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The International Transport Forum was created under a Declaration issued by the Council of Ministers of the ECMT (European Conference of Ministers of Transport) at its Ministerial Session in Dublin on 17 and 18 May 2006. It reflects the Ministers' will to transform the ECMT into an international forum whose specific objective is to help political leaders and a larger public better understand the role of transport as a key element in economic growth, as well as its effects on the social and environmental components of sustainable development.

Established under the legal authority of the Protocol of the ECMT signed in Brussels on 17 October 1953, as well as the appropriate legal instruments of the OECD, the Forum is considered an international entity endowed with all the necessary support structures and financing mechanisms. Its administrative headquarters is located in Paris.

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In 2004, the ECMT and the OECD created the Joint Transport Research Centre. The Centre conducts co-operative research programs that address all modes of transport that in turn support policy-making in member countries. Through some of its projects, the Centre also makes contributions to the activities of the International Transport Forum.

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FOREWORD

In most countries, the road network constitutes one of the largest community assets and is predominately government-owned. Road administrations must maintain, operate, improve, replace and preserve this asset while, at the same time, carefully managing the scarce financial and human resources needed to achieve these objectives.

Maintaining safe, comfortable and durable surfaces on heavily trafficked motorways and major roads has long been a major challenge to road owners and the operational units responsible for managing the construction and maintenance of their roads.

The issue of prolonged service life of road pavements has been a key concern for road professionals for more than a decade, heralded by the appearance of the term "long life pavements" as distinct from the term "durable" pavements, which has carried the notion of satisfactory pavement performance for many years.

"Long life pavements" are seen as particularly desirable on heavily trafficked roads to avoid the costs of road maintenance works, including the delays they inflict on road users, particularly in congested traffic conditions.

Since long life properties are considered achievable for the structural, unexposed layers of pavements, this study has focused on the surface or wearing courses of road pavements.

The objective of this second phase of the Economic Evaluation of Long Life Pavements project was to strengthen knowledge about the potential and the limitations of the two prospective candidate materials that had been identified in Phase I for further research as possible innovative long life wearing courses *i.e.: epoxy asphalt and high performance cementitious materials*.

The Long Life surfaces for Busy Roads report is the result of over two years of work by a group of expert researchers in the field of road pavements from many OECD and ITF countries. The report was prepared under the aegis of the Joint OECD/ITF Transport Research Centre.

ACKNOWLEDGEMENTS

The project has enjoyed the support of national road authorities and their research providers in many countries.

The task of the Working Group was greatly facilitated by the institutes that generously hosted and organised various meetings in support of the project and the many people who contributed their expertise.

The Working Group would like to warmly thank the following organisation in particular for their major contributions to the project as a whole and for their funding and support for the actual laboratory testing carried out in their country:

Organisation	**Country**
New South Wales (NSW) Roads and Traffic Authority (RTA)	Australia
Danish Road Institute (DRI)	Denmark
DBT Engineering	Denmark
Laboratoire Central des Ponts et Chaussées (LCPC)	France
Federal Highway Research Institute (BAST)	Germany
Transit New Zealand	New Zealand
State Road Scientific Research Institute (DerzhdorNDI)	Ukraine
Transport Research Laboratory (TRL) Ltd UK Highways Agency	United Kingdom
Turner Fairbank Highway Research Center	United States

ABSTRACT

ITRD[1] NUMBER E133540

While recent research has resulted in significant improvement in the durability of the structurally important base layers of road pavements, surface pavements have barely kept up with the increase in the loads and density of traffic. Frequent closures of roadways for the purpose of repairs and repaving constitute a growing problem for road administrations and road users, due to their costs, their limitations on road lane availability, the congestion and disruption they cause to traffic flows and the related delays and costs to road users.

In such environments, long life pavements using advanced surfaces potentially have a great deal to offer, particularly if they can provide high quality performance without the need for significant repair for more than 30 years. On highly trafficked roads, research has indicated that, in these circumstances, the benefits of avoiding major repairs and repavings may become large enough to justify the higher initial costs of such advanced pavement surfaces.

This report is the output of an expert Working Group with representatives from 18 countries which researched and tested Epoxy Asphalt and High Performance Cementitious Materials (HPCM) as candidates for advanced road surfaces.

The report outlines the testing undertaken during a period of over two years in national laboratories in eight OECD/ITF countries: Australia, Denmark, France, Germany, New Zealand, Ukraine, United Kingdom and United States. It provides the test results; assesses the performance of the materials on indicators important to longevity; identifies future research and construction issues; compares indicative costs with conventional (reference) materials; and draws conclusions on the potential use of these advanced surfacing materials on highly trafficked roads. The report also makes recommendations for the next stage of the work including proposed trials of these materials in the field.

Fields: Pavement design (23); bituminous binders and materials (31); concrete (32); other materials used in pavement layers (33).

Keywords: Bituminous mixture, cost benefit analysis, durability, economics of transport, epoxy resin, flexible pavement, high performance concrete, life cycle, long term, main road, motorway, OECD, pavement design, rigid pavement, surfacing, wearing course.

1. The International Transport Research Documentation (ITRD) database of published information on transport and transport research is administered by TRL on behalf of the Joint OECD/ITF Transport Research Centre. ITRD contains over 350 000 bibliographical references, and about 10 000 are added each year. Input to the ITRD database is provided by more than 30 renowned institutes and organisations from around the world. For more details about ITRD, please contact itrd@trl.co.uk or see the ITRD website at www.itrd.org.

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Long life surfacing for heavily trafficked roads

Maintaining safe, comfortable and durable surfaces on heavily trafficked motorways and major roads has long been a major challenge to road owners and their operational units, responsible for managing the construction and maintenance of their roads.

"Long life pavements" are seen as particularly desirable on heavily trafficked roads to avoid the costs of road maintenance works, including the delays they inflict on road users, particularly in congested traffic conditions. Since long life properties are considered achievable for the structural, unexposed layers of pavements, this study has focused on the surface or wearing courses of road pavements.

Taking potential user cost savings into account, the Phase I report concluded that: *"…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."*

Candidate materials for long life surfacing

In the current study, the two prospective candidate materials identified – *epoxy asphalt*; and *high performance cementitious materials (HPCM)* – were researched and tested by the national laboratories of the countries actively involved.

Epoxy Asphalt

Epoxy Asphalt has already demonstrated its ability to deliver 40 year service life as a road surfacing on steel bridge decks. The testing undertaken in this project focussed on its potential for long service life on underlying road pavements which are more flexible than stiff bridge decking.

The extensive testing undertaken indicated that Epoxy Asphalt should produce a durable, long lasting material suitable for use on heavily trafficked roads. It confirmed Epoxy Asphalt is a premium material that outperforms conventional binders on the important indicators of potential long service life.

The challenges of construction with this material are considered moderate as existing plant and equipment can be used. However, hardening of the material during delays in construction increases the risk of construction failures and damage to plant. It will also be important to establish when, after the initial blending of the Epoxy Asphalt, the curing reaction is complete, given the health effects of the uncured epoxy asphalt binder, which have resulted in restrictions on its use in some countries.

The conclusion reached is that, on the basis of its performance characteristics, Epoxy Asphalt surfacing material is ready for large scale demonstrations on the roads.

HPCM

The HPCM wearing course tested is an innovative new system which was developed during the study. It consists of a layer of ultra-high performance, steel fibre-reinforced fine mortar, in which hard, polish resistant aggregate particles are embedded, forming a 10 mm composite layer. The aim was to assess the feasibility of its use as an ultra-thin HPCM wearing course.

Testing has shown that HPCM has great strength and integrity. On the basis of the testing undertaken, there is a high probability that HPCM wearing courses will be practically maintenance-free during a likely service life of 30 years, even on high traffic roads.

Production of HPCM is seen as a manageable process using existing know-how and equipment. However, laying the HPCM mortar and inserting the chippings will require some modification of existing equipment or development of new equipment. Further testing in the field is also needed to achieve the best balance between mixing/handling/placing and the performance of the hardened material. Once this is done, it is expected the final HPCM product will be characterised by high safety, comfort, durability and moderate noise emissions and, on the basis of performance characteristics, will also be ready for field trials.

Comparison of Indicative Costs

Costs relative to conventional (reference) surfacings will be critically important for economic viability. For Epoxy Asphalt, the increased costs can be estimated with some confidence. For HPCM. Material, mixing and transport costs may be extrapolated from current practice, but the increase in paving costs will depend on new or modified paving equipment that will be required.

Indicative cost estimates provided for Epoxy Asphalt and HPCM surfacings suggest that, in Western Europe, their costs could be between 2 and 3 times the cost of conventional treatments.

While the estimates are indicative only, the cost premiums for the Epoxy and HPCM wearing courses, by comparison with conventional (reference) surfacing costs, are probably less than expected previously. In part, this is due to a better understanding of the costs and production processes involved; and in part to the significant recent increase in the cost of conventional asphalt surfacing, particularly in Western Europe.

On this basis, there are reasonable prospects for economically viable, long life surfacings on heavily trafficked roads in many countries. It is now clearly open to each country to consider on a case-by-case basis – using their own data and analysis – where and when such advanced surfacing could be used.

Proposed Field Trials

Limited field trials under traffic – either on the road network or off-road – as proposed in the report are the logical next phase. As always, there are risks with such larger-scale trials of new materials and techniques. Nevertheless, some road authorities, perhaps in partnership with industry, can be expected to take this next step. The report recommends:

- Coordinated programmes of field trials of the Epoxy Asphalt and HPCM surfacing materials, to begin by 2009 and be completed by 2011, which will research production, laying and quality control as well as cost – and demonstrate the performance of such surfacings under real traffic and environmental conditions.

- Interested road authorities be invited to register their interest in joining the proposed trials as soon as possible after the publication of this report.

EXECUTIVE SUMMARY

ES.1 Context

Maintaining safe, comfortable and durable surfaces on heavily trafficked motorways has long been a major challenge to road owners and their operational units, who manage the construction and maintenance of their roads.

Rigid concrete roads are often chosen for roads with much heavy traffic as they offer high strength and durability, but modern requirements for comfort and noise generation imply a limited initial macrotexture, which may lead to low skid resistance after some ten or twenty years of traffic.

Semi rigid pavements permit the use of flexible surfacing with a rigid, cementitious substrate, which can meet the bearing requirements for a heavy-duty road, but will require relatively frequent maintenance and repaving in order to provide the safety and comfort required, e.g. on motorways with high volumes of passenger vehicles travelling at relatively high speeds.

Flexible pavements, in which the surfacing as well as the base layer are made of flexible, bitumen-bound materials, constitute the third and probably most common pavement type for high-trafficked roads, despite their inherent problems of deformation and fatigue under the loads of the heavy-vehicle share of the traffic.

While recent research has resulted in significant improvement in the durability of the structurally important base layers of pavements, surface pavements have barely kept up with the increase in the loads and density of traffic. At the same time the demand for low noise pavements has also challenged the basic durability objective, inasmuch as the structures of low noise pavements tend to conflict with the service life of these pavements. Thus frequent closures of the roadways for the purpose of repairs and repaving are still the order of the day, but constitute a growing problem as an important factor in the increasing problems of congestion.

Therefore, “Long life surface pavements” have a great deal to offer on highly trafficked roads where road works are increasingly constrained because of the disturbances and delays they inflict on road users. In such environments, long life pavements will be expected to show high quality performance without the need for significant repair for more than 30 years. It is also in such environments that the benefits of avoiding major repairs and repavings may become large enough to justify the higher initial costs of such pavements.

ES.2 Phase I Report

The OECD/ECMT’s *Economic Evaluation of Long Life Pavements – Phase I* project was completed with the publication of the Phase I report in 2005.

The *Phase I* report explored the economic feasibility of long life surfacings and identified possible candidate materials, focussing on the performance characteristics and envelope of costs that would be required for such new wearing course materials to be economically viable.

ES.2.1 Phase I Findings

The Phase I report drew the following conclusions on economic viability[1]:

> *"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.*

Two prospective candidate materials – epoxy asphalt and high performance cementitious materials (HPCM) – were identified for further research as possible innovative long life wearing courses.

ES.3 Phase II Work – Findings

The scope of the Phase II study as approved by Transport Ministers in 2004 was as follows:

> *"This next phase of the project will coordinate sufficient initial testing by national testing laboratories to assess the durability of the wearing courses. This will involve small-scale testing (laboratory testing and accelerated load testing) of the most promising pavement materials".*

The intentions for the work in Phase II included to strengthen current knowledge about the potential and the limitations of the two materials *(Epoxy Asphalt and High Performance Cementitious Materials)* identified in Phase I as promising candidate materials.

The Working Group on Economic Evaluation of Long Life Pavements Phase II, which was established to undertake the project was chaired by Denmark and had 37 members from 18 countries and the Secretariat. This report documents and provides analyses of the results of this major coordinated research effort. A smaller group of members and countries led the research work. Nine national laboratories from 8 countries (Australia, Denmark, France, Germany, New Zealand, Ukraine, United Kingdom and Unites States) participated actively in the wearing course testing programmes, which were guided by Technical Coordinators from the US Federal Highway Administration's Turner Fairbank Highway Research Centre and France's Laboratoire Central des Ponts et Chausées (LCPC).

Each laboratory participating in the *Epoxy Asphalt* (EA) testing utilised local materials and standard as well as advanced test procedures (those typically used in the design of high volume pavements). Effectively the epoxy-asphalt pavement material was compared with a conventional reference pavement (typically with a modified binder) using the same testing and mix design. For *High Performance Cementitious Materials* (HPCM), in order to have a consistent set of data, each participating laboratory used the same constituents and mixtures in their tests.

It was recognised that the Epoxy Asphalt and HPCM surfaces will have to perform extremely well across a range of functional properties to be able to achieve the goal of a practically maintenance-free 30 year service life. Taken together, the testing provided valuable insights into the potential longevity of the EA and HPCM wearing courses when subjected to real traffic and environmental conditions.

ES.4 Epoxy Asphalt

Epoxy Asphalt is a premium material, which has been used for many years as a road surface on stiff bridge decking. The first such application, in San Francisco, is still meeting performance requirements, after 40 years of service. Over time, Epoxy Asphalt has been more widely used for stiff bridge decking applications in a number of other countries (*e.g.* recent extensive use in China).

Administrations have not used Epoxy Asphalt for regular road pavement surfaces as cheaper materials have been available which, although they may not last as long, could be replaced relatively easily and each time at moderate cost. The Phase II work provided an opportunity to test the properties and suitability of Epoxy Asphalt for use in such highway environments.

The many tests performed on the acid-based epoxy asphalt materials in this project covered all the important questions regarding the properties which are known to be critical for the durability and service life of a pavement under heavy traffic. The testing focussed in particular on the *fatigue* and fracture properties which are crucially important for longevity. The effect of oxidation on the binder properties and condition of the surfacing was also considered to be crucial.

ES.4.1 Main findings in Phase II testing of Epoxy Asphalt

On the basis of the comprehensive testing undertaken, acid-based Epoxy Asphalt mixtures were found to have greatly improved performance compared to conventional mixtures. In particular compared to conventional asphalts, cured epoxy asphalts are significantly:

- Stiffer (higher modulus) at service temperatures, with greater load spreading ability.
- More resistant to rutting.
- More resistant to low temperature crack initiation and propagation.
- More resistant to surface abrasion from tyre action, even after oxidation.
- More resistant to fatigue cracking (although the benefits are less marked at higher strain levels).
- Less susceptible to water induced damage.
- More resistant to oxidative degradation at ambient temperatures.

A limited accelerated pavement testing (APT) trial of epoxy Open Graded Porous Asphalt (OGPA) resulted in early signs of surface abrasion in the control section but not in the epoxy. Tests on the APT sections demonstrated that the skid resistance of epoxy asphalt was not significantly different from that of conventional asphalt.

In short, the tests undertaken confirmed that epoxy asphalt is a premium material that outperforms conventional binders. Test performance of the Epoxy Asphalt materials studied in this phase was considered greatly superior when compared with conventional materials, on the important indicators central to assessment of the potential for long service life.

