www.piarc.org
2023R20EN

MEASURES FOR IMPROVING RESILIENCE OF PAVEMENTS

A PIARC TECHNICAL REPORT

TECHNICAL COMMITTEE 4.1 *PAVEMENTS*

PIARC

STATEMENTS

The World Road Association (PIARC) is a nonprofit organisation established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport.

The study that is the subject of this report was defined in the PIARC Strategic Plan 2020–2023 and approved by the Council of the World Road Association, whose members are representatives of the member national governments. The members of the Technical Committee responsible for this report were nominated by the member national governments for their special competencies.

Any opinions, findings, conclusions, or recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of their parent organisations or agencies.

This report is available from the Internet site of the World Road Association (PIARC): http://www.piarc.org

World Road Association (PIARC)
Arche Sud 5° niveau
92055 La Défense cedex, France

International Standard Book Number: 978-2-84060-792-2

Front cover © Jostein Aksnes (Norwegian Public Roads Administration)

MEASURES FOR IMPROVING RESILIENCE OF PAVEMENTS

A PIARC TECHNICAL REPORT

TECHNICAL COMMITTEE 4.1 *PAVEMENTS*

AUTHORS/ ACKNOWLEDGEMENTS

This report has been prepared by the Technical Committee 4.1 *Pavements* of the World Road Association (PIARC).

The editors-in-chief of this report are:

- Margo BRIESSINCK (Belgium)
- Leila HASHEMIAN (Canada)

The contributors to the preparation of this report are:

- Gina AHLSTROM (USA)
- Joralf AURSTAD (Norway)
- Zsolt BOROS (Slovakia)
- Margo BRIESSINCK (Belgium)
- Simona FONTUL (Portugal)
- Mario JAIR (Argentina)
- Venkat LAKKAVALLI (Canada)
- Łukasz NICZKE (Poland)
- Sébastien PIETTE (Canada)
- Luc RENS (Belgium)
- Mohamed SALEH (Canada)
- Auckpath SAWANGSURIYA (Thailand)
- Thierry SEDRAN (France)
- Pahirangan SIVAPATHAM (Germany)

The language review of the original English version was done by Leila HASHEMIAN (Canada). The translation into French of the original version was produced by Pierre HONTOY (Belgium). The translation into Spanish of the original version was produced by Paul GARNICA (Mexico). Gina AHLSTROM (USA), Simona FONTUL (Portugal), and Caroline EVANS (Australia, chair of TC 1.4) were responsible for quality control in the preparation of this report.

The Technical Committee was chaired by Margo BRIESSINCK (Belgium). Gina AHLSTROM (USA), Aïda BERGAOUI SRIHA (Tunisa), and José DEL CERRO GRAU (Spain) were, respectively, the English, French and Spanish-speaking secretaries.

EXECUTIVE SUMMARY

2023R20EN

MEASURES FOR IMPROVING RESILIENCE OF PAVEMENTS

A PIARC TECHNICAL REPORT

This report discusses resilience in pavements with regard to various vulnerability issues resulting from disruptions or hazards due to climate change, vehicular traffic, and natural and human-caused disasters. For the purpose of this report, resilience is approached from a "bottom up" or object level perspective.

The possible impacts of the three categories of pavement stressors mentioned above—climate change, vehicular traffic, and natural and human-caused disasters—are described. Several measures to increase the resilience of pavements against these impacts are contemplated in this report. Although a given measure may be a useful solution for mitigating multiple adverse impacts of these stressors, measures are described separately with respect to each application area. The measures to increase resilience are grouped by pavement type: asphalt pavements, concrete pavements, and base layers.

These measures can be applied during the design phase of a pavement by using innovative materials, or by using an adapted design method, taking into account more extreme parameters such as increasing temperatures and more aggressive traffic loads.

CONTENTS

1. INTRODUCTION

There are many definitions of resilience. A key definition identified by TC 1.4 "Climate change and resilience of road networks" is [1-1]:

> *The ability of a system, community or society exposed to a hazardous event, a trend or a disturbance, to resist, absorb, accommodate, adapt to, transform, learn and recover from the induced effects in a timely and efficient manner that maintain their essential function, identity and structure.*

In this report, resilience is approached from a "bottom up" or object level perspective. Innovations in materials, pavement design, and construction methods can improve resilience of pavements to climate change hazards, increasing traffic and heavier loads, and natural and man-made hazards. In this report, the definition of resilience relates to the identification of measures and materials for enhancing infrastructure resilience of dedicated elements of the road.

Figure 1-1 shows an example of a "functionality curve" with the "resilience triangle" [1-2]. The horizontal axis represents time, and the vertical axis performance. In this case, the impact of the hazardous event on pavement performance is assumed to be instantaneous, while the recovery evolves linearly. The resilience triangle is an indicator of the loss of pavement resilience: the smaller the triangle is, the more resilient the pavement is. Moreover, a measure introduced to make a pavement more resilient is considered to be more effective if the functionality loss is smaller (e.g., by applying a more robust design or construction), the recovery period is smaller, or a combination of both.

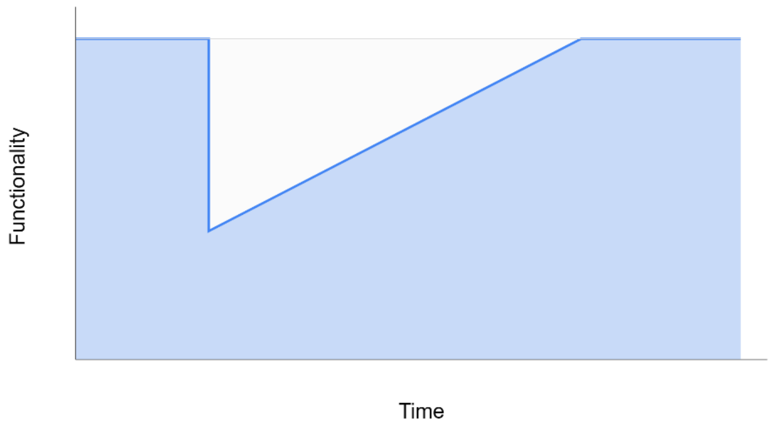

Figure 1-1: functionallity curve and resilience loss

This report discusses resilience in pavements with a focus on the various vulnerability issues resulting from disruptions or hazards due to climate change, vehicular traffic, and natural disasters. In addition, this report proposes engineering-informed adaptation measures intended for decision makers and engineering practitioners.

It should be noted that this report encompasses only pavement-related measures. Holistic solutions—e.g., planting trees to reduce the heat island effect, building higher dams to protect against sea-level rise, etc.—are not discussed. Moreover, network measures—e.g., redundancy related measures such as adding a detour route to the network in case one road is flooded—are not discussed.

Chapter 3 discusses the following pavement stressors:

- climate change
- vehicular traffic
- natural and man-made disasters

The impact of these stressors and possible measures are discussed in Chapters 4 to 6.

Chapters 7 gives a short description of the measures for asphalt and concrete pavements, measures for base layers, as well as other, more general measures.

2. METHODOLOGY

This report reviews recent developments in the adaptation of pavement assets to increase their resilience against climate change, vehicular traffic, and natural disasters and the resulting stressors. A literature search was carried in the context of pavement engineering using relevant keywords "climate change resilience", "adaptation strategies", and "mitigation measures". The literature search was limited to reliable materials and well-established databases, including Elsevier, as well as agency websites such as the United States Federal Highway Administration. The focus of the literature search was on research projects and studies with tested data and hypotheses from peer-reviewed journal papers, and official technical reports from governmental and federal agencies and departments of transportation in which a physical measure is recommended. There was also an emphasis on more recent literature, with a publication date range of 2010 to 2023 (with a few exceptions, as appropriate).

In addition to the literature search, members of PIARC's Technical Committee 4.1 held a series of brainstorming sessions to discuss different aspects of pavement resilience. This exercise led to a comprehensive list of different impacts on pavement, noting for each entry in the list the phenomenon in question, its impact, proposed measures, and approaches.

TC 4.1 also compiled a Collection of Case Studies [2-1] outlining measures to improve pavement resilience. These measures are referred to frequently in the current report.

This report lays a foundation for future work expanding on the same scope, as well as for experimental and modelling research work focused on adaptation solutions for decision makers and engineering practitioners.

3. AN OUTLINE OF SOURCES OF PAVEMENT STRESSORS

3.1. CLIMATE CHANGE-INDUCED PAVEMENT STRESSORS

Recent weather events have shown that infrastructure assets are vulnerable to climate change-related impacts; such vulnerabilities increase as the climate changes [3.1-1]. The existing models on global climate change, including even optimistic scenarios, show projections of a continuous change at an increasing rate over the next century [3.1-2]. In fact, climate change has produced a wide range of impacts that have affected infrastructure on a broad scale, though these are context-sensitive, meaning that they are subject to various influences specific to the location and to the adaptive resilience capacity of governments and communities in the given jurisdiction [3.1-3].

To give an approximate idea of what these future changes may look like, Figure 3.1-1 shows examples of a general increase in average air temperature and percentage change in summer precipitation, respectively, in the United States by the year 2050, derived from specific climate scenarios and sensitivity models [3.1-4].

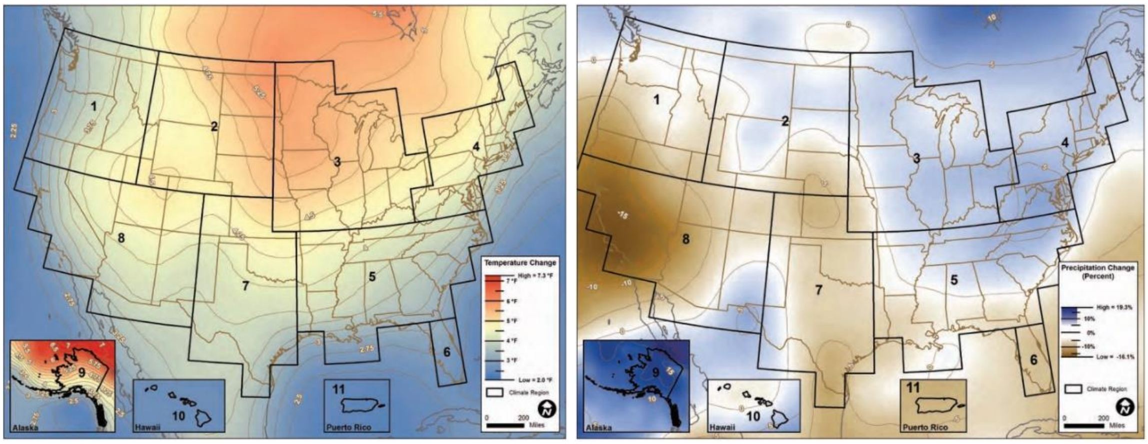

Figure 3.1-1: estimated increase in temperature (°F) in 2050 relative to 2010 (left); estimated percentage change in summer precipitation in 2050 relative to 2010 (right)

Rowan et al. [3.1-5] documented transportation asset sensitivities to a range of climate stressors. Extreme temperatures, precipitation, sea-level rise, storm surge, drought, freeze–thaw cycles, wind speed, cloud cover (or percent sunshine), and humidity are all stressors that could affect pavement systems.

If the scope of the analysis of climate stressors is extended to include subgrade soils, moreover, further impacts would include changes in frost penetration depth, changes in freeze–thaw and wet–dry cycles that affect the long-term durability and smoothness of pavement, and strength and deformation characteristics of soils. Of a similar significance is the impacts to permafrost, which is any ground that remains completely and continuously frozen for a period of at least two years (a phenomenon most common in higher latitudes). Permafrost thaw can affect the structural properties of the supporting soil in cold regions, leading to performance issues such as travel-way and shoulder deformation.

In this report, the following stressors are discussed:

- increase in temperature
- increased exposure to water

- changes in freeze–thaw cycle patterns
- longer periods of drought

3.2. VEHICULAR TRAFFIC-INDUCED PAVEMENT STRESSORS

Vehicular technology is also evolving, with an increasing emphasis on fuel efficiency and overall sustainability towards a circular economy. The structural pavement damage caused by heavy vehicles depends on loading pattern, axle loading, axle configuration, tyre contact pressure, and dynamic loading effects and their interactions.

