Feasibility of recycling thin surfacing back into thin surfacing systems

Most highway authorities have already experienced the impacts of climate change on their operations in recent years which have caused damage, accelerated deterioration, disruption and increased costs. The accepted climate models for the UK predict that by the 2050’s the UK in general will experience: drier, hotter summers; milder, wetter winters; more extreme rainfall events; and a rise in sea levels. The detailed changes vary across the country.

The Department for Transport commissioned TRL to improve the understanding among local highway engineers of the implications of the predicted change in climate parameters, such as rainfall and temperature, for highway pavements and how the impacts might be minimised. This report provides the detailed technical information which is the basis for a DfT guidance document, Maintaining Pavements in a Changing Climate.

This technical report describes the impact climate has on the different types of pavement; asphalt, concrete, modular and unbound. The vulnerability of a pavement to climate depends on factors such as pavement type and condition, local geology, traffic flow and proximity to hydrological features. The key climate variables for pavements are temperature, precipitation and soil moisture. The report describes the implications of changes in these variables for the maintenance of the different pavement types. Case studies are used to illustrate the types of impacts climate has had on highways.

Recommendations are given on how to adapt to the changing climate and advice is provided for highway engineers on assessing the risk of different climate hazards for their network. The use of adaptive maintenance practices such as permeable pavements and polymer modified binders is encouraged. Other more general actions, such as improving the overall condition of the pavement and providing adequate drainage systems are also encouraged.

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Published by
TRL
Crowthorne House, Nine Mile Ride
Wokingham, Berkshire RG40 3GA
United Kingdom
T: +44 (0) 1344 773131
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E: enquiries@trl.co.uk
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Price code: 4X
ISSN 0968-4093

Published Project Report
PPR184

The effects of climate change on highway pavements and how to minimise them: Technical report

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The effects of climate change on highway pavements and how to minimise them: Technical report

by T Willway, L Baldachin, S Reeves, M Harding, M McHale, and M Nunn

PPR 184
Client’s Reference: PPRO 04/37/03

PUBLISHED PROJECT REPORT
THE EFFECTS OF CLIMATE CHANGE ON CARRIAGEWAY AND
FOOTWAY PAVEMENT MAINTENANCE: TECHNICAL REPORT

by

T Willway, L Baldachin, S Reeves, M Harding, M McHale and M Nunn (TRL Limited)

Prepared for: Project Record: Contract PPRO 04/37/03 - Impacts of Climate
Change on Highway Maintenance
Client: Department for Transport,
Local Transport Strategy and Funding Division
(Edward Bunting)

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Approvals

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Executive summary

Most highway authorities have already experienced the impacts of climate change on their highways. In recent years, summer heatwaves, droughts and increased flooding have caused millions of pounds worth of damage and a significant amount of disruption to local residents and businesses. These extreme events are likely to occur in greater frequency and intensity in the future as the global temperature continues to rise. There are also less obvious effects on pavement deterioration caused by the increase in average temperature and changes in rainfall patterns. In order to minimise the costs and disruption caused by these impacts, it is vital to plan and adapt to the changing climate, rather than base decisions on the climate we experienced in the past.

DfT commissioned TRL to improve the understanding among local highway engineers of the implications of the predicted change in climate parameters, such as rainfall and temperature, for highways and how the impacts might be minimised. This document provides the detailed technical information which is the basis for a guidance document, *Maintaining Pavements in a Changing Climate* (Department for Transport, 2008), providing best practice and practical advice on choice of materials and construction methods.

This technical report describes the impact climate has on the different types of pavement; asphalt, concrete, modular and unbound. The vulnerability of a pavement to climate depends on factors such as pavement type and condition, but also on location-specific factors such as geology, traffic flow and proximity to water courses. The climate variables identified as having the most impact on pavements are temperature (extremes and average), precipitation and soil moisture. The changes in these variables predicted for the UK by the 2050’s (UKCIP, 2002) are discussed in the report. In general the UK can expect:

- Drier, hotter summers
- Milder wetter winters
- More extreme rainfall events
- Rise in sea levels

The detailed changes vary across the country. The implications of these changes for the highway maintenance of the different pavement types is described. Asphalt pavements are vulnerable to surface damage due to increased temperature, but more severe structural damage is caused by increases in water damage arising from wetter winters and more frequent intense rainfall events. Concrete pavements are less susceptible to water damage, but at risk from expansion beyond the capacity of joints in high temperatures. Case studies are used to illustrate the types of impacts climate can have on highways.

Recommendations are given on how to adapt to the changing climate and advice is provided for highway engineers on assessing the risk of different climate hazards for their network. The use of adaptive maintenance practices such as permeable pavements, polymer modified binders and improved routine maintenance of joint seals is encouraged. Other more general actions, such as improving the condition of the pavement and providing adequate drainage systems are also encouraged.
1 Introduction

Even if we make a significant reduction in greenhouse gas emissions tomorrow, we will need to cope with a changing climate for the next 40 or more years, due to past emissions. It is therefore important to plan and adapt to the climate predicted for the future, rather than base decisions on historic climate. This is particularly important when planning infrastructure, such as highways, that are designed to have a long lifetime.

Climate change is already having an influence on UK highways, for example drier summers causing more incidences of subsidence in South East England and wetter winters creating greater frequency of flooding. These extreme events are likely to occur more frequently in the future. There are also less obvious effects on pavement deterioration from increased average temperatures and changes in rainfall patterns. The impacts of climate change are not experienced uniformly across the UK. In the South East of England, high summer temperatures and drought are of major concern, in Scotland intense rainfall and storms have more impact. Soil type, topographical features, type and condition of the pavement all influence the severity of the climate impacts. Highway engineers have many factors to take into account when planning a highway maintenance strategy of which the changing climate is becoming increasingly significant.

In order to help local authorities assess the changing climate risks to their particular network, in December 2005 the Department for Transport (DfT) awarded TRL the contract PPRO 04/37/030 - Impacts of Climate Change on Highway Maintenance. The aim of the project was to improve understanding among highways engineers of how carriageway and footway pavement materials and designs may perform in the climate predicted for the UK to 2050 and the affect this will have on maintenance requirements. The project aims to provide guidance (Department for Transport, 2008) on maintenance regimes and practices that may mitigate the associated risks of accelerated deterioration or even catastrophic failure. This document provides technical detail in support of a best practice guidance document to be published as a “daughter document” to “Well-maintained Highways – Code of Practice for Highway Maintenance Management” published by the UK Roads Board in 2005.

The UKCIP02 climate projections for 2050 have been used in preparing this report. It should be noted that the climate is changing and what is suitable for 2020 may not be appropriate for 2050 or 2080. Procedures and practices should be periodically reviewed in this light.

It is important to note that this report was written and compiled prior to the flooding events during July 2007 and are therefore not mentioned when referring to extreme weather events and their impacts on the road network.

2 Purpose and scope of report

The purpose of this report is to:

- identify those climate parameters to which pavements are vulnerable;
- the effects of those parameters on pavement performance;
- how those parameters may change under climate change scenarios predicted for the UK in the 2050s;
- the impact of those changes on pavement performance and maintenance requirements; and
- recommendations, where possible, on maintenance treatments and materials that may prove cost-effective in the changing climate.

This includes changed deterioration patterns of pavements and the impact of extreme weather events, such as flooding and drought. The scope of this technical report includes:

- the implications of climate change on the maintenance of the fabric of carriageways and footways, including reconstruction activities; and
• drainage, in so much as inadequate drainage is a prime cause of deterioration of the pavement.

It excludes:

• Structures, embankments, verges, drainage, street furniture and lighting, driver behaviour and secondary impacts. Also excluded are the effects of high winds on bridges and high-sided vehicles, and increased roadside secondary fires on driver visibility.

• Initial highway design and construction

This report draws on existing technical knowledge, experiences of extremes of weather in the UK that might be indicative of the future norm and overseas climatic analogues.

A glossary is provided at the end of the report.

3 Research context

3.1 Local authorities’ responsibilities

Local authorities are responsible for managing and maintaining the majority of roads and footways in the UK. The fundamental responsibilities for highway maintenance are established in the Highways Act 1980 including Section 41 of the Act which imposes a duty on local highway authorities to maintain all highways maintainable at public expense within their areas, (with the exception of trunk roads and motorways, which the Highways Agency manages on behalf of the Secretary of State). More generally, the Local Government Act 1999 (The Stationery Office Limited, 1999) provides for the general duty of Best Value, imposing a duty on defined local authorities to:

• To ensure that services are responsive to the needs of citizens not the convenience of service providers

• To secure continuous improvement in the exercise of all its functions having regard to a combination of economy, efficiency and effectiveness.

Local authorities are guided in meeting these duties by:

• Codes of practice specifically for local highway authorities

• Case law and precedents arising from claims and legal proceedings

• Technical specifications, including the United Kingdom Pavement Management System (UKPMS)

• Highways Agency guidance aimed primarily at maintenance of the motorway and trunk road network

Guidance on design of highway maintenance works is provided in the current versions of the Design Manual for Roads and Bridges published by the Highways Agency. The Highways Agency is currently reviewing the Design Manual for Roads and Bridges, in order to assess which standards may need revision in the light of expected climate change.

Similarly the Agency publishes guidance on maintenance practices on Trunk Roads as the Trunk Road Maintenance Manual and a Manual of Contract Documents for Highway Works, Volume 1 Specification for Highway Works.

There are a wide range of technical specifications for materials, products and treatments for highway works. Some of these are obligatory, but many provide for significant discretion in their application to particular circumstances. Whilst not undervaluing technical specification and guidance, this discretion is important. If too high a specification is set, this will not only increase costs for the specific scheme, but may have implications for the maintenance of the remainder of the network and may reduce the potential for sustainability when resources are scarce.
UKPMS is the national standard for management systems for the assessment of network conditions and for the planning of investment and maintenance in the paved area of roads, kerbs, footways and cycle routes on local roads within the UK. UKPMS utilises inventory and condition data from both visual and machine surveys to propose options and requirements for remedial works based on projections of future condition using historic and engineering models of deterioration.

Whilst there are many examples of authorities making use of the full UKPMS functionality, the recommended treatment options are taken as guidance and used by the authority’s engineers along with their professional and local expertise and experience to determine the best value solution within local constraints. For example, whilst UKPMS may recommend a stretch of carriageway be planed off and resurfaced, authorities may choose to sacrifice kerb upstand to allow the cheaper option of a thin surfacing in order that equally urgent work be done elsewhere on the network. This selection of apparently cheaper options is particularly prevalent on non-principal and unclassified networks. Similarly there has been widespread use of thick micro asphalts on footways rather than more substantial regulating and resurfacing.

The first Code of Practice for Highway maintenance endorsed by the local government associations was published in 1983 and has been revised at intervals to take account of new and emerging developments in technology, policy and good practice. Whilst the Codes are non-statutory and do not provide detailed technical standards they are the yardstick by which courts will judge whether authorities have been reasonable in the provision of the highway.

The 2001 revision of the Code – “Delivering Best Value in Highway Maintenance” promoted the adoption of an asset management approach to highway maintenance, but did not give guidance on what that entailed. This was clarified in 2004 when the County Surveyor Society (CSS) published its “Framework for Highway Asset Management”.

Adopting an asset management approach was further endorsed by the DfT in its guidance for preparing the second round of local transport plans issued in 2004 which strongly recommends the development of asset management plans. In particular the Department requires local authorities to ensure that they “do not allow the total costs of maintenance to escalate by allowing assets to deteriorate to the extent the routine maintenance is no longer possible”. The guidance goes on to suggest that Local Authorities should be moving towards a whole-life maintenance approach to existing assets, and be able to demonstrate that they are exploiting their existing asset bases to their fullest potential and managing future maintenance liabilities efficiently. Similarly authorities should aim to ensure that maintenance works are not carried out more frequently than necessary.

To this end, to the extent that future climate change can be predicted, local authorities should anticipate it in their choice of maintenance materials and techniques, to minimise the whole life cost of the asset.

In July 2005, the Roads Board published a further update of the Code, “Well-maintained Highways”, which not only further endorsed asset management, but recognised the significance of climate change to delivering best value in management of the highway asset.

The Code acknowledges the key climate changes and implications for highway maintenance for the UK identified in the report “The Changing Climate: Impact on the Department for Transport” 2004. It cites a study undertaken by Cambridgeshire County Council to assess the potential financial implications of climate change for highway maintenance focussed on the impact of hotter, drier summers on summer maintenance costs and the impact of milder winters on winter maintenance costs. The study, which was based on the UK Climate Impact Programme scenarios and costing guidance (Metroeconomica, 2004) concluded that the substantial costs associated with road subsidence and surface damage arising from an increase in the frequency if hot dry summers are partially offset by cost savings in winter maintenance as a result of milder winters in a ratio of between 3:1 and 5:1.

The Code identifies the effect of high temperatures on running surfaces as likely to be the main consideration for the highway maintenance service. High temperatures can damage bituminous surfaces both by reducing skid resistance and increasing susceptibility to rutting. In very extreme
conditions concrete roads can suffer acute damage as a result of expansion beyond design predictions resulting in pop-outs and may need complete reconstruction.

Section 14 of Well-maintained Highways (Road Liaison Group, 2005) recommends that “authorities should research the likely effects of climate change for the delivery of highway maintenance services, taking into account their geography, topography and geology. They should identify risks particular to the authority, and plan, so far as practicable, to mitigate them”. The Code also recommends that the highway maintenance industry needs to adapt to climate change including collaborating to develop new and improved material, methods of construction and procedures.

To this end, local authorities need to anticipate climate change in their choice of maintenance materials and techniques, in order to minimise the whole life cost of the asset. In central government guidance (Local Government Association, 2003) it is suggested that local authorities should “assess the plausible range of future scenarios to determine the best degree of future-proofing for fixed long-term installations” and that “highway maintenance engineers should consider re-examining road structural design in response to drier summers and flood-proof roads which now face an increased risk of flooding”.

Whilst the investigation of the effects of climate change on maintenance of highway drainage is outside the scope of this proposal, the effects of inadequate drainage of the pavement structure must be considered as a root cause of deterioration.

“The Changing Climate” recommended that the Roads Liaison Group should provide guidance to local authorities on identifying the main climate change issues to be taken into account when planning road maintenance. To that end, the Department commissioned this research on behalf of the Roads Board to run alongside and complement the review of climate change adaptation requirements associated with the DMRB initiated by the Highways Agency earlier in 2005.

3.2 The changing climate in the UK

The Hadley Centre at the Meteorological Office is the UK’s official centre for climate change research. It uses supercomputers to model the changes in the global climate for the rest of the century. The UK Climate Impacts Programme (UKCIP) uses the output of these models to produce scenarios for the future UK climate. The current scenarios, UKCIP02 were used in this report (UKCIP, 2002). The next set of scenarios, UKCIP08 are due in 2008 and are being designed to be presented in a probabilistic manner, and therefore be more suitable for risk-based decision making.

The future climate scenarios are described in more detail in Section 8, but can be summarised as:

- Wetter and milder winters
- Drier and hotter summers
- More extreme rainfall events and storms
- Rising sea levels

The greatest changes will occur in the south east of England, the most heavily populated and prosperous region of the UK, but effects will be felt all over the UK. Some of the effects of extreme weather and the impact they can have on highways is already becoming evident throughout the UK, for example, the flooding in Boscastle in 2004 and subsidence in south east England caused by drought in 2003. These kinds of weather events will become more frequent in the future.

3.3 The need to assess the impact of climate change on highways

Highways are designed based on historic climate, however during their design life they could well be subjected to a very different climate. The cost of not taking this into consideration could be vast in terms of disruption to traffic, public safety and infrastructure repairs.

Highway drainage is repeatedly found to be incapable of coping with more prolonged and heavy rainfall not only resulting in increased flooding, but also deterioration of the pavement structure.
More frequent extremes give a sample of what may be normal within the next 40 to 50 years. By preparing for the future climate there is a chance of reducing this cost.

A change in climate will influence the most cost-effective method of carrying out highway maintenance. Climate change can both increase deterioration rates, necessitating more routine and structural maintenance, and create more severe damage through increased frequency of extreme events. The climate often interacts with other factors which further influence deterioration, for example, heavy traffic and extreme temperatures combining to cause more severe rutting.

A number of reports have highlighted the need for guidance on adapting UK highways to the future climate, both to prevent disruption to the public and decrease local authority maintenance costs.

In the report “The Changing Climate: Impact on the Department for Transport” (DfT, 2004) the key implications of climate change for highway maintenance were identified as:

- Increased risk of flooding from rivers, seas and inadequate drainage
- Deterioration and damage to highway structures from subsidence, heave and high temperatures
- Damages to structures from high winds
- Increased road safety problems as a result of adverse driving conditions and deterioration of infrastructure
- Effects on the management of trees, landscapes and biodiversity.

The London Climate Change Partnership (2006) also listed potential impacts. These are

- Carriageway rutting
- Embankment subsidence
- Deterioration of concrete
- Problems with expansion joints
- Increase in dust levels
- Reduction in skid resistance

The Changing Climate report also recommended that the Roads Liaison Group should provide guidance to local authorities on identifying the main climate change issues to be taken into account when planning road maintenance.

4 Climate and pavements

4.1 The influence of climate on pavements

Climate is defined as the regular weather conditions for an area. Weather is the day to day manifestation of this climate. Climate has a large influence on pavement construction and maintenance. Currently, the past climate is used to plan construction and maintenance activities. However, changes in the climate mean that practices currently used may not be appropriate for the future climate and therefore for the full life of the pavement. New highways are designed and constructed with a nominal design life of up to 40 years with the expectation that periodic replacement of the surface course will occur every 10 to 20 years. Ensuring highway construction and maintenance carried out now is suitable for the future climate is essential to prevent premature deterioration.

The weather has always been one of the primary factors that affect the performance of both carriageways and footways. However, the extent to which climate affects the pavement also depends on many other factors such as the characteristics of the pavement (materials, structure and
condition), traffic, underlying geology, geography and topography. Each of these may in themselves present a hazard to the pavement. In general the consequences of these hazards are deterioration of the surface, underlying layers and structure of the pavement and occasionally, in the event of extreme hazards, such as weather or traffic loading, catastrophic failure. The factors are also interlinked, for example greater traffic damage will occur to a pavement when it is wet. Similarly, high temperatures and a large volume of Heavy Goods Vehicle (HGV) traffic may not be sufficient separately to cause rutting, but when experienced together may result in deformation. Other problems such as diesel spills may only cause problems when certain climate conditions such as elevated temperatures exist.

In general, climate change will not introduce new consequences for the pavement, but increases the likelihood and scale of deterioration or catastrophic failure occurring as a result of the range of hazards presented. For example, there has always been a risk of rural roads on clay soils cracking as a result of shrinkage; however, the increased likelihood of hot dry summers following wet warm winters magnifies both the likelihood and scale of damage occurring.

4.2 Pavement characteristics

The characteristics of a pavement, including its vulnerability to climate will be determined by both the materials from which it is constructed and its design structure.

4.2.1 Pavement materials

The main types of material used on local authority roads are asphalt or concrete, but modular surfaces are increasingly used in shopping centres and residential areas.

Footways are most commonly surfaced with asphalt, but modular paving and concrete are also used. Thin flexible or thin rigid footways are constructed similarly to road pavements, but without the structural layer as they are not designed to take heavy vehicular traffic (although, they may be designed to withstand vehicle overrun). Figure 4.1 shows the structure of different types of footways designed for pedestrian-only use.

Cycle routes are generally part of the carriageway or the footway but where they are separate they may have unbound surfaces.

4.2.2 Pavement design

There are three different fundamental pavement structures, each of which is considered in this report:

**Asphalt pavements** – this covers a wide spectrum of pavement types which include fully flexible at one extreme and flexible composite at the other. These pavement types all have asphalt surfacing courses. However, the primary load spreading layer, or base layer, of a fully flexible pavement is asphalt and for flexible composite pavements it is a hydraulically bound material. Between these two extremes the base layer can include foamed or bitumen emulsion stabilised materials. They may also include the use of recycled aggregates, secondary aggregates or primary aggregates, as well as blends of bitumen and hydraulic binders.

**Rigid pavements** – these include rigid and rigid composite. The predominant load spreading course in these pavements is concrete. However, in a lot of cases the concrete layer will have been surfaced with a thin layer of asphalt.

**Modular pavements** – There are various types of modular paving. In this sense, modular means slabs, blocks or stone setts.
Pavement design and maintenance guidance is provided by Volume 7 DMRB. Various Parts of this document describe the different aspects of the pavement design. Interim Advice Note IAN 73/06 (Draft HD 25) provides additional material on pavement foundations. Additional guidance on the design of footways and cycle tracks is provided in AG26 (TRL, 2003).

Whilst local authorities may take account of this guidance, the construction of local highways, their use and the expectations of their stakeholders, particularly for non-principal and unclassified networks, are very different to trunk roads and motorways. Indeed many local authority roads were originally constructed before modern design standards were developed and their subsequent maintenance has often been little more than adding a new thin asphalt surface when required. As a result the structure of many of these roads has evolved over time and is unlikely to conform to existing standards. The structure may be unknown and vary throughout the length of the road.

4.2.2.1  Asphalt pavements

Asphalt pavements have several distinct layers, the names of which change from time to time. Currently they are, from the top surface: surface course, binder course, base, sub-base, capping and subgrade. The surface course and the binder course are often referred to collectively as the surfacing layers. The base is the main structural layer in the role of load spreading, although the binder course provides significant contribution. The sub-base, capping and subgrade are together known as the foundation. See Figure 4.2 for a summary illustration based on that found in the DMRB. This describes specified practice for new construction and the terminology used throughout this report.
Existing pavements may be variants of the above layers. Additional guidance is provided by TRL Laboratory Report 1132 (Powell et al, 1984).

In 2004 the versatility of the design method described in TRL Laboratory Report 1132 was increased to give the highway engineer a wider choice of materials and design configurations (Nunn, 2004). This was to facilitate the use of more economic and sustainable designs by making it easier to adopt environmentally-friendly design solutions that make the best use of new materials, recycled materials and a wider range of secondary aggregates and binders (Merrill et al, 2004). It also enabled stronger foundations, incorporating hydraulically bound materials, to be used (Chaddock and Roberts, 2006).

4.2.2.2 Rigid pavements

Rigid pavements comprise a concrete layer, the main structural element, laid onto a bound or unbound subbase layer. In the UK, there are four types of rigid pavements: jointed unreinforced concrete (URC), jointed reinforced concrete (JRC), continuously reinforced concrete pavement (CRCP) and continuously reinforced concrete base (CRCB). For the CRCB there is a requirement of a 100mm thick asphalt surface course. Concrete footways are normally not reinforced.

Jointed pavements, URC and JRC, comprise a series of concrete bays separated by expansion or contraction joints. They mainly suffer from progressive defects occurring at the joints resulting in increased maintenance costs to joints and bays. In general, these are no longer permitted by the Highways Agency for use on motorways and trunk roads, but existing jointed pavements are generally maintained with asphalt overlays. However, with these types of construction special treatments proposed by Coley and Carswell (2006) need to be considered to take into account the large thermal movements at the joints.

CRCP and CRCB were developed to overcome problems associated with joints. They contain continuous longitudinal reinforcement with no intermediate expansion or contraction joints. Thermal stresses within the concrete slab are relieved by transverse cracks, which are held tightly closed by the reinforcement. The elimination of joints within the slab enhances the structural integrity of the pavement and reduces the amount of water penetrating into the pavement and the associated pumping of fine materials, leading to enhanced foundation durability. CRCP and CRCB are currently the preferred rigid pavement construction of the Highways Agency. New designs for CRCP have been proposed by Hassan et al (2005) and are given HD26/06.

Whilst the thermal movements within the slab are relieved by controlled transverse cracking, a considerable amount of movements takes place at the ends (terminations) of continuously reinforced pavements. If this movement is not accounted for, it could cause damage to adjacent pavements or structures. For the CRCP, two termination systems of a ground beam anchorage (GBA) or a wide-flange steel beam (WFB) are commonly used. In both cases expansion joints between four transition bays, constructed as 5m long JRC bays at the slab end, are used to accommodate any residual or unforeseen movements. For the CRCB, only four ground anchor beams are used. CRCP and CRCB are suited to areas with poor ground conditions or on heavily trafficked roads where disruption to traffic for maintenance purposes should be a minimum.

The Government has recognised that noise from passing traffic is a concern for many people and gave a commitment in “A new deal for trunk roads in England”, published by the Department of the Environment, Transport and the Regions (DETR, 1998). It has been stated that the most appropriate noise reducing surfaces would be used in future on roads, where noise is a particular problem.

Further, to comply with statements given in the Government’s “Transport 2010: The Ten Year Plan”, also published by the DETR (DETR, 2000), new and existing lengths of concrete surfaced pavements in England will be required to be covered with a quiet surface, often asphalt.

Rigid pavements are laid on a bound subbase, (see Figure 4.2). Below the base is a similar foundation to flexible pavements. The basic rigid pavement without an asphalt surface is shown below.
4.2.2.3 Modular pavements

Modular footways (pavers and flags) are laid on a sand bedding on top of the sub-base. Modular pavements are an alternative for asphalt and concrete for low traffic roads, shared use areas and footways – they are not generally used for cycle routes. Modular footway surfacings may be concrete or brick pavers, or slabs; slabs are not recommended as surfacing where there will be any vehicular traffic. In some historic town centres stone setts are still in evidence as road surfacing.