ES.4.2 Conclusions on performance expectations for Epoxy Asphalt

Performance expectations for the longevity and durability of Epoxy Asphalt surfaces were built up during the project taking into account the results of the tests undertaken and experience with their relationship to longevity in the field. Nearly all the testing has indicated that Epoxy Asphalt should provide a durable long lasting surfacing, even in the most heavily trafficked road situations.

There must be close consideration of the type of epoxy materials to be used and great care in the choice of aggregates if the best performance is to be achieved. Epoxy asphalt needs close supervision at time of production and laying to ensure full mixing is carried out and that time and temperature are carefully monitored to achieve the best performance outcomes.

If all aspects of the process are correctly handled, Epoxy Asphalt should be able to provide a surfacing material that can be expected to meet the aim for a much extended, practically maintenance life, *i.e.* 30 years or more.

ES.4.3 Issues for future research and testing on Epoxy Asphalt

Important issues for consideration in future research include:

- *Curing and construction time.* Further laboratory studies are needed prior to any demonstration projects to optimise the curing profile with the desired rate of reaction for the local conditions (time for curing, distance of transport and laying etc).
- *Curing period.* It is important to establish when after the initial blending of the epoxy asphalt the reaction is complete.
- *Curing temperature.* Some epoxy systems have shown the ability to cure rather rapidly at a lower temperature than might be expected. The prospects for lower temperature curing – and the related potential for energy and cost savings during production – need further research.

ES.4.4 Construction issues for Epoxy Asphalt

Epoxy Asphalt is a material with high stiffness that can be applied in thin surface layers. Production experience to date for the relatively small quantities used has almost exclusively been with a batch plant that gives good control of mixing time – an important part of its subsequent curing and post-curing properties. However, for the trials in New Zealand a continuous mix drum plant was used without problems.

Due to the thermosetting nature of the material, extra care is required in the timing of manufacturing and construction phases to ensure the product is not over-cured before compaction. The risk of construction failures and damage to plant is greater than with conventional bitumen. For both these areas, the perceived risk is likely to diminish in importance as experience with the material grows.

When uncured, certain epoxy materials are strong allergy provoking compounds. These were not used for the Epoxy Asphalts in this project. However, if such materials are used, special equipment and safety precautions would be required for all involved in handling them while uncured.

ES.5 High Performance Cementitious Material (HPCM)

High-Performance Cementitious Material (HPCM) is an innovative product which was developed and tested for road surfacing applications for the first time during the present project. This pavement consists of a layer of ultra-high performance, fibre-reinforced fine mortar, in which hard, polish resistant aggregate particles are embedded, forming a 10 mm composite layer. As a new surfacing material with no obvious reference material, considerable work was undertaken on the development of HPCM mixes with the most suitable properties and evaluation of the HPCM needed to focus principally on the actual test results.

The initial mix-design developed based on early research was improved during the project. It evolved through a number of stages which included: selection of constituents, mix-design and laboratory application processes and assessment of behaviour. It was assessed against critical properties such as: skid resistance; binder function; protection of lower pavement layers; cracking behaviour; and bond between the cementitious mortar and the bituminous substrate.

Overall, the thickness of the fibre-reinforced mortar layer needed to be minimised for cost reasons. At the same time, it needed to be thick enough to allow for good penetration of the chippings in the fresh mortar.

The improved mix design took into account the results of the extensive materials testing undertaken by national laboratories. A thin cementitious surface layer is likely to develop discrete cracks unless the layer is restrained by the underlying pavement structure. However, regardless of the restraint provided by the bond to the underlying structure, micro cracks will inevitably develop to compensate for natural shrinkage and temperature strains. To ensure that crack openings remain micro level, some reinforcement is needed and – given the thinness of the mortar layer – the research indicated that it required steel fibres added to the mix to fully meet this need.

ES.5.1 Main findings in Phase II testing of HPCM

The test programme was undertaken primarily at laboratory scale and focussed on the main performance issues:

- General physical properties of HPCM particularly in regard to bond to substrate and capability to establish a lasting bonding of chippings to the matrix.
- Ductility and fatigue properties.
- Durability under environmental impact.
- Surface properties, noise and skid resistance.

Testing of the HPCM matrix for compressive strength, tensile strength and modulus of elasticity indicated the material can be characterised as High Strength/High Modulus. The results indicate HPCM wearing courses will have good bonding properties as well as durability, confirming these objectives have been achieved.

Testing at medium scale demonstrated that a durable bond between asphalt binder course and HPCM can be established, provided the asphalt surface prior to paving of HPCM has been carefully scarified and cleansed. It is also critical for this asphalt to be in the high range regarding E-modulus and temperature resistance. While a loss of chippings in the order of 10% could be expected, primarily in the very early stages of the pavement service life, the bonding between matrix and chippings appeared to be of a sufficiently high quality to indicate that the majority of the chippings will stay in place for the full service life of the pavement.

ES.5.2 Conclusions on performance expectations for HPCM

Testing has shown that HPCM has great strength and integrity. It is clear that certain requirements need to be met – including a strong and even lower layer and careful embedding of chippings – to ensure maximum performance.

By comparison with Epoxy Asphalt, the HPCM solution needs more development, including operational laying techniques, before being ready for commercial introduction as a long life surfacing.

However, the tests undertaken in Phase II at the same time the HPCM mix-design was being developed indicate there is a high probability that the current uncertainties about HPCM applications will be overcome.

From the testing and performance in the tests, it is considered that, if the HPCM layer performs well for the first 1-2 years, then it is unlikely to fail in the following years. It is the expectation that this surface, based on further trials, can be developed into a final product characterised by high safety, comfort, durability and limited noise emission.

ES.5.3 Issues for future research and testing on HPCM

A number of issues were identified for future research and testing, including:

- *Effect of water dosage on HPCM properties.* The water dosage has a significant impact on mortar engineering properties, such as: ease of mixing (at industrial scale) and workability; chippings loss; and bond with the asphalt.
- *Industrial application technology.* The adaptation of existing equipment or the practical development of new pavement laying equipment needs to be given a high priority to support the proposed Phase III field testing.
- *Two-dimension cracking tendency.* The test pad chosen for testing *two-dimension cracking tendency* needs to be fully representative of a real pavement and laid on a sufficiently stiff asphalt material.

ES.5.4 Construction issues for HPCM

Production of HPCM is seen as a manageable process using existing know-how and equipment. However, some modification of existing equipment or development of new equipment will be required for laying the HPCM mortar and inserting the chippings. Construction factors that are important include the availability of constituent materials, the mixing process and the workability of the freshly mixed material. The application of the chippings should ideally take place immediately after placing the thin mortar layer, i.e. with the same machine or with a chip spreader. A light rolling or tamping action is required to ensure the desired embedment of the chippings and a flat, even running surface.

ES.6 Summary Conclusions from the Project

The project reflects the concerns of road owners for the slow and limited innovation in pavement technology where industry has been leading the way for many years. It has intended and succeeded in demonstrating the scope for significant advances available in materials which are not normally considered in the traditional thinking of pavement development. Having now demonstrated the real potential for using alternative materials, it is expected that industry and road owners together can move towards the implementation of these innovations.

ES.6.1 Properties and performance of current premium pavements

Maintaining safe, comfortable and durable surfaces on heavily trafficked motorways has long been a major challenge to road owners and their operational units, who manage the construction and maintenance of their roads.

- Rigid concrete roads are often chosen for roads with much heavy traffic as they offer high strength and durability, but modern requirements for comfort and noise generation imply a limited initial macrotexture, which may lead to low skid resistance after some ten or twenty years of traffic.

- Semi rigid pavements permit the use of flexible surfacing with a rigid, cementitious substrate, which can meet the bearing requirements for a heavy-duty road, but will require relatively frequent maintenance and repaving in order to provide the safety and comfort required, *e.g.* on motorways with high volumes of passenger vehicles travelling at relatively high speeds.

- Flexible pavements, in which the surfacing as well as the base layer are made of flexible, bitumen-bound materials, constitute the third and probably most common pavement type for high-trafficked roads, despite their inherent problems of deformation and fatigue under the loads of the heavy-vehicle share of the traffic.

While recent research has resulted in significant improvement in the durability of the structurally important base layers of pavements, surface pavements have barely kept up with the increase in the loads and density of traffic. At the same time the demand for low noise pavements has also challenged the basic durability objective, inasmuch as the structures of low noise pavements tend to conflict with the service life of these pavements. Thus frequent closures of the roadways for the purpose of repairs and repaving are still the order of the day, but constitute a growing problem as an important factor in the increasing problems of congestion.

ES.6.2 Expected advantages of long life surface pavements

The two long life surface pavements types which have been the objects for the research described in this report are intended to serve as a cure to the problems of today's pavements. They are both developed with a target service life minimum of 30 years, and interpretations and extrapolations of the results of the tests conducted during this project do not contradict the assumptions that this target is achievable.

One of the two long life solutions, Epoxy Asphalt, has already demonstrated its ability to deliver such long service lives as pavement on bridge decks of steel. The laboratory tests and the testing in accelerated pavement loading facilities confirmed that this material has the superior qualities on performance indicators useful for assessing longevity, such as stiffness and resistance to rutting, low temperature cracking, fatigue cracking and surface abrasion (even after oxidation) and is less susceptibility to water induced damage.

Experiences from the testing as well as separate consideration of the available technologies provided insights into the production and construction process which will be needed for larger scale use of the EA materials for surface pavement on highways. It was concluded that these processes do not present unusual problems, although timing and proper protection of the workers' health are important considerations.

The other long life solution, High Performance Cementitious Material with steel fibre reinforcement, represents a novel application of a material class which has been intensively researched for other construction purposes in recent years. It was therefore known from the onset, that it provides exceptionally high strength, even when used as here in a wafer thin pavement of only 10 mm. Much research was spent on designing the concrete mix to achieve a composition of materials which is not susceptible to the formation of cracks, and then to determine the best way to ensure a long-lasting bond to the substrate. Further efforts were spent on finding ways of embedding the aggregates in the matrix in ways that make them stick and provide for a good multi-year friction performance. This challenge was also met. HPCM has, in short, demonstrated its long life performance capabilities by properties such as its ability to bond to the substrate and establish a lasting bonding of chippings to the matrix, its fatigue properties, durability under environmental impact, and its surface properties, particularly skid resistance.

Production of HPCM is seen as a manageable process using existing know-how and equipment, while it is less straightforward to lay it with existing technology without some modification or equipment development.

It is concluded that both materials, High Performance Cementitious Material with steel fibre reinforcement as well as Epoxy Asphalt, are likely – at high levels of probability – to be able to provide long life solutions to the demand for surface pavements which can be placed on existing pavements if these have a long remaining life.

There is of course a cost to this, which must be considered, and which is summarised in the next section and the associated table. It is also obvious that both materials now need to be tested under traffic in limited trials after using realistic production and laying methods. This is discussed in the final section.

ES.6.3 Indicative Costs for Epoxy Asphalt, HPCM and conventional wearing courses

This section provides a comparison between the indicative cost estimates for EA and HPCM surfacing. It also compares these indicative estimates with current surfacing costs using conventional (reference) surfacing materials.

The actual costs for both types of surfacing are, of course, likely to vary depending on the amount used, and a range of other factors including the experience of the contractor and supplier involved and the location and country/region concerned.

Epoxy Asphalt costs and risks

The indicative costs set out in the Table below were estimated principally on the price of natural aggregate materials and of epoxy asphalt materials, and a typical price for mixing, transport and paving, assuming use of current production technology. Because experience is very limited, only a few countries were able to provide cost estimates.

The skid resistance of an epoxy asphalt surface will lessen in time and may need restoration within the structural life of the surface layer. Such a treatment was considered in the economic analysis carried out in Phase I but has not been included within the initial works costs that are included in Table ES1.

HPCM costs and risks

As there are yet no commercial applications, there is currently greater uncertainty about HPCM surfacing materials and costs than about EA surfacing costs.

The indicative costs of HPCM wearing courses are assessed by extrapolation of material, mixing and transport costs for current cementitious pavements and on estimated paving costs, which will be higher – although how much higher will depend on any new or modified paving equipment that has to be developed.

Conventional (reference) surfacing

Cost estimates were provided by several countries and assume typical 30mm thin surfaces or SMA type wearing courses as used in each country. Responses indicated that current costs for conventional surfacing which had risen significantly – particularly in Western Europe – could now be taken as around EUR 20 per square metre. The actual range was from EUR 13-25, depending on location.

Comparison of indicative costs

Table ES. 1 shows indicative costs for Epoxy Asphalt, HPCM and conventional (reference) asphalt 30mm 'thin surfacing' which has been used as a typical standard base material. The figures in the table are thought to be realistic assessments of indicative costs, as may be appropriate in Western Europe.

Table ES.1. **Comparison of indicative costs between materials**

Description	**Typical Surfacing Costs in €/M² for Western Europe**		
	Epoxy Asphalt 30 mm wearing course	**HPCM 10 mm wearing course**	**Conventional 30 mm asphalt solution**
Expected Lifespan	**~30 years**	**~30 years**	**7-15 years**
Milling 50-100mm	0.75-1.25	0.75-1.25	0.75-1.6
Binder course (50mm)	6-10	8-12	6-12
Tack/bond coat	0.25		0.1
Wearing course	18-33.5	18-22	6-12
Total costs	25-45(1)	27-35	13-25(2)

Notes: (1) Cost of restoration (once) of skid resistance during the service life not included. (2) Costs of minor repairs during 15 years of service not included.

The estimates in Table ES.1 suggest that the cost of an advanced surfacing could be between 2 and 3 times the cost of a conventional resurfacing treatment. The indicative cost premiums for the Epoxy and HPCM wearing courses, by comparison with conventional (reference) surfacing costs, are probably less than assumed for Phase I of the study. In part, this is due to having a better understanding of the costs and production processes involved, but is also due in part to the significant increase in the cost of asphalt surfacing, particularly in Western Europe, in recent years.

The whole life costing exercise completed in Phase I showed that the use of advanced surfacing on high-traffic roads would result in net benefits when the discount rate used in the analysis is below about 6 % p.a. and when the advanced surfacing does not cost more than about three times as much as conventional materials. These benefits were estimated on a whole life cost analysis over a period of at least 30 years and take user delay costs during maintenance into account. The indicative cost estimates set out in Table ES.1 would appear to be broadly consistent with this envelope of costs.

In these circumstances, it is clearly for each country to consider, using their own analysis with their own national data to decide on a case-by-case basis, when advanced surfacing could be appropriate and whether the long term benefits including reduced maintenance costs and associated user cost savings outweigh the increased initial costs. However, the indications are that there are reasonable prospects that this will be the case.

Having now demonstrated the real potential for using alternative materials, it is expected that industry and road owners together can move towards the implementation of these innovations. It is also obvious that both materials now need to be tested under traffic in limited trials after using realistic production and laying methods. This is discussed in the final section.

ES.7 Recommendations for Phase III Trials

The research in Phase II has provided comprehensive results from laboratory testing and trials in various accelerated pavement testing machines.

The expectations for the durability and long-life capabilities of the materials are based on extrapolations of observations made during the testing reported here, but nobody can give full guarantees for the behaviour of materials in the extrapolated time domain. Therefore, if the potential economic benefits of these advanced technology pavements types are to be realised, then the innovation process must be taken to the next phase, in which the materials are tested in larger scales under real traffic on roads or off roads.

The project has therefore progressed to the point where limited field trials under traffic – either on the road network or off-road – are the logical next phase, and necessary if the potential economic benefits of these materials and techniques are to be realised. It is also obvious that – as always with such larger-scale trials of new materials and techniques – there are risks. Still, it is assumed that some road authorities, perhaps in partnership with industry, will be prepared to take this step.

While such steps could be taken individually, jointly planned and coordinated trials and demonstrations offer shortcuts to a broader based and earlier establishment of better practices for all.

