only.
- » **Apron taxiway.** A portion of a taxiway system located on an apron and intended to provide a through taxi route across the apron.

- » **Rapid exit taxiway** – a taxiway connected to a runway at an acute angle and designed to allow landing aeroplanes to turn off at higher speeds than are achieved on other exit taxiways thereby minimising runway occupancy times.

Taxiway strip An area including a taxiway and intended to protect an aeroplane operating on the taxiway and to reduce the risk of damage to an aeroplane accidentally running off the taxiway.

Touchdown zone The portion of a runway beyond the threshold where it is intended that landing aeroplanes will first contact the runway.

Unserviceable area The portion of the movement area not available for use by aircraft because of the physical condition or because of any obstacle affecting the area.

Pavement terms

ACN (aircraft classification number) A number expressing the relative effect of an aircraft on a pavement for a specific standard subgrade strength.

Base course The pavement layer or layers of material placed on a sub-base or subgrade to support a surface layer. In the case of rigid pavements, the concrete slab is sometimes called the 'base' in which case the supporting layer is called the sub-base'.

Birdbath Localised pavement depression causing water to pond after rainfall.

Bitumen A black viscous material obtained from the refinery processing of crude oil. It is solid at normal temperatures but softens when heated. It has excellent waterproofing properties and is a strong, inexpensive adhesive.

Bituminous concrete See Asphalt.

California bearing ratio (CBR) A very commonly used measure of the stiffness and strength of a subgrade or unbound pavement construction material. It expresses the material's stiffness relative to a standard, well compacted, high quality crushed rock base course material.

Cold-mix Similar to asphalt but the bitumen glue binding the stone and sand particles together is a bitumen temporarily softened by mixing with a cutter, usually kerosene, or a fluxing oil, usually diesel. Thus the aggregate/bitumen mixture is workable at normal temperatures and is still useable after storage in stockpiles for long periods. It hardens gradually, over a number of days and weeks, by the evaporation of cutter and fluxing oil. Cold-mix is used for pothole patching and larger emergency patching but should only be placed in thin layers (approximately 20 mm) otherwise the cutters and flux cannot evaporate and the cold-mix stays soft.

Cutback bitumen A bitumen mixed with a solvent such as kerosene, which then evaporates (usually after spraying) leaving the bitumen solid again. The remaining bitumen content is referred to as the residual bitumen.

Densely graded A term applied to asphalt and to crushed rock that contains a range of stone sizes, where the amount of each size is just sufficient to fill the gaps between the next largest size stones. A densely graded material can be compacted to form a very strong, dense mass containing few air voids.

Emulsion (bituminous emulsion) A liquid material comprising a continuous water phase with suspended minute globules of bitumen. The water evaporates and some might pass downwards into the pavement. The bitumen globules then join together to form a continuous layer. This process is called 'breaking' of the emulsion. The remaining bitumen content is referred to as the residual bitumen.

Erosion Gradual loss of fine stone particles from an aged asphalt surface. If not attended to, say by application of a SEST, larger stones will be eventually released that could damage to jet engines.

K-value The stiffness of a subgrade utilised for rigid pavement design, usually estimated from measured CBR.

Modulus The stiffness of a material expressed as the ratio between deformation and applied stress that causes the deformation, with a higher modulus implying a stiffer material.

Open graded friction course (OGFC) A porous asphalt surfacing layer 20 to 30 mm thick which contains 20 per cent air voids. It has a high surface texture and the voids allow water to drain from beneath vehicle tyres during rain, thereby reducing the risk of aquaplaning. Also called 'porous asphalt' and 'popcorn mix'.

Pavement concession One-off or ongoing permission granted at the discretion of the airport manager/owner to permit operations by aircraft with an ACN that exceeds the runway's published PCN.

PCN (pavement classification number) A number expressing the bearing strength of a pavement for unrestricted operations.