On footways the modular surfacing material is generally laid on bedding sand which is placed directly on the sub-base material (Figure 4.1). However, in some areas, slabs (especially on older footways) are laid on hydraulically bound material, applying a small amount of cement or mortar at each corner and in the centre of the slab. In areas which see vehicular traffic, such as pedestrianised town centres or housing estate roads, there is usually a bound base, which can be asphalt or concrete, underlying the bedding sand and modular surfacing, to provide a sufficiently strong load bearing layer.

4.3 Maintenance

The performance of a pavement gradually deteriorates over time, but it can be restored through maintenance. If the prime causes of deterioration are appropriately addressed in the design and the maintenance regime, deterioration can be anticipated and appropriate maintenance planned and undertaken in order to maintain the performance cost-effectively.

Based on a whole life concept, pavements are expected to deteriorate under the effects of traffic, ageing and the weather. Deterioration may occur at the road surface such as wearing of the surface course, loss of skid resistance or surface cracking. Such deterioration may be addressed through surface treatments. In time the structural layers of the pavement may deteriorate necessitating more substantial structural maintenance. This may be accelerated if routine and surface maintenance is neglected or if traffic loading and climatic factors regularly exceed design expectations. In extreme cases catastrophic failure may occur. This may be accelerated if routine and surface maintenance is neglected.

Preventive treatments slow the mechanisms of deterioration by addressing the cause of the deterioration, such as sealing the surface of the road to prevent water ingress. It is not always possible or cost-effective to undertake preventive treatment. A cost-effective regime will minimise expensive reactive treatments by optimising preventive, routine and programmed maintenance.

Levels of deterioration at which preventative maintenance work should be considered are defined in terms of investigatory levels. Performance levels are maintained at acceptable levels by replacing the defective part of the pavement but will then once more follow a standard deterioration curve. Where the performance drops below acceptable levels (intervention levels), expensive reactive treatment is
often required to restore performance. Guidance on cost-effective maintenance regimes is provided in “Well-maintained Highways”.

Thin flexible or thin rigid footways experience some of the same types of defects as flexible or rigid road pavements, although the thinner layers result in a lower thermal mass and hence heat and cool more quickly. In urban areas the heat from buildings can keep the footway surfacings warmer than carriageways.

Defects in modular pavements include rutting, missing paving units, rocking paving slabs, trips between slabs, and cracked slabs.

4.4 Performance measurement

The performance of a pavement can be measured using a number of assessment machines and methods. These include SCANNER, the Deflectograph, FWD, SCRIM or Grip Tester, visual condition surveys, etc. Performance monitoring can also be affected by the climate, for example the measurement of skid resistance is affected by temperature.

5 The vulnerability of asphalt pavements to climate

There are two main types of asphalt pavement: fully flexible (the most common form of construction in the UK) and flexible composite. The hydraulically bound base of a flexible composite pavement can be concrete, and can include secondary aggregate materials such as pulverised fuel ash or blastfurnace slag.

The material in this chapter may also be relevant for rigid pavements which have an asphalt surface.

The performance of these types of pavement is affected by climate, in particular temperature and moisture. This section looks at the impact of climate on materials at all levels within the pavement: on asphalt surfacings and in the main structural layers of the pavement. These functions are interdependent, as structural failure will affect the surface layers and damage to the surface layers can lead to deterioration of the structural layers.

5.1 The effect of climate on asphalt materials

There is a large variety of asphalt materials used for highway construction with different types and size of aggregates, different binders and possibly additives such as fibre or polymer. Recycled and secondary aggregates such as tyre crumb and china clay waste are also used.

5.1.1 Vulnerability to water

Moisture damage can take several forms: the most common being stripping. The term stripping is applied to asphalt mixtures that exhibit separation of asphalt binder film from aggregate surfaces (loss of adhesion) due to the action of moisture, exacerbated by traffic. Stripping is a physicochemical process which is influenced by the nature and condition of the aggregates and the chemistry and thickness of the binder film. It is accelerated by warmer, moist conditions. Generally basic aggregates, like limestone, are less prone to stripping than acidic aggregates, like granite and quartzite, which are more prone. Similarly, more viscous binders are less prone to being stripped and additives, such as amines and hydrated lime, can reduce an aggregate’s vulnerability to stripping.

The amount of stripping that occurs is exponentially related to the void content (Jørgensen, 2002) as the higher the void content the more likely water will be able to enter the material. Therefore the permeability and compaction of the asphalt are important. Stripping tends to begin at the base of the susceptible asphalt layer, because that is where the water is retained, and is usually well advanced before there are any visible signs on the surface. Stripping can lead to localised areas of deterioration and eventually total disintegration of the asphalt layer.

Amines are compounds with the functional group NR1R2R3. They can be added to increase the adhesion of the binder to the aggregates.
5.1.2 Vulnerability to temperature

5.1.2.1 Age hardening

Read and Whiteoak (2003) give an overview of age hardening of bitumen. The tendency for bitumen to harden has been known and studied for many years. Hardening of bitumen can occur during its storage and during the manufacturing process when it is mixed with aggregate, stored, transported and compacted in road pavements. Hardening also continues during the in-service life of the pavement. The hardening of bitumen during the in-service life of the road and the consequential effects on the mechanical properties of these materials are of primary interest for the future performance of the road.

The mechanisms of ageing are complex and Traxler (1961) and Petersen (1984) described the following primary mechanisms involved:

- Oxidation – Bitumen is slowly oxidized when in contact with oxygen;
- Loss of volatiles – Evaporation of volatile components;
- Steric hardening – Reorientation of bitumen molecules and crystallization of waxes;
- Exudation – Movement of oily components that exude from the bitumen into the aggregate;
- Polymerization induced by ultra-violet light from solar radiation.

As asphalt pavements and footways age throughout their service life, hardening of the bitumen binder occurs. In the base and binder courses this hardening is predominantly due to oxidation, although there may be some volatilization, absorption of the oily components of the bitumen by the aggregate and molecular structuring. Changes brought about by ultra-violet light are only important for the top few millimetres of the surfacing layer.

Age hardening increases the viscosity of the binder and this hardening depends on temperature, time and the bitumen film thickness. The hardening process will progress faster with higher pavement temperatures and greater porosity of the asphalt mixture. Lean asphalt mixtures with a high porosity caused by poor asphalt mixture design or insufficient compaction will be more prone to oxidative age hardening of the bitumen.

Excessive age hardening can result in brittle binder with significantly reduced ability to flow. This hardening produces both negative and positive effects. On the negative side, the asphalt becomes less flexible and more brittle. This will increase the risk of pavement cracking and fretting. While on the positive side it causes an increase in the stiffness modulus or load spreading ability of the asphalt mixture and improves deformation resistance.

In thin asphalt pavements age hardening is not desirable. It will decrease the ability of the pavement to flex under traffic loads and premature cracking will result from thermal and traffic induced stresses and strains. In thicker asphalt pavements, with greater than about 200 mm of asphalt, load and thermally induced cracking will be restricted to cracks initiating at the pavement surface and propagating downwards as the result of cyclic thermal stresses.

Hardening of the base and binder course materials of thick asphalt pavements increases their stiffness modulus and hence improves their load spreading ability. Nunn et al (1997) surveyed a number of in-service trunk roads and motorways and found no detrimental effect of age hardening in the lower asphalt layers (Leech and Nunn, 1997). In these pavements, ageing hardening was shown to reduce pavement deflection over time and reduce the risk of fatigue cracking. However, for good surface course performance it is essential that the bitumen in this layer remains ductile and does not harden significantly.

The occurrence of these cracks is dependent on the temperature regime the pavement is subjected to and the ageing potential of the bitumen which is related to its chemistry, mixture design
(volumetrics), level of compaction and the structure of the road. However, higher average temperatures will increase the rate of oxidative age hardening.

5.1.2.2  *Effect of temperature on stiffness*

The base layer is the main load spreading layer of a fully flexible pavement and the stiffness modulus is a measure of its load spreading ability. Asphalt pavements flex like a bending plate under the action of a wheel load. The degree of flexing is controlled by the support of the underlying foundation and the stiffness modulus of the asphalt. The more the asphalt layers flex the greater will be the horizontal tensile strains induced in the lower portion of the asphalt base layer and the vertical compressive strains induced in the subgrade. The higher these strains, the greater the risk of fatigue cracking in the asphalt base layer and structural deformation in the subgrade.

The sensitivity of stiffness modulus of asphalt with temperature is illustrated in Figure 5.1. These results were extracted from the TRL database of stiffness measurements derived using 3-point bending complex modulus test (Nunn and Smith, 1997). This shows that the sensitivity declines as the stiffness increases and that the sensitivity is typically in the range 0.12 to 0.06 per °C.

![Figure 5.1. Temperature sensitivity of asphalt at 20°C](image)

The situation in the pavement is complex as age hardening of the main structural layers of the pavement has the effect of both making the material more brittle and improving its load spreading ability. In thick fully flexible pavements, the age hardening, and hence stiffening, has been shown to benefit the pavement by causing the tensile strains that induce fatigue cracking to decrease and this more than compensates for any loss in crack resistance (Nunn et al, 1997).

5.2  *The impact of climate on the pavement structure*

5.2.1  *Overview*

The surface course of the pavement must provide a safe and comfortable ride for the road user. For this it must be durable and ideally fulfil functional characteristics such as good skid resistance, texture depth, minimise noise and spray and provide a surface that gives a driver a comfortable ride.
To be durable it needs to be able to maintain these functions by being deformation resistant, resistant to cracking and fretting and not susceptible to environmental degradation caused by water, temperature and solar radiation.

The surface course also has a role in protecting the underlying layers. For this it needs to be waterproof to prevent ingress of water to the underlying layers and eventually to the foundation. In the case of porous surface course materials, this role will fall to the binder course. To maintain impermeability, this layer should resist cracking.

To maintain a comfortable and safe ride the surface course should be deformation resistant so that differential rutting along the length of the road does not cause pavement unevenness. Ruts, if they become excessive, will trap water and this will increase the possibility of hydroplaning and poor visibility as the result of spray. A deformable surface will lose texture and skidding resistance more quickly as exposed aggregates will be more readily pushed into the pavement surface.

Age hardening will increase the risk of surface cracking and a brittle binder matrix will reduce the ability of the surface to retain the high PSV aggregates that provide good skid resistance, and fretting will result.

Research has shown that in flexible pavements, the top 100 mm or so of asphalt will deform during trafficking. Therefore, the binder course may be as susceptible to deformation as the surface course but its lower in-service temperature, due to the thermal insulation of the surface course, usually results in acceptable performance.

The road base is the main load spreading layer of the road. However, the binder course makes a significant contribution. This function is performed by virtue of their stiffness modulus and layer thickness. In this role these layers protect the much more vulnerable underlying subgrade from deformation. Any pavement failure emanating from lower pavement layers would require reconstruction of the whole pavement structure. In fully flexible pavements this layer is asphalt and in flexible composite pavements the base is a hydraulically bound material.

The road foundation consists of the subgrade, capping layer and subbase. At the time the road is being built, it acts as a construction platform on which to lay and compact the road base. In-service it provides the underlying support for the pavement. This support is at risk if water saturation occurs at this level. It must therefore be well drained and protected from water ingress.

For satisfactory performance and durability, all asphalt layers must be adequately compacted. For the lower, and thicker, road layers there are compaction criteria, but for the surfacing layer none are specifically given. Therefore, good volumetric design of the mixture is essential to ensure that the voids content is within an acceptable range when fully compacted; a mixture will be susceptible to ageing and fretting if the voids content is high, while a low value may indicate that the mixture is overfilled with bitumen and susceptibility to deformation. Too much bitumen will result in instability as the stone to stone contacts in the aggregate skeleton will be lost. A high air void content will also increase the permeability of the layer to air and water which will make it more prone to stripping and in situ ageing which will ultimately lead to brittle fracture at low pavement temperatures.

5.2.2 Surfacing performance

Until fairly recently, the most widely used surface course material on flexible pavements on the UK’s high speed trunk roads and motorways has been hot rolled asphalt (HRA) with a surface layer of pre-coated chippings that resist polishing. This results in high macro- and micro-textures which provide and maintain a high level of skid resistance. The HRA usually has low air voids content which minimises binder ageing and hardening. However, in order to accept and retain the pre-coated chippings, the asphalt consists of a bituminous mortar in which the larger aggregate particles are dispersed rather than being in contact with each other. Consequently, the deformation resistance of this material depends principally on the properties of the binder and the characteristics of the fine aggregate rather than on interlocking coarse aggregate.
Over the last decade proprietary thin surfacing materials have become the preferred surface course material on UK’s roads including local authority roads. The wide definition of a thin surfacing used by the British Board of Agrément’s Highway Authorities Product Approval Scheme (BBA-HAPAS) (BBA, 2004) is a proprietary bituminous product with suitable properties to provide a surface course that is laid at a nominal depth of less than 50 mm.

Possible surface damage that can occur on asphalt pavements includes rutting, cracking, potholes and fretting. Many factors can contribute to surface damage including traffic loading, aging and climate parameters such as high road surface temperatures and excess water. Surface damage produces poor ride quality and increased tyre noise.

The low albedo (proportion of light that is reflected) of asphalt surfacing means that it is an efficient absorber of solar radiation and during hot summer weather the temperature in the surface course can exceed 50°C. With climate change warming, high surface temperatures will be experienced more often in the future and damage associated with these conditions will become more prevalent.

The function of the surfacing is to provide a safe and comfortable riding surface for vehicles or pedestrians. This includes providing adequate skid/slip resistance and a level un-deformed and low noise surface. It also protects the structural layer of the highway, for example if the surface course cracks water can seep into the main structural layers and eventually into the foundations. Therefore durability and resistance to water are also required. In the following sub-sections the influence of climate on the performance of the surfacing is examined.

5.2.2.1 Skid resistance

Ice is a hazard on both carriageways and footways, but is not covered in this project, except in as much as it causes damage to the structure of the pavement.

5.2.2.1.1 Carriageways

The skid resistance of a pavement surface is related to texture depth (macro-texture) and the PSV of the aggregate (micro-texture). Micro-texture is the most important factor influencing skid resistance at low speeds and macro-texture at higher speeds. The standard of skid resistance required depends on the type of road. Approaches to crossings, traffic lights, bends and junctions require higher friction than straight stretches or roads where sudden braking is less likely.

Skid resistance decreases with surface age and wear. It is also influenced by climate parameters such as rainfall and temperature. The literature suggests that about eight percent of the total number of accidents in dry weather conditions involves skidding, for wet weather it is 27 percent. Surface aggregates provide wet friction by having a rough surface which penetrates water films. This "micro-texture" is polished under traffic in dusty summer conditions and restored during the harsher winter climate (Wilson and Burtwell, 2002). The rate of polishing depends on the traffic flow and the type of aggregate used in the road surface. However, longer dry periods and milder winters may also have an effect.

In addition to the influence of average temperatures, extreme temperatures also have an affect on skid resistance. High maximum temperatures and a prolonged duration of these high temperatures can cause fatting on asphalt surfacings. Fatt ing is when the asphalt binder fills the aggregate voids and then expands onto the pavement surface. It creates a shiny, sticky surface that can decrease skid resistance. High temperatures also reduce the deformation resistance of the asphalt mixture and surface aggregates can be pushed into the surface more easily, resulting in loss of texture.

Surface ruts are expected to develop quicker with higher temperatures and water can collect in these ruts and increase the risk of hydroplaning (see Section 5.2.3 on deformation).
5.2.2.1.2 Footways and cycle tracks

Fattening (Figure 5.2) can also be a slip hazard on footways and the bitumen can be walked into people’s homes and shops. Slip resistance on footways is affected by vegetation growth, such as moss and fallen leaves.

![Figure 5.2. Fatting of bituminous footway (TRL, 2003)](image)

**5.2.3 Deformation resistance of asphalt pavements**

**5.2.3.1 Carriageways**

Rutting is the result of deformation in one or more of the pavement layers caused by traffic loading. Ruts are longitudinal depressions along the wheel tracks caused by the passage of wheel loads permanently deforming pavement materials that lack sufficient internal stability. The load exerted on the pavement is heavily dependant on the weight of the vehicle, normally said to be according to the Fourth Power Law.

Variations in rut depth along the length of a road lead to unevenness and poor ride quality. It also has implications for safety: water can collect in the ruts and increase the risk of hydroplaning, poor visibility as the result of spray and it can affect steering. In extreme cases, and more especially in thin pavements, it can cause loss of structural strength as it reduces the effective pavement thickness.

Deformation manifests itself at the surface of the pavement as ruts. This is the summation of the deformation in all the pavement layers. However, there are two main sources of deformation. At one extreme the deformation is restricted to the uppermost asphalt layer or layers, termed surface rutting, and at the other extreme, the main component of deformation will arise in the subgrade and this is termed structural deformation.

Generally, deformation within the upper asphalt layers does not affect the structural integrity of the pavement unless it becomes excessive. An example of this form of deterioration is given in Figure 5.3, which shows a pavement cross-section in which the rutting can be seen to be confined to the surface course and binder course. Surface rutting can be a problem on heavily trafficked roads used by HGVs and in urban areas where there is slow moving traffic such as approaches to traffic lights.

On the other hand, excessive structural deformation in fully flexible pavements is a symptom of the load spreading ability of the asphalt and granular layers being insufficient to protect the subgrade from the effects of traffic and, if unchecked, it will lead eventually to a break-up of the pavement structure. Measurement of the rutting profile at the surface only, does not identify the source of the rutting. The consequences for pavement design and maintenance depend substantially on whether the deformation originates solely in the surfacing or deep within the pavement structure. The less deformable hydraulically bound base layer in a flexible-composite pavement protects the subgrade...
and hence structural deformation is rarely a problem with this type of pavement unless the hydraulically bound base layer fails.

Historical evidence from the UK trunk road system has shown (Nunn et al, 1997) that deformation predominately occurs in the top 100 mm of asphalt of fully flexible pavements with at least 200 mm of asphalt provided that the pavement is well constructed on a good foundation. It develops at a relatively low rate of typically 0.5 mm/ ms. Thinner pavements can deform at a much higher rate in which a large component of the deformation may occur in the subgrade (structural deformation), especially with pavements on weaker soils.

![Figure 5.3. Non-structural rutting (Nicholls and Carswell, 2001)](image)

The resistance to rutting of the asphalt surfacing depends on road temperature as well as traffic load. At high temperatures asphalt becomes more easily deformed and rutting is more likely to occur, particularly on highly trafficked roads. Research has found that the majority of surface rutting occurs on a few days of the year, when the temperature of the road surfacing exceeds 45°C (Nicholls and Carswell, 2001). There is also evidence that above a certain level of aggressiveness (combination of temperature and wheel load) asphalt materials can become relatively unstable (Weston et al, 2001; Corte et al, 1994). The wheel tracking test (BS 598-110) is used to evaluate the susceptibility of asphalt surfacing to rutting under traffic loading which can be carried out at temperatures of 45°C or 60°C.

Research carried out by TRL in Scotland (McHale, 1997) investigated the link between high temperatures and rutting. High-Speed Surveys were carried out and the measured rutting was compared to the maximum road temperatures between 1995 and 1996. Rutting does not develop in a linear manner and the overall rate of rutting tends to reduce with the age of the road, but higher rates are recorded during excessively hot summers. For a design life of 20 years for the surfacing layers, the average annual rate of rutting should be less than 0.5mm per year. A 10 mm rut depth signals that the distress is becoming serious and needs to be investigated and at 20 mm immediate action is required (DMRB 7.3.2 HD 29/94). This latter condition should not occur very often on trunk roads as earlier maintenance work should have prevented this state being reached, however it may be occur more frequently on lower category local authority roads. The study by McHale (1997) showed that the roads surveyed exhibited greater rutting than this, which would decrease the life to 12-15 years. As expected, a decrease in texture depth was also measured.

The susceptibility of asphalt’s deformation resistance to changes in temperature depends on the type of mixture. In turn, mixture types rely on the aggregate skeleton (such as SMA) being less susceptible than those relying on binder stiffness (such as HRA).
5.2.3.2 Footways and cycle tracks

Rutting can also occur on urban footways, where there is vehicle over run or vehicle access points. Asphalt footways normally have high penetration bitumen for ease of construction and compaction. This together with their relatively thin construction makes them particularly vulnerable to deformation in the asphalt layers and structural deformation by vehicle overrun, especially when high temperatures occur.

5.2.4 Cracking in asphalt pavements

5.2.4.1 Carriageways

Observations have shown that the majority of the cracks in the UK trunk road system initiate at the surface and propagate downwards. This is true of fully flexible pavements and of reflection cracks in as-laid flexible composite pavements (Nunn, 1989; Nesnas and Nunn, 2006). Oxidation and the action of UV radiation cause excessive hardening of the asphalt close to the pavement surface and the material to become brittle over time (Leech and Nunn, 1997). In this condition thermal and load induced stresses can cause crack initiation and propagation. Hotter weather will speed up the oxidation process and make the material more vulnerable to cracking and cooler diurnal temperatures will generate thermal tensile stresses that can cause crack initiation and propagation.

5.2.4.1.1 Surface cracking

Pavement cracking is a complex phenomenon that can be caused by several factors. It is associated with stresses induced in the asphalt layers by wheel loads, temperature changes or a combination of the two. An asphalt mixture, by virtue of the bitumen it contains, displays viscoelastic behaviour. That is, if an asphalt test specimen is strained to a predetermined point, and held constant, a stress will be induced. Depending on temperature, this stress will dissipate more or less quickly. This process is called relaxation. At high temperatures the viscous component dominates and total stress relaxation may take a few minutes, and at very low temperatures relaxation can take many hours or even days.

Cracks occur when the tensile stress and related strain induced by traffic and/or temperature variations exceed the breaking strength of the mixture. At elevated temperatures stress relaxation will prevent these stresses reaching a level that can cause cracking. While at low temperatures, the tensile condition will persist and, therefore pavement cracking will be more probable.

As the bitumen in a mix age hardens during its service life, it causes a progressive increase in the stiffness modulus of the asphalt together with a reduction in its stress relaxation capability. This will further increase the likelihood of pavement cracking.

Pavement cracking takes several forms, the most frequent being:

- Longitudinal cracking, occurring generally in the wheel-path;
- Transverse cracking, that can be in any lane and it is not necessarily associated with the wheel-path;
- Alligator or crocodile cracking, where longitudinal and transverse cracks link up forming a network of cracks; and
- Reflective cracking, resulting from an underlying defect.

Figure 5.4 is an example of transverse surface cracking of hardened surfacing in a UK motorway.
Traditionally, pavement design has only considered load associated cracking in which cracks initiate at the underside of the asphalt base layer caused by repeated pavement flexure under traffic. However with thicker asphalt pavements cracks invariably initiate at the surface and propagate downwards and can be any of the first three forms mentioned above.

These surface initiated cracks are generally the result of cyclic changes of temperature. In thick asphalt pavements, these cyclic, diurnal and annual changes are primarily responsible for crack propagation. In thinner pavements repeated loading by vehicles together with thermal loading will cause any crack to propagate through the remaining thickness of asphalt relatively quickly. Also thinner asphalt pavements that have age hardened are also more prone to cracking by any form of loading. A stiff, relatively thin brittle layer is vulnerable (eggshell effect).

5.2.4.1.2 Structural cracking

Structural cracking is bottom-up cracking of the asphalt base layer. This is considered to be a fatigue phenomenon induced by repeated tensile strains induced at the underside of the base layer by the passage of wheel loads. Thin fully flexible asphalt pavements are more at risk, especially as the base layers age harden.

With thick asphalt pavements this process may not occur as the reduction in the load induced tensile strain as a result of increased stiffness caused by age hardening may more than offset the loss in crack resistance.
5.2.4.1.3 Reflection cracking

A composite pavement consists of a continuously, laid hydraulically bound base under an asphalt surfacing. With cement bound base, a regular pattern of thermally induced transverse cracks appear in the base soon after laying and these begin to appear as reflection cracks in the asphalt surfacing several years later, as shown in Figure 5.4.

Extensive coring of in-service roads in the UK has shown that reflection cracks often start at the surface of the road and propagate downwards to meet an existing crack or joint in the underlying concrete layer (Nunn, 1989). Furthermore, this study has shown that environmental effects rather than traffic loading cause reflection cracks in as-laid composite pavements.

When the pavement is new, the surface course is ductile enough to withstand the thermally induced stresses but as the pavement ages it will progressively lose this capability. The study by Nunn (1989) showed that the occurrence of reflection cracking in as-laid pavements correlated with the strain the surface course could accommodate before cracking. This reduced with age and it is related to the type and volume of binder used.

In their early stages of development, the cracks are not considered to present a structural problem. Once they propagate through the asphalt layer, water infiltration and the pumping action of the traffic will weaken the foundation layers. At the same time the load transfer across the slab will deteriorate, and under these conditions, the cementitious slabs will move under heavy traffic and further cracking, spalling and general deterioration will result. The reflection cracking of a strengthening asphalt overlay over a crack of this nature will be dependent on traffic induced forces and the severity of the crack.