Dual tyre assemblies have been in use in heavy-duty trucks for many years and offer numerous benefits. For instance, it has been widely accepted that using dual tyres improves control, ensures proper weight distribution, and increases load-carrying ability. Placing dual tyres on both ends of a single axle nearly doubles the weight that the axle can carry, thereby improving fuel economy. However, under increasing pressure to accomplish "more with less", the trucking industry has been shifting increasingly toward a novel type of wide-base tyre called the ''super single tyre". The super single tyre is a low profile, wide-base tyre that has a load rating equal to or greater than a pair of conventional dual tyres. Compared to the conventional dual-tyre system, a super single tyre offers economic and environmental benefits such as improved fuel efficiency, reduced vehicle emissions, and so on. In addition, the super single tyre has been reported to improve vehicle ride quality due to its low gravity center. These tyres are also more durable, stronger, and lighter in weight. Recent studies observed that 18 tyres in a standard dual-tyre assembly can be replaced by just 10 super single tyres [3.2-1, 3.2-2].

A few recent studies have compared the pavement responses under dual tyres versus super single tyres, concluding that, with an increase in tyre pressure, the tensile strain increases for both types of tyre configurations; however, the increment is greater in the case of super single tyres. For super single tyres, with an increase in speed, the effect of axle load on the tensile strain is greater, suggesting that super single tyres induce more damage to pavement compared to dual tyre assemblies [3.2-2]. Moreover, although super single tyres are considered a promising alternative to standard single tyres, as they are deemed to reduce environmental impact due to reduced fuel use, particularly on high-traffic volume routes [3.2-3, 3.2-4], a few recent studies show that the contact stresses are different and can be more damaging to the pavement than those of standard dual tyres.

Similarly, the longer-than-standard lengths of trucks now being introduced to reduce vehicle operating costs and reduce speeds in urban areas and thereby improve safety and urban mobility also contribute to changes in pavement response.

Other low-carbon strategies include low- and zero-emission vehicles that will likely exceed the legally allowable axle or gross vehicle loads, although the extent of variations may depend based on the use of the vehicle. With an increased focus on the sustainability of road transportation, the prospect of an increase in the legal axle load limit for trucks—which varies from one country to another and influences pavement behaviour—is now being given consideration.

In the future, a decarbonised transportation system is a major step toward achieving climatic goals and vehicles using electric or hydrogen are a strategy being explored globally. Zero-emission vehicles may induce heavier axle loads than conventional internal combustion engine (ICE) type vehicles. This is attributable to additional weight due to the external storage units (i.e., batteries/cylinders) these vehicles feature, and this is a crucial factor directly responsible pavement deterioration. In the future, this phase transition taking place in public and commercial transportation will lead to additional costs to preserve pavement condition [3.2-5, 3.2-6].

Specifically, these heavier axle loads will likely increase damage to pavements and bring about an unintended consequence: increased GHG emissions resulting either from the construction of stronger pavements to accommodate the heavier load or from the increased maintenance and rehabilitation (M&R) activities to retain the existing functional condition [3.2-7].

Agencies should thus consider taking the next step of evaluating the resilience [3.2-8] and the vulnerability of their pavement network to these variables by monitoring trends and implementing adjustments to their practices as appropriate. The mix-design and pavement design inputs will need to be modified based on pavement models simulating dynamic vehicle specifications.

The frictional heat generated by moving vehicles' tyres is also thought to be a significant contributor to road distress. Because of frictional heat, the temperature of wheel tracks is slightly higher than the temperature of the rest of the pavement, resulting in a non-uniform distribution of road surface temperature (RST), which may be responsible for the development of cracks and the subsequent increase in permeability of existing roads as well as the lowering of mix density [3.2-9].

An increase in vehicular loading time may also decreases the resilient modulus. This is due to the behaviour of asphalt concrete as a viscoelastic material, meaning that it behaves as an elastic material under fast-moving loads but more like a viscous material under slow-moving loads. Hence, an increase in vehicle speed may cause premature pavement failure. Similarly, the accumulated strain has been shown to increase with an increase in pulse width, indicating that low-speed vehicles can cause permanent deformation (rutting) to asphalt pavements [3.2-10].

Continuous vehicular loading stresses can also lead to the onset of pavement distresses, which could indirectly influence drivers' concentration, vehicle operation, and road traffic accidents and directly affecting ride quality. Pavement roughness, for instance, is a factor that will be affected by heterogeneous traffic and loading conditions [3.2-11]. Furthermore, the length of the vehicle has a direct relationship with pavement stresses, although this may depend on the axle spacing or axle configuration and on load distribution on the vehicle.

In this report, the following vehicular traffic-induced stressors are discussed:

- increase in heavy traffic
- increase in vehicle or axle loads

3.3. NATURAL AND MAN-MADE DISASTER-INDUCED PAVEMENT STRESSOR

Transportation infrastructure can be subject to some unpredictive forces, and these have the potential to be devastating to pavements. Weather events, for instance, pose a risk to pavement infrastructure, affecting the structural and functional integrity of the pavement. These conditions induce stresses in the pavement, leading to various forms of pavement distress such as cracking, rutting, and heaving.

Some examples of natural disaster-induced pavement stressors include:

Ground Faulting: Earthquakes can induce ground movement that can in turn cause pavement layers to shift, crack, and fail. These ground failures may also cause differential settlements and loss of soil strength, leading to significant damage to pavements by inducing ground motion and faulting that lead to shear stresses in the pavement and, ultimately, to soil support failure.

Rise in groundwater table: It has been predicted that the sea level will rise in the coming years. Seawater can make its way into coastal aquifers and alter groundwater levels, causing threats to pavements. The subgrade strength properties will change, thereby weakening the pavement and reducing the pavement performance.

Urban Heat Island effect: Conventional concrete and asphalt pavements absorb solar energy, leading to the Urban Heat Island (UHI) effect and premature pavement failure.

Flooding: Floods can damage pavements by eroding the subgrade and base layers of the pavement, leading to a loss of support for the pavement. This erosion can also result in water infiltrating the pavement layers, leading to a loss of support and structural damage. Moreover, debris washing onto the carriageway from a flood event can make a road temporarily impassable. Overall, flood damage can be either short-term (immediately after the flood event) or long-term [3.2-10].

Hurricanes and strong winds: Strong winds from hurricanes and other severe weather events can cause significant damage to pavements, particularly by creating uplift forces that can displace the pavement layers.

Freeze–thaw cycles: Repeated cycles of freezing and thawing can cause pavement materials to expand and contract, leading to cracking and other forms of distress and decreasing the mechanical performance and service life of the pavement.

Wildfires: Wildfires cannot directly melt or damage the pavement unless there is oil leakage at the location to increase the temperature, but the after-effects—in the form of cracking, loss of strength, and localised deformation—can be severe. Additionally, there will be an increased load of fire-fighting vehicles on roadway segments that may not have been designed to sustain such scenarios.

Pore Water Pressure: High water table and high pore water pressure can lead to subgrade erosion and subgrade failure; in such scenarios, the structural stiffness of the material will reduce the service life of the pavement. Moreover, moisture exchange between the environment and the pavement structure may occur through precipitation infiltrations, through surface cracks and the embankments, or from beneath due to capillary suction and a high-water table [3.3-1].

Climate Change: Frequent and sudden changes in the climate can affect pavement service life [3.3-2]. Under extreme rainfall, the pavement gradually loses its surface texture depth, possibly leading to traffic accidents. On the other hand, during peak surface temperatures, the pavement material gradually loses its stiffness, potentially leading to sudden failure when the soil in the subgrade or the materials in the unbound layers shrinking due to sudden drops in temperature. Because of this phenomenon, the pavement will start to show differential settlements depending on their age, location, current characteristics and condition.

Man-made disasters such as overloading, poor construction, explosions, chemical spills, and vandalism also have an impact on the pavement's structural or functional performance, but these are not in the control of the designer, as there are no models based upon which to account for these issues in the pavement design. For this reason, pavement stressors cannot be fully accounted for in the design, although they can be mitigated to a certain extent through the use of climate prediction models [3.3-3].

In summary, these disasters can have a critical impact on the pavement, and it is vital to consider the potential effects of these events in the design and maintenance of pavement infrastructure. Resilient pavement design is the key to controlling these stressors, where durable, sustainable materials, proper drainage, and regular inspection and maintenance to detect critical concerns before they become severe can all play an important role.

Additionally, disaster preparedness plans should be in place to ensure a rapid response for the timely repair of road assets. Proper planning and implementation of mitigation strategies can reduce the risk of damage and ensure the long-term sustainability of pavement systems.

In this report, the following natural and man-made disaster-induced stressors are discussed:

- wildfires
- landslides
- volcanic activity and earthquakes
- avalanches
- armed conflict

4. CLIMATE CHANGE-INDUCED PAVEMENT STRESSORS AND POSSIBLE MEASURES

4.1. INCREASE IN TEMPERATURE

In asphalt pavements, an increase in temperature will cause the asphalt mix to become less stiff (lower stiffness modulus), resulting in increased fatigue cracking or corrugation (washboard). Possible measures to mitigate this issue include:

- using modified binders to increase fatigue resistance (7.1.1)
- designing the pavement with adapted fatigue laws (7.1.7)
- using harder binders to increase the stiffness (7.1.2)

The viscoelastic properties of asphalt mixes are temperature-dependent. At higher temperatures, the mix can become more sensitive to rutting or bleeding (with reduction of skid resistance). Possible measures to mitigate this issue include:

- using modified binders to increase rutting performance or to increase stiffness (7.1.1)
- using harder binders to increase the stiffness (7.1.2)
- using high-albedo aggregates to decrease the temperature of the pavement (7.1.4)
- using a light coating to decrease the temperature of the pavement (7.1.5)
- using special asphalt mixes (7.1.8)
- using concrete overlays (7.2.2)
- using phase-change materials (7.4.5)

Higher temperatures can accelerate the ageing of the bitumen, resulting in raveling and potholes. Possible measures to mitigate this issue include:

- using ageing-resistant materials (7.1.3)

In (jointed) concrete pavements, an increase in temperature increases the stresses in the pavement. As a result, the joints expand and blow-ups can occur. Possible measures to mitigate this issue include:

- design changes to include (more) expansion joints (7.2.4)
- design changes to consider more aggressive temperature gradients (7.2.5)

4.2. INCREASED EXPOSURE TO WATER

This impact is the result of different phenomena such as increases in precipitation, flash flooding, sea-level rise, and heavy rain or snow events. If a pavement is inundated for a long period, the bearing capacity of the structure will decrease, and the base layers may erode. Possible measures to mitigate these issues include:

- using permeable structures (7.3.2)
- taking into account major flood events in the design of the drainage system (7.4.1)
- using bound base layers (7.3.1)
- using concrete pavements (7.2.1)

For asphalt pavements, moisture damage can occur, resulting in ravelling or stripping. Possible measures to mitigate this issue include:

- using polymer-modified binders (7.1.1)
- designing water-resistant asphalt mixes (7.1.6)

4.3. CHANGES IN FREEZE–THAW PATTERNS

An increase in the frequency of freeze–thaw cycles requires more aggressive winter maintenance programs and more frequent salt spraying. Concrete pavements are particularly vulnerable to freeze–thaw damage. Possible measures to mitigate this issue include:

- designing concrete mixes for freeze–thaw resistance (7.2.6)

In damaged (asphalt) pavements, cracking can be accelerated if water can penetrate into the pavement and expand during the freezing period, resulting in an increase in the occurrence of potholes. Possible measures to mitigate this issue include:

- designing water-resistant asphalt mixes (7.1.6)

In colder climates, thawing historically occurred only at the end of the winter. Recent climate trends have increased cycles of thawing throughout the winter season. In such scenarios short periods (a few weeks) of low temperatures alternate with periods of higher temperatures, resulting in a weakening of the pavement structure. Possible measures to mitigate this issue include:

- using frost protection layers (7.3.4)

4.4. LONGER PERIODS OF DROUGHT

Longer periods of drought result in less ground water, and this can lead to shrinkage of the unbound base layers or the subgrade soil. Possible measures to mitigate this issue include:

- infiltration or buffering of rainwater (7.3.3)
- replacing or stabilizing the subgrade (7.3.5)

5. VEHICULAR TRAFFIC-INDUCED PAVEMENT STRESSORS AND POSSIBLE MEASURES

5.1. INCREASE IN HEAVY TRAFFIC

An increase in traffic can lead to premature failure. Possible measures to mitigate this issue include:

- designing the pavement for accurate and future anticipated traffic levels (7.4.3)

5.2. INCREASE IN VEHICLE OR AXLE LOADS

The following impacts and measures are also applicable to similar phenomena, such as channelized traffic.

