Department for Transport

Maintaining Pavements in a Changing Climate

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Contents

Executive summary

Climate change is already beginning to have 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. In order to avoid increased disruption of services and highway maintenance costs, it is vital to plan for and adapt to the climate predicted for the future, rather than basing decisions on historic climate.

In December 2005, DfT awarded TRL a contract, PPRO 04/37/030 – Impacts of Climate Change on Highway Maintenance. The objective of the project was to improve understanding among local authority highways engineers, and those working on their behalf, of the effects and implications of changes in rainfall, temperature and wind speeds on the infrastructure of the highway network and its structures and how these might best be mitigated. This document meets the requirement of the contract to provide best practice guidance for local highway authorities and contractors with practical advice on choice of materials and construction techniques to mitigate the effects of climate change on pavements. It is supported by a more detailed technical report (Willway *et al.*, 2008).

Climate has always presented a hazard to the condition of pavements, being one of the prime causes of deterioration, particularly in footways. The extent to which a pavement is vulnerable to climate is dependent on factors such as pavement type and condition, but also on other location-specific factors such as geology, proximity to water courses and traffic flow. This guidance identifies how climate impacts on the different types of pavement most commonly found on local authority highway networks: asphalt, rigid and modular pavements – for example, binder stripping from excess water, subsidence from soil moisture deficit and decreased resistance to rutting in elevated temperatures. It then considers how those impacts may change if the climate changes as predicted by the UKCIP02 scenarios to 2050.

In general, the UK can expect drier, hotter summers, milder wetter winters and more extreme rainfall events. The detailed changes vary across the country. The major hazards for pavement condition caused by climate change will be excess water, higher mean and extreme temperatures and high soil moisture deficit.[1] In addition, the change in seasons may have implications, in particular for conditions under which maintenance activities are undertaken. 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.

The implications of this different climate for highway maintenance on the different pavement types are described the report. In summary, properly designed, constructed and maintained pavements are at a low–medium risk of damage, even with the pessimistic predictions of climate in 2050; however, the likelihood and magnitude of consequences increase dramatically with inadequate condition, whether as a result of poor design, construction or maintenance. The risk is then further magnified by the presence of other hazards, in particular inadequate drainage and moisture-susceptible soil.

Asphalt pavements are vulnerable not only to surface damage as a result of increased temperature, but also to more severe structural damage as a result of increases in excess water arising from wetter winters and more prolonged heavy rainfall. Conversely, rigid pavements are less susceptible to excess water, but more at risk due to increased temperature causing expansion beyond the capacity of joints. This in turn can result in cracks and failed sealant at joints increasing the vulnerability to water ingress. Modular pavements are also prone to expansion and contraction and may be prone to damage through excess water when newly laid. All pavement types are vulnerable to increased soil moisture deficit leading to more shrinkage and heave on moisture-susceptible soils.

Advice is provided for highway engineers on assessing the risk of different climate hazards for their network. Recommendations are given on how to reduce the risks associated with climate change by ensuring good construction and maintenance practice and adopting adaptive maintenance techniques.

Case studies of the impacts weather can have on highways and adaptive techniques already trialled, both in the UK and abroad, are used to illustrate the guidance. These have been provided by local authorities or obtained from literature or the internet.

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

1 Soil moisture deficit (SMD) is the difference measured in millimetres between the actual soil moisture state and its state at field capacity (saturated, but allowed to drain naturally). The SMD increases in spring and decreases in the autumn, peaking in July/August.

CHAPTER 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, as a result of past emissions. It is therefore important to plan for and adapt to the climate predicted for the future, rather than basing decisions on historic climate. This is particularly important when planning infrastructure, such as highways, that is designed to have a long lifetime.

Current highways and their maintenance are designed based on historic climate. However, as the climate changes, they could be subjected to very different climatic conditions over their design life. The cost of not adapting could be vast in terms of disruption to traffic, public safety and infrastructure repairs. Climate change is already beginning to have 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. This kind of weather event will become more frequent in the future.

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 due to adverse driving conditions and deterioration of infrastructure;
- effects on the management of trees, landscapes and biodiversity.

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.

In July 2005, the Roads Board published the latest update of the Code *Well-maintained Highways* (Roads Liaison Group, 2005), which recognises the significance of climate change in delivering best value in management of the highway asset. The Code identified the effect of high temperatures on asphalt road surfaces as likely to be the main concern for the highway maintenance service.

Section 14 of *Well-maintained Highways* 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 that end, in December 2005, DfT awarded TRL a contract, PPRO 04/37/030 – Impacts of Climate Change on Highway Maintenance. The objective of the project was improve understanding among local authority highways engineers, and those working on their behalf, of the effects and implications of climate change on pavements. This document meets the requirement of the contract to provide best practice guidance for local highway authorities, their consultants and contractors with practical advice on choice of materials and construction techniques to mitigate the effects of climate change on pavements.

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

CHAPTER 2
Purpose and scope of guidance

This document identifies:

- climate parameters that affect pavement condition and maintenance need;
- how those climate parameters may change to 2050;
- the potential effects of those changes on pavements condition and maintenance need;
- other factors that influence that effect; and
- potential mitigation actions, including adaptive maintenance.

The scope of this guidance includes:

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

The guidance draws upon existing technical knowledge of the effects of extremes of weather in the UK on pavements that might be indicative of the future norm and also overseas climatic analogues.

In order to simplify the guidance, the document refers to an accompanying, more detailed, report (Willway *et al.*, 2008) for specific technical detail.

CHAPTER 3
Climate and pavements

3.1 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, used in this report 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 South East England, the most heavily populated and prosperous region of the UK, but effects will be felt all over the UK.

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.

3.2 The influence of climate on pavements

Climate has a large influence on pavement construction and maintenance. Currently, past climate is used to plan construction and maintenance activities. However, changes in 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 generally designed and constructed for a nominal design life of up to 40 years, with the expectation that periodic replacement of the surface course will occur every 10 to 15 years. Ensuring that highway construction and maintenance carried out now is suitable for the future climate is essential in preventing premature deterioration over time.

The climate has always been one of the primary factors that affect the performance of both carriageway and footway pavements. 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), drainage, underlying geology, topography and traffic. Each of these may in itself 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 weather, catastrophic failure. The hazards are also inter-linked, for example rutting due to heavy traffic increases at high temperatures.

In general, climate change will not introduce new consequences for the pavement, but may increase 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.