Polymer modified bitumen (PMB) Bitumen that is improved by the addition of polymers, usually 3-8% by mass. Polymers can be elastomeric (rubbery) or elastomeric (hard) and result in higher performing bitumen for asphalt production and/or spray sealing. Different PMBs have advantages and disadvantages and polymer must be thoroughly blended into the bitumen and care must be taken to prevent subsequent degradation or segregation of the PMB.

Porous asphalt friction course See open graded friction course.

Priming. The spraying of a low viscosity (ie. very fluid) bituminous material, often cut-back bitumen or bitumen emulsion, onto a prepared pavement to ensure that the subsequent sprayed seal or bituminous concrete layer will adhere properly. The prime should be 'thin' enough to penetrate the pavement by 5–10 mm, and bind the fine dusty fractions of the pavement together. It should not be so 'thick': that it sits like a skin on the surface but should not be so 'thin' that it penetrates the pavement too far thereby failing to bind the surface fines together.

Pre-mix asphalt Proprietary materials for emergency and temporary repair of pot holes and other defects in pavements. Available in 20 kg buckets and larger bags, the bituminous binder hardens once exposed to air and the material is compacted. Once compacted and in place, the material is similar to hot mixed asphalt but is not considered to be durable.

Preservation Usually referring to asphalt surface layers, the application of a thin layer of bituminous or similar product to extend the expected life between asphalt overlays.

Rejuvenation See preservation.

Residual bitumen The bitumen left on the pavement after water or solvent has evaporated from sprayed bituminous emulsion or cutback bitumen respectively. For example, since bituminous emulsion usually consists of water and bitumen in equal parts, 0.8 litres per square metre would have to be sprayed to produce 0.4 litres per square metre of residual bitumen.

Rubberised bitumen Bitumen that is modified by dissolving a percentage of rubber (2–7 per cent) in it for improved asphalt and sprayed seal performance. Rubberised bitumen softens less than bitumen with increasing temperature and hardens and embrittles less than bitumen at colder temperatures. Consequently, hot weather rutting and cold weather cracking are both reduced.

SEST (surface enrichment spray treatment) A light bituminous spray treatment applied to an asphalt or sprayed seal surface to extend the life of the bituminous binder, to seal fine cracks and to assist in retaining surface stones. Also referred to as a 'fog spray'.

Sprayed seal A pavement surfacing constructed by spraying the surface with hot bitumen, then spreading a layer of stones and pressing them into the adhesive bitumen.

Stabilisation Improving a pavement subgrade or layer by mixing an additional material with it. The additive may be other granular material, cement, lime or bitumen, chemical additive or a combination of the above

Stone mastic asphalt (SMA) A rut-resistant asphalt used as a thin (2–3 stones thick) surfacing layer. It contains a high proportion of course stones so as to achieve a stone-on-stone skeleton to resist deformation. The spaces between stones are filled with a stiff, impermeable mastic of polymer modified bitumen and filler to which fibres have been added to prevent the bitumen from draining out of the aggregate during production and transportation.

Subgrade The upper part of the soil, natural or imported, upon which the pavement is built.

Sub-base course The pavement layer or layers of selected material placed on a subgrade to support a base course.

Surface layer (wearing course) The top layer of a pavement structure.

Surface texture The surface texture of a pavement is measured by the sand patch test or by laser survey of the pavement surface.

Unbound pavement (granular pavement) An unbound pavement is composed of individual stone particles, or 'aggregates', that are not bound (i.e. not 'glued') to each other. Loads are transmitted through the pavement structure via the normal and frictional forces developed at the point contacts between particles. Because no 'glue' is involved, tensile forces cannot be resisted and cannot develop. Therefore, the concept of fatigue cracking is not relevant.

Uniform grading A potentially confusing term, referring to a mixture of stones in which most are of similar size. When applied to gravel or crushed rock, for example it would mean that they were not 'well graded'. A sealing aggregate should be uniformly graded. A base course gravel should be well graded.

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