Such a coordinated trials programme would aim to demonstrate that the performance assumed from the laboratory tests and the accelerated testing will hold within the period of the trial under real traffic and environmental conditions – and that a large number of collateral aims and the material-specific aims described below will also be achieved.

ES.7.1 Overall aims of the trials

The overall aim of a coordinated programme of field trials of the Epoxy Asphalt and HPCM surfacings – which offer real prospects for use on long life pavements – is as follows:

- To demonstrate that the performance envisaged on the basis of the laboratory tests and the accelerated testing will hold within the period of the trial under real traffic and environmental conditions.

Collateral aims include to:

- Develop construction methods (in particular substrate preparation requirements) that are compatible with the properties of the materials and the quantum and quality specifications of the resulting pavement.
- Improve the basis for realistic estimation of construction costs using these materials.
- Study variations in performance under varying conditions of traffic, the effects of limited variations in aggregate properties which can affect long-term friction properties and the noise properties of the test pavements under real traffic.
- Increase the comfort level for contractors by providing opportunities for them to gain experience with these advanced paving materials.

The last of these is especially important. As contractors move up the learning curve, it can be expected that construction practices will adapt as necessary and the paving costs of advanced surfacings will ultimately drop as experience and volumes increase.

ES.7.2 Specific targets for Epoxy Asphalt Phase III trials

The Epoxy Asphalt material is ready for large scale demonstrations on the roads, and the challenges of producing and laying this material are considered as moderate. The major practical issue is linked to the health effects of the uncured epoxy asphalt binder, which has resulted in serious restrictions to use in some countries. Any reservations by the health authorities should therefore be prompted and cleared at this stage.

There are a number of EA-specific trial aims, including: testing of locally available materials; determining the performance of EA materials having different chemical formulations – and the impact of aggregate type on long life surface characteristics; testing of various EA layer thicknesses; and testing in various climatic regions.

ES.7.3 Specific targets for HPCM trials

There are a number of HPCM-specific trial aims, including: use of locally available materials as opposed to material from one supplier; development of techniques for laying the mortar and inserting the chippings; and testing of several asphalt base courses and several mixtures with water-cement ratio ranging from 0.20 to 0.30 to achieve the best balance between mixing/handling/placing and the performance of the hardened material.

ES.7.4 Proposed Phase III Field Trials: Summary of Recommendations

Field trials are recommended to: allow the new surfacing materials to be tested on the ground in real traffic and environmental conditions; promote improved production and laying techniques and the development of new equipment where needed; and to focus on quality control.

It is recommended that:

- Interested road authorities be invited to register with the JTRC Secretariat their interest in joining the proposed trials as soon as possible after the publication of this report and before a year has passed.
- When a minimum of three trial offers have been received with any of the materials, a preparatory meeting be called by the host organisation. Such preparatory meetings must appoint a project coordinator and agree on the fundamental plans and principles for the management of the trials.
- Participants may begin trials whenever it suits their plans after the preparatory meeting, but not later than May 2009. The trials must last a minimum of 2 years and must be terminated no later than May 2011.
- Participants must be prepared to deliver their final report within 3 months after their trials have been completed and no later than in July 2011. The two consolidated reports, one for each type of material, are drafted by the coordinators for the two series of trials and final meetings are held to edit and agree the final versions of the reports.

It is further recommended that:

- The JTRC assumes the role of the host organisation and responsibility for calling the meetings of the participants in this Field Trial phase.
- The responsibility for the funding and management of the field trials as well as recording and disseminating of the results of the trials rests with the sponsoring organisations, the participants and the project coordinators.

NOTE

1. The typical costs of roadworks referenced in the findings of the Phase I report are specified in US dollars and take into account exchange rates applicable at the time the Phase I report was being prepared.

1. BACKGROUND AND CONTEXT

1.1 Background

The properties of road pavements have been the object of a large and rich research tradition for more than 50 years, an important topic on university curricula for students of road engineering, the catch word in titles of innumerable seminars and congresses and a target for decisions of huge economic consequence for road owners and contractors.

The issue of prolonged service life of road pavements has been a key concern for road professionals for more than a decade, heralded by the appearance of the term "long life pavements" as distinct from the term "durable" pavements, which has carried the notion of satisfactory pavement performance for many years.

"Long life pavements" are seen as particularly desirable on heavily trafficked roads to avoid the costs of road maintenance works, including the delays they inflict on road users, particularly in congested traffic conditions. In such environments, long life pavements would be expected to show high quality performance without the need for significant repair for more than 30 years. It is also in such environments that the benefits of avoiding major repairs and re-pavements may become large enough to justify the higher initial costs of such pavements.

It has been demonstrated that long life as just described is achievable for the subsurface pavement layers, but the surface layer or wearing course, which is critical for safe and comfortable driving, remains the Achilles' heel of the concept. This thin uppermost pavement layer is more than any other part of the structure exposed to air, sun and weather, and to the wear, tear and deformation of the traffic it carries.

1.2 Context for long life wearing courses

In most Member countries, the road network constitutes one of the largest community assets and is predominately government-owned. Road administrations must maintain, operate, improve, replace and preserve this asset while, at the same time, carefully managing the scarce financial and human resources needed to achieve these objectives. All of this is accomplished under the close scrutiny of the public who pay for and are regular users of the road network, and who increasingly demand improved levels of service in terms of safety, reliability, environmental impact and comfort.

In this context, Governments are clearly expecting road administrations to improve the efficiency of, and accountability for, the management of the road network. Indeed, in many countries, local highway authorities face formal accountability and reporting requirements on how they manage their assets.

Many road administrations have adopted an asset management approach, which, as applied to the roads sector represents "a systematic process of maintaining, upgrading and operating assets, combining engineering principles with sound business practice and economic rationale, and providing tools to facilitate a more organised and flexible approach to making the decisions necessary to achieve the public's expectations".

The Economic Evaluation of Long Life Pavements – Phase I report (OECD, 2005) summarised the current context and importance of the Long Life Pavements project in the following terms:

> *"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.*
>
> *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".*

1.3 Whole life costing

More and more, it is important to look at a project on a long-term basis. The concept of whole life costing is not new and has been adopted by many road administrations. It requires an economic assessment which considers significant current and projected cost flows over a whole life period of analysis, expressed in monetary value. The projected costs are those needed to achieve defined levels of performance, including reliability, safety and availability.

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) 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.

For highways, private sector involvement is often seen not only as an initial source of capital but also as a way to introduce innovation and alternative thinking to the construction process. With generally longer-term commitments of the private organisations than previously experienced, recent history has shown that their design organisations and contractors will look at materials and the construction process with the aim to reducing overall costs including those associated with long-term maintenance.

In the context of improving sustainability in the longer term, consideration also needs to be given to the potential for recycling of the whole pavement at the end of its useful life. Recycling potential will depend on the materials involved – *e.g.* whether the pavement is epoxy asphalt or cement based – as well as on the quality of the aggregates used.

1.3.1 Are long life pavements affordable?

Improved and alternative advanced pavement materials are needed to reduce the need for maintenance, alleviate congestion and reduce costs to road owners as well as road users.

The "big" question then is: Is it economically viable to spend more money initially on advanced surfacing systems that will save money on roadworks and reduce congestion, when the analysis is carried out in whole life cost terms?

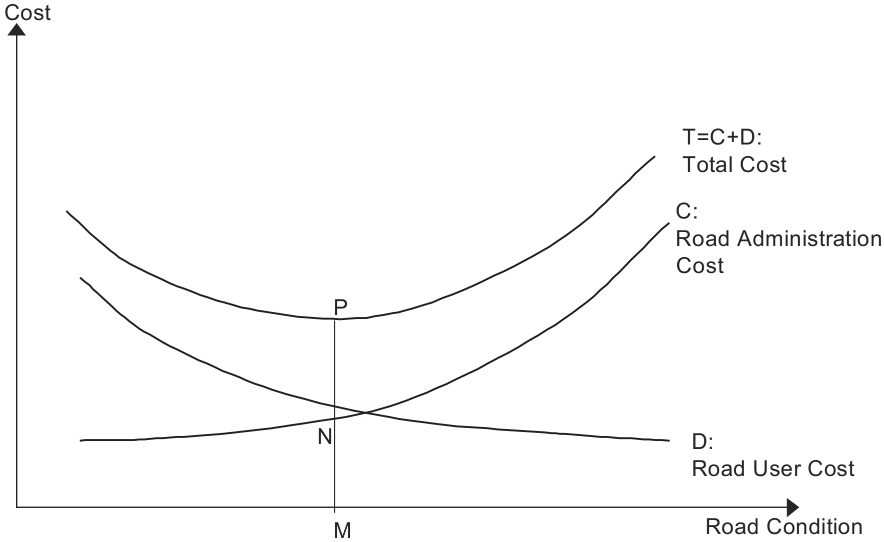
1.3.2 Recent worldwide experience

Research undertaken over the last 10 to 15 years has explored the whole-of-life costs that need to be considered in answering the "big" question. These costs include vehicle operation costs, accident costs, and delays during maintenance and rehabilitation.

The OECD report *'Road maintenance and rehabilitation: funding and allocation strategies'* (OECD, 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 4.1, which is taken from the OECD report.

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

Figure 1.1. **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).

Different pavement types have different cost profiles over their lives. Initial construction costs of a pavement are often surpassed by the costs of its operation. There are many other aspects that 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 condition, that are likely to lead to diversity in construction, operating and user costs. Further differences can be expected between countries 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.

All such aspects need to be considered in detail to allow proper assessments to be made. The next section highlights the findings of the first Phase of the Economic Evaluation of Long Life Pavements project, which explored these issues in more detail.

2. KEY FINDNGS OF PHASE I STUDY

2.1 Overview

The first phase of this study, the *Economic Evaluation of Long Life Pavements – Phase 1* (OECD, 2005) – was undertaken as part of the OECD's Road Transport Research and Intermodal Linkages (RTR) Programme that terminated in December 2003.

The Phase I work assessed the likely envelope of costs for economic viability of new long life wearing courses, taking into account all the costs involved including initial construction costs as well as savings in maintenance costs and user cost savings expected in the longer term.

2.2 Economic Findings – Long Life Pavements Phase I Report

The Phase I 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. The Phase I report 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 and incidents, 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.

The Phase 1 work could only carry out an indicative economic analysis since the advanced materials required had not, in the initial stage of the study, been identified or tested. As the possible materials and their properties were being investigated, the economic analysis focussed on the envelope of costs and performance that would be required for such new wearing course materials to be economically viable. The ranges of the basic criteria used for the analysis that was carried out for high traffic roads were as follows:

- Traffic: 40 000 to 100 000 AADT.
- Proportion of heavy vehicles: 5 to 20%.
- Discount rate: 3 to 10%.
- Surfacing cost: 3 times or 5 times current costs for reference materials.
- Life of advanced surfacing before maintenance: 30 or 40 years.
- Traffic growth rate: 1 or 2% pa.

The economic analysis undertaken in Phase I showed that in certain circumstances there could be considerable economic benefit in developing new long life pavement wearing courses with the appropriate performance characteristics. The detailed findings included in the Executive Summary of the Phase I report were as follows[1]:

> *"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".*

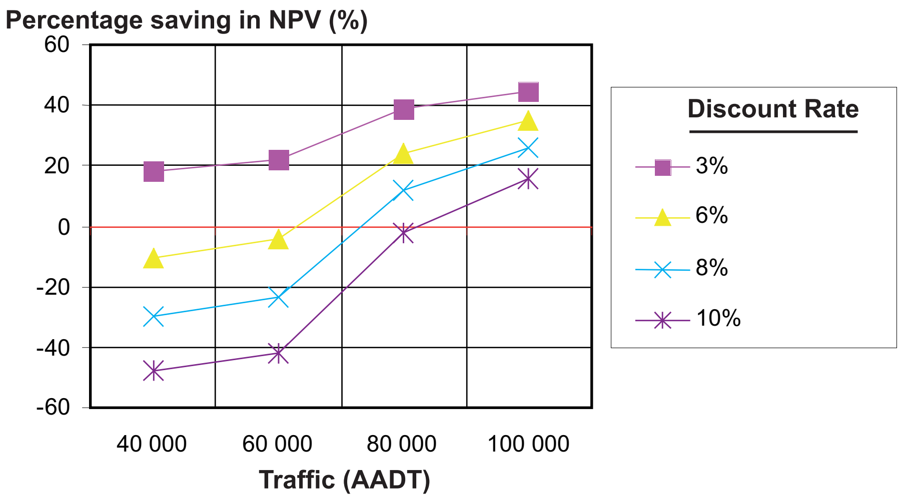
The main conclusion from the economic analysis was therefore that, under the standard modelling case with the assumptions outlined, there are likely to be economic benefits in using long life wearing courses when the initial cost is around three times traditional surfacings and traffic levels are high. As well, the analysis showed the importance of user costs. Advanced long life wearing courses will be more economic when user costs are taken into account, as there are significant benefits in avoiding maintenance disruption to road users.

2.2.1 Results of sensitivity testing

The results of variations in some of the key parameters and assumptions used in the economic analysis are highlighted in Figure 4.1, which shows 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 2.2 assumes that the advanced surfacing costs three times more than traditional surfacing and shows that the outcome of the analysis 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 2.2. **Results of sensitivity analysis**



Source : OECD (2005)

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.

For the advanced surfacing options, the sensitivity testing indicated that:

∑ The net present value (NPV) of savings over the traditional surfacing option increases as the traffic flow increases or as the discount rate decreases.

- 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).

In summary, the advanced surfacing could 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.

2.2.2 *Findings concerning candidate wearing course materials*

The Phase 1 investigation examined a wide variety of possible materials in various groupings. The requirements and necessary properties of suitable advanced materials were considered and possible candidates listed. The materials were considered against a set of headings under the following major criteria:

Design	Maintenance
Testing	Anticipated Lifetime
Production	Cost
Construction	User Criteria
Health and Safety	Availability

The results of the comparison allowed recommendation of materials for the following phase of the project. Wider aspects of prefabrication and accelerated paving practices were also considered.

The 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 (EA).***
- ***High Performance Cementitious Material (HPCM).***

The findings included in the Executive Summary of the Phase I report were as follows:

"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[2]

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."

2.2.3 Towards Phase II

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

There were also suggestions on the steps to be taken during the Phase II work – which were helpful in getting the work underway – including:

> *"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".*

2.3 The Phase II Study

The testing programmes actually developed for the Epoxy Asphalt and High Performance Cementitious Materials are set out in detail in Chapters 4 and 5. These chapters also highlight the results of these testing programmes and, in conjunction with the assessments in Chapter 6, lead into the findings and conclusions about the suitability of these materials for long life surfacings which are set out in the later chapters of this report.

NOTES

1. The typical costs of roadworks referenced in the findings of the Phase I report are specified in US dollars and take into account exchange rates applicable at the time the Phase I report was being prepared.

2. The need for an epoxy bound friction course was later abandoned.

3. PHASE II – MANDATE, SCOPE AND ORGANISATION

3.1 Mandate

The Mandate of the Joint Transport Research Centre approved by OECD Council in 2003 was as follows:

> *"The Centre shall promote economic development and contribute to structural improvements of OECD and ITF economies, through co-operative transport research programmes addressing all modes of inland transport and their intermodal linkages in a wider economic, social, environmental and institutional context".*

The Joint Transport Research Centre's Programme of Work (2004-2006) was approved by Transport Ministers of OECD and ITF countries in Ljubljana in May 2004 [CEMT/CM(2004)9].

The Centre's Strategic Directions and Programme of Work were also approved by OECD Council [C(2004)123], in July 2004.

3.2 Phase II Project Scope

The proposed scope of the Long Life Pavements Phase II study as approved by Transport Ministers in 2004 included:

> *"This next phase of the project will coordinate sufficient initial testing by national testing laboratories to assess the durability of the wearing courses. This will involve small-scale testing (laboratory testing and accelerated load testing) of the most promising pavement materials".*

The objective of this second phase of the project was to strengthen knowledge about the potential and the limitations of the two prospective candidate materials that had been identified for further research as possible innovative long life wearing courses in Phase I *i.e: epoxy asphalt and high performance cementitious materials*.