Combination of high temperature and other factors causing rutting

In 2006, rutting (Figure 3.1) and areas of surface pushing were observed on the approaches to two major junctions on the HA network. The surface course was originally hot rolled asphalt (HRA), but was planed and resurfaced with 30 mm of propriety thin surfacing in November 2005 and a high friction surfacing (HFS) laid adjacent to the junction.

Investigation of the two sites showed that the deterioration was the result of a number of factors. In one area, diesel contamination whilst laying, together with the elevated temperatures experienced in the summer of 2006, had caused further softening of the bitumen binder. In other areas, the combination of heavy commercial traffic and high temperatures had caused the underlying HRA to deform in the wheel tracks. Another contributory factor suggested was the construction of the HFS too soon after the thin surfacing. The resultant surfacing.

Figure 3.1 HRA deforming in wheel-tracking test

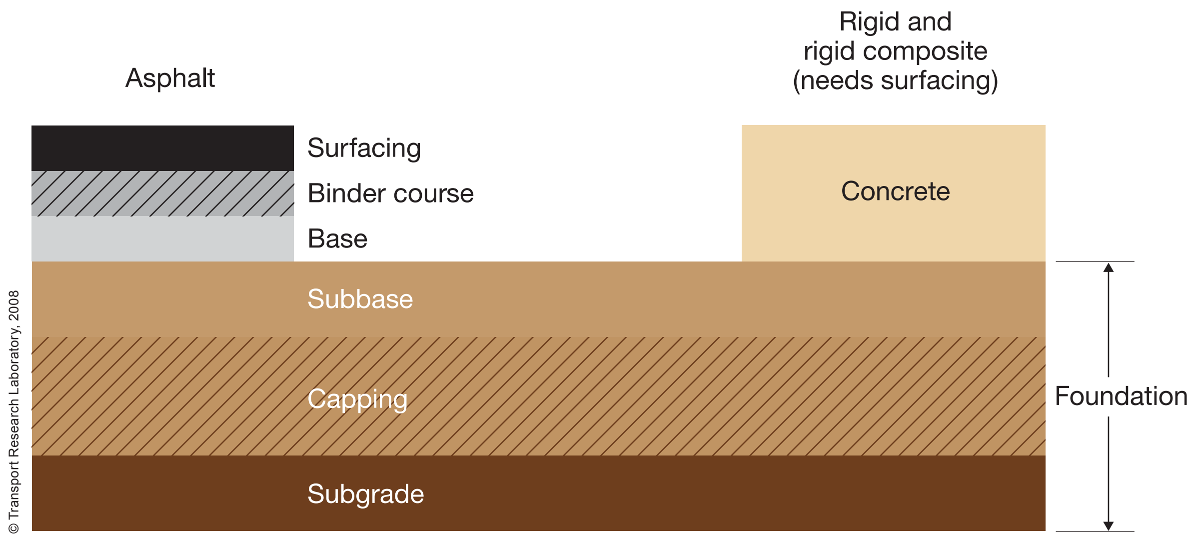

Figure 3.2 Structure of typical asphalt and rigid pavements, based on the* Design Manual for Roads and Bridges *(DMRB), Vol. 7 (Highways Agency* et al.*)

3.3 Pavement characteristics

There are three fundamental pavement types: asphalt, rigid and modular. Figure 3.2 shows the basic structure of these pavements.

The majority of local authority roads are asphalt or concrete, but modular surfaces are increasingly used in shopping centres and residential areas. Footways and cycle tracks can be modular, thin flexible or thin rigid or, occasionally, unbound. 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).

Pavement design and maintenance guidance is provided by Volume 7 of the *Design Manual for Roads and Bridges* (DMRB) (Highways Agency *et al.*). 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 follow this guidance, the design, construction and maintenance of local highways, their use and the expectations of their stakeholders are very different from trunk roads and motorways, particularly non-principal and unclassified networks. Indeed, many local authority roads were originally constructed before modern design standards came about, 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.

Guidance on cost-effective maintenance regimes for local authority roads is provided in *Well-maintained Highways* (Roads Liaison Group, 2005).

A detailed assessment of the influence of climate on the separate materials used throughout the layers of pavement can be found in Section 4 of Willway *et al.*, 2008 (*The effects of climate change on highway pavements and how to minimise them: Technical report*).

CHAPTER 4

The effects of climate on asphalt pavements

Asphalt pavements have several layers which all play a different role. Currently, these are referred to from the top surface as: surface course, binder course, base, subbase, capping and subgrade. The surface course and the binder course are often referred to collectively as the surfacing. The base is the main structural layer, although the binder course provides significant contribution. The subbase, capping and subgrade are together known as the foundation. See Figure 3.2 for a summary illustration based on that found in the DMRB (Highways Agency *et al.*).

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

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

The performance of asphalt pavements is affected by climate, in particular temperature and moisture. The climate impacts on the materials within the pavement, from the asphalt surface course, through the main structural layers down to the subgrade. These functions are interdependent, because structural failure of the base will affect the surface layers, and damage to the surface layers can lead to deterioration of the lower layers.

The effects of climate on asphalt pavements are described in more detail in Section 5 of the accompanying technical report (Willway *et al.*, 2008) and are summarised below.

4.1 Effects of water

Water can have the following impacts on the materials and structure of asphalt pavements:

4.1.1 Binder stripping

Stripping is the separation of asphalt binder film from the aggregate surface due to the action of moisture and is exacerbated by traffic. Stripping tends to begin at the base of the susceptible asphalt layer and is usually well advanced

Example of binder stripping in an asphalt pavement

Devon County Council has used locally sourced quartzite as a highway aggregate for decades. However, this type of aggregate is prone to stripping and the Council has found that the warmer, wetter winters experienced recently have led to rapid deterioration in surfacings constructed with this material. In particular, the A3052 has exhibited surface deterioration, wheel track and other cracking, rapid formation of potholes, sudden edge deformation and haunch failure due to disintegration of those asphalt layers using quartzitic material. Figure 4.1 shows a core taken from the A3052. The layer containing quartzite layer has been reduced to gravel, providing no structural strength for the pavement. Devon County Council has submitted a bid to the Department for Transport for £5 million to rectify the problem. In severe cases, total reconstruction will be necessary.

Figure 4.1 Core showing binder stripping in A3052

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. Stripping is accelerated by warm moist conditions.

Generally, basic aggregates, such as limestone, are less prone to stripping than acidic aggregates, such as granite and quartzite. More viscous binders are less prone to being stripped. Additives, such as amine and hydrated lime, can reduce an aggregate's vulnerability to stripping. Permeability and compaction of the asphalt are also important.

