Economic Evaluation of Long-Life Pavements

PHASE 1

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Phase 1

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Foreword

The OECD brings together 30 member countries and helps governments meet the challenges of a globalised economy. The OECD's Programme of Research on Road Transport and Intermodal linkages (RTR), which ended in 2003, took a co-operative international approach to addressing transport issues among OECD member countries.

The mission of the RTR Programme was to promote economic development in OECD member countries by enhancing transport safety, efficiency and sustainability through a co-operative research programme on road and intermodal transport. The Programme recommended options for the development and implementation of effective transport policies for members and encouraged outreach activities for non-member countries.

From 1 January 2004, following a decision by the OECD Council and ECMT Ministers, a Joint OECD/ECMT Transport Research Centre was established. It brings together the previously separate activities of the OECD's RTR Programme and the ECMT's economic research activities.

This study on the Economic Evaluation of Long-life Pavements – Phase I was carried out by an OECD Working Group under the RTR Programme 2001-03. The report explores the economic case and technical prospects for the development and use of long-life wearing courses for the pavements of highly trafficked roads. It draws conclusions, based on economic analysis, on the circumstances under which long-life wearing courses that involve a higher initial construction cost may be economically viable. It also identifies the material properties and performance likely to be needed as well as classes of possible candidate wearing course materials.

This study is published on the responsibility of the Secretary-General of the OECD.

ABSTRACT

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In many nations with mature road networks, new road construction typically accounts for around 50% of the road budget. Much of the remainder of national road budgets is spent on maintenance and rehabilitation of existing roads. Current road construction methods and materials contribute to this outcome, as they lead to recurrent maintenance requirements that can only be met at a relatively high cost.

The Long-life Pavements project as approved by member countries set out to determine if the costs of future maintenance and repaving and the resulting road user delays have reached a level on high-traffic roads where long-life pavements are economically justified. For this to be the case, the reduced maintenance and other associated costs (*e.g.* user costs) would at least need to compensate for higher costs of construction.

Based on the co-operative international research undertaken, the report draws conclusions on the availability of suitable materials that can support the development of long-life surface layers for road pavements. It assesses the economic case for developing such pavements for highly trafficked roads.

The report provides guidelines for a research programme to be carried out as part of Phase II of this project. The objective of this further work will be to assess the real capacity of candidate materials and their suitability for use as long-life wearing courses.

Fields: (61) Equipment and maintenance methods, (30) Materials, (10) Economics and administration.

Key words: maintenance, pavement, durability, resurfacing, international, cost benefit analysis, wearing course, material (construction), repair.

* The OECD International Transport Documentation (ITRD) database contains more than 300 000 bibliographical references on transport research literature. About 10 000 references are added each year from the world’s published literature on transport. ITRD is a powerful tool to identify global research on transport, each record containing an informative abstract.

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Executive Summary

Governments have devoted considerable resources to the development of high-quality transport networks – particularly road networks – which subsequently need adequate maintenance.

In many nations with mature road networks, new road construction typically accounts for around 50% of the road budget. Much of the remainder of national road budgets is spent on maintenance and rehabilitation of existing roads. Current road construction methods and materials contribute to this outcome, as they lead to recurrent maintenance requirements that can only be met at a relatively high cost.

In recent years, innovation in the road sector has focused on economic and organisational structures, while changes in road paving techniques have been much less dramatic. Rather, they have at best been incremental. Yet, in order to optimise national highway budgets, whole-life costing methods are increasingly used to determine how, where and when to best spend budget funding on road construction and maintenance. Within this framework, the shift to full maintenance contracting has helped reduce costs, and the adoption of long-term contracts has helped establish an environment in which the development of more durable pavement types could be stimulated.

A survey of member countries shows that pavements in use on high-traffic roads are typically re-surfaced every ten years (depending on local conditions). Within the ten-year period, there may be some other road maintenance closures for pavement repairs like patching and sealing. Indeed, the initial construction costs of a pavement are often surpassed by the costs of its life-cycle maintenance and operation. From a roads-budget viewpoint, maintenance work incurred in future years may seem preferable to increased capital expenditure now.

However, apart from the direct costs of maintenance funded from road administration budgets, road maintenance also imposes significant costs on users. On highly trafficked roads in particular, road maintenance is likely to cause traffic congestion and disruption to normal traffic flows. Despite the measures taken by road maintenance operations, the costs to users in many locations are high and increasing. Hence, there are growing pressures for long-life road infrastructure pavements that require minimal maintenance and can therefore avoid many of these future costs to road administrations and users.

Outlook

Road infrastructure investment has generally increased less in many countries than road traffic. If these trends continue, the outcome will be increasing intensity of road traffic on road networks in the future. These trends support the view that there will be increasing numbers and proportions of roads which are highly trafficked and therefore candidates for more durable pavements at higher construction costs.

Aims of the project

The Long-life Pavements project, as approved by member countries, set out to determine if the costs of future maintenance and repaving and the resulting road-user delays have reached a level on high-traffic roads where long-life pavements are economically justified. For this to be the case, the reduced maintenance and other associated costs (*e.g.* user costs) would at least need to compensate for higher costs of construction.

In developing a long-life pavement, it is necessary to consider the performance of the whole pavement, complete from its surfacing down to its foundation. This report focuses on the surface layer of pavements; other studies are currently under way which focus on long-life pavement structures, but not the surface layer.

Economic findings

The economic analysis shows that there could be considerable economic benefit in developing new pavement wearing courses. From a cost viewpoint, long-life pavement surfacing costing around three times that of traditional wearing courses would be economically feasible for a range of high-traffic roads. This would depend on an expected life of 30 years, discount rates of 6% or less and annual average daily traffic (AADT) of 80 000 or more.

Sensitivity testing was carried out to establish the broad envelope of conditions under which long-life pavement surfacing becomes economically feasible. This work assessed the effect of different discount rates (3-10%), traffic levels (40 000 to 100 000 AADT), durability (30- or 40-year long-life pavements), wearing course cost (three-fold increase or five-fold increase), the proportion of heavy vehicles (5-20%) and the effect of day-time or night-time maintenance schedules. Details are provided in the report.

Such increases in wearing course costs need to be seen in the context of typical pavement construction costs. For the example scheme chosen, a dual three-lane motorway, pavement construction costs would amount to USD 1.8 million to USD 2.25 million per carriageway kilometre. This estimate includes features such as earthworks, drainage, line markings, safety fences, etc., but not other structures such as over or under bridges, gantries, etc.

At present, the surface layer (the wearing course) of such pavements represents around 9-12% of the above indicative pavement construction costs. A three-fold increase in the wearing course cost would imply an increase in overall pavement structure construction costs of up to 24%, and the surface layer would then represent around 30% of the construction costs.

Of course, the total construction costs of high-traffic roads are extremely variable, depending not only on pavement construction costs but also on the number of bridges, tunnels and earthworks actually involved. Overall average costs per kilometre increase to between USD 3.15 million and USD 3.6 million per carriageway kilometre, taking these other costs into account. In this respect, a three-fold increase in the cost of the surface layer of the pavement would have a lower impact in terms of overall motorway construction costs per kilometre, *i.e.* between 10% and 15%, and the surface layer would represent between 5% and 20% of the total construction cost. If a completely new road scheme were to be examined, this percentage would be even lower when total costs including structures, land purchase, design costs and communications are taken into account.

Long-life wearing courses for which these indicative evaluations have been undertaken are not yet in general use. The cost, the life, the condition and the maintenance arrangements included in the analysis of the advanced surfacing are targets and assumed to be achievable. Their technical feasibility is the focus of the subsequent research stages of the work.

Findings related to wearing course materials

A review of advanced surfacing materials, currently under research or in limited use in small-scale projects, indicated that there are indeed materials that could be feasible for long-life surfacing of the standard assumed in the analysis.

From the review of materials, the study concluded that two types of materials in particular had the potential to fulfil the requirements. These were:

- *Epoxy asphalt*

Considerable field data and performance histories exist on epoxy asphalt, which has been used on various bridge decks. Of particular note is that the epoxy asphalt placed on the San Mateo bridge deck in the United States back in 1967 is still performing well.

- *High-performance cementitious materials with an epoxy friction course*

For high-performance cementitious materials (HPCM), while all of the data stems from laboratory efforts, the properties are quite remarkable, particularly their strength and flexure properties. Possible shortcomings of this product, namely, poor noise and splash reduction and friction properties, can probably be overcome with improvement of its macrotexture.

A long-life wearing course will have to withstand very long-term traffic (and traffic growth) as well as varying environmental conditions. A period of testing and development work will be required to establish which materials can reliably produce maintenance-free longevity within the cost envelopes outlined. A review of testing methods set out in the report identifies tests that can be used to simulate ageing and study cracking, de-bonding, rutting, ravelling and polishing performance. The need for testing to establish, in addition, drainage and noise performance is also emphasised.

In summary, based on the co-operative international research undertaken, the report concludes that there are materials potentially available that can support the development of long-life surface layers for road pavements. In addition, provided such materials prove to have the necessary technical properties, there are strong economic arguments for developing such pavements for highly trafficked roads.

The report provides guidelines for a research programme to be carried out as part of Phase II of this project. The objective of this further work will be to assess the real capacity of the candidate materials and their suitability as long-life wearing courses.

Chapter 1

Introduction

Reforms in the road sector, evolving policies regarding road building and maintenance contracts and the development of specialist pavement types for bridge decks have made a review of the economic analyses of long-life pavements timely.

Transport and mobility are essential for economic and social development. For this reason, developed countries have devoted considerable resources to the development of high-quality transport networks which need to be adequately maintained. Current road construction methods lead to significant maintenance requirements, which can only be met at a very high cost. The continued growth in road traffic and axle loads and the pressure to restrain government spending put growing pressures on road authorities to come up with new solutions. At the same time, the cost to economies due to congestion and disruption during road works on high volume roads has become unacceptably high. There are growing pressures for long-life road infrastructures that require minimal maintenance.

Reforms in the road sector

The past decade has seen major changes in the working methods of road authorities in most OECD countries. As governments have sought to have the market regulate the costs of providing transport networks, the number of public employees engaged in physical work on the roads has decreased. National road authorities increasingly contract private industry to design, build (or rehabilitate) and maintain road infrastructure.

As this process develops, long-term maintenance contracts lasting in excess of 12 to 15 years are becoming commonplace, and many road authorities now contract the supervision tasks to specialised private companies. The long-standing choice between public or privately owned, operated and funded roads is being enriched by many intermediate forms of ownership and funding as governments attempt to reduce their financial involvement in transport infrastructure ownership and operation.

This narrowing of the role of many public road authorities has resulted in much restructuring to fundamentally very lean organisations. Agencies with responsibility for the letting and administration of contracts for maintenance, construction and knowledge as their main, if not their only role, are a recent innovation.

The next phase seems likely to be the transformation of public road administrations into limited companies with or without the government as majority stockholder. Such corporatisations are yet to be seen on a larger scale. One rationale for such restructuring is the associated contribution that revised structural arrangements can make to the financing of both infrastructure expenditure and infrastructure maintenance. Shadow tolls, direct road pricing or other traffic-dependent cash flow may fund the activities of such organisations. In such circumstances, the role of the government can be focused more on economic, safety and environmental regulation and ensuring the public interest in relation to the services provided by such companies.

It is fairly clear that in recent years innovation in the road sector has concentrated on economic and organisational structures, while changes in technology have been less dramatic, apart from some obvious advances in traffic informatics. However, one of the attractions in the shift to full maintenance contracting and the adoption of long-term contracts is the prospect that it could stimulate the development of more durable pavement types.

Economic value of road assets

The road infrastructure of a nation represents a huge capital value, the result of large investments through several generations. The economic value of this asset is generally the current depreciated replacement cost of the construction of the entire network. Running costs (or a nation's road budget) includes the cost of maintaining, rehabilitating and extending the network at a level that satisfies the needs of today's society. These costs, expressed as a percentage of the value of the asset, will vary between nations depending on government policy and the condition of the network. Running costs are a reflection of the initial quantity, quality, maintenance history and current and expected future traffic loads. Hence, there is no typical percentage value; Table 1.1 outlines the costs in the United States. Common to all nations is the obligation to reduce the future costs of maintaining the capital value of the asset. Longer-life pavements would provide a significant contribution to reducing the costs of future maintenance.

Table 1.1. United States national highway system value and expenditure

Total length of paved roads	2.6 million miles
National highway (length)	160 000 miles (most is over 35 years old)
Shortfall to maintain condition	USD 11.3 billion
Annual hot mastic asphalt investment	USD 15 billion (500 million tons of HMA, 30 million tons of binder)

Source: US Federal Highway Administration.

Road policy directions

Congestion problems on high-traffic roads during periods of road maintenance are now a major concern in most countries. Different approaches are taken to take account of this problem. Some agencies have set targets; others now take road-user costs into account when planning road works which have a significant impact on the approach taken. Maintenance is now often only scheduled off-peak, mostly at night, and there are increasing pressures to carry out work quickly.

Other areas of policy priority are the environment and safety. Noise reduction has become a high priority for some authorities and is likely to become increasingly important in many countries as higher standards are set.

Focus on pavement types

This report focuses on the surface layer of pavements, recognising that it is essential to consider the whole pavement, complete from surfacing down to foundation. Obtaining a long-life wearing course requires more than can be achieved by improving the properties of the wearing course itself. If not properly designed and constructed, the layers below the wearing course will lose structural strength (*e.g.* due to traffic loads, temperature variations, the intrusion of water and freeze-thaw cycles) which will reduce the life of the wearing course, regardless of how well it is designed and constructed. The wearing course is an important interdependent component of the whole pavement. A durable and faultless wearing course acts to protect the base layers against the intrusion of water from above, which is essential to maintain its strength and serviceable life.

In designing a wearing course, there are several technical requirements in addition to its service life. The friction and drainage properties are essential to prevent accidents by providing effective braking, limiting the loss of visibility from spray and splash in wet conditions and reducing the risk of hydroplaning during heavy or extended rainfall. Open-textured pavement surfaces have been developed to improve drainage at the surface. This tends to result in a shorter service life because of the added exposure to oxidation of the bituminous binder and the resulting progressive loss of aggregates from the pavement surface.

In recent years, noise-reducing wearing courses have gained widespread usage on heavily trafficked roads near residential areas. Such pavements may initially reduce noise by up to 6 decibels (dB) and can be an alternative or supplement to noise barriers. However, the service life of current noise-reducing pavements (which work by having a structure with many air voids) can be quite short (6-8 years). The quantifiable benefit here is the savings in other noise-reducing measures, which would otherwise be required in order to comply with national noise limits.

These examples show that more stringent standards for pavement drainage and noise are becoming the norm. It will be essential that the properties of new long-life wearing courses match up at least to current best practice, as they will be in use for many years.

Scope (definition of road type)

Although the quest for long-life pavements should ideally cover all types of roads, there are factors other than durability that limit the service life of a wearing course.

Insufficient strength resulting in deformation of the underlying structure is a frequent cause of premature distress in the wearing course. This is typically found in roads that have come to carry more traffic than they were designed for. Such roads do not warrant the use of novel and relatively expensive pavement types unless they are fully rehabilitated to give the structural strength required to carry the actual and expected traffic.

Roads that cover utilities (*e.g.* sewers, water pipes, electrical cables, telecom cables), as do most city streets and suburban residential roads, are subject to frequent digging, refilling and resurfacing. Long-service wearing courses would therefore not be suited to such roads.

This narrows the scope of the project to roads with structural strength that is compatible with the traffic they are carrying and that do not contain underground services to which the owners have a privileged right to gain access. In addition, to justify the cost of a long-life pavement, it is likely that user-delay costs during maintenance would be significant. Therefore, the scope is further narrowed to roads with major and increasing traffic counts.

Current ongoing work of other international organisations

There are a number of other related international projects, which have recently been completed or are under way. Their results have, to an extent, been integrated into the work of the group as they may influence the next phases of this project. They are:

- The European Long-life Pavements Group (ELLPAG) project, "Making Best Use of Long-life Pavements in Europe".
- The European Union's project Fully Optimised Road Maintenance (FORMAT), COST action 324 on "Long-term Performance of Road Pavements".
- The World Road Association's (PIARC) work on "Whole-Life Costing and Asset Management Systems".

The first two of these projects are still under way, and their aims and objectives are briefly presented below.

ELLPAG, an expert group of the Forum of European Highway Research Laboratories (FEHRL) was commissioned by the Conference of European Directors of Roads (CEDR) to initiate a research project on "Making Best Use of Long-life Pavements in Europe". The project is multi-phased and its long-term objective is to produce a user-friendly Best Practice Guidance note on long-life pavement design and maintenance for all the common types of pavement construction used in Europe. As justification for this work, ELLPAG states that, "In the right socio-economic conditions, the use of long-life pavement design can be clearly seen as a sustainable solution to the problem of providing efficient, safe and durable road networks in European countries... ...the proposed work is highly complementary to OECD-RTR Special Project..." [referring to this project]. While the OECD project focuses on the long-life aspects and economic issues of wearing courses, the European ELLPAG project has its emphasis on the structural pavement layers. Phase 1 of the ELLPAG project, which was started in September 2003, has now been completed and work has now moved on to review semi-flexible pavements as part of Phase 2. This second phase of the work should be completed by the end of 2004.

FORMAT is designed to enhance the efficiency and safety of road networks by providing the means to reduce the number, duration and size of road works for pavement maintenance purposes. The research also focuses on reducing the associated delays and hence the costs for road users as they negotiate these work zones. In order to achieve these objectives, key aspects of the planning and execution of the pavement maintenance process will be optimised in a fully integrated usable set of pavement maintenance procedures. Four topics key to road pavement maintenance form the subject of this research effort: pavement condition monitoring, maintenance techniques, safety at work zones and the surrounding areas, and cost-benefit analysis. Thus, FORMAT and the present project have the common aim to reduce the overall costs of maintaining the surfacing of road pavements and their results may well reduce the scope for the use of long-life and maintenance-free, but also more costly pavements.

Terms of reference of this project

The expected outcome of this project is the development of new long-life pavement surfacing. Today, pavements with bitumen or cement binders dominate the market. They function well in a wide range of traffic and climate conditions and have few environmental disadvantages.

However, although quality products are available, most pavements exhibit shortcomings in terms of durability, road-user qualities, strength and repair needs. This translates into poor maintenance economy when these pavements face the challenge of the increasing vehicle-mass limits and higher density of traffic on the arterial roads of today and the near future.

It is well known that various types of synthetic binders (alone or as modifiers to conventional binders) may offer very durable, low-noise, wear-resistant pavements, which provide good protection of the underlying structure and can be laid with a very short construction time and minimum disruption of traffic. Such materials have so far almost exclusively been used on bridges where the higher initial costs are easily justified by the benefits in terms of longer life and better protection of the structure. However, with such characteristics, they should also be considered for much wider applications on heavily trafficked roads.

Currently, industry-based research in pavements is focused on the traditional binder materials, partially because of the costs of advanced binders and partially because road administrations show little inclination to accept higher initial pavement costs to obtain longer service lives. Therefore, it does not appear likely that the industry, on its own initiative, will push the frontier of innovation as far as is desirable if the full potential of today's material technology is to be used for better road pavements. This situation may change, if analyses show that the properties of alternative binders – when total service life is considered – can attract a very large and increasing market.

Increased understanding of pavements for heavily trafficked roads has led, in recent times, to the concept of long-life or perpetual pavements. In broad terms this relates to the structural pavement layers and not to the upper wearing or surface courses. The requirement to produce a long-life structure is being clarified in other, ongoing projects; this project looks in particular at the economic aspects of long-life surfacing layers.

The objectives of the project are therefore as follows:

- Identify the policy direction of road administrations in the management and financing of roads infrastructure.
- Review the evaluation framework to determine the economic viability of large-scale use of such pavements on heavily trafficked roads.
- Summarise and consolidate existing knowledge about alternative binders for pavements in the road infrastructure.
- Establish the functional and environmental properties of such binders in pavements for large-scale applications.
- Plan and prepare for the execution of suitable demonstration projects.

The project is planned to have three phases: Phase I: concept viability; Phase II: concept development: and Phase III: full-scale testing.

Phase I, concept viability, is the topic of this report:

- Chapter 2 outlines the performance of traditional pavements that are currently in use.
- Chapter 3 studies the evaluation frameworks used to assess the economic viability of pavements.
- Chapter 4 examines the economic feasibility of long-life pavement surfacing.
- Chapter 5 reviews the potential materials and paving techniques for long-life pavements.
- Chapter 6 addresses the technical requirements for long-life pavement surface layer and guidelines for the assessment of candidate solutions.

Phase II, concept development, will comprise three activities:

- Task 5: Design, laboratory testing.
- Task 6: Accelerated load testing.
- Task 7: Construction technology and methods.

Phase III, full-scale testing will be carried out by member countries. The OECD project group will co-operate to plan the tests.

Chapter 2

Traditional Pavements for High-traffic Roads

Different pavement types have evolved in different countries to take account of prevailing climatic conditions, traffic levels, funding levels and management agencies. This chapter summarises typical existing traditional wearing courses that are constructed on highly trafficked roads. The purpose is twofold. First, the information will be used to carry out a comparative analysis between existing traditional wearing courses and new long-life wearing courses (Chapter 4). In addition, Chapter 5 discusses new materials and the performance potential of long-life wearing courses. The information from this chapter benchmarks the performance that can be achieved with traditional paving methods. The performance of new materials can be compared to this benchmark.

A questionnaire was prepared to obtain information on existing traditional pavements (see Annex A). The questionnaire focused primarily on conventional asphalt pavements, although some information on concrete pavements was also collected. Twelve countries responded: Canada, Denmark, Finland, France, Hungary, Netherlands, Norway, Poland, Portugal, Sweden, United Kingdom, and United States.

Additional information was obtained from recent studies by PIARC (2002), the Transportation Research Board (2001, 2002) and the European Commission on Road Transport Research (1999).

The questionnaire was designed to provide technical and economic information regarding agency paving practices, with particular emphasis on the wearing course. The information requested was restricted to highly trafficked pavements (minimum of 10 000 average daily traffic [ADT] with over 15% heavy trucks). It was to be assumed that the materials, construction and drainage for the project would result in substantive structural capacity (*i.e.* that the pavement structure had a long service life, with periodic wearing course maintenance and renewal anticipated). The properties of the wearing course (expected life, initial costs, thickness, materials and design methods) could then be isolated and analysed independently from the properties of the overall structure or underlying materials.

Agencies were requested to respond using specific projects recently carried out. It was anticipated that an average standard and performance could be identified and used for the analysis.

Initial costs and maintenance strategies

Table 2.1 shows the initial costs of wearing course materials, the typical thicknesses, the expected life, maintenance strategies and closure durations. The existing mix type or generic mix name, used to locally identify the mix, are noted. This is the primary source of information used in the comparative analysis between traditional or existing pavements and the advanced, high-technology pavements in Chapter 5.

Initial costs include only the costs of the materials, the mixing, haul, placement and traffic control for the work. These costs are the all-inclusive contractor's bid costs for work and do not include such items as design costs, agency project supervision costs or other ancillary project costs. The costs also are only for the wearing course and not for underlying structural layers or for detailed preparation work required before paving. This eliminates as many unnecessary variables as possible while still obtaining sufficient data for a comparative analysis. All costs were reported in USD per square metre of wearing course. Combined with initial costs and expected life, additional economic information required for analysis includes maintenance strategies, maintenance costs, schedules and closure duration for maintenance. Data on residual values were not collected in this survey as nations do not generally hold this information.

Labour costs have a strong influence on initial construction costs and local labour rates vary considerably from country to country. There was no attempt to normalise initial pavement costs owing to varying labour rates; only the average and range of values as reported are presented. The average labour rates to place advanced pavements were used in the economic comparative analysis in this report. Analysis for specific national cases is left to the relevant administrations to carry out.

Table 2.1 shows that:

- Stone mastic asphalt (SMA) is the predominant wearing course mix reported and was therefore used as the primary indicator of typical wearing course mix types and costs.
- Thicknesses varied from 25-50 mm, initial costs range from approximately USD 3.50 (low) to USD 15.60 (high) per square metre.
- The ranges of thickness for other mix types were a much broader range between 20 mm and 50 mm with the value of 50 mm reported for many differing mix types. The thickness of the wearing course layer had an impact on the price as the thinner layers were less expensive, as expected. Mix thickness was reported to be as thin as 20 mm for thin surfacing layers in Denmark and in Sweden.
- Western European initial costs are slightly higher than those of the Nordic and North American countries. Some of the factors involved in these differences have already been discussed; however, over the course of the project the USD-EUR exchange rate has changed by some 20%, so comparisons are only approximate. The costs given in the tables were reported in USD in December 2002 (average exchange rate that month was USD 1 ≈ EUR 0.98).
- In Finland and Norway, the initial costs for mixes that are over 30 mm in thickness are slightly lower than those for western European countries. Costs range from USD 5.00 to USD 6.70.
- The North American mixes consisted of Superpave, stone mastic and also the agency's typical traditional mix types (examples, class 1 mix or dense friction course). The initial costs range from USD 3.00 to USD 5.60.

Table 2.1. Initial costs and maintenance strategies for wearing courses

Country	Initial costs (USD/sq m)	Thickness (mm)	Expected life of wearing course (yrs)	Maintenance strategy	Year	Costs (lane km)	Closure duration (days)	Notes
Canada								
1.	5.50	50	15	Crack seal	2,9,15	1 000	0.2	Superpave
				Surface seal/hot in place	12	20 000	2	
				Mill and replace	15	30 000	1	
2.	5.25	50	15	Crack seal	2	1 000	0.2	Class 1 mix
				Patch	10	10 000	1	
				Surface seal/hot in place	12	20 000	2	
				Mill and replace	15	30 000	4	
3.	3.00	40	15	Crack seal	3,9,15	1 000	1	Dense friction course
				Patch	9,15	8 000	1	
				Mill and replace	19	73 000	1	
Denmark								
1.	5.30	20	14	Crack seal	8	1 000	0.33	TB (thin-layer)
				Patch	10,13	3 000	0.33	
				Overlay	14	20 000	1	
2.	9.50	35	14	Crack seal	8	1 000	0.33	SMA
				Patch	10,13	3 000	0.33	
				Mill and replace	14	35 000	1	
Finland								
	5.00	40	5	Mill and replace	5	20 000	0.5	
France	3.00	25	16 (8 for truck lane)	Crack seal	5		1	
				Thermo-recycling (truck ln)	8			
				Mill and replace	16			
Hungary								
	8.00	40	7	Patch	3	100	0.5	SMA
				Patch	5	200	0.5	
				Overlay	7	100 000	1	
Netherlands								
1.	10.60	50	15	Mill and replace rt ln	9	65 000	0.8	Porous asphalt pavement, new construction
2.	15.60	50	15	Mill and replace both lns	15	86 000	0.8	Porous asphalt pavement, rehab
Norway								
	6.70	35	5	Mill and replace	5	24 300	1	SMA
Poland								
1.	6.94	40	10	Thin overlay	10	20 000	0.5	SMA
				Mill and replace	20	26 000	0.75	
2.	9.20	50	10	Thin overlay	10	24 000	0.4	Asphalt concrete
				Mill and replace	20	32 000	1	
Portugal								
	3.44	40	15	Crack seal	3,6,12	2 600	2	SMA
				Mill and replace	15	16 000	1	
Sweden								
1.	3.00	20	9	Mill and replace	9	15 000	1	TSK thin layer
2.	6.00	40	13	Seal coat (sdi)	9	4 000	0.2	SMA
				Mil and replace	13	30 000	2	
UK								
1.	6.61	25	9	Crack seal, mill and replace	8,9			SMA
2.	8.61	30	9	Crack seal	8	2 000	0.5	
				Mill and replace	9	34 000	0.4	
3.	9.50	30	9	Mill and replace	9,27	20 000	0.5	
				Mill and replace	18,35	33 000	1	
USA								
1.	4.90	50	18	Crack seal	3			HMA
				Surface seal	8	3 500	0.04	Minnesota
				Overlay	18	20 000	1	
2.	5.60	50	10	Crack seal	5,10	2 000	1	SMA
				Mill and replace	10	27 000	2	Colorado
3.	35.00	320	30	Crack seal	20	320 000	10	Concrete
				Grinding	20	240 000	10	Florida
				Overlay	30			

Source: Based on responses to the OECD questionnaire.