An increased vehicle load has little effect on the pavement, provided that the increased load is distributed over more axles. An increased axle load, on the other hand, can lead to premature fatigue failure. The use of super single tyres with their higher contact pressure results in higher stresses in the pavement, in turn leading to premature fatigue failure. Possible measures to mitigate these issues include:

- designing the pavement for accurate and future predicted axle loads (7.4.2)

For flexible pavements, increased axle loads can result in more permanent deformation (rutting or corrugation). Possible measures to mitigate this issue include:

- using harder binders to increase the stiffness (7.1.2)
- using special asphalt mixes (7.1.8)
- using separate truck lanes constructed with concrete pavement (7.2.3)
- distributing the load over the lane to reduce the impact of channelized traffic due to platooning (7.4.4)

6. NATURAL AND MAN-MADE DISASTER-INDUCED PAVEMENT STRESSORS AND POSSIBLE MEASURES

6.1. WILDFIRE

Wildfires can have an impact on the surface of the pavement, resulting in ageing of the bitumen or scaling. Possible measures to mitigate these issues include:

- using ageing-resistant materials (7.1.3)

6.2. LANDSLIDES

Landslides have impacts on the entire road structure. For possible measures to mitigate these issues, the interested reader may refer to the Literature Review “Increasing Resilience of Earth Structures to Natural Hazards” [6.2-1] or the Collection of Case Studies “Resilience of Earth Structures” by Technical Committee 4.3 (Earthworks) [6.2-2].

6.3. VOLCANIC ACTIVITY AND EARTHQUAKES

Volcanic activity and earthquakes have a major impact on the integrity of a pavement, but there are no known pavement-related measures to mitigate these risks.

6.4. AVALANCHES

If an avalanche damages the entire road structure, the impacts are comparable to those of a landslide.

6.5. ARMED CONFLICT

Armed conflict can have a major impact on the entire road infrastructure.

Armed conflicts can indeed have a major impact on the entire road infrastructure of a region or country. The consequences of armed conflicts on roads can be devastating, affecting transportation, economic activities, and the overall well-being of the affected population. Here's an explanation of how armed conflicts can impact road infrastructure, along with some references to academic sources:

Physical Damage:	During armed conflicts, roads and bridges can be direct targets of attacks or collateral damage. The destruction caused by bombings, shelling, or other military operations can render roads impassable and disrupt transportation routes. This not only affects the movement of people and goods but also hinders emergency response efforts [6.5-1].
Lack of Maintenance:	Ongoing armed conflicts can disrupt routine road maintenance and repair activities. Civil authorities may struggle to allocate resources and personnel for road upkeep during times of conflict, leading to the deterioration of road conditions over time [6.5-2].

Landmines and Explosive Remnants:	In some conflict zones, landmines and explosive remnants of war may be left behind after the active fighting has ceased. These deadly hazards can pose serious threats to road users, hindering safe access for civilians and reconstruction efforts [6.5-3].
Displacement of Communities:	Armed conflicts often force people to flee their homes and seek safer areas. Mass displacement can put additional strain on road infrastructure in neighboring regions, as more people and vehicles use alternative routes. This increased traffic can lead to congestion and road deterioration [6.5-4].
Economic Impact:	The destruction and disruption of road infrastructure can severely impact economic activities and trade. Businesses may suffer losses due to interrupted supply chains, decreased accessibility to markets, and increased transportation costs [6.5-5].
Humanitarian Response:	In conflict-affected areas, humanitarian organizations face challenges in delivering aid and assistance to those in need due to damaged or blocked roads. Access to food, water, healthcare, and shelter can be severely limited during active conflicts, affecting the well-being of affected populations [6.5-6].
Rebuilding Costs:	Once the conflict ends, rebuilding and rehabilitating the road infrastructure can be a daunting and costly task. Funds and resources that could have been used for other development projects may need to be diverted to restore vital transportation networks [6.5-7].

7. OVERVIEW OF MEASURES

7.1. MEASURES FOR ASPHALT PAVEMENTS

7.1.1. Using polymer-modified binders

Traditional bitumen, derived from the distillation and/or blowing of crude oils, possess satisfactory mechanical properties for use in asphalt pavements under moderate traffic and climatic conditions. The use of harder oxidised binders improves the high-temperature performance, but can compromise the low-temperature properties. Modified bitumen as a solution to increase the viscoelastic range plays a principal role in determining many aspects of road performance. Typical modifiers of bitumen are polymer, reclaimed tyre rubber, fibres (synthetic and mineral) and chemical compounds [7.1.1-1]. Table 7.1.1-1 and Figure 7.7.1-1 show some examples of these modifiers.

Type of modifier	Examples	Abbreviation
Thermoplastic elastomers	Styrene–butadiene–styrene elastomer (linear or radial) Styrene–butadiene rubber Styrene–isoprene–styrene elastomer Styrene–ethylene–butadiene–styrene elastomer Polybutadiene Polyisoprolene	SBS SBR SIS SEBS PBD PI
Recycled material	Crumb rubber Plastics	CR
Fibres	Lignin Cellulose Basalt Glass fibres Asbestos Polypropylene	PP
Natural asphalt	Trinidad Lake Asphalt Gilsonite	TLA
Chemical compounds	Adhesion improvers (organic amines) Antioxidants (phenol derivatives) Waxes	

Table 7.1.1-1 Examples of additives used to modify bitumen

(A) (B) (C)

Figure 7.1.1-1: bitumen modifiers: SBS (A) crumb rubber (B) synthetic fibres (C) [7.1.1-2, 7.1.1-3]

Polymer modification is a widely used method to improve bitumen properties. There are primarily two classes of polymers—elastomers and plastomers—that are considered suitable for bitumen modification [7.1.1-4]. The properties of polymer-modified bitumen are dependent on the polymer characteristics and content, the properties of the bitumen, as well as the nature of the blending process. The most common elastomer is thermoplastic rubber, which is obtained through the polymerisation of styrene and butadiene or styrene and isoprene [7.1.1-5]. The use of thermoplastic rubber raises the softening point and increases the viscosity of bitumen. In addition, elastomeric compounds improve the binder's elasticity and lower its breaking point. Figure 7.1.1-2 shows the microstructure of a modified binder.

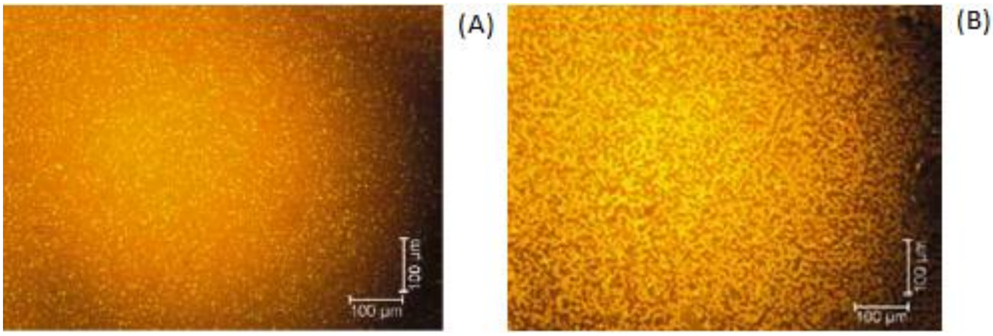

Figure 7.1.1-2: microstructure of a typical polymer-modified bitumen (A) and microstructure of a high-polymer-modified bitumen (B) [7.1.1-6]

The typical content of SBS in bitumen modification is 3-5% wt. Using higher contents of polymer (i.e., more than 5% wt.) in bitumen modification increases the polymeric phase, resulting in a high modified bitumen (Figure 7.1.1-2). High modified bitumen has a softening point above 80 °C and is denser and more elastic in consistency, necessitating higher compaction and mixing temperatures [7.1.1-6]. Polymer modification has beneficial effects on bitumen binders and therefore on road pavements. These include decreased thermal susceptibility and permanent deformation (rutting) and increased resistance to low-temperature and fatigue cracking (Figure 7.1.1-3).

Crumb rubber (CR) reclaimed from old scrap tyres can be used to modify and improve the performance of conventional bitumen while providing a use for disposed-of tyres. In the "wet" process, the CR modifier is added to the bitumen, prior to the manufacture of the hot asphalt. In the "dry" process, the CR modifier is mixed directly into the conventionally-prepared asphalt at the paddle mixer. The concentration of CR in bitumen is typically between 8% and 15% [7.1.1-1], however it can be lower or up to 22 % depending on the processing and country [7.1.1-7]. The addition of CR into virgin asphalt induces a significant increase in binder viscosity. The addition of CR into bitumen, meanwhile, can result in a hot-mix asphalt (HMA) with better resistance to rutting, fatigue cracking, and thermal cracking [7.1.1-8].

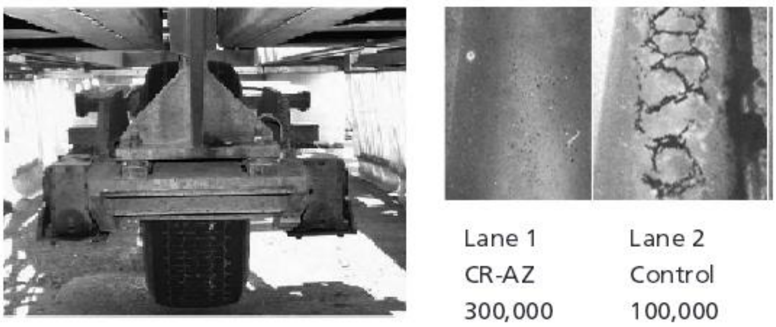

Figure 7.1.1-3: ALF testing device and comparison of crumb rubber (CR) and control pavement section after completion of loading [7.1.1-8]

Fibre-modified materials, such as basalt fibre, lignin fibre, polyester fibre, asbestos fibre, and carbon fibre, are commonly used in asphalt mixtures [7.1.1-9]. The most important properties of fibres with respect to bitumen and pavement applications are their thermo-stability, physical and mechanical properties, and chemical stability. The use of fibre additives has a reinforcing effect and significantly influences the performance of the asphalt binder and asphalt mixture. The unique characteristics of fibre-reinforced bitumen increase the consistency of binder. The softening point increases with fibre content in the binder in fibre-reinforced bitumen, while the ductility decreases [7.1.1-10]. During the modification process, a fibre network forms that reduces the temperature sensitivity of the binder. The addition of fibre can also improve the properties of the asphalt mixture, such as its high-temperature stability, low-temperature crack resistance, and water susceptibility.

Other additives include chemical and natural compounds to improve adhesion to aggregate, reduce viscosity, increase ageing resistance, and rutting resistance. For instance, common waxes have been used in the production of warm mix asphalt to raise the viscosity of the binder above the melting point of the binder [7.1.1-11]. Moreover, emulsifiers and surfactants, which do not reduce the binder viscosity but improve the coating of aggregates, have been used as anti-stripping agents (i.e., fatty amine derivatives). In some cases, the required properties can be modified by adding "natural" bitumen.

7.1.2. Using harder binders

Recent research and development results show that, in order to achieve high resistance to the increased aggressivity caused by climate and traffic, both the performance of the binder properties and the type and composition of the aggregates must be considered in the optimisation process.

Asphalt mixes with conventional paving grade and polymer-modified bitumen (for example, 25/55-55 A) as the surface course and binder course, respectively, are extremely susceptible to high shear and strain stresses. This leads to plastic deformation and the breaking out of individual aggregates at the surface. This mix is therefore not suitable for heavily stressed traffic surfaces.