3.2.1 Principal Tasks

The principal tasks to be undertaken in Phase II of the project included:

- Assemble available information regarding the use of the candidate materials for pavement construction (design, construction, long-term behaviour) – based on the experience of the countries participating in Phase II. Identify the knowledge gaps and specify the higher performance (mechanical and environmental durability, use-performance) requirements.
- Define an experimental programme aimed at filling the knowledge gaps, improving the performance of the materials where needed and assessing the real long term performance of the materials, when placed on different types of support structures (noting such supports must also have long-life structural characteristics).

- Test the wearing courses under conditions that reflect expected requirements, taking into account possible future changes in policy or demand – such as in relation to mass limits, traffic mix and speed. This will allow comparisons with the performance of typical materials used today.
- Ensure co-operation on the research work amongst the different laboratories participating in Phase II, in order to make best use of the test facilities and human and other resources and create synergies.
- Assess the technical suitability and real prospects of the candidate materials in the construction of long-life wearing course.
- Identify and consider any research results that bear on the conclusions of the economic evaluations undertaken in Phase I or the physical conditions which might best suit the use of such materials as long life wearing courses (support, traffic, loads, climate).

3.2.2 Issues

Some key issues related to the Terms of Reference that needed to be addressed included:

- The design of the wearing course material and of the wearing course itself (thickness) in order to: resist traffic and environmental conditions; protect the underlying layers from surface water; and offer durable friction properties throughout the service life.
- Enhancement of anti-noise and anti-splash performances.
- Construction technology considerations such as: support for the long-life wearing course; link with the support (tack coat and need for a binder course); conditions of placement for the wearing course (including health issues); and curing time before and after reopening to traffic.
- Recycling at the end of its life.

The further research on these possible innovative long life wearing courses was to be done by rigorous testing in the laboratory and, if justified by the results obtained, selected tests in accelerated loading facilities. Complex, long and expensive full scale testing was not envisaged, but it was expected that some development of the materials may have needed to be accommodated. Full scale road tests would only be considered in a third and final phase of the project.

3.3 Project Organisation

3.3.1 Working Method

The Phase II work was undertaken by a research Working Group, working on a cooperative international basis. Members of the Working Group were nominated by member countries on the basis of their expertise in the areas to be researched. The Working Group was organised and its work co-ordinated by the Chair and JTRC Secretariat. The Secretariat also assisted with the drafting of the content, findings and conclusions and finalisation of the report for publication. Further details on the JTRC's Working Group methods are set out in CEMT/OCDE/JTRC(2004)4.

The expected term of a research Working Group project is typically 18 months during which three or four meetings will normally be held. In the case of this project, which involved considerable original research and laboratory testing, it was recognised that the work would need to run over a longer period than is generally the case for such Working Groups.

3.3.2 *Project participation*

The Working Group on Economic Evaluation of Long Life Pavements – Phase II, which was established to undertake the project, was chaired by Mr. Jorgen Christensen (Denmark) and had 37 members from 18 countries and the Secretariat.

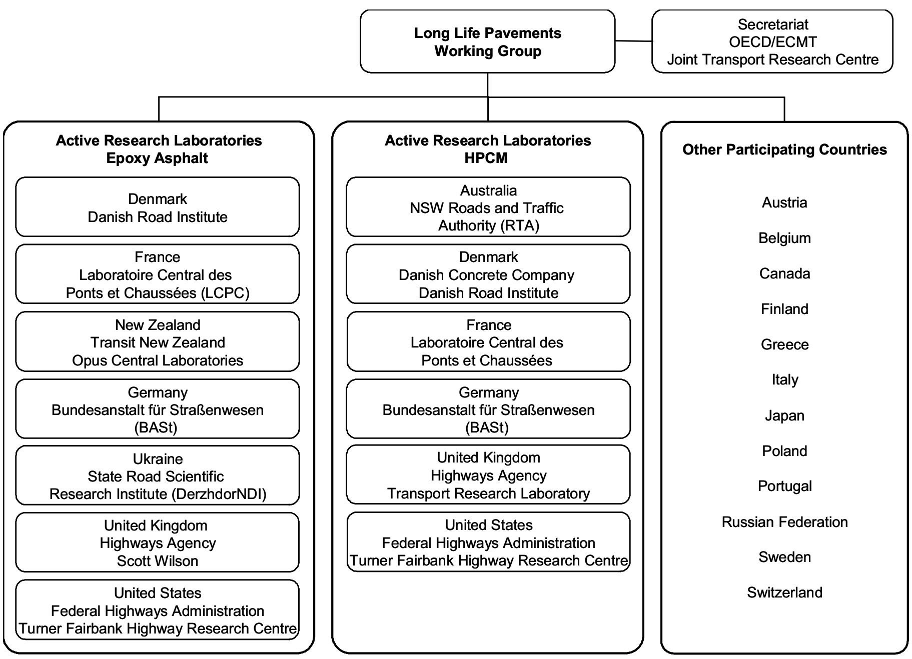
Countries whose working group members participated most actively in the project and had laboratories actively involved in laboratory testing were: Australia, Denmark, France, Germany, New Zealand, Ukraine, United Kingdom, United States. National laboratories from these eight member countries participated in the wearing course testing programmes, which were led by Technical Coordinators from the Federal Highway Administration in the United States and the Laboratoire Centrale des Ponts et Chausees (LCPC) in France.

A number of other countries nominated working group members who participated actively or by correspondence but whose laboratories were not involved in laboratory testing, including: Austria, Belgium, Greece, Italy, Japan, Poland, Portugal, Russian Federation, Switzerland and Sweden. External reviewers from Canada and Finland reviewed the draft Final Report.

A chart showing the project organisation and participation is attached (see Figure 3.1).

A list of Working Group participants is provided in Annex B.

Figure 3.1. **Project Participation**



3.3.3 *Outputs*

The project outputs were expected to be of interest to many road administrations. This would be particularly the case if the testing confirmed the potential for the *epoxy asphalt and high performance cementitious material* surfacings to increase the longevity of wearing courses on heavily trafficked roads – and to be able to do so at reduced overall costs in present value terms.

4. EPOXY ASPHALT: TESTING AND TEST RESULTS

4.1 Introduction

The Phase I study identified two families of candidate materials that appeared likely to be able to meet the economic and technical requirements for long life wearing courses. One of these was the family of epoxy asphalt materials; the other was the family of high performance cementitious materials (HPCM).

This chapter is concerned solely with the *epoxy asphalt* family of materials and describes the findings of Phase II of this project in respect of the Epoxy Asphalt materials tested. The aim of Phase II was to research the behaviour and properties of the materials identified as candidates and test them sufficiently to assess their suitability for use in long life wearing courses.

The testing of the Epoxy Asphalt was part of a joint research effort involving a number of national institutions from Denmark, France, Germany, New Zealand (NZ), Ukraine, United Kingdom (UK) and United States (USA).

Epoxy Asphalt is a premium material. Historically, the high cost associated with its placement has limited its use to orthotropic bridge decks. Balala reported on the rational for selecting this binder for the San Mateo Bridge in San Francisco in 1967 [1], and Gaul reported on its continued good performance 30 years after placement [2]. The Epoxy Asphalt group work assessed whether this long-life durability extends to the highway environment as well, when subjected to more severe climatic environments.

The research approach taken in the Epoxy Asphalt group was to have participating laboratories identify and utilize local sources of epoxy asphalt and compare the characteristics and performance results with those of a reference material. The reference material is a *bitumen-aggregate mix system* that each laboratory identified as having an outstanding performance history and about which each had extensive working knowledge.

In conducting the comparison, *the epoxy asphalt would merely replace the bitumen in the reference material*; all other aspects of the selected system would remain the same. That is, identical binder contents and air voids would be maintained. Since the epoxy asphalt reacts with the aggregate, the need to consider bitumen-aggregate pairing was deemed to be of little consequence.

Adopting this approach allowed the participating countries to focus on their likely application of epoxy asphalt using local materials and standard test procedures while providing a qualitative assessment of expected field performance. Participants could then report the data generated from this investigation in terms of their significance for a long-life surfacing material and the implications for pavement life.

Aspects of pavement performance that were deemed as potentially problematic (*i.e.*, *fatigue* and *fracture properties*) have been emphasized in this study.

4.2 Material Selection

4.2.1 Epoxy Asphalt Selection

Conventional bituminous binders are thermoplastics; they become soft when heated and harden when cooled. Epoxies on the other hand are thermosetting materials, that is, they have the property of becoming permanently hard and rigid once cured. Two significant consequences of this are: firstly, that traditional test methods and characterization protocols in many cases had to be modified to accommodate the thermosetting behaviour of epoxy asphalt; and second, a thorough knowledge of the curing history is paramount to obtaining useful data.

Epoxy Asphalt is a two-part system that results from the reaction of a curing agent (Part A) with a bitumen/ resinous component (Part B). These components are shown individually in Figure 4.1 and post blending in Figure 4.2.

Figure 4.1. **Two Components of Epoxy Asphalt**

Part A Part B

Source: Turner-Fairbank Highway Research Center (United States).

Figure 4.2. **Demonstration of Handling Characteristics**

Source: Turner-Fairbank Highway Research Center (United States).

The handling characteristics prior to curing are similar to those of conventional bitumen. The chemical composition of the curing agent will largely dictate curing rates, and the bitumen imparts flexibility in the epoxy asphalt and largely determines its susceptibility to oxidation and moisture damage.

The resulting cross-linked binder exhibits both flexibility as well as memory as demonstrated in Figure 4.3. When a cured beam of epoxy asphalt is bent, it recovers its original shape within a short period of time.

Figure 4.3. **Demonstration of Memory Effects in Epoxy Asphalt**

Source: Turner-Fairbank Highway Research Center (United States).

The countries whose laboratories were involved in the Epoxy Asphalt group work and the types of epoxy asphalts evaluated are noted in Table 4.1, where some manufacturing characteristics are also provided. Seven different epoxy asphalts were obtained by the participating laboratories and evaluated. These included three different curing agents: *Amine*, *Amino* and *Acid Based*. The acid based epoxy asphalts used by the participating laboratories in Denmark, NZ, UK and the USA were obtained locally but are essentially from a common source. The percentage of epoxy binder in these systems ranged from 15-50% by weight and curing temperatures employed went from ambient to 135°C.

Table 4.1. **Epoxy Asphalt Systems Investigated by Laboratories and Processing Conditions Employed**

Laboratory	Epoxy Asphalt (Supplier)	Epoxy %	Mixing Temperature	Curing Rate
Denmark*	Acid Based (Colas)	14.5	120-135°C	Moderate
France	Amine Based Viagrip®Eurovia	41	Ambient	Rapid
	Amine Based Pontalco M®Eurovia	41	Ambient	Moderate
Germany	Amino Based	25	130°C	Rapid
	Acid with Catalyst	25	130°C	Moderate
	Acid without Catalyst	25	130°C	Moderate
New Zealand	Acid Based (ChemCoSystem)	15	125°C	Moderate
Ukraine	Acid Based CHS-EPOXY	25	130°C	Moderate
	Acid Based (Kompozit)	21		Moderate
	Epoxy-Polyurethane	20		Moderate
UK	Acid Based (Colas)	14.5	120-135°C	Moderate
USA	Acid based (ChemCoSystem)	15	150°C	Moderate

*Samples provided by UK.

4.2.2 Reference materials

The reference materials selected represent quality asphalt mix systems that have been extensively tested or have long performance histories available. Mix designs ranged from fine (Hot Mix Asphalt (HMA)) to coarse aggregate gradations (Stone Mastic Asphalt (SMA)), and from low porosity to high for the open grade porous asphalt (OGPA) investigated by New Zealand.

The reference materials selected represent quality asphalt mix systems that have been extensively tested or have long performance histories available. Some additional details regarding the laboratory and field performance history of these materials are provided in the Appendices (see A1)

Laboratories in both France (LCPC) and the UK (Scott Wilson) investigated the application of epoxy asphalt to two mix designs. LCPC used a semi coarse asphalt mix (BBSG) thick solution and a very thin asphalt mix (BBTM) a surfacing mixture with a high macrotexture. Scott Wilson used a Hot Rolled Asphalt (HRA) and a proprietary Stone Mastic Asphalt (SMA).

Table 4.2. **Reference Mix Designs**

Laboratory	**Reference Design and Targeted Control Properties**			
	Mix Design Type	**Binder Grade**	**Binder Content %**	**Air Voids %**
France	BBTM	10/20 pen	5.7	18
	BBSG	35/50 pen	5.8	6
Germany	SMA	50/70 pen		
New Zealand	Open Grade Porous Asphalt	80/100 pen	4.7	20.4
Ukraine	Dense Graded	60/90 pen	7	
UK	HRA	40/60 pen	7.2	6
	SMA		6	6
USA	HMA	PG 70-22	5.3	7

4.3 Binder Properties

4.3.1 Curing Behaviour

Preliminary testing was conducted on the binder properties to become familiar with working with a two-part binder and ascertaining the curing characteristics of the epoxy asphalt.

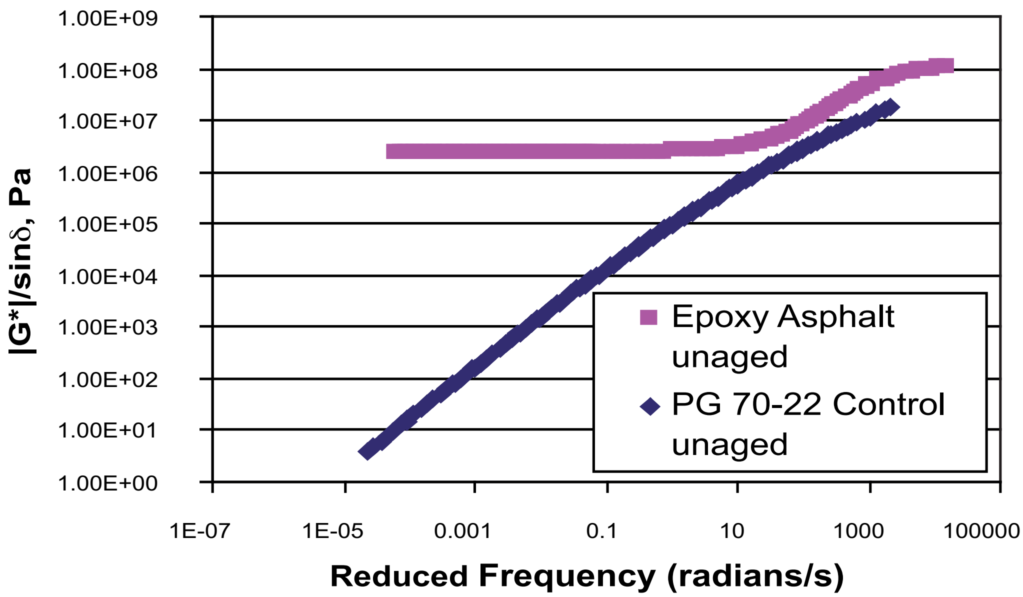
Conventional specifications and associated conditioning schemes are not amenable to evaluating epoxy asphalt. The uncured epoxy asphalt is too fluid at ambient conditions and there is no relationship between its properties in that state and its cured properties. On the other hand, the cured binder is more akin to a flexible plastic as shown in Figure 4.3. Consequently, a number of fundamental and empirical approaches were developed or adapted to evaluate the curing characteristics of the various epoxy asphalts. A list of the methods employed to evaluate the curing characteristics of the binders is shown in Appendix A3. Conditions for manufacturing and curing the epoxy asphalts mixtures are described in Section 4.4.

4.3.2 Rheological Properties

Rheological measurements were made on cured bars of epoxy asphalt. The intermediate and high temperature characteristics of epoxy asphalt can be evaluated on a Dynamic Shear Rheometer (DSR) with a set of torsion bar fixtures. Data were generated over a range of temperatures using a frequency sweep covering the range from 0.1 – 100 radians/s at very low levels of strain of about 10-3 to be within the linear viscoelastic range of response. The data at all temperatures and frequencies were consolidated to the reference temperature of 28°C by appropriate shifting using the time-temperature superposition principle.