- Open graded friction course (porous asphalt surfacing) is the predominant mix used in the Netherlands. Initial costs are from USD 10.00 (for new construction) to USD 15.60 (for rehabilitation) per square metre. Noise reduction is a very important consideration for the Netherlands and open graded friction course is therefore the pavement type of choice by policy. The use of open graded friction course can reduce noise levels by 2-3 dB which is comparable to the benefit obtained from the construction of noise barrier walls which are expensive. On analysis of the costs, the use of open graded friction course has a distinct cost/benefit advantage, especially in urban environments.
- The survey did not ask for data on routine maintenance costs. It should not be assumed that they are the same for different pavement types (but it is likely that they are similar). Where data are missing in tables, it can be taken that information was not provided in the initial response.

For the comparative economic analysis, a stone mastic mix with thickness of 30 mm was chosen to represent the predominant surfacing at a cost of USD 8.00 per square metre.

Expected life

Stone mastic wearing courses have an expected life ranging from five to 15 years. The low values are reported in Finland and Norway where studded tyres are in use throughout the winter. The level of traffic also has a big impact on the life of the surfacing. For multilane facilities, the heavily trafficked (often slower, heavy-vehicle lane) have an expected life of from six to eight years with the less trafficked lane lasting up to 15 years.

From the data provided, with consideration of the estimated values, the value of ten years was selected as the average expected life to be used for the economic evaluation.

Maintenance strategies

The end of life for the wearing course occurs when an additional layer is required or the surfacing is milled and replaced. Its lifespan is often extended by intermediate maintenance strategies including crack sealing and/or patching. Additional or more robust maintenance strategies are not as common but include surface seal, seal coat or chip seal treatments. There is also a defined strategy of not performing any maintenance at all up until the time of milling and replacement.

Maintenance strategies are dependent on pavement performance in the field. The strategies selected for the economic comparative analysis were based on averages and with consideration of maintenance strategies obtained from the models used in Chapter 5.

Maintenance costs

Typical costs of crack sealing operations range from USD 1 000 to USD 2 600 per lane kilometre. The typical costs of patching range from USD 3 000 to USD 10 000 per lane kilometre. The costs of a surface seal or chip seal range from USD 4 000 to USD 20 000 per lane kilometre.

Closure duration for maintenance activities

Typical road closure durations for crack sealing operations range from 0.2 to 1.0 days per lane kilometre, and typical road closure durations for patching were from 0.33 to 1.0 days. Road closure durations for surface seal or chip seal ranged from 0.2 to 2.0 days.

Table 2.2. Existing pavement design and failure criteria

Country	Traffic			Design method	Expected life (yrs) wearing course	Failure IRI	Criteria Ruts (mm)	Distress Cracking (%)	Are road user costs considered?	Comments
	AADT (k)	ESALs (millions)	% heavy trucks							
Canada	32	20	22	Provincial methods	15	2.2	15		No	HMA 2750 MPa, CBC 200 MPa, SB100 MPa
				AASHTO						SG 20-75 MPa
Denmark	60	5	8	Danish standards	14	3.5	15		No	Skid resistance spec 0.5 Stiffness modulus for HMA 3K MPa
Finland	17-45		15	Tables	5		13		No	Studded tire use
France	25		19	National standards	8-16		15-20		Yes	Expected life, 8 yrs for truck lane only
Hungary	20	18	10	National standards	7	3.2	14	25	No	
Netherlands	55	36	17	Netherlands method	9	2.5	18	20	Yes	Horizontal tensile strain 125 ms Skid resistance spec .44 SFC
Norway	22	3	15	Norwegian	5	4	25		No	Studded tire use
Poland	20	14	20	Catalogue	10	4.4	20	20	Yes	Horizontal tensile strain 125 ms, vertical 275 ms Static creep modulus >14 MPa
Portugal	11	19	15	Shell method	15	3.5	15		Yes	Skid resistance spec 0.4
Sweden	13	25	10	ATB (Swedish)	13	2.5	17	10	Yes	Skid resistance spec 0.5
United Kingdom	111	106	15	TRL report LR1132	9	RQI	20	3	Yes	By policy, no new concrete Fatigue formulas are used, skid spec 0.35 SFC
United States	29	13	14	Fla DOT	30	2.4			No	Concrete, Florida
	10	10	15	Mn DOT	18		13		No	Minnesota
	129	12	11	AASHTO	10	2.2	14	15	Yes	Colorado

Source: Based on responses to the OECD questionnaire.

Existing pavement design and failure criteria

Table 2.2 provides information on traffic, design methods, expected life of the wearing course, failure criteria used by agencies with respect to smoothness, rutting, distress and skid resistance. Information on agency policy is also included where obtained.

The typical design methods reported by agencies included methods based on the Shell method, Asphalt Institute, AASHTO, provincial standards, national standards complete with catalogues and charts available to suit the local conditions. The publication

COST 333, *The Development of New Bituminous Pavement Design Method*, by the European Commission Directorate General Transport (1999) is a complete compendium of the pavement design methods employed by EU countries.

The design methods take into account the effects of traffic, environment, sub-grade soils and construction materials to obtain a structural design, and most methods refer to design charts for the design or to confirm the design.

The pavement design life was typically 20 years or longer. This design life is distinct from the expected life of the wearing course, as the surfacing would be renewed or replaced during this time.

Other information of interest to note is as follows:

- The International Roughness Index (IRI) is used extensively by most agencies as a measure of pavement performance and also as a measure of construction quality for projects. The IRI values for failure criteria depend on agency budgets, but the reported failure criteria for IRI were noted to vary from 2.2 to 4.4, with 2.4 as a common response.
- Similarly, the rut depth criteria to initiate maintenance were reported to be from 13 to 25 mm with 15 mm as a common response.
- Over 50% of the responses noted that road user costs are taken into account for design purposes.
- Skid resistance is a common failure criteria used by agencies and a minimum skid value was noted from 0.35 to 0.4.
- Maximum horizontal tensile strain data for the wearing course was provided by two agencies at a level of 125 ms.
- Noise measurements were not routinely made for these facilities in general but one agency, the United Kingdom, reported that noise considerations precluded the use of concrete surfaces for new construction. Noise reduction is a very important consideration for the Netherlands.

Typical pavement structures

Table 2.3 details the typical pavement structures used for paving projects on high-traffic roads. Special sections such as roundabouts and heavy vehicle staging areas were not considered. The data show the thickness of the wearing course, total asphalt thickness for pavement structures and total granular thicknesses. These data were not used for economic analysis but are of interest for agencies to benchmark typical designs and to compare designs, for estimation purposes, with the advanced, high-technology pavements. Typical structures were reported as follows:

- Wearing courses were generally 30-40 mm in thickness.
- Underlying hot mix asphalt (HMA) layer or layers from 200 mm to 240 mm in thickness.
- Underlying granular base layer or layers from 300 mm to 1.2 m.

Thick layers of asphalt and granular layers were reported. The total thickness of asphalt layers varied from 150 mm to 400 mm with a common response of 200-270 mm. The thickness of granular layers varied significantly from 150 mm to up to 2 metres. Thick granular layers are used in a cold climate to prevent uneven frost heave from causing cracking and roughness on a pavement surface.

The percentage of asphalt thickness as compared to the total structure thickness varied from 9% to 75% but with a common response of 20-40%.

Table 2.3. Typical pavement structures

Country	Typical structure HMA = hot mix asphalt SMA=stone mastic asphalt CBC=crushed based course SB=subbase	Wearing course thickness (mm)	Total asphalt thickness (mm)	Granular thickness (mm)	Total thickness (mm)	% asphalt of total structure	Structural equivalency (CGE)[1]
Canada	230mm HMA, 150mm CBC, 300mm,SB, silt	50	230	450	680	34%	910
Denmark	20mm SMA, 60mm HMA binder, 180mm HMA base	20	260	600	860	30%	1 120
	50mm asphalt, 200mm HMA, 450mm CBC	50	200	450	650	31%	850
	150mm HMA, 300mm CBC, 300mm SB, silt	50	150	600	750	20%	900
Finland	40mm SMA, thick granular	40	200	2 000	2 200	9%	2 400
France	25mm+40mm+80mm asphalt,270mm+200mm HB	25	145	470	615	24%	760
Hungary	40mm SMA, 160mm HMA, 300mm CBC	40	200	300	500	40%	700
Netherlands	50mm porous asphalt, 350mm HMA, 1m sand	50	400	1 000	1 400	29%	1 800
Norway	35mm SMA, 185mm HMA, 700mm CBC	35	220	700	920	24%	1 140
Poland	40mm SMA,90mmHMA,140mm CBC,200mm SB	40	130	340	470	28%	600
Portugal	40mm SMA, 230mm HMA, 350mm granular	40	270	350	620	44%	890
Sweden	40mm SMA, 200mm HMA, 1m granular	40	240	1 000	1 240	19%	1 480
United Kingdom	30mm SMA on HMA on granular	30	310	180	490	63%	800
	30mm SMA on HMA on cement	30	390	150	540	72%	930
	30mm SMA on thick HMA	30	450	150	600	75%	1 050
United States	Concrete, 320mm, 1 200mm base		320	1 200	1 520	21%	1 840

1. Structural equivalency is equal to two times the asphalt thickness plus the granular thickness (approximation).

Source: Based on responses to the OECD questionnaire.

Characteristics of existing pavement materials

Table 2.4 provides information on the mix materials used for asphalt pavement structures. The information includes bitumen content, bitumen type, aggregate gradation, maximum aggregate size, air voids and compaction details.

Bitumen content varies from 4.5% to 6.4%. The gradation of stone mastic asphalt contains 70-80% stone with 5-8% fines. The maximum aggregate size was noted to be 19 mm with a common maximum aggregate size noted from 10-16 mm. The air voids for a typical mix were commonly reported at 4% with the open graded materials reported at 20%. The bitumen types are noted using penetration grades (PG) and the grades typically reported were from 50-100.

Table 2.4. Existing pavement materials characteristics

Country Type of mix	Initial costs (USD/sq m)	Thickness (mm)	Bitumen content (%)	Min. compaction (%)	Gradation stone/sand/filler	Max. agg. size (mm)	Air voids (%)	Bitumen type
Canada								
Superpave	5.50	60	5.6	90.5 (Rice)	55/40/5	19	4	PG 64-28
Dense friction course	3.00	40	4.8	90.5 (Rice)	51/49/0	16	6.8	80-100
Denmark								
TB	5.30	20	5		69/19/7	8		70-100
SMA	9.50	35	6	95	73/13/8	11	7	40-60
Finland								
SMA	5.00	40	6.1		91/0/9	16	2,8	80
France								
	3.00	25	5.5		70/27.5/7.5			
Hungary								
SMA	8.00	40	6.4	97	74/14/11	12	4.3	30/60S
Netherlands								
Porous AP	10.60	50	4.5	97	75/20/5	16	20	70-100
Norway								
SMA	6.70	35	6.3	98	64/26/11	11	3	70-100
Poland								
SMA	6.94	40	6.2	98	78/11/11	12.8	4	50
AP	9.20	50	5.7	98	80/15/5	12.8	3	60
Portugal								
SMA	3.44	40	5.5		80/15/5	14	4	50-70
Sweden								
TSK	3.00	20	5.5			16		70-100
SMA	6.00	40	6.3			16		70-100
United Kingdom								
Hitex	8.61	30	5		72/22/6	14	4 to 8	50
Safepave	8.15	30	4.7		70/22/8	14	4 to 8	50
United States								
Superpave	4.90	50	6	92 (Rice)		12.5	4	64-34
SMA	5.60	50	6.2		76/17/7	19	4	76-28

Source: Based on responses to the OECD questionnaire.

The southern European countries use a bitumen grade from 50-70 PG values, while the northern countries use a grade from 70-100 owing to the different climates. Canadian penetration grade (PG) values are typically from 80-100 in the southern areas with grades from 150-200 used in the northern areas. The United States and parts of Canada use performance grades for asphalt supply as part of Superpave paving specifications and commonly grades of 64-22 were noted. In northern areas, the PGs are of the order 58-28 or 58-34.

The use of fibres was noted for stone mastic asphalts, and the use of modified asphalts was noted to be rare in many countries.

Summary

For the economic analysis, a wearing course thickness of 30 mm was chosen. The initial costs of these pavement wearing courses were selected at USD 8.00 per square metre of asphalt wearing course materials placed (which is at the upper end of reported costs for this thickness of wearing course).

Stone mastic and superpave are the traditional or conventional wearing course materials of choice for OECD agencies.

The expected life of these surface materials until replacement was generally about ten years.

Several maintenance strategies were employed by OECD agencies:

- No maintenance until milling and replacement or end of life.
- A one-time only crack sealing operation.
- One application of crack sealing combined with one additional application of patching/crack sealing.
- Crack sealing combined with a robust surface/chip seal programme.

Typical crack sealing costs ranged from USD 1 000-2 600 per lane kilometre and typical patching costs ranged from USD 3 000-10 000 per kilometre. Surface/chip seal costs are from USD 4 000 to USD 20 000 per lane kilometre.

Closure durations ranged from 0.2-1.0 days for crack sealing and patching, and chip sealing road closure durations were noted ranging from 0.2-2.0 days.

References

PIARC (2003), *A Fact Finding Review of Performance Specifications in 2002,* PIARC, Paris.

Transportation Research Board (2001), *Perpetual Bituminous Pavements*, Transportation Research Circular No. 503, December.

Transportation Research Board (2002), *Assessing and Evaluating Pavements*, Transportation Research Record No. 1806.

European Commission Transport Research (1999), *Cost 333 – Development of New Bituminous Pavement Design Method: Final Report*, Brussels.

Chapter 3

Evaluation Frameworks

This chapter examines the evaluation methods used to plan and execute road building and maintenance over the life of a pavement. Several models are briefly reviewed and the most suitable are selected for use in this study.

Introduction

After several decades of road building, many OECD countries are completing their primary road network and reducing expenditure on new roads. However, the road budgets required to maintain this infrastructure are higher than ever.

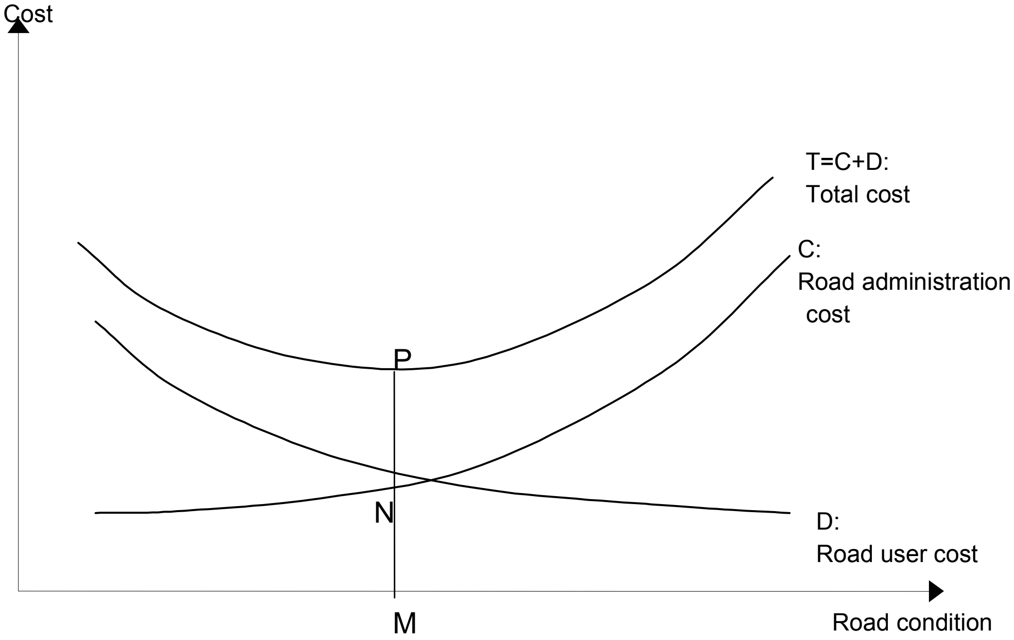
This report gives particular consideration to the potential for improved road surfacing techniques and innovative materials that will provide a pavement with true long-life that requires little or no maintenance. It is expected that these innovative surfacing options will initially be more expensive than traditional surfaces but have lower maintenance and rehabilitation costs.

At present, managing road maintenance requires a balance between maintaining a road in suitable condition and keeping within a restricted budget, requirements which lead to conflicting pressures. On the one hand, routine road maintenance is essential to maintain pavement condition over the long term. Any savings made by deferring routine maintenance in the short term will generally be lost several-fold as the pavements will later need full reconstruction. On the other hand, road maintenance budgets are under increasing pressure in all countries and it is difficult, if not impossible, always to undertake the maintenance needed at the time required.

In the past, many administrations focused principally on the direct costs to the road administration of undertaking or deferring road maintenance. However, decisions on the extent and timing of road maintenance have wider impacts which increasingly have needed to be taken into account in the maintenance decision-making processes. One of these is the effect of undertaking or deferring road maintenance on road-user costs, which increase as pavements deteriorate but can also increase significantly during maintenance periods. Initially, where road-user costs were taken into account at all, the extent of doing so was limited to on-site traffic arrangements that improved safety or reduced congestion in the vicinity of the work. However, more recently, there has been increasing pressure on road administrations to take road-user costs fully into account in their assessments and decision making on the nature and timing of the maintenance to be undertaken.

Research undertaken over the last 10-15 years has explored the costs that need to be considered. These include vehicle operation costs, accident costs and delays during maintenance and rehabilitation. The OECD report, *Road Maintenance and Rehabilitation: Funding and Allocation Strategies* (1994), summarised the likely contribution of the range of direct road administration and user costs and their potential impacts on the maintenance strategies adopted. These are demonstrated in Figure 3.1, which is taken from the OECD report.

Figure 3.1. Engineering-economic approach to optimising road rehabilitation and maintenance



M = Optimal road condition.
MN = Budget to sustain optimal road condition.
MP = Total cost to sustain optimal road condition.
Source: OECD, 1994.

As can be seen from this indicative graph, if road administrations base their decisions only on minimising direct road administration costs, they are likely to undertake road maintenance at times that impose higher costs on road users and result in less than optimal total project costs.

Recognising these wider impacts and in response to pressure from road users, many governments have put in place requirements for road administrations to take proper account of congestion and other costs caused by road works. For heavily trafficked roads in particular, maintenance is now often required to be undertaken during off-peak hours (nights and weekends) to minimise certain road-user costs. Of course, such requirements can increase the direct road project costs and therefore budget pressures on road administrations.

These are all driving factors in the current examination of the potential benefits and possible economic viability of longer-life pavements. Given that their economic viability depends on total costs spread over the pavement life, higher initial costs may be justified if pavement performance is sufficiently improved. With longer periods between maintenance and costs, including user delays reduced, total project costs may also be reduced. It is only when an analysis of the full cost throughout the life of a pavement is carried out that the benefits of a long-life pavement can be realistically assessed. Using whole-life costing techniques permits a full analysis of the economic drivers during the life of the pavement and will allow the benefits of an improved pavement to be identified and the overall project costs to be assessed and considered.

The following section focuses on whole-life costing approaches that can be used to assess the viability of innovative long-life wearing courses. The material summarises international practice on whole-of-life costing, based on the results from PIARC studies on the subject. Next are discussed the factors that are important to consider when assessing alternative pavements and finally, a number of models that can be used to evaluate pavement performance are identified and discussed.

Whole-life costing – world experience

Different pavement types have different cost profiles over their lives. Initial construction costs of a pavement are often surpassed by the costs of operation. Whole-life costing analysis is used to identify the extent and timing of the costs involved and to help choose the most cost-effective pavement type. Whole-life costing analysis uses net present worth (NPW) or net present value (NPV) for the assessment of future costs to provide a common basis of comparison of those costs. A social time preference rate or discount rate (which reflects the social value attached to current versus future expenditures and benefits) is used to reduce the value of costs that occur in the future to a common base year.

The use of whole-life cost techniques to consider the total cost of projects is well established in the construction world. PIARC (2000a, 2000b) have examined whole-life costing of pavements in some detail.

PIARC put forward the following definition of whole-life costing used by the United States Department of Transportation:

> … a process for evaluating the total economic worth of a useable project by analysing initial costs and discounted future costs, such as maintenance, user, reconstruction, rehabilitation, restoring and resurfacing costs over the life of the project …

The PIARC reports considered the various uses of whole-life costing techniques for a range of highway pavement-related projects. These encompass the many aspects and stages of a road pavement project, from project inception through design, construction and maintenance and finally to disposal. The costs are incurred by various groups and include the costs to highway authorities, costs to the road user, road accident costs and other social costs.

In fact, the PIARC reports indicate that there was a considerable variation in approaches across different highway authorities, including the factors that should be taken into account when carrying out a whole-life cost analysis. The three significant components that were more often included in the analysis were construction costs, costs of future works and user and social costs. It is perhaps for the last of these three that there is the greatest variation between authorities, with their decisions possibly related in part to the availability of reliable data for the analysis.

Social costs are often difficult to evaluate but may include environmental costs (such as increased noise and pollution) as well as increased energy use during maintenance and disruption and costs to neighbouring properties. Benefits brought about by improvements following construction or maintenance may also need to be considered in the analysis.

Many other aspects could have an effect on a whole-life cost analysis, and most likely these will vary significantly from region to region. Variations can be expected, for example, in road type, pavement type and road conditions and these are likely to lead to diversity in construction, operating and user costs. Further differences among countries can be expected in the evaluation parameters, such as the analysis period for the assessment of the project, the discount rate to be used in the analysis and the salvage value (or residual value) of the works at the end of the evaluation period.

It is particularly relevant to note the variation in the annual discount rate reported as used in the various countries. The rate varied from 3% to 12% (1998 values). Table 3.1 shows the annual discount rates in use in 2003.

Table 3.1. Discount rates used in selected countries

Country	Discount rate (percent)
Canada	7
Denmark	7-8[1]
Finland	5
France	8
Hungary	10
Netherlands	4
Norway	8
Poland	8
Sweden	4
United Kingdom	3.5
United States	3-5

1. Actual discount rate is 6%; however, other factors are also applied giving an effective rate of between 7-8%.

Source: Based on responses to the OECD questionnaire.

The PIARC report showed considerable variation in the length of the evaluation period used by the various countries in the whole-life costing of traditional road works. The number of countries using the different evaluation periods was as shown in Table 3.2.

Table 3.2. Evaluation periods for whole-life costing of traditional road works

	Evaluation period (years)				
	0-10	11-20	21-30	31-40	> 40
	No. of countries				
New construction					
- Asphalt	1	14	5	3	0
- Concrete	1	4	9	6	0
Maintenance					
- Asphalt	5	10	1	1	0
- Concrete	8	4	3	2	0
Network evaluation	4	4	4	1	1

Source: PIARC, 2000a, 2000b.

Road user and societal costs

In the questionnaire responses in Chapter 2, only half took indirect or user costs into account in any whole-life cost analysis. This was surprising, given the findings of the PIARC reports and the fact that user costs can have a major impact on an analysis, particularly for the heavily trafficked roads considered in this report.

As traffic increases, the effect of congestion on road users also increases. The value of time for road users continues to increase, and the effect of any delay costs incurred by road users becomes even larger and therefore more important in a whole-life cost analysis. Although the provision of accurate data can sometimes be difficult, user costs and societal costs should be considered. If possible, they should include the following:

- User delay costs:
  - Cost of delays to users during maintenance works both through the worksite and along any diversion route.
  - Costs of delays to road users due to congestion.
- Vehicle operating costs:
  - Costs of vehicle delay during maintenance works (particularly for commercial vehicles).
  - Increased vehicle wear (particularly tyres) as pavements deteriorate.
  - Increased fuel consumption due to deteriorating pavements and during delays.
- Accident costs:
  - Costs of increased traffic accidents during maintenance works.
  - Costs of increased traffic accidents as roads deteriorate.
  - Costs of accidents to road workers during maintenance.

- Environmental costs:
  - Noise costs (possibly related to barrier costs).
  - Pollution costs.
  - Energy costs.
  - Costs of using scarce primary aggregates and other similar environmental aspects of material use.
  - Landfill costs for removed material.
  - Costs of winter maintenance (including run-off of de-icing solutions).
  - Possible costs to wildlife and vegetation.

Evaluation frameworks

The cost model that would be most suitable to assess the economic benefits of an advanced surfacing system should be able to compare the different costs of the materials under consideration and allow assessment of a wide variety of different road types. The model should ideally include the following variables and allow their alteration by the user: traffic flow, traffic growth, traffic mix, age of pavement, climate, road-user costs, residual value of pavements, discount rates.

The economic benefits need to reflect the advantages that should come from a truly long-life pavement. The model should be able to calculate the savings that will come from:

- A reduction in maintenance.
- The reduction in congestion and the improved safety associated with less maintenance and less pavement degeneration.
- Any fuel savings and savings in operation costs by vehicles.
- Other savings (accidents, environmental, etc.).

Ideally, models should be able to assess the need for future treatments based on the recorded condition of the road. Less sophisticated models should allow for future maintenance to be decided and entered by an experienced user. In either case, consideration should be given to the following when assessing pavement condition: cracking, rutting, skid resistance, structural strength and longitudinal evenness.

Allowance should be made for minimum levels of service and these should be adjustable to allow for the different service requirements around the world.

There are other issues that also need to be considered when assessing the suitability of a cost model. These may not all be essential but their consideration, in some form, should be part of any analysis. They include:

- Construction costs (on site and off site).
- Health and safety aspects of new pavements types (on site and off site).
- Risk analysis of new pavements in use (*e.g.* spillage of dangerous goods).
- Common definitions for all variables.

- Key assumptions/variables that should be tested under sensitivity analysis.
- Time horizon (minimum 30-35 years).

Because the model may be used by different countries, further needs should be considered if a model is to be suitable for the type of analysis that has been undertaken for this report. These include allowance for different currencies, the different terminology and use of language, and the requirement for software support and user support. Some of these needs may be met by well-produced user information or manuals and by flexibility in the software that allows scope for the different inputs required.

Evaluation models available

For this report, consideration needed to be given to the availability of models that would be able to analyse the economic aspects of long-life pavements under the scenarios being tested. These required comparisons of the performance of the advanced long-life wearing courses that are described in Chapter 5 with the traditional wearing courses in use around the world. An ideal model would be one that is generally available and supported throughout the world and has an extensive and experienced user base to provide general consistency. It is important for it to be able to be adapted for the many variations in road types, conditions and climates.

The PIARC reports discussed previously did not provide details of all the whole-life cost models that were being used in the various countries. In general terms, each country or authority that uses whole-life costing has developed its own model. One reason for this could be that with the rapid development of computers, the handling of the large number of variables has become a more straightforward task and cost models suitable for each specific purpose are easier to develop.

However, some models that are available are used internationally and these models were examined to assess their suitability. The various whole-life cost models examined are listed and discussed in Annex A. This should not be considered to be an exhaustive list, given that the purpose of this report was not to review cost models. The requirement was to find a model suitable for the purpose identified. Among the models examined, two are discussed here in more detail.