4.1.2 Freeze–thaw

Once water enters the structure of the pavement, it is prone to damage from freeze–thaw cycles. The water expands when frozen and shrinks when melted, generating tensile stress in the pavement. This process can create cracks, which propagate through the structure with each freeze–thaw cycle. The vulnerability of the pavement depends on the characteristics of material, such as its permeability and the condition, i.e. the presence of surface cracks.

In addition, frost-heave freezing draws up water from the subbase, increasing the amount of water in the pavement.

4.2 Effects of temperature

The temperature profile can influence the deterioration of asphalt pavements in the following ways:

4.2.1 Age hardening

Age hardening increases the viscosity of the binder and 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.

Excessive age hardening can result in brittle binder with significantly reduced flow capabilities. This hardening produces both negative and positive effects.

In thin asphalt pavements, age hardening is not desirable, as it will decrease the ability of the pavement to flex under traffic loads. In addition, premature cracking will result from thermal and traffic induced stresses and strains.

Hardening of the base and binder course materials of thick asphalt pavements increases their stiffness modulus and hence improves their load-spreading ability.

Higher average temperatures increase the rate of oxidative age hardening and will therefore accelerate the appearance of surface cracks.

4.2.2 Cracking

Observations in the UK have shown that the majority of the cracks in fully flexible and flexible composite pavements initiate at the road surface and propagate downwards. 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. In this condition, thermal and load-induced stresses can cause crack initiation and propagation. Hotter weather speeds up the oxidation process and makes the material more vulnerable to cracking, while cooler diurnal temperatures generate thermal tensile stresses that can cause crack initiation and propagation.

4.2.3 Stiffness

The base layer is the main load-spreading layer in a fully flexible pavement, and the stiffness modulus is a measure of its load-spreading ability. The higher the temperature, the lower the stiffness modulus and the greater the risk of fatigue cracking in the asphalt base layer and structural deformation in the subgrade.

4.2.4 Rutting

The resistance to rutting of the asphalt surfacing depends on road temperature as well as the traffic load. At high temperatures, asphalt becomes more susceptible to deformation, and rutting is more likely to occur, particularly on highly trafficked roads and at low traffic speeds. Research has found that the majority of rutting in the asphalt surfacing occurs on a few days of the year, when the temperature of the road surfacing exceeds 45°C.

Example of hot temperatures damaging asphalt pavements

The exceptional heat in the summer of 2006 caused significant damage to the rural highways of Leicestershire. As a lot of these roads have evolved from cart tracks, they often consist of only a thin bituminous surfacing on top of the granular layers that have then been maintained over the years with multiple surfacing dressings. The lack of full depth asphalt construction, as is found on the county's trunk and principal roads, makes the rural highways more vulnerable to climate change. In July 2006 around 80 km of these roads were damaged by the high temperatures. The softened road surface led to rapid formation of clusters of potholes and wheel-track rutting. Loss of texture depth resulted in a decreased skid resistance. This loss of skid resistance is particularly dangerous to motorcyclists and cyclists. Leicestershire County Council used salt spreaders to apply dust to the road surface, temporarily filled the potholes and patched repairs. An approximate average cost of undertaking more permanent repairs to these roads, by a thin resurfacing to 'seal' the surface and prepare it for future surface dressing, would cost in the order of £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 has applied for additional funding to help adapt these roads to the higher temperatures expected from climate change.

The susceptibility of an asphalt's deformation resistance to changes in temperature depends on the type of mixture. Rutting resistance can be increased by using a more angular aggregate and an aggregate grading that provides a good aggregate skeleton and/or a binder with better high-temperature properties and good mixture design.

4.3 Maintenance practice

During extended periods of hot, sunny conditions, asphalt can remain workable for a considerable time, making it difficult to maintain profile during compaction and, in the case of hot rolled asphalt 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 high enough to allow excessive rutting and the rapid embedment of any chippings, with the latter again causing a reduction of texture depth. These conditions would be compounded in conditions where traffic intensity is high and speeds are restricted.

The rate of cooling of the asphalt mat depends on environmental factors and the characteristics of material. The most important material factor is thickness of the layer, followed by the wind speed and difference between the asphalt temperature and ambient temperature. Higher winds and lower temperatures increase the cooling rate.

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

CHAPTER 5

The effects of climate on rigid pavements

Rigid pavements comprise a concrete layer, the main structural element, laid onto a bound or unbound subbase layer. Below the base is a similar foundation to flexible pavements. The basic rigid pavement without an asphalt surface is shown in Figure 3.2.

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 100 mm 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, ongoing maintenance costs to joints and bays. Whilst local authorities are unlikely to lay new URC or JRC pavements (in general, these are no longer permitted by the Highways Agency for use on motorways and trunk roads), existing jointed pavements are generally maintained with asphalt overlays.

CRCP and CRCB were developed to overcome problems associated with joints. They contain continuous reinforcement along the line of the road with no intermediate expansion or contraction joints. Thermally induced transverse cracks can relieve tensile stresses. The elimination of joints within the slab enhances the structural integrity of the pavement, as well as reducing the amount of water penetrating into the pavement and the associated pumping of fine materials, leading to enhanced foundation durability.

Whilst the thermal movements within the slab are relieved by controlled transverse cracking, a considerable amount of movement takes place at the ends (terminations) of continuously reinforced pavements. If not accounted for, this movement can cause damage to adjacent pavements or structures.

The effect of climate on rigid pavements is described in more detail in Section 6 of the accompanying technical report (Willway *et al.*, 2008).

5.1 Effects of water

Concrete is generally regarded as impervious to water. However, water can enter the underlying layers from the surface through poorly maintained joint seals or wide cracks. The likelihood of water penetration is increased by inadequate/poorly maintained drainage systems and in road cuttings with steep sides. The effects of water under a slab are:

- weakening of the foundation and subgrade by reducing the stiffness of the layers (see Chapter 8);
- vertical movements at joints leading to stepping;
- erosion of the unbound subbase and/or subgrade material leading to voiding and decreasing structural support.

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

Water penetration can lead to loss of subbase support and accumulation of detritus in the joint gap, which will impair thermal movement of the joint and could lead to the situation known as a compression failure or colloquially as a ‘blow-up’.

5.2 Effects of 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. With the requirement to cover concrete surfaces with asphalt, higher temperatures in the underlying concrete may be created. The specific effects on concrete of an overlying layer at a higher temperature have yet to be assessed.