Modelling reflection cracking in as-laid composite pavements has generally treated the asphalt as a passive layer that has to respond to movements in the concrete layer. These models either assume that the thermal opening and closing of the crack in the cement bound layer or shearing caused by traffic will induce a high stress concentration in the asphalt immediately above the crack that will cause a crack to initiate and propagate upwards. These models have not considered that.

A thermal model of a composite pavement, illustrated in Figure 5.6, can provide a qualitative explanation for the observed manner in which reflection cracks initiate at the surface and propagate downwards (Nesnas and Nunn, 2006). The time to onset of this cracking is dependant on:

- temperature versus brittleness relationship for the wearing course;
- the thickness of the asphalt layers;
- the resistance of the binder to age hardening and exposure to the environment;
- the temperature regime during construction and pavement life;
- the spacing of the transverse cracks in the hydraulically bound base;

Figure 5.5. Reflection cracks in flexible-composite motorway
- the thermal expansion coefficient of the hydraulically bound base – this is related to the aggregate used; and
- the type of hydraulic binder used – some slow curing hydraulic binders do not crack transversely during the curing process.

![Diagram of surface initiated reflection cracking](image)

**Figure 5.6. Schematic diagram for surface initiated reflection cracking** *(Nesnas and Nunn, 2006)*

Subgrade heave and shrinkage mainly affects thinly constructed rural roads in high plasticity index (PI) clay areas. Their life can be affected by the shrinkage and heaving movements in subgrade soils. Problems can be caused by high PI soil drying out during periods of drought and then wetting up during prolonged wet periods. The vicinity of trees close to the pavement system which draw more moisture from underneath the pavements, lack of adequate roadside ditches for drainage conditions and poor drainage can compound any problems.

Differential heave or shrinkage in the subgrade can cause pavement unevenness and the asphalt layers to crack. While excess soil shrinkage can cause reflection cracking in the surfacing layers. Any cracks in these roads will allow moisture to enter the asphalt and a pumping action will cause an undermining in the moisture-susceptible subgrade and cause secondary cracking.

### 5.2.4.2 Footways and cycle tracks

In thinner asphalt pavements, including footways, cycle paths and car parks, the processes are likely to be similar to those experienced with carriageways. However, thinner pavements that become brittle will be more vulnerable and relative light loads may cause mosaic cracking *(eggshell effect)*.

### 5.2.5 Moisture damage to asphalt pavements

#### 5.2.5.1 Stripping

Some pavements are more prone to this phenomenon than others, depending on the type of aggregate and binder viscosity. Pavement design, mix design and construction can also influence susceptibility to stripping.

Stripping normally manifests itself as a loss of integrity of the material. Figure 5.7 is an example of stripped material in which dense bitumen macadam could be easily removed from a trial pit with a jackhammer and shovel. Uncoated aggregate and fines can be seen. Stripping is likely to be limited to small areas and if allowed to progress will cause crazing, pumping of fines to the surface and potholes.
Water can enter the pavement and become trapped between two layers of asphalt. The asphalt may then fail as a consequence of repeated hydraulic pressures caused by traffic loading physically scouring the asphalt from the aggregate. The action is so aggressive that all asphalt will probably fail under these conditions. This form of stripping is a mechanical failure of the asphalt pavement system, and moisture sensitivity tests are irrelevant (Kandhal and Rickards, 2001).

To avoid these problems, water should be prevented from penetrating the road surfacing and if it does the underlying layers should not be susceptible to moisture damage. The area of the road that is most susceptible to trapped water is in the region of longitudinal construction joints or asphalt layer interfaces. An example of a problem at longitudinal joints is illustrated Figure 5.8. All the water that collected in the excavated pit seeped out of the saturated, poorly compacted material adjacent to the longitudinal joint. The excavated material is shown in Figure 5.7.

Once water enters the road it can not only travel vertically downwards through cracks and porous material, but it can also travel laterally for considerable distances through material that is often poorly compacted at the horizontal asphalt layer interfaces.
Thin surface courses are now generally used on the UK network. These are proprietary materials and HAPAS accreditation ensures that they are fit for purpose. However, there is a suspicion that with high texture depth requirements and a thin layer, the surfacing is likely to be porous in some locations. These coupled with the high hydraulic pressures generated under a loaded tyre can then force the water into the road, causing the potential for rapid deterioration. This places more emphasis on the layer under the thin surfacing being impermeable to water and thereby protecting the remainder of the road. The high hydraulic pressures at the tyre / pavement surface interface can also cause surface scouring.

Aggregate segregation is another issue that results in asphalt with a high air voids content that is permeable. Segregation is generally localised and occurs where asphalt has a predominance of fine or course aggregate. The separation occurs mechanically during transport and placement of asphalt. Asphalt mixtures manufactured with larger stone sizes are more vulnerable and therefore the move away from using DBM with a 40 mm to a 32 mm maximum aggregate size has helped to reduce the problem. It can result in patches of material that are highly porous.

It is also possible for water to migrate upwards from the subgrade as the result of diurnal temperature gradients. In this process, known as hydrogenesis, moisture migrates upwards if the temperature increases with depth. The term is especially applied to base and soil substrates under highway pavements where a thermal pumping action can cause the inhalation of humid air, which then condenses, causing an ever increasing moisture content and sometimes stripping and instability.

5.2.5.2 Freeze-thaw effects

Water that has entered the pavement is subject to the process of freezing and thawing during the winter. The water expands when frozen and shrinks when melted generating tensile stress in the pavement. This can create cracks which propagate through the structure with each freeze-thaw cycle. The number of freeze-thaw cycles can be increased by de-icers. The vulnerability of the pavement depends on the characteristics of material, such as its porosity and the condition, i.e. the presence of surface cracks. Frost heave will occur if the construction material absorbs water, so good drainage helps to prevent frost heave.

In addition, freezing draws up water from the subbase, increasing the amount of water in the pavement. Freezing of a pavement takes place from the surface downwards, drawing water up from lower levels. Layers of ice form causing the road to expand upwards, i.e. "heave".

Freeze-thaw is less of a problem where winter conditions are such that the ground remains frozen or does not freeze at all.

5.3 Climatic influences considered in pavement design methodology

5.3.1 Fully flexible pavements

Fully flexible carriageway pavements in the UK are designed according to the methodology described by Powell et al (1984). Design is carried out using a standard or equivalent temperature condition of 20°C. The equivalent pavement temperature is the single uniform temperature at which the pavement life is the same as under the temperature distributions occurring in the field. This is a traffic and damage weighted average temperature that takes into account the spectrum of pavement surface temperatures and temperature gradients experience by a pavement in a typical year.

The temperature histogram used was measured in a typical year within a TRL experimental pavement on the Alconbury Bypass. The year that these measurements were made is uncertain but it was prior to 1979. The mean pavement temperature is higher than the mean air temperature. Typically the mean air temperature is in the region of 10°C and the traffic weighted mean pavement temperature is approximately 15°C. Pavement temperatures are higher than air temperatures and damage resulting from asphalt fatigue and structural deformation is approximately related to the fourth power of the traffic induced strain (Powell et al, 1984). These strains increase as the stiffness modulus (load spreading ability) decreases as the pavement temperature increases. Therefore the
relationship between the mean air temperature and the traffic and damaged weighted mean temperature will be non-linear. An increase of 1°C in the mean air temperature may increase the mean traffic weighted temperature by approximately 1.5°C and the traffic and damage weighted mean temperature may increase by approximately 2.0°C. This may not be strictly true, but a more rigorous analysis is required to determine the sensitivity between air temperature and the damage and traffic weighted average temperature would be time consuming.

It should be borne in mind that the behaviour of the pavement and the materials from which it is constructed is highly complex and is not completely understood. A more rigorous analysis may not be justified.

The sensitivity of the structural life of a typical fully flexible pavement has been determined. The construction of this pavement is shown in Table 5.1. The design stiffness is 5.4 MPa for a HDM base incorporating nominal 50 penetration bitumen.

Table 5.1. The reference structure used to assess sensitivity of pavement performance to temperature

<table>
<thead>
<tr>
<th>Layer</th>
<th>Thickness (mm)</th>
<th>Stiffness modulus for standard conditions (GPa)</th>
<th>Increase in equivalent pavement temperature (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thin surface course</td>
<td>35</td>
<td>2.0</td>
<td>1.84</td>
</tr>
<tr>
<td>Base</td>
<td>315</td>
<td>5.4</td>
<td>4.97</td>
</tr>
<tr>
<td>Granular sub-base</td>
<td>225</td>
<td>0.15</td>
<td>0.15</td>
</tr>
<tr>
<td>Subgrade CBR – 5%</td>
<td>Semi-infinite</td>
<td>0.05</td>
<td>0.05</td>
</tr>
<tr>
<td>Nominal Pavement life</td>
<td>36 msa</td>
<td>30 msa</td>
<td>24 msa</td>
</tr>
</tbody>
</table>

Table 5.1 gives the calculated nominal design life in msa (million standard axles) and the predicted sensitivity in this life for a change in equivalent pavement temperature. The pavement life was determined using the method developed by Powell et al (1984). This is the design methodology adopted by the UK Highways Agency. The design life is the time at which maintenance should be carried out to prevent major maintenance. The equivalent pavement temperature used for pavement design in the UK is 20°C and it was assumed that the stiffness modulus of the asphalt is reduced by 8 percent for an increase in temperature of 1°C. As pointed out earlier, the relationship between the mean air temperature and the equivalent pavement temperature is non-linear and a 1°C increase in mean air temperature may equate to an increase in equivalent pavement temperature of about 2°C.

This suggests that the nominal structural life of the pavement, for the example given, will be reduced by about 17 percent for an increase in the equivalent pavement temperature of 1°C. However, this does not reflect the probabilistic nature of pavement life.

A more practical way of interpreting these results is to recognise that pavement life is subject to variability, and that the nominal design life predicted using the methodology described in LR1132 presents the 85 percent probability that the pavement will survive that life without requiring structural maintenance. An increase in the equivalent pavement temperature of 1°C will result in a reduction of the probability of a pavement achieving its design life without requiring structural maintenance from 85 percent to about 81.8 percent and an increase of 2°C in equivalent pavement temperature will reduce this probability to 78.2 percent. Alternatively, to compensate for a 1°C increase in equivalent pavement temperature would require increasing the thickness of the asphalt.
layer by three per cent to retain the same structural life. The design curves for these two situations are shown in Figure 5.9.

![Design Curve for Roads with HDM/DBM50 Roadbase](image)

Figure 5.9. Sensitivity of pavement design to 1°C increase in the equivalent pavement temperature

### 5.3.2 Flexible composite pavements

Flexible composite pavements have a hydraulically bound base course. Traditionally the predominant hydraulic binder used was cement. However, because of concerns about sustainability the design method was modified in 2004 (Nunn, 2004) to give the highway engineer a wider choice of materials and design configurations. The increased versatility allowed new materials, recycled materials and a wider range of secondary aggregates and binders to be used.

The effect of climate on the performance of a cement bound material (CBM) base only will be discussed in this section.

The stresses induced in a CBM base result from both traffic and thermal loading. The thermal component is associated with restrained thermal warping. On a hot day the temperature in the pavement reduces in depth. Unlike with asphalt, stress relaxation cannot occur and the upper surface of the CBM layer expands more than the underside. The slab is restrained from warping by its own weight and therefore a restrained thermal warping stress is generated in the material. Under some conditions the restrained thermal warping stress can be comparable to the traffic induced stress.

In the design method described in LR 1132 (Powell et al, 1984), this stress component was calculated for a pavement temperature gradient typical of a warm day. The result was then combined with the traffic induced component to develop pavement design criteria that were calibrated using performance results from TRL experimental pavements (Nunn, 1992).

The thermal stress component is influenced by the thermal gradient in the pavement, the dimensions of the concrete slab, the flexural strength of the CBM, the insulating effect and the albedo of the asphalt cover and the thermal expansion coefficient of CBM. Because of its greater ability to absorb thermal radiation a thin asphalt covering on a warm day could increase the temperature at the surface of the concrete slab. A thicker layer acts as an insulating layer and reduces the temperature variation.
at the surface of the slab. Thermal considerations have led to thicker designs for gravel CBMs which had a higher expansion coefficient and lower flexural strength compared to crushed limestone and granite CBMs.

An increase in temperature is likely to increase the level of the restrained thermal warping stress and increase the risk of premature cracking of the base course. However this may only apply to flexible composite pavements constructed before the mid-1990s. Two developments have since taken place. Firstly CBM base layers are now pre-cracked transversely at approximately three metre intervals (Ellis et al, 1997). This is to reduce the risk, or delay the onset, of reflection cracking. Reducing the spacing between the transverse cracks will reduce the thermal movements at the cracks that are a causal factor in reflection cracking. Reducing the slab size will also reduce the level of restrained warping stress.

Secondly the more versatile approach to pavement design (Nunn, 2004) now allows other hydraulically bound material to be used. Hydraulic binders such as ground or granulated blast furnace slag (GGBS or GBS) cure more slowly and regular transverse cracks may not be generated in the base course. Therefore flexible-composite pavements using these and similar hydraulic binders will not be so susceptible to cracking caused by climate change.

5.4 Maintenance

Changes in climate can also affect maintenance practice, in particular the construction of asphalt materials. Guidance on the maintenance of flexible pavements is provided by Volume 7, Section 4, Part 1 – HD 31/94 of the DMRB and Well-maintained Highways which itself refers to UKPMS recommended treatments.

During extended periods of hot, sunny conditions, asphalt can remain workable for a considerable time making it difficult to maintain profile during compaction. In the case of HRA surface course with added pre-coated chippings, it may be difficult to achieve the required texture depth. The newly laid surfacing layers of a pavement may also maintain temperatures after opening to traffic that are sufficiently high to allow excessive rutting and the rapid embedment of any chippings, with the latter again causing a reduction of texture depth. The effects are compounded where traffic intensity is high and speeds are restricted. Excessive loss of texture depth and rutting may affect vehicle steering and braking.

The rate of cooling of the asphalt material depends on environmental factors and the characteristics of the material. Higher winds and lower temperatures increase the cooling rate. The cooling rate is also influenced by temperature, thermal conductivity, specific heat, surface albedo (reflection coefficient) and layer thickness. The most important material factor is thickness of the layer, followed by wind speed and the temperature difference between the asphalt temperature and the ambient temperature. For fixed conditions, the cooling time is proportional to the asphalt layer thickness raised to the power 1.8 (Daines, 1985).

An asphalt surfacing needs to cool to a temperature somewhat below 50°C before it can be opened to traffic. A newly laid asphalt layer will not cool sufficiently under conditions of intense solar radiation. Newly laid asphalt has an albedo of close to zero, making it an efficient absorber of solar radiation and hence it will generally be significantly hotter than the day time air temperature. The temperature of asphalt surface course can exceed 50°C in summer. The road surface temperature is normally 35 percent higher than the air temperature, but at times of intense solar radiation its temperature can be up to 75 percent higher.

Differences in thermal characteristics between patches and the original pavement may lead to greater deterioration around reinstatements. Water may also leak into the pavement structure at the joints of patches.

Asphalt should not be laid when ground temperatures are below 2°C or in wet and windy weather. Road materials containing cement shall not be laid when the air temperature in the shade is below 3°C. Asphalt materials should also not be laid when ground temperatures are below 2°C or in wet and windy weather. These conditions will result in the rapid cooling of the bottom of the asphalt
layer, making compaction difficult. This poor compaction will, in turn, result in air voids remaining in the bottom of the asphalt layer.

6 The vulnerability of rigid pavements to climate

Concrete is a versatile material which has many benefits including the ability to resist high temperatures and penetration of liquids, including fuels from spillages. Concrete is not damaged by vehicle fire and it generally maintains its shape and properties. Concrete pavements are able to withstand extremes of hot climatic conditions and are widely used for concrete pavements in the southern European countries and in the southern states of the USA. A CRCP for road construction has the advantages of being a durable material and having a long service life, with the potential to last for an indeterminate period. The high stiffness of concrete provides a good distribution of traffic loading leading to low stresses in the underlying materials. Concrete mixtures can be made with a wide range of materials, including recycled and secondary aggregates and binders, which make it an adaptable material suitable for use in hot climates.

Properly designed and constructed rigid pavements require comparatively little maintenance or repair. Not all defects have the same influence on the rate of deterioration of the pavement. Indeed, some defects evident at the time of construction do not deteriorate with time and traffic and are of little consequence. However, other defects can lead to deterioration of the pavement and will inevitably require maintenance to restore the pavement to a satisfactory condition.

The major parameters associated with rigid construction which climate warming and periods of long high precipitation could affect are considered below.

6.1 Types of aggregates

Road construction has a high demand for aggregates and the coarse aggregate has the greatest volume of the concrete constituents, and so greatly influences the thermal properties of the concrete. Aggregate, for use in concrete, is traditionally specified by a combination of physical and mechanical properties with the belief that the higher the strength of aggregate the higher the strength of the concrete.

The two major types of aggregate used in the UK for road construction are quartz gravel and limestone. Quartz gravel exhibits superior strength properties with a high coefficient of expansion and a low porosity, whereas a limestone aggregate is much softer, has a lower coefficient of expansion and gives a high porosity. When incorporated in concrete, the limestone aggregate gives higher strength properties and lower thermal movement than gravel. Therefore, it can be concluded that the strength and performance properties of concrete are not limited to the mechanical properties of aggregates, but rather a combination of surface texture, mineralogy, particle shape, coefficient of expansion and optimisation of the concrete mixture.

Field observations of CRCP performance in Texas by Guiterrez de Velasco and McCullough (1978) and in the UK by Hassan et al (2005) indicated that pavements built with different coarse aggregates had significant differences in their performance when laid on different types of subbase.

A visual condition survey of CRCP slabs in the UK has shown that the average transverse crack spacing is related to the aggregate type and the foundation type. Figure 6.1 clearly shows the average crack spacing in CRCP concrete with a limestone aggregate was approximately twice that in a quartz gravel CRCP concrete, irrespective of the subbase type.
The long-term performance of CRCP is mainly influenced by medium and wide cracks since these cracks are associated with loss of aggregate interlock, compromising structural integrity, and there is more vulnerability to reinforcement corrosion and deterioration of the foundation from surface water penetration, compromising durability. In HD29/94 (DMRB 7.3.2) medium cracks are defined as between 0.5mm and 1.5mm and wide cracks are greater than 1.5mm. Figure 6.2 shows that for both aggregate types, a higher percentage of medium cracks are found with the unbound subbase than the other subbase types. Only a small percentage of wide cracks were observed, and that these tend to occur more with the quartz gravel aggregate. The percentage of medium cracks for the quartz gravel aggregate was much higher than for the limestone aggregate. Conversely, more fine cracks were found with the limestone aggregate than the quartz gravel. Since a better long-term performance of CRCP is likely to occur if fine and hair cracks (in HD29/94 hair and fine cracks are defined as those with a width up to 0.5mm, with hair cracks observed only with difficulty) rather than medium and wide cracks are present, CRCP with limestone aggregate should perform better than CRCP with quartz gravel aggregate.
In the USA, some states limit the coefficient of thermal expansion of concrete to a maximum value $10.8 \times 10^{-6}$ per °C. In the UK, there is no requirement to control the thermal expansion of concrete pavements. Typical values for siliceous gravel concrete are $11$ to $13 \times 10^{-6}$ per °C and for limestone concrete are $5.9$ to $7.4 \times 10^{-6}$ per °C (Neville, 1995).

The use of low thermal coefficient coarse aggregate is recommended by Jimenez et al (1992). If either a coarse aggregate with a high thermal coefficient is used or hot-weather construction is proposed, provision should be made to minimize the concrete set temperature to maintain the lowest possible thermally induced stresses. The advantages of using aggregates with a low thermal coefficient of expansion is recognised in the UK, and HD26/06 states that aggregates with a thermal expansion of less than $10 \times 10^{-6}$ per °C must be used for concrete with a 28 day flexural strength of 5.5MPa or greater.

6.2 Concrete temperature

Thermal gradients in concrete pavements can create uneven internal stresses which can then give rise to curling or warping, sometimes called hogging, of the slabs. These can be compounded by loading from passing traffic. Large changes in temperature generate thermal contraction and expansion of the slabs which, if not taken into consideration at the design stage, can generate unacceptably large longitudinal internal stresses and excessive movements at joints. For concrete overlaid with asphalt or a TSS, the temperature in the underlying concrete may be modified. Under the present climatic conditions there is no indication that on hot days the top of the concrete, which has been overlaid with asphalt, has a higher temperature range or a higher maximum temperature than concrete with an exposed surface. However, the effects of longer periods of sustained high temperatures on the concrete have yet to be assessed.

The effect of climatic conditions on road temperatures has been determined in three sections of rigid construction, one in Derbyshire and two in Yorkshire, from thermocouples installed at a range of depths in the concrete. The temperatures were recorded for a minimum period of 12 months at 30 minute intervals and, depending on the site, the measurements were made between October 1994 and October 2001. One site comprised lengths of CRCP with an exposed concrete surface, a thin 22mm Ultra Mince (UL-M) surfacing or a thin 40mm Stone Mastic Asphalt (SMA) surfacing. The other two sites comprised lengths of CRCP with an exposed surface and adjacent lengths of CRCB with a 100mm thick asphalt surfacing.

With the advent of global warming, and a change in the climatic temperatures, this temperature data will give an insight into temperatures and temperature gradients experienced in concrete slabs at the end of the 1990s, and before the predicted start of regular high temperature periods.

6.2.1 The monthly maximum and minimum temperatures

The effect of the current range of climatic temperatures on the maximum and minimum slab temperatures which occurred in a month for a CRCP with an exposed surface, CRCP with thin surfacings and a CRCB with a 100mm thick asphalt surfacing were analysed. The maximum air temperatures were generally higher than the concrete temperatures, and the minimum air temperatures were always lower than the concrete temperatures, usually by up to 5°C.

The maximum and minimum concrete temperatures are given as a range of temperatures in Table 6.1. This table shows that the maximum range of average temperatures for concrete with an exposed surface was 35.6°C. When an asphalt overlay was applied the range was reduced by approximately 2°C. As a consequence, the addition of an overlay has not disadvantaged the thermal characteristics of the concrete.
Table 6.1. Maximum and minimum concrete temperatures

<table>
<thead>
<tr>
<th>Site</th>
<th>Period</th>
<th>Overlay</th>
<th>Average concrete</th>
<th>Top of concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Max °C</td>
<td>Min °C</td>
</tr>
<tr>
<td>CRCP</td>
<td>August 2000 – July 2001</td>
<td>None (Exposed surface)</td>
<td>33.4</td>
<td>-2.2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>22mm UL-M on CRCP</td>
<td>33.3</td>
<td>-0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>40mm SMA on CRCP</td>
<td>31.9</td>
<td>-2.0</td>
</tr>
<tr>
<td>CRCB</td>
<td>Nov. 1994 – Oct 1995</td>
<td>None (Exposed surface)</td>
<td>33.2</td>
<td>-1.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>100mm Asphalt on CRCB</td>
<td>32.3</td>
<td>-0.6</td>
</tr>
</tbody>
</table>

6.2.2 Top of concrete temperatures

Temperatures measured at the top of the concrete slab are considered to better reflect the temperatures which will have the greatest influence on the thermal movements at concrete surface cracks.

The results showed that on the CRCP site, the maximum monthly temperature at the top of the CRCP with an exposed surface was up to 5°C greater than the air temperature. With longer periods of hot weather, this difference may become greater. However, on both sites the minimum monthly concrete temperature was higher than the air temperature.

The range of temperatures is also shown in Table 6.1. This table shows that the range of average temperatures for concrete with an exposed surface was 45.0°C. The range of temperatures encountered at the top of the concrete can be up to 9°C greater than the range of average concrete temperature.

6.2.3 Temperatures during a three-day hot period and a three-day cold period

On the CRCP site the concrete temperatures at the top, middle and bottom of the slab were recorded at half hourly intervals over the three day hottest period in summer and the three day coldest period in winter.

The temperatures recorded over the 3-day hot period are shown in Figure 6.3. This shows that on the hottest day, the maximum temperature at the top of the concrete reached 41°C for the exposed CRCP, but only 38°C and 36°C for the concrete with the UL-M overlay and SMA overlay respectively. At the bottom of the concrete the temperature range was much lower, being 6°C, 5°C, and 3°C for the exposed CRCP, the concrete with the UL-M overlay, and the concrete with the SMA overlay, respectively.
Figure 6.3. Slab temperatures during a 3 day hot period
A feature of this period of hot weather was that the high temperatures occurred only over a few consecutive days. However, should high temperatures occur over a longer period, then the concrete temperatures are likely to be increased, since the concrete will have the opportunity to absorb a greater amount of solar heat.

Figure 6.4. Slab temperatures during a 3-day cold period
The temperatures recorded over the 3-day cold period are shown in Figure 6.4. This shows that on the coldest 24 hour period the range between the highest and lowest concrete temperatures at the top of the concrete slabs was small, with values of 5°C, 1°C, and 2°C for the exposed CRCP, the concrete with the UL-M overlay, and the concrete with the SMA overlay, respectively. At the bottom of the concrete, the range of temperatures was even smaller, being 1°C for all three concretes.