HDM-4 model

The HDM-4 model is a highway development and management system for investigating road investment choices. It is sponsored by the World Bank, and PIARC has assumed the leading role in its management and in the co-ordination of its development. Early versions of the HDM model were suited to developing countries in particular but the scope of the latest version has been widened so that the model can cater for the wide-ranging needs of road agencies, designers and funders across the world. It was previously suited particularly to tropical climates but its suitability has now been extended to frozen climates. It currently has registrations in nearly 100 countries.

The HDM-4 model allows for the consideration and assessment of new development works. It will analyse both single sections of a road or a larger network, it can be used to predict future changes in performance, and it can be refined and calibrated for a particular country or region. The system is compiled with a wide range of mathematical and logic models that enable such predictions of future performance and costs. It provides a powerful reporting facility for data and analysis results and these can be exported to standard database or spreadsheet packages.

Because of the model's initial development for tropical climates and the recent extension to cold climates, there is some doubt about its suitability for temperate climates. Limited trials in eastern European countries indicated that HDM-4 may not be able to represent the conditions in these areas or allow for their types of pavement and heavy traffic conditions. As a very powerful model with the large number of modules (covering the very many aspects that can be included in the analysis), it appears somewhat cumbersome and inappropriate for relatively straightforward applications. Despite the HDM-4 model's wide circulation across many countries, it is thought that there may be only a very limited number of experienced users who are sufficiently proficient in its use and who have available the accurate local background data required for its calibration. Nevertheless, the HDM-4 model is an internationally recognised model and is therefore a useful reference for an international evaluation of different pavement types.

UK-SAS/PASI Model

TRL in the United Kingdom, working for the Highways Agency, has adapted an existing model, the Scheme Analysis System (SAS) to allow its use in different countries. The SAS model is used to analyse treatment options for maintenance schemes on the trunk road network in England and to identify the options that provide good value for money in whole-life cost terms. Based on an Excel spreadsheet, this road project evaluation model allows the user to compare options for different maintenance regimes.

The PASI model was developed by TRL as a variation of the SAS model to make it more suitable for international use, and it is also suitable for both concrete and bituminous pavements. In the PASI model, various currencies can be represented and users may use their own descriptive terms and apply their own cost and output rates for maintenance treatments and traffic management options.

The model includes the capability to make allowances for user costs based on delay times, for residual value and for different treatments on different lanes of the highway. All local background data can be entered or typical values from available UK data can be used. As the model is based on a spreadsheet, it has been kept relatively straightforward. The user needs to enter a realistic maintenance regime for each of the pavement options being considered. There is the option to include other costs in the analysis, such as initial construction cost, operating costs or any other associated costs or benefits. They can be entered either as part of the initial maintenance cost or as costs incurred in future years of the analysis period. All costs are discounted to a base year which allows a valid comparison of NPVs of costs between the project options considered.

The intention is that the same model will be used by the ELLPAG project (see Chapter 1) in its evaluation of options for the structural layers of long-life pavements.

Suitability and use of the selected models

The HDM-4 and PASI models were selected on the basis of their ability to fulfil (as much as possible) the requirements set out in the evaluation framework discussed above. Their availability and, in the case of the PASI model, its ease of use with little experience or training were other important considerations. The models have been used in this report as examples of the models required by the whole-life costing assessment approach. Although it was intended to run the models in tandem and analyse examples in the same manner, it was found that this was not a realistic approach. Further discussion on the reasons for this and the manner in which the models were used is provided in Chapter 4.

The task is to compare two main scenarios for various traffic flows and other variables and to establish the criteria that would allow an advanced surfacing to become economically advantageous. Reflecting current practice, a maintenance profile for an example road needed to be established for traditional surfacing using standard maintenance techniques. This was done with input from the survey as reported in Chapter 2. The cost analysis for this scenario had to be compared with the cost of the same road finished with a long-life wearing course, taking into account the improved maintenance profile using advanced surfacing materials. For both options, the existing pavement was assumed to be showing surface deterioration (surface rutting, cracking, unevenness or loss of texture) and in need of a new surface layer.

It will be seen that the maintenance treatments in the analysis relate only to the surfacing layers and thus assume that the structural layers do not require attention. In all cases, it has been a fundamental assumption that the underlying existing road structure is of sufficient strength and condition to be described as a "long-life" road and will not need reconstructing during the period of the analysis. Because the maintenance profile, in the case of the PASI model, is defined by the user and is not related to deterioration relationships, the condition of the structural layers may be ignored. The full results of this analysis are described in Chapter 4.

References

OECD (1994), *Road Maintenance and Rehabilitation: Funding and Allocation Strategies,* OECD, Paris.

PIARC (2000a), *Whole-life Costing of Roads – Flexible Pavements*, PIARC, Paris.

PIARC (2000b), *Whole-life Costing of Roads – Concrete Pavements*, PIARC, Paris.

Chapter 4

Economic Feasibility of Long-life Pavement Surfacing

This chapter contains an analysis of the economic feasibility of advanced pavement surfacings. The analysis shows that in certain situations, advanced wearing courses with higher initial costs are justified. The longer life of the surfacing and associated reduction in maintenance costs over its lifetime compensates for the higher initial costs.

Introduction

Using data from Chapter 2, an assessment is made of the whole-life costs of traditional wearing courses, based on typical surface maintenance strategies and taking into account associated costs to road users.

The same steps are followed in respect of the innovative long-life wearing courses that are to be evaluated. In this case, the whole-life costs encompass the higher initial wearing course costs and the lower costs associated with reduced maintenance and lower user delay costs over the evaluation period.

The whole-life costs of both cases are then discounted to the present time to give the net present value (NPV) of the costs of the innovative wearing course options by comparison with traditional approaches

Models used

The whole-life cost models that were chosen for this analysis were described in the preceding chapter. The analysis relied mainly on the Project Analysis System – International (PASI) model. The HDM-4 model was used principally for the consideration of vehicle operating costs. Details on the use of the models are provided in Annex A.

Data available

Accurate and reliable whole-life cost modelling depends on the availability of accurate input data. To obtain robust results, it is important to use the best data available for initial calculations and predictions of future maintenance requirements.

Chapter 2 examined recent data from various countries on the costs of wearing courses and standard maintenance treatments, their performance and the periods between treatments.

For the many variables for which details were not available from the survey reported in Chapter 2, experience from typical applications helped determine the approach and values for use in the analysis. The specific value or the range of values adopted are explained later in this chapter.

Maintenance works result in increased costs to road users due to the resulting disruption and traffic delays; these costs are therefore an essential part of the whole-life cost analysis related to maintenance works. For the calculations carried out by the PASI model, the delays during maintenance work, related to the traffic management option selected, are converted into costs and included in the evaluation of total costs.

Basis of analysis

Example scheme

The analysis has used an example of a pre-constructed road built with a long-life pavement in good structural condition but with surface layers in need of replacement. The scheme was based on a dual three-lane motorway, 4 km in length and generally without major inclines, junctions or corners. The analysis was designed to compare the total costs over a 45-year evaluation period of two alternative initial treatments, either treating the pavement with a traditional surface treatment or with an advanced long-life surfacing system.

Traditional treatment

The input data used for the analysis are based on the responses to the questionnaire reported in Chapter 2. Although costs and treatments varied considerably between countries, the values used reflect a treatment regime that would be considered representative of current practice in many countries.

Surfacing: 30 mm (SMA type or similar)

Surface replacement: 30 mm every 8 years for very heavy traffic, every 10 years for heavy traffic, 100 mm every 16 years for very heavy traffic and every 20 years for heavy traffic

Cost: USD 8/sq m for 30 mm resurfacing (removal and replacement)

It was assumed that when the surfacing is replaced, existing surfacing layers would be milled or planed out before replacement with a new wearing course. The questionnaire results indicated that many countries used a process of sealing cracks between main resurfacing treatments and thereby extended the periods between these major interventions. This treatment has also been considered as part of an alternative maintenance strategy for the analysis of schemes carrying lower levels of traffic.

Advanced wearing course

The aim for the advanced wearing course option was to assess the cost and performance criteria that would make the advanced (long-life) surfacings economically viable when road works and user costs are considered. Given the lack of current experience with such innovative surfacings, judgements had be made on their likely performance. The analysis undertaken therefore reflected "what if" scenarios based on current expectations.

The maintenance regimes used in the analysis were based on certain assumptions:

Cost of advanced surfacing:	3 times or 5 times the cost of traditional treatment
Advanced surfacing life before replacement:	30 years or 40 years
Surface treatment:	Treatment for skidding resistance at intermediate periods

Such increases in wearing course costs need to be seen in the context of typical pavement construction costs. For the example scheme chosen of a dual three-lane motorway, pavement construction costs would amount to USD 1.8 million to USD 2.25 million per carriageway kilometre. This estimate includes features such as earthworks, drainage, line markings, safety fences, etc., but not other structures such as over or under bridges, gantries, etc.

At present, the surface layer (the wearing course) of such pavements represents around 9-12% of the above indicative pavement construction costs. A three-fold increase in the wearing course cost would imply an increase in overall pavement structure construction costs of up to 24%, and the surface layer would then represent around 30% of the construction costs.

Of course, the total construction costs of high-traffic roads are extremely variable, depending not only on pavement construction costs but also on the number of bridges, tunnels and earthworks actually involved. Overall average costs per kilometre increase to between USD 3.15 million and USD 3.6 million per carriageway kilometre, taking these other costs into account. In this respect, a three-fold increase in the cost of the surface layer of the pavement would have a lower impact in terms of overall motorway construction costs per kilometre, *i.e.* between 10-15%, and the surface layer would represent between 5% and 20% of the total construction cost. If a completely new road scheme were to be examined, this percentage would be even lower when total costs including structures, land purchase, design costs and communications were taken into account.

Maintenance profiles

Advanced surfacing with 40-year life

The maintenance profiles used in the analysis for different levels of traffic – ranging from 40 000 to 100 000 average annual daily traffic (AADT) – are shown in Table 4.1. These are based on experience with the traditional surfacings and assumptions about maintenance likely to be required for the advanced surfacing with a life of 40 years.

The advanced surfacing was given an intermediate treatment called “retexture”. The exact nature of this treatment has not been specified but it indicates that an allowance has been made to restore and maintain an acceptable level of skid resistance throughout the evaluation period.

Table 4.1. Maintenance profiles comparison over 40 years

Traffic: 40 000 & 60 000 (AADT[1])				Traffic: 80 000 & 100 000 (AADT[1])			
Traditional		*Advanced*		*Traditional*		*Advanced*	
Year 0	30 mm surface	Year 0	Advanced surfacing	Year 0	30 mm surface	Year 0	Advanced surfacing
Year 10	30 mm surface	Year 20	Retexture	Year 8	30 mm surface	Year 15	Retexture
Year 20	100 mm surface	Year 40	Advanced surfacing	Year 16	100 mm surface	Year 30	Retexture
Year 30	30 mm surface			Year 24	30 mm surface	Year 40	Advanced surfacing
Year 40	100 mm surface			Year 32	30 mm surface		
				Year 40	100 mm surface		

1. AADT: annual average daily traffic in two directions of all vehicles.

Advanced surfacing with 30-year life

The adjustments to the maintenance profile when the advanced surfacing has a shorter life of 30 years are shown in Table 4.2.

Table 4.2. Maintenance profiles comparison for advanced surfacing with 30-year life

Traffic = 40 000 & 60 000 (AADT)		Traffic = 80 000 & 100 000 (AADT)	
Year 0	Advanced surfacing	Year 0	Advanced surfacing
Year 15	Retexture	Year 10	Retexture
Year 30	Advanced surfacing	Year 20	Retexture
Year 44	Retexture	Year 30	Advanced surfacing
		Year 40	Retexture

1. AADT: annual average daily traffic in two directions of all vehicles.

Crack sealing maintenance treatment

The maintenance profile with the alternative crack sealing treatment option (instead of replacement with traditional surfacing) is shown in Table 4.3. This option was considered for the lower traffic flow levels only.

Table 4.3. Maintenance profile for traditional surfacing for crack sealing option

Traffic = 40 000 & 60 000 AADT only *Traditional*	
Year 0	30 mm surface
Year 5	Seal cracks
Year 10	Seal cracks
Year 15	30 mm surface
Year 20	Seal cracks
Year 25	Seal cracks
Year 30	100 mm surface
Year 35	Seal cracks
Year 40	Seal cracks
Year 45	30 mm surface

Standard test case

A "standard" test case developed for testing, analysis and comparison of the NPV of costs involved the following set of parameters and conditions:

Cost of advanced surfacing:	Three times the cost of traditional surfacing
Life of advance surfacing:	40 years
Traffic level (AADT):	80 000
Proportion of heavy vehicles:	15%
Discount rate:	6% a year
Work pattern:	Night-time work

This "standard" test case has also been used as the base from which to examine the impact on the NPV of costs of variables such as the traffic growth rates and way of working (*i.e.* carrying out maintenance work at night or during daytime).

Variables, assumptions and sensitivity testing

Of course, levels of actual traffic vary from project to project, and discount rates vary across the OECD countries. Each country faces different economic conditions and there are possible differences in matters such as traffic management regimes. The analysis therefore considered different scenarios and a range of values to ensure that the conditions normally encountered in the various countries are covered.

The variables involved in the sensitivity testing and the ranges tested are:

Cost of advanced surfacing:	3 times and 5 times the cost of the traditional surfacing
Life of surfacing:	30 years and 40 years
Traffic levels (AADT):	40 000, 60 000, 80 000, 100 000
Proportion of heavy vehicles:	5%, 10%, 15%, 20%
Discount rate:	3%, 6%, 8%, 10%

Because of the nature of pavements – with many variables that can affect pavement performance and different maintenance practices used in different countries – it was not possible to gather data on all aspects of the analysis in a way suitable for use in the model. The following notes highlight the areas where assumptions had to be made for the PASI analysis and also clarify the values or conditions that were used. A summary of the results of this testing is shown later in this chapter, and full details are included in Annex D.

User costs**:** User costs due to delays and disruption at road works sites during maintenance were calculated from look-up tables included in the PASI model. The look-up tables have been created from the United Kingdom Department for Transport model QUADRO (Queues and delays at road works sites) which uses the UK value of time for the evaluation. Examination of the values of time from various countries appears to indicate that, for some vehicle groups, the UK values may be at the lower end of the range for the countries considered. Higher values of time would have a significant impact on user cost estimates and therefore on the outcome of the evaluations. Future work could consider adjustment of the values used to make them more representative.

Traffic management arrangements and costs: Different traffic management options will influence the delay times experienced by motorists and hence user delay costs. Traffic management arrangements during maintenance that were most appropriate to the particular surface treatment and traffic level were selected from the options currently used on the UK trunk road network. Given that basic operational arrangements do not seem to vary significantly between countries when calculating user costs, the use of one source for the required data seemed sensible. This provides a consistent basis for comparing user costs associated with different treatment options.

Output rates**:** The work output rate is used to calculate the time for each surface treatment and thus the period during which delays may occur. For traditional surfacing, the output rate for each selected treatment was based on the questionnaire results presented in Chapter 2. Since advanced long-life surfacing has not yet been laid in a full-scale trial, no actual values for the work output rate are available. The values used were therefore based on an assessment of an appropriate rate for working with this type of material (see Annex B).

Working hours**:** The available length of the daily working period determines the total time required for carrying out each surface treatment, and this, in turn, affects the costs to road users. Except where mentioned otherwise, the analysis assumed all surface treatments were scheduled to take place at night. This is now the common working method for maintenance on most high-traffic roads. The analysis was based on an eight-hour working period for night work, the alternative being a ten-hour period for daytime work. For night work, in addition to the reduced hours, the PASI model takes account of the lower volume of traffic which results in a reduction of delay costs compared with daytime work. A comparison of the NPVs for the “standard” test case with night work and the alternative of daytime work are given later in this chapter. Further work could test the sensitivity of the NPV to changes in these values.

***Traffic growth*:** It is difficult to make an accurate assessment of traffic growth, if a single value is to be used to cover the whole of the evaluation period. Future traffic growth will be affected by a number of factors – including the state of global and national economies and national policy settings – and will therefore be different for each nation. Growth rates are also likely to be dissimilar for different types of vehicles, from cars through to heavy freight vehicles.

An average annual growth in traffic of 1% per year was used in all the standard test case analysis runs. This growth rate may be low for some countries. However, capacity problems may arise if a higher value is used when considering roads with high levels of traffic at the start of the analysis. For example, a road with an initial daily traffic flow (AADT) of 100 000 vehicles and growing at 2% a year will need capacity for 220 000 vehicles after 40 years.

To allow for examination of the effect of other growth rates, an analysis run was also carried out on the standard test case using the following variation in growth rates over the evaluation period:

First 10 years:	2% a year
Following 10 years:	1.5% a year
Thereafter:	1% a year

***Residual value*:** It is important that an allowance is made for the residual value of the surfacing at the end of the analysis period to take into account the value added by a treatment in the last years of the evaluation period. The PASI model evaluates residual value as a proportion of the cost of this final treatment in relation to the number of years of surfacing life remaining at the end of the evaluation period.

Results for the “standard” test case

With the assumptions outlined above, the economic analysis showed good prospects of innovative long-life pavements being economically viable.

The results of the analysis of the “standard” test case are set out in Table 4.4. They show the contribution that each of the different cost elements makes to the NPV of costs. For traditional surfacing with a relatively high traffic flow (80 000 AADT), it can be seen that initial costs, future maintenance costs and user costs make a significant contribution to the NPV of costs. The NPV of total works costs are not very different for the traditional and long-life wearing course options. For advanced surfacing, it is clear that it is the reduction in user costs that mainly counteracts the higher initial cost to give the advanced surfacing a lower NPV of costs and therefore a favourable economic outcome.

Table 4.4. Standard test case results

Surface treatment costs	Net present value (USD 000s)	
Contributing factors	*Traditional*	*Advanced*
Initial works costs (treatment in year 0)	480.48	1 441.44
Maintenance works	1 084.21	282.21
User costs (delays)	1 278.65	515.90
Traffic management costs	259.04	168.69
Residual value	-43.63	-91.63
Total net present value (NPV)	3 058.75	2 316.61
Difference		742.14
Percentage difference		24.3%
User costs (VOCs) from HDM-4 model	1 354.31	1 353.81
Difference in user costs		-0.50
Adjusted NPV including difference in VOCs	3 058.75	2 316.11

The values for vehicle operating costs (VOCs) obtained by running the World Bank HDM-4 model are also included in Table 4.4. The HDM-4 model is capable of analysing a wide range of pavement conditions. The HDM-4 analysis resulted in large values for the total VOCs associated with the individual strategies. However, it was found that for the small changes in road condition that are discussed in this analysis, the model calculated only small differences in VOCs and few trends were apparent.

Given the high relative value of the VOCs, it is appropriate either to take a proportion of these into the calculation or to use the difference in their values; for Table 4.4 the latter choice was made. It can be seen that inclusion of the VOC difference estimated using the HDM-4 model has no significant impact on the difference in the NPVs of the two options. The table sets out the results of the analysis, which show the contributions made by each of the factors to the NPV of costs result.

Results with variations in some standard case assumptions

The effects of varying some of the basic parameters used in the "standard" case have also been examined.

Daytime work

Table 4.5 shows the results of an analysis with the same average daily traffic flow but with the maintenance work carried out during the day rather than at night. Traffic flows are higher during the day, resulting in greater traffic delays compared to night-time work and significantly higher user costs. As a result, the overall costs are higher for traditional and alternative long-life surface approaches. As well, the savings when using advanced surfacing are increased in day-time work scenarios. This indicates that the standard test case results presented, based on night work for all the maintenance interventions, provide a conservative assessment of the possible NPV benefits.

Table 4.5. "Standard" case but with maintenance work carried out during daytime

Surface treatment costs	Net present value (USD 000s)	
Contributing factors	*Traditional*	*Advanced*
Initial works costs	480.48	1 441.44
Maintenance costs	1 084.21	282.21
User costs (delays)	4 215.70	1 719.68
Traffic management costs	253.50	165.90
Residual value	-43.63	-91.63
Total NPV	5 990.26	3 517.60
Difference		2 472.66
Percentage difference		41.3%

Note: AADT = 80 000, 15% heavy vehicles, three times cost, 40-year life, 1% traffic growth.

Differential traffic growth rates

The other variation from the "standard" case considered differential traffic growth. Instead of the steady 1% traffic growth used in the standard test results, the variable traffic growth described earlier was used in the analysis, *i.e.* an annual growth rate of 2% during the first ten years, 1.5% for the next ten years and then 1% for the following ten years (*i.e.* from year 20 onwards). The results are shown in Table 4.6.

Table 4.6 "Standard" case parameters but differential traffic growth rates

Surface treatment cost	Net present value of costs (USD 000s)	
Contributing factors	*Traditional*	*Advanced*
Initial works costs	480.48	1 441.44
Maintenance costs	1 084.21	282.21
User costs (delays)	1 997.11	766.31
Traffic management costs	258 04	168.69
Residual value	-43.63	-91.63
Total NPV	3 777.21	2 567.02
Difference		1 210.19
Percentage difference		32%

Note: AADT = 80 000, 15% heavy vehicles, three times cost, 40-year life, 1% traffic growth.

At higher growth rates, the advanced surfacing option becomes more attractive relative to traditional surfacing methods. Although the changes from the standard case are not as large as those caused by a change from night-time to day-time work, the analysis again suggests that the standard test case results reflect a conservative approach to the analysis.

Crack seal maintenance

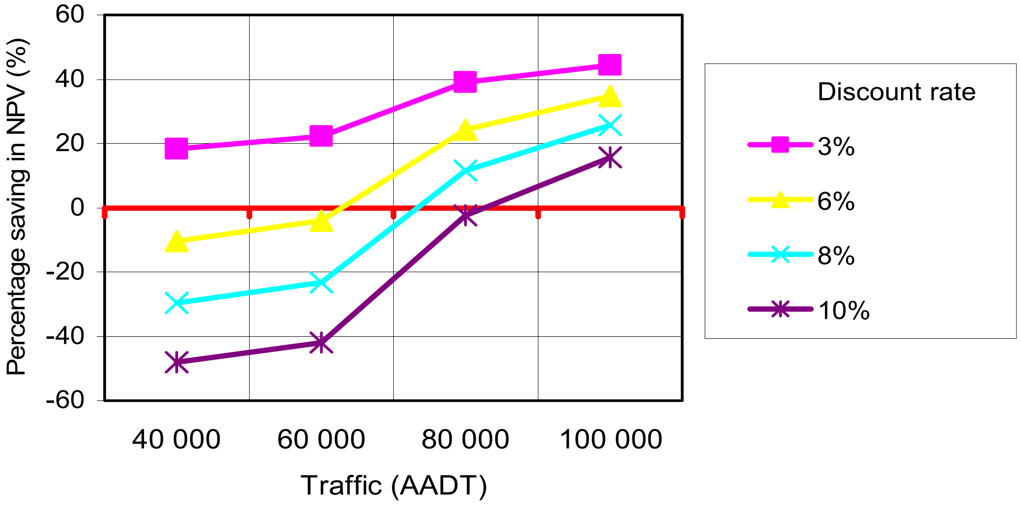
The analysis reported above centred on maintenance regimes in which the traditional surfacing was replaced rather than having the surface cracks sealed as an intermediate treatment. An alternative approach is to undertake crack sealing as an intermediate treatment, an option considered suitable only for lower traffic levels. The crack seal option was modelled for the lower traffic levels and the results for the few cases considered are shown in Annex D. The treatment costs for the crack seal options were between 13% and 22% cheaper than the traditional surfacing previously considered. However, it can be seen that only a few of the situations modelled show an advantage for the advanced surfacing, an outcome that is principally related to the low traffic volumes for which the crack sealing option can be applied.

Results of sensitivity testing

The analysis explored the impact of variations in some of the key parameters and assumptions. The results are given in Figures 4.1 to 4.4 and show the percentage saving in the NPV of costs of the advanced long-life surfacing over the traditional surfacing (a positive value above the zero axis indicates a saving if a long-life surfacing is used).

Figure 4.1 assumes that the advance surfacing costs three times more than traditional surfacing and shows that the outcome is very sensitive to the discount rate chosen. At high discount rates, long-life wearing courses would only be economical on highly trafficked roads (*e.g.* above around 80 000 AADT).

Figure 4.1. Percentage saving in NPV: 3 times cost, 15% heavy vehicles, 40-year life



If the initial cost of the long-life wearing course is five times the cost of traditional surfaces, such surfaces would only be economical on quite highly trafficked roads in countries with very low discount rates (see Figure 4.2).

Figure 4.2. Percentage saving in NPV: 5 times cost, 15% heavy vehicles, 40-year life

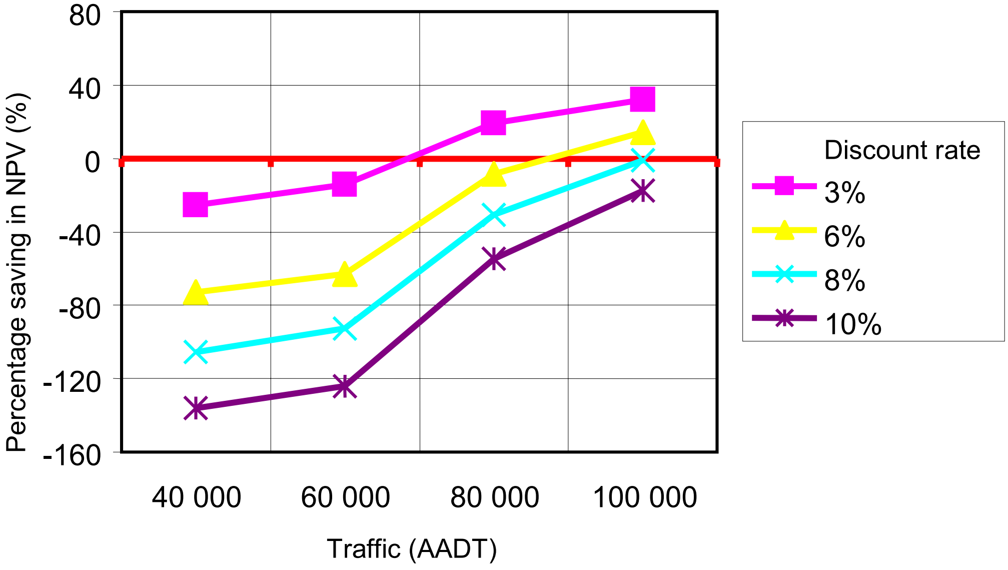


Figure 4.3 explores the impact if the effective life of the wearing course is 30 years instead of 40 years. The economic results for a wearing course costing three times traditional surfacings are less favourable if the pavements have a 30-year life (Figure 4.3) than if they have a 40-year life (Figure 4.1).