The coarse aggregate has the greatest volume of the concrete constituents, and so its coefficient of expansion greatly influences the thermal properties of the concrete.

The tensile stresses which develop in reinforced concrete slabs can be relieved by thermally induced transverse cracks. This feature is the *modus operandi* of a CRCP. 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 a function of the climatic conditions at the time of paving.

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. It may be the case that compression failures are 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.

5.3 Maintenance

Early-life surface damage can be caused by paving in periods of wet weather without taking special care to prevent the concrete surface being damaged by the water. Damage can be manifested as surface damage to the concrete, destroying the applied texture.

Excessive surface water during curing can lead to reduced strength and long-term durability, freeze–thaw damage from lack of air entrainment and the ability of the concrete matrix to retain the aggregate. These problems can be identified as a pattern of crazing on the surface.

Paving should also be restricted in periods of excessively high temperatures.

CHAPTER 6
The effects of climate on modular pavements

Modular pavements are an alternative for asphalt and concrete for low traffic roads and 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 and prestigious streetscape projects, natural stone in the form of flagstones, setts and cubes is commonly used.

On footways, the modular surfacing material is generally laid on bedding sand directly on subbase material, and sand is also used as jointing 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. However, on older footways, slabs may be laid on hydraulically bound material. In areas that 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.

Defects in modular pavements include rutting, missing paving units, rocking paving slabs, trips between slabs, and cracked slabs. Weed growth in cracks, between slabs/modules and at the backs of footways, can be a problem.

The effects of climate on modular pavements are described in more detail in Section 5 of the accompanying technical report (Willway *et al.*, 2008) and are summarised below.

6.1 Effects of water

Most modular surfacing is porous in the short term, i.e. following construction, but largely impermeable in the long term. On footways, water can drain through the surface into the subbase and 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. Non-water-susceptible bedding sands (single sized) are commonly used in road constructions to permit the flow of water in the pavement's early life.

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 jointing in footways will result in gaps large enough to trap shoe heels. Further removal of bedding sand will result in paving modules being unevenly supported, leading to rocking slabs and deformation in the paving surface, and thus to trip hazards.

In trafficked areas the removal of jointing will allow paving modules to move horizontally and vertically. This is especially likely to happen where the traffic is turning and braking. Once vertical interlock has been lost, the pavement will cease to behave as a composite layer and traffic loads will be carried independently by blocks transmitting very high stresses into the bedding layer. The opening-up of joints will also permit the access of water, which will accelerate the breakdown of the bedding material below.

6.2 Effects of temperature

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, 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 increase with larger slabs. Indeed, there have been incidents of ‘blow-up’ where no allowance for the expansion of slabs under hot conditions has been made. This type of failure typically occurs in squares and public spaces where slabs are locked or restrained between buildings; lack of expansion joints results in lifting and cracking of 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.

Concrete modules laid in close proximity without chamfered edges 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.

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.

6.3 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 subbase – and any bound layers underlying the modular surfacing.

Excessive water can drain into the foundation reducing its load bearing efficiency. The effects on the subbase and subgrade are discussed in Chapter 8. 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 that are hazardous to pedestrians.

CHAPTER 7

The effects of climate on flexible and rigid footways

Thin flexible or thin rigid footways experience some of the same type of problems 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. Vegetation is a particular issue for footways, for example weed and moss growth in cracks and between a footway and adjacent wall. Vegetation accelerates deterioration of the footway and can also be a slip hazard for pedestrians. Vegetation growth is influenced by the length of the growing season. In times of drought, tree roots can grow, seeking water, and cause deformation of the footway and trip hazards. They may also remove moisture from the soil, which can cause subsidence.

CHAPTER 8
The effect of climate on foundations

The effects of climate on foundations are described in more detail in Section 9 of the accompanying technical report (Willway *et al.*, 2008) and are summarised below.

8.1 Effects of water

Ineffective 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.

Apart from the effect of water on the strength of the subgrade, prolonged water saturation will also have adverse effects on the stability of a granular foundation layers and can result or substantial deformation.

Where cracks propagate through the pavement layers, water ingress into the lower layers and the subsequent action of the traffic will cause pumping of material from the lower layers. This both decreases the support from the lower layers and weakens the material.

Large changes in moisture content can cause soil to expand and shrink substantially, causing the pavements above to heave and subside. Highways located where the underlying soil is highly plastic (clays etc.) or consists of peat will be particularly vulnerable. A related problem is caused by differences in soil moisture between verges and the pavement subgrade. In the UK, verges are often wetter than the subgrade in winter and drier in summer. This leads to moisture transfer. As the clay swells and shrinks with moisture content, the edge of the pavement rises and falls with respect to the crown, producing longitudinal cracking. In urban areas where the verges are impervious, the water is inhibited from entering the ground and trees near the highway, or in footways, which can draw up a large quantity of moisture from the soil.

Example of cracking in asphalt pavements due to soil moisture deficit

The prolonged dry weather during the summer and autumn of 2003 led to clay shrinkage and cracking on the highways of Hampshire (Figure 8.1). 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 are 25 mm or more wide and extend deep into the subgrade 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 repairs required was found to vary from site to site. Repairs included joint sealing, 100 mm inlays, 200 mm inlays and geogrids. This is estimated to cost around £3 million.

There are currently no data available to fully illustrate the effectiveness of these repairs.

Figure 8.1 Cracking caused by clay shrinkage in Hampshire

CHAPTER 9

Climate parameters that impact on highways and how these will change

The investigated climate parameters are discussed in more detail in Section 10 of the accompanying technical report (Willway *et al.*, 2008).

9.1 Changes in climate parameters

The UK Climate Impacts Programme 2002 (UKCIP02) scenarios are used for this project. The UKCIP02 scenarios are the most detailed climate scenarios currently available for the UK and provide predictions of the change in climate parameters that the UK could experience in 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 are due to be released in 2008.

The scenarios are based on four different emissions scenarios: low, medium-low, medium-high and high, based on future carbon dioxide concentrations of 525, 562, 715 and 810 ppm compared to the 2002 concentrations of approximately 370 ppm.

Examples of annual temperature and winter precipitation data from the UKCIP02 climate change scenarios (Hulme *et al.*, 2002) are shown in Figure 9.1. Predictions vary according to region, with a southeast-to-northwest gradient to the changes, with those in the south east being generally larger in extent than those in north Scotland.

Table 9.1 provides a very broad overview of climate changes averaged over the whole of the UK. These data are rounded to the nearest degree or per cent and mask considerable regional variation. More detail is provided in Willway *et al.*, 2008, Appendix A.