Figure 6.3 and Figure 6.4 show that in both the hottest and coldest periods there was time lag, or temperature gradient, between the extremes in air temperature and the extremes in the concrete temperatures. These time lags varied between 1.5 hours at the top of the slab and 6 hours at the bottom of the slab. Where the concrete had the 40mm SMA overlay, the time shift increased to 2 hours at the top of the slab and to 8 hours at the bottom of the slab.

6.3 Cracking

The tensile stresses which develop in reinforced concrete slabs can be relieved by thermally induced transverse cracks. This feature is the \textit{modus operandi} of a CRCP which is designed to form transverse cracks at regular intervals to relieve internal thermally induced stresses within the slab. The transverse cracks are kept tightly closed by the reinforcement which ensures structural integrity, good load transfer and little surface water reaching the foundation. The spacing of the transverse cracks is considered to be a function of the aggregate type, the concrete strength, the amount of longitudinal reinforcement, the friction between the underside of the CRCP and the subbase, and the climatic conditions at the time of paving.

During the very early life, up to 24 hours, of the concrete after paving, thermal cracking can occur because the modulus of elasticity of the setting concrete rises more quickly than the flexural strength and the concrete may exhibit tensile stresses which it cannot sustain without forming a crack to relieve the stress. Large variations in temperature during the initial curing period are more likely to induce large stresses which lead to the formation of cracks. Early life cracking, especially in a URC, will generally arise from the warping stress generated in the night following the day of construction. In particular, slabs paved around noon in the Spring and Autumn, when the temperature range in the first 24 hours is large, are most likely to be affected. This can be shown from the results of transverse crack spacing in a new CRCP section of motorway where paving took place at different times of the year and included a length through a tunnel. An analysis of the transverse crack spacing, after four years, indicated that the largest values were in the sections that were laid when the range of maximum and minimum daily air temperatures would have been least during the curing period. One was in the tunnel where a reasonable constant temperature would be expected, and the other was laid during a period of cold weather over a 24 hour period.

The transverse crack pattern in a CRCP or CRCB is an important factor for a satisfactory long-term performance. Where transverse cracks are induced at a large spacing the cracks themselves may be wide, resulting in a reduction of aggregate interlock and higher stresses on the longitudinal reinforcement, which may eventually rupture and provide a passageway for surface water to penetrate the lower layers. Transverse cracks which are induced at a close spacing and may be connected by longitudinal cracking or areas of bifurcated cracks can lead to a localised defect where blocks of concrete become loose and break away from the surface. These are commonly known as a punchout when pieces of material break away from the surface or a punchdown when pieces of material are pushed into the underlying layers. No cracks of any type are expected in a URC, whereas hair and narrow transverse cracks are a feature of reinforced rigid pavements and do not detract from the performance of the concrete pavement. Generally, the thermal movement across hair and fine cracks in CRCP is small, between 0.03mm/30°C and 0.19mm/30°C, especially in comparison with thermal movements at joints, but under the passage of traffic, and in extremes of climatic temperature changes, especially during freeze/thaw cycles in wet periods, cracks in an exposed concrete surface can deteriorate to the condition where the arris becomes spalled or develops into a pattern of linked cracks.
In the USA, a study by Suh and McCullough (1994) of crack widths in CRCP measured over a relatively short period (9 to 35 days after construction), showed that the season when paving was carried out and the coarse aggregate type were found to be the two most significant factors affecting the crack width for a given age and temperature. Cracks that occurred during the first 3 days after construction were significantly wider than those that occurred later, and so could form a path for surface water to the lower layers. It is believed that the increase in crack width is a function of the residual shrinkage (drying shrinkage after formation of the crack), and an early-age crack will have higher shrinkage than a later-age crack consequently resulting in greater crack width.

Reflection cracking is considered to be the main pavement distress for overlaid concrete pavements and various methods have been applied to prevent such distress. Reflection crack spacing and crack widths can influence the structural integrity and durability of the pavement, and can provide a route for surface water to penetrate to the steel reinforcement and the underlying materials. These cracks open and close with temperature, and when a CRC slab is overlaid with an asphalt surfacing an improved performance of the combined pavement would be achieved by the ability of the overlay to resist reflection cracking and rutting through traffic and environmental loadings. Therefore, it would be beneficial if the asphalt overlay could bridge these cracks and provide a seal to the pavement. A typical reflection crack is illustrated in Figure 6.5.

![Figure 6.5. Reflection crack from underlying crack in concrete](image)

The results from visual condition surveys on CRCP sites with a thin surfacing and CRCB sites with a 100mm asphalt surfacing showed that the numbers of transverse cracking in the overlay were related to a particular site. Only three of the five sites inspected showed signs of transverse cracking in an overlay.

### 6.4 Surface damage

The surface of concrete is generally robust, and deterioration of the concrete from pieces of material or aggregate breaking away from the surface, either close to a joint or in the main slab can be an
indication of freeze/thaw damage, poor compaction of the material or problems with the mixture. Once the surface starts to deteriorate, loose pieces of material may come away and cause a hazard to passing traffic.

Early-life surface damage in particular can be caused from paving in periods of wet weather unless special precautions are taken to prevent the concrete surface being damaged by the water. Rain damage can be manifested as surface damage to the concrete destroying the applied texture. In the past many techniques were used to provide a suitable surface texture, these include wet surface plastic grooving with tines, surface brushing, and cutting grooves in the hardened concrete. More recently, a special surface treatment that exposes the aggregate in the surface of the concrete, and uses specially selected aggregates, has been employed principally to reduce the noise at the tyre/road interface. Problems with the concrete mixture from excessive surface water during curing can lead to high water content which will lead to reduced strength and adversely affect the long-term durability, freeze/thaw damage from lack of air entrainment and the ability for the concrete matrix to retain the aggregate. These problems can be identified as a pattern of crazing on the surface.

Flooding of an asphalt surface on a CRC can lead to the textured asphalt surface becoming clogged with detritus and difficult to reinstate to a satisfactory skid resistance and noise characteristic. An exposed aggregate concrete surface (EAS) used as the surface texture is easily cleaned and can mitigate this problem.

6.5 Joints

Transverse joints, either contraction or expansion, are placed at regular intervals in a length of jointed concrete to relieve the tensile stresses induced by thermal changes during the initial curing period, and then from the effects of daily and seasonal temperature changes. In a CRCP, no transverse joints are placed within the main slab, but only at the terminations since the amount of movement at the ends of a slab can be significant, and if not taken into consideration, can cause damage to adjacent pavements or structures. The two systems of terminations, a Ground Beam Anchorage (GBA) and a Wide-flange Steel Beam (WFB) require expansion joints between transition bays to accommodate any residual or unforeseen movements of the slab end.

The long-term performance of well constructed joints in a pavement is related to the amount of thermal movements from climatic conditions, and has a direct effect on the overall performance of the pavement by allowing a joint to perform satisfactorily. It is important that adequate load transfer efficiency is maintained, differential movement of the slabs either side of the joint is kept to a minimum, and that good support is provided to the slabs at the joint. To ensure the joints are working as intended, the joint gap should be free to open and close and the joints kept permanently sealed to avoid ingress of water and detritus. Water penetration can lead to loss of subbase support, and accumulation of detritus in the joint gap will impair thermal movement of the joint, and could lead to the situation known as a compression failure or colloquially as a “blow-up”. Excessive spalling along a joint arris could be an early indication of sufficiently high stresses which will lead to a compression failure. An example of severe spalling at a joint is illustrated in Figure 6.6.

![Figure 6.6. Example of severe joint spalling (CPMM, 2001)](image-url)
It has been found that CRC slabs can extend by progressively smaller distances in summer, relative to its previous summer position. A possible explanation for this phenomenon is that in winter detritus collects in the crack opening which, in summer during thermal expansion causes the slab to extend more than the previous summer. If the expansion results in only little movement at the joint, and the slab if fully restrained at the ends, compressive forces can build up in the slab leading to a compressive failure. The risk of this occurring is potentially greater in periods of extremely high summer temperatures. This problem can be exasperated because of problems associated with joint sealant failures caused by a lack of bonded area. This effect is not limited to the ends of CRC slabs, but can occur in jointed pavements. An extreme example of sealant failure in a WFB joint in a CRCP termination is illustrated in Figure 6.7.

![Figure 6.7. Debonding of the joint sealant at the WFB (Hassan et al, 2005)](image)

For satisfactory pavement performance of transverse joints in slabs to accommodate seasonal opening and closing, the gap at the joints must remain sealed with a propriety sealant. Sealants are classified according to their ability to perform satisfactorily with the amount of thermal joint movement that a sealant is required to accommodate. BS 6213 (2000) defines this movement as the movement accommodation factor (MAF). Many manufacturers of joint sealants for concrete pavements recommend a MAF class 25, that is, the maximum thermal movement of a joint should not be more than 25 percent of the minimum width of the joint groove. Specifications for expansion joints in concrete pavements given in the Manual of Contract Documents for Highway Works Volume 1 (MCHW1) require that the minimum groove width is 30mm for hot and cold applied sealants. Therefore, in order to comply with the recommendation of the joint sealant manufacturers and to ensure that the joint seal functions as intended, the movement of an expansion joint should not exceed 7.5mm. Examples of adhesion and cohesion joint sealant problems are illustrated in Figure 6.8.
The temperature at the time of construction will influence the initial movements of the transverse joints. Slabs laid in periods of high summer temperatures will be subjected to a larger gap across the joint in winter than slabs laid in cooler summer weather. For a CRCP constructed in winter, an initial seasonal summer expansion at the end of the slab will occur. In contrast, those constructed in summer will exhibit an initial contraction in the first winter.

To determine the amount of movement taking place across joints, movement measurements were made twice a year; once in winter when the ambient temperature was low and again in summer when the ambient temperature was high. The seasonal thermal movements across a joint have been expressed for a temperature range of 30°C, the maximum range of temperature likely to occur in an average year at the time that the measurements were made. However, the actual temperature range could be greater than 30°C since the movement measurements were not necessarily carried out at the period when the maximum or minimum temperature occurred in a slab. For example, typical maximum summer and minimum winter temperatures at five CRCP sites at the time of measurements are given in Table 6.2.

**Table 6.2. Maximum and minimum monitored slab temperatures**

<table>
<thead>
<tr>
<th>Site</th>
<th>Seasonal CRCP temperature</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Maximum (°C)</td>
<td>Minimum (°C)</td>
</tr>
<tr>
<td>Site A</td>
<td>30.8</td>
<td>-3.2</td>
</tr>
<tr>
<td>Site C</td>
<td>32.1</td>
<td>0.6</td>
</tr>
<tr>
<td>Site D</td>
<td>32.4</td>
<td>2.2</td>
</tr>
<tr>
<td>Site E</td>
<td>25.2</td>
<td>-1.1</td>
</tr>
<tr>
<td>Site F</td>
<td>31.8</td>
<td>-1.8</td>
</tr>
</tbody>
</table>

Based on measurements made on jointed slabs, the average seasonal thermal movement across contraction joints in unreinforced concrete pavements has been shown as between 0.15 and 4.4 mm/30°C and, in reinforced concrete as between 3.7 and 10.7 mm/30°C. Values across expansion joints in reinforced concrete pavements were higher, and ranged between 3.9 and
13.0 mm/30ºC. These values indicate that at some joints the movement across a joint exceeded the 7.5mm recommendation of the joint sealant manufacturers for a 30ºC temperature difference.

An outcome of this is that with the Government’s intent to cover new and existing lengths of concrete pavements in England with a quiet asphalt surface, the asphalt overlay is unlikely to be successful in bridging joints in jointed concrete pavements unless special treatments given by Coley and Carswell (2006) are undertaken.

An important consideration in developing designs for a CRCP slab is the amount of thermal movement at the terminations to a slab and at the expansion joints between the transition bays. The movement across expansion joints between transition bays at terminations to CRCP slabs and the end movements of CRC slabs has been reported by Hassan et al. (2005). In both types of CRCP termination expansion joints between transition bays are used to accommodate any residual or unforeseen movements of the slab end. At the CRCB sites the ends are unrestrained and no transition bays are incorporated into the termination detail. The average expansion joint movements at terminations with an exposed concrete surface constructed to the current MCHW3 were 10.5mm/30ºC and 6.3mm/30ºC for the GBA and WFB terminations, respectively. This indicates that the movement at GBA terminations, where the expansion joints have to accommodate the end movement of the CRCP slab and the expansion of the transition bays exceeds the movement across a joint exceeded the 7.5mm recommendation of the joint sealant manufacturers. At wide flange steel beam terminations the thermal movement is accommodated within the steel beam and the expansion joints accommodate any unforeseen movements of the beam. At these terminations the expansion joint movement is less than the 7.5 mm recommendation.

Expressing the seasonal thermal movement across a joint for a temperature range of 30ºC may no longer be appropriate with the effect of global warming on concrete temperatures. Temperatures recorded at CRCP with exposed an exposed surface indicate that a value of at least 40ºC may be more appropriate. With respect to the season thermal joint movements, the amount of movement during a twelve month period would then be equivalent to an increase of approximately 33 percent compared with the movements calculated using the 30ºC range. An example of the effects of applying a 40ºC, rather than the 30ºC, temperature range for expansion joint movements at CRCP terminations constructed to the current MCHW3 is to increase the annual movements from 10.5mm/30ºC to 14mm/40ºC for a GBA termination, and from 6.3mm/30ºC to 8.4mm/40ºC for a WFB termination. In both terminations, the movements would exceed the 7.5mm recommendation of the joint sealant manufacturers.

### 6.6 Compression failure

Until the 1980s, the phenomenon of compression failures in jointed roads in the UK was considered a freak, one-off event although three had occurred as early as 1949. Since then, there have been many repetitions of the phenomenon, especially on two motorways in the long hot summer of 1993. It was noted that immediately prior to the date of the compression failure the daily temperature range was usually greatest. This is to be expected when the sky is clear both at night and during the day (when the long periods of sunshine were recorded). The occurrence of compression failures was found to be associated with the hottest and coldest monthly range of temperature in that year (as indicated by the averages of the daily maximum or daily minimum temperatures respectively). It may be the case that compression failures may be more prevalent after colder winters when joints are more open and there is greater opportunity for the ingress of grit, especially if followed by unusually high summer temperatures. The main cause stems from joint seals not being maintained in a satisfactory condition to keep out any detritus. An example of a compression failure is illustrated in Figure 6.9.
It cannot be assumed that the incidence of hot weather will always result in a compression failure. An analysis of the temperature records showed that, although compression failures do occur at or close to the time when peak temperatures arise, they do not always occur. It will depend on whether or not a section of pavement has reached a critical condition according to what degree the contributory factors are present. Various forms of weakness introduced into pavements have been identified as making them more prone to compression failures, these include temporary repairs using materials that are weak in compression, poor compaction over part of the slab depth during construction, and incompressible inserts for crack inducement used at joints. The very fact that the crack at a contraction joint needs to be induced by creating a plane of weakness will inevitably lead to localised increases in the compressive stresses at the joint. This is because, in forming the plane of weakness, a saw cut is made or materials are inserted into the concrete such that only two thirds, or at the most three quarters, of the slab depth is capable of transmitting compressive forces by direct contact of concrete to concrete across the joint. Any eccentricities at the joint section will offset the centre of thrust away from the neutral axis of the slab, thus making the joint more prone to a buckling failure. The presence of weak material at this section, such as poorly compacted concrete or temporary repair material will increase the stress in the remainder of the section.

Compression failures have also been noticed where a series of transverse joints have not been constructed satisfactorily, and so do not allow any thermal movement. In this case the additional thermal movements cannot be accommodated in those joints that are freely moving.

6.7 Effects of water

Concrete is generally regarded as impervious to water. However, jointed pavements are designed to have discontinuities in the form of joints and CRCP has discontinuities in the form of naturally formed transverse cracks. Water can enter the underlying layers through the poorly maintained joint seals or through wide surface cracks. Water penetrating the lower layers (WSDOT, 2006), can result in movement of material underneath the concrete or, under traffic loading, pumping to the surface of fine material through joints and cracks from underneath the concrete block as a result of inadequate slab support. The effects of water under a slab are:

- Weakening of the foundation and the subgrade by reducing the stiffness of the layers.
- Differential vertical movements at joints leading to stepping.
- Erosion of the unbound subbase and/or subgrade material leading to voiding and decreasing structural support.
Whilst concrete, as a material, is largely unaffected by periods of intense rain, the areas for concern will lie with water penetrating the lower layers and efficient surface drainage to prevent it from becoming a hazard to the travelling public. Both these concerns are described in Section 5.

6.8 Durability of concrete pavements

Water and temperature changes could greatly influence the durability of concrete. Generally, all forms of physical and chemical deterioration of concrete involves water in one way or another. Water acts as the media for carrying out aggressive substances, such as chloride and sulphate ions, from surrounding environments into concrete. The presence of water in concrete influences its hydration and shrinkage properties at early ages and causes damage due to freeze-thaw. High temperatures could accelerate any chemical reactions take place in concrete as well as the rate of penetration of harmful substances. Whereas concrete exposed to cold weather could suffer from low strength development and frost damage.

The main durability concerns related to concrete pavements are reinforcement corrosion and alkali-silica reaction, which are discussed in the following sections.

6.8.1 Corrosion of reinforcement

Discontinuities in reinforced concrete pavements, in forms of cracks and joints, have the potential to allow the penetration of de-icing water causing corrosion of the steel reinforcement. The corrosion of reinforcement is a fairly slow process, usually taking many years to develop, but could be accelerated in warmer and wetter weather. It involves two stages of corrosion, initiation and propagation.

Experience from concrete bridges indicates the onset of reinforcement corrosion takes about 15 to 20 years (Vassie, 1987). This is mainly dependent upon many variables such as the chloride concentration in the vicinity of reinforcement, the quality and thickness of the concrete cover to reinforcement, the number of wetting and drying cycles and the maintenance history.

Hassan et al (2005) reported the corrosion behaviour of CRCP sites in the UK. The initiation period, for the chloride ions to reach the reinforcement in sufficient quantities to initiate corrosion, was found to be between 7 and 12 years. However, the threshold chloride concentration for corrosion initiation was much higher than that of concrete structures.

During the propagation period, the corrosion proceeds at a rate, mainly dependent on the temperature and the availability of both oxygen and water, until a certain unacceptable level of deterioration is developed. When steel corrodes, the cross sectional area of the steel is reduced due to the formation of the brown rust. The rust formed occupies greater volume, several times, than the original reinforcement and therefore generates an internal pressure in the concrete and can result in cracking, known as corrosion cracks. Figure 6.10 illustrates an example of corrosion cracking originating at the reinforcement and travelling up towards the road surface.

![Figure 6.10. Example of corrosion cracking (Hassan et al, 2005)]
When corrosion occurs in CRCP, the corrosion level is much less and more localised on the longitudinal reinforcement than on the transverse reinforcement, coinciding with transverse cracks. As the longitudinal reinforcement bars have greater influence on the structural performance of pavements than transverse bars, there could be no significant consequences of corrosion damage on CRCP in the UK.

6.8.2 Alkali-silica reaction

Alkali silica reaction (ASR) is a chemical reaction that occurs between the alkaline pore solution of the cement paste and certain forms of silica present in the aggregate. The hydroxide ions, from cement hydration, disrupt or dissolve the siliceous aggregate particles forming a gel product. With the availability of moisture, the gel can expand causing internal stresses and consequently cracking. The process of ASR is accelerated at high temperatures and the level of damage is dependent on the presence of a critical amount of reactive aggregate, sufficient alkali and moisture within the concrete. All these factors need to occur at the same time to initiate and maintain ASR and if any of them is absent, damage will not occur.

ASR is believed not to be of great concern for concrete pavement in the UK. Experience in the USA on the use of recycled concrete aggregate (RCA) in concrete pavements could increase the risk of ASR, especially if ASR had previously damaged the recycled concrete. Cuttell et al. (1997) reported signs of localised areas of ASR cracking with widespread distress in concrete pavements constructed with RCA from old concrete suffering from ASR. However, the risk could be much reduced by the use of low-alkali cements and cement replacement materials such as fly ash and slag.

6.8.3 Freeze-thaw resistance

During frost periods, water-saturated concrete is subjected to deterioration due to the effect of frost damage. As the temperature of concrete is reduced water freezes into ice with an increase of volume, which causes an internal pressure on the pore structure of concrete. Cycles of freezing and thawing are therefore destructive when the internal pressure exceeds the tensile strength of concrete. Air entraining admixtures are commonly used with fresh concrete to produce air bubbles to accommodate the increased volume of ice.

With reduced periods of frost in climate changes as well as sealing the surface of concrete pavements with asphalt overlays, the risk of frost damage could be greatly mitigated.

6.8.4 Sulphate attack

Sulphate salts, when present in concrete, react with hydrated cement causing expansive products. The expansion increases under wet conditions and high temperatures. The consequences of sulphate attack include disruptive expansion, cracking and loss of cohesion and strength of concrete.

Sources of sulphate salts could be from contaminated aggregate and from groundwater. Appropriate selection of concrete constituent materials and separation of the concrete pavement layer from contaminated ground water could greatly minimise the risk of sulphate attack.

6.8.5 Summary

Provided that concrete pavement contains no deleterious substances, changes in climate conditions are unlikely to influence its durability. Climate changes would include warmer summers, increased rainfalls and less spells of frosts. Whilst water and heat could accelerate chemical reactions in concrete, appropriate selection of constituent materials could greatly minimise these harmful reactions. Current practice of covering the surface of concrete pavement with asphalt surfacing should reduce the ingress of deleterious substances from the surrounding environment and enhance its durability. The reduced spells of frost period should also contribute to enhanced durability by reducing the amount of de-icing salts used on pavements and the risk of frost damage.
6.9 Pavement design

The use of a CRCP, either as new construction or as a maintenance option, is seen as providing a long-life sustainable structure which should require little maintenance during its life. The properties of the available materials and the new designs should largely ensure that it is fit for the climatic changes forecast. Provisos would be to ensure that there is adequate drainage with the ability to adequately remove the surface water and joint sealant manufacturers can produce sealants which will meet the predicted larger joint movements. Although new and existing lengths of concrete pavements in England are required to be covered with a quiet surface it is considered that a thin surfacing offers little in the way of structural benefit to the pavement.

Proposals for new designs for CRCP thickness based on a range of concrete flexural strengths and different foundation classes were reported by Hassen et al (2005). These new CRCP design curves have been used to update the CRCP and CRCB design curves and are now given in HD26/06 (DMRB 7.2.3). The new design curves specify concrete strength as a flexural strength and give a choice of the three foundation classes with bound subbases. This has the advantage to allow the benefits of a thinner concrete slab on a stronger foundation.

Future developments to the design of rigid pavements in the UK to take into account the predicted change to hotter climatic conditions should be made in light of designs developed in countries with hotter climates, such as those on the Southern Europe or the southern states of the USA.

Recently introduced European Standards from CEN (Comité Européen de Normalisation), which are published for use in the UK by the British Standards Institution (BSI), for the functional requirements of a pavement concrete, are given in EN 13877-2 (BSI 2004). This standard covers tests on the finished concrete pavement and encompasses countries with a range of climatic conditions, from the cold Nordic countries to the hotter Southern European countries.

6.10 Maintenance

Proper maintenance of rigid roads is important if the structure is to have a reasonable expectancy of remaining in a satisfactory condition to achieve its design life. It is particularly important that minor defects do not deteriorate to require major repair. When it is necessary to undertake temporary or emergency repairs quickly using materials which can trafficked in a short time permanent repairs should be made as soon as practical. The recommendations for maintenance and repair of rigid pavements in the UK are given in the HD32/94 (DMRB 7.4.2), and more detailed advice is given in the Concrete Pavement Maintenance Manual (CPMM) by The Highways Agency and Britpave (2001).

The advice given in these two documents covers maintenance for both types of jointed pavement and CRCP, and includes:

- Concrete surface treatments to restore surface texture.
- Full depth repairs for CRCP and bay replacements in jointed pavements.
- Partial depth repairs for shallow surface spalling.
- Joint sealing, joint repairs and joint replacement.
- Under slab pressure or vacuum grouting at cracks or joints with vertical movement. Slab lifting in conjunction with pressure or vacuum grouting at areas of settlement.

The purpose of the repair is to maintain the pavement in a safe and serviceable condition and strengthening is usually required when either, the residual life of the pavement has expired and periodic maintenance has become uneconomic, or, when predicted increases in traffic indicate that the pavement will quickly become unserviceable.
7 The vulnerability of modular pavements to climate

Modular paving is most commonly concrete blocks or slabs, which expand and contract with temperature changes. Modular surfacing is generally laid on bedding sand, and sand is also used as grouting material, to fill in the gaps between adjacent blocks or slabs. Without this gap the modular surface would be liable to crack and deform as it expanded. Modular surfacing is porous and on footways water drains through the surface into the sub-base and the underlying soil. On modular roads the water may drain through to the underlying bound base layer, which should be cambered to allow this water to escape to the road drainage.

7.1 Effect of temperature

Bedding sand supports the modular surfacing and has some flexibility. When a slab becomes hot at the surface the slab will warp; the top surface will expand more than the underneath of the slab, causing it to become slightly concave at the side in contact with the bedding sand. However, the sand has some give, and will continue to provide some support to the entire slab. If slabs are laid directly on concrete support would only be provided to the edges in this case, with the concave centre of the slab unsupported. Slabs on concrete or other rigid bases become very susceptible to cracking with expansion and contraction, particularly if there is any vehicular traffic loading the unsupported centre of the slab. This effect will be increase with larger slabs.