The master plots showed that the values of the rheological parameters for the epoxy asphalt are in a very different range than what is normally obtained for conventional asphalts or other polymer-modified asphalts. In order to get some idea of the difference in the rheological behaviour of the epoxy asphalt, comparisons of the properties of the epoxy asphalt are done vis-à-vis a conventional unmodified high performance grade (PG) asphalt, namely a US PG70-22 grade control. Master Plots of the Superpave Complex Modulus (|G*|) divided by the Sine of the Phase Angle (δ) Parameter (|G*|/sinδ) vs. the Reduced Frequency Curves at a Reference Temperature of 28°C for Epoxy Asphalt and Performance Graded (PG) 70-22 are set out in Figure 4.4. It can be seen from the plots in Figure 4.4 that, while the Superpave parameter |G*|/sinδ values are close to each other and follow the same trend at high frequencies or equivalently low temperatures, the same is not the case at low frequencies or equivalently, high temperatures. The epoxy asphalt retains its high Superpave parameter |G*|/sinδ values even at very low frequencies (which are equivalent to high temperatures), indicating that epoxy asphalts should provide excellent rutting resistance.

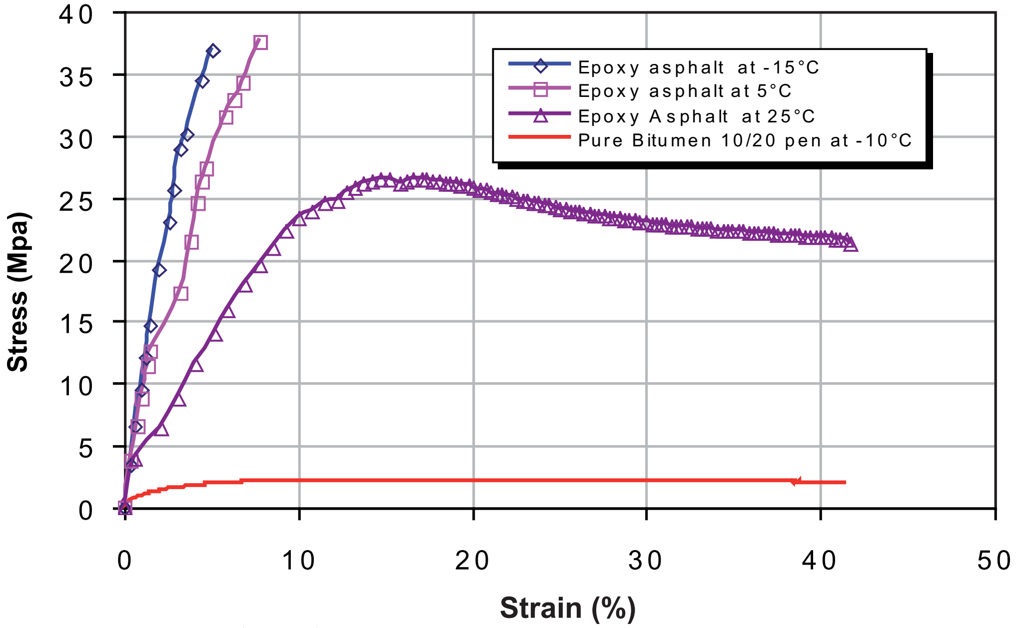
Figure 4.4. **Master Plots of the Rheological Properties of Superpave and Epoxy Asphalt**



Source: Turner-Fairbank Highway Research Center (United States).

The low temperature properties of cured epoxy asphalt specimens were measured on the Bending Beam Rheometer (BBR) and with the Direct Tension Test. The former was used to determine the Superpave binder criteria from m and S values. The unaged cured epoxy asphalt graded a PG x-10 – a useful range down to –10°C or for use under a moderate climate. Tensile properties of a different epoxy asphalt, Viagrip were measured using the Direct Tension Test and found to be 10 times greater than that of a hard (10/20 pen) binder. The results are shown in Figure 5, which shows plots to the point of failure. These results help explain the relatively higher low-temperature Performamce Grade values due to higher stiffness of the epoxy asphalt at low temperatures. However, the samples would fail at lower strain rates.

Figure 4.5. **Stress Strain Curves for Epoxy Asphalt and Hard Bitumen at Different Temperatures**



Source: F. Hammoum, LCPC (France).

4.3.3 Oxidation Susceptibility

The application of conventional bitumen short and long-term aging conditioning procedures to epoxy asphalt binders is not relevant. As the ultimate application of this material is as a surface course, the effect of UV oxidation on the binder properties was deemed most critical. To this end cured beams were conditioned in a Q-Panel Xenon Test Chamber. Conditioning cycles entailed the application of UV light for 55 minutes followed by 5 minutes of misting with chilled water (5°C). The surface temperature during the "lit cycle" was 85°C. Specimens were conditioned from 1 day to 16 weeks. Visual examination showed the side exposed to UV had "greyed" and showed evidence of cracks that were arrested by the crosslinking nature of the epoxy system. The rheological results are shown in the Appendices (see A4).

4.4 Mix Properties

4.4.1 Manufacture

Standardized protocols provided by the suppliers were used in the manufacture of most of the epoxy asphalt mixtures. As the acid based epoxy asphalts used by Denmark, NZ, UK and USA are essentially the same, aspects of this protocol are mentioned here; some processing conditions for the other epoxy asphalts were noted previously in Table 4.1.

Following blending of the binder and aggregate, a 'holding' period of 30 minutes at the mix temperature (130ºC) allows the reaction to proceed to some extent before compaction. No difficulties were encountered following this procedure, and the times/temperatures involved are compatible with use in conventional asphalt manufacturing plant. In terms of mixture workability, the epoxy asphalt materials behaved similarly to the control materials and required no special handling procedures. However, it should be recognised that the thermosetting binder used in the epoxy asphalts, since it does not have reversible viscosity (cannot be re-melted) after curing, will render the epoxy asphalt mixture more sensitive to workmanship (any error cannot be rectified once the chemical reaction has taken place).

4.4.2 Evaluation of Curing

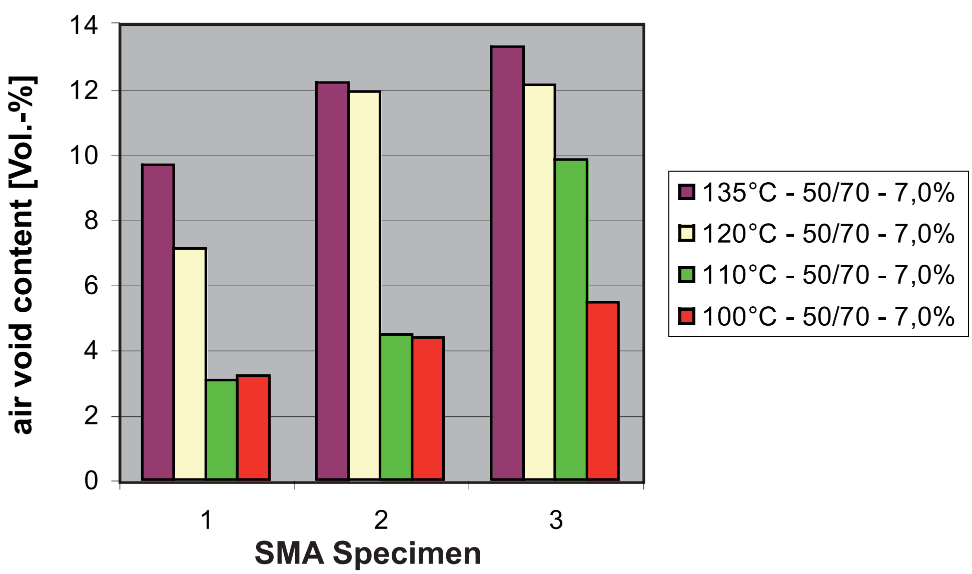
It is characteristic of thermoset products that, after production, they continue to cure and increase in strength/stiffness; the rate of curing depends on the ambient temperature. A number of characterization methods for monitoring the curing of the mix were taken; these are noted in Table 4.3 and essentially can be classified as three curing approaches.

Table 4.3 **Approaches used to assess the curing characteristics of the epoxy asphalt mixes**

Laboratory	Characterization Method	Property Measured	Specimen Curing Times/Temperatures
Germany	Slab compaction Hamburg rutting device with rubber wheel	Air void content Rut depth	30 min/100-135°C 0-60 min/13°C
France	Direct Tensile modulus	Modulus	3 day – 1 month/ambient
New Zealand	Indirect Tensile Stiffness Modulus [ITSM]	Modulus	0-300 hours/8°C
Ukraine	Compressive Strength Test Wheel Track Test	Modulus Rut depth	1-28 Days/2°C
UK	DSR on mastics Indirect Tensile Stiffness Modulus	Complex Modulus Modulus	1-80 Days/2°C

First there is an interest in assessing the effect of curing time on workability. German researchers at BASt evaluated the air voids and rutting resistance of slabs to determine the suitability of the curing characteristics of a given epoxy asphalt. The amino cured epoxy asphalt cured too quickly, and compactibility of the loose mix became an issue. At higher curing temperatures, the air voids were found to increase as did the rut depth of the tested slabs – see Figure 4.6.

Figure 4.6. **Air Void Content of Epoxy Asphalt Slabs Produced at Different Mix Temperatures**



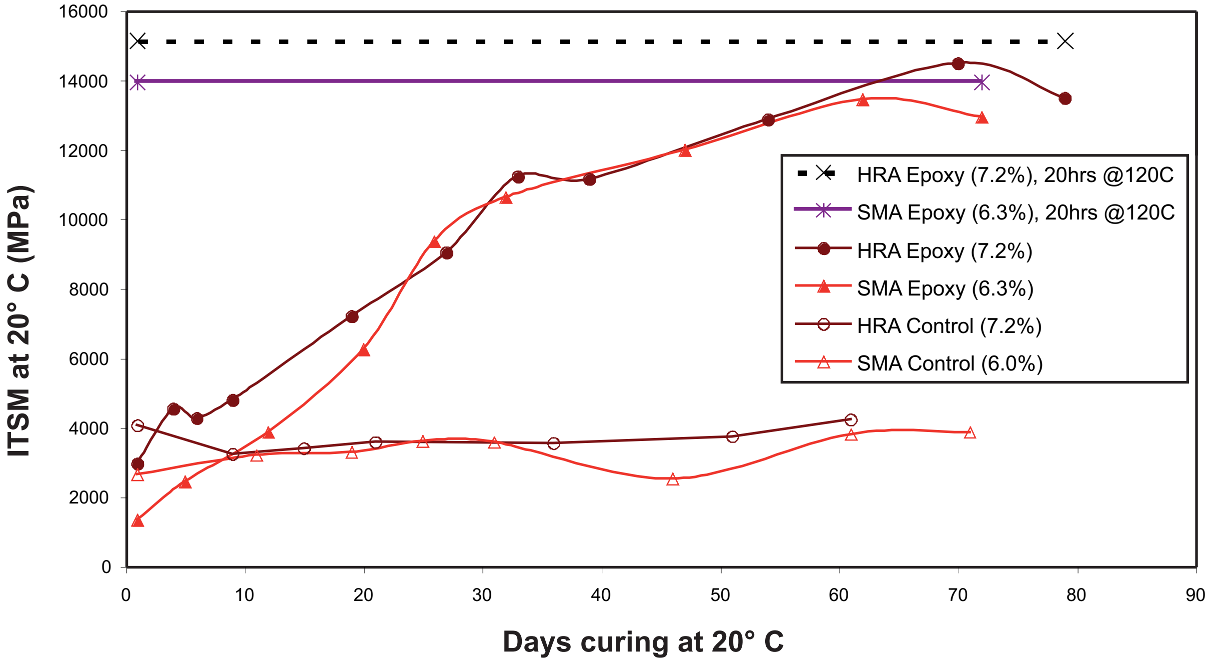
Source: Stefan Ludwig, Bundesanstalt für Straßenwesen (BASt) (Germany).

Secondly, there is the need to determine the fully cured or long-term properties. This was typically done by curing the epoxy asphalt mixtures at 85ºC for 120 hours. Subsequent increases in modulus after heating for up to 300 hours were small indicating that the curing is effectively complete after 120 hours. By comparison the modulus of the control specimens increased only from 840 MPa immediately following manufacture to 2 500 MPa after the 120 hour heating period. The use of elevated temperatures is useful for demonstrating that certain criteria can be met under these conditions and is useful for quality control of the epoxy asphalt production, but the high temperature curing may not capture the real life situation.

The third approach used by researchers in the UK and Ukraine was to demonstrate that the chemical reaction had proceeded satisfactorily in the mixture at more realistic temperatures. The Marshall stability tests and wheel testing were carried out on epoxy asphalt samples after conditioning at ambient temperature (20°C) for 24 hours to represent the early life or short term field aging condition and longer times to establish "long term" properties.

Researchers in the UK monitored the mixture stiffness of the HRA and SMA over a period of 70-80 days. As shown in Figure 4.7, the HRA Epoxy had a higher initial stiffness than the SMA Epoxy, but by around the 25-day curing mark both mixtures were of similar stiffness. The level of stiffness of both materials was comparable from 25 days up to 60 days, and the maximum stiffness of 13 500 MPa (SMA)/14 500 MPa (HRA) was reached at around 60-70 days. This maximum stiffness was found to be comparable with that determined after conditioning at 120°C for 20 hours and after conditioning at 85°C for 120 hours. The latter procedure was used by researchers at both TFHRC and the Scott Wilson to simulate long term curing of asphalt mixtures and is considered to be an acceptable compromise to accelerate the curing within a practical time frame, without causing unrealistic changes in mixture properties as a result of the elevated temperature, and was adopted for use in this project.

Figure 4.7. **Indirect Tensile Stiffness Modulus (ITSM) results for HRA and SMA epoxy asphalts cured at 20C**



Source: Richard Elliott, Scott Wilson Pavement Engineering (United Kingdom).

4.4.3 High Temperature Permanent Deformation

Deformation Resistance

Scott Wilson researchers found that in the ‘uncured’ condition, both HRA and SMA epoxy materials exhibited deformation resistance that was at least comparable to that of their respective control materials. This indicates that the early life rut resistance of the epoxy materials would not be dissimilar to that of standard asphalt mixtures. However, this assessment is complicated by the fact that the tests used to determine deformation resistance are carried out at elevated temperature, and samples have to be conditioned for several hours at the elevated test temperature before testing. This conditioning will inevitably produce a certain degree of accelerated curing. The significance of this is considered to be relatively small in terms of the risk of early age rutting with these materials, nevertheless, this issue was re-assessed during the Accelerated Load Testing and is discussed in Section 4.7.

In the fully cured condition, the HRA and SMA epoxy mixtures demonstrated deformation resistance at 40°C (repeated load creep) and 60°C (wheel tracking) between 2 and 8 times greater than that of the respective control materials, indicating a massive improvement in resistance to rutting compared with that of standard asphalt mixtures. The epoxy asphalt mixtures showed virtually no deformation in the wheel track test; at these levels of deformation, these materials would be considered suitable for use on most of the heavily stressed sites requiring very high rut resistance on the UK trunk road network (up to at least 135 msa (80kN standard axles), or 80 000 AADT (both directions) where the proportion of heavy goods vehicles is 15%).

The overall conclusion from this work on deformation resistance is that there is little risk of rutting where epoxy asphalt surfacing is combined with a competent substrate. Simple Performance Test results on HMA shown in the Appendices (see A5) lend support to this fact.

4.4.4 Moisture Damage

Tensile Strength and Resistance to Moisture Damage

There is no unequivocal laboratory testing method for determining the susceptibility to water of in-service bituminous material. However, it has been known for some time that loss of bond due to water damage appears to be more readily measured by tensile type tests. For tensile strength, Lottman (1982) suggested a threshold value of retained “strength” of 70% for deeming a mixture to be sensitive to water, whilst the Strategic Highway Research Programme (SHRP) specification recommended a minimum retained indirect tensile strength ratio of 80%; the SHRP procedure was adopted for use in this project (at SWPE).