As part of a study on the development of high-stable asphalts, an innovative binder (high-polymer-modified bitumen PmB 10/40-75 A, for the central European climate) with high deformation resistance at high temperatures, sufficient relaxation capacity at low temperatures and good affinity to the aggregate was shown to be suitable for the asphalt surface course and asphalt binder course. Indeed, the use of the high-polymer-modified bitumen, PmB10/40-65 A, significantly increases the polymer content in the asphalt mix and leads to a considerable improvement in its resistance to permanent deformation under high temperatures. The composition of the asphalt mix should also be optimised in terms of stability (crushed stone-rich composition) and impermeability. Fully crushed aggregates of category C100/0 and crushed sand should be used as aggregates so that a grain structure with high internal shear strength, and thus high resistance to deformation and bearing capacity, is achieved. In addition, a thick bitumen film should be targeted through increased binder content so that the mix, in combination with a hard bitumen and optimised grading curve, brings a significantly improved service life.

7.1.3. Using ageing-resistant materials

The ageing of bitumen is a physico-chemical process caused by exposure to oxygen, UV, and/or high temperatures. The oxidation makes the binder harder and more brittle, leading to cracking of the asphalt pavement. Various anti-ageing additives—such as an antioxidant, a polymer stabiliser, an organic or synthetic warm-mix asphalt additive, an asphalt modifier, or a co-polymer enhanced with anti-oxidant agents, a filler, and a UV antioxidant—can be used to make the asphalt more resistant to ageing [7.1.3-1].

The Collection of Case Studies [2-1] contains a similar case from Indonesia, "Resilient and sustainable pavement preservation solutions with Reacted and Activated Rubber".

7.1.4. Using high albedo aggregates

Extreme climatic events such as the combination of a heat period with tropical nights are occurring more frequently, although the intensity of these events varies greatly from region to region. Marked changes, especially with regard to daily maximum temperatures and the intensity of periods, are being observed in increasing frequency worldwide. The durability of road pavements is significantly influenced by these climatic changes.

To counteract the adverse consequences of climatic changes, material adaptations with regard to the thermo-physical and photometric material properties can be implemented in the mix design and production of climate-optimised asphalts. Optimisation of the photometric properties can be achieved by using light-coloured aggregates (quartzite) and synthetic binders with pigments. Regarding the thermo-physical properties, asphalt mixes with increased thermal conductivity (quartzite, limestone) and reduced thermal conductivity (electro-furnace slag) can be used for all asphalt layers.

A recent study by Schroedter et al. [7.1.4-1] showed that asphalt pavement variants featuring a light-coloured surface course and an aggregate with a higher thermal conductivity achieved the lowest heating development. Temperature increases in the asphalt base layer, it should be noted, depend on the thermal conductivity of the asphalt base layer and of the asphalt binder layer. In their study, the lowest heating development was achieved by the variant with a light-coloured and heat-conducting asphalt surface layer on an asphalt binder and an asphalt base layer with low thermal conductivity. In the lower third of the asphalt base layer temperature, differences of more than 5 °C compared to the conventional variant were achieved.

Surface courses with a high reflectivity are also very effective in reducing temperatures in the overall structure. As such, in the aforementioned study, the asphalt variants with a dark surface layer, although they had been optimised in terms of their thermo-physical material properties, did not achieve a significant reduction in heat development in the asphalt wearing course.

In summary, the adverse effects of extreme temperatures on the performance behaviour of asphalt can be successfully counteracted in a number of ways. For example, the above mentioned aggregates and binders, such as high polymer-modified bitumen (PmB H), can be incorporated.

7.1.5. Using a light coating

In a study by Emery et al. [7.1.5-1] on two taxiways at Pearson International Airport (Toronto, Canada), a light hydrated lime coating was applied on the upper surface course of the finished HMA to increase the albedo and surface colour effects on thermal behaviour. Albedo, or solar reflectance, is the percentage of solar energy reflected by a surface, and it is the primary determinant of a material's maximal surface temperature. The result of albedo is less black-body absorption and a lower temperature. Hence, the use of such a coating is an adaptation that could reduce the environmental impact of warm surface drainage runoff and reduce heat island effects in urban areas. Such a measure would also bring positive impacts in terms of both reduced costs and reduced use of energy resources.

The Collection of Case Studies [2-1] contains a similar case from Japan, “Study on the mitigation of heat island effect achieved by different pavement technologies”.

7.1.6. Designing water-resistant asphalt mixes

As a medium-term solution to combat the impact of increased frequency of intense precipitation events, the World Road Association [7.1.6-1] recommended adjustments to asphalt mix design to improve resistance to water damage by the use of special additives and fillers. It was also suggested to mitigate precipitation effects by developing hydrophobic coatings suitable for use at the micromechanical and/or pavement surfacing level. The discussion is expanded to possible leaching of deleterious substances. It is recommended that materials be bound or isolated as rising groundwater levels could cause leaching of contaminants.

The Collection of Case Studies [2-1] contains a similar case from Japan, “Anti-freezing pavement”.

7.1.7. Designing the pavement with adapted fatigue laws

In a research project funded by partner highway administrations across several European countries, entitled “Pavement Performance and Remediation Requirements following Climate Change” [7.1.7-1], the impact of climate change on highways was studied. A variety of pavement types and representative climatic zones were included, and the study examined differences in moisture content resulting from climate change. The study concluded that, for pavements with a long design life, road design methods need to be updated to ensure adequate performance amid climate change, especially for the bottom pavement layers, which cannot be accessed for modification during future rehabilitation and reconstruction.

Knott et al. [7.1.7-2] addressed seasonal pavement response trends in a recent study on short-term pavement adaptation planning. Their study used a hybrid bottom–up/top–down approach to quantify the impact of an incremental temperature rise from 0 °C to 5 °C on a two-lane regional connector in coastal New Hampshire. A simple adaptation strategy to increase the thickness of the pavement layers was then investigated. The primary distress mechanisms were assumed to be fatigue cracking and rutting, whereas thermal cracking was not considered. The study concluded that, in order for the pavement to achieve its design life with minimal (85%) reliability, an increase in the range of 7% to 32% in the thickness of the HMA layer would be required (to ensure the integrity of the base and subgrade layers). This recommendation was based on the rise in temperature projected by the year 2080 (with a 95% confidence interval), and the assumption that the thickness of the base layer (406 mm gravel) is held constant. The study also examined the required gravel base layer thickness when assuming that the HMA layer is held constant at 140 mm.

As the previous study suggests, the pavement design should take into account the design temperature, mainly with respect to the fatigue law, and should update it accordingly with the increase in air temperature over time.

7.1.8. Using special asphalt mixes

Traditional mixtures for wearing courses, such as stone mastic asphalt (SMA) or porous asphalt (PA), have a high resistance to permanent deformation [7.1.8-1]. This resistance comes from the high percentage of coarse aggregates (80% or more). This coarse stone skeleton has more stone-to-stone contact than a dense asphalt mix, giving it a high degree of stability.

A composite surface courses (CSC) combines the jointless design of asphalt with a high-strength cement-based mortar. In this manner, it is possible to produce surface courses that can withstand high mechanical loads. Compared with concrete, CSC can withstand higher point loads at lower paving thicknesses. Due to the dense microstructure of the mortar, high impermeability and resistance to chemical substances are also achieved. Moreover, CSC can typically be produced without joints [7.1.8-2].

CSC consists of an open porous asphalt layer with a large volume of air voids (25–30% by vol.) and a special flowing mortar. During construction, the open porous asphalt layer produced in the first steps is backfilled with the mortar in a subsequent operation the following day. The individual components—i.e., open porous asphalt layer and mortar—are combined to form the composite (semi-rigid) surface course.

Composite surface courses are used as wearing courses in traffic areas subject to particularly heavy loads, e.g., parking areas for heavy loading vehicles, bus stops/terminals, and industrial areas as shown in Figure 7.1.8-1. In addition, this layer is impermeable to water and can be used for pavements in handling areas for water-polluting substances.

Figure 7.1.8-1: bus terminal, Wuppertal, Germany (Photo: Sivapatham)

Paving of a CSC requires a suitable base. In general, the CSC is placed on a base of asphalt or a hydraulically bound base course. In any case, the base should be bonded, stable, load-bearing, clean, and uniform. To avoid the segregation and penetration of mortar in the base layer, air voids in the base layer must not be too high (recommendation < 6% by volume). To ensure proper paving of the composite surface, it is imperative that the accessible voids of the open porous asphalt are filled with the mortar throughout the entire thickness of the layer. In this regard, with increasing layer thickness the filling of air voids becomes difficult. For this reason, it is recommended to select a paving thickness in the range of 40 mm to 60 mm. In addition, the particle shape significantly influences the filling of air voids.

The recommended mix for an open porous asphalt consists of a coarse aggregate (one aggregate product size: 8/11 or 11/16), filler, paving-grade bitumen or polymer-modified bitumen as the binder, and fibre as the binder carrier. The viscosity of the mortar should in any case be such that it fills the accessible voids of the open porous asphalt over the entire layer thickness by the effect of its own weight alone, i.e., without additional vibration.

Finally, for use in low-income countries the Climate Resilient Sustainable Road Pavement Surfacing (CRISPS) project studied three types of road surfacing technologies. Its goal was to achieve an affordable high-volume road resilient to climate change and traffic demands. The pavements studied were Modified Epoxy Chip Seals (MECS), Modified Epoxy Asphalt Surfaces (MEAS), and Fibre Mastic Asphalt (FMA) [7.1.8-3].

7.2. MEASURES FOR CONCRETE PAVEMENTS

7.2.1. Using concrete pavements

Several studies have shown that stiffer pavements, because they are less susceptible to damage when the subgrade/base is inundated, are more resilient. Compared to flexible pavements, they have (1) a less pronounced drop in performance over time; (2) a quicker opening time, (3) a shorter structural recovery time, and (4) less susceptibility to secondary damage.

Figure 7.2.1-1: I-95 Flooding, 11-12-2020 (photo: Greg Dean, ACPA)

Concrete pavements are long-lasting and are built to withstand changes in temperature or moisture [7.2.1-1], as concrete stiffness remains constant in a range of ambient conditions. Moreover, concrete is not susceptible to softening or rutting, and can withstand the heat from forest or other fire events. Concrete roads are also less susceptible to the swelling or shrinking of the subgrade compared to flexible pavements, and as such they are the better suited to cohesive soils such as clay.

Flooding can have a detrimental effect on the pavement structure (see Figure 7.2.1-1). Among the different types of concrete roads, continuously reinforced concrete pavements (CRCP) are thought to be the most robust, especially in terms of their resilience to flooding [7.2.1-2, 7.2.1-3]. The continuous reinforcement creates a bridging effect, distributing the load over saturated bases and enabling the pavement to withstand local subsidence. In Texas, several sections of CRCP were subjected to frequent flooding and inundation due to extreme weather events and to traffic loads four to five times the expected levels, while incurring minimal annual maintenance costs, thus proving the robustness and resilience of this pavement type.

The Collection of Case Studies [2-1] describes two cases from the United States, including the aforementioned case in Texas:

- New concrete road in Florida designed to minimise flood damage
- Continuously reinforced concrete pavement resilience in Texas

7.2.2. Using concrete overlays

Concrete overlays are a promising solution for creating stiffer, more resilient pavement structures.

Figure 7.2.2-1: fibre-reinforced concrete overlay of asphalt-surfaced local road Grant County, Indiana, USA, 2020 (photo: ACPA)

A concrete overlay over an existing asphalt pavement (abbreviated COA in the American vernacular) can be either a bonded COA (COA-B) or an unbonded COA (COA-U). COA-B is a 4-to-6-in (100 mm to 150 mm) concrete overlay placed on the prepared surface of an existing asphalt pavement (Figure 7.2.2-1) [7.2.2-1]. These overlays are used when the existing asphalt is in good structural condition but has some surface distress. Bonded overlays of asphalt act as a composite pavement system in which both the concrete and asphalt share the load-carrying capability of the pavement system. As such, there needs to be at least 3 in (75 mm) of existing asphalt left in place in order to achieve the composite action. These overlays also often contain fibres to hold tightly together the small cracks that may develop, and they make use of shorter joint spacing compared to traditional jointed plain concrete pavements, typically 6 feet (2 m), to minimise environmental stresses.

Unbonded concrete overlays of asphalt are 6 in (150 mm) thick or greater and are used when the existing pavement is badly deteriorated or is less than 3 in (75 mm) in thickness. In such cases, the existing asphalt is treated as a stabilised base course and the new overlay is essentially a new concrete pavement on a strong base. While the typical thickness of unbonded overlays of asphalt for low-volume traffic applications is between 5 in and 7 in (125 mm to 175 mm), it can be up to 11 in (325 mm) in the case of high-volume, heavy traffic applications (and even greater for airfield applications).