Figure 4.3. Percentage saving in NPV: 3 times cost, 15% heavy vehicles, 30-year life

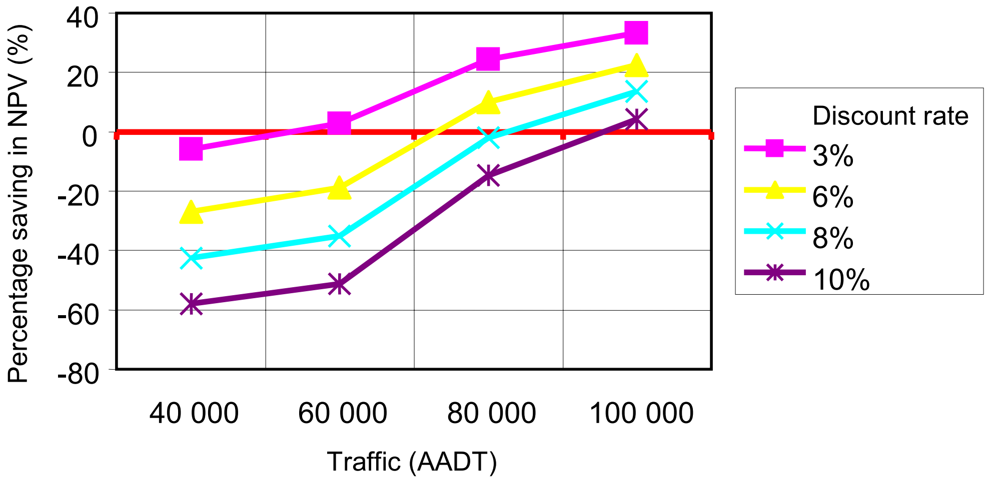
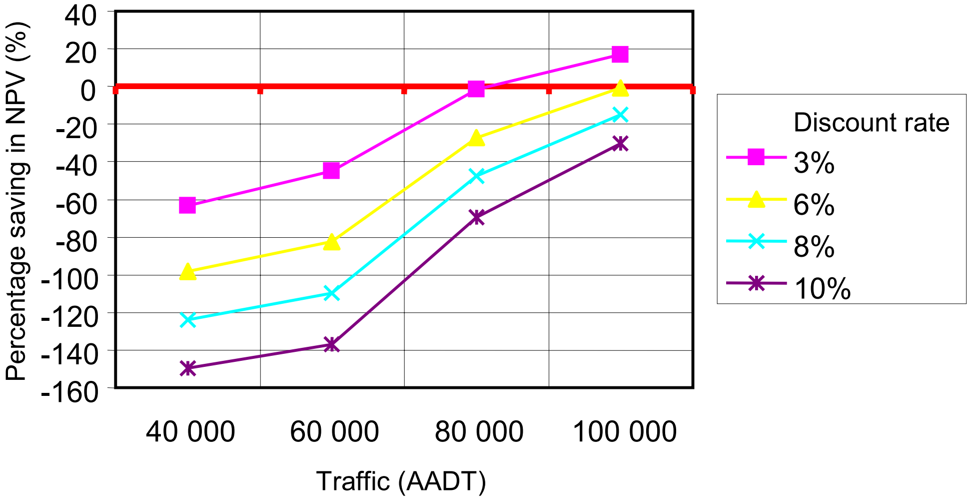


Figure 4.4 assesses the impact on viability of both a high initial cost (five times) and a 30-year life. The results indicate that long-life pavements would be uneconomical if their initial costs were five times the cost of a traditional surface but they could only achieve a 30-year life.

Figure 4.4. Percentage saving in NPV: 5 times cost, 15% heavy vehicles, 30 years life



The full set of results from the runs of the PASI model which encompassed the variables discussed above can be found in Annex D. The tables in Annex D have been shaded where the differences in NPV figures show an economic advantage for the advanced surfacing. It can be seen that this occurs, not unexpectedly, at higher traffic flows and for lower discount rates.

Discussion of results

A number of points should be borne in mind when the results shown above are considered:

- Importantly, it should be remembered that the long-life wearing courses for which these indicative evaluations have been undertaken are not yet in general use. Therefore, the cost, the life, condition and maintenance arrangements included in the analysis of the advanced surfacing have had to be assumed. However, the analysis indicates the broad envelopes in which the costs of the new wearing courses would need to fall for them to be economically viable. Further work on the development of these materials and their actual costs and performance is required and when available will provide data for an accurate assessment of their whole life cost.

- For the conditions of analysis assumed in this study, there are whole-life cost benefits associated with the use of advanced surfacing only when the traffic flows are relatively high and discount rates are moderate or low. The main driver of increased benefits is the reduction in costs to road users. In current road projects, there is generally increasing pressure to reduce road maintenance disruption to users at sites with high traffic flows. The model results are consistent with this pressure. The use of advanced surfacing with long-life pavements may offer a particularly appropriate way to meet the need for minimum disruption to users.

- At the lowest traffic flow considered (AADT of 40 000), the NPV associated with the advanced surfacing shows a saving only with a 3% discount rate (Figure 4.1). The chart also appears to suggest that with a 3% discount rate, and the conditions assumed in this analysis, long-life wearing course savings may be obtained at traffic flows of less than 40 000 AADT. Experience suggests this is unlikely. Further work would be necessary before any such conclusion could be drawn.
- The same maintenance profile was used for the different percentages of heavy vehicles when realistically the surfacing would give better service for lower percentages of heavy vehicles.
- It has been assumed that the traffic management arrangements for all the maintenance treatments are similar (with slight differences between lighter and heavy traffic flows). Again, further work in this area would allow consideration of traffic options that may fit more realistically with the actual traffic being considered.

Variations between models

Although the HDM-4 model was used and analysis undertaken to replicate the results from the PASI model, the results obtained with the HDM-4 model showed only very small differences between the maintenance options for several reasons which are outlined below.

As explained above, to replicate the required maintenance regime in HDM-4 for modelling purposes, it was necessary to consider the road to be in relatively good condition (in HDM-4 terms) with low IRI values. This assumption contributed to the small differences in the NPVs of costs that were obtained. Further work with the HDM-4 model has shown that the savings in user costs (*i.e.* vehicle operating costs and travel time costs) between the traditional surfacing maintenance profile and the advanced surfacing maintenance profile are increased by 33 times when traditional surfacing maintenance is based on the typical road conditions found in Poland and some other eastern European countries. This is based on the maintenance appropriate for a road with an IRI value of 4.4 rather than 2.5, the value that has been used for the analysis in this report. This shows that when VOCs are taken into account, the overall condition of the road will have a more significant effect on the analysis.

Conclusions from the economic analysis

Under the standard modelling case with the assumptions outlined, the economic analysis indicates that there are likely to be economic benefits in using long-life wearing courses when the initial cost is around three times that of traditional surfacings and traffic levels are high. Advanced surfacing can generally be expected to be economically viable for traffic levels above around 70 000-80 000 AADT. With discount rates below 6%, long-life wearing courses could be viable at 60 000 AADT or even between 40 000 and 60 000 AADT.

For the advanced surfacing option, the NPV saving over the traditional surfacing increases as the traffic flow increases or as the discount rate decreases. As well, the analysis has shown that advanced long-life wearing courses with a 40-year life will be more economical when user costs are taken into account, as there are significant benefits in avoiding disruption to road users due to maintenance.

The analysis of cases other than the standard one and the sensitivity testing undertaken leads to the following additional conclusions:

- There are likely to be at least some savings for heavily trafficked roads (above 80 000 AADT) at any of the discount rates assessed.
- The savings increase as the percentage of heavy vehicles increases (given that this leads to higher user costs) because advanced surfacings reduce disruption costs to users. However, the percentage of heavy goods vehicles has a lower than expected effect on NPV. This is mainly because the impact of the proportion of heavy vehicles is considered only in the calculation of delay costs. The analysis does not take account of the effects on maintenance requirements.

While the analysis indicates that there are clearly circumstances where long-life wearing courses could be economically viable, it is also evident that there are many conditions under which advanced surfacing options are not likely to provide a saving in whole-life cost terms. From the analysis and charts, it can be seen for example that:

- The discount rate has a significant effect on the results and only the schemes with the highest traffic levels show a saving when the discount rate is 10%.
- Except at very low discount rates (*i.e.* 3%) and high traffic volumes, high-cost pavements *(i.e.* five times the cost of traditional pavements) would not be expected to be economically viable.
- At traffic levels around 60 000 vehicles per day and below, the use of advanced surfacing will not provide a saving in whole-life cost terms, except at low discount rates (*e.g.* 3% a year).
- When traffic levels are around 40 000 vehicles a day, experience suggests that there are very few situations in which a saving could be made and even where savings are indicated, these might not be achieved.

In general, the values and the assumptions that have been used in the analysis are considered to be on the conservative side. Although some of the assumptions made may be open to discussion, it has also been shown that the results are relatively robust across a range of values and that small adjustments to values would not alter the main conclusions.

The roads that have been considered in the analysis have been assumed to be in overall good condition with a sound structure and an even surface. For roads that may not be in such good condition and that are more uneven with a higher IRI value, as may be found in some eastern European countries, the vehicle operating costs become a much more influential factor. Roads with high IRI values may be indicative of a weaker underlying structure and the pavement structures would need to be upgraded before long-life wearing courses could be considered.

Possible implications for different countries

The results of the analysis indicate that advanced surfacing treatments can show an economic advantage for countries that have roads with high traffic levels, especially if these countries use moderate or low discount rates in assessing project feasibilities.

The analysis is based on representative values for the traditional treatments and estimated values (on the basis of engineering knowledge) for the advanced wearing courses. It can therefore only give an indication of any savings in whole-life costs. In relation to different countries, it should be noted that:

- Inputs such as the use of traffic management options vary from one country to another.
- User costs play an important part in the analysis but assessment practices differ across countries.
- Each country should carry out a similar analysis using their own data for treatment costs and output rates, traffic flows and traffic management options, vehicle and user costs and discount rate.

To ensure a realistic assessment of costs over the long evaluation period, further detailed analysis could be carried out by individual countries to examine in more detail some of the variables discussed in this report. This further analysis could include:

- Use of country-specific real cost data for traditional surfacing rather than the single “representative” value used in the standard test case assessments.
- Further variations in the maintenance profiles that make allowance for the different traffic flows and proportions of heavy vehicles.
- Improved estimation of the consequences of working with the advanced surfacing.
- Impact of the condition of the existing pavement on the long-term performance of the advanced surfacing, particularly where the structural condition or evenness are poor.
- Further examination of the economics of the advanced surfacing over a wider range of road types, traffic flows, discount rates and evaluation periods.
- Sensitivity to other traffic management arrangements, ways of working and hours of work.
- Sensitivity of user costs to values of time and calculations of delays at road works.

Chapter 5

Next-generation Pavements for High-traffic Highways

This chapter examines a number of different wearing courses that have been developed to withstand high loading with minimal maintenance. These are generally used for small-scale projects and may not yet be suitable for mainstream use. Two materials are considered to have developmental potential to produce long-life wearing courses and are recommended for further examination.

Advancing the next generation of pavements will require a unified effort by producers, contractors, and user agencies. Long-life performance of a pavement is dependent on three things: good design, good materials and successful placement. Failure of any one of these aspects will severely compromise the longevity of the pavement and lead to premature distress and failures.

Developing a wearing course with a design life of 30, 40 or even 50 years will require significant effort from researchers. Current performance-based models developed for shorter time frames may not necessarily extrapolate to such long-term horizons. Better tools for characterising and predicting the extent of traffic loading and environmental effects will ultimately be needed. The chemical reactions and physical conditions associated with ageing and weathering of pavements need to be integrated with the performance-based mechanical testing typically employed in pavement analysis.

This chapter considers the properties and modes of production for various paving materials and systems capable of meeting the stringent performance attributes required of a long-life wearing course. Discussion of any particular product should not be taken as an endorsement but rather an acknowledgement of the existence of performance data.

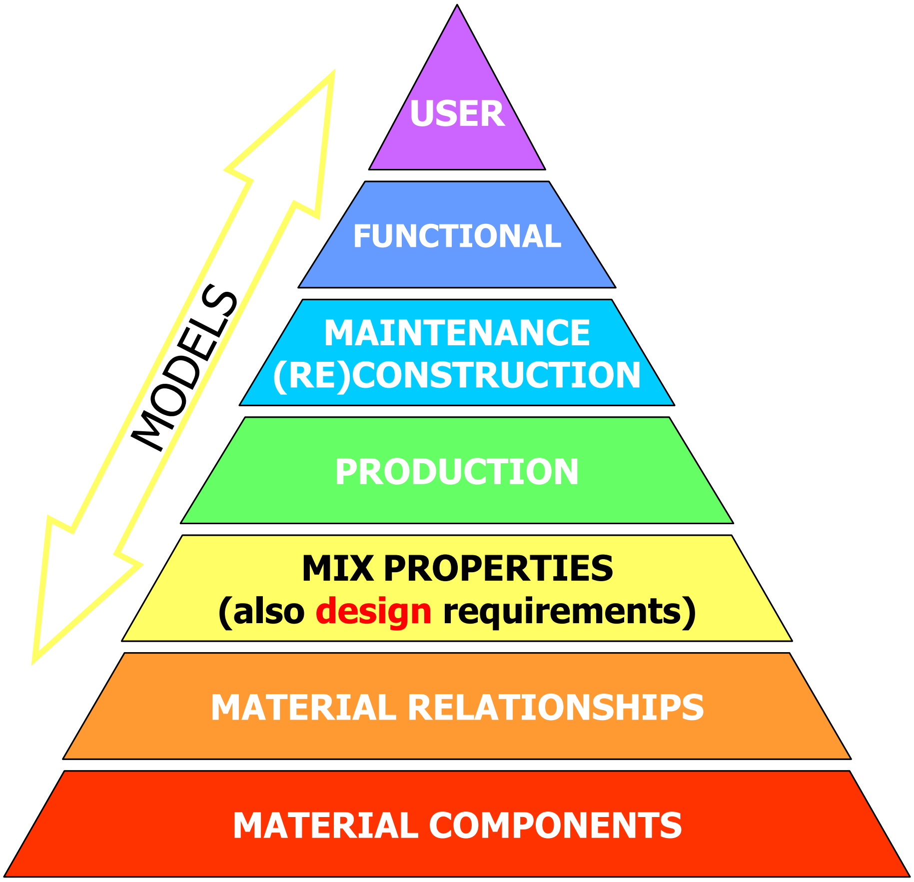
Pyramid of relationships

The relationships necessary to establish long-life wearing courses can be illustrated as shown in Figure 5.1. The pyramid encompasses the traditional triangular relationship involving materials, design and construction, and also includes user and functional aspects.

Societal issues are at the top of the pyramid. These include: user-related issues such as comfort, sustainability, cost and accessibility, and functional issues from the perspectives of motorists and user agencies. The performance criteria from the viewpoint of motorists include the following:

- Ride (drivability/smoothness).
- Friction.
- Noise.
- Spray/splash.
- Reflectivity.
- Chemical spill tolerance.

Figure 5.1. Conceptual relationship pyramid for long-term wearing courses



Source: Adapted from J. Th. van der Zwan.

Societal expectations and climatic conditions largely determine these performance criteria. Engineers can directly measure the above properties but also base their judgements on the various distress elements. Degradation and distress elements would include:

- Cracking.
- Rutting (longitudinal surface depression in the wheel path).
- Ravelling (loss of aggregate).
- Faulting (difference in elevation across a joint or crack).
- Scaling (deterioration of surface of concrete pavements).
- Polishing (reduced surface friction).
- Pitting (studded tyre wear).
- Debonding and delamination (loss of mechanical continuity between two adjacent courses, such as the wearing course and the binder course).

At the next level are contractor-related issues that arise during production and construction of pavements or during their maintenance and reconstruction. Typical construction issues include thickness of the pavement, surface preparation, time-to-construct (cure time if applicable), mode of construction, paving environment, load limitations and geometry issues, as well as traffic control and safety (worker and motorist) issues. During reconstruction and maintenance, these same issues apply; however, a few additional issues require attention. All these aspects are an important part of maintenance, but consideration should also be given to various types of recycling, the frequency and difficulty of repairs as well as the environmental aspects. Production issues include mixing, handling, transport, compaction, environmental, temperature, time and load limitations during curing.

The following three segments of the pyramid relate to design and material selection. Mix properties essentially reflect design parameters/requirements and include strength, cost, temperature, workability, air voids, modulus and shrinkage. Many of these properties are captured in existing design procedures; for example, asphalt hot mix might employ the US Superpave models to relate traffic and mix properties. Material relationships include factors such as the gradation, volumetrics and fineness of the material. Material components are largely dictated by chemical composition and the impact on physical and mechanical properties. Examples would include asphaltic and cementitious materials, aggregates, water and synthetic binders. Due to the diversity of types of materials available and under development, consideration of health issues and fire hazards associated with all stages of use of material should be addressed.

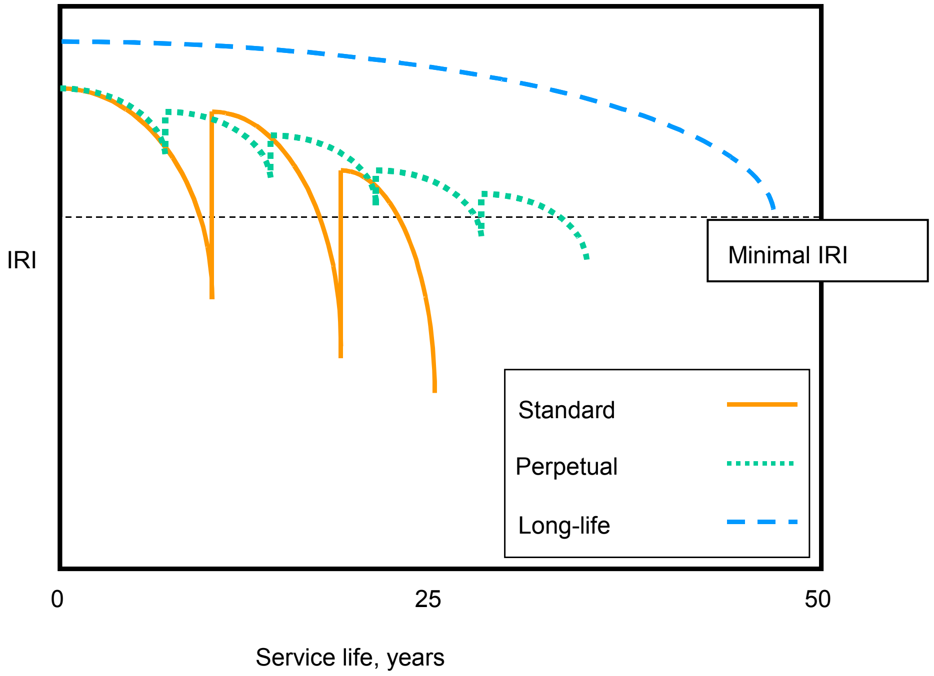
Consideration was given to the interrelationships between the various segments of the pyramid in advancing a selection of materials for the next phase of study.

Performance

As noted in Chapter 2, wearing courses may only survive five years for asphaltic pavements and 20 years for cementitious pavements. Around these timings, some form of maintenance may be needed if one or more critical functional parameters require some form of remediation. For example, if the deterioration in performance is limited to a loss of skid resistance, only a retexturing of the surface may be required. On the other hand, excessive rutting would require a more significant maintenance strategy such as milling and repaving.

For each of the functional parameters, performance can be plotted against time. Ride quality or pavement smoothness is one physical quantity that readily affects road deterioration: as ride quality diminishes, road wear accelerates. This is illustrated in Figure 5.2.

Figure 5.2. Conceptualised relationships between service life and IRI for standard, perpetual and long-life pavements



Source: Author.

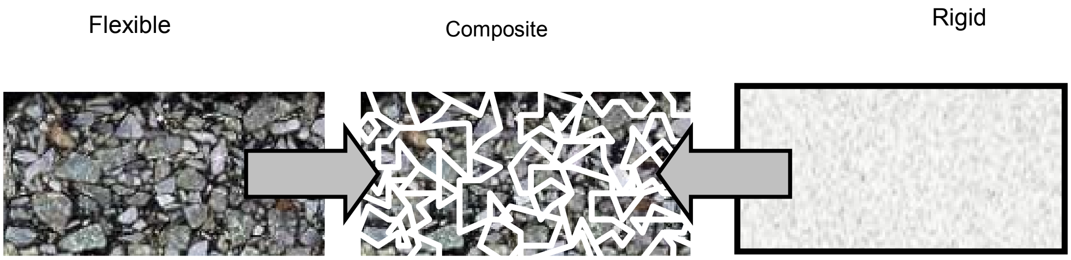
When the pavement quality deteriorates below established values, work carried out in line with a maintenance strategy may improve the performance nearly to the original quality. Subsequent maintenance procedures are likely to have lessening effects on mitigating the distresses, and the pavement may have to be replaced. One of the concepts behind perpetual pavements or a preservation strategy is to be proactive and conduct maintenance strategies before the pavements reach a critical distress value. The key here is to address the causes and not the symptoms. This strategy should improve pavement lifetime as well as provide users with a better ride. The long-life or no-intrusion solution is to employ superior-performing materials that are initially better and require minimal maintenance over a significantly longer period. It is important to eventually associate the end of long-life with some operating condition limit.

Review of advanced materials

Much of the information regarding advanced materials for consideration in this chapter has been drawn from their performance as wearing courses on bridge decks. These materials are considerably more expensive than those used in the production of conventional asphalt and concrete pavements. Justification for their use in bridge decks has been based on one or more of the following factors: longer lifetimes, ability to withstand severe strains, protection of the bridge deck and structural considerations. For example, obtaining comparable strengths from reduced pavement thickness reduces the dead weight of the bridge. Many of these justifications are also applicable to long-life wearing courses, and thus warrant their consideration as potential materials.

All paving materials can be grouped into one of four main categories: asphaltic, cementitious, composite or synthetic. The end products can have attributes akin to existing flexible and rigid pavements, or somewhere in between, as shown in Figure 5.3. The overall trend is to increase the strength of flexible systems and increase the flexibility of rigid systems.

Figure 5.3. Broad classifications of various paving materials



Source: Author.

Asphalt binders (flexible pavements)

Modified asphalt binders are produced via a number of different processes. Largely these are attained via air blowing through the addition of polyphophoric acid or some other reactant, or through the incorporation of polymers. The discussion here is limited to polymer modification, as mere processing of the binder is not felt to produce materials with the properties expected for a long-life pavement.

Polymer modification of the asphalt binder is effected by one of three routes. The polymer is blended with the binders, reacted with the binder, or reactive polymers are used to polymerize the system.

Blending entails the mechanical blending of the polymer with the asphalt binder. Elastomeric polymers such as SBS (styrene-butadiene-styrene) are generally compatible with the binder and become dispersed in the asphalt. Many plastomeric polymers such as EVA (ethylene vinyl acetate) and PE (polyethylene) tend to phase separate. That is, polymer-rich and asphalt-rich zones are formed. The rheological properties of these zones will be quite different and hence the dispersion of the polymer in the asphalt needs to be addressed through the use of in-line blending or mechanical agitation prior to asphalt production.

Reacted polymers are those systems that chemically link or react the polymer with the polar (asphaltene) molecules in the asphalt binder. This is achieved through vulcanisation (with sulphur or sulphur-containing compounds) or the incorporation of reactive species with the polymer. Since the polymer is grafted or attached to the asphalt, better dispersion of the polymer in the asphalt results. Grafting also reduces the reactivity of the modified asphalt to oxidative degradation since much of the chemistry occurs at the reactive sites on the asphalt. This is the predominate method of polymer inclusion today.

Reactive polymers are those systems that undergo polymerisation reactions. Epoxy-asphalt is one example. (Synthetic binders are examples for non-asphaltic systems.) Most of the reactive sites in the asphalt are chemically bound/cross-linked to the polymer. Consequently these materials exhibit excellent resistance to chemical and environmental attack. These are extensively cross-linked systems and require a cure time.

Testing and performance are more akin to those for a rigid pavement, and specialised equipment and operations are required.

High polymer loadings using blended or reactive polymers can adequately address rheological and strength problems (*e.g.* permanent deformation and cracking), but may not address the chemistry problems associated with ageing, stripping and moisture damage. New, more expensive polymers such as SEBS (styrene-ethylene-butylene-styrene) that are more resistant to oxidative attack are available but remain relatively untested in the paving market. Furthermore, the viscosities of these modified asphalts would require precise control of the temperature, timing, mixing and compaction, which current paving equipment cannot provide. High polymer loadings may result in increased viscosities and cause significant handling and lay-down problems especially with hand work. For these reasons, the asphalt emphasis will be placed on reactive polymer modification.

Epoxy asphalt

The epoxy asphalt binder is a two-phase, thermoset chemical system in which a slow curing acid epoxy (continuous phase) is blended with conventional asphalt (discontinuous phase). The components of this binder are premixed in a pug mill prior to combining with heated aggregates in a conventional asphalt batch plant. Placement and compaction of the mat are conducted with conventional asphalt paving equipment. A hot spray application of a more viscous epoxy asphalt tack coat precedes the laying of the epoxy asphalt concrete. While the pavement can be opened to traffic once the pavement has cooled to ambient temperatures, the epoxy asphalt takes two to six weeks to fully cure.

Chemical and physical properties for the binder and bond coat are listed in Tables 5.1 and 5.2 and for the epoxy asphalt cement in Table 5.3. Once cured, the epoxy asphalt binder behaves like a thermoset polymer. As it does not soften like conventional asphalts at elevated temperatures, bleeding and/or flushing of the binder is essentially eliminated. One consequence of this is to permit the use of mix designs with low void contents (target less than 3% air voids); this results in an impervious pavement.

Performance history for this material has been limited to bridge decks. Over 50 000 tons have been placed on steel and concrete bridge decks since 1967. The climate range in which this material has been placed varies from -10°C to 33°C. One of the first applications was the 1967 paving of the orthotropic steel deck span of the San Mateo-Hayward Bridge across San Francisco Bay. This is still in excellent condition and exhibits only minor distresses. Of note is that this climate is rather benign; there is little or no freezing and no utilisation of de-icer. The pavement is, however, exposed to a lot of ultraviolent radiation.

Table 5.1. Chemical properties of binder and epoxy tack coat

Property	Test value		Test method
	Binder	Tack coat	
Resin component			
Epoxide equivalent	185 to 192	185 to 192	ASTM D1652
Viscosity @ 23 ˚C, Pa.s	10 to 16	10 to 16	ASTM D445
Minimum flash point ˚C	204	204	ASTM D92
Specific gravity	1.16 to 1.17	1.16 to 1.17	ASTM D 1475
Curing agent/asphalt			
Acid value, mg KOH/g	44 to 55	44 to 55	ASTM D664
Viscosity, mPa.s@ 99˚C	.140 to .250	1.2 to 1.6	Brookfield HBT
Flash point, ˚C, minimum	204	271	ASTM D 92
Specific gravity	1.00 to 1.01	1.00 to 1.01	ASTM D 1475

Source: Gaul (1993).

Table 5.2. Physical properties of binder and epoxy tack coat

Property	Test value		Test method
	Binder	Tack coat	
Tensile strength, MPa @ 23˚C, minimum	1.4 – 2.1	4.8-9.0	ASTM D 412
Tensile elongation, % @ 23˚C, minimum	175-300	175-225	ASTM D 412
Water absorption, % @ 25˚C, maximum	0.3	0.3	ASTM D 570
Heat deflection temperature, ˚C,	-25 to 0	-18 to -15	ASTM D 648

Source: Gaul (1993).

Successful installations require attention to proper design and the use of appropriate aggregates. Batch plants have been used for mixing to ensure that tight compliance with component ratio and mixing requirements are maintained. Aggregate temperature control (between 143° and 154°C) and early compaction (breakdown before the temperature falls below 82°C and finish rolling before matt temperature drops below 66°C) are critical as is the use of a tack coat with good adhesive properties.

Table 5.3. Physical properties of epoxy asphalt concrete Gaul 1993)

Property	Test value			Test method
	Epoxy asphalt after initial cure	Epoxy asphalt after final cure	Asphalt	
Marshall stability	540 to 630	3 600 to 6 300	1 125	ASTM D 1559
@60˚C kg flow value @ 60˚C, mm	2.0	2.0	2.8	
Recovery %, minimum	0	60	0	
Marshall stability				ASTM D 1559
@204 ˚C, kg		1 800	Flows	
Compressive properties @25˚C				ASTM D 695
Strength, MPa	n.a.	23.4	n.a.	
Modulus of elasticity, MPa	n.a.	1 150	n.a.	
Flexural properties @25˚C				ASTM C 293
Modulus of rupture, MPa	n.a.	4.4	56	
Modulus of elasticity, MPa	n.a.	2 618	n.a.	
Max. deflection, mm	n.a.	3.8	3.0	
Air voids, %	1 to 2	1 to 2	3 to 5	ASTM D 2041

Note: n.a. = not available.