The test procedure requires two sets of specimens (dry and conditioned sub-sets) with similar mixture type and volumetrics; the retained indirect tensile strength is calculated based upon the ratio of the mean indirect tensile strength of the conditioned sub-sets to that of the dry sub-sets. The moisture conditioning is carried out by subjecting the conditioned sub-sets to vacuum saturation followed by a freeze-thaw and other temperature conditioning cycles.

In the ‘uncured’ condition, both HRA and SMA epoxy materials exhibited comparable tensile strengths at 25°C to that of their respective control materials, indicating that the early life tensile strength of the epoxy materials would not be dissimilar to that of standard asphalt mixtures. In the fully cured condition, the HRA and SMA epoxy mixtures demonstrated tensile strength at 25°C up to 3 times greater than that of the respective control materials.

In terms of resistance to moisture, the epoxy materials were not considered to be susceptible to moisture damage, even at early age *i.e.* before the chemical setting process was complete, when compared against the SHRP criterion of 80% retained tensile strength. In order to further assess the resistance to moisture of these materials, an extended testing protocol was developed involving 6 freeze-thaw cycles (compared with the 1 cycle required in the SHRP procedure). At the completion of testing, the HRA epoxy showed improved retained tensile strength compared with that of the control, whereas the SMA epoxy and control showed comparable, albeit good, performance.

Other approaches to evaluating moisture damage include the application of "torture tests" such as the Hamburg Wheel Tracking Device and the Pine Rut Tester. These are subjective tests but prove to be excellent screening tools when properly calibrated with field samples. These too showed significant improvement in performance of the epoxy asphalt relative to the control materials. Additional details are provided in the Appendices (see A5).

4.4.5 Fracture – Fatigue

Fatigue Resistance

Conventional wisdom has been that there are two principal distress mechanisms influencing the performance of flexible pavements, namely fatigue cracking in the asphalt base and *structural rutting* emanating from deformation of the pavement foundation. For 'typical' bound road pavements, the critical tensile 'design' strain associated with fatigue cracking at the base of the bound layers, under a moving wheel load, may be taken to be of the order of 30-200 microstrain).

As *fatigue* is a phenomenon normally associated with in-service conditions, fatigue testing for this project was only carried out on aged samples. The Scott Wilson researchers found that the (indirect tensile) fatigue life of the epoxy mixtures was always greater than that of the respective control mixtures at 'design' strain; in fact, the fatigue life of the HRA and SMA epoxy asphalt was at least 10 times greater than that of the control asphalt at these levels of strain.

In thick, well-constructed flexible pavements the deterioration observed is principally surface (bituminous) rutting and surface initiated cracking. Any improved *fatigue performance* of the epoxy asphalt would be beneficial in resisting top down traffic induced cracking. In addition, it is worth noting that, with localised effects, the strain at the tyre-road interface may be much higher than that at the base of the bound layers. Where thin asphalt overlays are used over, for example, concrete pavements in low temperature conditions, or where ground movement is involved, the magnitude of any movements may be much larger.

It is useful therefore to also compare results at high strain, and it is notable that the improved fatigue performance of the epoxy asphalt, compared with that of the control materials, was only marginal at high strain. It was therefore important to assess the performance of the epoxy asphalt materials under high strain conditions in the ALF tests (as is discussed in section 4.6). It is also valuable to assess other laboratory fatigue characteristics such as those discussed in Appendix A5 using other configurations, for example, the 4-point bending beam.

4.4.6 Direct Fracture and Low Temperature Cracking Tests

Thermal Crack Resistance

The low temperature performance of the epoxy asphalt was assessed at Scott Wilson using a simple bending (flexural) test. This was carried out at a low temperature typical for UK conditions (5ºC). These low temperature bending beam test results showed that the epoxy asphalts developed increased strength/toughness after ageing but with reduced ductility/flexibility, compared with the control materials. This behaviour is consistent with the high strain characteristics predicted from the fatigue data. This may limit applications for epoxy asphalt in practice; for example, to use over stiff foundations, in order to minimise the level of deflection (or tensile strain) within the epoxy material.

Some newly advanced laboratory characterization tests for low temperature cracking were used to evaluate Epoxy Asphalt and are shown in the Appendices (see A5).

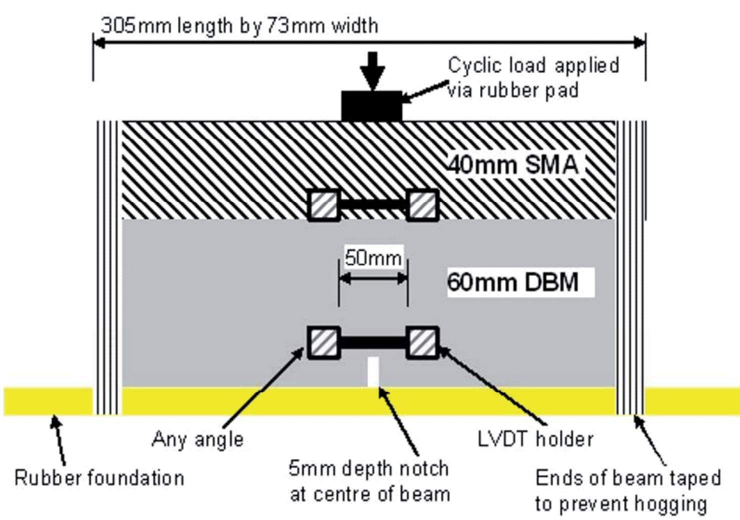
4.5 Composite Testing

The preceding mixture tests simulate the stresses and strains that the mixture is subjected to in a pavement section or lift. The next stage of testing was to evaluate the performance of epoxy asphalt lifts over flexible and rigid bases. These small-scale pavement simulations can provide insight as to the performance of full-scale accelerated tests or actual roadways. In fact distresses such as reflection cracking and lift delamination can more readily be evaluated in the laboratory setting; testing of the former was not planned for any of the APT experiments.

4.5.1 Asphalt Overlay Testing

The performance of epoxy asphalt over a flexible base was evaluated and compared with that of a control. Researchers at Scott Wilson sought to assess the flexural and fatigue behaviour of composite beams as well as the debonding characteristics of the lifts. The test configuration is shown schematically in Figure 4.8.

Figure 4.8. **Schematic for Testing Flexible Composite Systems**

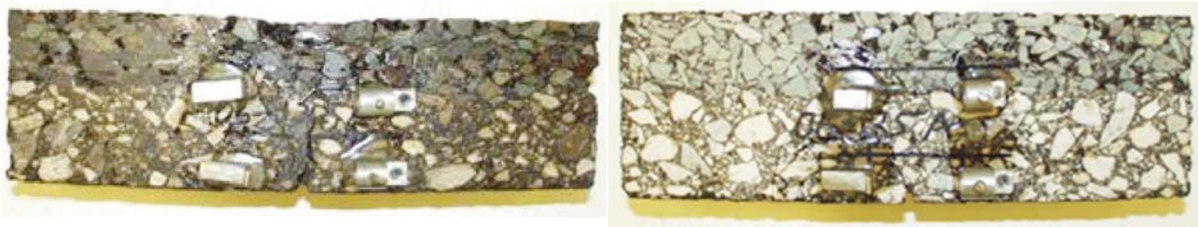


Source: Richard Elliott, Scott Wilson Pavement Engineering (United Kingdom).

A 40mm thick SMA surfacing was compacted onto a 60mm thick Dense Bitumen Macadam (DBM) base using a roller compactor. A bond coat was used in all cases. The composite slabs were sliced into test beams and stress controlled tested using a hydraulic loading actuator. The specimens were notched and two LVDT's were attached to the centre line of each beam, one at the bottom of the composite beam and one just above the interface, as shown in Figure 4.9.

Figure 4.9. **Tested specimen configuration**

(a) Conventional asphalt over DBM Base (b) Epoxy Asphalt over DBM Base



Source: Richard Elliott, Scott Wilson Pavement Engineering (United Kingdom).

As shown in Figure 4.9, at all applied load levels, the performance of the acid based epoxy asphalt surfaced beams was far superior to that of the control beams in terms of cumulative creep strains, crack propagation and overall sustained damage.

Two approaches were taken to evaluate lift delamination. One is the Leutner shear test that was carried out on cores cut from composite slabs for both HRA and SMA surfacing mixture types.

Testing on the apparatus shown in Figure 4.10 was carried out at 5°C, 20°C, and 40°C. In all cases the failure, as shown in Figure 4.11, was at the interface between the surface and the base course.

The strength of the bond coat seemed to be the controlling factor; consequently, there was no indication that the epoxy modified mix behaved better or worse than the control mix.

Figure 4.10. **Leutner test apparatus**

Source: Richard Elliott, Scott Wilson Pavement Engineering (United Kingdom).

Figure 4.11. **Appearance of specimen following Leutner shear test**

(a) Control SMA (40/60pen) (b) SMA Epoxy, both on DBM (100/150pen)

Source: Richard Elliott, Scott Wilson Pavement Engineering United Kingdom).

The second approach to lift delamination was the Torque Bond Test. In this test a specimen is clamped below the interface being tested with a rigidly fixed gripping unit. A steel plate is adhered to the top surface of the specimen prior to testing. A torque wrench is attaché to the plate and a torque is applied until the specimen fails. The maximum torque is recorded. An example of the manual torque test in operation is shown in Figure 4.12.

Figure 4.12. **Manual torque bond test in progress**

Source: Richard Elliott, Scott Wilson Pavement Engineering (United Kingdom).

A series of torque tests were carried out at 20°C and 40°C. In almost all cases failure occurred in the lower modulus DBM layer; examples of failed specimen are shown in Figure 4.13. These results were somewhat expected as the DBM layer was manufactured using a 100/150 pen grade binder. Unfortunately, it is not possible to determine whether the epoxy asphalt mixes performed better or worse than the control mixes.

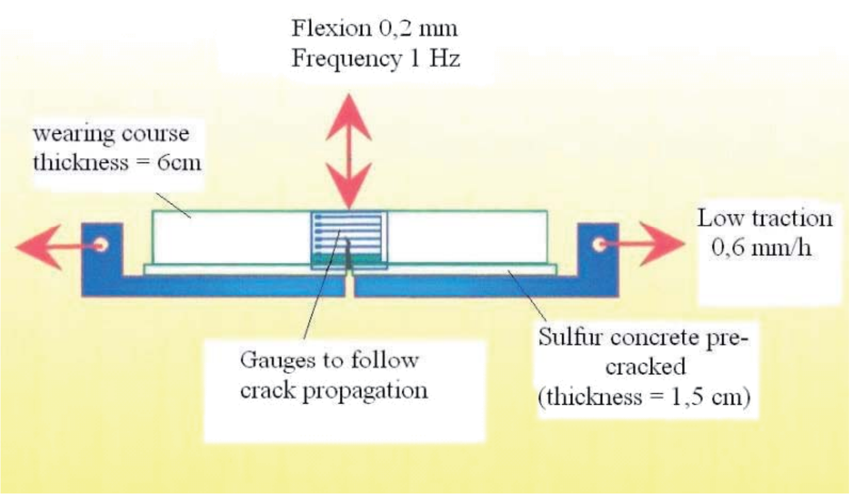
Figure 4.13. **Appearance of torque test failure plane SMA (Epoxy) on DBM (100/150pen)**

Source: Richard Elliott, Scott Wilson Pavement Engineering (United Kingdom).

4.5.2 Concrete Overlay Testing

Two approaches were undertaken with regard to epoxy asphalt over a rigid base. LCPC evaluated the resistance to crack initiation and fracture propagation of their thick solution (BBSG) over concrete. In these experiments, the amine based epoxy was compared with a 35/50 pen bitumen. A schematic of the thermal crack apparatus is shown with loading conditions in Figure 4.14.

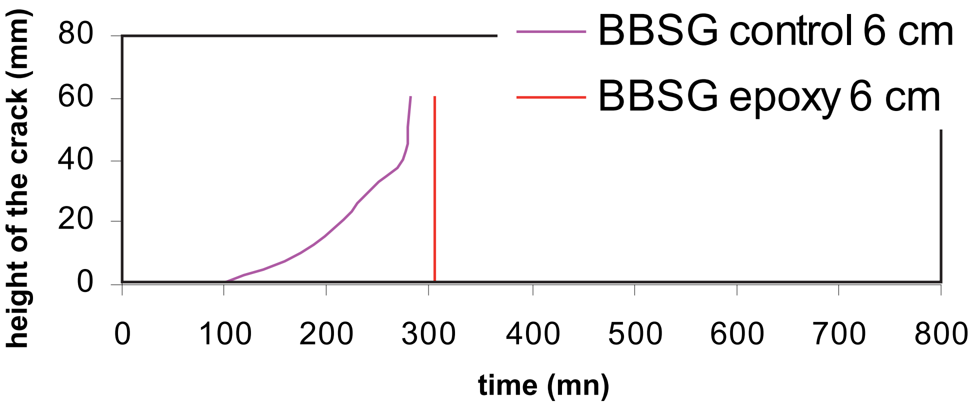
Figure 4.14. **Schematic of French Overlay Tester**



Source: N. Vulcano-Greullet, LRPC Autun (France).

A slab (130 x 590 x 80 mm) of the thick solution system (BBSG) is bound to a notched concrete. The slab is under strain controlled loading while also being subjected to tensile loading. Results for the control and amine based epoxy asphalts run at 5°C are shown in Figure 15. Cracking of the control is initiated at 100 min and continues to propagate up to the ultimate failure at 280 min. The epoxy asphalt is significantly more resistant to crack initiation but once initiated, the crack propagates very quickly.

Figure 4.15 **Crack propagation of control and EA specimens during Thermal Crack Testing**



Source: N. Vulcano-Greullet, LRPC Autun (France).

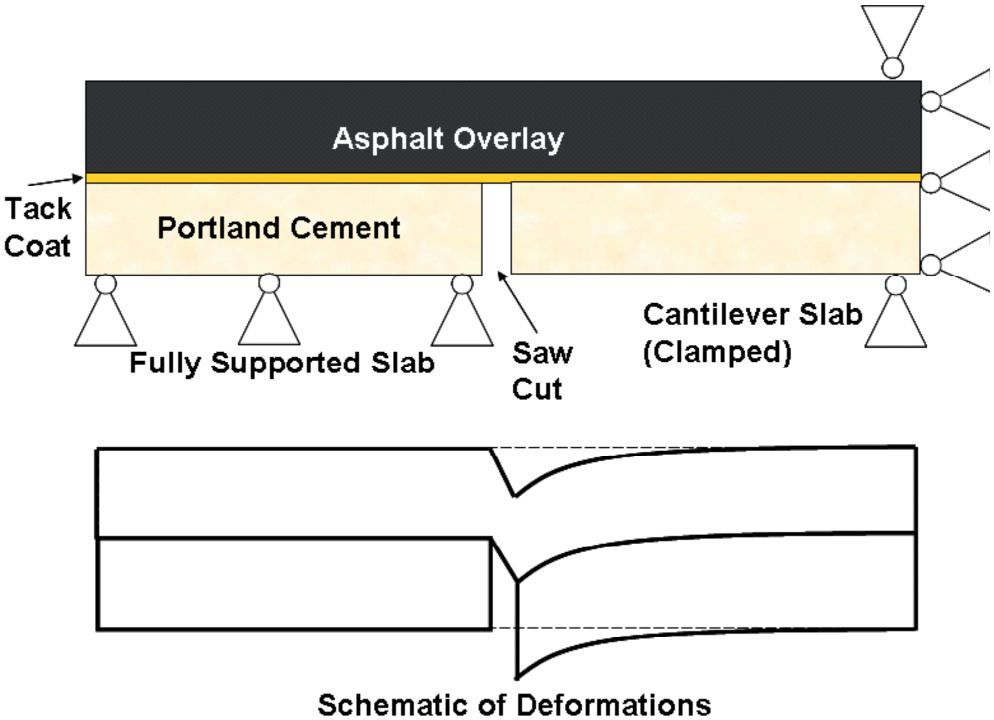
At Turner Fairbank Highway Research Centre (TFHRC), three mixtures overlaying concrete were tested; the reference dense graded mixture described earlier in this report with both the control unmodified asphalt binder and epoxy asphalt binder, and an asphalt rubber mixture made with a gap-graded aggregate gradation and the crumb rubber blended with the base binder by the Arizona wet process. The latter had performed well compared to other reference mixtures in earlier ALF tests and in the Simple Performance Test protocol (see Appendix: Figure A5.1)

A schematic of the experimental set up for the controlled stress test is shown in Figure 4.16, and the French Pavement Rutting tester (FPRT) being run on a composite slab is shown in Figure 4.17. The FPRT was used to apply repetitive, reciprocating wheel loads. The inflation pressure of the wheels was 100 psi and the wheel load calibrated to 1 200 lbs. A conventional Portland cement concrete mixture was cast in asphalt mould to 40 mm depth and cured in a warm moist environmental chamber. The compressive strength of the mixture was greater than 30 000 psi. The surface of the Portland cement slab was hand finished with a trowel. No tining or other texturing was performed.