7.2.3. Using separate truck lanes constructed with concrete pavement

As noted above, concrete is characterised by high stiffness. When built to the given requirements, concrete roadways can have a long service life without deformation and are therefore particularly suitable for heavy traffic. With asphalt as a flexible variant applied in conjunction with concrete, a higher noise reduction can be achieved, and construction and maintenance can be carried out more easily and quickly. Such applications are particularly suitable for lower axle loads.

As climate change increases, more extreme weather events and specifically longer periods of heat are being forecast. Under these conditions and especially in combination with heavy traffic loads, the risk of rutting is high. One way to counter this effect and to make the road infrastructure more resilient is to customise the construction method for different individualised lanes of traffic. For instance, the primary lane and hard shoulder could be constructed of concrete, but the second, and further lanes constructed of asphalt. This approach has already attained promising results, particularly on the motorway A61 in Germany (Figure 7.2.3-1), where a notable case used unreinforced concrete slabs for the concrete lane and SMA or mastic asphalt for the asphalt lanes.

Figure 7.2.3-1: trial site on motorway A61 in Germany

The longitudinal joint between the two construction methods is essential in this approach. In the case of asphalt, temperature movements and stresses occur continuously over time in the longitudinal direction. In the case of concrete slabs, temperature-induced movements (of up to several millimeters) and stresses are concentrated at the transverse joints at intervals of 5 m. This leads to stress peaks in the vicinity of each transverse joint. In practical applications of this approach to date, the practice has been to not permanently close this joint. Accordingly, a drain slot is made in the concrete through which penetrating water can be drained into the subsoil.

Alternatively, the concrete lane can be designed as a continuously reinforced concrete pavement. Rather than featuring joints spaced 5 m apart, this type of construction creates free transverse cracks spaced between about 0.7 m and 2.5 m apart with crack opening widths of just 0.5 mm. With this structural design, the stress peaks described above can be significantly reduced, the longitudinal joint can be sealed better, and the overall system (adjacent asphalt and concrete lanes) can be made significantly more durable. The first trial site for this system was set up on a motorway in Germany in 2021 (Figure 7.2.3-1).

The Collection of Case Studies [2-1] contains cases from Germany, “Continuously reinforced concrete pavement and mastix asphalt in parallel: trial site on motorway A61”.

7.2.4. Design changes to include (more) expansion joints

One of the characteristics of hardened concrete is that it is subject to thermal movements: it expands when the temperature rises and contracts when it falls. The extent to which a material expands or contracts under the influence of temperature is determined by the coefficient of thermal expansion, α. For concrete, α is about 10^{-5} m/m/°C.

The formula representing unconfined deformation, meanwhile, is

$$\Delta L = L \cdot \alpha \cdot \Delta T$$

where ΔL is the length change of the concrete slab or continuous row of concrete slabs, ΔT is the considered temperature difference, and L is the movable length of the slab or row of concrete slabs. For a long row of slabs, it is only at the ends that displacement will be measured during expansion, whereas, further from the ends, the movement of concrete pavement is counteracted by the deadweight of the fronting slabs and the effect of friction on the sub-base. Moreover, the concrete is subject to other forms of shrinkage due to water loss, including the hygrometric or plastic shrinkage during the first day after pouring and the further drying shrinkage of the hardened concrete. A precise calculation of the possible movements of a concrete pavement must take into account of all of these influences.

Expansion in concrete causes compressive stresses. This in itself does not pose a problem, as concrete is highly resistant to compression. Moreover, it creates a prestressing effect that counteracts bending and tensile stresses and is therefore beneficial for the service life of the pavement. However, this assumes that the concrete pavement has a uniform thickness, particularly at the joints, as well as a uniform quality. If this is not the case (e.g., due to provisional local repairs in the pavement), eccentric compressive forces may arise, resulting in stress concentrations that cause the concrete to fragment and, ultimately, buckle (also referred to as a “blow-up” of the pavement). In other words, weak spots in the concrete pavement are at the root of this type of distress.

One of the measures to prevent blow-ups of jointed plain concrete pavements (JPCP), apart from ensuring a uniform concrete mix and appropriate compaction, is to add a number of expansion joints, primarily in the end-section of the pavement (Figure 7.2.4-1). This allows some movement of the pavement and, consequently, a relief of the compressive forces. The number of expansion joints to include should be calculated taking into account all relevant parameters, including the temperature at the time of construction and the expected friction with the sub-base layer [7.2.4-1].

Figure 7.2.4-1: a series of expansion joints at the end of a jointed concrete pavement, Wisconsin, USA (photo: Luc Rens)

7.2.5. Design changes to consider more aggressive temperature gradients

Temperature and moisture variations across the depth of concrete pavements result in unique deflection behaviours referred to as curling and warping. Repeated slab curvature changes due to curling and warping, combined with traffic loading, can accelerate fatigue failure, including top-down and bottom-up transverse, longitudinal, and corner cracking [7.2.5-1].

Wistuba and Walther [7.2.5-2] conducted a parameter study in six European cities to consider the effects of climate change in a pavement's mechanistic design, drawing upon the linear-elastic multilayer theory. In their work, they considered every hour of the design period for the purpose of calculating temperature-induced stresses and strains in the pavement. They concluded that knowledge of local temperature is of paramount importance, as it influences the results of design, and that, for some climates in the central Europe region, there is a need to adapt pavement structural design to future requirements. Detailed recommendations as to what aspects of design ought to be adapted were not included in the study.

7.2.6. Designing concrete mixes for freeze–thaw resistance

Increasingly intense freeze–thaw cycles, combined with increased use of deicing salts, can lead to increased surface damage (scaling) of concrete pavements (Figure 7.2.6-1). This can be counteracted by either an appropriate content of entrained air in the concrete mixture or the application of a hydrophobic sealer on the surface.

Figure 7.2.6-1: de-icing salts on concrete, Belgium (photo: Luc Rens)

7.3. MEASURES FOR BASE LAYERS

7.3.1. Using bound base layers

In addition to concrete pavement, hydraulically bound base layers are also robust solutions since they can better withstand the effects of flooding compared to unbound granular layers. Indeed, cement-bound granular mixtures (Figure 7.3.1-1), including lean concrete and roller-compacted concrete, are highly erosion- and frost-resistant materials for base layers.

Figure 7.3.1-1: cement-bound base layer, A14, Belgium, 2011 (photo: Luc Rens)

The Collection of Case Studies [2-1] contains cases from the United States, "Pavement Flood Recovery: an Iowa case study", and Slovakia, "Homogenization layer – a green, innovative, sustainable, and resilient answer for reconstruction of existing cement-concrete roads".

7.3.2. Using permeable structures

A potential solution to address the adverse effect of the increase in precipitation intensity resulting from climate change is the use of porous pavements as a resilient solution against extreme weather events. In this respect, Zhu et al. [7.3.2-1] conducted a study to simulate the effect of permeable pavement using a storm water management model (SWMM) on controlling stormwater and reducing surface runoff. This type of pavement was found to be capable of reducing the delay peak time and some surface runoff by more than 50%. In their study, it should be noted, a permeable material is defined as a porous surface layer on top of an open-graded aggregate base layer. Although there is no specific mention in their study of adaptation to climate change, this type of pavement structure was shown to be a promising potential engineering-informed adaptation measure that can be tailored towards climate change-induced stressors.

In carrying out such adaptation interventions, it is important to be aware of issues specific to this type of pavement, including those pertaining to durability and functionality. For example, a study by Hu et al. [7.3.2-2] experimentally investigated the moisture sensitivity and damage evolution of porous asphalt mixtures, and their main finding was that, under long-term moisture damage, the moisture sensitivity of porous asphalt mixtures is a concern. They also found that tensile strength and resilience modulus decreased with increasing loading cycles, and noted that, in order to extend the service life of porous asphalt mixtures, maintenance is needed when the decrement of these properties exceeds 60%. Furthermore, moisture damage was found to have a significant influence, and an accelerating effect, on the damage evolution of porous asphalt mixtures. The interested reader may refer to Wu et al. [7.3.2-3] for a discussion of durability and functionality, as well as of the common distresses for open-graded friction course mixtures (i.e., the broad term for porous asphalt concrete).

The Collection of Case Studies [2-1] contains a case from Canada, "Permeable pavement to improve resilience of infrastructure".

7.3.3. Infiltration or buffering of rainwater

Climate change can have adverse effects on water management. It has been noted, for instance, that lengthy periods of dry conditions can lower the level of the ground water, even to the extent that the water levels of rivers and canals can become so low that transportation over water is disrupted [7.3.3-1]. When rainy conditions return, it is crucial to use the opportunity to raise the ground water level as much as possible. For this reason, immediately evacuating pavement runoff water to sewer or drainage systems or via canals to rivers and to the sea is to be avoided.

Several methods are available to infiltrate rainwater locally:

- surface infiltration: pavement runoff water infiltrates directly into the soil,
- underground infiltration: pavement runoff water infiltrates into the soil via specialised underground infiltration infrastructure,
- mixed infiltration: a combination of surface and underground infiltration is used.

The preferable option is to use surface infiltration (green areas, ditches, infiltration meadows). In such cases, a specific mode of construction is not required; the efficiency of the system can be visually observed and, if necessary, restored, and maintenance is relatively easy. However, in some cases surface infiltration is not feasible, such as in dense urban areas, areas with little area available for green space, and industrial areas where infiltration is not an option because of the risk of pollution.

Crucial for infiltration is the condition of the soil, especially its permeability, which determines its infiltration capabilities. In highly permeable soils (e.g., sand), rainwater can easily infiltrate (Figure 7.3.3-1). In the case of low-permeability soils (e.g., clay), the water should be buffered underground prior to delayed evacuation.

Several underground infiltration solutions exist [7.3.3-2]:

- pervious pavements
- horizontal infiltration pipes of synthetic material (PVC, HDPE, etc.) in porous concrete
- vertical infiltration drains
- infiltration boxes
- geotextile reinforcement with in-plane enhanced drainage

Figure 7.3.3-1: carpool parking in Kruisem with infiltration meadows, infiltration ditches and pervious bituminous pavements (photo: Agency for Roads and Traffic, Belgium)

The Collection of Case Studies [2-1] contains a case from Belgium, “Rainwater storage in base layers in Flanders”.

7.3.4. Using frost protection layers

When roads in cold regions are built on underlying frost-susceptible soils, special precautions must be taken. Upon freezing, these soils may draw up additional water to the frost zone, causing frost heave and, in turn, a significant adverse effect on driving conditions. In the next cycle of thawing, moreover, the higher water content may cause severe bearing capacity issues, decreasing both the serviceability and the design service lifetime of the road.

Freezing should in such cases be limited to the road superstructure. This can be done by placing an extra frost protection layer under the sub-base layer (Figure 7.3.4-1), thereby preventing the frost from penetrating into the subgrade material. This layer then also serves as an added layer necessary to satisfy the bearing capacity requirements.

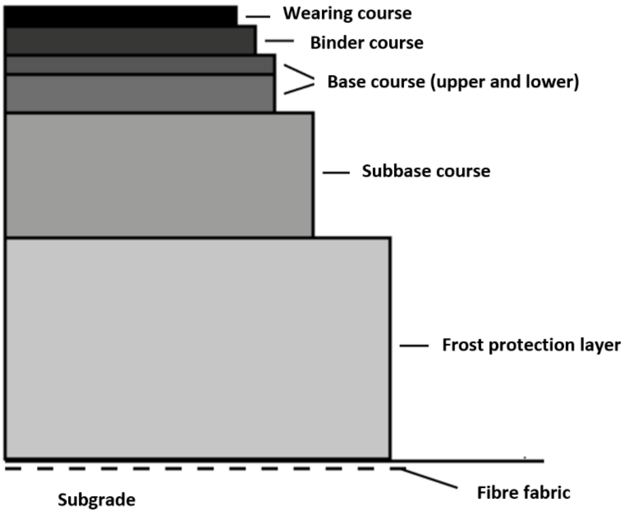

Figure 7.3.4-1: a typical Norwegian road construction with frost protecting layer (high volume road, poor subgrade)

A variety of materials can be used as frost protection. Depending on material selection and winter conditions, the thickness can vary significantly from 0.05 m to 1.0 m.