Source: Gaul (1993).

A number of paving issues contribute to the high cost or slow placement of this material. Current production is in the order of 60 tons/hr (1 lane mile/8 hr shift). The slow element in this is the metering, mixing and dispensing of the binder and bond coat, particularly as this is labour-intensive. The process uses batch plant techniques (limited quantities of 2 to 4 tons made at one time), whereas most hot-mix plants are moving towards continuous output drum plants. Timing is tight between allowing the material to cure and being unable to adequately compact the mix. The haul time available is dependent on the average batch temperature of the truckload. At a temperature of 116°C, the minimum haul time is 42 minutes and the maximum 62 minutes. At 127°C this window drops to between 35 and 43 minutes. Finally, during the two- to six-week cure time, the epoxy asphalt may be susceptible to flushing.

In comparison with conventional asphalt mixes, epoxy asphalt is capable of withstanding much higher strains and consequently offers much better fatigue resistance. Its high shear strength approaches that of concrete, giving it superior rut resistance. The elastic modulus is roughly one-tenth that of Portland cement concrete (PCC); this helps it resist shear failures.

When constructed properly, there is good adhesion to the underlying structure, and the modes of distress are akin to those of PCC. The distress modes include: mechanical gouging, fire pitting (associated with vehicle fires), pot holing, joint crumbling and loss of skid resistance. In addition, since the thermal expansion is not the same as for concrete, debonding between the epoxy and the underlying surface can occur.

Health and safety considerations during the manufacture of the hot mix are slightly greater than for conventional asphalt at the mixing plant. The resins prior to blending require some care in their handling. Personnel preparing the epoxy should utilise personal breathing apparatus (masks). Once blended, handling requirements for the mix are essentially the same. Owing to slow placement of the tack coat, workers are subjected to longer exposure to fumes. Paving aspects are the same as for conventional asphalt.

In order to advance the use of this or similar products, better skid tests are needed, as well as models to predict loss of friction with time or level of loading. In addition, models for evaluating splash and noise characteristics need to be advanced.

Currently, the material costs for epoxy asphalt are in the order of USD 22/m^2; batch plant expenses are close to USD 11/m^2, and installation will run about USD 11/m^2. Total cost will be close to USD 44/m^2.

Rigid pavements

Materials used in the construction of rigid pavements can be grouped into two categories: Portland cement concrete and high-performance cementitious materials (HPCM).

Portland cement concrete

Among the conventional paving materials, PCC pavements offer strength and durability. Presently, new solutions such as whitetopping and unbonded overlays are being evaluated and could compete with conventional asphalt solutions. The use of more recycled and less new cement per unit surface area could lower the initial cost. Also, the use of pre-cast concrete panels may lead both to faster construction and to reduced user delays.

However, societal issues rather than engineering issues often restrict the use of PCC. The rigidity of the pavement structure and the surface texture give rise to more significant noise. The joints often contribute to a loss in smoothness of the pavement. Improvements in the quality control of the grade profile are being reflected in the production of smoother PCC, thereby reducing joint-induced noise. Tined and textured surfaces have been used to reduce splash and noise, respectively. A second approach has been to alter the PCC through construction of porous pavements. This provides some initial absorbing or dissipating attributes. Once these pores are filled or clogged with debris there may in time be a reduction in noise abatement. France has experimented with the installation of thick porous PCC pavements to reduce noise.

The porosity of PCC can be enhanced by a number of approaches. The hydrated cement paste can be altered through the use of air-entraining/entrapping agents. Gap-graded aggregates can be used. A third alternative for enhancing porosity is the use of mixtures with low sand content. Other approaches include the use of porous aggregate and the inclusion of rubber particles. The inclusion of low stiffness fibres or polymer inclusions reduces the stiffness of the pavement and increases the viscous-dampening capacity of the concrete. These inclusions (air and or rubber particles) absorb sound but also lower the elastic modulus of the PCC. Care must be used in the construction of such concretes to minimise segregation and reduction of strength.

Premature failures of PCC have been attributed to a number of factors. Several of these are:

- Freeze-thaw cycling of pavement.
- Sulphate attack (internal and external).
- Alkali-aggregate reaction.
- Corrosion of reinforcing steel.

It has been shown that by adjusting paving techniques or by using aggregates with different hardness, it is possible to produce a pavement with improved skid resistance.

High-performance cementitious materials

A number of products are represented in this class of materials. Reactive powder mortars and reactive powder concretes are two types of products that are currently undergoing extensive testing. Commercial names are MSCC and Cemtec®. These are exceptionally high-strength, fibre-reinforced super-plasticised silica-fume systems characterised by very low ratios of water to cementitious materials. Most of these are highly homogeneous owing to the replacement of traditional aggregate with very fine sand with particle sizes in the range of 150-400 µm. Though the market focus for such materials has not been pavements, their high tensile and compressive strengths and extremely low porosity indicate that this will be a very durable material. The low porosity will significantly reduce many of the sources of premature failure in PCC noted above.

High cost is the biggest obstacle to using this material. Most of these products use steel fibres, super-plasticisers, and other admixtures such as accelerators in concentrations four to six times higher than those used for usual concrete mixtures. Controlled curing can significantly improve the performance of these materials but will further increase the cost. Consequently, this will be a very expensive product in the short term. The low ratios of water to cementitious materials make some of these materials very sticky; this will make handling and placement somewhat more difficult. Table 5.4 provides a comparison between the composition and properties for HPCM and PCC.

One of the characteristics of HPCM composites is their low permeability. This attribute will reduce or eliminate factors that often lead to premature failures in PCC. Unfortunately, this material introduces its own set of problems. Chief among these are frictional and sound characteristics. The homogeneity of the cement composites eliminates not only segregation problems but also the pavement texture. The non-porous nature of these composites should enhance the physical properties and reduce premature failures but at the same time will have adverse effect on noise and splash abatement. Consequently, the immediate surface will need to be modified such that sound, friction and splash requirements are met.

HPCMs are relatively new. While they exhibit exceptional properties and hold great promise for long-term use in pavements, much research is still needed. Determining proper curing conditions and rates may be key to advancing with this class of materials. Once a market is established, the cost of this material would be expected to drop. Current material costs are in the order of USD 200/ton, or approximately USD 5 per square metre for a 10 mm depth pavement layer.

Table 5.4. Range of compositions and mechanical properties for typical high-performance cementitious materials and Portland cement concretes

Cement type	High-performance cementitious materials	Portland cement concrete
Water/cement ratio	<.2	<.5
Number of different fibres	1-3	0
% fibres	11	0
Super-plasticisers (% of cement dosage)	1-2	0-1
Silica fume (% of cement dosage)	20-25	0-10
Permeability (m^2)	10^{-18}-10^{-17}	10^{-17}-10^{-16}
Tensile strength	8-20 MPa	
Compressive strength	200-230 MPa	80-100 MPa
Flexural strength	40 MPa	7 MPa
Fracture toughness	30 x10^3 J/m^2	<1 x 10^3 J/m
Abrasion	1.2 x 10-12 m^2/s	275 x 10-12 m^2/s

Source: Kosmatka *et al.* (2002).

Composite pavements

Composite mixtures have been improved to take advantage of the best of asphalt and concrete. The resulting composite combines the flexibility and jointlessness of bituminous mixture with the stiffness and wear resistance of a cementitious material (Anderton, 2000).

These are typically open-graded asphalt mixes that have been grouted with a modified cement. A number of products are commercially available. These include: resin modified pavement, Densiphalt, and Duraphalt.

The open graded mix used in Densiphalt is typical of an open-graded friction course (OGFC) and has a high asphalt content. Cellulose fibres are often used to prevent draindown (the process where the binder runs out of the mix during preparation of mix specimen in the laboratory and presumably during field placement). Densiphalt uses a lower asphalt cement content. All of these products use an open void structure of 25-30%. The mortar used is much finer than that used in PCC; this leads to higher density packing and overall reduction in the permeability of the pavement. This gives it excellent freeze-thaw resistance, improves its resistance to de-icers (road salt), oil and chemicals.

Physical properties for resin modified pavement are shown in Table 5.5. Relative to asphalt pavements, the composite has a higher stiffness modulus, lower temperature sensitivity, higher resistance to permanent deformation and improved fatigue performance at lower strain levels. The asphalt is placed with conventional equipment, and rolling is done with non-vibrating rollers. The mortar is pumped onto the asphalt and manually spread. The mortar surface can be treated to improve the surface texture (skid resistance, ride quality or aesthetics).

This product has a ten-year history of use on runways, roads and ports in Australia, Europe and the United States. Current costs are estimated at USD 12-14.50/m^2 for a 35 mm wearing course. Regarding performance, the newly constructed pavements tend to have less than desirable friction numbers. These values do improve as the surface wears and develops a macrotexture. With regard to long-term pavement performance, there are little data, as these composite materials have not been placed on heavily trafficked roads.

These products are relatively impervious; this should mitigate oxidative and moisture-related damage. However, the asphalt and the resin additive in resin-modified pavement contain styrene butadene rubber. Both are susceptible to oxidative reactions. Long-term environmental effects need to be researched, particularly surface-initiated distress such as embrittlement and ravelling. In addition, the long-term application of the composite in cold (Nordic) and high freeze-thaw environments needs to be validated.

Table 5.5. Physical properties of Densiphalt

Technical properties	Physical properties	Test procedure
Compressive strength	50 MN/m^3 870 psi (5 days) 1500 (28 days) 5-7 MPa (1 day) 8-12 MPa (28 days)	BS 1881
Setting time (mortar)	8-12 hrs	EN 196-3
Flexural/tensile strength	3.5 MN/m^3/507 psi	EN 196
E-modulus	8 MN/m^3 1160-1740 psi 10-14 MPa	DWW 94530
Frost/thaw resistance	0.01 kg/m^3/very good	SS 137244 method IIA
Impermeability	Non-permeable	DIN 18130
Coefficient of expansion	12.5 x 10^{-6}/°C	EN 1770
Wear resistance	6-8 cm^3/50 cm^2	DIN 52 108
Friction	Up to 0.75	Stradographe

Source: Duvall (2003).

Synthetic binders

A number of synthetic binders have been used in paving bridge decks around the world. These binders can be categorised as epoxy, urethane epoxy or acrylic binders. These are typically sprayed on the deck, and the aggregate is broadcast and rolled onto the thin film. In general, these wearing courses are quite thin and very impermeable. The paving issues and material characteristics are similar to those for the epoxy asphalt.

Attainment of good performance is contingent on the following:

- Primer needs to have good adhesion to the base.
- Viscosity of the binder needs to be low in order to flow into air voids.
- Chippings must be durable and have good friction characteristics.

Accelerants are typically used to reduce the cure time. These times are comparable to that of epoxy asphalt. Namely, heavy traffic can be tolerated within two hours, and the material is fully cured within 24 hours. One big difference is that the synthetic binders can be blended on site and the “ticking clock” is not as critical.

The thin wearing courses, such as those using aggregates smaller than 5 mm are quite impervious to water and provide excellent resistance to chemical attack by de-icers, ageing, and chemical spills. The life expectancy of these systems is from ten to 20 years. Some of these very thin wearing courses are susceptible to blading during snow removal.

It has been able to formulate or modify existing synthetic materials to accommodate any given pavement temperature range. Italgrip is an epoxy-based product that has been marketed in a number of diverse environments for its friction properties. A thin film of the binder is spread over the existing surface and steel slag chips (1 to 4 mm) are broadcast onto this film. This product provides a macrotexture to the surface and has the added benefit of reducing splash and noise. The product is easy to place and sets in 4-6 hours. The cost of this material is on the order of USD 20/m^2. The Netherlands has experimented with porous synthetic wearing courses. Researchers there have looked at the loss of skid resistance and noise reduction. They made no mention regarding the rate of clogging of the porous matrix.

Limitations of synthetic binders are generally associated with its laydown. Current formulations are susceptible to moisture before they are fully cured. Thus paving must be curtailed under adverse or even inclement weather. Placement of primer is labour-intensive and slow.

Aggregates

The longevity of the wearing course will ultimately be dictated by the weakest link. In effect, the aggregate quality is as critical as the binder. A hard durable, polish-resistant aggregate is needed for the given environmental and load conditions. The aggregate gradation and properties should be consistent and meet design parameters. Information on aggregate morphology and its impact on strength, mix stiffness, reactivity and reactivity with binder is needed. Standard aggregate testing addresses physical attributes such as strength (*e.g.* using the Los Angeles abrasion test, EN 1097-2), size, coefficient of thermal expansion, as well as performance characteristics such as adhesive and friction properties (Saarela, 1993).

The importance of aggregate is evident in the performance data presented in Chapter 2. The Swedish roads reportedly use a more durable aggregate than Norway or Finland (Jacobson, 1997; Gustafsson, 1997). The durability of the aggregate becomes particularly important when studded tyres are used. Wear rutting by studded tyres on heavily trafficked roads is one of the major sources of pavement deteriorations in cold climates, especially in Norway where studded tyres are used even on trucks. During the mid-1990s in Sweden, for roads with annual average daily traffic (AADT) greater than 4 000, wear from studded tyres (estimated to be 300 000 tons) caused the main share of total rutting (50-70%) (Gustafson, 1997). Since then, wear caused by studded tyres has significantly decreased owing to the increasing use of high-performance surfacing (*e.g.* SMA mix with high wear resistance aggregate) and use of lightweight studs. The total wear on Swedish roads by the late 1990s has been calculated to be 130 000 tons during winter (Jacobson, 1997, 1999; Gustafson, 1997). However, the effect of an abraded quantity of asphalt material on environment is still questionable. In Sweden, a model has been developed and validated for the prediction of wear rutting (Jacobson and Wågberg, 1998). Input parameters are mixture characteristics, traffic volume with studded tyres, road geometry and climatic conditions.

Thus, resistance of surfacing to the effects of studded tyres is one of the most important parameters in the mix design procedures in all Scandinavian countries except Denmark. The following parameters have shown considerable influence on the wear resistance of wearing course:

- The quality of the coarse aggregate.
- The content of the coarse aggregate.
- The maximum aggregate size.
- Impact of stud which is related to the speed of the vehicle and mass of the stud.
- Abrasion and scratches of the stud.
- Moisture and traffic volume.

There is also a hypothesis that the wear increases with a decrease in the adhesion between aggregate and bitumen. Therefore, the binder could have an important effect on the wearing resistance of surfacing layers. It has been reported (Saarela, 1993) that bitumen type may improve the wearing resistance of dense asphalt surfacing if a soft rather than a hard bitumen is selected or a modified binder is used when testing at moderate temperature. This effect has not been significant when testing an SMA mix, but in cold conditions (around -15°C) using modified binder when the conventional binder is becoming brittle gives a significant improvement. Another important factor from the standpoint of wear resistance is the effect of moisture which is almost constant during the winter period. The wear resistance of asphalt concrete decreases significantly under wet conditions. Using high-performance surfacing with a synthetic binder that is not susceptible to brittleness at low temperatures and has good adhesion characteristics under wet conditions may significantly improve the wear properties of surfacing.

Denmark has evaluated the use of fine chips (1-3 or 3-5 mm) from natural and manufactured aggregates. In a study of the performance of synthetic binders with three aggregates, calcined bauxite, quartz and electric arc steel slags were used. Of these, the calcined bauxite gave the best long-term skid performance.

The importance of the microtexture is routinely demonstrated in PCC. Aggregates of differing durability are employed to create a microtexture. The resulting differential wear of such aggregate mixes maintains a microtexture which provides for better friction characteristics of the surface layer.

Construction

Paving practices and options

On-site, continuous production is by far the dominant paving practice. Materials are processed at the construction site. For asphalt pavements, once they are cooled, the traffic is allowed on the mat.

However, for materials requiring long cure times, off-site production offers a number of benefits. These include:

- Reduction in the length of paving trains.
- Pavements are constructed outside the work zone in a safer and controlled environment.

- Faster construction. Curing can take place over a long time and under optimum conditions.
- Better quality assurance and control of the paving materials. Curing of materials can be conducted under optimal conditions (for example, rates, temperatures, etc., can be controlled). Placement involves fully cured material thereby lessening the risk of potentially damaging stress cracks.
- Prefabrication reduces many of the worker hazards that can occur on site. Because of the faster installation, there will be less exposure to traffic. Any fume hazards can be efficiently controlled in the fabrication plant and will be minimised on site.

There are some disadvantages to prefabrication. It may be more costly, prefabricated sections may need to be successfully bonded to the pavement layer, or jointing may involve difficulties.

Different modes of placement are being tested in the Netherlands. Rigid systems are placed as slabs and flexible pavements are laid in a continuous manner.

Evaluation

Prior to selecting a material for use in a long-life wearing course, a number of factors need to be taken into consideration. These include design, construction and maintenance issues as well as end-user and other societal issues. Table 5.6 contains a subjective ranking of various materials with regard to a number of these criteria. The materials included in this comparison are highly modified reacted asphalt, reactive modified asphalt, synthetic binder, asphalt-cement composite, and HPCM. A lower number reflects beneficial qualities for the particular criterion.

The ease of design and testing of the reacted modified asphalt and HPCM are considered comparable to current asphalt mixes and PCC, respectively. The other materials are viewed as being somewhat more difficult to design and test. The composite requires the design of the open-graded asphalt mix and optimisation of grout properties, and the reactive modified asphalts and synthetic binders have complex relationships in terms of chemical and physical properties.

Production for flexible materials is likely to be on site. Flexible materials with extensive cross-linking, such as the reactive modified asphalts and synthetic binders, would be amenable to both on-site and off-site production. The complex curing conditions required by the HPCM would limit production to off-site slab production.

Three construction issues are considered: the complexity of the construction (weather, transport logistics, etc.), speed and ease of paving. The reacted modified asphalt is expected to be comparable in complexity and speed to conventional hot mix asphalt. The reactive modified and synthetic binders require placement of a critical tack coat and careful monitoring of weather and cure time. Off-site construction of pavement slabs or rolls should reduce the complexity and enhance the speed of construction. The composite requires two steps: construction of open-graded mix followed by filling voids with grout. Curing conditions for the HPCM are more critical than those for PCC. The speed of paving materials requiring long cure times would be enhanced by production off-site. All of the materials will be somewhat more difficult to pave than their existing counterparts.

Table 5.6. Comparison of various materials

	Flexible systems	< -- >	Rigid systems		
	Reacted modified asphalts	Reactive modified asphalts	Synthetic binders	Composites	Reactive powder concrete
Design	1	2	2	2	1
Testing	1	2	2	2	1
Production	On site	On/off site	On/off site	On site	Off site
Construction	112	21-32	21-32	22-32	22-32
Complexity	1	2	2	2	2
Speed	1		1-3		2-3
Ease of paving	2	2	2	2	2
Health and safety	122	211	211	111	1-211
Worker health	1	2	2	1	1-2
Fire hazard	2	1	1	1	1
Spill damage	2	1	1	1	1
Maintenance					
Ease	1	2	2	2	2
Anticipated cost	3	2	2	3	1
User criteria					
Smoothness	1	1-3	1-3	1	1-3
Noise	1	1-2	1-2	2	3
Skid resistance	2	1	1	2	3
Splash	1	1	1	2	3
Ability to recycle	Completely	Yes	Yes	Yes	Yes
Anticipated lifetime					
Years	15-25	20-30+	20-30+	15-25	40+
Cost	2	2-3	3	2	4

Note: Lower number indicates beneficial qualities.

Source: Author.

Health and safety issues do not appear to be significantly different from those encountered with current practice. Workers blending epoxy or synthetic binders should utilise personal breathing apparatuses while blending components. Once blended, fume risks are minimal. As little is reported regarding health issues (if any) for the super-plasticisers, similar precautions should apply to the HPCM. Aside from the reacted modified asphalt, these materials will not sustain combustion and for the most part are resistant to acid and base spills.

Maintenance is perceived to be easier for the reacted modified asphalt but at a higher cost. This material is not expected to be as durable as the others and may require additional or more frequent maintenance. Durability of the composite is also unknown and may require additional maintenance. The other systems require a cure time that slightly complicates their usage in maintenance.

All of the materials should yield smooth roads and satisfy user criteria. The materials made off site into slabs will have joints. Slabs that are improperly placed or shift post-construction will reduce pavement smoothness. Noise will be more of a factor for the non-porous, rigid materials, in particular the HPCM. Skid resistance will initially be slightly worse for the reacted modified and composite systems until the respective binder and mortar wear off. The HPCM, owing to its homogeneity, will require some sort of surface texturing. Splash characteristics will follow the same trend. Water spray and splash is more likely to be a problem for the less porous and more homogeneous materials.

All of these materials would be amenable to some level of recycling. The reacted modified asphalt can be recycled and used throughout the pavement and has a salvage value. The other materials are likely to be recycled like PCC or as a black rock. Their end use could be in the lower lifts, in the base course or as fill; any generated fines may end up in a land fill.

Recommendation

One material meriting consideration as a candidate for additional research on long-life wearing courses is epoxy asphalt. Considerable field data and performance histories on various bridge decks are available. Of particular note is the fact that the epoxy asphalt placed on the San Mateo bridge deck back in 1967 is still performing well. This material would serve as a low-risk candidate and essentially uses established paving practices.

A second group of materials worth consideration are high-performance cementitious materials. While all of the data stem from laboratory work, the properties are quite remarkable, particularly their strength and flexure properties. The shortcomings of this product, namely, poor noise and splash reduction and friction properties, can be overcome with improvement of its macrotexture. One approach to this is a product such as Italgrip, whereby a fine coating of epoxy has a durable manufactured aggregate broadcast into it. The costs are anticipated to be considerably higher than for the other materials discussed, although costs would be expected to drop once production becomes routine. Development of less expensive plasticisers for HPCM would also help lower its cost. This material is offered as a high-risk, but potentially highly durable, option that would utilise off-site manufacturing and slab construction. Other possible candidates may be less attractive owing to a combination of anticipated life, whole life costs or short performance history.

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Chapter 6

Concept Development: Technical Requirements for Long-life Pavement Surface Layer and Guidelines for the Assessment of Candidate Solutions

This chapter defines the guidelines for a research programme that would fully assess candidate materials for use in long-life wearing courses.

This chapter is divided into four parts. Because a long-life surfacing will need to be laid on a long-life structure, a first section details the assumptions about the behaviour of the underlying layers. Next, the performance requirements for long-life surface layers are described and the failure modes of surfacing and their causes are detailed. From this information, the tests that can assess the performance of candidate materials for long-life surfacing can be derived, and the following section provides a non-exhaustive set of available (or easily adapted) laboratory tests. The final section summarises and prioritises the main requirements for a research programme to assess wearing course behaviour.

Context of the study

The focus of this chapter is the wearing course layer of a pavement, recognising that all layers play an integral part in the behaviour of a pavement. For the purposes of this chapter, the underlying structural layers of the pavement are assumed to be long-life. This section discusses the assumptions about the behaviour of the structural course. This will be needed to define and design test methods to assess the performance of candidates for long-life wearing courses.

Definition of structural and surface layers

The structural (or support) part of the pavement comprises the layers that participate in the flexural resistance of pavements (a maximum of 50 cm). They include the natural soil, the subgrade, subbase and base course (LCPC-SETRA-USIRF manual, 1997).

The surface course consists of the top layers. It can be a single layer (the wearing course) or, more generally, a composite system, including the wearing course, binder course and the tack coat between the binder course and the top of the structural part of the pavement. This chapter focuses primarily on the surface course of the structure.

Hypotheses for the behaviour of structural layers

One of the main assumptions of this project is that the structural layers behave as a long-life support, at least for the expected conditions of traffic. The support is assumed to have the following characteristics:

- Its deformation is entirely reversible under the traffic (permanent deformations would require resurfacing and would therefore not be long-life).

- This reversibility can be either of elastic or viscoelastic type and may depend on temperature and the velocity of the traffic. The relationship between deformation and load may or may not be linear.
- Its surface can be continuous or discontinuous.
- Assumptions must be made about the dilation coefficients.

For supports with a linear elastic behaviour, the behaviour under traffic can be characterised by one parameter: the maximum horizontal contraction (strain) at the surface of the support under the passing of a unit wheel load ($\varepsilon^{\circ}{}_{SC\max}$). Such data can be obtained by modelling the support, using a multilayer elastic model. This data cannot be directly derived from the deflection and the radius of curvature,[1] the typical measurements taken at the pavement surface.

Based on existing pavement techniques, three main groups need to be considered for the supporting layer: asphalt mix (*e.g.* flexible pavements), Portland cement concrete (long-life wearing course over a rigid pavement) and hydraulic bound mix. In the first case, the surface can be assumed continuous, with no cracks. In the last two cases the existence of transversal and possibly longitudinal joints or cracks will have to be considered. Bridges may also need to be considered as a fourth situation. Depending on their type, bridge pavements can involve specific mechanical behaviour, especially of the wearing course.

An important feature of the pavement layers (support and surface) is their thermal behaviour. This includes the diffusive properties (*e.g.* heat exchange surface coefficient) which play an important role in the vertical temperature profiles. The thermal dilation behaviour of the different layers may have a strong effect on the wearing course behaviour and its junction with the support. Studies have also shown that thermal stresses can be significantly diminished in the presence of viscoelastic materials. It is therefore important to know whether the support or wearing course have viscoelastic behaviour.

The research will therefore have to concentrate not only on the wearing course itself, but will also have to determine on which type of support it might be applied.

The following sections will propose tests at different scales to assess the properties of long-life wearing course. Some of these will need to simulate the expected behaviour of the support and the most appropriate type of support will have to be determined. While this can be achieved by constructing the real support structure for full-scale tests, representative substitutes will have to be found for laboratory and smaller-scale tests.

Technical and performance requirements for surface layers

This section reviews the overall "technological" requirements for the pavement surface layers and the need for enhanced performance for long-life pavement surface layers. The main causes of loss of performance over time are detailed. The main deterioration mechanisms, when they are known, are also discussed. This information is

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[1] The curvature radius R under unit load enables to calculate the strain gradient within the wearing course, if needed, for instance in the case of a thick composite surface course. Thus the maximum horizontal contraction in the wearing course under the load P and at height z above the support is given by:

$$\varepsilon_{SC\max}(z) = P(\varepsilon^{\circ}{}_{SC\max} + R\,z).$$

needed for the assessment of new long-life pavement surface layer solutions. Experimental tests must be related to identified needs and can aim to reproduce either the cause of deterioration or the nature of the disorder (and sometimes both).

The requirements for the wearing course and the structural course are very different. The structural course withstands the traffic load and transforms it into admissible vertical stress on the soil. The wearing course should ensure safe driving conditions for road users and protection of the underlying layers. To achieve this, the wearing course should meet a number of criteria which will be further discussed in this section:

- Construction feasibility and quality.
- Mechanical durability.
- Road user performance requirements such as skid resistance, drainability and acoustic performance.
- Reparability and recyclability, either for periodic repairs or at end of life (which cannot be excluded even in the case of long-life pavement surface layers).

Construction requirements (workability, maturing, health, environment)

Workability of pavement materials is essential for the construction of pavements. Homogeneous layers should be easily attained, with constant thickness and performance, over long distances. This condition is all the more important in the case of surface layers, for which thickness is generally relatively small and for which properties, especially user properties, have to be as constant as possible along the same road.

Compactability has to be balanced in the case of bituminous concrete: sufficient for the setting of the material, but not too high in order to avoid rutting later on. The homogeneity and stability of the mix are also important to prevent segregation between aggregates of different size.