The cured Portland cement concrete slabs were removed and placed back in the asphalt slab moulds for placing the asphalt mixture overlay. A tack coat was used between the asphalt and concrete mixes. Epoxy asphalt binder was used as the tack coat. The loose hot mix asphalt was placed in the mould above the Portland cement then spread and compacted in a linear kneading compactor to approximately 7% air void content in the asphalt mixture. The composite slabs were then cooled, and a wet diamond saw was used to place a saw cut through the Portland cement concrete in the centre of the composite slab.

The slab was supported in the French Pavement Rut tester such that it would create Mode II cracking or shearing. (Thermal opening and closing of cracks or joints corresponds to a Mode I mechanism.) One half of the slab was fully supported. The other half of the slab was clamped at one end and not supported at the saw cut, approximating a cantilever type of deformation.

Figure 4.16. **Schematic for Composite Testing of Epoxy Asphalt and Reference Asphalt on Portland Cement Concrete Slabs**



Source: Turner Fairbank Highway Research Centre (United States).

Figure 4.17. **Composite Testing of Slab using the French Wheel Track Test**

Source: Turner Fairbank Highway Research Centre (United States).

The number of cycles to full crack propagation through the asphalt overlay was observed. The gap graded asphalt rubber mixture failed in less than 100 cycles. (This was surprising as the binder performed extremely well during earlier ALF experiments.)

The reference dense graded mix failed in approximately 1 600 cycles. The dense graded epoxy asphalt mixture did not initiate or propagate crack. The only visible damage was delamination in the vicinity of the saw joint.

The results from the three different crack propagation studies simulating rigid and flexible bases suggest that epoxy asphalt mixtures provide superior resistance to crack initiation. The cross-linked nature of the epoxy system resists crack propagation but, once bonds are broken, they are unlikely to heal.

4.6 Embrittlement

The Cantabro Test was used to measure the mixture cohesion of aged and unoxidized OGPA specimens. The test [21] is based on the Los Angeles Abrasion test, Figure 4.18. Cylinders of compacted mix are tumbled in a steel drum for 300 revolutions at 30 rpm.

Figure 4.18. **Cantabro Device (Los Angeles Abrasion)**

Source: Phil Herrington, Opus Central Laboratories (New Zealand).

The weight of aggregate lost from the specimen through abrasion is recorded as a percentage of the original weight. The condition of specimens before and after testing is illustrated in Figure 4.19.

Figure 4.19. **Mix Specimens Before (left) and After (right) the Cantabro Test**

Source: Phil Herrington, Opus Central Laboratories (New Zealand).

Control and epoxy specimens were oxidised by heating at 85°C for 38 days to simulate approximately seven years of aging in the field for OGPA surfacings in New Zealand [21].

The mean modulus of the cured epoxy OGPA specimens (120 hours at 85°C) was 4 300 MPa compared with 840 MPa for the control specimens. The uncured epoxy mixture modulus, 570 MPa, was lower but still comparable to that of the control. After oxidation the epoxy modulus increased to 7 000 MPa compared with 4 000 MPa for the control. Cantabro test results are given in Table 4.4.

Table 4.4. **Summary of Cantabro test results**

	Percentage Mass lost (%± 95% confidence limits)			
	10 °C		**25 °C**	
Mixture	**Initial**	**After oxidation (909 hrs, 85ºC)**	**Initial**	**After oxidation (909 hrs, 85ºC)**
Epoxy (cured)	14.9 ± 4.6	17.6 ± 4.6	16.2 ± 3.2	13.0 ± 2.7
Control	53.2 ± 5.2	72.1 ± 7.7	16.5 ± 3.0	30.6 ± 4.2

Despite the high modulus of the cured epoxy material, the Cantabro test results of the unoxidised mixture are comparable to that of the control at 25°C and significantly better at 10°C. After oxidation mass losses both at 10°C and 25°C are much lower than that of the control. In fact over the range of conditions used, the epoxy specimens were essentially unaffected both by temperature or oxidation.

As surface ravelling is the principal failure mode for OGPA, these results suggest a markedly improved field life for epoxy bitumen OGPA compared to the standard material.

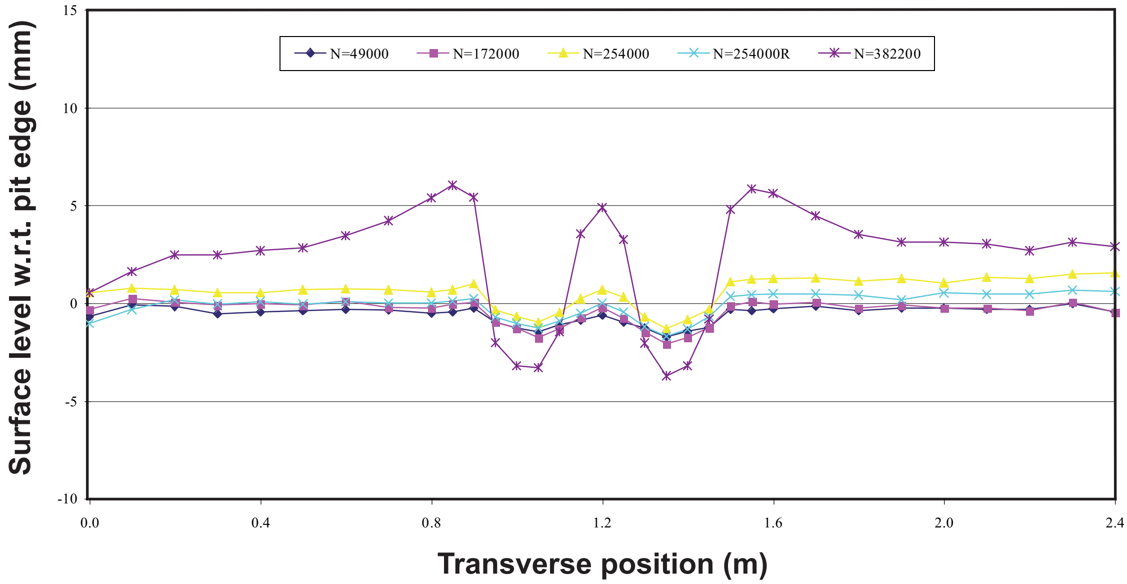
4.7 Accelerated Pavement Testing

4.7.1 TRL

Trial sections were laid at the Pavement Test Facility at TRL to determine the performance of the epoxy asphalt and HPCM surfacings under the action of traffic. A third section using a standard surfacing, a proprietary thin surface material, an SMA marketed as Masterpave, was laid as the control. The trial involved trafficking the three sections for one million standard axles (msa) at 20°C and then increasing the pavement temperature to 35°C for an additional 0.5 msa. Results are shown in Figure 4.20 at different numbers of passes. Additional details regarding the experiment and facility are discussed in Chapter 5.

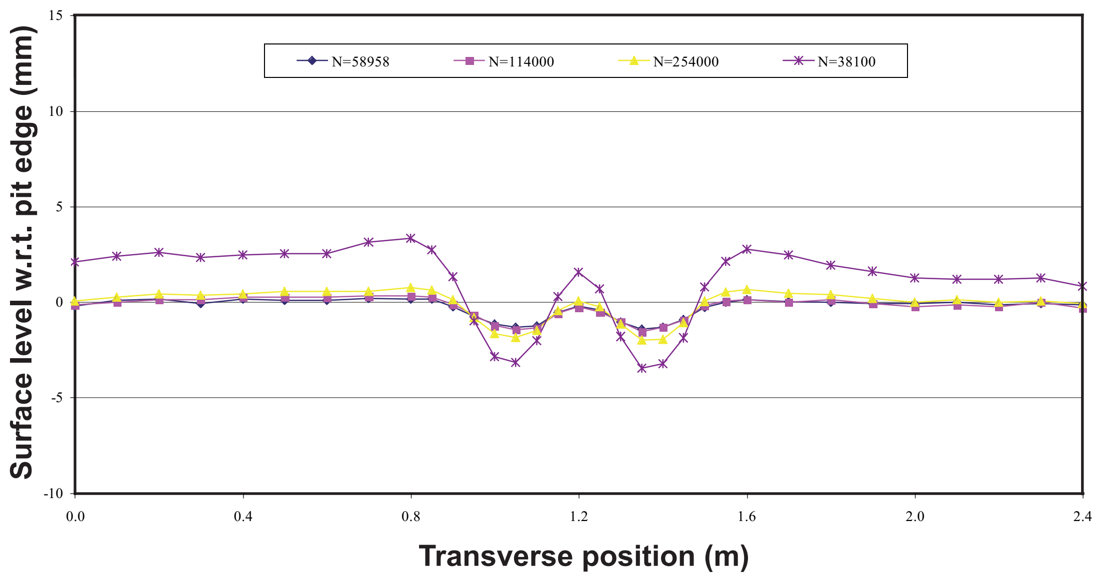
The epoxy asphalt and control sections exhibited similar rut resistance when loaded at 20°C. Loading at 35°C caused both sections to rut, with the epoxy asphalt section providing the better resistance of the two, Figure 4.21.

Figure 4.20. **Surface profile – Masterpave control (section 2)**



Source: Transport Research Laboratory (TRL) Ltd. (United Kingdom).

Figure 4.21. **Surface profile – Epoxy Asphalt (section 3)**



Source: Transport Research Laboratory (TRL) Ltd. (United Kingdom).

Much of the rutting in the epoxy asphalt section occurred in the underlying layer constructed with a 125 pen dense bitumen macadam. Intermittent longitudinal cracking was observed in the wheelpath of the epoxy asphalt section due to the canalised trafficking.

These results suggest that for new construction, epoxy asphalt be placed on a stiffer layer or the underlying layer is exposed to permit oxidative hardening.

4.7.2 Canterbury Accelerated Pavement Testing Indoor facility (CAPTIF)

CAPTIF is a 58 m long (along the centreline), unheated indoor circular test track located in Christchurch New Zealand. A trial of epoxy OGPA was conducted to assess early life performance and any practical difficulties associated with full-scale manufacture and construction of the material.

The trial consisted of adjacent control and epoxy OGPA sections each 6 m long, 2 m wide and 30_35 mm thick. The OGPAs were laid on a 200 mm thick pad of dense graded asphalt. An SBS polymer modified bitumen emulsion (about 0.63 L/m2) tack coat was applied and allowed to break before the OGPAs were placed. Temperatures during compaction were 80–94°C and 75–80°C for the epoxy and control mixtures respectively. No problems in handling or compaction of the epoxy OGPA were noted; its behaviour and appearance was indistinguishable from that of the control material. No unusual fuming or smell was noted.

Owing to time constraints it was not feasible to traffic the epoxy OGPA as it cured over a period of several months. Instead, curing of the epoxy OGPAs was accelerated using heaters, maintaining an average surface temperature of 29.7°C over a period of 13 days.

The rate of cure of the epoxy OGPA was monitored by measuring the modulus of 100 mm diameter cylindrical (Marshall) blocks prepared at the time of construction and placed on the surface of the test sections. After 13 days, when trafficking began, the modulus of the epoxy OGPA had reached about 57% of the fully cured value of 3909 MPa.

The test sections were trafficked for 198 000 wheel passes over a period of about three weeks. A load of 40 kN was used on each wheel set (equivalent to an 8.2 tonne axle load). After 175 000 passes the tyres were set at an angle of 1.5° from the tangent to increase drag on the surface. The surface temperature during trafficking averaged 12.1°C.

Visually the epoxy OGPA appeared unaffected by trafficking but the control section, although not extensively damaged, lost a significant amount of chips from the surface at points along the length of the wheelpath.

Neither section exhibited excessive rutting after 198 000 passes. Rutting in the control section increased continually with trafficking (up to 4.3 mm) whilst the rutting in the epoxy section stabilised after about 60 000 passes (at about 2.5 mm), probably reflecting the fact that the OGPA was only partially cured when trafficking commenced. Under field conditions, trafficking will occur on essentially uncured epoxy asphalt, though there is no reason to suppose that early rutting will be any more severe than that associated with equivalent standard asphalt mixtures (the moduli of the uncured epoxy and control OGPAs are comparable, see section 4.6).

Initial skid resistance, in the wheelpath, was comparable for both sites, demonstrating that the epoxy bitumen was not inherently more slippery than conventional asphalt. After 198 000 passes the skid resistance of the epoxy section, although still acceptable in practice, had decreased slightly, whereas that of the control site had increased beyond its initial value. One explanation for these results is that bitumen had worn from the aggregate surfaces in the control section whereas, in the epoxy OGPA, the binder had instead ‘polished’ onto the aggregate surfaces in some way, resulting in a reduction in skid resistance. However, the visual appearance of the materials did not appear to be significantly different and a more likely explanation is that the increase in skid resistance of the control section was due to the test results being affected by the surface disruption and abrasion damage observed on its surface.

4.7.3 Danish Asphalt Rut Tester (DART)

From the Test Pavement Facility at TRL (see 4.6.1) four large pavement slabs (1 100 x 1 400 mm approx.) were extracted from an unloaded part of the Epoxy Asphalt pavement. The samples were transported to Denmark for accelerated testing with respect to permanent deformation in the Danish Asphalt Rut Tester. This equipment can perform accelerated full scale loadings which resembles a quarter of a slow moving lorry (up to 130 kN axle load at 5 km/h) under full climatic control with independent temperature regulation of the top and bottom of the bituminous bound pavement structure creating a realistic temperature gradient down through the pavement. A transversal stochastic wander of the wheel carriage is introduced during the loadings to further resemble reality.

The test pavement was evaluated under test conditions normally used for assessing the rutting potential of different pavement design on Danish motorways [19]. The conditions are 100 kN axle load, Super Single tyre, 900 kPa, 5 km/h, transversal wander stochastically following a Normal distribution with a standard deviation of 100 mm and a top down temperature gradient from 40°C to 20°C. Two slabs were tested according to these parameters, while the other two slabs were tested at an elevated temperature gradient from 50°C at the top and 30°C at the bottom.

The slabs showed in the two test situations either similar or less permanent deformation compared with earlier experience from Danish Motorway pavements. The majority of the rutting measured on the surface took place in the two bituminous base layers through a combination of densification and plastic flow of the relatively soft base layer material. Virtually no rutting could be determined in the epoxy asphalt surface layer. No debonding or delamination between the epoxy asphalt and the base layer could be detected.