Natural or crushed aggregates

The aggregate used in this layer should be a well-graded material with a particle size up to 200 mm. In terms of thermal protection, the key factor is the amount of water that the material can hold. It is favourable to have a finer and well-graded particle distribution in order to increase the rate of water retention. Typical values of thermal conductivity range from 0.5 W/mK to 1.5 W/mK.

Lightweight aggregates

There are two types of lightweight aggregates—foamglass and expanded clay. These materials are very similar to one another in terms of their insulating properties, each with a thermal conductivity in a dry state of approximately 0.1 W/mK. For field conditions in which materials adsorb some water on the particle surface, meanwhile, the thermal conductivity is approximately 0.18 W/mK. The typical thickness for a frost protection layer composed of lightweight aggregates is between 0.2 m and 0.5 m.

Extruded polystyrene (XPS)

Extruded polystyrene (XPS) is the most effective of all frost protection materials, having a thermal conductivity of approximately 0.025 W/mK. Because of its low thermal conductivity, the typical layer thickness ranges from 50 mm to 100 mm. XPS should be installed between layers of fine material in order to avoid damage.

Geotextile reinforcement with in-plane enhanced drainage

Geotextile reinforcement with in-plane enhanced drainage can reduce ice lens formation and pavement heave through the rapid removal of rainfall infiltration (Figure 7.3.4-2). It can also reduce subgrade weakening through reinforcement and rapid removal of water from melting lenses. Consequently, it helps to prevent saturation of the subgrade and minimises ice lens formation during the freezing season.

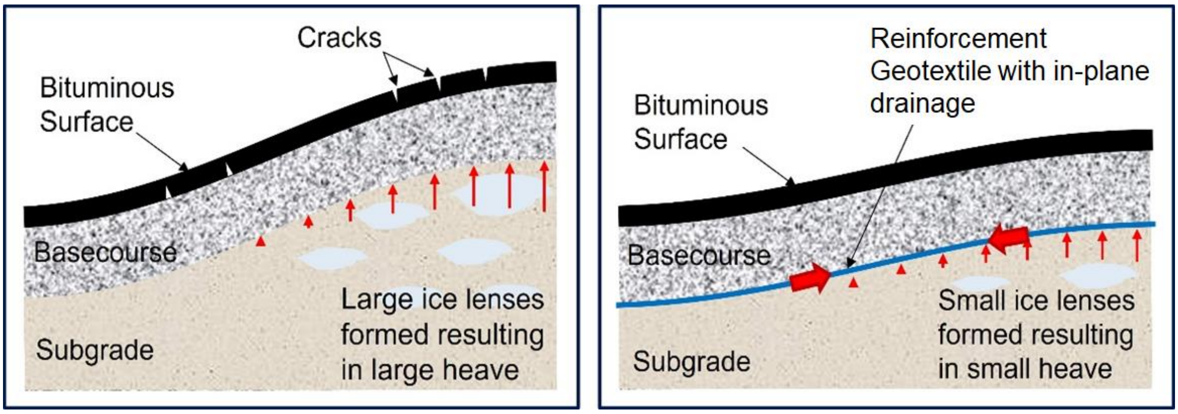

Figure 7.3.4-2: geotextile reinforcement.

The Collection of Case Studies [2-1] contains cases from Norway, "Performance of frost protection materials for road design", and from Canada, "The performance of different insulation materials".

7.3.5. Replacing or stabilizing the subgrade

Shrinkage of the unbound base and of the subgrade typically results from wet and dry cycles due to seasonal weather changes, as well as reduced ground water due to sustained periods of drought. The resulting changes in pore water pressure, both positive and negative (suction), can induce plastic strain and initiate tension cracks on the pavement. In addition, surface water may ingress through the cracks, the mobilised shear strength may decrease, and progressive failure may occur. The wetting and drying cycles of shrink-swell soils often induce large shrinkage and swelling strains, resulting in volumetric changes and corresponding failures in the form of cracking and heaving. These cracks developing in pavements can further allow intrusion of moisture to the subgrade, resulting in a weakening of the subgrade and loss of the pavement's foundation support [7.3.5-1, 7.3.5-2]. Luo and Prozzi [7.3.5-3] found that non-uniform matric suction changes in the subgrade can cause shrinkage stresses in the subgrade and pavement structure, and that this stress concentration can be large enough to drive the crack to propagate further to the pavement surface. Take and Bolton [7.3.5-4] observed that seasonal pore pressure cycles in slope can also drive the mechanism of slope creep, ultimately leading to progressive failure through the development of cracks towards the crest of the slope and a shear rupture at the toe. Factors influencing shrink-swell soils include soil properties (e.g., clay mineralogy, plasticity, density, void ratio, etc.), environmental factors (e.g., climate, groundwater, vegetation, drainage, etc.), and state of stress (e.g., net normal stress, suction stress, etc.) [7.3.5-5].

Stabilisation of the base and subgrade is the most effective measure when dealing with soils that are susceptible to shrinkage-swelling due to changes in moisture content. The effectiveness of lime, cement, and fly ash for stabilisation of the base and subgrade depends on the physicochemical characteristics of both soil and additives. The application of different types and amounts of chemical additives may cause variations in the strength, durability, and performance of the stabilised base and subgrade. Cement stabilisation is more effective for granular and low plastic soils, e.g., silty and sandy soils, whereas lime stabilisation is more suitable for cohesive and highly plastic soils, e.g., clayey soils, expansive clay, etc. Fly ash stabilisation does not exhibit a similar degree of strength, workability, or durability due to its relatively low lime (or calcium) content. The combination of different additives can be more efficient in improving problematic soils. For instance, the addition of fly ash with lime to expansive soils has been found to improve performance as compared to fly ash alone [7.3.5-6], and the addition of lime in a clay-fly ash mix has been found to be effective for reducing the swelling properties of expansive soils [7.3.5-7].

7.4. Other measures

7.4.1. Taking into account major flood events in the design of the drainage system

Besides overloading, environmental factors such as extreme temperatures and the presence of water, mainly in the pavement structure, can significantly affect pavement deterioration. The main concern in this regard is that a combination of these factors (namely thin or unpaved roads, asphalt concrete stiffness not adequately designed for service temperature, poor road maintenance, and overloading due to lack of enforcement) can represent critical scenarios, and these most frequently occur together in LMIC. These combinations of factors can reduce the pavement lifespan to less than half of the designed life [7.4.1-1].

7.4.2. Designing the pavement for accurate axle loads

Maximum axle loads are directly linked to infrastructure design parameters through the 4th power law (in the case of flexible pavements) and through the 6th to 12th power laws (in the case of semirigid and rigid pavements). As such, the damage suffered by infrastructure when design limits are exceeded is exponential. In turn, further damage (from overloading) leads to a greater need for repairs and maintenance [7.4.1-1].

Particularly for flexible pavements, which feature thin asphalt wearing courses and a weak subgrade, increasing or sustained overloading can lead to accelerated fatigue cracking and secondary rutting. In fact, total failure (breakage) can be reached within only a few days in the case of flexible pavements (e.g., secondary roads), if traffic loads significantly exceed design loads.

Moreover, with increasing temperatures, as already referred to in 7.1.7, the pavement failure laws must be adapted. Pavement deterioration mechanisms can be expected to become more significant due to climate change, as wearing course rutting and rapid top-down cracking due to accelerated bitumen ageing become more pronounced.

However, pavement resilience can be improved if the design is adapted to the expected future axle loads, and if the weight control of the traffic can be adequately enforced, using, for example, Weight in Motion systems.

Changes to electric power supply with the implementation of Heavy-Duty Zero Emission Vehicles (ZEVs) are expected to increase the load per axle due to increased battery weight (Figure 7.4.2-1) [7.4.2-1]. Additionally, there is a trend toward increasing the weight and dimensions of transport vehicles for heavy goods, as well as toward the increased use of European Modular Systems (EMSs) for road freight transport. The pavement design must take these trends into account in order to ensure the resilience of the infrastructure.

The Collection of Case Studies [2-1] contains a case from Portugal, “Simplified pavement solutions for roundabout intersections – standard catalog”, and a case from the Czech Republic, “Use of fibreglass grids to improve the durability of repaired low-volume roads”.

Figure 7.4.2-1 Next-generation Fuel Cell Truck (photo: Toyota Motor Corporation, https://global.toyota/).

7.4.3. Designing the pavement for accurate and predicted traffic levels

The effect of overloading on the residual life of pavement depends on various factors, such as type of traffic, load distribution, vehicle wheel and suspension, as well as the type of pavement and its condition, thickness, uniformity, cracking, etc. The consequences of overloading can be specifically mitigated in a number of ways, such as improved vehicle loading practices, reducing the frequency and severity of overloading through more robust enforcement, using 'road friendly' suspension systems, and following road design principles that take into account heavy traffic loads and that accurately consider local temperature conditions. The leading principle in road infrastructure design should be to account for the real-world situation, and not an ideal situation with perfect compliance. This, of course, requires a good understanding of actual and predicted vehicle loads, and, thus, effective monitoring practices [7.4.1-1].

Today it is possible to have a thorough register of the traffic on a given pavement section. Nevertheless, traffic levels can vary over time on a given road section. The information gathered over the course of the road's service life can be used as the basis for adopting adequate and timely maintenance and rehabilitation practices based on realistic readings of traffic levels. An iterative pavement design approach can be used to adapt the design, taking into account real traffic levels [7.4.3-1].

Additionally, there are practices that can be applied to extend the pavement service life. These include ensuring proper distribution of load among the vehicle axles, use of twin tyres, and—one of the most critical—effective road maintenance to minimise road unevenness and corrugation and to prevent water stagnation on the surface and water infiltration into the pavement structure.

7.4.4. Distributing the load over the lane to reduce the impact of platooning

The automatisation of vehicles has led to growing interest in the implementation of connected autonomous trucks in "platoons" (Figure 7.4.4-1). The purposes of platooning are to reduce driver fatigue, traffic congestion, fuel consumption, and GHG emissions and to improve road safety. However, platooning generates load stress configurations that typically are not considered in the classical design of pavement structures. Bearing in mind the viscoelastic nature of the asphalt layers, the short inter-truck distance and the lack of wandering between trucks during platooning mean that there is little relaxation of load strains between trucks compared to under traditional traffic loads (refer to the increase in strain peaks illustrated in Figure 7.4.4-1). As such, for the same number of trucks, an increase in cumulative fatigue damage and a reduction in pavement service life will be observed if measures are not taken to counteract these effects.

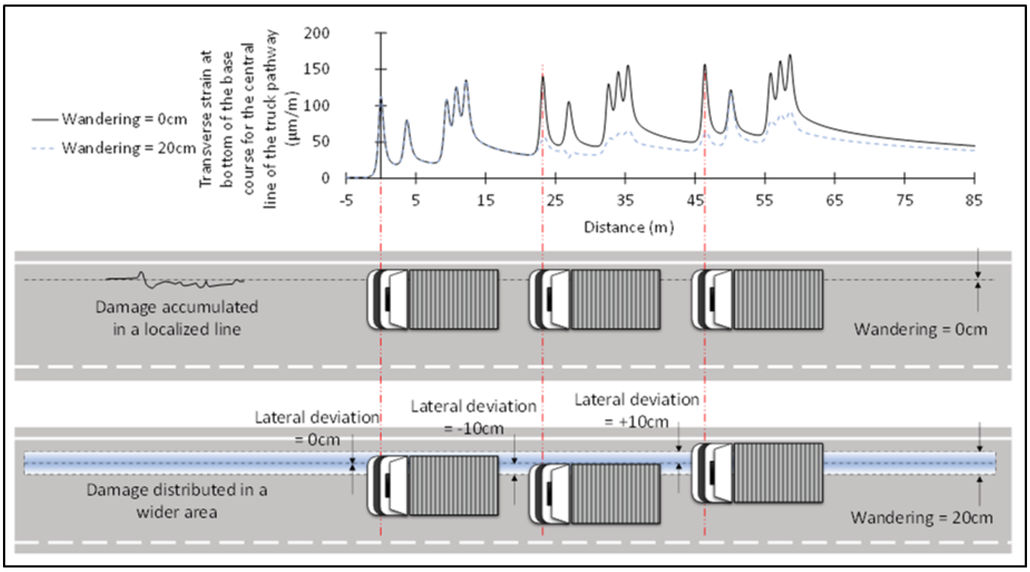

Figure 7.4.4-1: example of wandering patterns among trucks in the platoon (truck speed = 80 km/h, pavement temperature = 35 °C, inter-truck time gap = 0.5 s).