Some materials (hydraulic concrete mix, cold asphalt mix, etc.) require curing or maturing times before the road can be opened to traffic, and this is another constraint which has to be taken into account. While not a disqualifying factor in itself, it may have an impact on the applicability of a pavement technique depending on the context.

A primary concern with any new pavement technique is that it is neither detrimental to the health of the construction workers nor to the environment. This objective is one of the main reasons for the development of cold asphalt mix techniques. Such criteria apply mainly in the case of on-site construction. The situation may be different in the case of prefabrication; dedicated industrial sites will solve many of the difficulties encountered on site and could offer the possibility for the introduction of many other materials. However, other challenges may arise, such as storing the prefabricated surface layer in good condition and its application on site.

These construction aspects will need to be addressed and fully developed during the later testing phases, including large-scale tests.

Mechanical performance and durability

Once constructed, surface layers must resist initial and long-term loading from traffic, climatic conditions and other sources. The surface layers also need to protect the pavement structure from damage (particularly from rainfall) to ensure the durability of the whole structure.

The following sections detail the main degradations and causes which long-life pavement surface layers will have to withstand. The assessment will also concern the bonds between the individual layers and the bond with the support.

Resistance to rutting

Thick asphalt surface layers are especially at risk of rutting owing to the direct impact of the tyre pressure of heavy vehicles (around 8 MPa). The phenomenon is linked to the viscoelastic rheology of bitumen binders (it does not exist for hydraulic binder mixes). Repeated loads induced by traffic increase the permanent deformation in asphalt mixes. The risk increases in hot weather (the viscosity of the binder is lowered), in areas of low speed (for example areas prone to congestion), in sharply curved sections or in braking areas (the presence of shear stresses is an unfavourable factor). The thickness of the layers is an important parameter: the thinner, the lesser risk of rutting.

Long-life pavement surface layers will have to be rut-proof, regardless of the climatic conditions. Most pavement laboratories have rut-testing apparatus and this test could be readily performed.

Another source of rutting may be due to wear of the pavement surface in the wheel path. This may be an important issue for long-life pavement surface layers, particularly where studded winter tyres are in use.

Resistance to cracking

Cracking in surface layers must be avoided not only because of deterioration of the surface, but also because it can be detrimental to the whole pavement structure, particularly because of water penetration into the underlying layers. This results in weathering, debonding between pavement layers (possibly enhanced by traffic loads and resulting hydraulic overpressure), loss of bearing capacity and the formation of ice lenses within the structure.

Fatigue cracking of the structural layers (from bottom to top) is due to the repetition of tensile stresses induced by the traffic. This is in theory not a problem for surface layers which are primarily subjected to compressive stresses under traffic loading. However, experience shows that wearing courses are not exempt from severe cracks, even when laid on sound structural layers in good condition. There are several causes which have not yet all been fully identified. The following are the most important causes and types of cracking.

Thermal cracking

Thermal cracking (generally transversal) is one of the primary risks of cracking in surface layers. Freezing temperatures induce negative horizontal displacements and/or tensile stresses, which are exacerbated by their cyclical nature. This phenomenon is complex and not yet fully understood. It depends on the:

- Temperature profile evolution within the whole pavement thickness.
- Different dilation coefficients of the different layers.

- Support structure, whether continuous or not (for example, transversal or longitudinal joints).
- Rheology of materials, especially if these are highly thermosensitive viscoelastic materials such as asphalt mix (Faure *et al.,* 1999).
- Tensile strength of materials, possibly thermosensitive as well and depending on the past thermal history of the materials (thermal fatigue under daily and yearly temperature cycles).

In general, the harder the material, the greater the risk of thermal cracking. Thermal cracking is a major issue in Portland cement concrete (PCC) pavements, and is mitigated through transverse joints or continuous steel reinforcement for example. The risk can be limited in asphalt pavements by an appropriate choice of the bitumen hardness based on the local climatic conditions. A compromise must be found between preventing thermal cracking at low temperatures and rutting under elevated temperatures. For asphalt materials, the wider the climatic temperature ranges they are subjected to, the more challenging their design.

Studying thermal cracking in laboratory conditions is a complex and lengthy task, particularly if the effects of thermal fatigue are included (this would require the simulation of numerous thermal cycles). The extrapolation of such results to on-site behaviour of pavement materials is risky, since it is a combination of the climatic conditions and traffic loading that causes the damage. An evaluation will need to be supported by a literature review of all available qualitative and quantitative information from past experience. Laboratory testing will primarily focus on the thermal behaviour of the materials: dilation coefficients (to be compared with that of the support), rheology (elastic or viscoelastic, thermo-susceptibility) and thermal conductivity.

Reflective cracking

Reflective cracking is another important source of distress in surface layers. It is characterised by an upwards cracking process of the surface layer, generally initiating from transversal discontinuities of the support. It typically happens in semi-rigid pavements, with a lean concrete base course. It is mainly due to the repetition of traffic loads, but, as mentioned above, low temperature conditions may also have a negative impact by further opening the support discontinuities, inducing tensile stress in the surface layers and decreasing load transfer.

An evaluation of surface layers cannot be entirely disconnected from the performance of the support and the bonding conditions. Discontinuous supports may *a priori* be discounted as a structure for long-life pavement surface layers solution as they are a severe case. However, the behaviour of long-life wearing course solutions in the case of cracks in the support needs to be studied since such conditions can never be totally discounted. A device developed to study the behaviour of semi-rigid pavements and more specifically reflective cracking prevention is described below.

Top-to-bottom cracking

Top-to-bottom cracking has been commonly observed, generally as longitudinal cracks initiating at the surface of pavements in the traffic wheel path. This is different from thermal or reflective cracking, and several explanations have been advanced for this phenomenon, which is not yet fully understood.

It may be caused by the heterogeneous pressure distribution exerted by tyres on pavements (De Beer *et al.,* 2002). This cannot in itself explain the propagation of cracks several centimetres below the pavement surface, however; thermal gradient in the surface layers may also have an effect. Another possible explanation is the significant horizontal tensile stresses that may arise at the surface of pavement following the passage of vehicles owing to the viscoelastic behaviour of bituminous mix (Tamagny *et al.*, 2004). Whatever the explanation, the risk of this distress mode will have to be addressed in the research of candidates for long-life pavement surface layers.

Debonding

Debonding between layers that are initially stuck together is an important potential distress mode in multilayered structures. The risk may be the bond between the support and the long-life pavement surface layers (assuming that the surface is stuck continuously on the underlying support) or between the binder course and the wearing course in the case of a two-layer composite surface course.

The main cause of debonding is traffic, which can induce debonding in modes I, II or III.[2] Variations of temperature with depth and time and intrusion of water (or water condensation) between layers can exacerbate the mechanism.

Ageing

A lot of materials are susceptible to ageing, with their chemical composition evolving over time mainly by oxidation. This leads to changes in their physical properties, which are generally not favourable for the durability of the structure.

This is typically the case for asphalt materials (both for pure bitumen and in particular for polymer modified bitumen). These materials become increasingly stiff with time and lose some of their positive properties such as stress relaxation or healing. As they become weaker, the risks of cracking (whatever the cause), debonding and ravelling increase (AIPCR-LCPC guide, 1999).

Hot summer conditions strongly accelerate oxidation.[3] It is also believed that ultraviolet radiation can play a role. The effect is therefore mainly a problem in the surface layers which are the most directly exposed to oxygen and ultraviolet radiation.

The rolling thin-film oven test (RTFOT) laboratory test has been developed to evaluate this effect in asphalt materials in a short time frame. Case studies of traditional materials have been used to develop relationships between the RTFOT ageing and the ageing that occurs on site.

Ageing will be an important issue for long-life pavement surface layers, which by definition have to be especially durable.

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[2] This is the classical terminology for the different modes of propagation of cracks.

[3] Many chemical reactions respond to kinetic laws of Arrhenius type, $\dot{\alpha} = Ae^{-k/RT}$, which are highly sensitive to the Kelvin temperature T.

Specific demand for the wearing course

The wearing course must fulfil a set of specific demands in relation to its functional use. This section briefly describes the set of performances required to carry traffic safely.

Need for a durable and high-performance texture

Skid resistance is the most important requirement for road users, especially under wet conditions. For the classical bitumen or cement wearing course, skid resistance is mainly due to the granular composition (grading curve) of the materials and also to the properties of the particles themselves. Together, these create geometrical irregularities at the road surface at different scales (from micrometre to centimetre or decimetre), providing skid resistance and drainage at the tyre/pavement contact area. For Portland cement concrete slabs, grooves are added during construction to provide additional "irregularities", thereby improving both drainage and skid resistance (Martinez, 1977).

The complex geometry of the wearing course defines its texture: the micro-texture is at the scale of surface irregularities of the aggregate and the macrostructure at the scale of the mix. High macro-texture is necessary to provide drainage channels to remove the bulk of the water between the vehicle tyre and the road surface. High micro-texture is needed for the tyre to penetrate the thin layer of film water and achieve dry contact with the road. Skid resistance must be maintained throughout the life of a wearing course, regardless of the loading (traffic, climate) that it experiences.

The requirements for adequate initial-use properties are well known for classical wearing course materials. The evolution and durability of these properties as a function of the road environment (traffic and climate) are also fairly well known for these materials.

Finding materials with long-life user properties will be one of the key tasks in developing long-life wearing courses. Finding the right tests and protocols to establish the durability of such materials will be a challenging task, not only because the tests will have to be accelerated, but also because the sources of deterioration and distress mechanisms are numerous and complex. The main forms of deterioration observed on site are ravelling, stripping, weathering, polishing and loss of skid resistance.

Ravelling and weathering are the progressive deterioration of an asphalt concrete macro-texture with a loss of bond between aggregates and the asphalt binder. As a result, the wearing course surface loses aggregate particles (ravelling) and asphalt binder (weathering). There is a combination of several causes:

- Traffic load, especially in the presence of tangential forces (decelerating areas, roundabouts).
- Rainfall.
- Ageing and hardening of asphalt binder.
- The use of studded tyres (Torbjörn, 1993).
- Spill of chemical agents.

Wearing courses with high air void content (*e.g.* porous asphalts) are more sensitive to ravelling, owing to a lower cohesion between aggregates, increased exposure to rainfall and acceleration of the ageing process.

Polishing is the wear and loss of granulate microtexture (angularity, surface irregularities) in the wheel path due to the abrasion by tyres over the long term. Polished wheel paths look very smooth, even shiny. In extreme cases such abrasion can give rise to ruts in the wheel path. Surface friction is considerably reduced and the risk of accidents increases due to loss of skid resistance. The selection of appropriate aggregates with especially high resistance to polishing is of primary importance in the design of wearing course materials. Specific tests have been developed to assess such performance (Delalande, 1992).

Natural rock aggregates currently used in wearing courses are generally not sufficiently resistant to polishing for long-life pavement surface layers (at least for high-traffic roads). Aggregates for long-life surfaces would need to have very high performance over the long term and would probably come from "artificial" sources. Alternatively, the surface texture (micro and macro) may have to be produced by other means.

Enhanced drainability

Surface drainage is essential to preserve skid resistance in wet conditions and to protect the underlying pavement structure. The pavement transverse surface should be designed to provide for rapid runoff of water during rainstorms. It is also important to reduce spray in wet conditions, particularly on heavily trafficked roads with a lot of trucks. Long-life pavement design will have to meet these performance requirements and maintain them over the lifetime of the pavement.

Acoustic properties

Reduction of traffic noise is one of the most important objectives for road agencies in developed countries, particularly on highly trafficked roads in built-up areas. As these roads are among the most likely candidates for long-life pavements, they will have to meet high standards in terms of reduced noise. The noise performance of long-life wearing courses will therefore have to be established. Other methods of reducing road noise are possible (noise barriers, Helmoltz resonators); however, many road agencies have a distinct preference for low noise road surfaces (as evidenced by the decline in PCC wearing courses for this reason).

Others properties for long-life pavements

A number of other features will have to be developed to minimise periodic maintenance. For example, road markings will have to be as durable as the surface layers. Other road signs, features and green verges will have to be designed so that routine maintenance and cleaning can be carried out without disrupting traffic.

Reparation, maintenance, recycling

Finally, although the long-life pavement solutions should not theoretically need any maintenance for very long periods, repair and replacement of long-life pavement surface layers should be easily achieved. Unforeseen events (earthquakes, fires) could require rapid and efficient repair, preferably to a long-life standard. As an example, it is well known that the lack of easy and rapid repair techniques for rigid pavements is an important drawback to an increase in their use in some countries.

Finally, the long-life pavements should not cause problems for future generations. End-of-life recycling or disposal must also be considered as well as any problems arising in the research.

Experimental assessment of candidates for long-life pavement surface layers

There is currently no general validated methodology to assess the properties of surface layers. This section will examine the tests that can best assess the performance of candidate solutions and give some guidelines for developing a full experimental programme in Phase II of this study.

General considerations to help define the experimental campaign

Context of use

This report has defined the general conditions in which long-life pavements will likely be viable, that is, high traffic roads in urban or interurban areas. The first task of Phase II will be to define the numerical parameters to be investigated, such as the intensity of loads (vertical but also transversal, in the case of turns or slopes), the type of support, the temperatures, including frost or surface moisture conditions. These parameters will have to take into account the different permitted axle loads in participating countries, the type of pavement structures in use and typical designs including slopes and turns.

Available knowledge and gaps

Another key task is to gather all the information already available about the candidate long-life pavement surface layers. This task has been started in Chapter 5; however, collaboration with the road owners may be required to fully identify the use conditions and behaviour of the materials, where difficulties have been encountered, and what gaps there are in knowledge.

Assessment or development

The testing will depend on the extent of the knowledge about the performance of the new material. Many of the tests described in this chapter focus on assessing the performance of candidate materials and whether they are suitable for long-life pavement surfaces. Research may also be carried out to optimise materials that have demonstrated properties with proven durability. Such studies will have to focus more on development work, for example to reduce noise and splash, or to ensure that they are feasible on different support layers.

Defining the required level of performance

Most tests discussed here are only indirectly related to the real performance of the structure. Performance criteria will therefore have to be established using comparisons with current pavement surface materials. Long-life materials will have to behave better than traditional solutions. It should be possible in most cases to extend experimental correlation between the test responses and life duration.

Note that for repeated tests, criteria could be established either in terms of a higher performance level for the usual number of load repetitions or for the same level of performance but for a higher number of repetitions.

The different means of testing used in the pavement domain

Many tests have been developed in the pavement domain to assess the quality of "materials". These range from small-scale (cheaper) tests that can be carried out in laboratories to full-scale simulations, which are expensive and time-consuming. The following sections will describe the following groups of tests:

- Tests on the material itself (laboratory scale).
- Tests on the components entering into the composition of the materials (laboratory scale).
- Small-scale simulation tests of traffic using mini accelerated loading facility (ALF) tests.
- Full-scale tests performed on real pavements and on real sites or ALF sites.

Phase II of the project will focus on laboratory testing and development, and if successful techniques are established, full scale tests could be carried out in Phase III.

Test of the long-life pavement surface layers material at laboratory scale

Assessment of volumetric properties

Table 6.1 lists the main characteristics that need to be measured and classical tests used to measure these properties. In pavement mechanics the response of materials to small strains is quite important. The elastic, viscoelastic and thermo-viscoelastic properties give useful information about the risk of deterioration. In particular, this information can be used to assess the risk of thermal cracking at low temperatures and the risk of permanent deformation at high temperatures, since viscoelasticity helps to relax thermal stresses on the one hand, but increases the risk of rutting on the other.

Table 6.1. Pavement characteristics and tests

Characteristics to be measured	Testing means
Mechanical resilient response of the materials, within the range of strains induced by the traffic (at different temperatures) or by thermal variation: priority n° 1, in the absence of available knowledge	Loading/unloading cycles: Possible device: press, complex modulus apparatus (for viscoelastic rheology diametral compression – Nottingham Asphalt Tester), triaxial testing, temperature control
Risk of permanent strains (at high temperature)	Rutting testers, triaxial testing with repeated loading with temperature control cell; vacuum repeated load axial test, wheel track rutting tests
Risk of fatigue	Repeated tensile and/or compressive loading with a press and under uniaxial or flexural modes, indirect tensile repeated loading
Resistance to tensile strength (at different temperatures)	Uniaxial tensile test, indirect tensile test (Brazilian test or indirect tensile stiffness modulus)
Resistance to tensile thermal strains	Thermal restrained strain tests, buckling and delamination test
Change of strain with temperature	Measurement of thermal coefficients of expansion
Ageing and sensitivity to water	Use of thermodynamic vessels at different temperatures and pressures, with oxygen gas, high moisture or other, submission to ultra-violet rays (UK saturated asphalt tensile stiffness test)

Rutting testers are typically used to assess the resistance of bituminous mixes to permanent deformation (Figure 6.1).

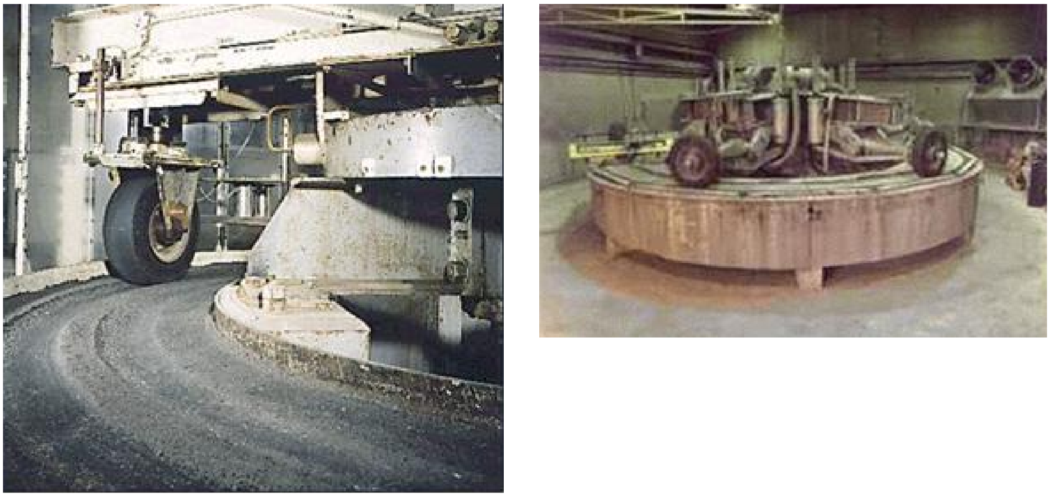
These should be used to test candidate long-life surface layers that may be sensitive to permanent deformation. This may be the case if the material includes a viscoelastic binder (at temperature of use) and if it is supposed to have a significant stiffness in the pavement (say > 4 cm). This test would not be relevant for mixes with epoxy resin binder in a thin layer or for mixes based on Portland cement binders.

Although in theory pavement surfaces are not susceptible to fatigue cracking, as they are mainly subjected to compressive loads, top-to-bottom cracking is well documented although the reasons are not yet fully understood. For this reason, fatigue testing of long-life pavement surface layers should be carried out and the results compared to the performance of materials currently in use.

The dilation coefficients of the materials are very valuable information and should be compared to that of adjacent materials. If there is a large difference and the surface material is elastic, then there is a risk of cracks, delamination, curling or warping of parts of the pavement surface. This will be particularly acute for low or high temperatures. Such tests are therefore strongly recommended, particularly for elastic materials and where no information is already available.

The previous test can be extended to measure the maximum tensile stress at rupture. This can be done through direct tensile stress test or indirect tensile stress, like the Brazilian test. The maximum tensile stress due to thermal shrinkage can then be compared with the resistance of the material. This will allow the range of temperatures to be established under which the surface can operate without failing.

Figure 6.1. Circular rutting testers



A: Diameter 4 m

B: Diameter 5.25 m

Source: Shell, Delft.

Source: VTI, Sweden.

Thermal shrinkage tests on bar specimens with zero displacement at both ends will establish conditions under which thermal cracking will occur. This records the thermal stress versus the temperature until the rupture of the specimen. Such tests are particularly useful for thermo-viscoelastic materials, for which changes of temperature induce both thermal stresses and changes of creep properties.

Volumetric ageing tests will be especially important for candidates for long-life pavement surface layers. The pressure automated vessel (PAV) test is a well-established test for bituminous materials in which mix specimen are submitted to oxygen gas pressures and elevated temperature for a certain period of time. The test is known to accelerate the ageing of bituminous mixes and some correlation has been established between the duration of the PAV test and the real ageing of pavements. The effect of the ageing is assessed through the evolution of some of the mechanical properties (such as stiffness, creep curves, maximum tensile stress). The tests have been developed for bituminous materials so that some adaptation of the procedures will probably be needed for long-life solutions, depending on the chemical composition of the mix and the likely chemical reactions.

Tests for surface properties

Table 6.2 summarises the main surface wear characteristics in order of priority and the experimental test that can measure their durability.

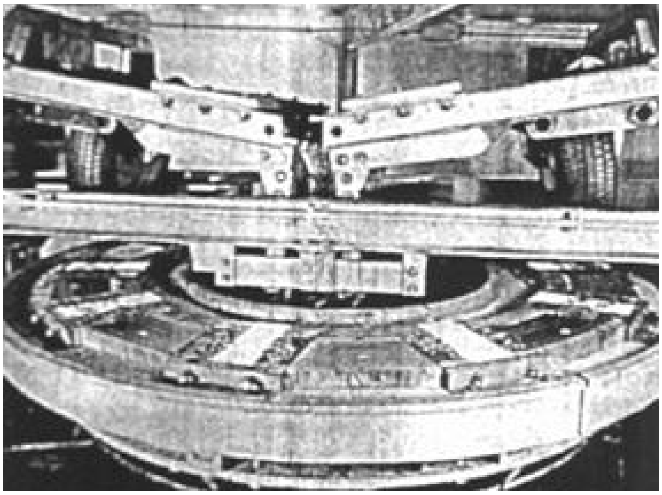
Table 6.2. Surface wear characteristics and tests

Characteristics to be measured	Testing means
Risks of delamination with the support	Delamination tests, under repeated loading, *e.g.* test on a two-layer beam (candidate + support) in flexural mode
Risks of ravelling, stripping, wear and skid resistance	Small carrousels for testing wear (see Figure 6.2) Use or development of local tribological tests under alternative tangential loading (see Figure 6.3) Measurement of skid resistance by pendulum test
Resistance to chemical spilling	Test main chemical spills (oil, fuel, de-icing agents)

To simulate wear due to the traffic, rutting testers (see Figure 6.1) could be used. Some of these can apply tangential forces at the wheel/pavement contact (Jolivet, 1999; Nicholls, 1997).

Equipment to measure the tribological properties of materials is currently under development (Figure 6.3). This test studies the wear that occurs at the surface of materials and could be useful to examine the durability of candidate materials.

Figure 6.2. Carrousel for testing wear



Characteristics:

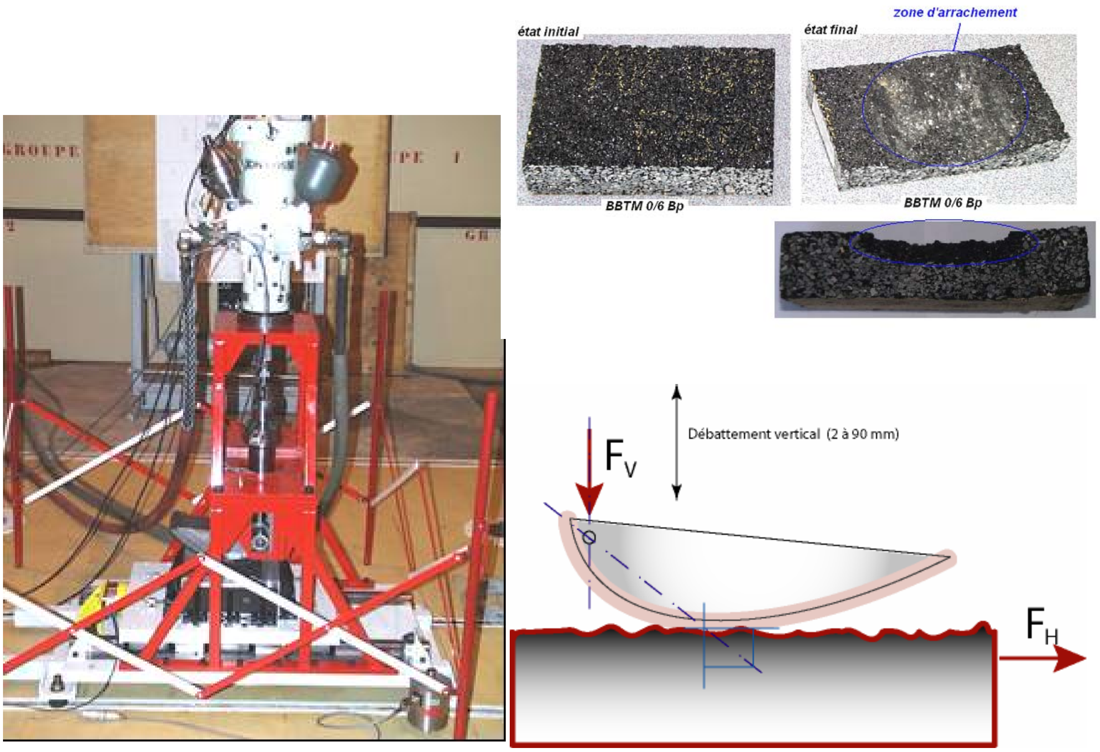
- Circular table with 2.10 m diameter
- 6 specimens to be tested at the same time
- Two tyres 195/70 VR 14
- Vertical loading 5000 ± 200 N
- Testing temperature 10 ± 2°C

Source: TRL, United Kingdom.

Tests at the components scale

There are tests that focus on the properties of the basic components that enter pavement mixes and their interaction. For example, for bituminous mixes, many tests have been developed concerning the bitumen itself, the binder (filler + bitumen), the mastic (filler + sand + bitumen), the aggregates or the interaction (adhesion) between aggregates and the binder or the mastic.

Figure 6.3. Experimental device to measure tribological properties of wearing course materials



Experimental device developed at LCPC to study tribological properties of wearing course materials

Top: examples of wear obtained on bituminous mixes
Bottom: specimen and principle of vertical and alternative tangential loading

Source: LCPC, France.

There are rarely straightforward quantitative relationships between the properties of basic materials and their properties at the mix level. However, many statistical relationships have been developed at the component and at the mix scales, leading to a more profound understanding of mix behaviour and to guidelines for improving pavement materials. For example, many (standardised) specifications have been derived for binders and granulates which ensure the quality of the final mix, if the right formulation rules are applied.

Such an approach will be very useful to evaluate the properties of candidate materials for long-life pavement surface layers. Using epoxy-resin mix as an example, three applications could be envisaged:

- Study (and possibly optimisation) of the rheology and ageing of the epoxy resin.
- Research on high-specification granulates to ensure long-life skid resistance.
- Optimisation of the adhesive properties between resin and granulates.

Small-scale simulation tests

There are a number of laboratory-scale testing devices which can more or less simulate the effect of traffic on pavement surface layers, using vertically loaded rolling wheels circulating on pavement slabs. Rutting testers, which are classically used for the assessment of the resistance of bituminous mixes to permanent deformation, could be used for this purpose (Figure 6.1). The experimental procedures would need to be adapted in order to simulate the real response of pavements. This means that the experimental slabs will have to be prepared to reproduce not only the long-life pavement surface layers but also the supporting layers. Due to the small thickness of specimen used, a substitute will have to be found for the supporting layers, with global equivalent behaviour (stiffness and possibly small permanent deformation). Some climatic conditions could be simulated in these tests such as temperature changes and rain. However, it may be prohibitively expensive to simulate extreme conditions (such as freezing).