When the temperature cools the reverse happens; the surface cools more quickly than the underneath side of the slab and the slab becomes concave on its top surface. This results in the edges of the slab curling up slightly, again making them susceptible to cracking if loaded and possibly causing trips. Continual heating and cooling, causing expansion and contraction, can cause slabs to crack even if no vehicle loading occurs. Greater extremes in temperature would exacerbate this mechanism.

Concrete modules laid in close proximity are prone to spalling when they expand in hot weather – the expansion causes the edges to butt hard against each other causing edge deterioration. The use of spacers to provide sufficient gap and grouting sand to fill this gap (rather than a rigid cement grouting) mitigates this problem. However, the problem may be more pronounced if extreme changes of temperature occur.

7.2 Effect of water

Water can affect modular surfacing by removing the bedding and grouting sand. Excessive water, such as frequent torrential rain or flooding, may wash out grouting and bedding sand. Removal of grouting sand will allow paving modules to move sideways. This is especially likely to happen in trafficked situations where the traffic will tend to push the blocks in the direction of traffic – especially if traffic is braking. Gaps large enough to trap shoe heels will soon appear and wide gaps will result in trip hazards.

7.3 The effects on structural layers

Although the surface of a modular pavement may provide some load spreading ability (concrete blocks are said to “lock-up” under loading and act as a flexible pavement surface) the structural strength is largely dependent on the pavement foundation – subgrade and sub-base – and any bound layers underlying the modular surfacing. Effects of climate on asphalt and concrete have been discussed in Sections 5 and 6.

Excessive water can drain into the foundation reducing its load bearing efficiency. The effects on the sub-base and subgrade are discussed in section 5.2.6. Water in the foundation will reduce the pavement’s structural capacity and the pavement is liable to deformation under loading. This would not normally be a problem with footways subject only to pedestrian traffic, but could become a severe problem if the footway or other modular pavement is subject to any vehicular traffic.

Deformation of the pavement will lead to movement of the surface modules resulting in cracking and spalling of modules and trips which are hazardous to pedestrians.
7.4 Modular pavement design

Problems due to temperature changes, especially where there may be vehicular use of the pavement, are more pronounced for large paving slabs than for smaller slabs or concrete blocks. New modular pavements should be designed with small element modules, not large slabs, as surfacing. The performance of well designed small element modular pavement surfacings is unlikely to be much affected by changes in temperature. However, the effects of temperature and water on the foundation may have more effect on the pavement because of its porous nature and the lack of load bearing capacity of the surface. For example, continual wetting and drying of a clay subgrade will lead to expansion and contraction and cracking of the clay. This may result in bedding sand movement and movement of surface modules.

7.5 Maintenance

Large paving slabs are most affected by expansion and contraction and by vehicle over-run causing cracking and subsequent trips or rocking slabs. These problems are likely to become more pronounced in more extreme temperatures.

8 The vulnerability of unbound highways to climate

Unbound highways in the UK are mostly footways. They can be damaged by erosion. The erosion of unbound highways is dependant on the number of users and the weather. Warmer weather in summer will increase the number of people participating in outdoor activities such as walking. This disturbs the soil cover making the soil particles more easily removed by the impact of raindrops. The increase in winter rainfall and more intense rainfall events will accelerate the erosion. The presence of protective snow cover on hill paths will reduce and be replaced by an increase in freeze-thaw cycles, breaking down the rock. Paths do not erode at a constant rate, but fail suddenly. Modelling of the erosion process has been performed using the variation of path width, amount of bare soil, and depth of gullying as parameters; these are associated with slope, popularity, rainfall, and, to a lesser extent, vegetation and soil type.

If a path is restored when there is minor damage it can cost around £5,000 (McEvoy, 2006). Without repair it can deteriorate to major damage in as little time as six months. Then the repair costs could rise to as much as £30,000. Steep, heavily used paths can be restored with a set of zig-zags replacing a direct but eroded route. There are best-practice guidelines for path repair and restoration.

9 Vulnerability of foundations to climate

The main purpose of the foundation is to distribute the applied traffic loads to the underlying subgrade without allowing distress in the foundation layers or in the overlying layers during the construction and the service life of the pavement.

The main threat presented by the climate to the foundations of pavements (of asphalt, rigid or footway) is too much or too little moisture.

9.1 Subgrade strength

Water can reach the sub-grade layer below the road pavement by seeping down from cracks in the road surface by capillary action from increased water table levels. Inffective sub-surface drainage can lead to saturation of the unbound pavement construction, loss of fine material, settlement and premature pavement failure. The strength of subgrade soils with high plasticity will decrease significantly once it becomes saturated and can lead to the rapid deterioration in the upper pavement layers. Adding lime and/or concrete to the clayey soil at construction reduces the plasticity of the material and makes it less susceptible to water inundation (Thøgersen, 2006).
Apart from the effect of water on the strength of the sub-grade, prolonged water saturation can have adverse effects on the stability of a highway’s granular foundation layers. If the sub-base or subgrade becomes saturated the amount of aggregate contact and interlock is reduced decreasing shear strength. The presence of water in the voids allows the aggregates to move when load is applied. This can cause rutting or large deformations.

### 9.2 Subsidence

The PI relates proportionally to the shrinkage potential of the soil. Clay soils (present in southern England), have a large PI, contracting and expanding substantially with changes in moisture content. This can cause subsidence (a downward movement) in drought and heave (an upward movement) in floods.

A related problem is caused by differences in soil moisture between verges and the pavement sub-grade. In the UK, verges are wetter than the sub-grade in winter and drier in summer. This leads to moisture transfer. As the clay swells and shrinks with moisture content, this causes the edge of the pavement to rise and fall with respect to the crown producing longitudinal cracking.

Factors which aggravate this effect include impervious urban surfaces, which prevent water from entering the ground and trees near the highway which can draw up a large quantity of moisture from the soil. The Road Research Laboratory (RRL, 1952) recommended that when soil is clay with plasticity index in excess of 35 per cent, forest trees should not be planted closer than 15m from the road edge and planting fast growing trees like poplars should be avoided.

The National Soils Resource Institute at Cranfield University has compiled maps of the different types of soil throughout the country (Figure 9.2). Soil data, maps, site reports, subsidence risk models and so on are available from their website: www.landis.org.uk.

The internal forces present in soil depend on clay mineralogy, soil water chemistry and suction and are balanced by the external forces of applied stress and capillary tension. This equilibrium is influenced by a number of factors acting within the soil-water system. This includes:

- Soil mineralogy- swelling/shrinking potential depends on the amount and type of clay minerals present and the arrangement and specific surface of the clay particles.
- Soil water chemistry- type and concentration of cations in the water, e.g. sodium cations (such as from road salt) increases water adsorption.
- Soil suction - osmotic and matrix suction. Osmotic suction is a function of the chemical activity and mineralogy of the soil and matrix suction is due to the capillary effects of the air/water interfaces.
- Plasticity - swelling/shrinking potential is related to amount of clay sized soil particles.
- Dry density - this depends on compaction.
Micro-scale swelling involves the hydration of clay mineral platelets, and macro-scale swelling is concerned with the high suctions in the capillaries during wetting. Both can cause volume change and associated changes in effective stress.

The plasticity limits are a PL of four percent (a value used for Class 2A – wet cohesive material) and the upper limit is taken as 1.2 percent, a moisture content at which clayey soil has sufficient strength for trafficability. The swelling pressure developed by a compacted clayey fill is a function of the dry density, moisture content, soil type, initial stress state and degree of confinement placed on the soil.

Highway structures or roadside walls or other nearby building may also be affected by subsidence and collapse onto the highway.

10 Climate parameters that impact on highways and how these will change

10.1 Climate parameters relevant to highways

Figure 10.1 summarises the climate variables relevant to highway maintenance available from global and regional climate models. Climate variables can be divided into different types:

- Primary variables- the fundamental features of a climate, such as temperature, wind and precipitation.
- Synoptic variables- climate aspects resulting from the primary variables, such as pressure.
• **Compound variables** - aspects influenced by a number of primary variables, such as humidity which is dependant on temperature, precipitation and pressure.

• **Proxy variables** - factors which give an indication of climate, such as soil moisture, which is dictated by temperature, precipitation and evapo-transpiration.

Of these variables three ‘primary climate variables’ - temperature, precipitation and wind speed and one ‘proxy’ climate variable - soil moisture are most relevant to the weather affecting pavement deterioration. Cloud cover (as a proxy for UV radiation), mean sea level and growing season are also relevant to a lesser degree.

### 10.2 Changes in climate parameters

#### 10.2.1 UK Climate Impacts Programme 2002 (UKCIP02) scenarios

The UK Climate Impacts Programme 2002 (UKCIP02) scenarios are used for this project. The scenarios are based on the Hadley Centre’s Global Climate Model HadCM3 and Regional Climate Model (RCM) HadRM3 that provides outputs on a 50km grid over the UK. The UKCIP02 scenarios are the most detailed climate scenarios available for the UK and consequently are one of the main tools used by Government and the private sector for climate change impacts and adaptation assessments for different sectors of the economy (e.g. see OST, 2004). They provide predictions of the change in climate parameters that the UK could experience. The time slices examined are the 2020s (2011 to 2040), 2050s (2041 to 2070) and 2080s (2071 to 2100). For the purpose of this project projections up to 2050s will be used, as this is the time scale most relevant to highway projects. New climate scenarios for the UK, currently being developed and are due to be released in 2008.

![Diagram of climate variables relevant to highway maintenance](image.png)

**Figure 10.1. Climate variables relevant to highway maintenance**

The scenarios are based on four different emissions scenarios, Low, Medium-Low, Medium-High and High, based on future atmospheric carbon dioxide concentrations of 525, 562, 715 and 810 ppm compared to the 2002 concentrations of approximately 370 ppm (Hulme et al., 2002).

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*Evapo-transpiration, the combination of evaporation and plant transpiration is the loss of water from plant leaves.*
Examples of annual temperature and winter precipitation data from the UKCIP02 climate change scenarios (Hulme et al., 2002) are shown in Figure 10.2 and further maps are included in Appendix A. Predictions vary according to region, with a southeast-to-northwest gradient to the changes. Changes in the south east are generally larger in extent than those in north Scotland.

Figure 10.2. Examples of the UKCIP02 climate change scenarios (UKCIP, 2002)
Table 10.1 provides a very broad overview of climate changes averaged over the whole of the UK. These data are rounded to the nearest degree or percent and obviously mask considerable regional variation that can be seen from the tables in Appendix A.

**Table 10.1. Summary of climate change scenario data averaged for the UK land cells**

<table>
<thead>
<tr>
<th>Climate Variable</th>
<th>UKCIP02 Time-slices</th>
<th>2020s</th>
<th>2050s</th>
<th>2080s</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Precipitation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual</td>
<td>↓ 2%</td>
<td>↓ 3-4%</td>
<td>↓ 4-6%</td>
<td></td>
</tr>
<tr>
<td>Winter</td>
<td>↑ 4-5%</td>
<td>↑ 7-12%</td>
<td>↑ 11-20%</td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>↓ 8-10%</td>
<td>↓ 14-23%</td>
<td>↓ 24-47%</td>
<td></td>
</tr>
<tr>
<td><strong>Temperature (daily mean)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual</td>
<td>↑ 1°C</td>
<td>↑ 1-2°C</td>
<td>↑ 2-4°C</td>
<td></td>
</tr>
<tr>
<td>Winter</td>
<td>↑ 1°C</td>
<td>↑ 1-2°C</td>
<td>↑ 1-3°C</td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>↑ 1°C</td>
<td>↑ 1-2°C</td>
<td>↑ 2-4°C</td>
<td></td>
</tr>
<tr>
<td><strong>Wind speed (average)</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual</td>
<td>Unchanged</td>
<td>Unchanged</td>
<td>↑ 1m/s</td>
<td></td>
</tr>
<tr>
<td>Winter</td>
<td>↑ 1 m/s</td>
<td>↑ 1-2m/s</td>
<td>↑ 2-4m/s</td>
<td></td>
</tr>
<tr>
<td>Summer</td>
<td>Unchanged</td>
<td>↓ 1m/s</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Winter refers to the months of December, January and February. Summer refers to the months of June, July and August.*

The following sections summarise the characteristic changes in the relevant parameters which will be of potential significance to pavement maintenance.

**10.2.2 Temperature profile**

The changes to temperature expected to occur by 2050 are given in Table 10.2.

**Table 10.2. Changes in temperature**

| Characteristic change | Annual average temperatures will rise by between 2°C and 3.5°C depending on the region and scenario. Changes will be greatest under the high emissions scenario in all cases. Summers and winters will be warmer and the chance of extremely hot conditions, such as the heat wave in August 2003, are greatly increased. The temperatures experienced in summer 2003 are likely to be considered “normal” by 2050. As a result an extreme heatwave event is likely to be several degrees hotter than at present. Average lowest temperatures is likely to rise in line with annual average. Average highest temperature likely to rise in line with annual average. Average annual range similar, but possibility of more extreme extremes. Diurnal variations – similar range about a higher mean in line with annual average. Less likely to be freezing; therefore less freeze thaw cycles. Extreme cold days in winter will be less frequent and less intense. However, natural variability will mean that extreme cold periods still occur, but they will become increasingly rare events. |
| Confidence | Regular font = High confidence. *Italic font = Low confidence* |
### 10.2.3 Precipitation

Table 10.3 gives the changes predicted in precipitation.

#### Table 10.3. Changes in precipitation

<table>
<thead>
<tr>
<th>Characteristic change</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual average precipitation across the UK may decrease slightly and snowfall is unlikely in some future scenarios. The main characteristics of rainfall are the increases in seasonality, i.e. greater increases in rainfall in winter and less in summer. These changes are most striking through analysis of 3 month winter (Dec-Jan-Feb) and summer (Jun-Jul-Aug) data. In addition to these seasonal changes there are likely to be changes in rainfall intensity including increases in winter months. The number of winter intense rainfall days (35mm – 45mm in northwest Scotland; 20mm in southeast England) are expected to increase; doubling by the 2080s. Intense rainfall events are expected to become less common in summer.</td>
</tr>
</tbody>
</table>
| Confidence | High for increases in winter  
Medium for decrease in summer |

### 10.2.4 Wind speed

Table 10.4 gives the changes in wind speed predicted for the 2050s.

#### Table 10.4. Changes in wind speeds

<table>
<thead>
<tr>
<th>Characteristic change</th>
<th>There will be some seasonal changes in wind speeds with windier winters and lower wind speeds in summer. However climate models are not particularly good at predicting wind so data should be treated with caution.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Confidence</td>
<td>Low</td>
</tr>
</tbody>
</table>

### 10.2.5 Soil moisture

Changes in soil moisture are given in Table 10.5.

#### Table 10.5. Changes in soil moisture

| Characteristic change | Soil moistures are expected to reduce in all areas, under all scenarios during the summer months. Large reductions in soil moisture contents, particularly in the South East of England with 30 percent reduction by the 2050s and 40 percent reduction by the 2080s under the High Emissions scenario.  
Slight increase over most of Scotland in winter.  
In winter, increases of up to 10% are expected in Scotland, Northern Ireland and Northern England. Southern and central England is expected to see a decrease in soil moisture as increased temperature and reduced humidity increase evaporation rates.  
The pattern and magnitude of soil moisture changes in autumn are similar to those in summer. This is indicative of the long time taken to restore water levels following increasingly dry and hot summers. |
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Confidence</td>
<td>High – reported in UKCIP02. To be treated with caution as local soils are highly variable.</td>
</tr>
</tbody>
</table>
10.2.6 UV radiation/cloud cover
Changes in UV radiation and cloud cover are given in Table 10.6.

Table 10.6. Changes in UV radiation and cloud cover

<table>
<thead>
<tr>
<th>Characteristic change</th>
<th>Slightly increase in Cloud cover in the winter. In spring and autumn cloud cover decreases over all but northwest Scotland. Large decreases in cloud cover in the summer, especially in the south.</th>
<th>Low</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Increases in UV radiation in the summer especially in the south.</td>
<td></td>
</tr>
</tbody>
</table>

10.2.7 Growing season
The changes in growing season are given in Table 10.7.

Table 10.7. Changes in the growing season

<table>
<thead>
<tr>
<th>Characteristic change</th>
<th>Significant increase in thermal growing season length across all regions and scenarios, but the largest increases in the southeast,</th>
<th>High  (Note: this characteristic refers only to the thermal conditions and does not take account of water availability nor day length.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

10.2.8 Sea level
Models predict we are already committed to significant warming and sea level rise. Conservative estimates (Meehl et al., 2005), based on carbon concentrations in the year 2000 (now exceeded) predict an increase in global sea level of 10cm as a result of the change in temperature only. This does not include the melting of sea or land-based ice and other similar factors which could raise the sea level by metres.

Table 10.8 gives the change in sea level predicted for the 2050s.

Table 10.8. Change in sea level

<table>
<thead>
<tr>
<th>Characteristic change</th>
<th>Rise in sea level. Sea level rise is affected by changes in global sea levels, and by local isostatic adjustments following the last ice age. Global sea level will be in the range of 7 – 36cm depending on scenario, to which the local isostatic adjustment must be added (-7 to +11cm depending on region). Sediment consolidation also has an effect and can be very localised and vary over relatively short stretches of coastline. Storm surge levels will also be affected. Models suggest that storm surge height may increase off the southeast coast and decrease in the Bristol Channel. However the uncertainties are very large.</th>
<th>High for global sea level change</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Storm surge – low</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
11 Examples of extreme weather events which have affected pavements

11.1 Local authority case studies

The effects of the changing climate on UK highways are already being observed. Some local authorities have already had to deal with the effects of flooding, drought and extreme temperatures on their network. In the future, these effects will become more pronounced and occur more frequently. Therefore it is important to examine these events and identify any lessons that can be learned about the climate hazards that caused the events, other contributory factors or good practices that can be shared with other local authorities.

124 Local Authorities were asked to provide case studies of weather events which impacted on highway pavements. Whilst around 25 initially volunteered case studies, when asked for documentation of effects on the pavement, few were able to provide it. Those that did normally had collected the information to support bids for additional funding. There was far more information available on the management of the event as it occurred (e.g. traffic management during flooding) which is outside the scope of this research. It appears that the nature of these events is that in the majority of cases, all the authorities’ resources are focussed on dealing with the problem at hand. After the event is over, there is the aftermath and backlog of routine business to deal with and more chronic effects such as damage to the pavement are just added to the existing, often un-quantified backlog and few assessments of the more long term effects are carried out. Although this is understandable, in order to learn from these events, it would be useful if the damage inflicted on the highway could be assessed and documented. In addition, where assessments are made they can be used to inform bids for additional funding from the Government to repair the damage caused.

The information that has been received is summarised below. Case studies all involve carriageways, probably as damage to these causes the most threat to public safety and disruption.

11.1.1 Experiences of flooding causing damage to the pavement

11.1.1.1 East Sussex

In 2000 East Sussex experienced their wettest Autumn on record causing massive flooding. The majority of the main roads became impassable and both short term and long term damage was inflicted on the highway infrastructure. Damage was caused by both the water itself and the force of the current and objects swept along by the flow. When the floods receded debris was left behind on the road surface including vegetation, stones, silt and in some regions sewage, diesel fuel and oil. Specialist road cleaning equipment had to be hired to clear the roads of debris and oil etc. The material removed was classified by the Environment Agency as environmentally hazardous and had to be disposed of in compliance with the prevailing regulations incurring extra costs. The debris also blocked the highway drains and gullies leading to localised flooding every time significant rain occurred. This problem occurred for weeks after the flooding, as the silt was continually washed into the drains and gullies and these had to be repeatedly cleared. Surveys of the road damage and bridges inspections had to be carried out. Other flood damage included:

Road edges erosion: Road edge damage occurred on hundreds of miles of road. Un-kerbed rural roads were particularly affected and the freeze-thaw cycles of the winter exacerbated the damage.

Subsidence and heave: The standing water caused subsidence and heave of the road surface in some regions.

Embankments and culverts damage: Embankments and culverts were washed away leading to collapse of unsupported roads and subsidence.

Landslips: The saturation of the soil and the elevated ground water levels meant any subsequent rain could not be absorbed. Several landslips occurred leading to the closure of roads. The major landslips require specialist investigation by geotechnical and civil engineers in order to find a permanent solution.
East Sussex County Council was also subjected to a large number of claims from residents relating to flooding from the highway. This was caused by insufficient highway drainage and culverts that were too small to cope with the intensity of the rainfall, etc. Local farmers also requested that debris from damaged roads be removed from their fields. This has to be disposed of as building waste creating further cost. The total amount of damage to the highway was estimated to be around £4.4 million. Figure 11.1 shows some of the damage incurred.

![Figure 11.1. Erosion of road surface due to flooding and edge deterioration in East Sussex](© East Sussex County Council)

11.1.2 Hampshire

Prolonged rainfall in the autumn and winter of 2000/2001, where three times the normal amount of rain fell, raised the ground water levels in Hampshire to their highest in 200 years. Due to the geology of Hampshire, the county suffered not only fluvial flooding, but also ground water flooding. The chalk aquifers present in Hampshire and other parts of the south east normally absorb autumn/winter rainfall and slowly release it into chalk streams over the summer. However due to the unprecedented rainfall the aquifers could not absorb all the water and dry valleys and dormant springs were reactivated. A number of these were on or adjacent to highways. This meant many roads were impassable and some rural roads remained flooded for five months. The water logged roads were damaged further by freeze-thaw action in the winter months. Around £1.4 million was spent on emergency repairs, £2.1 million was spent on running repairs and in same cases the whole road structure was damaged requiring remedial work, this cost an additional £5.8 million. The total highway bill including structures and drainage came to around £10 million.

11.1.2 Experiences of drought affecting the pavement

11.1.2.1 Cambridgeshire

The summer of 2003 was very hot and dry for a prolonged period leading to subsidence of road surfaces throughout England and Wales. This was a particular problem in Cambridgeshire as the peat soil of the Fens is particularly sensitive to changes in moisture content. Soil shrinkage caused cracking and deformation of the highways making them unsafe and forcing Cambridgeshire County Council to spend around £1.1 million on emergency repairs. They also carried out a survey of the highway network and identified a large number of additional structural maintenance schemes in need of urgent attention as a result of the drought. This cost a further £3.5 million on top of the scheduled maintenance of £19 million.

Cambridgeshire County Council used the information collected during the summer of 2003 together with the UKCIP02 scenarios to estimate the impact of climate change on their future highway budget. They estimated the additional costs due to subsidence over the period 2010-2100 ranges from £18 to £27 million under low and high climate scenarios respectively. Corresponding total costs in undiscounted terms are between £95 million and £162 million. They also looked at the
savings acquired through less winter maintenance. They estimated that the costs from subsidence outweighed the benefits from less winter maintenance by 3 to 1 or 5 to 1 if there is no discounting. This assumes that future droughts are similar to that experienced in 2003 and that maintenance regimes and the highway network length do not change.

11.1.2.2 Lancashire

Prolonged dry periods are a particular problem for a type of road in Lancashire built on peat, which is referred to as a moss road. In the past these roads were little used apart from by farm vehicles. However with the industrialisation of the area they are becoming commuter networks. The roads have developed over hundreds of years and therefore lack the foundation construction necessary to withstand the increased axle loading. The lowering of the water table for agriculture has left the roads raised several metres above the level of the surrounding fields with steep slopes either side. As the embankments dry in summer the slopes begin to crack, exposing the underlying peat. This shrinks as it dries in summer and then expands during wet winters causing movement of the slope and steps to develop in the road. Further warm weather causes cracking and the road becomes uneven and unsafe within a short space of time. As a result the speed limit has to be decreased for safety reasons. Emergency repairs, filling in potholes, cracks and removal of badly damaged areas, can cost £2,000 to £3,000 per km per year.

In 1991/1992 Lancashire County Council undertook trials to find a permanent solution to this destructive cycle. The options they identified included:

**Recycling the peat:** This involves harrowing the existing surface to a depth of up to 18 inches. The material is broken down as far as possible and additional bitumen added before further harrowing. It is then re-spread and rolled to form a very open-textured surface finish. This is surface dressed to provide waterproofing and a new skid resistant surface. The estimated cost for this option is £35,000 to £45,000 per km.

**Strengthening the road with geogrid:** This requires either the removal of the existing road surface by planing or regulating the original surface prior to pinning a steel mesh reinforcement to the sub-base. The steel mesh (Mesh Track), from Belgium was thought to be the best type of geogrid. Once positioned, the steel mesh is covered with a 'slurry seal' and one or two layers of bituminous macadam are laid on top to bring the road up to its new surface level. The estimated cost of this option is £60,000 to £100,000 per km.

**Completely removing and replacing the peat:** This is the ideal long term solutions and would enable the road to be brought down to the level of the surrounding fields. However this is also the most expensive option, costing an estimated £300,000 per km.
The Council has applied for government funding to carry out the replacement and bring these roads up to the standard of the rest of the network. This will cost in the region of £6 million. Ideally the work will be carried out over the next few years before the drier summers anticipated as a result of climate change cause even more damage.