Various recent studies have evaluated the impact of platooning on pavement service life. Among them, work package 4 of the recent European project Ensemble (H2020 Research and Innovation Program, grant agreement No. 769115) evaluated solutions at full scale to mitigate this problem and increase the resilience of pavements subjected to platooning. The effects of parameters such as traffic distribution over the course of a year and over the course of a day, platoons as a percentage of overall traffic, truck loads, number of trucks in the platoon configuration, lateral wandering, and inter-truck distances were all evaluated. This study demonstrated the importance of carefully configuring these parameters in a manner that ensures the successful implementation of vehicle automatisation and platooning without significantly compromising the pavement's service life. Recent numerical modelling-based projections have already shown that increasing the lateral wheel wandering and increasing the inter-vehicle distance may be effective strategies for managing platooning configurations. For example, these studies have found that, for trucks driving in 3-truck platoons at 80 km/h with a truck time-gap of 0.8 s and a lateral deviation of ±20 cm, the damage associated with the fatigue of the pavement will be 58% higher than when only using individual driving trucks (inter-vehicle time-gaps of 3 s or more). Meanwhile, it was demonstrated that, if a higher lateral wandering of ±40 cm is maintained for these platoons, the fatigue damage can be limited to just 37%. This analysis shows that increased lateral wandering is a promising option to mitigate platooning-induced damage to pavement.

One of the notable potential benefits of platooning, of course, is that road authorities are afforded the opportunity to influence the parameters according to which platooning trucks operate on the roadway. Depending on the state of the pavement and the specific situation, the road authorities can mandate a certain headway, maximum speed, number of trucks in one platoon, inter-truck time gaps, and even lateral positioning.

The Collection of Case Studies [2-1] contains a case from France, “Evaluation of truck platooning on road structures”.

7.4.5. Using phase-change materials

Phase-change materials (PCM) are materials that can absorb or release heat at a certain temperature when they melt or solidify, i.e., the phase change between the solid and liquid phases. Various types of PCMs are available:

- organic: paraffins or non-paraffin compounds (ether, glycol, etc.)
- inorganic: salt hydrates or metallics
- eutectic types: a mix of different types of PCMs (organic–inorganic, organic–organic, or inorganic–inorganic)

The operating temperature can be effectively managed by selecting the appropriate PCM. In this way, extreme temperatures in the material can be avoided or reduced.

PCMs have been successfully deployed for this purpose in both asphalt mixes [7.4.5-1] and concrete mixes [7.4.5-2]. The incorporation of PCMs with a suitable phase transition temperature, enthalpy of phase change, and degree of dispersion in concrete mixes has been shown to alleviate thermal cracking and freeze–thaw-related deterioration [7.4.5-3]. The use of PCMs in asphalt mixes, meanwhile, can reduce the temperature of the asphalt pavement (to reduce rutting or heat island effect, for instance), or it can be applied to increase the temperature in order to mitigate low-temperature cracking.

There are various techniques for incorporating PCMs in asphalt or concrete mixes:

- encapsulation: PCMs are encapsulated in a protective shell with a diameter of 1 µm to 1 mm (micro-encapsulation) or larger than 1 mm (macro-encapsulation)
- shape-stabilisation: PCMs are absorbed into porous materials (e.g., light-weight aggregates)
- direct incorporation

8. CONCLUSIONS

A resilient pavement can maintain its function under stressors caused by climate change, heavy traffic loads, and, in some cases, natural or man-made disasters. Several measures are available to increase a pavements resilience to climate change effects and to changes in vehicular traffic loads. It is more difficult to make a pavement resilient to natural or man-made disasters because of the extreme disruptive impact of those events, and due to the age, condition, characteristics and location of pavements, which influence its vulnerability.

Some resiliency measures are related to the choice of pavement material itself, while others may be related to the design and construction of the roadway or to the way the infrastructure is managed and maintained. Some of the technologies to improve resiliency, although well-established from a technical perspective, may have yet to be accepted as a standard practice in some jurisdictions or among some road infrastructure owners. This include the use of cement-treated base layers or concrete pavements to make the pavement more robust, and the use of polymer-modified bitumen to alter the properties of asphalt pavement.

Accurate assessment or prediction of the pavement stressors can lead to an adapted design method for the entire road structure, where adaptations may include higher design temperatures, designing for accurate traffic loads, and taking into account more frequent freeze–thaw cycles.

The measures proposed in this report can be applied in all countries, HIC as well as LMIC, where the stressors occur.

9. RECOMMENDATIONS

9.1. Recommendations for decisions makers

A pavement structure can be designed and constructed to be more resilient to climate-change, traffic, and natural or man-made stressors:

- by using an adapted design method to take into account future changes to the climate and to traffic loads
- by using innovative materials and construction methods

A combination of measures may be necessary in order to adequately address multiple stressors and thereby increasing a pavements resilience.

9.2. Recommendations for PIARC

This report focuses on measures in the design phase to reduce the impact of a hazard and alter its functionality curve to reduce resistance loss. Techniques to minimise recovery time are not addressed herein and could be the subject of a future report.

10. GLOSSARY

Term	Definition
CR	crumb rubber
CRCP	continuously reinforced concrete pavement
EV	electric vehicle
GHG	greenhouse gas
HMA	hot mix asphalt
JPCP	jointed plain concrete pavement
LMIC	low and middle-income countries
PCM	phase-change material
PmB	polymer-modified bitumen
stiffness	the ability to resist to deformation
UHI	Urban Heat Island

11. REFERENCES

[1-1] PIARC (2021) Internal document 2021BN1.4EN, Terminology on Resilience and Coordination with Related PIARC Technical Committees.

[1-2] L. F. Gay, S. K. Sinha (2013) Resilience of Civil Infrastructure Systems: Literature Review for Improved Asset Management; International Journal of Critical Infrastructures, January 2013. https://www.researchgate.net/publication/264437671

[2-1] PIARC (2022) Collection of Case studies 2022R25EN, Measures for Improving Resilience of Pavements.

[3.1-1] A. Choate, B. Dix, A. Wong, B. Rodehorst, W. Jaglom, J. Keller, J. Lennon, C. Dorney, R. Kuchibhotla, J. Mallela (2017) Synthesis of Approaches for Addressing Resilience in Project Development; Federal Highway Administration: Washington, DC, USA.

[3.1-2] T. Stocker (2013) Climate Change 2013: The Physical Science Basis: Working Group I Contribution to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change; Cambridge University Press: Cambridge, UK.

[3.1-3] S. Muench, T. Van Dam (2015) Climate Change Adaptation for Pavements. [Techbrief] No. FHWA-HIF-15-015; Federal Highway Administration: Washington, DC, USA.

[3.1-4] M. Meyer, M. Flood, J. Keller, J. Lennon, G. McVoy, C. Dorney, K. Leonard, R. Hyman, J. Smith (2014) Strategic Issues Facing Transportation: Climate Change, Extreme Weather Events, and the Highway System: Practitioner's Guide and Research Report; NCHRP Report 750; Transportation Research Board of the National Academies: Washington, DC, USA.

[3.1-5] E. Rowan, C. Evans, M. Riley-Gilbert, R. Hyman, R. Kafalenos, B. Beucler, B. Rodehorst, A. Choate, P. Schultz (2013) Assessing the Sensitivity of Transportation Assets to Extreme Weather Events and Climate Change; Transportation Research Record. 2013, 2326, 16–23. https://doi.org/10.3141/2326-03

[3.2-1] G. Wang, R. Roque (2011) Impact of Wide-Based Tires on the Near-Surface Pavement Stress States Based on Three-Dimensional Tire-Pavement Interaction Model; Road Materials and Pavement Design 12(3), 639–662. http://dx.doi.org/10.1080/14680629.2011.9695264

[3.2-2] R. R. Fedujwar, U. C. Sahoo (2023) Pavement Responses Under Wide Base Tyres Subjected to Moving Loads; International Journal of Transportation Science and Technology, 12(2), 549–559. https://doi.org/10.1016/j.ijtst.2022.05.006

[3.2-3] J. Ponniah, R. Haas, Z. Jiang, R. Madill (2009) Wide Base Single Tires vs. Dual Tires: Assessment of Impact on Asphalt Pavements; In Proceedings of the Annual Conference of the Transportation Association of Canada; Vancouver, British Columbia, Canada.

[3.2-4] M. M. Nojumi, M. Basavarajappa, L. Hashemian, A. Bayat (2021) Investigation of the Impact of Tire Configurations on Different Pavement Structures Using Finite Element Analysis; International Journal of Pavement Research and Technology, 15(4), 847–862. http://dx.doi.org/10.1007/s42947-021-00057-7

[3.2-5] J.M. Low, R.S. Haszeldine, G.P. Harrison (2022) The Hidden Cost of Road Maintenance Due to the Increased Weight of Battery and Hydrogen Trucks and Buses —a Perspective; Clean Technologies and Environmental Policy, 25, 757–770.

[3.2-6] J.M. Low, S. Haszeldine, G. Harrison (2022). Weight Gain of Battery and Hydrogen Zero Emission Vehicles Over Internal Combustion Vehicles: Consequential Increases in Road Wear; Preprint. DOI: 10.21203/rs.3.rs-1435405/v1

[3.2-7] J. Harvey, A. Saboori, M. Miller, C. Kim, M. Jaller, J. Lea, A. Kendall, A. Saboori (2020) Effects of Increased Weights of Alternative Fuel Trucks on Pavement and Bridges, University of California Institute of Transportation Studies, Davis, CA, USA, Report No. UC-ITS-2020-19, 99 pages.

[3.2-8] CEN (2021) Guidelines for the assessment of resilience of transport infrastructure to potentially disruptive events, CWA 17819.

[3.2-9] M. I. Khan, S. Y. B. Z. Abidin, M. H. Sutanto, F. Wong, M. Bujang (2021) Simulating the Impact of Vehicle Speed on the Life of Bituminous Pavement; IOP Conference Series: Earth and Environmental Science, Volume 1022, Proceedings of the 6th International Conference on Civil and Environmental Engineering for Sustainability (IConCEES 2021). https://iopscience.iop.org/article/10.1088/1755-1315/1022/1/012040

[3.2-10] D. Lu, S. Tighe, W.-C. Xie (2018) Impact of Flood Hazards on Pavement Performance; International Journal of Pavement Engineering 21(6), 746–752. http://dx.doi.org/10.1080/10298436.2018.1508844

[3.2-11] M. O. Popoola, O. A. Apampa, O. Adekitan (2020) Impact of Pavement Roughness on Traffic Safety under Heterogeneous Traffic Conditions; Nigerian Journal of Technological Development, 17(1). https://doi.org/10.4314/njtd.v17i1.2

[3.3-1] F. Salour, S. Erlingsson (2014) Impact of Groundwater Level on the Mechanical Response of a Flexible Pavement Structure, VTI rapport 808A; https://www.diva-portal.org/smash/get/diva2:706306/FULLTEXT01.pdf

[3.3-2] S. T. Swarna, K. Hossain (2022) Climate Change Impact and Adaptation for Highway Asphalt Pavements: A Literature Review; Canadian Journal of Civil Engineering, 49(7), 1109–1120. https://doi.org/10.1139/cjce-2021-0209

[3.3-3] C.E. Zapata, D. Andrei, M.W. Witczak (2007) Incorporation of Environmental Effects in Pavement Design; Road Materials and Pavement Design, 8(4), 667–693. http://dx.doi.org/10.1080/14680629.2007.9690094

[6.2-1] PIARC (2022) Literature Review, Increasing Resilience of Earth Structures to Natural Hazards.

[6.2-2] PIARC (2022) Collection of Case Studies, Resilience of Earth Structures.

[6.5-1] S. J. Williams (2017) Infrastructure, Emergency Management, and the Military: Climate and Social Drivers of Vulnerability; Environment and Planning C: Politics and Space, 35(3), 392-414.