In addition, some of these testing machines allow tangential forces to be introduced at the contact between the wheel (which can be drifted) and the experimental slab in order to study the resistance of the surface layer to wear, stripping or ravelling (Figure 6.2).

Full-scale tests

Full-scale tests give very valuable information about the behaviour of pavement structures under traffic and possibly other sources of loading. They can indicate both how they respond to the passing of a vehicle and how they respond over time under traffic and climatic conditions. The main distress modes over time can be identified and the main improvements that are needed are highlighted. In addition, they provide an understanding of the construction and placement of the material and possible difficulties. Two types of full-scale tests are used in practice. In the first category, an experimental section is placed into a road open to traffic and seamlessly merged with the rest of the pavement. Data can be collected on traffic, climatic history, strain and stress characterisation. Over long observation periods, the information gathered can be very useful. The experimental section might be under-designed for the real traffic conditions in order to accelerate (hopefully in a realistic way) the damaging process and be able to study it. This kind of test is only foreseen for Phase III of this project.

The second category of full-scale tests are the accelerated loading facility tests which are used in many OECD countries (Figure 6.4). These facilities simulate accelerated traffic conditions and from that point of view can give early insight into the performance of pavements over time. However, it is generally not possible on this type of facility to accelerate the climatic cycles and the ageing of the material. Moreover, the number of parameters that can be studied generally remains limited. Great attention must therefore be given to the preparation of these tests, which must have precisely defined goals. Depending on the type of ALF and the extent of the test sections, the costs and complexity of the tests may differ significantly. Figure 6.4 shows two very different types of ALF: a 120 m circular track which allows different structures to be tested at the same time; and a linear one for which the tested length is only 2 meters.

Figure 6.4. Two types of accelerated loading facility

Circular fatigue carrousel (diameter 20 m)

Linear fatigue machine (length 2 m)

Source: LCPC, France.

Source: TRL, United Kingdom.

Recommendations for Phase II research programme

Chapter 5 recommended further research on epoxy asphalt wearing course and high-performance cementitious materials (HPCM) pavements. These materials and processes are at different stages of development. While epoxy asphalts are already in use on bridge decks, information on HPCM is limited to laboratory data. The following steps will need to be carried out in Phase II:

Step 1: Identify all performance data available for specimen materials and processes.

Step 2: Identify performance "unknowns" that will have to be tested for.

Step 3: Identify performance weaknesses that will have to be overcome.

Step 4: Identify laboratory tests that are available for use in participating laboratories. A list of tests has been outlined in this chapter and these are summarised in Table 6.3. Other tests may be available that have not been discussed here.

Step 5: Establish testing programme. This will include:

- Assessment tests to identify performance unknowns.
- Development programme to overcome performance weaknesses.

Step 6: Evaluate the results from the testing programme. Further weaknesses may be identified which will require a further development programme.

Table 6.3. Summary of laboratory tests

Characteristics to be measured	Testing means
Mechanical resilient response of the materials, within the range of strains induced by the traffic or thermal variation at different temperatures); priority n°1, in the absence of already available knowledge	Loading/unloading cycles with a compression device for the measurement of complex modulus (for viscoelstic rheology), indirect tensile test (Brazilian test or ITSM), triaxial testing , + temperature control
Risk of permanent strains (at high temperature)	Rutting testers, triaxial testing with repeated loading with temperature control cell. Vacuum RLAT/wheel track rutting tests
Risk of fatigue	Repeated tensile and/or compressive loading with a press and under uniaxial or flexural modes, indirect tensile repeated loading
Resistance to tensile strains (at different temperatures)	Uniaxial tensile test, indirect tensile test
Resistance to thermal strains	Thermal restrained strain tests buckling and delamination test
Change of strain with temperature	Measurement of thermal coefficient of expansion
Ageing and sensitivity to water	Use of autoclaves at different temperatures and pressures, with oxygen gas, high moisture or other, submission to ultraviolet rays (UK SATS test)
Risks of delamination with the support	Delamination tests, under repeated loading, *e.g.* test on a two-layer beam (candidate + support) in flexural mode)
Risks of ravelling, stripping, wear of skid resistance	Small carrousels for testing wear (see Figure 6.2) Use or development of local tribological tests under alternative tangential loading (see Figure 6.3) Measurement of skid resistance by pendulum test
Resistance to chemical spilling	Test main chemical spills (oil, fuel, de-icing agents)
Rheology of the materials	
Skid resistance of high-specification aggregates	
Optimisation of adhesive properties between resin and granulates	

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Chapter 7

Summary and Conclusions

This chapter summarises the results of the study and draws conclusions preparatory to Phase II of the project.

The scope of Phase I of this project encompasses the examination of the surfacing of road pavements for major highways that are carrying a high level of traffic with a significant proportion of heavy goods vehicles. These roads are assumed to have considerable structural strength which in recent terminology would be termed long-life or perpetual pavements. While aspects of long-life road structure are being considered by other international groups, this report has centred on the examination of high-performance wearing courses. The wearing course for a road is required to have many qualities including resistance to ageing, moisture and thermal fatigue as well as friction and drainage properties. To date, the project has examined the material properties that would be required for a long-life surfacing and also examined the economic aspects to evaluate what criteria, both in the terms of cost and life expectancy, are required to give value for money. The study, the first of a project in three phases, concentrated on four areas:

- Existing materials and how they are used and identifying the maintenance policies used by road administrations.
- New materials likely to include new binders, their performance characteristics with indications of their cost.
- Economic considerations and examination of where more costly materials may be economically worthwhile in the long term.
- Examination of the technical performance requirements for new materials and examination of an appropriate testing regime.

Review of current paving practices

A review of paving practices in participating countries provided valuable information on materials currently in use, their properties, the maintenance regimes employed by road agencies and the cost information associated with the materials and their maintenance. There is remarkable consistency between the countries studied. Similar materials are being used, and the basic cost information was consistent enough to provide one cost value that was subsequently used for the economic evaluations. There were minor variations among three regional groups, Western Europe, Americas and Nordic countries. These groups, besides having similar levels of cost for supplying and laying surfacing material, also demonstrated similar maintenance regimes.

Economic analysis

The study tested the theory that the provision of an advanced long-life road surfacing at higher initial cost may be economically worthwhile (in whole-life cost terms) compared with a conventional surface, when user costs are considered. Chapter 3 reviewed the aspects that should be considered for an economic analysis and emphasised the importance that road user costs played in any analysis. Highly trafficked roads easily become congested as a result of accidents, road maintenance or under-capacity and this congestion causes increased costs to road users: private individuals, industry and businesses, including road freight operators and their customers, and therefore the wider community.

Although there are many aspects that could be considered as part of an economic evaluation, they all depend on the availability of sufficiently accurate data in order to complete an acceptable analysis. With modern computers, it is now relatively straightforward to carry out these analyses and various models are available. Chapter 3 examined the requirements for this type of analysis in an international context and looked at some of the models available. Although by no means a fully comprehensive review, a variety of models have been discussed in the context of this project. Two models were considered appropriate to be used, based on availability, ease of use and familiarity, together with the availability of matching data. The World Bank’s HDM-4 model is widely available and has a wide range of mathematical and logic modules that can be refined and calibrated for a particular country. Because it is a powerful model, it is not always appropriate for straightforward or simple applications and the outputs prepared and used for this report eventually had only a limited application. The other model that was used for the analysis in this report was a development of a UK model used for assessment of maintenance scheme and called PASI.

These models were used to compare the whole-life costs of traditional and advanced surfacing options. Maintenance regimes for various traffic and cost options were examined with the advanced surfacing using different initial costs. Because the costs for an advanced surfacing were uncertain, the initial costs for this treatment were entered as a proportion of the cost for a traditional treatment. In this way, the relative cost or the relative increase in cost at which an advanced surfacing would still be cost-effective could be determined.

The cost evaluations described in Chapter 4 produced the conditions that would apply for an advanced surfacing to create an economic advantage over a traditional surfacing treatment. Variations in discount rate, costs and amounts of traffic were considered and various combinations explored. The results show that in a number of countries there would be an economic advantage to using an advanced long-life surfacing with higher initial costs rather than traditional wearing courses. The sensitivity testing undertaken showed that:

- Some savings are likely for heavily trafficked roads (above 80 000 AADT) at any usual discount rate.
- Only schemes with the heaviest traffic levels will show a saving at discount rates as high as 10%.
- At lower traffic levels around 60 000 AADT, there will only be a saving at low discount rates (about 3%).

- When traffic levels are around 40 000 AADT or lower, there are unlikely to be worthwhile savings.
- Except at very low discount rates (*i.e.* 3%) and high traffic volumes, high-cost wearing courses (*i.e.* five times the costs of traditional wearing courses) would not be expected to be economically viable.

Such increases in wearing course costs need to be seen in the context of typical pavement construction costs. For the example scheme chosen of a dual three-lane motorway, pavement construction costs would amount to USD 1.8 million to USD 2.25 million per carriageway kilometre. This estimate includes features such as earthworks, drainage, line markings, safety fences, etc., but not other structures such as over or under bridges, gantries, etc.

At present, the surface layer (the wearing course) of such pavements represents around 9-12% of the above indicative pavement construction costs. A three-fold increase in the wearing course cost would imply an increase in overall pavement structure construction costs of up to 24%, and the surface layer would then represent around 30% of the construction costs.

Of course, the total construction costs of high-traffic roads are extremely variable depending not only on pavement construction costs but also on the number of bridges, tunnels and earthworks actually involved. Overall average costs per kilometre increase to between USD 3.15 million and USD 3.6 million per carriageway kilometre, taking these other costs into account. In this respect, a three-fold increase in the cost of the surface layer of the pavement would have a lower impact in terms of overall motorway construction costs per kilometre, *i.e.* between 10% and 15%, and the surface layer would represent between 5% and 20% of the total construction cost. If a completely new road scheme were to be examined, this percentage would be even lower when total costs including structures, land purchase, design costs and communications are taken into account.

Advanced paving materials and techniques

Chapter 5 examined the availability and characteristics of various groupings of advanced materials for road surfacing. These materials showed some potential to meet the requirements of long-life wearing courses: they should be long-lasting, provide ongoing skid resistance with continuing texture that reduces spray, and be provided at a cost that gives value for money. Many of the types of surfacing that have been examined have either not been used in a highway context or only for relatively small areas of work such as bridge decks. Surfacing for bridge decking often requires materials to be exceptionally resilient, to be strong but flexible because of the greater stresses and strains compared to conventional materials. One aspect of future work into advanced materials will be to develop ways in which these materials can be laid on a road, possibly by adapting or redesigning paving machines that can then provide a realistic output for large areas.

From the review of materials in Chapter 5, two particular types of material showed that they had potential to fulfil the requirements. These were epoxy asphalt and high-performance cementitious materials with an epoxy friction course.

Phase II of the project should further examine these materials and carry out development work. Other materials that were considered in Chapter 5 may also have the necessary properties but perhaps the data are not fully available for assessment. These and other materials should not be totally disregarded and it may well be appropriate for their properties to be reviewed at a later stage.

Towards Phase II

The guidelines for a research programme to be carried out as part of Phase II are established in Chapter 6. The objective of this further work will be to assess the real capacity of the candidate materials and to see if they deserve long-life wearing course status.

This further work will establish the properties necessary for the advanced surfacing in terms of resistance to rutting, cracking, ravelling, stripping and weathering but must also examine other important aspects including long-term polishing and loss of skid resistance, spray reduction and noise emissions. The review in Chapter 6 highlights the necessary criteria and examines a possible testing programme and the extent that this will be required, including the importance of full-scale testing and the use of accelerated load testing techniques. Phase II should include the following steps:

Step 1: Identify all performance data available for specimen materials and processes.

Step 2: Identify performance “unknowns” that will have to be tested for.

Step 3: Identify performance weaknesses that will have to be overcome.

Step 4: Identify laboratory tests that are available for use in participating country laboratories as outlined in this report and further proposed by other participants.

Step 5: Establish testing programme. This will include:

  - Assessment tests to identify performance unknowns.
  - Development programme to overcome performance weaknesses.

Step 6: Evaluate the results from the testing programme. Further weaknesses may be identified which will require a further development programme.

Annex A

Questionnaire – Flexible Pavements

Background

The information obtained from this questionnaire will be used for an OECD project titled “Economic Analysis of the Technical Potential for Long-life Pavements”. We have deliberately attempted to make the questionnaire as concise and as direct as possible to provide only the information we require. Thank you, in advance, for taking the time to respond. The questionnaire is focused on existing or conventional pavement practices performed by your agency and is focused on asphalt pavements.

This questionnaire is designed to provide technical and economic information regarding your agency’s existing paving practices; specifically requested is information on the top surface pavement layer, sometimes referred to as a wearing course. The questionnaire asks for information regarding initial construction costs of the top surface pavement layer or wearing course, the expected life and a description, timing and costs of expected maintenance strategies to be performed. Also requested is brief information on design procedures, pavement materials used for this layer and your agency’s description or definition of expected life of the pavement in terms of failure criteria such as rutting, distress and smoothness. A life cycle or whole-life analysis will be conducted and the information will be used to compare existing agency practices with newly developed or potentially longer-life pavements. It must be emphasised that the information requested is for the existing or conventional type of pavements typically used on high-traffic highways and the information requested is for the top surface layer only.

There are assumptions that should be considered before responding. The requested information is to be confined to the wearing course only. The underlying structural layers of asphalt mix, concrete or granular base and sub-base are assumed to be of substantive quality and substantive structural capacity. This is to focus the requested information on the design, materials, costs and life expectancy of the wearing course only. To better define the surface layer, it is assumed that the structure would typically consist of sub-grade soils, sub-base and/or base materials, an intermediate pavement layer or layers and a surface wearing course or top course layer. This is a general or conceptual design, which may have different thicknesses or perhaps some layers may not be represented. However, for the purpose of the questionnaire, the wearing course layer is the top layer. It is considered that this layer would have a defined expected life, an initial cost for the top layer only and require some level of maintenance. At the end of the service life, this layer would then be replaced or potentially overlaid.

The information requested would be potentially obtainable from a specific project within your agency. As a generalisation, it is hoped that the design would approximate the structure described above. The project would be for a high-traffic highway or dual carriageway/freeway and the expected traffic volumes would be at a minimum of 10 000 ADT with 15% heavy trucks. As an assumption, the construction for this project would involve the use of typical or high-quality materials and construction techniques. The design would result in high-quality structural capacity and drainage.

The information requested is only concerned with a project within your agency's jurisdiction that would be considered typical for the type of facility as described above. There is space for comments after each question, so if you consider that there is information that would be of value for the analysis, please add your comments as you see fit. This questionnaire will be sent to OECD countries. With life-cycle cost analysis involving user-delay costs, it may well be determined that high-technology or different paving materials will potentially provide an alternative to the conventional pavements in use today. Thank you for your time to respond.

Existing Pavement Structure Design

For a project in your agency's jurisdiction, as described above, could you please provide the following?

General Information

Project location

Brief project scope (*e.g.* x km new construction four-lane highway with two bridges)

....

Brief description of the pavement structure for this project

....

Approximate asphalt mix (tonnes) for the wearing course for this project

Comments

Climate

Project climatic environment, please check appropriate box.

WET/NO FREEZE...................................... ☐ WET/FREEZE... ☐
DRY/NO FREEZE...................................... ☐ DRY/FREEZE... ☐

Is the project area subject to freeze thaw cycles?

Yes ☐ No ☐ if yes, how many per winter ....

Comments or any special considerations regarding climate for your project ....

....

Traffic

The project would be for a high-traffic facility. Please provide the following:

ADT (approximate) ....

ESALs (approximate, 80 kN per axle equivalency) ....

or ESALs (if you use the definition of 100 kN per axle equivalency) ....

Percent heavy trucks ....

Comments or special considerations regarding traffic ....

Design criteria

Please provide a brief description of your pavement design procedure *e.g.* AASHTO or other.

....

Please provide information for the following:

For design, what criteria with respect to fatigue cracking (horizontal tensile strain at the underside of the asphalt layer) do you use?

For design, what criteria with respect to structural deformation (vertical compressive strain at the top of the sub-grade) do you use?

For design, what values for elastic stiffness or modulus do you use?

Any other design criteria?

Design life: Years .... ESALs………………….

Failure criterion. What do you consider as your limiting or terminal condition at the end of pavement life with respect to the following:

Roughness (IRI) .... or other measure of roughness...........

Rutting (mm).............

Fatigue (%)................

Distress *e.g.* cracking, thermal cracking ....

Do you consider road user costs?

Yes .... ☐ No .... ☐

Would you consider a concrete wearing course as an alternative?

Yes .... ☐ No .... ☐

Comments

Pavement Costs, Materials and Performance Requirements

For the wearing course only for your selected project, please provide the requested information under column 1 below. If you have a different or additional wearing course mixes that you use occasionally, could you please provide the information in column 2 or 3 below. As an example, column 1 may be a first class conventional mix and column 2 may be a stone mastic or a superpave mix.

Typical values for selected mix	**Mix type or name of mix**		
	1................	**2**................	**3**................
Initial cost in USD per square metre. See Note 1 below	....	....	....
Layer thickness for this project (mm)	....	....	....
Information of interest			
Approximate bitumen content	....	....	....
Specified degree of compaction	....	....	....
Grading curve (% by weight of mix)			
Stone / sand / filler	....../....../......	....../....../......	....../....../......
Max. size aggregate (mm)	....	....	....
Specified percent air voids	....	....	....
Mix stiffness (if known, resilient modulus)	....	....	....
Bitumen type by penetration or by PG grading	....	....	....
Aggregate comments	....	....	....
Polymers used (if any, yes or no)	....	....	....
Polymer content (% by weight of binder, if used)			
Fibre content (% by weight of binder, if used)	....	....	....
Other additives if any, *e.g.* latex, rubber, please specify	....	....	....
Performance requirements:	....	....	....
Rut resistance (mm)	....	....	....
Smoothness (spec used, if any)	....	....	....
Noise (spec used, if any)	....	....	....
Skid resistance (spec used, if any)	....	....	....

Note 1. Initial costs are an important factor for this study. For consistency, initial cost is to include only the costs of the materials in the asphalt mix, the mixing, haul and placement. In other words, the costs would include the all-inclusive contractor's bid costs for the work but would not include the design costs or the agency's project supervision costs or other project ancillary costs. The costs are only for the wearing course and not for the underlying structural layers. Please report the costs in USD per square metre.

Comments

Estimated Maintenance Strategies

For each of the wearing course pavements that you listed in the table above, can you provide an estimate of the maintenance treatments, timing and approximate costs. Please complete the following table:

Mix type or name (No ……)	Estimated maintenance treatments						Remarks
	Estimated maintenance treatment	Approximate timing (*i.e.* what year after construction)	Performance indicator intervention criteria (threshold levels)		Costs (USD/ lane km)	Work zone duration (days per km/lane)	
	Code (see below)		Code	Value			
1.							
2.							
3.							
Example: Conventional Mix No. 1	CS	Year 3, 6 and 12	suc + stc	5%	4 000	2	Crack seal at yr 3, 6, 12 with expected patching and slurry seal with complete mill and replace at yr 15.
	PA	8	STC	ALL	10 000	2	
	SS	10	RA	10% (OF AREA)	15 000	1.5	
	MR	15	RU	15 MM	28 000	1	

Estimated maintenance treatments	CODE	Performance indicator	Code
Crack sealing	CS	Rutting	RU
Patching	PA	Skid resistance	SK
Fog sealing	FS	Structural adequacy (deflection)	ST
Rejuvenation	R	Surface cracking	SUC
Slurry seal	SS	Structural cracking	STC
Surface chip or graded seal	SD1	Ravelling	RA
Thin Overlay	OV	Smoothness (IRI)	LP
Overlay or Mill and Replace (End of Life)	MR		

Annex B

Whole-life Cost Cycle Models Considered

Evaluation of models

The models listed here are not be considered to be all those that may have been suitable. It was not necessary as part of this report to carry out a survey of all possible pavement whole-life cost models. The following are the models that were easily located and the background information is provided here only for interest.

HDM-4

The HDM-4 is a highway development and management system for investigating road investment choices. It is sponsored by the World Bank, and PIARC has assumed the leading role in its management and in the co-ordination of the development project. Early versions of the HDM model were developed particularly to suit developing countries, but the scope of the latest version has been widened so that the model can cater for the wide-ranging needs of road agencies, designers and funders across the world. It was previously particularly suited for tropical climates but has now been extended for frozen climates. It has currently registrations in nearly 100 countries.

FHWA – Concrete –PaveSpec3.0

This model, for concrete pavements only, can examine whole-life costs as part of software designed to develop performance-related specifications. The model allows different maintenance regimes to be set up and is designed to allow cost comparisons to be made, in whole-life cost terms, for alternative specifications. It only considers jointed plain concrete pavements but does allow the inclusion of user costs (travel time, vehicle operating costs, accident costs and discomfort costs), and these can be adjusted by a fixed percentage. It does not appear easy to separate the calculation of future costs from other outputs or to easily compare different evaluations side by side. All units are in USD and inches, feet, yards and miles.

FHWA – HMA Spec (Flex version of PavSpec3)

A flexible pavement version of the model above is being developed and was not available during the preparation of this report.

FHWA – LCCA software (real cost)

This software, based on an Excel spreadsheet, analyses cost differences between project alternatives. It follows the FHWA best practice LCCA (life-cycle cost analysis) methodology. It calculates life-cycle values for both agency and user costs associated with the construction and rehabilitation for the pavement structure under consideration. It requires the user to enter individual construction or rehabilitation costs but calculates user costs.

The software performs both deterministic and probabilistic modelling of pavements, and outputs are provided in tabular and graphic format. Following a probabilistic analysis, there are considerable output variations, including probability distribution and cumulative density functions. The method for calculating user costs compares traffic demand with roadway capacity on an hour-by-hour basis by examining resulting traffic conditions. It will carry an analysis for any period up to 40 years.

User costs are calculated using a standard FHWA method based on US experience. These are fixed unless the user enters their own user costs instead. The software must be run on Excel 2000 and will not work with earlier versions. All units are currently shown in USD, miles, feet and mph. There appears to be no reason, if all background data are suitably adjusted, for metric units not to be used, although screens will still refer to original US units. It is understood that the software could easily be changed to reflect other units or none at all. Since the user enters the maintenance descriptions, costs and times, it can analyse both bituminous and concrete pavements.

Pav-Eco

A European Commission 4th Framework project examined the evaluation of life-cycle costs of pavement and studied the effects of road infrastructure maintenance for new links into a road network. No single model was produced but universal guidelines and a framework for the comparison of the life-cycle costs for different maintenance strategies were produced. The experience and the framework established under this project have led to development work for a new European cost model. This was not available at the time of preparation of this report.

Quebec – TRDI

The Province of Quebec uses a whole-life cost model developed by TRDI (Texas Research and Development, Inc.) as part of their Pavement Management System. This software is also used in some US states and allows users to enter their own treatment costs, and although non-works costs (delay or user costs) are included in the analysis, these are fixed and based on US experience. This software is available commercially, is well supported and is reported to be user friendly and accessible. It has both deterministic and probabilistic options.

Colorado

Model developed by the Colorado Asphalt Association. The user can enter maintenance costs and various maintenance options can be selected including those entered by the user. The analysis does not allow for user costs, and there is no facility to enter traffic information.

United States Asphalt Pavement Alliance LCCA Software

This software requires inputs similar to the FHWA software described above. It can also carry out both deterministic and probabilistic analyses, although there is less graphical output than with the FHWA tool. It includes the calculation of user costs and this is largely based on FHWA principles. These can be altered but this may require a certain amount of experience. All units are American; it appears that these cannot be altered although if all data input is metric, the output should be metric. Since the maintenance descriptions, costs and times are entered by the user, the software can analyse both bituminous and concrete pavements. Since it has an option for limited inclusion of time-related costs, this may be relevant for concrete pavements

United Kingdom's SAS model

Based on an Excel spreadsheet, this model allows the user to compare options for different maintenance regimes. The model includes allowance for user costs, residual value and different treatments on different lanes of the highway. All local background data can be entered, or typical values can be used from the UK data provided. This model requires the user to input an appropriate maintenance profile together with associated costs and work output rates. It can be adapted for international use and is suitable for concrete and bituminous pavements.

Annex C

Application of HDM-4 Model

HDM-4 version 1.3 was used to estimate the economic viability of pavements with long-life wearing courses. The economic analysis was based on the concept of "life-cycle analysis", and the "project analysis" application was selected for the required evaluation. The following main steps were considered for the analysis:

- Pavement performance.
- Life-cycle deterioration predictions.
- Maintenance effects and costs.
- Road user costs and benefits; total transport costs.
- Economic indicators for defined maintenance/improvement alternatives.

For this report, the "by section" mode of analysis was specified to determine the economic comparisons for the two project alternatives being considered, *i.e.* the traditional wearing course and the pavement with the advanced, long-life wearing course.

The following procedure was used for the project analysis:

- Project description specifying:
    1. Road section to be analysed. Pavement strength was characterised by the adjusted structural number SNP, calculated on the basis of the thickness of layers, layer strength coefficients and subgrade CBR (California bearing ratio) value.
    2. Vehicle fleet that contains the vehicle types using the section analysed.
    3. Annual average daily traffic (AADT), traffic composition and expected growth for each vehicle type. Six vehicle types were selected: car, utility, bus, medium truck, heavy truck, articulated truck.
    4. The alternatives to be analysed, as a sequence of maintenance works applied to the section.
- Specifying the discount rate, start year and duration of the analysis period.
- Selecting the required outputs.
- Carrying out sensitivity analyses by varying the values of selected input parameters: AADT, traffic growth rate, discount rate. The values used were the same as for the PASI model analysis. Specific time intervals of maintenance works for the alternatives were defined for each traffic load category (AADT, traffic growth).

Some modifications were required to a typical HDM-4 project analysis owing to the limited input data available regarding performance models. Typically, calibration factors (coefficients) were used to customise performance models and distress models to reflect the specific climate and environmental conditions of the given road section. Several project alternatives assigned to road sections were analysed to determine the most cost-effective alternative for each section.

The analysis contained characteristics for one test road section, based on information received from the questionnaire responses. The analysis was carried out using the two alternatives with the selected set of maintenance treatments at constant time intervals for the given traffic load category, which were obtained from the questionnaire results and as part of the agreed standard scenarios.

Intervention levels (threshold values) for the selected performance and/or distress attributes, treatment type and the resultant effect on the pavement gave a pavement performance characteristic for both alternatives. Calibration factors were not available, but the agreed information about performance made it possible to simulate performance curves on a trial-and-error basis, starting from default values of 1 for the most sensitive calibration factors, giving performance curves that reflected the specified threshold values and time intervals of maintenance treatments for each alternative. Average roughness (IRI m/km, by section) was used to check the adequacy of the next step of the performance simulation.

Typically, one set of calibration factors was defined for each road section. To simulate the improved performance of the alternative with the advanced wearing course, an apparent maintenance treatment (with the unit costs close to 0) in the first year of analysis cycle was included for the sequence of maintenance works. This made it possible to apply a different set of calibration factors to those used for the first alternative.

As described in Chapter 4, the values obtained from HDM-4 gave only small differences in vehicle operating costs (VOCs) for the different types of surfacing with no clear trends. Although it was hoped that the HDM-4 modelling would be able to provide VOC data for inclusion in the analysis, as can be seen in Table 4.4, differences were small and did not affect the outcome of the comparisons.

A variation on the initial modelling incorporated conditions more usual in eastern European countries. As described in Chapter 4, this variation, using a higher IRI value, established that vehicle operating costs, not surprisingly, show a greater difference as road conditions deteriorate.