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

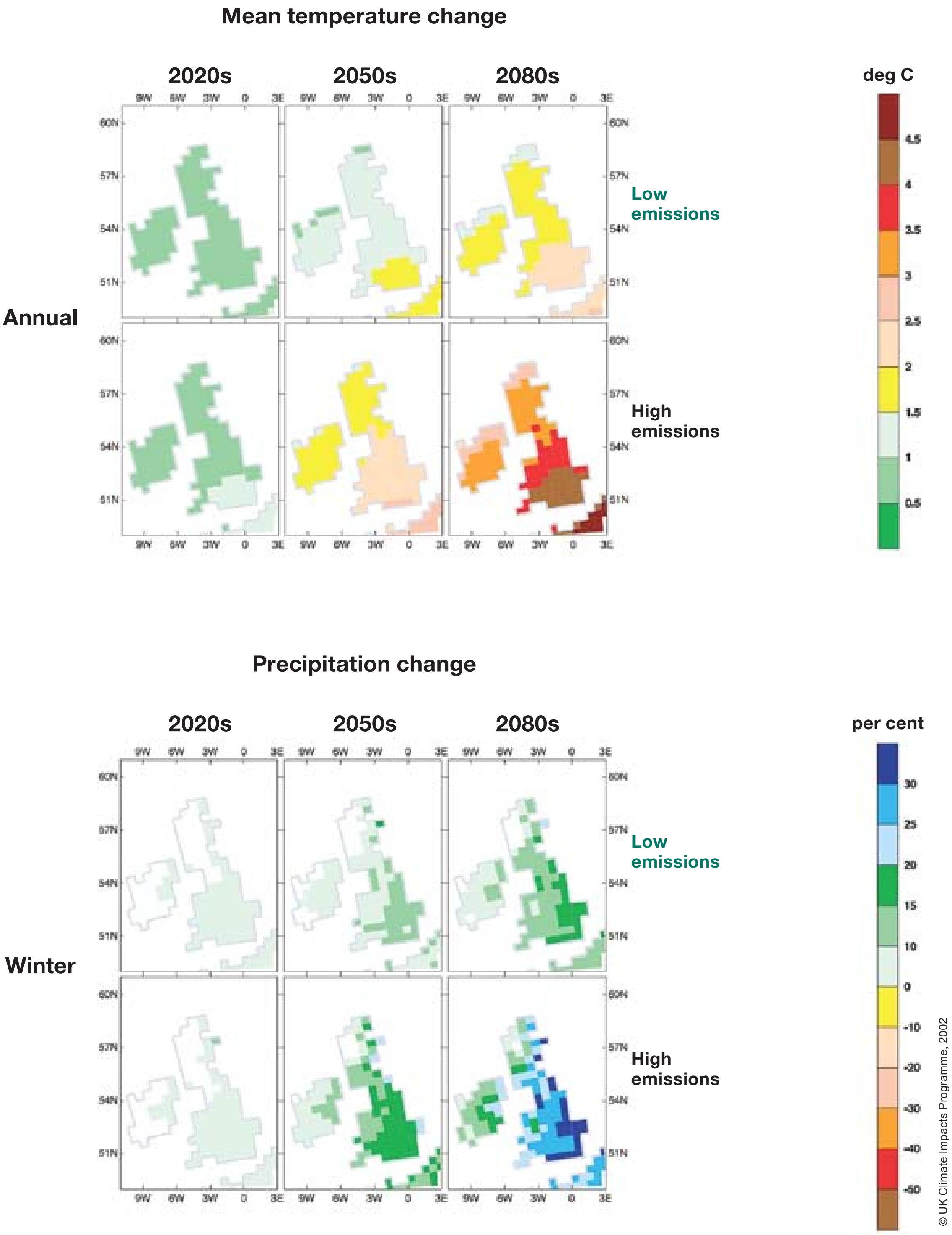

Figure 9.1 Examples of the UKCIP02 climate change scenarios (Source: UKCIP02 Climate Change Scenarios)

Table 9.1 Summary of climate change scenario data averaged for the UK land cells

Climate variable	UKCIP02 time-slices		
	2020s	2050s	2080s
Precipitation			
Annual	↓ 2%	↓ 3–4%	↓ 4–6%
Winter	↑ 4–5%	↑ 7–12%	↑ 11–20%
Summer	↓ 8–10%	↓ 14–23%	↓ 24–47%
Temperature (daily mean)			
Annual	↑ 1°C	↑ 1–2°C	↑ 2–4°C
Winter	↑ 1°C	↑ 1–2°C	↑ 1–3°C
Summer	↑ 1°C	↑ 1–2°C	↑ 2–4°C
Wind speed (average)			
Annual	Unchanged	Unchanged	↑ 1 m/s
Winter	↑ 1 m/s	↑ 1–2 m/s	↑ 2–4 m/s
Summer	Unchanged	↓ 1 m/s	↓ 1 m/s
Soil moisture content	***Example data for south east of England only***		
Annual	*↓ 1–3%*	*↓ 3–6%*	*↓ 3–9%*
Winter	*Unchanged*	*Unchanged*	*↑ 0–3%*
Summer	*↓ 3–4%*	*↓ 5–10%*	*↓ 6–15%+*

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

9.2 Temperature profile

The changes to temperature expected to occur by 2050 are given in Table 9.2.

Table 9.2 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 the mid-2040s. As a result, an extreme heatwave event is likely to be several degrees hotter than at present. Less likely to be below 0°C; therefore fewer freeze–thaw cycles. Extremes 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	High

9.3 Precipitation

Table 9.3 gives the changes predicted in precipitation.

Table 9.3 Changes in precipitation

Characteristic change	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 three-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 (35–45 mm in north west Scotland; 20 mm in south east England) are expected to increase; doubling by the 2080s. Intense rainfall events are expected to become less common in summer.
Confidence	High for increases in winter Medium for decrease in summer

9.4 Wind speed

Table 9.4 gives the changes in wind speed predicted for the 2050s.

Table 9.4 Changes in wind speeds

Characteristic change	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.
Confidence	Low

9.5 Soil moisture

Changes in soil moisture are given in Table 9.5.

Table 9.5 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 per cent reduction by the 2050s and 40 per cent reduction by the 2080s under the High Emissions scenario. In winter, increases of up to 10 per cent are expected in Scotland, Northern Ireland and northern England. Southern and central England are 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.
Confidence	High – reported in UKCIP02. To be treated with caution, as local soils are highly variable.