11.1.2.3 Hampshire

The prolonged lack of rain during the summer and autumn of 2003 led to clay shrinkage and reflective cracking on the highways of Hampshire. In some areas the shrinkage cracks have extended beyond the shoulder into the carriageway and there are many incidents where vertical displacement at the longitudinal crack has occurred. Some of the cracks were 25mm or more wide and extend deep into the sub-grade material. Approximately £400,000 was spent on emergency repairs. These funds were diverted from routine maintenance and resulted in an increase in the maintenance backlog.

The nature of the more permanent repair that was required was found to vary from site to site. Repairs included joint sealing, 100mm inlays, 200mm inlays and geogrids. This is estimated to cost around £3 million. Figure 11.3 shows the large cracks that developed in the bituminous carriageways.

![Figure 11.3. Cracking due to clay shrinkage in Hampshire](© Hampshire County Council)

11.1.2.4 East Sussex

In the dry summer of 2003 highways in East Sussex suffered damage due to the shrinkage and movement of sub-grade. The high temperatures also caused loss of surface texture and therefore decreased skid resistance. The surface required retexturing. However the major damage was in the early Autumn, when the shrinkage of the clay and silt sub-grade caused longitudinal cracking and displacement in older roads that were not constructed up to modern standards. This was particularly apparent where mature trees were close to the verge. East Sussex’s highway network consists of 40 percent concrete roads. These were particularly badly affected, suffering differential slab movement and in some cases broken backs. Uneven signs were erected and emergency repairs including patching, resurfacing and slab raising were undertaken. Cracks had to be sealed in time for winter with more permanent repairs to be undertaken in the Spring. The cost was around £5.6 million. Figure 11.4 shows the cracking and displacement in the bituminous carriageways.
11.1.2.5  Lincolnshire

Lincolnshire County Council have carried out a trial assessing methods of preventing cracking on an asphalt carriageway prone to damage from cyclic changes in soil moisture. The section of the A1073 used in the trial had been subject to longitudinal cracking and severe disruption of the surface profile for several years (see Figure 11.5). The cracks were normally filled with hot bitumen or a bituminous inlay spanning the crack, but the cracks returned within a short space of time. The cause of the damage was identified as the cyclic shrinkage and heave of the underlying clay soils.

In 1997/1998 seven test sections were laid on a 700 metre site on the A1073 to compare methods of preventing damage from soil moisture changes. These included sections composed of one or two sheets of steel reinforcement grid and varying depths of Dense Binder Course (DBC) and also one section with a concrete base. The open drains adjacent to the road were filled in on some sections to move the wetting/drying front away from the road. The sections were monitored over six years using visual surveys, rolling straight edge surveys and transverse profiles to assess their condition. It was found that the sections with mesh and at least 155mm of DBC were in a good structural condition, as was the section built with a concrete base and 75mm DBC. Filling in the drains also helped prevent cracking. The trial demonstrated that geomesh and increasing embankment width can help stabilise carriageways prone to cracking due to soil moisture variations. More research is needed to establish the cost effectiveness of the treatment and the optimum thickness of the bituminous inlay.
11.1.3 Experiences of the effects of high temperatures affecting the pavement

11.1.3.1 Leicestershire

The exceptional heat experience in the summer of 2006 caused significant damage to the rural highways of Leicestershire. As these roads have evolved from cart tracks, they often consist of only a thin bituminous surfacing on top of the track with multiple surfacing dressings laid over the years to preserve the road. The lack of full depth construction as found on the County’s trunk and principal roads make them more vulnerable to heat damage. In July 2006 around 80km of these roads were damaged by the high temperatures. The softened road surface lead to rapid formation of clusters of potholes and wheel track rutting. Loss of texture depth resulted in a decreased skid resistance. The loss of skid resistance is particularly dangerous to motorcyclists and cyclists. Leicestershire County Council used salt spreaders to apply dust to the road surface; temporary filled the potholes and patched repairs. In some cases temporary road closure was required. Temporary repairs cost over £10,000. Permanent repairs to the roads by resurfacing are estimated to cost around £2 million. This expenditure would decrease the budget available to maintain the County’s busier roads and meet performance targets. The Highways and Transportation Department have applied for additional funding to carry out this work.

11.2 Other examples

Many other examples of climate impacts on UK roads can be found in literature and the internet. As with the above case studies, it is the extreme disasters, which are mentioned. These normally consist of the problems associated with highway management during flooding, drought and high temperature extremes.

11.2.1 Excess water

Highway damage due to excess water can be the consequence of flooding, landslides or erosion.

11.2.1.1 Flood damage

One of the most memorable cases of flooding in recent years is in the village of Boscastle on 16th August 2004. In just four hours around 196mms of rain fell. The intense rainfall caused the River Valency to break its banks flooding the village of Boscastle. The damage to highways included water damage, fallen trees blocking roads, stone bridge parapets collapsing when cars were swept into them and footbridges being washed away. Roads had to be completely rebuilt and road bridges foundations were undermined.

Also, in August 2004, a 30 mile section of the A9 between Perth and Pitlochry was shut after torrential rain. Heavy machinery was used to clear thousands of tonnes of mud and debris which poured across both carriageways just north of Dunkeld. The mud was up to 8 foot deep. Motorists could not be diverted because of flooding on minor roads. All traffic to and from the north had to go through Aberdeen.

Figure 11.6. A9 Scotland, August 2004
11.2.1.2 Landslides

Soil erosion by wind, water and frost is a particular problem in Scotland. The soil erosion can cause landslides, blocking roads and footways. Heavy rainfall in Scotland has caused a number of landslides onto roads, as shown in Figure 11.7. Recent landslides include on the A9 in 2002, on the A83 between Glen Kinglas and to the north of Cairndow (9 August), the A9 to the north of Dunkeld (11 August), and the A85 at Glen Ogle (18 August).

Figure 11.7. Damage to A9 Raigmore Slip Road, Inverness, 2002, following heavy rainfall
(Photograph courtesy of BEAR Scotland Ltd)

In the Shetland Islands on 19 September 2003 there was torrential rain causing flooding. The heavy rainfall caused large amounts of peat to slide down the hillslide onto the main road at Channerwick, South Mainland in the Shetland Islands. As a result of this and further floods in August 2004 a review (Shetland Island Council, 2004) was commissioned on flood risks and a workshop on the impacts of climate change was held. This resulted in work being performed to improve culverts and a rain gauge was fitted. The report stated that watercourses had been neglected and that culverts should be designed for a 1 in 200 year storm rather than the current 1 in 100. All culverts and road drains are inspected periodically and more frequently after unduly severe weather/storm conditions. The ‘Novel approaches to mitigation of peat slide risk, an example from Channerwick, Shetland’ received the 2005 Glossop Award (Andrew Mills Halcrow).

Figure 11.8. Channerwick, Shetland Islands, 2003

11.2.1.3 Coastal Erosion

The report by DEFRA and the Environment Agency on Soft Cliffs, (DEFRA and EA, 2002) describes the types of coastal erosion that can occur. Roads and footways along the coast can be
affected by coastal flooding from storm surges and rising in sea levels. This also results in increased erosion. The south east of England is particularly prone to this as the coast is composed of soft rocks which are more easily eroded.

In 2006, large cracks appeared on the promenade along Felixstowe sea front in Suffolk due to coastal erosion. The undermining of the seawall and subsequent movement has damaged the promenade and lengths of it have had to be cordoned off. It was feared the promenade may collapse and emergency work was carried out on 20 May 2006 to protect it. Rock was placed at the base of the promenade wall in an attempt to halt the collapse.

11.2.2 Soil moisture deficit

The most recent wide-spread occurrence of soil moisture deficit was experienced in southern England during the summer of 2003. The reported damage included subsidence, severe cracking and damage from tree roots. Table 11.1 gives the estimated cost of the damage of the 2003 drought by local authorities.

<table>
<thead>
<tr>
<th>Authority</th>
<th>Reported drought damage (£000)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lincolnshire</td>
<td>7,397</td>
</tr>
<tr>
<td>Essex</td>
<td>5,614</td>
</tr>
<tr>
<td>East Sussex</td>
<td>5,568</td>
</tr>
<tr>
<td>Kent</td>
<td>4,167</td>
</tr>
<tr>
<td>Cambridgeshire</td>
<td>3,522</td>
</tr>
<tr>
<td>Hampshire</td>
<td>3,030</td>
</tr>
<tr>
<td>Peterborough</td>
<td>2,400</td>
</tr>
<tr>
<td>West Sussex</td>
<td>2,221</td>
</tr>
<tr>
<td>Isle of Wight</td>
<td>1,500</td>
</tr>
<tr>
<td>Wiltshire</td>
<td>1,302</td>
</tr>
<tr>
<td>Buckinghamshire</td>
<td>1,200</td>
</tr>
<tr>
<td>Surrey</td>
<td>1,000</td>
</tr>
<tr>
<td>Suffolk</td>
<td>750</td>
</tr>
<tr>
<td>Norfolk</td>
<td>650</td>
</tr>
<tr>
<td>Bedfordshire</td>
<td>300</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>40,621</strong></td>
</tr>
</tbody>
</table>
11.2.2.1 Subsidence and cracking

Subsidence occurred due to the desiccation and shrinkage of organic sub strata (e.g. peaty deposits) in the Peterborough area of The Fens during the summer of 2003 (New Civil Engineer, 2003).

Oxfordshire City Council estimated the damage to their network due to soil shrinkage in the summer of 2003 was £4.6 million. This included major reconstruction of a section of the A329.

11.2.2.2 Tree root damage to footways

Hammersmith and Fulham council experienced an increase in subsidence claims in 2003/2004 from £100k to £500k caused by tree root growth (Well-maintained Highways, 2005).

11.2.3 High temperatures

Past high temperatures have caused local authorities to spread rock dust, sand or grit onto bituminous carriageways to absorb melting bitumen and increase skid resistance. Speeds limits have also been reduced, signs warning the public erected and in extreme cases roads closed. In July 2006, extreme high temperatures effected highways in Devon and Cornwall, Staffordshire and Cumbria and County Durham. Figure 11.10 shows a heat damaged carriageway in Cumbria.

![Figure 11.10. Heat damaged bituminous carriageways in Cumbria](image)

11.3 International examples

Many other countries already experience more extreme weather events than the UK as part of their normal climate. An examination of how these are dealt with may be provide some useful ideas for preparing for the climate the UK will experience in the future.

11.4 Summary

All the case studies demonstrate the impact that climate can have on highways and the huge costs involved. It is also evident that unique local aspects that have not previously been a problem can combine with a change in climate to have huge impacts. Local authorities need to examine the particular characteristics of their network and assess how the changes in climate could interact with these, what are the risks of this occurring is and what can be done to reduce these risks.
12 Implications of climate change for pavements

The deterioration of highway pavements is affected by many interacting factors and climate is a significant part of this. The change in climate necessitates that the risk of deterioration is reassessed and steps are taken to reduce this risk. This section discusses the risk of impacts occurring as a result of climate change and provides some potential techniques for adapting to climate change.

Consideration of the climate parameters which affect pavements according to the literature and evidenced by case studies and the climate change scenarios suggest that the major hazards for pavements caused by climate change will be excess water, high road temperatures and large changes in soil moisture. Other less severe hazards include prolonged dry periods, increased wind speeds, decreases in summer cloud cover, increased UV radiation in summer and rising sea levels. These hazards and proposed adaptive maintenance measures are illustrated in Figure 12.1, Figure 12.2 and Figure 12.3.

12.1 Other hazards influencing pavement deterioration

From the expertise and experiences detailed above, the factors (non-climate hazards) other than pavement type and climate that determine the likelihood and magnitude of climate impacts are:

- Geology – Type of underlying soil - e.g. clay, plasticity index
- Geography – Proximity to coast or river with potential for flooding
  - Water table level
  - Topography
  - Exposure
  - Within cutting/embankment
- Drainage – which needs to be sufficient and well maintained
- Pavement condition – e.g. surface cracks can allow water to enter foundations
- Traffic flow – The impact of traffic on the road can depend on the weather both directly and indirectly. For example there is increased rutting in asphalt roads, when hot, especially if the traffic is heavy and slow moving. Indirect effects could include the diversion of traffic, especially HGVs, to roads unsuitable for them due to normal routes being disrupted as a result of weather events. Also traffic to tourist spots could increase, as warmer weather increases the time people spend outside.
Structural and material mix design to be modified as a consequence of the following:

**Wetter and warmer winters**
- Increased intensity / duration of rainfall resulting in greater risk of:
  - Local flooding
  - Excess spray
  - Potential pollution of watercourses
- Unsealed road margins allowing increased wetting and possibly swelling of soil in verge and beneath pavement edge (Soil type dependent)
- Embankment
  - Cutting
- Higher water table
- Storing water in porous pavements to reduce impact on drainage system and reduce costs

**Hotter and drier summers**
- Higher road temperatures causing:
  - Reduced load spreading (stiffness) of asphalt
  - Increased expansion of concrete pavements and potential blow-ups
- Inadequate subsurface drainage weakening subgrade soil
- Vegetation and drought increasing soil shrinkage in verge and pavement edge (Soil type dependent)

**Local issue:** For roads adjacent to seas, rivers and ditches, increased risk of flooding and undermining of road edge

**Increased traffic loading** due to greater likelihood of local road diversions caused by adverse weather events

Figure 12.1. Effect of climate change on structural maintenance need
Road maintenance procedures to be changed to account for the following:

- Higher road temperatures increasing:
  - The extent of setting of surface dressings
  - Newer formation of cracks

- Higher road temperatures increasing:
  - Surface cracking due to greater oxidation of asphalt

- Greater soil erosion increasing risk of blocked gulleys/flooding and more material deposited on roads

- Higher road temperatures increasing:
  - The extent of fatigue of surface dressings
  - Different windows of opportunity of various maintenance activities

- Increased incidence of fires causing damage to asphalt pavements

- Change in vegetation type and weed growth

- Warmer winters and reduced need for deicing

- More frequent local earth slips undermining pavement edge

- More frequent local earth slips blocking roads

- Increased occurrence of high winds causing more damage to roads

- Increased occurrence of high winds causing more damage to roads

- Increased occurrence of high winds causing more damage to roads

Key:

Figure 12.2. Effect of climate change on routine pavement maintenance
Wetter winters

- Cutting
- Embankment

Hotter and drier summers

- Construction of overlays to strengthen asphalt pavement whose load spreading has been markedly reduced
- Insertion of expansion joints for concrete roads to prevent "blow-ups"
- Removal of trees etc on soils liable to shrink

Regional variations

- Upgrade or installation of edge drains
- Drain mitigates effect of excess winter rain
- Application of surfacing with adequate resistance to cracking and water penetration
- Application of surfacings that are more deformation resistant

Define regions likely to have marked increase in rainfall
Define regions likely to have sufficiently high temperatures that threaten structural capacity of pavement
Define regions likely to suffer from soil shrinkage

Figure 12.3. Pragmatic maintenance options based on accessible road features of road surface and verge
12.2 Assessing and mitigating the risk

Risk can be defined in terms of the likelihood of a consequence occurring and the magnitude of that consequence.

Both the likelihood of a climate change hazard impacting on highway maintenance and the magnitude of that impact will depend on the likelihood and magnitude of that climate change hazard occurring and the presence of other hazards. The UKCIP Technical Report; “Climate adaptation: Risk, uncertainty and decision-making” (Willows and Connell, 2003) defines risk and uncertainty and proposes a detailed pathway model of linking hazards (climate and non-climate factors), receptors and decision criteria. However, pragmatically it is reasonable to consider that the likelihood of there being an impact will primarily be determined by the likelihood of that climate change hazard occurring, whilst the magnitude of the impact for will depend upon the magnitude of that change and the presence of other hazards.

Accordingly, the following generic risk assessments identify, for each climate change hazard, the relevant climate change parameters that will enable an assessment of the likelihood and magnitude of that climate hazard. This can be undertaken for any particular region in the UK using the data provided in Appendix A, e.g. average annual rainfall for excess water. Other relevant factors, such as geological and geographical features, are also identified and potential mitigation measures suggested, before consideration of risks and mitigation measures associated with particular pavement types.

12.3 Increase in excess water

Excess water on highways can originate from:

- Coastal flooding- high tides or storm surges breach sea defences and flood coastal regions
- Fluvial flooding- heavy rainfall causes rivers and streams to burst their banks
- Surface water flooding- intense rainfall in a short time overwhelms drainage systems
- Groundwater flooding- underground aquifers overflow onto the surface, high groundwater levels can stop water draining through SUDS
- Blocked drainage systems including SUDS can exacerbate the situation creating localised flooding.

Water may enter the pavement structure through cracks in the surface or by capillary action from increased water table levels beneath the foundations. Surface water may seep through cracks, or in the case of concrete - joints, and into the pavement structure. Sub-surface water from a range of sources can enter the road foundations from below. These sources include an increased water table level, moisture held in soil voids or drawn upward from a water table by capillary forces, moisture that moves laterally beneath a pavement from an external source (e.g. pervious water-bearing strata, etc.).

The Asphalt Industry Alliance produced a press release (Asphalt Industry Alliance, 2002) describing the damage water causes to roads if it can reach the subbase. It suggested more money should be spent repairing roads so the increase in floods does not cause so much damage. It also pointed out repairing the damage to subbase costs more and causes more traffic delays than repairing surface defects to ensure no water enters the road structure. They state that as the level of minor damage increases, so too does the need for major structural roadworks. The corresponding increase of both has been monitored by the Annual Local Authority Road Maintenance (ALARM) survey.

12.3.1 Climate hazards

More prolonged and heavy rain in winter (Proxy Climate Change parameter – change in average winter rainfall precipitation) will cause an increase in groundwater levels and reduction in drainage capacity. This is predicted to be particularly significant in the North East of England, South East
England and Central East England and in all regions by 2080s under all scenarios. Greater occurrence of intense rainfall events, particularly following prolonged dry periods when the ground compacts and is unable to absorb water will increase the frequency of floods inland. This will result in water damage of roads and pavements becoming more common. Also clogging of the road texture in asphalt pavements will increase due to the deposited debris by flood water and greater soil erosion. Landslides from embankments are also more likely to occur damaging and blocking roads. This is a particular problem in Scotland and the North West.

The increased sea levels experienced in 2050 will result in greater coastal erosion, affecting coastal roads and footways, particularly in the south east. Storm surges (related to sea and wind levels) may also cause greater flooding of coastal highways.

12.3.2 Other hazards

Other hazards which may increase the magnitude of the impact of excess water on the pavement include:

Table 12.1. Hazards influencing the impact of excess water on the pavement

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Commentary</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Geology</td>
<td>Soils with a high plasticity such as clay will increase the risk.</td>
</tr>
<tr>
<td>2. Geography (including topography)</td>
<td>Area within flood plains or adjacent to the sea, particularly if sea defences are less than adequate are at increased risk. High water table also increases the risk. Shallow aquifers which hold water close to the surface.</td>
</tr>
<tr>
<td>3. Drainage</td>
<td>Inadequate or poorly maintained drainage significantly increases the risk of damage.</td>
</tr>
<tr>
<td>4. Pavement condition</td>
<td>Surface cracks allow water to enter the pavement structure.</td>
</tr>
<tr>
<td>5. Pavement design</td>
<td>Pavements that have evolved rather than been designed may not have the resistance to water damage.</td>
</tr>
<tr>
<td>6. Traffic Flow</td>
<td>Pavements with a traffic flow in excess of design. Pavements carrying high numbers of HGVs and /or farm traffic are more prone to damage through excess water.</td>
</tr>
</tbody>
</table>

12.3.3 Consequences of increased excess water

In addition to more frequent and severe flooding, the consequences to pavements of increasing amounts of excess water will be:

- More water entering and remaining in the pavement structure resulting in increased potholing, rutting and cracking and rapid structural and surface deterioration.
- More frequent incidences of debris being deposited by water seeping up to the surface though the pavement, for example, a raised water table can deposit calcium sulphate on the road surface as it dries, filling gaps in the road microtexture and leading to a decrease in skid resistance.
• Increased ground water levels causing embankments to become unstable and collapse onto pavements causing damage to the road surface, this is a particular problem in Scotland (Winter, 2005).

• Overflowing sewage systems contaminating flood water causing further damage and public health issues. This may lead to problems when dealing with the flood water, as it can not be pumped directly into water courses.

• The rapid flow of excess water creating scouring effects damaging the road surface.

• Erosion occurring on coastal roads or footways (Figure 12.4).

• Debris washed into gulleys, blocking them. This causes problems with subsequent rainfall and can damage the pavement if they leak.

• Opportunity to harvest water.

For asphalt pavements the concerns are:

• Water within the structure can cause stripping of the bitumen binder from the aggregate resulting in potholing, cracking, leaching of fines to the surface and structural failure of the road;

• Hydraulic pressure generated under the tyre can causing rapid deterioration of the surface through scouring;

• The presence of water accelerates polishing and reduction of skid resistance of the exposed aggregate;

• Saturation of the pavement foundation will cause premature failure;

• Changing moisture content will cause heave and subsidence of expansive clay subgrades;

• Rainwater runoff from impermeable pavement surfaces will be increased, with the risk that the surface storm water sewers will be overloaded and cause flooding on the pavement and to adjacent land and property.

For rigid pavements there is a higher risk of water penetrating the lower layers through joints and cracks.

Figure 12.4. Coastal erosion in Suffolk
12.3.4 *Actions to reduce the risk for all pavement types*

Preventative steps to reduce this risk in all pavement types include:

- ensuring sufficient and well maintained drainage to cope with the increased frequency of intense rainfall events (including sub-base and surface drainage); and
- making sure the pavement is in good condition, so that no water enters the structural layers.

Other methods of reducing the risk of deterioration specific to the type of pavement are described below.

12.3.5 *Potential methods of reducing the risk for asphalt pavements*

The best remedy for many of the problems is to take measures to prevent water ingress into the pavement in the first place, and if water does get in to remove it efficiently with good drainage.

To prevent water ingress and the resulting problems of moisture in asphalt layers, all asphalt layers should be well compacted and contain adequate binder. The asphalt in the surfacing should be impermeable to water and the foundation (and surface) drainage should function so that water does not accumulate under the road. The surfacing layers should resist deformation and not be prone to surface cracking.

Durability of asphalt material can be enhanced by good material design. The mixture should be very stable with a good aggregate skeleton and a high binder volume that practically fills all the voids in the fully compacted material without causing the asphalt to become unstable, and prone to deformation, by overfilling. The air voids content of the resultant mixture should be low enough to make the mixture impermeable to water. Permeability falls rapidly for materials with air voids of less than 8 percent and it is virtually zero for air voids below 4 percent. This is illustrated in Figure 12.5.

![Graph showing how permeability changes with air voids percentage](image)

**Figure 12.5. Graph showing how permeability changes with air voids percentage**

Aggregate segregation is another issue that results in asphalt with a high air voids content that is permeable. Segregation is generally localised and it is where asphalt has a predominance of fine or course aggregate. The separation occurs mechanically during transport and placement of asphalt and asphalt mixtures manufactured with larger stone sizes are more vulnerable. The move away from
using macadam with a 40 mm to a smaller maximum aggregate size has helped to reduce the problem. Segregation can result in patches of material that are highly porous.

Attention also needs to be paid to construction detail. Environmental influences may bring about changes that initiate at weak points in the pavement structure that may allow water to penetrate and cause the weakness to have an impact on the pavement structure. This may then result in a domino effect that will accelerate pavement deterioration. For example, the area of the road that is most susceptible to trapped water is in the region of longitudinal construction joints. Material in the vicinity of longitudinal construction joints generally has higher air voids content than the surrounding material and offers the potential for water to enter the road. Longitudinal joints should not coincide with the wheel path, joints in different layers should be staggered, material should be well compacted up to the joint and there should be a good bond across the joint. Ideally, all asphalt layers should be well bonded to one another so that the full thickness of asphalt is contiguous.

The recent move towards thin surface courses, instead of traditional hot rolled asphalt (HRA) surface and binder courses in the UK, has increased the risk of moisture entering the road. This is the case especially if the layer immediately below the surface course comprises of a relatively lean, coarse graded mixture that is not well compacted. This situation has resulted in some instances of problems relating to water ingress. In many cases these problems occurred close to longitudinal joints or when the layer below the surface course was poorly compacted under adverse conditions. Under these conditions bonding between layers is often minimal.

An impermeable binder course coupled with good construction practice will provide added protection against these forms of pavement deterioration. Enrobé a Module Élevé (EME) is currently being introduced by the Highways Agency (Sanders and Nunn, 2005). It is a base/binder course material incorporating a hard binder which gives it good load spreading ability and makes it highly resistant to deformation. It has a high content of bitumen and low air voids content designed to combine good mechanical performance with impermeability and durability. These attributes make it an ideal binder course material to be placed under a thin surface course. It has been in widespread use in France for over 20 years with good performance (SETRA, 1997). The mixture is designed in the laboratory to be workable and durable and to have high elastic stiffness, high deformation resistance and good fatigue resistance. It also uses aggregate sizes that are smaller than those traditionally used in the UK and therefore is less prone to segregation.