[6.5-2] R.G. Thompson, R.D. Warburton (2017) The Impacts of Political Instability on Public Service Delivery; World Development, 96, 128-142.

[6.5-3] R. Picciotto, C. Dandeker (Eds.) (2018) Roads: An Anthropology of Infrastructure and Expertise; Cornell University Press.

[6.5-4] F. Laczko, C. Aghazarm (2009) Migration, Environment and Climate Change: Assessing the Evidence; International Organization for Migration (IOM) Migration Research Series No. 31.

[6.5-5] Independent Evaluation Group (2015) World Bank Group Assistance to Low-Income Fragile and Conflict-Affected States: An Independent Evaluation.

[6.5-6] L.A. Fast, A.J. Weigert (2016) A Conceptual Framework for Understanding the Direct and Indirect Effects of Natural Disasters and Technological Accidents on Industrial Facilities; Natural Hazards Review, 17(3), 04016002.

[6.5-7] International Monetary Fund (IMF) (2015) Public Investment in a Developing Country: The Case of Road Infrastructure in Nigeria.

[7.1.1-1] R. N. Hunter, A. Self, J. Read, chapter 8; In the Shell Bitumen Handbook, 6th Edition, pp. 149–180.

[7.1.1-2] D. Wisniewski, M. Slowik, J. Kempa, A. Lewandowska, J. Malinowska (2020) Assessment of Impact of Aramid Fibre Addition on the Mechanical Properties of Selected Asphalt Mixtures; Materials, 13(15), 3302.

[7.1.1-3] H. Zhang, Y. Zhang, J. Chen, W. Liu, W. Wang (2022) Effect of Desulfurization Process Variables on the Properties of Crumb Rubber Modified Asphalt; Polymers, 14(7), 1365.

[7.1.1-4] U. Isacsson, X. Lu (1999) Characterization of Bitumens Modified with SEBS, EVA and EBA Polymers, Journal of Materials Science, 34, 3737–3745. https://doi.org/10.1023/A:1004636329521

[7.1.1-5] I. Gawel, M. Kalabinska, J. Pilat (2001) Road bitumen, WKŁ, 2nd Edition, pp. 145–179.

[7.1.1-6] K. Blazejowski, M. Wojcik-Wisniewska, W. Baranowska (2018) Bitumen Handbook 2018, Orlen Asfalt Sp.

[7.1.1-7] FHWA (2021) Recycled Tire Rubber-Hybrid GTR Binders and Dry Added GTR - How to use the in Asphalt Pavement Mixtures, Publication Number FHWA-HIF-22-011, https://www.fhwa.dot.gov/pavement/recycling/Recycle_Tire_Rubber_Mixture.pdf

[7.1.1-8] L. Santucci (2009) Rubber Roads: Waste Tires Find a Home, Technology transfer program, 1(2).

[7.1.1-9] S.M. Abtahi, M. Sheikhzadeh, S.M. Hejazi (2010) Fiber-Reinforced Asphalt-Concrete – A Review; Construction and Building Materials, 24, 871–877.

[7.1.1-10] F. Gou, R. Li, S. Lu, Y. Bi, H. He (2020) Evaluation of the Effect of Fiber Type, Length, and Content on Asphalt Properties and Asphalt Mixture Performance; Materials, 13(7), 1556.

[7.1.1-11] P. Caputo, A.A. Abe, V. Loise, M. Porto, P. Calandra, R. Angelico, C.O. Rossi (2020) The Role of Additives in Warm Mix Asphalt Technology: An Insight into Their Mechanisms of Improving an Emerging Technology; Nanomaterials, 10, 1202.

[7.1.4-1] T. Schroedter, P. Sivapatham (2022) Development of Asphalt Pavement with Regard to the Thermo-physical and Photometric Material Properties; In Proceedings of the 16th World Winter Service and Road Resilience Congress, PIARC, Calgary, 7–11 February 2022.

[7.1.3-1] I.G. do Nascimento Camargo, T.B. Dhia, A. Loulizi, B. Hofko, J. Mirwald (2021) Anti-Aging Additives: Proposed Evaluation Process Based on Literature Review; Road Materials and Pavement Design, Volume 22. https://doi.org/10.1080/14680629.2021.1906738

[7.1.5-1] J.J. Emery, P. Guo, D.F. Stolle, J. Hernandez, L. Zhang, (2014) Light-Coloured Grey Asphalt Pavements: From theory to practice; International Journal of Pavement Engineering , 15, 23–35.

[7.1.6-1] World Road Association (2013) Dealing with the Effects of Climate Change on Road Pavements; A Report of Working Group; World Road Association: Paris, France; Volume 5.

[7.1.7-1] A. Dawson (2010) Pavement Performance and Remediation Requirements Following Climate Change (P2R2C2); Summary Final Report, ERA-NET ROAD; University of Nottingham: Nottingham, UK.

[7.1.7-2] J.F. Knott, J.E. Sias, E.V. Dave, J.M. Jacobs (2019) Seasonal and Long-Term Changes to Pavement Life Caused by Rising Temperatures from Climate Change, Transportation Research Record, 2673, 267–278.

[7.1.8-1] REAAA (2018) Report on FEHRL Scanning Tour to South Korea and Japan: Infrastructure Resilience, https://www.reaaa.net/report-on-fehrl-scanning-tour-to-south-korea-and-japan-infrastructure-resilience/

[7.1.8-2] Research Association for Roads and Traffic (FGSV) (2010) Technical Bulletin for the Production of Semi-Rigid Surface Courses (original in German); FGSV-Nr: 729, ISBN: 978-3-941790-51-3, Cologne, Germany.

[7.1.8-3] CRISPS project (2023) https://more.bham.ac.uk/hvt-crisps/

[7.2.1-1] Higher Resilience (2021) EUPAVE Fact sheet, Brussels, available on https://www.eupave.eu/resources/fact-sheet-climate-resilience/

[7.2.1-2] R. Oyediji, S.L. Tighe (2021) Impacts of Flooding on Concrete Pavement; Proceedings of the 12th ICCP (978-0-578-33418-9).

[7.2.1-3] J. Mack, G. Dean, L. Wathne (2023) Improving Pavement Resiliency to Flooding: A Case for Concrete Pavements; In Proceedings of the 14th International Symposium on Concrete Roads, Krakow, Poland.

[7.2.2-1] G. Fick, J. Gross, M.B. Snyder, D. Harrington, J. Roesler, T. Cackler (2021) Guide to Concrete Overlays, Fourth Edition, A guide from National Concrete Pavement Technology Center and Iowa State University, https://intrans.iastate.edu/app/uploads/2021/11/guide_to_concrete_overlays_4th_Ed_web.pdf

[7.2.4-1] L. Rens (2017) Soulèvement de Chaussées en Béton (Buckling of Concrete Roads); FEBELCEM, D/2017/0280/06, Brussels.

[7.2.5-1] H. Ceylan, S. Yang, K. Gopalakrishnan, S. Kim, P. Taylor, A. Alhasan (2016) Impact of Curling and Warping on Concrete Pavement; Technical Report IHRB Project TR-668. Institute for Transportation, Iowa State University, Ames, IA, USA.

[7.2.5-2] M.P. Wistuba, A. Walther (2013) Consideration of Climate Change in the Mechanistic Pavement Design; Road Materials and Pavement Design, 14, 227–241.

[7.3.2-1] H. Zhu, M. Yu, J. Zhu, H. Lu, R. Cao (2019) Simulation study on effect of permeable pavement on reducing flood risk of urban runoff. International Journal of Transportation Science and Technology, 8, 373–382. https://doi.org/10.1016/j.ijtst.2018.12.001

[7.3.2-2] X. Hu, X. Wang, N. Zheng, Q. Li, J. Shi (2021) Experimental Investigation of Moisture Sensitivity and Damage Evolution of Porous Asphalt Mixtures; Materials, 14, 7151.

[7.3.2-3] H. Wu, J. Yu, W. Song, J. Zou, Q. Song, L. Zhou (2020) A Critical State-of-the-Art Review of Durability and Functionality of Open-Graded Friction Course Mixtures. Construction and Building Materials, 237, 117759. https://doi.org/10.1016/j.conbuildmat.2019.117759

[7.3.3-1] Reuters (2022) Low Rhine Water Levels Threaten Germany's Economic Growth, 10 August 2022, available online at https://www.reuters.com/markets/commodities/low-rhine-water-levels-another-drain-germanys-economy-2022-08-10/

[7.3.3-2] H. Pötz (2016) Green-Blue Grids, Manual for Resilient Cities, ISBN 978-90-9029822-1. Available online at https://www.urbangreenbluegrids.com/

[7.3.5-1] A. Jotisankasa, B. Vardhanabhuti, K. Lousuphap, A. Sawangsuriya (2011) Mechanisms of Longitudinal Cracks Along Highway Shoulder in Central Thailand; In Proceedings of the 5th Asian-Pacific Conf. on Unsaturated Soils, Pattaya, Thailand.

[7.3.5-2] A. Sawangsuriya, A. Jotisankasa, B. Vardhanabhuti, K. Lousuphap (2011) Identification of Potentially Expansive Soils Causing Longitudinal Cracks Along Pavement Shoulder in Central Thailand; In Proceedings of the 5th Asian-Pacific Conf. on Unsaturated Soils, Pattaya, Thailand.

[7.3.5-3] R. Luo, J.A. Prozzi (2008) Development of Longitudinal Cracks on Pavement over Shrinking Subgrade; In Proceedings of the Transportation Research Board Annual Meeting, Paper No. 08-1034.

[7.3.5-4] W.A. Take, M.D. Bolton (2004) Identification of Seasonal Slope Behaviour Mechanisms from Centrifuge Case Studies. Advances in Geotechnical Engineering. In Proceedings of the Skempton Conference, Volume 2, T. Telford.

[7.3.5-5] J.D. Nelson, D.J. Miller (1992) Expansive Soils Problems and Practice in Foundation and Pavement engineering; John Wiley and Sons, New York, NY, USA.

[7.3.5-6] P.G. Nicholson, V. Kashyap (1993) Fly Ash Stabilization of Tropical Hawaiian Soils, Fly Ash for Soil Improvement; Geotechnical Special Publication No. 36, ASCE, pp. 15–29.

[7.3.5-7] Z. Nalbantoglu, E. Gucbilmez (2001) Improvement of Calcareous Expansive Soils in Semi-Arid Environments; Journal of Arid Environment, No. 47, pp. 453–463.

[7.4.1-1] PIARC (2022) Overweight Vehicles Impact on Road Infrastructure and Safety; 2020. 2022SP01EN - PIARC Special Project. PIARC Ref.: 2022SP01. ISBN: 978-2-84060-674-1, Number of pages: 139., available online at https://www.piarc.org/en/order-library/36918-en-Overweight%20Vehicles:%20Impact%20On%20Road%20Infrastructure%20And%20Safety

[7.4.2-1] J.M. Low, S. Haszeldine, G. Harrison (2022) Weight Gain of Battery and Hydrogen Zero Emission Vehicles over Internal Combustion Vehicles: Consequential Increases in Road Wear; Research Square. DOI: https://doi.org/10.21203/rs.3.rs-1435405/v1

[7.4.3-1] C. Torres-Machí, A. Chamorro, C. Videla, E. Pellicer, V. Yepes (2014) An Iterative Approach for the Optimization of Pavement Maintenance Management at the Network Level; The Scientific World Journal, Article ID 524329, 11 pages. https://doi.org/10.1155/2014/524329

[7.4.5-1] I. Kumalasari, M. Napiah, M.H. Sutanto (2018) A Review on Phase Change Materials Incorporation in Asphalt Pavement; Indonesian Journal of Science & Technology, 3(2), 171–179. https://ejournal.upi.edu/index.php/ijost/article/view/12762

[7.4.5-2] R. Sharma, J.G. Jang, J.W. Hu (2022) Phase-Change Materials in Concrete: Opportunities and Challenges for Sustainable Construction and Building Materials; Materials, 15(1), 335. https://doi.org/10.3390/ma15010335

[7.4.5-3] ECLIPS project (2018) Enhancing Concrete Life in Infrastructure through Phase-Change Systems. https://www.infravation.net/projects/ECLIPS

World Road Association (PIARC)

La Grande Arche, Paroi Sud, 5e étage, F-92055 La Défense cedex