9.6 UV radiation/cloud cover

Changes in UV radiation and cloud cover are given in Table 9.6.

Table 9.6 Changes in UV radiation and cloud cover

Characteristic change	Slight increase in cloud cover in the winter. In spring and autumn, cloud cover decreases over all but north west Scotland. Large decreases in cloud cover in the summer, especially in the South. Increases in UV radiation in the summer, especially in the South.
Confidence	Low

9.7 Growing season

The changes in growing season are given in Table 9.7.

Table 9.7 Changes in the growing season

Characteristic change	Significant increase in thermal growing season length across all regions and scenarios, but the largest increases in the South East,
Confidence	High (Note: This characteristic refers only to the thermal conditions and does not take account of water availability, nor length of day.)

9.8 Sea level

Models predict we are already committed to significant warming and sea level rise. Conservative estimates, based on carbon concentrations in the year 2000, predict an increase in global sea level of 10 cm 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 9.8 gives the change in sea level predicted for the 2050s.

Table 9.8 Change in sea level

Characteristic change	Rise in sea level. Sea-level rise is affected by both changes in global sea levels, and by local isostatic adjustments following the last ice age. Global sea level will be in the range of 7–36 cm, depending on scenario, to which the local isostatic adjustment must be added (–7 to +11 cm, depending on region). Sediment consolidation also has an effect and can be very localised, varying over relatively short stretches of coastline. Storm surge levels will also be affected. Models suggest that storm surge height may increase off the south east coast and decrease in the Bristol Channel. However, the uncertainties are very large.
Confidence	High – global sea level change Low – storm surge

CHAPTER 10
Implications of climate change for pavements

The change in climate predicted for the UK to 2050 can be summarised as wetter warmer winters and hotter dryer summers. Highway engineers have already faced some of the maintenance issues caused by a changing climate. Many have also experienced some of the impacts that extreme weather can have on highways. Unfortunately, these experiences are often not well documented. The case studies that have been compiled and are used within this guidance have all demonstrated that:

- each network is unique, with its own particular vulnerabilities;
- local authorities have particular problems with highways that have ‘evolved’ rather than being designed and constructed to existing standards;
- many factors can contribute to the failure of a highway, of which climate can be one;
- damage caused by the weather can be extremely expensive and disruptive.

10.1 Major climate change hazards

The experience of extremes of weather to date, 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 risk of climate change impacting on highway 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 10.1, whilst the mechanisms of deterioration in asphalt, rigid and modular pavements of climate change are summarised in Table 10.2.

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 10.3.

Table 10.1 Summary of risks associated with, and consequences of, climate change

Predicted effect	Climate change	Pavement risks	Other risks	Consequences
Excess water	• More prolonged and heavy rain in winter; • More frequent intense rainfall events, particularly following prolonged dry periods when the ground is unable to absorb water; • Rising sea levels; • Storm surges (related to sea and wind levels).	• Pavement structure – all pavements are vulnerable to excess water. Well-constructed and maintained rigid pavements are less vulnerable, unless temperature increases. Modular pavements will be more vulnerable to water damage when newly laid; • Pavement condition – the presence of cracks will allow water to enter the pavement structure; • Pavement design – pavements that have evolved rather than been designed may not have the resistance to water damage.	• Geology – underlying soils such as clay and peat with a high plasticity index; • Location – within flood plains, adjacent to the sea (particularly if sea defences are less than adequate) or above a high water table or aquifer; • Drainage – blocked gullies or inadequate or poorly maintained drainage. Intense rainfall may result in more detritus further blocking gullies; • Traffic flow – roads with an excessive proportion of HGVs or farm traffic are more prone to damage through excess water.	• Rapid structural and surface deterioration; • Loss of skid resistance; • Embankments becoming unstable and collapsing. This is a particular problem in Scotland; • Erosion occurring on coastal roads or footways; • Hydroplaning in water-filled ruts.

Predicted effect	Climate change	Pavement risks	Other risks	Consequences
High temperatures	• An increase in the average annual temperature; • An increase in the frequency and temperature of high summer extremes; • An increase in the frequency of extremely warm summer days (the daily average temperature that is exceeded, on average, on 10 per cent of days); • Exposure of the pavement to UV radiation.	• Pavement structure – the risk to thick asphalt pavements is surface deformation and deterioration. However, thin asphalt pavements are more vulnerable to structural deterioration. High temperature is a greater risk to rigid pavements in poor condition, in particular jointed concrete, as it can lead to either failure of joint sealants or, in extreme cases, a compression failure, known colloquially as a 'blow-up'. The performance of well-designed small element modular pavement surfacings is unlikely to be much affected by changes in temperature; • Pavement condition – cracked/damaged surfaces leave materials more exposed to high temperature; • Pavement design – pavements that have evolved rather than being designed may not have the resistance to high temperature effects; • Joint replacement – longitudinal stresses and bay expansion can cause practical problems during maintenance activities.	• Traffic flow – roads with an excessive proportion of HGVs or farm traffic.	• Rapid structural and surface deterioration; • Loss of skid resistance; • Potential benefits are a decrease in the incidences of frost and snow, reduced freeze–thaw damage and less damage as a result of frost heave; • The health and safety of the construction workers may need to be considered in relation to working in hotter summer conditions; • Contributing to the increase in ambient temperature and the heat island effect.[2]

Predicted effect	Climate change	Pavement risks	Other risks	Consequences
High soil moisture deficit (SMD)	• Seasonality of rainfall coupled with higher summer temperatures will increase the SMD.	• Pavement structure – SMD causes soil shrinkage that undermines the foundations. All pavement types are affected, in particular tree-lined roads and footways (trees extract moisture from the soil, increasing SMD) and modular pavements (due to the lack of load-bearing capacity of the surface); • Pavement condition – cracking in asphalt and rigid pavements; • Pavement design – the problems of ground movement as a result of soil shrinkage will not have been considered where pavements have 'evolved' rather than being designed during a formal process.	• Underlying soils having high plasticity or organic; • Proximity to trees; • An excessive proportion of HGVs in the traffic flow.	• Subsidence and cracking of carriageway and footway; • An indirect impact of soil moisture deficit on ground movement is that buildings, walls and other structures near highways could subside damaging the pavement.

2 The urban heat island (UHI) effect occurs when city temperatures are higher than those in suburban and rural areas, primarily because growing numbers of buildings and paved areas have supplanted vegetation and trees. Moreover, human activity itself generates heat. Roads will contribute to the increase in the ambient temperature of urban environments. Urban heat islands are of interest primarily because they have the potential to directly influence the health and welfare of urban residents.