Annex D

PASI Model – Data Input and Results

Input data

Assumptions that have been made as part of the analysis using the PASI model:

Base year:	2003	
Evaluation period:	45 years	
Scheme length:	4 km	
Closure length for traffic management:	5 km	
Traffic growth rate:	1% (except for results shown in Table 4.6)	
Output rates:	Traditional 30 mm:	600 sq m/hr
	Traditional 100 mm:	450 sq m/hr
	Advanced:	600 sq m/hr
	Retexture:	1 200 sq m/hr
Way of working:	Night-time working for all maintenance treatments (except for results shown in Table 4.5)	

Cost and output rates are not affected by the time (night or day) of working

Traffic management arrangements for the treatments were based on two variations depending on the traffic levels. All traffic management used contra flow arrangements, whereby one or more lanes of traffic are directed to the opposite side of the central reservation to flow in reverse direction against the usual flow, in clearly defined and separated lanes. For the 40 000 and 60 000 AADT traffic levels, the arrangement allowed two traffic lanes to flow in each direction during the works. For the higher traffic flows (80 000 and 100 000 AADT), the arrangement allowed two lanes in one direction and three lanes in the other utilising narrowed lanes.

Difference in NPV and percentage savings

Advanced = three times cost of traditional, 30 years life

Traffic		40 000				60 000				80 000				100 000			
	Heavy vehicles	5%	10%	15%	20%	5%	10%	15%	20%	5%	10%	15%	20%	5%	10%	15%	20%
Discount rate 3%	Trad	2 362.83	2 364.44	2 366.08	2 367.68	2 516.55	2 673.68	2 833.39	2 993.09	4 442.12	4 839.67	5 237.21	5 634.79	6 846.87	7 620.70	8 394.52	9 168.35
	Advanced	2 503.49	2 504.90	2 506.34	2 507.77	2 587.11	2 668.07	2 750.90	2 833.73	3 564.71	3 758.78	3 952.84	4 146.92	4 807.36	5 205.54	5 603.84	6 001.93
	Diff	- 140.66	- 140.46	- 140.26	- 140.09	- 70.56	5.61	82.49	159.36	877.41	1 080.89	1 284.37	1 487.87	2 039.51	2 415.16	2 790.68	3 166.42
	%	- 5.95	- 5.94	- 5.93	- 5.92	- 2.80	0.21	2.91	5.32	19.75	22.33	24.52	26.41	29.79	31.69	33.24	34.54
6%	Trad	1 581.32	1 582.03	1 582.74	1 583.46	1 654.94	1 714.38	1 774.62	1 834.87	2 648.25	2 853.50	3 058.75	3 264.01	4 015.35	4 439.49	4 863.66	5 287.82
	Advanced	2 007.60	2 008.10	2 008.60	2 009.10	2 048.84	2 077.21	2 106.09	2 134.95	2 550.55	2 653.31	2 756.05	2 858.80	3 306.83	3 541.03	3 775.21	4 009.41
	Diff	- 426.28	- 426.07	- 425.86	- 425.64	- 393.90	- 362.83	- 331.47	- 300.08	97.70	200.19	302.70	405.21	708.52	898.46	1 088.45	1 278.41
	%	- 26.96	- 26.93	- 26.91	- 26.88	- 23.80	- 21.16	- 18.68	- 16.35	3.69	7.02	9.90	12.41	17.65	20.24	22.38	24.18
8%	Trad	1 293.49	1 293.92	1 294.37	1 294.81	1 344.55	1 377.65	1 411.17	1 444.65	2 032.62	2 175.74	2 318.87	2 462.00	3 058.19	3 370.39	3 682.58	3 994.78
	Advanced	1 843.59	1 843.85	1 844.11	1 844.37	1 873.94	1 889.05	1 904.41	1 919.74	2 217.20	2 290.72	2 365.25	2 437.77	2 815.73	2 997.81	3 179.91	3 361.99
	Diff	- 550.10	- 549.93	- 549.74	- 549.56	- 529.39	- 511.40	- 493.24	- 475.09	- 184.58	- 114.98	- 46.38	24.23	242.46	372.58	502.67	632.79
	%	- 42.53	- 42.50	- 42.47	- 42.44	- 39.37	- 37.12	- 34.95	- 32.89	- 9.08	- 5.28	- 2.00	0.98	7.93	11.05	13.65	15.84
10%	Trad	1 104.99	1 105.28	1 105.57	1 105.85	1 143.88	1 163.42	1 183.13	1 202.84	1 645.06	1 750.88	1 856.70	1 962.53	2 461.82	2 706.99	2 952.16	3 197.35
	Advanced	1 745.62	1 745.77	1 745.92	1 746.06	1 770.53	1 779.12	1 787.81	1 796.51	2 017.11	2 073.39	2 129.68	2 185.98	2 521.33	2 672.77	2 824.21	2 975.64
	Diff	- 640.63	- 640.49	- 640.35	- 640.21	- 626.65	- 615.70	- 604.68	- 593.67	- 372.05	- 322.51	- 272.98	- 223.45	- 59.51	34.22	127.95	221.71
	%	- 57.98	- 57.95	- 57.92	- 57.89	- 54.78	- 52.92	- 51.11	- 49.36	- 22.62	- 18.42	- 14.70	- 11.39	- 2.42	1.26	4.33	6.93

40 years life

Traffic		40 000				60 000				80 000				100 000			
	Heavy vehicles	5%	10%	15%	20%	5%	10%	15%	20%	5%	10%	15%	20%	5%	10%	15%	20%
Discount rate 3%	Trad	2 362.83	2 364.10	2 366.10	2 367.70	2 516.55	2 673.70	2 833.40	2 993.09	4 442.12	4 839.67	5 237.21	5 634.79	6 846.87	7 620.70	8 394.50	9 168.35
	Advanced	1 931.06	1 931.70	1 932.40	1 933.04	2 019.56	2 109.60	2 201.50	2 293.30	2 859.86	3 027.76	3 195.69	3 363.62	3 945.54	4 306.20	4 666.86	5 027.53
	Diff	431.77	432.40	433.70	434.66	496.99	564.10	631.90	699.79	1 582.26	1 811.91	2 041.52	2 271.17	2 901.33	3 314.50	3 727.64	4 140.82
	%	18.27	18.29	18.33	18.36	19.75	21.10	22.30	23.38	35.62	37.44	38.98	40.31	42.37	43.49	44.41	45.16
6%	Trad	1 581.32	1 583.03	1 582.74	1 583.46	1 654.94	1 714.40	1 774.60	1 834.87	2 648.25	2 853.50	3 058.75	3 264.01	4 015.35	4 439.50	4 863.70	5 287.82
	Advanced	1 744.55	1 744.80	1 745.04	1 745.29	1 786.24	1 816.70	1 847.90	1 879.01	2 153.15	2 234.89	2 316.61	2 398.34	2 781.01	2 979.30	3 177.60	3 375.95
	Diff	- 163.23	- 161.77	- 162.30	- 161.83	- 131.30	- 102.30	- 73.30	- 44.14	495.10	618.61	742.14	865.67	1 234.34	1 460.20	1 686.10	1 911.87
	%	- 10.32	- 10.22	- 10.25	- 10.22	- 7.93	- 5.97	- 4.13	- 2.41	18.70	21.68	24.26	26.52	30.74	32.89	34.67	36.16
8%	Trad	1 293.49	1 293.92	1 294.37	1 294.81	1 344.55	1 377.60	1 411.20	1 444.65	2 032.62	2 175.74	2 318.87	2 462.00	3 058.19	3 370.40	3 682.60	3 994.78
	Advanced	1 678.25	1 678.38	1 678.51	1 678.64	1 708.02	1 723.60	1 738.40	1 755.27	1 936.49	1 993.53	2 050.58	2 107.64	2 432.14	2 584.60	2 737.00	2 889.40
	Diff	- 384.76	- 384.46	- 384.14	- 383.83	- 363.47	- 346.00	- 327.20	- 310.62	96.13	182.21	268.29	354.36	626.05	785.80	945.60	1 105.38
	%	- 29.75	- 29.71	- 29.68	- 29.64	- 27.03	- 25.12	- 23.19	- 21.50	4.73	8.37	11.57	14.39	20.47	23.31	25.68	27.67
10%	Trad	1 104.99	1 105.28	1 105.57	1 105.85	1 143.88	1 163.40	1 183.10	1 202.84	1 645.06	1 750.88	1 856.70	1 962.53	2 461.82	2 707.00	2 952.20	3 197.35
	Advanced	1 637.75	1 637.82	1 637.89	1 637.97	1 661.69	1 670.00	1 678.50	1 687.02	1 813.22	1 856.83	1 900.43	1 944.04	2 236.27	2 364.00	2 491.70	2 619.35
	Diff	- 532.76	- 532.54	- 532.32	- 532.12	- 517.81	- 506.60	- 495.40	- 484.18	- 168.16	- 105.95	- 43.73	18.49	225.55	343.00	460.50	578.00
	%	- 48.21	- 48.18	- 48.15	- 48.12	- 45.27	- 43.54	- 41.87	- 40.25	- 10.22	- 6.05	- 2.36	0.94	9.16	12.67	15.60	18.08

Difference in NPV and percentage savings

Advanced = five times cost of traditional, 30 years life

Traffic		40 000				60 000				80 000				100 000			
	Heavy vehicles	5%	10%	15%	20%	5%	10%	15%	20%	5%	10%	15%	20%	5%	10%	15%	20%
Discount rate 3%	Trad	2 362.83	2 364.44	2 366.08	2 367.68	2 516.55	2 673.70	2 833.39	2 993.09	4 442.12	4 839.67	5 237.21	5 634.79	6 846.87	7 620.70	8 394.52	9 168.35
	Advanced	3 860.36	3 861.77	3 863.21	3 864.64	3 943.98	4 024.94	4 107.77	4 190.60	4 921.58	5 115.65	5 309.71	5 503.79	6 164.23	6 562.41	6 960.61	7 358.80
	Diff	-1 497.53	-1 497.33	-1 497.13	-1 496.96	-1 427.43	-1 351.24	-1 274.38	-1 197.51	-479.46	-275.98	-72.50	131.00	682.64	1 058.29	1 433.91	1 809.55
	%	-63.38	-63.33	-63.27	-63.22	-56.72	-50.54	-44.98	-40.01	-10.79	-5.70	-1.38	**2.32**	**9.97**	**13.89**	**17.08**	**19.74**
6%	Trad	1 581.32	1 582.03	1 582.74	1 583.46	1 654.94	1 714.38	1 774.62	1 834.87	2 648.25	2 853.50	3 058.75	3 264.01	4 015.35	4 439.49	4 863.66	5 287.82
	Advanced	3 135.87	3 136.37	3 136.87	3 137.37	3 177.11	3 205.48	3 234.36	3 263.77	3 678.82	3 781.58	3 884.32	3 987.07	4 435.10	4 669.30	4 903.48	5 137.68
	Diff	-1 554.55	-1 554.34	-1 554.13	-1 553.91	-1 522.17	-1 491.10	-1 459.74	-1 428.90	-1 030.57	-928.08	-825.57	-723.06	-419.75	-229.81	-39.82	150.14
	%	-98.31	-98.25	-98.19	-98.13	-91.98	-86.98	-82.26	-77.87	-38.92	-32.52	-26.99	-22.15	-10.45	-5.18	-0.82	**2.84**
8%	Trad	1 293.49	1 293.92	1 294.37	1 294.81	1 344.55	1 377.65	1 411.17	1 444.65	2 032.62	2 175.74	2 318.87	2 462.00	3 058.19	3 370.39	3 682.58	3 994.78
	Advanced	2 900.04	2 900.30	2 900.56	2 900.82	2 930.39	2 945.50	2 960.86	2 976.19	3 273.65	3 347.17	3 420.70	3 494.22	3 872.18	4 054.26	4 236.36	4 418.44
	Diff	-1 606.55	-1 606.38	-1 606.19	-1 606.01	-1 585.84	-1 567.85	-1 549.69	-1 531.54	-1 241.03	-1 171.43	-1 101.83	-1 032.22	-813.99	-683.87	-553.78	-423.66
	%	-124.20	-124.15	-124.09	-124.03	-117.95	-113.81	-109.82	-106.01	-61.06	-53.84	-47.52	-41.93	-26.62	-20.29	-15.04	-10.61
10%	Trad	1 104.99	1 105.28	1 105.57	1 105.85	1 143.88	1 163.42	1 183.13	1 202.84	1 645.06	1 750.88	1 856.70	1 962.53	2 461.82	2 706.99	2 952.16	3 197.35
	Advanced	2 761.65	2 761.80	2 761.95	2 762.09	2 786.56	2 795.15	2 803.84	2 812.54	3 033.14	3 089.42	3 145.71	3 202.01	3 537.36	3 688.80	3 840.24	3 991.67
	Diff	-1 656.66	-1 656.52	-1 656.38	-1 656.24	-1 642.68	-1 631.73	-1 620.71	-1 609.70	-1 388.08	-1 338.54	-1 289.01	-1 239.48	-1 075.54	-981.81	-888.08	-794.32
	%	-149.93	-149.87	-149.82	-149.77	-143.61	-140.25	-136.98	-133.82	-84.38	-76.45	-69.42	-63.16	-43.69	-36.27	-30.08	-24.84

40 years

Traffic		40 000				60 000				80 000				100 000			
	Heavy vehicles	5%	10%	15%	20%	5%	10%	15%	20%	5%	10%	15%	20%	5%	10%	15%	20%
Discount rate 3%	Trad	2 362.83	2 364.08	2 366.08	2 367.70	2 516.55	2 673.70	2 833.40	2 993.09	4 442.12	4 839.67	5 237.21	5 634.79	6 846.87	7 602.70	8 394.50	9 168.35
	Advanced	2 964.26	2 964.92	2 965.58	2 966.24	3 052.76	3 142.80	3 234.70	3 326.69	3 893.06	4 060.96	4 228.89	4 396.00	4 978.74	5 339.40	5 700.10	6 060.73
	Diff	-601.43	-600.84	-599.50	-598.54	-536.21	-469.10	-401.30	-333.60	549.06	778.71	1 008.32	1 238.79	1 868.13	2 263.30	2 694.40	3 107.62
	%	-25.45	-25.42	-25.34	-25.28	-21.31	-17.54	-14.16	-11.15	**12.36**	**16.09**	**19.25**	**21.98**	**27.28**	**29.77**	**32.10**	**33.90**
6%	Trad	1 581.32	1 582.03	1 582.74	1 583.46	1 654.94	1 714.40	1 744.60	1 834.87	2 648.25	2 853.50	3 058.75	3 264.01	4 015.35	4 439.50	4 863.70	5 287.82
	Advanced	2 737.85	2 738.10	2 738.34	2 738.59	2 779.54	2 810.00	2 841.20	2 872.31	3 146.45	3 228.19	3 309.91	3 391.64	3 774.31	3 972.60	4 170.90	4 369.25
	Diff	-1 156.53	-1 156.07	-1 155.60	-1 155.13	-1 124.60	-1 095.60	-1 096.60	-1 037.44	-498.20	-374.69	-251.16	-127.63	241.04	466.90	692.80	918.57
	%	-73.14	-73.08	-73.01	-72.95	-67.95	-63.91	-62.86	-56.54	-18.81	-13.13	-8.21	-3.91	**6.00**	**10.52**	**14.24**	**17.37**
8%	Trad	1 293.49	1 293.92	1 294.37	1 294.81	1 344.55	1 377.60	1 411.20	1 444.65	2 032.62	2 175.74	2 318.87	2 462.00	3 058.19	3 370.40	3 682.60	3 994.78
	Advanced	2 657.10	2 657.23	2 657.36	2 657.49	2 686.87	2 702.40	2 718.30	2 734.12	2 915.34	2 972.38	3 029.43	3 086.49	3 410.99	3 563.40	3 715.80	3 868.25
	Diff	-1 363.61	-1 363.31	-1 362.99	-1 362.68	-1 342.32	-1 324.80	-1 307.10	-1 289.47	-882.72	-796.64	-710.56	-624.49	-352.80	-193.00	-33.20	126.53
	%	-105.42	-105.36	-105.30	-105.24	-99.83	-96.17	-92.62	-89.26	-43.43	-36.61	-30.64	-25.37	-11.54	-5.73	-0.90	**3.17**
10%	Trad	1 104.99	1 105.28	1 105.57	1 105.85	1 143.88	1 163.40	1 183.10	1 202.84	1 645.06	1 750.88	1 856.70	1 962.53	2 461.82	2 707.00	2 952.20	3 197.35
	Advanced	2 608.40	2 608.47	2 608.54	2 608.62	2 632.34	2 640.70	2 649.50	2 657.67	2 783.87	2 827.48	2 871.08	2 914.69	3 206.92	3 334.60	3 462.30	3 590.02
	Diff	-1 503.41	-1 503.19	-1 502.97	-1 502.77	-1 488.46	-1 477.30	-1 466.40	-1 454.83	-1 138.81	-1 076.60	-1 014.38	-952.16	-745.10	-627.60	-510.10	-392.67
	%	-136.06	-136.00	-135.95	-135.89	-130.12	-126.98	-123.95	-120.95	-69.23	-61.49	-54.63	-48.52	-30.27	-23.18	-17.28	-12.28

Results for crack seal option

Considered for 40-year life for 40 000 and 60 000 AADT only.

Traditional surfacing based on crack sealing option

Advanced – 3 times cost of traditional, 40 years life

	Traffic (AADT)	40 000				60 000			
	Heavy vehicles	5%	10%	15%	20%	5%	10%	15%	20%
Disc. rate 3%	Trad-seal	1 822.84	1 826.60	1 830.35	1 834.12	1 997.82	2 183.42	2 389.85	2 596.30
	Advanced	1 931.06	1 931.72	1 932.38	1 933.04	2 019.56	2 109.59	2 201.55	2 293.49
	Diff	-108.22	-105.12	-102.03	-98.92	-21.74	73.83	188.30	302.81
	%	-5.9	-5.8	-5.6	-5.4	-1.1	3.4	7.9	11.7
6%	Trad-seal	1 237.89	1 239.25	1 240.55	1 241.89	1 312.35	1 374.81	1 443.90	1 512.99
	Advanced	1 744.55	1 744.80	1 745.04	1 745.29	1 786.24	1 816.75	1 847.88	1 879.01
	Diff	-506.66	-505.55	-504.49	-503.40	-473.89	-441.94	-403.98	-366.02
	%	-40.9	-40.8	-40.7	-40.5	-36.1	-32.1	-28.0	-24.2
8%	Trad-seal	1 034.44	1 035.18	1 035.88	1 036.60	1 083.48	1 115.89	1 151.41	1 186.95
	Advanced	1 678.25	1 678.38	1 678.51	1 678.64	1 708.02	1 723.57	1 739.42	1 755.27
	Diff	-643.81	-643.20	-642.63	-642.04	-624.54	-607.68	-588.01	-568.32
	%	-62.2	-62.1	-62.0	-61.9	-57.6	-54.5	-51.1	-47.9
10%	Trad-seal	906.65	907.07	907.48	907.90	942.98	960.90	980.32	999.78
	Advanced	1 637.75	1 637.82	1 637.89	1 637.97	1 661.69	1 670.04	1 678.53	1 687.02
	Diff	-731.10	-730.75	-730.41	-730.07	-718.71	-709.14	-698.21	-687.24
	%	-80.6	-80.6	-80.5	-80.4	-76.2	-73.8	-71.2	-68.7

Annex E

Working Group on Economic Evaluation of Long-life Pavements: Phase I

List of Working Group Members

AUSTRALIA
Anthony OCKWELL
Department of Transport and Regional Services

BELGIUM
Ann VANELSTRAETE
Belgium Road Research Centre

CANADA
Michael F. OLIVER
Ministry of Transportation, Canada

DENMARK
Jørgen CHRISTENSEN (Chair)
Danish Road Institute

Finn THOEGERSEN
Danish Road Institute

FINLAND
Heikki JAMSA
Finnish Asphalt Association

FRANCE
Nicole COUTANT
LCPC

Jean-Michel PIAU
LCPC

Patrice RETOUR
LCPC

HUNGARY
Andras GULYAS
Technical and Information Services on National Roads

István SZARKA
Technical and Information State Services on National Roads

NETHERLANDS
Govert SWEERE
Ministry of Transport, Public Works and Water Management

J.J. VAN DER VUSSE
Ministry of Transport, Public Works and Water Management

NORWAY
Sverre DIGERNES
Norwegian Public Roads Administration

POLAND
Wlodzimierz SUPERNAK
General Directorate for National Roads and Motorways

SWEDEN
Safwat SAID
Swedish National Road and Transport Research Institute (VTI)

SWITZERLAND
Markus CAPREZ
Swiss Federal Institute of Technology (ETH)

UNITED KINGDOM
Wyn LLOYD
United Kingdom Highways Agency

UNITED STATES
Jack YOUTCHEFF
Federal Highway Administration, Turner-Fairbank Highway Research Center

OECD SECRETARIAT
Ceallach LEVINS
John WHITE

Glossary

Advanced wearing course: This is a wearing course consisting of high-technology materials with the properties that would permit a substantive increase in durability with a substantive increase in expected life, perhaps 30 years or more.

Aggregate: Hard inert, mineral material consisting of gravel, sand, crushed stone and recycled materials.

Base (course): Base course is a layer of specified, selected material of designed thickness, placed immediately below the surfacing materials constructed on the subgrade soils or on subbase materials for the purpose of adding structural capacity, distributing load, providing drainage or minimising frost action. Base course materials can be granular or an asphalt or cement bound granular material.

Bitumen: Asphalt cement, a dark brown to black cementitious material, in which the predominant constituents are bitumens, occur in nature and are obtained as residue in petroleum manufacturing and are used as binder in asphalt aggregate mixes.

Crushed base course (CBC): Crushed granular aggregate placed as base course material.

Crushed granular equivalency (CGE): A structural design term used as an approximate measure of expressing the contribution of each pavement structural layer component in terms of an equivalent thickness of granular base. The CGE is the structural equivalency and is equal to approximately two times the asphalt thickness plus the total thickness of the underlying granular layers.

Dense friction course (DFC): A commonly used, high-quality designed mix using a well-graded aggregate (even distribution of aggregate particulate sizes throughout the mix) gravel, sand and mineral filler such that a dense, non-permeable mix and aggregate structure is achieved.

Design life: The design life is the structural design life used for design purposes. The design life considers the entire road structure, including subbase, base and surface layers.

End of life: For the wearing course, the end of pavement life occurs when the top surface layer is rehabilitated, replaced, removed, milled or overlaid.

Expected life: The expected life is the life, in years, of the surface layer before rehabilitation. The expected life is based on empirical data or agency experience.

Hot mix asphalt (HMA): High-quality, controlled mixture of aggregate and asphalt binder that is mixed in a heated condition in an asphalt plant and placed on the road with a mechanical paver and compacted to ensure good pavement performance. Hot mix asphalt can be a stone mastic asphalt or a Superpave asphalt or an open graded friction course asphalt.

International roughness index (IRI): This is defined as the measure of the pavement smoothness based on the longitudinal profile of the pavement surface as defined in the World Bank Technical Paper Number 46, "Guidelines for Conducting and Calibrating Road Roughness Measurements".

Long-life pavement: A long-life pavement is a structural pavement that maintains structural capacity and strength over time. The load resistance and durability are provided by a series of layers. In theory, for asphalt pavements, the lower asphalt layer provides high fatigue resistance, the intermediate layer provides rut resistance and the upper layer provides a durable wearing surface. The wearing surface provides the required characteristics regarding skid resistance, durability and noise. With an increase in the thickness of asphalt layers, the pavement would be designed such that rutting and fatigue cracking would not occur and the pavement, with periodic maintenance or replacement of the wearing course, would achieve a long life.

Maintenance: Maintenance activities are measures that maintain the integrity of the surface with respect to smoothness, distress, rutting, skid resistance and appearance, without necessarily increasing the structural strength of the pavement. Routine maintenance treatments include crack sealing, pothole repair, patching, spall repairs, slab repairs, crack and joint sealing, slab repair, fog sealing, levelling and drainage improvements. Major maintenance includes deep patching, scarification, texturisation, load transfer slab repair, chip seal, slurry seal and micro-surfacing. Maintenance extends pavement life by several years, commonly from two to five but can be up to approximately 12 years. With respect to the wearing course for a pavement, maintenance does not result in the end of life of the wearing course.

Open graded friction course (OGFC): or very porous asphalt is commonly used throughout all OECD countries but predominantly in the European countries. This mix is a gap-graded quality mix, permeable with a high void content and is used to reduce noise and splash and spray while maintaining friction requirements. Open graded friction course pavements require a highly processed aggregate and strict attention to asphalt content and construction details.

Other additional mix types reported by OECD agencies included the standard mix types successfully used over time by agencies. These mix types have been termed by the agencies as a dense graded mix, dense graded friction course, class 1, coarse, medium or fine mix. These mix types are simply referred to as hot mix asphalt (HMA). These mixes would be considered the workhorse type of mix used for many years by agencies and they typically consist of a straight-run standard binder (non-modified) with a well-graded aggregate gradation.

Pavement structural layers: Pavement layers are the combination of material layers constructed over the subgrade soils or rock in order to provide an acceptable structural facility on which to operate vehicles. The structural layers may typically consist of a wearing course, surface layer, base course layer and subbase layer.

Rehabilitation: Rehabilitation activities are maintenance techniques that are required to renew or extend the pavement life when roughness, lack of structural integrity, or excessive surface distress results in an unacceptable pavement in terms of serviceability, increased user costs and concerns for safety. Rehabilitation may also be used to strengthen an existing pavement. Rehabilitation is necessary when the condition of the pavement is such that maintenance techniques are no longer able to keep the pavement in an acceptable condition cost effectively. Rehabilitation treatments are generally more costly than maintenance treatments. After rehabilitation, the condition of the highway would be considered to be similar or near to that achieved during the initial construction. Rehabilitation techniques include overlaying or resurfacing, milling and replacing or resurfacing, hot in-place recycling, cold in-place recycling, reconstruction and full-depth reclamation. With respect to the wearing course, rehabilitation results in end of pavement life and upon rehabilitation, a new life cycle for the wearing course would begin.

Stone matrix or stone mastic asphalt (SMA): Hot mix asphalt containing a premium rut-resistant mix with high-quality materials. Aggregates are typically cubical and are hard, abrasion-resistant crushed stone. The mix contains gap-graded, coarse aggregates with mineral filler and additives such as fibres. The matrix would be obtained by using polymer modified bitumen or a relatively stiff unmodified bitumen. This quality mix would be very useful in urban areas with high truck volumes. The SMA provides a stone skeleton, rock-on-rock particle contact, for the primary load carrying requirement. The matrix provides the additional mix stiffness and consists of fibres, mineral filler and a polymer modified binder or a relatively stiff unmodified binder. Many agencies have experience with this mix type and its use is common throughout the European OECD agencies.

Subbase (SB): The layer of select compacted granular material within the pavement structure, placed on the subgrade soils and which is overlain by the base course materials.

Subgrade (SG): The completed earthworks within the road prism prior to the construction of the pavement granular subbase and base or other pavement layers. The subgrade consists of the *in situ* material of the roadbed and any fill materials.

Superpave: The Superpave mix is a quality rut-resistant mix with a high rock content providing a stone on stone load-carrying capacity similar to SMA but typically containing a more graded aggregate and is without fibres. A quality hot mix "superior performing pavement" derived from the US SHRP programme, consisting of a rut-resistant, durable mix using quality planned and specified aggregates and specified bitumen selection methods complete with a quality rigorous mix design method using standardised protocols and equipment.

Wearing course: The wearing course is the top layer of a pavement structure which provides the riding surface for vehicles. It is designed to be resistant to rutting, weathering, thermal cracking and wear. The wearing course requires periodic maintenance and replacement and the underlying structural layers are considered as long-life or permanent pavement layers with little or no maintenance requirements.

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