Additives, such as hydrated lime or proprietary surface active agents can improve the bond between the bitumen and aggregate. The use of 1 to 3 per cent hydrated lime as part of the filler content has traditionally been used as an anti-stripping agent.

It is generally recommended that prior to the use of any additive, laboratory testing should be carried out to optimise the type and amount of additive to be used for a given aggregate bitumen combination.

A move to stronger foundations incorporating hydraulically bound materials (Chaddock and Roberts, 2006) will make the road foundation less susceptible to moisture.

### 12.3.6 Potential methods of reducing the risk for concrete pavements

A properly designed and constructed rigid pavement should require comparatively little maintenance or repair from the effects of climate change. However, some defects evident at the time of construction and other defects which manifest during the life of the pavement will inevitably require maintenance to restore the pavement to a satisfactory condition. It is anticipated that the UK climate could become similar to that experienced in southern European countries, which already successfully use rigid pavements for road construction. Therefore, the potential methods for reducing the risk have already been considered in these countries and their designs should be reviewed. The major effects of climate change on rigid pavements and methods of mitigation are summarised below.

- Joint seals will need to be maintained permanently in a good condition to prevent water ingress to the foundation through joints.
• Ensure adequate drainage to remove water from the surface of the road at all times.
• During concrete paving provide adequate protection to prevent water damage to the surface of the concrete.
• Consider the use of an exposed open textured aggregate concrete surface for a low noise layer as there is no risk of clogging from detritus on a flooded road.

12.3.7 Potential methods of reducing the risk for modular pavements
Changing the foundation to a modular pavement may mitigate problems caused by the effects of water. Modular paving is frequently used in town centres and over large areas such as car parks. It is not desirable to seal the surface of all such pavements to prevent water ingress as this leads to excessive run-off in heavy rain and loss of water percolating into the ground and through to aquifers. However, systems are available where modular paving is laid on a porous foundation, generally consisting of aggregate with few fines. To prevent loss of sand the bedding sand may be separated from this coarse aggregate foundation using permeable geotextiles. This allows water from heavy rainfall to be held in the foundation material, with no loss of load bearing capacity, from whence it will gradually soak into the underlying soil.

12.4 Higher temperatures
12.4.1 Climate hazards
There will be both an increase in the average annual temperature pavements are subjected to, and more damagingly, an increase in the frequency and temperature of summer extremes. By the 2050s the extremely high summer temperatures experienced in 2003 will be considered average. By the 2080s, extreme summer temperatures could be as much as 8°C higher than those at present. There is also expected to be a 10 to 20 fold increase in the frequency of extremely warm summer days (the daily average temperature that is exceeded, on average, on 10 per cent of days). Higher mean and extreme temperatures will lead to higher pavement temperatures.

The Proxy Climate Change parameter is mean temperature. Some information on the frequency and intensity of daily extremes is given in the UKCIP02 scenarios. The UKCIP08 scenarios, to be released in 2008, will present temperature data in a probabilistic manner. This will help practitioners assess more extreme events and assist in the development of risk based solutions.

This is predicted to be particularly significant in North East England, South East England and Central East England and in all regions by 2080s under all scenarios.

12.4.2 Other hazards
Other hazards may increase the magnitude of the impact of higher temperatures on the pavement. These include the condition of the pavement, decreased summer cloud cover, the exposure of the pavement to UV radiation and the extent and nature of trafficking relative to its “design” flow.

In summer the diurnal temperature range increases across all scenarios and almost all of the country – the exceptions being the coastal margins of Scotland and Northern Ireland. In winter the diurnal range decreases slightly. Greater variations in diurnal, annual average and extreme temperatures can cause increased stresses in pavements causing cracking. In rigid pavements, the greatest impact will be at joints. If a joint cannot absorb all the thermal movement through an insufficient gap, the large stresses built up can lead to a compression failure.

12.4.3 Consequences of higher pavement temperatures
Incidences of frost and snow should decrease, resulting in less damage as a result of frost heave. For asphalt pavements with the current design:
• Higher pavement temperatures will accelerate age hardening of the bitumen. This will cause the binder to become brittle and increase the incidence of surface cracking and fretting. It will also result in the asphalt becoming more susceptible to cracking as a result of thermal stresses.

• Higher temperatures will lead to more surface rutting presenting a danger to the road user when water ponds in the ruts.

• Higher temperatures will result in reduced skid resistance as a result of fatting and chipping embedment.

• In flexible composite pavements the onset of reflection cracking will be accelerated as a result of increased variations in diurnal temperatures.

• Roads will contribute to the increase in the ambient temperature of urban environments (heat island effect).

• The times of the day and year when asphalt can be successfully laid will be influenced by adverse hot weather, cold weather and rainfall.

• Opportunities to use pavements as an energy source.

For rigid pavements with the current design:

• Joints may not be sufficiently wide to take into account the greater range of temperature experienced by the pavement or the composition of joint sealants may not be able to take into account the greater joint movement. This could lead to compression failure.

• The initial curing period may be increased by the higher temperatures. However, a longer paving period will be available in the milder winters.

• The incidence of reflection cracking from underlying cracks and joints may become more frequent.

• The asphalt overlay on concrete will be subjected to similar effects as a flexible pavement.

• This risk of reinforcement corrosion could be reduced with less use of de-icing salts due to reduced frost periods associated with climate changes.

There are also indirect effects of all pavement types, such as an increase in traffic to tourist spots as a result of warmer weather increasing the time people spend outside.

12.4.4 Actions to reduce the risk for all pavement types

Ensuring the pavement is in good condition will reduce the risk in all pavement types. More specific techniques for the different pavement types are described below.

Additionally, the health and safety of the construction workers will need to be considered in relation to working in hotter summer conditions.

12.4.5 Potential methods of reducing the risk for asphalts pavements

Asphalt technology is evolving continually and there is now much more research being undertaken by the bitumen industry to modify binders to improve the performance of asphalt. It is likely that as climatic problems become more apparent this will trigger the asphalt industry to be responsive in producing solutions.

All effects related to increased pavement temperature could be mitigated by artificially reducing pavement temperatures. This would reduce age hardening, deformation and loss of load spreading ability. Methods such as extracting low grade heat (Carder, 2005) from the pavement and coating the pavement with a reflecting layer (see 12.4.5.4) are possible but may only be economic in special cases.
It should be possible to learn from other industrialised countries that experience more extreme climatic conditions than in the UK.

In general, the risk from most forms of distress can be reduced by good material design and construction practice including pavement and surface drainage (see Section 4.2.2). The most appropriate materials and design for the site need to be determined.

12.4.5.1 Deformation in the asphalt layers

Recently there has been a move away from traditional surface course of HRA to proprietary thin surfacing systems (Nichols, 2001). There is an on-going programme for assessing these materials (Nichols and Carswell, 2004). To date the performance of these materials suggests that in some respects they are superior to HRA.

Thin surfacing technology was developed in France during the 1980s based on a better understanding of the rheology of modified binders. The mixtures were initially introduced through the Avis Technique. The Avis Technique allows material to be used within the limits set out within the document until national specifications can be produced. These systems have performed well in France and as a result they have been introduced into the UK. Initially the introduction was via franchises between UK and French companies.

France has a much warmer summer climate than the UK and it is expected that with climate change Southern England will have a summer climate with similarities to that of the Loire Valley by 2050. Therefore materials that have been proven under French climatic condition should perform well under the future climatic condition predicted for the UK.

Traditional HRA is inherently more susceptible to deformation. It is a gap graded mixture that relies on the interlock of the sand fines for deformation resistance. The large stones are not in contact with one another and primarily act as bulk filler. The new generation of proprietary thin surfacing materials generally have good aggregate skeletons with stone to stone contact that can resist deformation better. In addition polymer modified binders are normally used to enhance the high temperature properties of the bitumen. Thin surface course materials developed in France are likely to be able to cope with the hotter forecast UK summers better.

The move to thinner wearing courses means that the binder course will be closer to the near tyre stresses that cause deformation and it too will need to be as resistant to deformation as the surface course. The move towards a high modulus binder course, Enrobé a Module Élevé (EME), by the Highways Agency will reduce the risk of deformation in this layer. Sanders and Nunn (2004) demonstrated that, in terms of its rutting behaviour, this material could carry approximately 40 per cent more heavy traffic, compared with a deformation resistant HDM binder course. It also had other advantages referred to in Section 11.1.4.

12.4.5.2 Pavement cracking

Top-down or surface cracking is a related to age hardening of the surface course, with the top several millimetres ageing more than the bulk of the layer. Top-down cracking is not necessarily a serious issue in thick pavements with greater than about 200 mm of asphalt. Generally they appear to stabilise after penetrating about 100 mm and then progress, depending on the thickness of the pavement, very slowly.

In thinner pavements the occurrence of any sort of a crack is generally more serious as it can propagate through the remaining thickness of the pavement relatively easily. Surface cracking is less likely if softer bitumen or bitumen less prone to age hardening is used. Softer bitumen makes the material more susceptible to deformation, but softer bitumen can be modified using polymers to give them better high temperature characteristics. Many of the proprietary thin surface course materials employ polymer modifiers and therefore may be less susceptible to cracking provided that they are laid on a good substrate.
Increasing the binder film thickness and reducing the air voids content also reduce the rate of age hardening. Surfacing materials like stone mastic asphalt (SMA) have a high binder content and hence binder film thicknesses. This material also incorporates polymer or fibre to prevent the high content of binder draining from the mix during manufacture and transport.

The risk of structural or fatigue cracking can be reduced by the use of stiffer foundations. These will reduce the amount the structural layers have to flex under load. The mixture property that is most sensitive to fatigue cracking is binder volume. Therefore good mixture design with adequate binder and good compaction will have an important bearing.

With flexible composite pavements the use of hydraulic binder that cure more slowly than CBM will prevent well defined transverse shrinkage cracks forming in the base layer soon after construction. Ultimately these cause reflection cracks in the asphalt surfacing. Base layers incorporating slower curing hydraulic binders processed from blast furnace slag (Nunn and Hassan, 2003), phosphoric slag (Walsh, 1999) or fly ash develop finer more diffuse cracks in the base that are less prone to thermal effects and hence reflection cracking. Materials such as foamed bitumen stabilised materials containing cement are also less prone to thermal effects (Merrill et al, 2004).

12.4.5.3 Prediction of pavement design life

It is likely but by no means certain that the equivalent pavement temperature would need to be increased to cope with future climate change (see section 5.3.1). The assumption would be that more structural damage would occur at higher pavement temperatures. At higher temperatures the load spreading layers of the main asphalt layers of a flexible pavement would reduce and the traffic induced strains at critical locations in the pavement would increase and hence cause more damage.

However, it is also possible that the pavement foundation would dry out more during the dryer summers and this together with more ageing of the structural layers of asphalt would have the opposite effect. The greater stiffness of the foundation layers could counteract the effect of the reduced stiffness of the asphalt layers. An in-depth study would be required to resolve this issue.

As things stand, if the equivalent pavement temperature rises in line with the increase in average ambient temperature, research suggests that the probability of a fully flexible pavement surviving its nominal design life without requiring structural maintenance will be reduced from 85 percent to 81.8 percent as a result of an increase in equivalent pavement temperature of 1°C. A 2°C increase in equivalent pavement temperature will reduce this probability to 78.2 percent. Alternatively, the thickness of the asphalt layer would need to be increased by between 3 percent and 6 percent to retain the same structural life.

With flexible composite pavements the calculation of design life is more complex as, in addition to calculating the traffic induced stresses, restrained thermal warping stresses are also estimated. The degree of thermal warping depends on the temperature gradient within the concrete slab, the thermal properties of the concrete and the thickness of the asphalt cover. The thermal gradients will be a function of the diurnal temperature changes, with hotter days followed by cooler nights increasing the restrained thermal warping stresses and hence risk of the concrete base cracking.

Both for the fully flexible and flexible composite case a more in-depth study of the complex situation would be required. This would also need to consider that the basic design methodology was developed over twenty years ago (Powell et al, 1984). The method was based on the performance of roads that had carried, at that time, up to 20 msa. The results were conservatively extrapolated to the future design requirement of 100 msa. It is possible the designs predicted have built-in structural reserve and are able to cope with future climate changes.

12.4.5.4 Heat island effect

Pavements are considered to be one of the main causes of the heat island effect. Cambridge Systematics (2005) carried out a review for US Environmental Protection Agency on cooling pavements to avert the heat island effect. Their review showed that cool pavements can be achieved
with existing paving technologies and do not require new materials. Possible mechanisms for creating a cool pavement that have been studied to date are:

- increased surface reflectance, which reduces the solar radiation absorbed by the pavement;
- increased permeability, which cools the pavement through evaporation of water; and
- a composite structure for noise reduction, which also has been found to emit lower levels of heat at night.

Several conventional paving technologies now exist that can apply these mechanisms. For example, greater reflectance can be provided by conventional concrete, roller-compacted concrete, concrete-over-asphalt (whitetopping and ultra-thin whitetopping), asphalt concrete and surface dressing with light-coloured aggregate, and asphalt pavements with modified colour. Porous pavements can be built with asphalt concrete, portland cement concrete, or unbound surfaces such as stone, brick, or grass. The composite structure used for noise reduction plus night time temperature benefits comprises rubber asphalt surfacing over conventional concrete slabs. It should be noted that specific pavement technologies with cool attributes will not always be appropriate for all uses; some may be better suited to light traffic areas, for instance; others to areas where noise management is considered crucial. In addition, certain paving technologies may not always be appropriate or feasible.

A paper by Kubo et al (2006) deals with the heat island effect in large cities, which has become a social issue in Japan. This paper examines the effect of the water retention pavements and the heat shield pavements against the heat island effect. Heat shield pavements have a coating of hollow ceramic particles and special pigment to control the adsorption of incoming solar radiation and energy. These materials reflect the infrared wavelengths. The heat shield is a coating 0.5 to 1.0 mm thick that can be applied rapidly without altering other characteristics of the pavement surface.

The surface temperatures and the air temperatures above these new pavements and control pavements were monitored, an accelerated loading test was undertaken and the impact of the reduction in the surface temperature on the air temperature was simulated. The temperature monitoring showed that reductions of up to about 16°C in the pavement surface temperature and about 1°C in the air temperature could be achieved. This improves the city environment for pedestrians. A by-product of temperature reduction in pavements is greater rut resistance and improved pavement performance.

12.4.5.5 Maintenance

The quality of the laid asphalt is paramount. Good materials and construction practice are required. Asphalt should not be laid when ground temperatures are below 2°C or in wet and windy weather. Road materials containing cement shall not be laid when the air temperature in the shade is below 3°C. Adverse hot weather conditions can also be problematic for laying asphalt in maintenance situations, especially when there is pressure to open the road to traffic as soon as possible.

Nicholls and Carswell (2001) identified certain actions that will help to minimise potential problems that can arise when laying hot asphalt material in adverse hot weather conditions. These actions are summarized as follows:

- **Mixture selection** - The selection of deformation-resistant mixtures can mitigate, to a limited extent, the effect of premature deformation in adverse hot weather conditions. The rutting resistance of the binder course should also be considered.

- **Delivery temperature** - Asphalt mixtures delivered to site at temperatures higher than necessary not only increase the time available for compaction but can also render the asphalt too workable to lay; it also wastes energy and promotes binder hardening. The delivery temperatures during hot weather should only be high enough to achieve the required workability. This temperature is constrained by the mixing temperature (which again is dependent on the grade of binder used and the type of mixture) and the time that the mixture is transported in thermally insulated lorries.
• **Layer thickness** - The laid thickness markedly affects the time available for compaction, although contract specifications will normally have stipulated thicknesses for each asphalt layer. More flexible contract specifications would allow thinner layers to be used in hot weather conditions and thicker layers in cold weather conditions.

• **Compaction plant** - The use of a relatively light roller for initial compaction could be considered during hot weather conditions. A reduction in roller mass would diminish the risk of non-compliance with texture depth requirements, but needs to be balanced by the overarching need to gain adequate compaction.

• **Time of day** - Laying during the evening and night has additional advantages during hot weather. The lower air temperatures, and a reduced level or absence of solar radiation, will reduce the cooling time needed before the subsequent hot overlay or opening to traffic. If the weather and traffic conditions are such that the risk of premature damage to a newly opened surface is unacceptable in, for example, a speed-restricted contraflow system, a cessation of laying should be considered.

Cessation of laying during the hottest part of the day, say when the road surface temperature exceeds 45°C, will not only help the Contractor to minimise problems of achieving asphalt compliance in terms of profile and texture depth, but will also enable the surface to cool sufficiently to enable the resumption of laying in the evening.

12.4.6 **Potential methods of reducing the risk for concrete pavements**

It would be expected that a rigid pavement with an exposed concrete surface which is regularly maintained in good condition should not deteriorate any quicker as a result of climatic changes. However, an issue could be the perceived increase in the amount of seasonal joint movements at joints with the joint gap opening and closing beyond the current range of movement specified by sealant manufacturers. The use of an asphalt overlay over a concrete pavement will present the same maintenance problems as those identified in Section 5. Methods of reducing the risk are:

• The current design for joints may need to be modified with a wider gap to take into account a greater range of movement experienced by the pavement.

• Ensure joints are sealed so dust and debris can not penetrate and prevent expansion.

• The composition of joint sealants may need to be modified to cope with the potential greater joint movement.

• Newly paved concrete will need more protection from solar heat during the initial curing period, and paving restricted in periods of excessively high temperatures.

• Consider the use of an exposed open textured aggregate concrete surface for a low noise layer. This is less likely to be affected by the predicted higher temperatures than a thin asphalt surface.

• The concrete course aggregates may need to be restricted to those with a low coefficient of expansion to reduce the amount of thermal movements across cracks and joints. This does not preclude the use of secondary or recycled materials.

• Modify concrete mixture designs by using selected additives to achieve suitable workability and setting times during the period of paving and curing.

• Concrete mixtures may no longer need to be air entrained to protect against freeze/thaw effects.

• A review of concrete pavement design in countries with hotter climatic conditions could be considered.

12.4.7 **Potential methods of reducing the risk for modular and unbound pavements**

Reducing the size of the element modules can reduce the susceptibility of modular pavements to damage from higher temperatures.
12.5 Increased soil moisture deficit

Soil moisture deficit (SMD) is a measure of a soil’s capacity to absorb water. It is the difference between the actual soil moisture and its state when it is saturated, but allowed to drain naturally (referred to as field capacity). SMD is measured in millimetres, with field capacity being a SMD of zero. In the UK, the SMD increases in Spring and decreases in the Autumn, peaking in July/August. Low rainfall and high evaporation rates caused by high temperatures increase the SMD. The predicted seasonality of rainfall coupled with higher Summer temperatures will increase the SMD. The lack of moisture causes some soils such as clay and peat to shrink significantly, which can cause subsidence.

SMD is predicted to increase in all climate change scenarios.

Footways will also be affected by subsidence, but have the additional problem of tree roots. In drought the trees extract moisture from the soil adding to the SMD. Damaged footways can be a safety hazard and this could lead to an increase in claims due to trips.

The increased SMD, particularly in the South East, will result in more subsidence and cracking as susceptible soil underneath pavements lose water in prolonged dry periods.

There could also be indirect impacts from increased SMD. Buildings, walls and other structures near highways could subside damaging the highway.

12.5.1 Climate hazards

Hotter dryer summers with decreased cloudiness and increased evapo-transpiration will result in greater levels of soil moisture deficit. This will be particularly acute in the South East. However SMD will increase across most of the country in all seasons. Warmer wetter winters reduce the SMD in winter in England but still show a decrease of up to 10 percent in soil moisture. Scotland, Northern Ireland and Wales show a slight increase in soil moisture in the winter.

The Proxy Climate Change parameter is soil moisture.

12.5.2 Other hazards

Other hazards which may increase the magnitude of the impact of soil moisture deficit on the pavement include:

<table>
<thead>
<tr>
<th>Hazard</th>
<th>Commentary</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.Geology</td>
<td>Soils with a high plasticity such as clay will increase the risk. South East particularly prone.</td>
</tr>
<tr>
<td>2.Geography including topography</td>
<td>Proximity to trees.</td>
</tr>
<tr>
<td>3.Drainage</td>
<td>Inadequate or poorly maintained drainage significantly increases the risk of damage.</td>
</tr>
<tr>
<td>4.Pavement condition</td>
<td>Surface cracks</td>
</tr>
<tr>
<td>5.Pavement design</td>
<td>Pavements that have evolved rather than been designed may lack the structural strength to resist the ground movement caused by soil shrinkage.</td>
</tr>
<tr>
<td>6.Traffic Flow</td>
<td>In excess of design flow. High number HGVs, farm traffic.</td>
</tr>
</tbody>
</table>
12.5.3 Actions to reduce the risk for all pavement types

Preventative steps to reduce this risk in all pavement types include:

- the quality of the laid pavement is paramount. Good materials and construction practice are required;
- ensuring sufficient and well maintained drainage to cope with the increased frequency of intense rainfall events; and,
- making sure the pavement is in good condition.

If the plasticity index of the local soil is too high for road foundations, gravel may be imported, but aggregate extraction and transportation is expensive and detrimental to the environment. Backfilling with the excavated material is preferable.

Adding lime and/or concrete to the clayey soil can stabilise it (Thøgersen, 2006).

It is likely that foundations will need to be deeper in the future, and more use of reinforcement such as geotextiles may be required, to overcome these effects. A move to stronger foundations incorporating hydraulically bound materials (Chaddock and Roberts, 2006) will make the road foundation less susceptible to moisture.

Where soil is clay with a high plasticity index avoid planting/remove forest trees from within at least 15m from the road edge and fast growing trees like poplars should be avoided.

Tree maintenance regimes should be established and followed to control the size of the tree and its water requirements.

The impact of variable soil moisture can be reduced by widening embankments or reinforcing the subbase with materials such as geosynthetics and geogrids.

12.6 Consequences of climate change having a lesser impact on pavements

12.6.1 Prolonged dry periods

As well as contributing to increased soil-moisture deficit, prolonged dry periods may also cause the following problems:

12.6.1.1 Loss of skid resistance

Surface roadstone provides wet friction by having a rough surface which penetrates water films. This "microtexture" is polished under traffic in dusty summer conditions, and restored during the harsher winter climate. If this balance changes, the specifications for stone polishing resistance will need to be reconsidered.

12.6.1.2 Fire risk

Vehicle and nearby vegetation fires are more probable in hot drought conditions and can damage pavements. It is estimated that the rise in the number of secondary (outdoor) fires due to a 1°C summer temperature increase would be in the range 24,000 - 40,000 (Palutikof, 1996). Vehicle fires in tunnels can be particularly destructive. The high temperatures can melt the asphalt or cause spalling of concrete and thermal movements can lead to cracking. Water and foam used by fire fighters can also damage the road surface, but less so with a concrete surface.

The HA currently use a design fire of 125 MW for 60 minutes for tunnels on motorways and other trunk roads (Andrews, 1996). Some experiments have been performed on the ignition of asphalt (Carvel, 2006).

In contrast, concrete is able to resist high temperatures and is not damaged by vehicle fire and it generally maintains its shape and properties. It does not emit harmful fumes, has a high fire safety
factor and does not contribute to the fire load. These factors contribute to concrete being the preferred EU surface material for tunnels.

12.6.1.3 Increased pollution from first flush

When it does eventually rain after a drought, the first flush contains a high concentration of pollutants. This may cause run-off that does not meet European Water Framework Directive standards. Lower river levels results in less dilution for the pollutants and it is predicated that late summer mean monthly river flows will reduce by up to 34 per cent by the 2020s (Arnell, 2003).

12.6.1.4 Indirect effects

Lack of water, can lead to indirect damage to roads. During the dry summer of 1995, 2500 water-tankers fed standpipes in Yorkshire every day for six weeks. This led to damage of £1m to the roads.

12.6.2 Wider variation in temperature

The summer diurnal temperature range is predicted to increase across all scenarios and almost all of the country. The only exceptions to this are the coastal margins of Scotland and Northern Ireland. In winter, the diurnal range is predicted to decrease slightly.

Greater variations in diurnal, annual average and extreme temperatures can cause increased stresses in pavements causing cracking. The greatest impact will be at joints in rigid pavements. If a joint cannot absorb all the thermal movement through an insufficient gap, the large stresses built up can lead to a compression failure. Existing cracks in pavements open and close though the day night and day. Dust and detritus get into the crack at night (when it is cool and widest), preventing it closing during the day as the pavement expands causing further cracking and spalling and subsequent failure. While asphalt roads are less susceptible to cracking as a result of expansion and contractions, asphalt roads fail in this way in desert regions with no traffic.

In flexible composite pavements, the onset of reflection cracking will be accelerated as the result of increased variations in diurnal temperature. Bitumen is particularly susceptible to temperature changes, and wider temperature ranges will make it harder to select a binder that will not deform in the hot weather nor crack in the cold weather.

Larger paving slabs may expand and contract causing cracking and subsequent trips or rocking slabs.

12.6.3 Increase in length of the growing season

Lengthening of the growing season will increase the vulnerability of pavements, particularly footways and channels, to damage from weed growth. Whilst verges are not covered in this project, it is worth noting that verges will need cutting more frequently and more weed treatment carried out.

A longer growing season could allow weeds or other vegetation produce a greater quantity of seeds, these seeds can be readily deposited by animals or wind blown in the gaps of joints and reduce the efficiency of the joint to freely move.