Table 10.2 Summary of climate-induced pavement deterioration and consequences

Climate change	Asphalt	Rigid	Modular
Excess water	• Binder stripping, particularly at asphalt layer interfaces; • Surface scouring; • Hydroplaning in water-filled ruts; • Accelerated polishing of surfacing.	• Water passing through cracks and joints; • Surface damage during paving.	• Erosion of jointing and bedding sands resulting in the loss of structural support, rutting, spalling, cracking, movement of modules and formation of trips.
	• Weakening of subbase or subgrade materials in foundations.		
Soil moisture deficit	• Subsidence; • Cracking.		
High temperatures	• Increased rutting; • Fatting, resulting in reduced skid resistance; • Binder softening, resulting in loss of surface integrity; • More rapid age hardening of binder, resulting in increased cracking; • Contribution to heat island effect.	• Warping of concrete; • Large seasonal joint movements; • Compression failures at joints in badly-constructed or poorly maintained roads; • Workability and curing problems with the concrete mixture.	• Expansion, leading to cracking and spalling at interfaces and possible blow-up with large slabs; • Bedding settlement creating warping and trips; • Continuous expansion and contraction causing cracking; • NB: Effects are greater in larger slabs.

Table 10.3 Summary of potential adaptation measures

Climate change	Asphalt	Rigid	Modular
Excess water	• Ensure asphalt layers are well compacted (particularly at longitudinal joints) and contain adequate binder. • Use an impermeable binder course with a high bitumen content and low air voids such as Enrobé à module Elevé (EME2). • Use binders with good water-resistant properties. • Use anti-stripping agents (e.g. hydrated lime)/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.	• Ensure properly maintained joint seals. • Consider open-textured aggregate concrete surfacing as a low noise layer. as it is less susceptible to clogging. • Restrict concrete paving during periods of heavy rain.	• Lay on a porous foundation. • Use concrete block paving with enlarged joints (specifically designed for permeable pavements). • Use geotextile under bedding sand.
	• Good materials and construction practice, e.g. locate construction joints away from wheel tracks. • It is vital to ensure there is sufficient and well maintained drainage to cope with the increased frequency of intense rainfall events. • Make sure the pavement is maintained in good condition, so that no water enters the structural layers. • Stronger hydraulically-bound foundations.		

Climate change	Asphalt / Rigid / Modular
Soil moisture variations	**e** Ensure sufficient and well maintained drainage to cope with the increased frequency of intense rainfall events.
	e Ensure the pavement is in good condition.
v = variable moisture content	**e** Stronger foundations incorporating hydraulically-bound materials.
e = excess moisture content	**e** If the moisture content of the local soil is too high for road foundations, granular material may be imported or soil stabilised.
d = moisture deficit	**v** Stabilising clay soil by adding lime and/or cement can improve the strength of the foundation and reduce its susceptibility to moisture.
	d Deeper foundations, and more use of reinforcement such as geotextiles may be required.
	v The use of reinforcement in bay replacements for rigid pavements.
	v Use of reinforcement to treat existing cracks.
	d Where soil is clay with a high plasticity index, avoid planting/remove forest trees from within at least 15 m from the road edge, and avoid fast-growing trees such as poplars. ‘Thirsty’ (broad-leaf) trees should not be planted near the carriageway. Shrubs must be not planted within 3 m of the carriageway and trees not within 5 m of it. Large trees should be placed at least 7.5 m away from the edge of the carriageway (DMRB) (Highways Agency *et al.*).
	d Tree maintenance regimes should be established and followed to control the size of the tree and its water requirements.
	v Promote methods of reducing moisture changes in shoulders of embankments.
	d Widen embankments where shrinkage cracks are a problem.
	e Ensure longitudinal cracks in the pavement are sealed, prior to permanent solution.

Climate change	Asphalt	Rigid	Modular
High temperatures	• Use rut-resistant asphalt surfacings. • Use modified binders to reduce rutting and cracking. • Increased use of modified binders for surface dressings. • Increased adoption of EME as a binder course. • Treat 'fatted' areas with hot fine aggregate. • Remove all rut-prone material (HRA surface course) during routine resurfacing operations.	• Ensure properly maintained joint seals. • Upgrade joint seal composition. • Use a low coefficient of expansion coarse aggregates in the mixture. • Modify the concrete mixture to ensure adequate workability and curing time. • Restrict concrete paving during periods of high temperatures. • Use exposed open-textured aggregate surfaces as low noise layers as an alternative to asphalt. • Air-entrained concrete is not as necessary if freeze–thaw cycles decrease.	• Replace large slabs with small element slabs or blocks.
	• Good materials and construction practice. • Ensure the pavement is in good condition. • Increase surface reflectance, which reduces the solar radiation absorbed by the pavement, using 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. • Stiffer foundations utilising slower-curing hydraulic binders, such as those processed from blastfurnace slag. • Increased permeability could cool the pavement through the evaporation of water. • Use a composite structure (rubber asphalt surfacing over conventional concrete slabs) for noise reduction, which also has been found to emit lower levels of heat at night. • Develop water retention and heat-shield pavements.		

10.2 Maintenance practices

The change in seasons predicted may have implications. In particular, it may affect the conditions under which maintenance activities are undertaken, both with regard to the effect on the pavement and to avoid health and safety issues for workers as a result of temperatures, storms and winds.

10.2.1 Maintaining asphalt pavements

Actions that will help to minimise potential problems that can arise when laying hot asphalt material in adverse hot weather conditions are summarised as follows:

- Selection of deformation-resistant mixtures.
- An asphalt mixture delivery temperature just high enough to achieve the required workability. This is constrained by the mixing temperature (which again is dependent on the grade and type of binder used), and the length of time the mixture is contained in thermally insulated lorries during transport.
- Flexible contract specifications to allow thinner layer thickness to be used in hot weather and thicker in cold weather. Use of a relatively light roller for initial compaction in hot weather would diminish the risk of non-compliance with texture depth requirements (whilst still aiming to achieve adequate compaction).
- Laying during the evening and night in hot weather to enable the substrate to cool more rapidly and therefore reduce the cooling time required for subsequent hot overlay or opening to traffic.
- 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 in 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.
- The season may need to be moved to allow for thicker layers to cool prior to opening to traffic.
- Consider changes in the surface dressing season to accommodate climate changes.

10.2.2 Maintaining rigid pavements

If paving has to take place during wet weather, special care should be taken to protect the surface from rain. Paving should be restricted to cooler periods of the day during higher temperatures in summer. It may be necessary to adjust the paving season to avoid high summer and exploit the warmer winters. Newly paved concrete may need more protection from solar heat during the initial curing period. Concrete mixture designs could be modified by using selected additives to achieve suitable workability and setting times during the period of paving and curing. Consider using concrete mixtures made with aggregates with a low coefficient of thermal expansion. Special care is required during the replacement of defective joints (in jointed pavements) throughout periods of high and rising temperatures.

10.2.2 Maintaining modular pavements

Jointing and bedding sands should be neither too dry nor saturated to facilitate compaction. During paving, the sand should not be left for extended periods, as this makes it vulnerable to moisture content changes from rain and evaporation; if necessary, sands should be lifted and replaced from a covered stockpile.

10.3 Consequences of climate change having a lesser impact on pavements

In comparison to the major climate hazards, of lesser significance to the pavement will be:

10.3.1 Prolonged dry periods

Prolonged try periods can lead to:

- loss of skid resistance;

(Surface roadstone provides wet friction by having a rough surface that 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.)

- damage to pavement surface caused by increased number of vehicle and vegetation fires;
- increased pollution from first flush following drought.

10.3.2 Temperature variations

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 through the night and day. Dust and detritus can get into the crack at night (when it is cool and at its 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 contraction, 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.

10.3.3 Increase in length of the growing season

An increase in the length of the growing season will increase the vulnerability of pavements, particularly footways and channels, to damage resulting from plant growth. Whilst verges are not covered in this project, it is worth noting that verges will need cutting more frequently.

10.3.4 Less frost and snow

Winter maintenance constitutes a considerable proportion of the highway authority budget, and milder winters should reduce the need for winter maintenance. Empirical relationships between temperature and historic rates of salt use tentatively suggest that a warming of 3–4°C could decrease salt and sand use by between 20 and 70 per cent, resulting in substantial savings annually. However, this saving may be offset somewhat by the effect of increased rainfall washing away salt.

10.3.5 Increased wind speeds

An increase in wind strength and storms may lead to increased damage to the pavement surface from debris such as structures, trees and overturned vehicles. Maintenance activities may also need to be scheduled to avoid health and safety issues for workers. It should be noted that the changes in wind speed predicted in the UKCIP 2002 scenarios should be treated with more caution than other climate parameter such as changes in temperature or rainfall.

Increased wind speeds will reduce the window when asphalt can be laid successfully, because wind speed has a significant influence on the rate of cooling.

10.3.6 Increased UV radiation/reduced cloud cover

A slight reduction in cloud cover in south east England 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 deformation. Planting trees to provide shade may reduce the risk, but may also exacerbate the risks associated with soil moisture deficit. UV radiation may also cause health and safety issues for workers that may be reduced by providing improved protective clothing and skin creams.

10.3.7 Rising sea level

Rising sea level and storm surges may cause permanent immersion, tidal immersion and an increased impact of salt content. The increased sea levels predicted in 2050, combined with increased wind speeds, may result in greater coastal erosion, affecting coastal roads and footways, particularly in the South East.

Example of coastal erosion of affecting footways

In 2006, large cracks appeared on the promenade along Felixstowe sea front in Suffolk due to coastal erosion (Figure 10.1). The undermining of the seawall and the subsequent movement has damaged the promenade, and lengths of it had to be cordoned off. It was feared the promenade might collapse, and emergency work was carried out on 20 May 2006 to protect it. Tonnes of rock were placed by Suffolk Coastal District Council at the base of the promenade wall in an attempt to halt the collapse. These temporary measures cost over £500,000. The Council has submitted a bid for a £6 million groyne replacement scheme, but so far has been unable to obtain funding.

Figure 10.1 Damage to Felixstowe promenade from sea erosion

CHAPTER 11
Examples of good practice

Some adaptation to climate change is already taking place. In addition to the examples of good practice used to illustrate this guidance, the types of activities being undertaken in response to climate change by local authorities are:

- 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 it uses 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 successfully able to adapt highways to the future climate.

The use of geomesh to increase the ability of a highway to withstand soil moisture deficit

Lincolnshire County Council has carried out a trial assessing the use of steel reinforcement grid to prevent cracking on an asphalt carriageway prone to damage from 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 11.1). The cracks were normally filled with hot bitumen or a bituminous inlay spanning the crack, but the cracks returned within a short time. The cause of the damage was identified as the cyclic shrinkage and heave of the underlying clay soils.

In 1997/98 seven test sections were laid on a 700 metre site on the A1073. These have no mesh, or one or two sheets of mesh 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 155 mm of DBC were in a good structural condition, as was the section built with a concrete base and 75 mm DBC. Filling in the drains also helped prevent cracking. The trial demonstrated that geomesh 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.

Figure 11.1 Site of the Lincolnshire geomesh trial before treatment

CHAPTER 12

Recommendations

The key recommendation to come out of this work is that, as a matter of urgency, each highway authority should assess the vulnerability of its highway network to climate change. 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 are:

- Prepare the risk assessment with the full engagement of members and staff. This is likely to include reviewing existing maintenance and management strategies and plans in the light of the risks posed by climate change.
- Undertake a sustainability audit of maintenance and management plans, including ensuring that the practices used to adapt to climate change are not themselves contributing to climate change.
- 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 UKCIP: Presentation to UKCIP User Forum 2007; http://www.ukcip.org.uk).
- 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 effects of climate on maintenance backlog, possibly through Local Transport Plans.
- Support the Department in reviewing pavement designs, specifications and practices used in those countries which have climatic conditions likely to be experienced in the UK. If necessary, incorporate changes into the current UK specifications.
- Aid the Roads Board in identifying priorities for further climate change research.

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Glossary

Asphalt	Generic name of bitumen aggregate mixture
Asphalt pavements	Fully flexible and flexible composite pavements
DMRB	*Design Manual for Roads and Bridges*
EME	Enrobé à module élevé
HGV	Heavy goods vehicle
HRA	Hot rolled asphalt
Impermeable	Having zero hydraulic conductivity
Impervious	Not allowing water to infiltrate; effectively interchangeable with impermeable
Infiltrate	Soak into a material
Permeable	Allowing water to infiltrate
Porous	Having a high voids content (volume of voids as percentage of total volume)
Stripping	Failure of the aggregate bitumen bond, caused by water
UHI	Urban heat island
UKCIP	UK Climate Impacts Programme
UKCIP02	UK Climate Impacts Programme 2002

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