12.6.4 Less frost and snow

Winter service is a large part of highway authorities’ budget. The cost is dependant on the number of times spreaders go out to treat the roads. This depends on the number and length of the occurrences of frost and snow and the amount of rain which washes the salt off the roads. Frost prediction will become more difficult as the number of marginal nights where the temperature hovers above zero is increased. The increased winter rainfall also means more re-application of de-icer, as it is washed off the road.

Empirical relationships between temperature and historic rates of salt use (Andrey et al. 2001b, McCabe 1995, Cornford and Thornes 1996) tentatively suggest that a warming of 3°C to 4°C could
decrease de-icer use by between 20 and 70 percent resulting in substantial savings annually, however this saving may be offset somewhat by the effect of increased rainfall.

Whilst the milder winters should reduce the need for winter service, it is important to retain the ability to deal with these situations as they will still occur, albeit at a lower frequency. For example, retaining a gritter fleet and salt stock and reviewing winter service plans annually.

12.6.5  Increased wind speeds

A rise in wind strength will lead to an increase in the frequency of high-sided vehicles overturning and trees, structures and other debris being blown onto the road surface and damaging it. Wind may cause more leaves to fall onto the road surface affecting skid resistance. The increase in growing season may make this occur for a longer period.

Increased wind speeds will reduce the window when asphalt can be laid successfully because it has a major influence on the rate of cooling and, hence, time available for compaction.

Increased wind speeds and storms may also cause health and safety issues for workers as the wind will move or blow over temporary traffic furniture and signs.

It should be noted that the changes in wind speed predicted in the UKCIP 2002 scenarios are presented with low levels of confidence, and should be treated with more caution than other climate parameters, such as changes in temperature or precipitation.

12.6.6  Increased UV radiation and reduced cloud cover

A slight reduction in cloud cover in the South East in summer will result in more exposure of roads to direct sunlight. This increase can be problematic during extreme heat periods, increasing the amount of fatting and reducing skid resistance.

12.6.7  Sea level

Sea levels rises and increased wind will cause greater erosion, affecting coastal roads and footways, particularly in the south east. The effects of rising sea level on coastal roads include:

- Permanent immersion - highways could be permanently lost to the sea as land is eroded
- Tidal immersion - highways could become immersed at high tide
- Gradual erosion of the shoreline
- Increased corrosion due to the salt content - highways that are now closer to the sea may suffer from damage due to high salt levels

An increase in storm surges (related to sea and wind levels) may also cause more incidents of flooding on coastal highways.
13 Summary and conclusions

The change in climate predicted in the UKCIP 2002 scenarios for the UK to 2050 can be summarised as wetter warmer winters and hotter dryer summers. There will also be more intense rainfall events and the sea level will rise. Highway engineers have already faced some of the maintenance issues caused by these climate changes and many have experienced some of the impacts that extreme weather can have on their highways. Unfortunately these experiences are often not well documented.

These experiences of extremes of weather to date, the technical literature and the climate change scenarios suggest that the major climate hazards for road pavement will be excess water, higher mean and extreme temperatures and high soil moisture deficit. The extent of the risk that these, and other less significant, hazards pose to pavement condition and maintenance will depend on the risk of that climate change occurring and other factors such as pavement type, condition, soil type and drainage.

The risk factors and consequences of the major climate hazards on pavements in the UK are summarised in Table 13.1. The mechanisms of deterioration in asphalt, rigid and modular pavements of climate change are summarised in Table 13.2. Lessons learnt from the past experiences in the UK and abroad suggest that that potential methods of adapting to the major climate hazards of the future are as listed in Table 13.3.

The change in seasons may affect the conditions under which maintenance activities are undertaken, both with regard to the affect on the pavement and to avoid health and safety issues for workers as a result of temperatures, storms and winds. Actions which may help minimise potential problems include:

- Prolonged dry periods leading to loss of skid resistance;
- laying deformation resistant asphalt mixes in thin layers in hot weather;
- restricting laying periods to the cooler part of the day to allow materials to cool;
- restricting laying periods to the cooler part of the day to reduce the effect of extreme temperatures on the work-force and;
- protecting the surface of rigid pavements when laying during excessively wet weather.

Other less severe hazards include:

- Prolonged dry periods leading to loss of skid resistance;
- Damage to pavement surface caused by increased number of vehicle and vegetation fires;
- Increased pollution from first flush following drought;
- Greater diurnal temperature variations causing pavements to crack;
- Increases in the growing season and the damage caused by weeds;
- Increased wind speeds may lead to increased damage to the pavement surface from debris such as structures, trees and overturned vehicles;
- Decreases in summer cloud cover and related increase in UV radiation increasing the amount of fatting and deformation of surfaces;
- Less frost and snow reducing the need for winter maintenance;
Distinct coastal issues include:

- Rising sea level and storm surges may cause permanent immersion;
- tidal immersion;
- an increased impact of salt content;
- increased wind speeds;
- increased coastal erosion, affecting coastal roads and footways, particularly in the South East.

The evidence provided by local authorities who have already experienced extremes of weather has demonstrated that each network is unique with its own particular vulnerabilities and that damage caused by the weather can be extremely expensive and disruptive. However, some adaptation to climate change is already taking place including:

- Monitoring ground water levels in Hampshire;
- Changes in asphalt standards;
- Long term programmes for locating and assessing the adequacy and condition of current drainage in numerous authorities including West Sussex;
- Programmes of drainage improvements such as completion of 29 drainage schemes including two larger schemes at Aston Tirrold and Brize Norton, Oxfordshire;
- Devon County Council has changed the aggregate they use to one less prone to stripping;
- Trialling of reinforcement of roads to reduce subsidence such as in Lincolnshire.

By expanding these types of activities and introducing more preventive, rather than reactive maintenance measures local authorities will be able to successfully adapt highways to the future climate.
Table 13.1. Summary of risks associated with, and consequences of, climate change

<table>
<thead>
<tr>
<th>Climate Change Hazard</th>
<th>Climate Change</th>
<th>Pavement Risks</th>
<th>Other Risks</th>
<th>Consequences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excess water</td>
<td>More prolonged and heavy rain in winter</td>
<td>Pavement type – asphalt, rigid or modular</td>
<td>Geology - Underlying strata such as clay and peat with a high plasticity index</td>
<td>Rapid structural and surface deterioration</td>
</tr>
<tr>
<td></td>
<td>More frequent intense rainfall events</td>
<td>Pavement condition, in particular the presence of cracks which can allow water to enter the structure</td>
<td>Location - within flood plains, adjacent to the sea or above a high water table or aquifer</td>
<td>Loss of skid resistance</td>
</tr>
<tr>
<td></td>
<td>Rising sea levels</td>
<td>Quality of original construction and subsequent maintenance</td>
<td>Drainage - Blocked gullies or inadequate or poorly maintained drainage</td>
<td>Embankments becoming unstable and collapsing</td>
</tr>
<tr>
<td></td>
<td>Storm surges (related to sea and wind levels)</td>
<td>Evolved pavements</td>
<td>Traffic flow - Roads with an excessive proportion of HGV’s</td>
<td>Erosion occurring on coastal roads or footways</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Hydroplaning in water filled ruts</td>
</tr>
<tr>
<td>High temperatures</td>
<td>An increase in the average annual temperature</td>
<td>Pavement design – thick/thin pavements: asphalt, rigid or modular</td>
<td>Traffic flow - Roads with an excessive proportion of HGV’s</td>
<td>Damaged road surfaces</td>
</tr>
<tr>
<td></td>
<td>An increase in the frequency and temperature of summer extremes</td>
<td>Surface deformation</td>
<td>Loss of skid resistance</td>
<td>Rapid structural and surface deterioration</td>
</tr>
<tr>
<td></td>
<td>An increase in the frequency of extremely warm summer days</td>
<td>Pavement condition</td>
<td>Reduced freeze/thaw damage and frost heave</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Exposure of the pavement to UV radiation</td>
<td>Evolved pavements</td>
<td>The health and safety of the construction workers</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Inappropriate repairs to concrete pavements</td>
<td>Contributing to the increase in ambient temperature and the heat island effect</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Joint replacement – longitudinal stresses and bay expansion</td>
<td></td>
<td></td>
</tr>
<tr>
<td>High Soil Moisture Deficit</td>
<td>Seasonality of rainfall coupled with higher summer temperatures will increase the SMD</td>
<td>All pavement types</td>
<td>Underlying soils having more plastic characteristics or organic content</td>
<td>Subsidence and cracking of carriageway and footway pavements</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Tree lined roads and footways and modular pavements</td>
<td>Proximity to trees</td>
<td>Buildings, walls and other structures near highways could subside, thereby damaging the pavement</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pavement condition</td>
<td>Inadequate and/or poorly maintained drainage</td>
<td></td>
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<tr>
<td></td>
<td></td>
<td>Evolved pavements</td>
<td>An excessive proportion of HGVs in the traffic flow</td>
<td></td>
</tr>
<tr>
<td>Climate Change Hazard</td>
<td>Asphalt</td>
<td>Rigid</td>
<td>Modular</td>
<td></td>
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<td>-----------------------</td>
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<td>---------</td>
<td></td>
</tr>
<tr>
<td>Binder stripping, particularly at asphalt layer interfaces</td>
<td>Surface damage during paving</td>
<td>Joint failure</td>
<td>Surface cracking</td>
<td></td>
</tr>
<tr>
<td>Excess water</td>
<td>Water passing through cracks and joints</td>
<td>Increased rutting</td>
<td>Increased rutting</td>
<td></td>
</tr>
<tr>
<td>Soil Moisture Deficit</td>
<td>Subsidence</td>
<td>Subsidence</td>
<td>Subsidence</td>
<td></td>
</tr>
<tr>
<td>High Temperatures</td>
<td>Increased cracking</td>
<td>Increased cracking</td>
<td>Increased cracking</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Binding softening in water filled ruts</td>
<td>Binding softening in water filled ruts</td>
<td>Binding softening in water filled ruts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Fatting, resulting in reduced skid resistance</td>
<td>Fatting, resulting in reduced skid resistance</td>
<td>Fatting, resulting in reduced skid resistance</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Increased age hardening of binder, resulting in increased cracking</td>
<td>Increased age hardening of binder, resulting in increased cracking</td>
<td>Increased age hardening of binder, resulting in increased cracking</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Large seasonal joint movements</td>
<td>Large seasonal joint movements</td>
<td>Large seasonal joint movements</td>
<td></td>
</tr>
<tr>
<td>Expansion leading to cracking and warping of concrete</td>
<td>Warping of concrete</td>
<td>Warping of concrete</td>
<td>Warping of concrete</td>
<td></td>
</tr>
<tr>
<td>Soil subsidence and possible blow</td>
<td>Surface scouring</td>
<td>Surface scouring</td>
<td>Surface scouring</td>
<td></td>
</tr>
<tr>
<td>Erosion of jointing and bedding sands, resulting in the loss of structural support, warping of concrete and foundation settlement cr eating warping and trips</td>
<td>Water passing through cracks and joints</td>
<td>Water passing through cracks and joints</td>
<td>Water passing through cracks and joints</td>
<td></td>
</tr>
<tr>
<td>NB: Effects are greater in larger slabs</td>
<td>Contamination to bare bedding effect</td>
<td>Contamination to bare bedding effect</td>
<td>Contamination to bare bedding effect</td>
<td></td>
</tr>
<tr>
<td>Continuous expansion and contraction of joints, resulting in the loss of structural support, warping of concrete and foundation settlement cr eating warping and trips</td>
<td>Workability and curing problems with the concrete mix</td>
<td>Workability and curing problems with the concrete mix</td>
<td>Workability and curing problems with the concrete mix</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Large seasonal joint movements</td>
<td>Large seasonal joint movements</td>
<td>Large seasonal joint movements</td>
<td></td>
</tr>
<tr>
<td>Table 13.2: Summary of climate induced pavement deterioration and consequences</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 13.3. Summary of potential adaptation measures

<table>
<thead>
<tr>
<th>Climate Change Hazard</th>
<th>Asphalt</th>
<th>Rigid</th>
<th>Modular</th>
</tr>
</thead>
</table>
| Excess water          | ▪ Ensure asphalt layers are well-compacted and contain adequate binder  
                        ▪ Use an impermeable binder with a high bitumen content and low air voids such as Enrobé à module Élevé (EME2)  
                        ▪ Use binders with good water resistant properties  
                        ▪ Use anti-stripping agents and more viscous binders to reduce stripping  
                        ▪ Use bond coats to reduce voids at layer interfaces  
                        ▪ Encourage permeable pavements where appropriate to reduce runoff problems  
                        ▪ Surface dress to maintain seal  
                        ▪ Good materials and construction practice e.g. locate construction joints away from wheel tracks  
                        ▪ Ensuring there is sufficient and well maintained drainage to cope with the increased frequency of intense rainfall events is vital  
                        ▪ Making sure the pavement is maintained in good condition, so that no water enters the structural layers  
                        ▪ Stronger hydraulically bound foundations | ▪ Ensure properly maintained joint seals  
                        ▪ Consider open-textured aggregate concrete surfacing as a surface texture as it is less susceptible to clogging than an asphalt surface  
                        ▪ Restrict concrete paving during periods of heavy rain | ▪ Lay on a porous foundation  
                        ▪ Use concrete block paving with enlarged joints  
                        ▪ Use of geotextile under bedding sand |
| Soil moisture variations | ▪ Stabilising clay soil by adding lime and/or cement can improve the strength of the foundation and reduce it’s susceptibility to moisture  
                        ▪ Deeper foundations, and more use of reinforcement such as geotextiles may be required  
                        ▪ The use of reinforcement in bay replacements for rigid pavements  
                        ▪ Use of reinforcement to treat existing cracks | ▪ e ▪ v ▪ d |
| v = variable moisture content | e ▪ Ensuring sufficient and well maintained drainage to cope with the increased frequency of intense rainfall events  
                        ▪ Ensuring the pavement is in good condition  
                        ▪ Stronger foundations incorporating hydraulically bound materials  
                        ▪ If the moisture content of the local soil is too high for road foundations, import granular material or stabilise the soil | e |
| e = excess moisture content | v |
| d = moisture deficit | d |
Climate Change Hazard

Asphalt

Rigid

Modular

Soil moisture contd…

Where soil is clay with a high plasticity index:
- Avoid planting/remove forest trees from within at least 15m from the road edge.
- Avoid planting fast growing or "thirsty" (broad leaf) trees near the carriageway.

Tree maintenance regimes should be established and followed to control the size of the tree and its water requirements.

Promote methods of reducing moisture changes in shoulders of embankments.

Widen embankments where shrinkage cracks are a problem.

Ensure the pavement is in good condition.

Good materials and construction practice.

High temperatures

Ensure long-term asphalt surfacings are used.

Use modified binders to reuse rutting and cracking.

Increased use of modified binders for surface dressing.

Increased adoption of EME2 as a binder course.

Treat ‘fatted’ areas with hot fine aggregate.

Remove all rut prone material (HRA surface course) during routine resurfacing operations.

Reduce all prone materials (HRA surface).

Treatments to reduce rutting effects on the drainage course.

Landscape, surface treatments (HR, HA, LA), surface dressing, etc.

Increased permeability could cool the pavement through the evaporation of water.

Use a composite structure for noise reduction, which has been found to emit lower levels of heat at night.

Incorporate green roof and green wall technologies, absorbent concrete and surface dressing with high-reflective aggregate, and spatial planning with lower-maintenance crops.

Increased surface reflectance, which reduces the solar radiation absorbed by the pavement using conventional concrete, other conventional concrete, or fibre-reinforced concrete.

Develop water retention and heat shield pavements.

Use a composite structure for noise reduction, which has been found to emit lower levels of heat at night.

Incorporate green roof and green wall technologies, absorbent concrete and surface dressing with high-reflective aggregate, and spatial planning with lower-maintenance crops.

Increased surface reflectance, which reduces the solar radiation absorbed by the pavement using conventional concrete, other conventional concrete, or fibre-reinforced concrete.

Ensure the pavement is in good condition.

Good materials and construction practice.

High temperatures

Ensure long-term asphalt surfacings are used.

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Increased surface reflectance, which reduces the solar radiation absorbed by the pavement using conventional concrete, other conventional concrete, or fibre-reinforced concrete.

Ensure the pavement is in good condition.

Good materials and construction practice.
14 Recommendations

The key recommendation to come out of this work is that each highway authority should assess the vulnerability of its highway network to climate change as a matter of urgency. In doing so authorities should make full use of their local knowledge of their network and how it has been affected by extreme weather events in the past. Whilst each authority’s risk assessment and solution will be unique, authorities would benefit from recording and sharing their experiences of climate effects on their networks.

Specific recommendations for local authorities, the UK National Government and the UK Roads Liaison Group are given below.

14.1 That local authorities:

- Carry out a risk assessment of the local highway network in the light of predicted changes in climate.
- Undertake a sustainability audit of maintenance and management plans, including ensuring that adaptation measures do not significantly contribute to increased greenhouse gas emissions.
- Record and monitor weather effects on the local highway network and share the lessons learnt with other local authorities. Compiling a Local Climate Impacts Profile (LCLIP) can assist in this. (See ‘Presentation to UKCIP User Forum 2007’ Slides 21 to 33 www.ukcip.org.uk and Oxfordshire County Council).
- Keep to maintenance schedules and hence avoid small defects becoming major repairs. Well maintained roads are less vulnerable to climate effects. This includes ensuring adequate drainage provision and maintenance of gullies.
- Support the Department for Transport in developing a mechanism to report the effect of climate on maintenance backlog possibly through Local Transport Plans.
- Support the Department in reviewing pavement designs, specifications and practices used those countries which have climatic conditions likely to be experienced in the UK. If necessary, incorporate changes into the current UK specifications.
- Aid the UK Roads Liaison Group in identifying priorities for further climate change research.

14.2 That the UK National Governments and the UK Roads Liaison Group:

- Encourages local authorities to monitor the effects of climate change on their networks and share and learn from their own and others’ experiences by establishing a mechanism to report the effect of climate on maintenance backlog
- Develops guidance for local authorities on assessing the risks to their footway and carriageway networks posed by climate change.
- Supports fundamental research into the effects of elevated temperatures combined with high rainfall on evolved pavements including foundations
- Reviews the pavement designs, specifications and practices used in those countries which have climatic conditions likely to be experienced in the UK. and incorporates the changes into the current UK specifications as appropriate.
- Undertakes a risk assessment of the effects of climate change on:
Based on the above, prioritises development of guidance for highway authorities into managing the risks of climate change.

Encourages the asphalt industry to develop solutions to the problems caused by climate change.

Acknowledgements

The work described in this report was carried out in the Infrastructure and Environment Division of TRL Limited. The authors are grateful to:

- Edward Bunting, Rachel Ward, Victoria Waite (Department for Transport) and Chris Capps (Cambridgeshire County Council) for steering the project on behalf of the UK Roads Board;
- HR Wallingford who extracted and analysed the climate parameter data;
- Cambridgeshire County Council, Lancashire County Council, Hampshire County Council, East Sussex County Council, Devon County Council and Leicestershire County Council that provided case study evidence;
- V Atkinson, B Chaddock, S Done, K Hassan, C Jones, C Nicholls and all experts at TRL who provided advice; and,
- Phil Sivell (TRL Limited) who provided climate change advice and carried out the quality review and auditing of this report.
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- Volume 1 Series 900: Road Pavements - Bituminous Bound Materials
- Volume 2 Series 900NG: Road Pavements - Bituminous Bound Materials


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<td>Asphalt</td>
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<td>Having zero hydraulic conductivity</td>
</tr>
<tr>
<td>Impervious</td>
<td>Not allowing water to infiltrate; effectively interchangeable with impermeable</td>
</tr>
<tr>
<td>Infiltration</td>
<td>Process whereby water soaks into a material</td>
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<tr>
<td>Permeability</td>
<td>Same meaning as hydraulic conductivity</td>
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## Appendix A  UKCIP02 Data Extraction Tables

### A.1 Data tables for temperature based on UKCIP02

#### Table 14.1. Annual increases in temperature (°C)

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### Table 14.3. Seasonal increases in temperature (°C) – Spring (March, April, May)

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### Table 14.4. Seasonal increases in temperature (°C) - Summer (June, July, August)

| Region | UK | NE | EE | SS | SE | SW | WE | CEE | NEE | SEE | SWE | SEW | NW | NE | ES | SS | NS | FE | SE |
|--------|----|----|----|----|----|----|----|-----|-----|-----|-----|-----|----|----|----|----|----|----|----|----|----|
| 2020s  | 1.4 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 |
| 2050s  | 1.4 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 |
| 2080s  | 1.4 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 | 1.3 |

**Scenario**

- High Emission
- Medium-High Emission
- Medium-Low Emission
- Low Emission
### Table 14.5. Seasonal increases in temperature (°C) - Autumn (September, October, November)

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Table 14.6. Annual increases in rainfall (%)

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Note: Total precipitation includes rain, snow, sleet and hail.
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Table 14.7. Seasonal increases in rainfall (%) - Winter (December, January, February)
Table 14.8. Seasonal increases in rainfall (%) - Spring (March, April, May)

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- High Emission
- Medium-High Emission
- Medium-Low Emission
- Low Emission

United Kingdom
Northern Europe
Southern Europe
Central Europe
Western Europe
Northern Europe
Southern Europe
Central Europe
Western Europe
Northern Island
United Kingdom

Note: The table shows the percentage increase in rainfall for each region under different emission scenarios for the years 2020s, 2050s, and 2080s.
Table 14.9. Seasonal increases in rainfall (%) - Summer (June, July, August)

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- Autumn (September, October, November)
- Table 14.10. Seasonal increases in rainfall (%)
- Published Project Report
- TRL Limited
- TRK Limited
A.3 Data tables for wind speed based on UKCIP02

Table 14.11. Annual increases in 10m wind speed (m/s)

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Table 14.12. Seasonal increases in 10m wind speed (m/s) - Winter (December, January, February)

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*Published Project Report*
Table 14.13. Seasonal increases in 10m wind speed (m/s) - Spring (March, April, May)

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2040s

2070s

High Emission

Medium-High Emission

Medium-Low Emission

Low Emission

UK

Region

Published Project Report
Table 14.15. Seasonal increases in 10m wind speed (m/s) - Autumn (September, October, November)

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### Table 14.16. Seasonal increases in snowfall (%) - Winter (December, January, February)

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Winter (December, January, February)

Table 14.16. Seasonal increases in snowfall (%) -
Abstract

Most highway authorities have already experienced the impacts of climate change on their operations in recent years which have caused damage, accelerated deterioration, disruption and increased costs. The accepted climate models for the UK predict that by the 2050’s the UK in general will experience: drier, hotter summers; milder, wetter winters; more extreme rainfall events; and a rise in sea levels. The detailed changes vary across the country.

The Department for Transport commissioned TRL to improve the understanding among local highway engineers of the implications of the predicted change in climate parameters, such as rainfall and temperature, for highway pavements and how the impacts might be minimised. This report provides the detailed technical information which is the basis for a DfT guidance document, *Maintaining Pavements in a Changing Climate*.

This technical report describes the impact climate has on the different types of pavement; asphalt, concrete, modular and unbound. The vulnerability of a pavement to climate depends on factors such as pavement type and condition, local geology, traffic flow and proximity to hydrological features. The key climate variables for pavements are temperature, precipitation and soil moisture. The report describes the implications of changes in these variables for the maintenance of the different pavement types. Case studies are used to illustrate the types of impacts climate has had on highways.

Recommendations are given on how to adapt to the changing climate and advice is provided for highway engineers on assessing the risk of different climate hazards for their network. The use of adaptive maintenance practices such as permeable pavements and polymer modified binders is encouraged. Other more general actions, such as improving the overall condition of the pavement and providing adequate drainage systems are also encouraged.
The effects of climate change on highway pavements and how to minimise them:
Technical report

Most highway authorities have already experienced the impacts of climate change on their operations in recent years which have caused damage, accelerated deterioration, disruption and increased costs. The accepted climate models for the UK predict that by the 2050’s the UK in general will experience: drier, hotter summers; milder, wetter winters; more extreme rainfall events; and a rise in sea levels. The detailed changes vary across the country.

The Department for Transport commissioned TRL to improve the understanding among local highway engineers of the implications of the predicted change in climate parameters, such as rainfall and temperature, for highway pavements and how the impacts might be minimised. This report provides the detailed technical information which is the basis for a DfT guidance document, Maintaining Pavements in a Changing Climate.

This technical report describes the impact climate has on the different types of pavement; asphalt, concrete, modular and unbound. The vulnerability of a pavement to climate depends on factors such as pavement type and condition, local geology, traffic flow and proximity to hydrological features. The key climate variables for pavements are temperature, precipitation and soil moisture. The report describes the implications of changes in these variables for the maintenance of the different pavement types. Case studies are used to illustrate the types of impacts climate has had on highways.

Recommendations are given on how to adapt to the changing climate and advice is provided for highway engineers on assessing the risk of different climate hazards for their network. The use of adaptive maintenance practices such as permeable pavements and polymer modified binders is encouraged. Other more general actions, such as improving the overall condition of the pavement and providing adequate drainage systems are also encouraged.

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