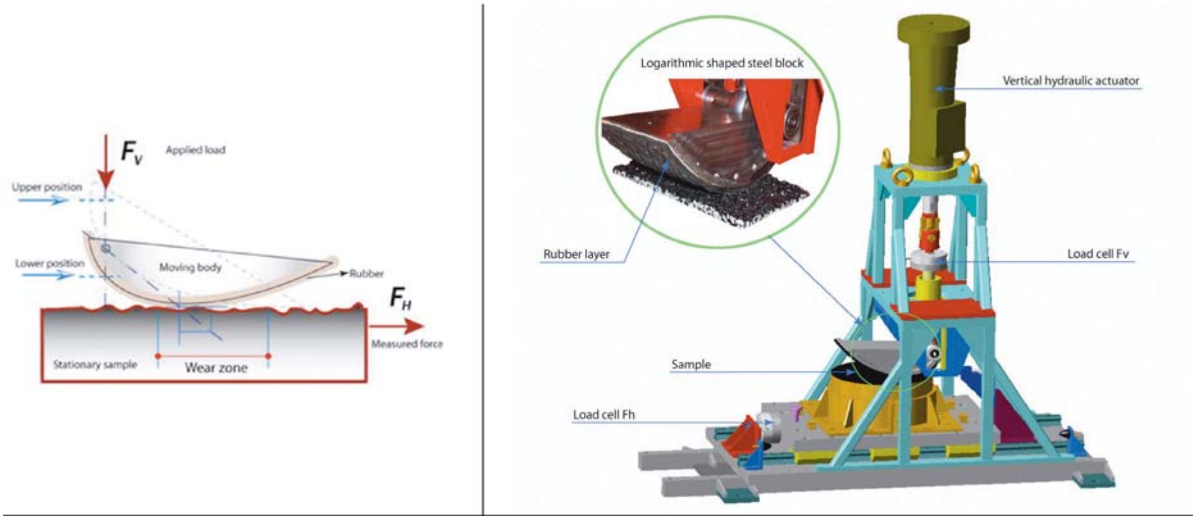
4.8 Evaluation of Surface Characteristics

Surface characteristics of epoxy asphalt mixtures were determined on both laboratory compacted slabs as well as on the full-scale accelerated pavement test sections. This testing was limited to an evaluation of ravelling characteristics and friction properties.

4.8.1 Resistance to shear stress/ravelling

A new experimental device named T2R has been used to evaluate the shear resistance of asphalt mixtures used in road construction in France. The test procedure consists of applying a cyclic load in compression on the loading block. Due to the logarithmic effect of the shape of loading block, the angle of the loading force to the specimen remains constant throughout the test. The cyclic movements of the loading block on the specimen progressively deteriorate the surface of the specimen and cause loss of aggregates. Usually, tribometer devices measure wear resistance under imposed displacement. This new device proposed by Stefani *et al* [22] allows the device to maintain a constant load level whatever the state of the surface damage (see Figure 22). This result is obtained by using a logarithmic shaped block, loaded with a vertical load. The device allows the same ratio between the vertical load and horizontal shear force to be maintained throughout the test (Patent Number FR 06 50 054) [22]. In the contact area, the force depends on the texture depth of the bituminous surfacings and the rheological properties of the materials in contact (rubber, bituminous mix).

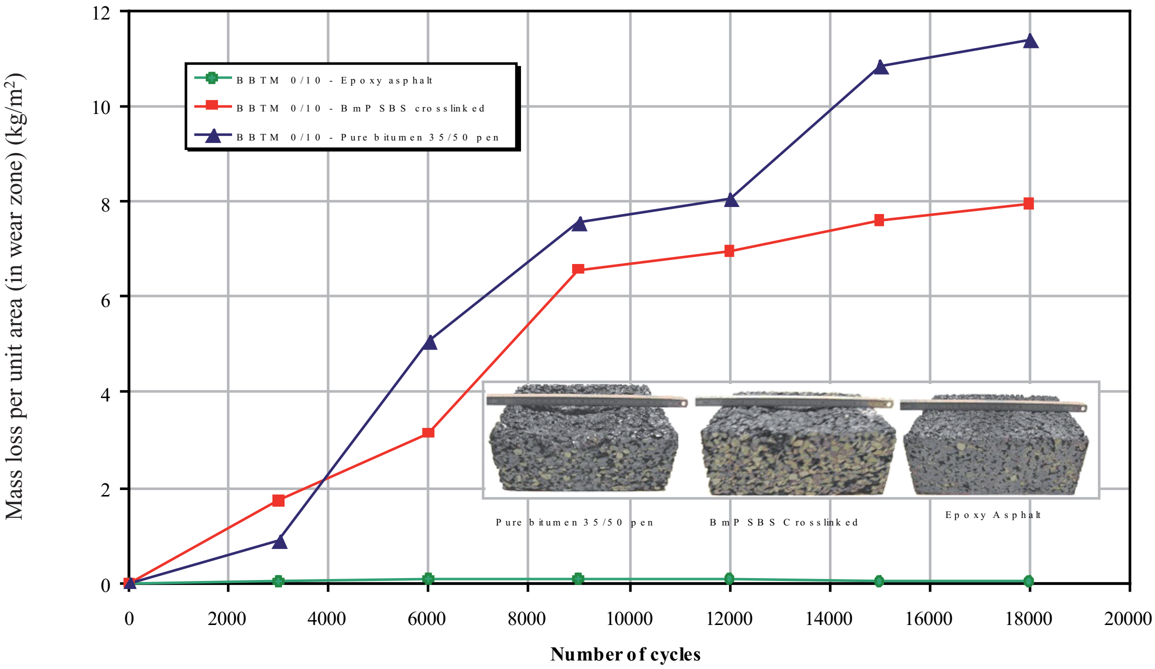
Figure 4.22. **LCPC T2R Device for Evaluating Resistance to Shear Stress**



Source: F. Hammoum, Laboratoire Central des Ponts et Chaussées (France).

The T2R was used to evaluate the resistance to shear stress for BBTM mixes made with three different binders: a conventional 35/50 pen, a polymer modified and epoxy asphalt. This was done by measuring the amount of wear as defined as the loss of material from the contact zone. The quantity of material removed was measured as a function of time. The results for these materials are shown in Figure 4.23.

Figure 4.23. **Evolution of mass loss with number of cycles at ambient temperature for different bituminous mixes**



Source: F. Hammoum, Laboratoire Central des Ponts et Chaussées (France).

The epoxy asphalt exhibited minimal wear and clearly outperformed the polymer modified and control bitumen suggesting that epoxy asphalt may perform well in open graded friction courses that may be susceptible to ravelling.

4.8.2 Friction

In addition to the testing and results outlined in 4.7.2, a friction tester was used to evaluate the control (Masterpave) and epoxy asphalt pavement test sections placed at TRL. The epoxy asphalt had a skid resistance value of 75 and that of the Masterpave was 65. Following trafficking both values were found to increase; the skid resistance value for the epoxy asphalt section rose to 79 and that of the Masterpave to 76. This increase is probably due to the bitumen coating being removed from the aggregate and the higher skid resistance of the aggregate taking effect.

4.8.3 Noise

No experiments were performed comparing the noise characteristics of epoxy asphalts with conventional bitumen. The expected outcome is that the mix design has a more significant impact on noise than does the nature of the bitumen.

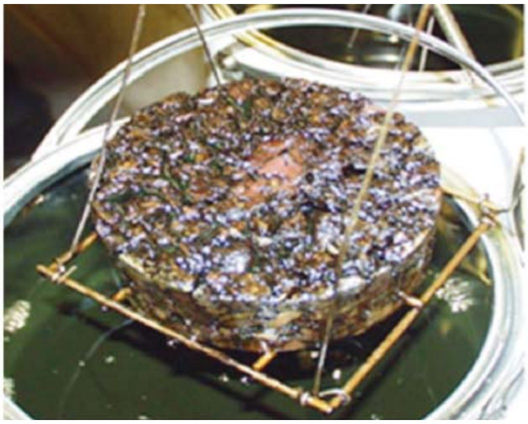
4.9 Miscellaneous

4.9.1 Resistance to Fuel Spillage

The resistance of bituminous paving mixtures to dissolution from fuel spillage was evaluated using the Diesel Immersion Test. The test procedure consists of placing compacted specimen in a mesh frame followed by total immersion of the specimen in 5 litre tins filled with diesel at laboratory ambient temperature. In all cases the specimens are kept approximately 25 mm off the bottom of the tin and completely covered by the solvent. After approximately 10 minutes immersion, the initial immersed mass is measured by hanging the frame assembly underneath a balance while maintaining the core complete immersed. The procedure is repeated daily for the required length of time. Figure 24 shows a specimen being weighed while suspended in diesel. The figures clearly show that overall the epoxy HRA mixes were unaffected by the exposure to the hydrocarbon. Similar results were found for the HRA mixes.

Figure 4.24. **SMA Specimens Immersed in Diesel for 8 Days**

Control



Epoxy Asphalt

Source: Richard Elliott, Scott Wilson Pavement Engineering.

4.9.2 Recyclability

Gyratory cores of epoxy asphalt were crushed using a hammer mill and frequently sieved to obtain a wide distribution of sized material. The crushed material was aged to simulate recovered asphalt pavement (RAP) storage. Epoxy asphalt RAP was blended in with reference aggregate to achieve a 20% blend and similar gradation. Of note is that the epoxy asphalt RAP has more texture than that of conventional RAP. This should provide a better interlocking structure and hence a higher modulus mixture. The recycle mix performed similar to conventional RAP with regard to workability and the perceived level of volatiles.

4.10 Summary and Conclusions

In the course of this study a large amount of data were collected in seven laboratories. The aim of this study was to research the behaviour and properties of the materials identified as candidates and test them sufficiently to assess their suitability for use in long life wearing courses.

By specifying the use of local materials, a number of different types of epoxy asphalt were identified and extensively evaluated in this study as binders and as a component in various mixture systems. These data were compared with conventional bitumen mixtures. This work not only advanced the understanding and potential application of epoxy asphalt as a surface material but also provided insight and support for new characterisation tools under development which evaluate fatigue and crack propagation.

Manufacturing guidelines were provided by the various epoxy asphalt suppliers; these addressed blending compositions, mixing temperatures, as well as curing times and temperatures. Nevertheless, familiarisation with the two-part binder and consideration of its curing history and establishment of protocols for conditioning the given epoxy asphalt is paramount to successful testing and evaluation of the material. To this end three types of tests were conducted: one to evaluate the rate of curing, a second to determine the properties of the fully cured system, and the third, to determine the effect of incomplete curing on performance of the epoxy asphalt.

For convenience the epoxy asphalts evaluated were classified as moderate curing (amine and amino based) and slow curing (acid based) epoxy asphalts. The moderate curing amine and amino based epoxy asphalts were somewhat problematic in that the systems cured too quickly to allow proper compaction; this resulted in higher air voids of the compacted specimens. Consequently the rapid setting epoxies do not appear to be compatible for use in a conventional hot mix plant. These materials may perform well in a cold mix operation though data would be needed to determine this. Despite the labelling of fast or slow curing, care will need to be exercised in the use of epoxies to ensure adequate curing has taken place prior to its trafficking.

The binder properties for the epoxy asphalts evaluated were greatly superior to conventional bitumen. The cross-linked epoxy asphalts are stiffer, have significantly greater cohesive strengths, offer greater resistance to shear stress, and are less susceptible to oxidation.

The epoxy asphalt mixtures provided significant improvement in terms of rut resistance, moisture resistance, and fatigue life when subjected to low strains. When subjected to high strains the improvement of epoxy asphalt over conventional binders is not as marked and sensitive to the mix design. This suggests that epoxy asphalt may be limited to use in surfacings over very stiff foundations and was confirmed by accelerated pavement testing at TRL (as discussed below). A second area of concern was the loss of ductility at lower temperatures, as these losses were greater for the epoxy asphalts mixtures (and binders). To determine whether this loss exposes a potential limitation to utilization of epoxy asphalt, several new approaches to evaluating crack initiation and propagation were employed. However, all of the approaches indicated that epoxy asphalt is a tougher material and exhibits significantly greater resistance to both aspects of cracking.

The embrittlement testing that simulates the resistance of an OGPA mixture to ravelling in the field, gave results that mirrored those of the binder rheology. The epoxy asphalt cures but does not age significantly; simulated aged (7 years) epoxy asphalt significantly outperformed the control. A limited accelerated pavement testing (APT) trial using CAPTIF resulted in early signs of surface abrasion in the control section but not in the epoxy.

Empirical composite specimen testing was conducted to evaluate epoxy asphalt over both flexible and rigid bases. The performance of the epoxy specimens was far superior to that of the control specimen in terms of cumulative creep strains, crack propagation and overall sustained damage. Comparison testing of the interface strength proved inconclusive results as the bond coat was the controlling factor or failure occurred in the lower layer.

The laboratory binder and mixture results were validated by the three APT experiments. The epoxy asphalt sections outperformed those of the control. One important lesson learned was that the epoxy should be placed over a sufficiently stiff base to prevent rutting of the underlying layer. While the epoxy asphalt resists deformation, excessive deformations in the lower section may translate and give rise to longitudinal cracks or tearing of the surface layer. These APT results are somewhat limited as they reflect the performance of a single epoxy asphalt product; nevertheless, this improved performance should be reflected in other epoxy systems.

System characteristics such as skid resistance and polishing are largely dictated by aggregate properties and mix design. The APT control and epoxy sections exhibited similar skid resistances when first placed. Following loading of the sections, the values for the control tended to improve as the control surface experienced abrasion damage whereas that of the epoxy asphalt was minimal.

In a test designed to simulation fuel spillage, the epoxy mixtures were found to be extremely resistant to diesel immersion, showing negligible mass loss. In comparison, the HRA control mixtures failed within 4 days of immersion.

In short, the many tests performed on epoxy asphalt materials were planned to cover all important questions regarding the properties which are known to be critical for the durability and service life of a pavement under heavy traffic. These tests all indicate that the use of epoxy asphalt should significantly extend the service life relative to conventional binders.

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5. HIGH PERFORMANCE CEMENTITIOUS MATERIAL: TESTING AND TEST RESULTS

5.1 Introduction: an innovative hydraulic material for wearing courses

During the Phase II work, two technical families of candidate long life wearing courses were tested and evaluated: one a bituminous and the other a cementitious surfacing material. The development, testing and evaluation of the cementitious surfacing material is presented in this chapter.

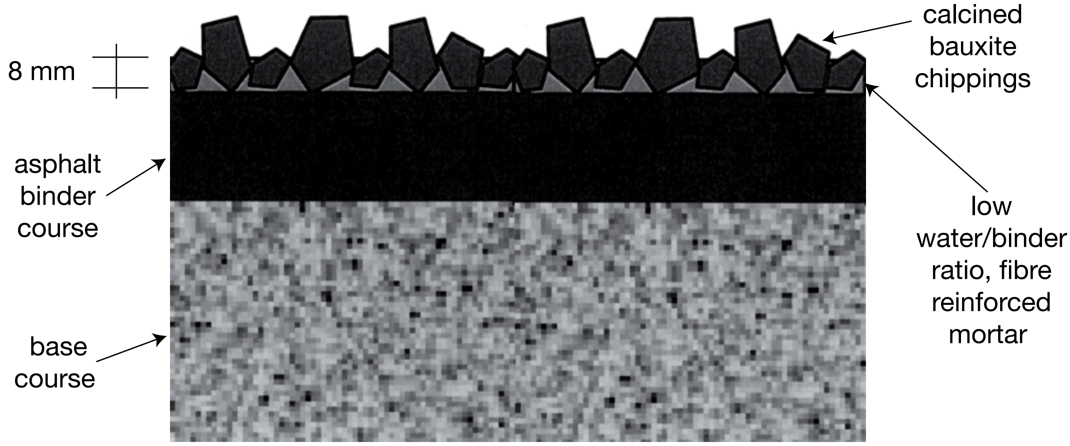
The innovative High-Performance Cementitious Material (HPCM) under consideration consists of an 8-mm layer of ultra-high performance, fibre-reinforced fine mortar, in which hard, polish resistant aggregate particles are embedded. The development of the HPCM material included the following stages and deliberations: selection of constituents, mix-design, laboratory application processes, and assessment of behaviour in various tests encompassing a range of deterioration processes, such as abrasion, fatigue, restrained shrinkage cracking, freeze-and-thaw, etc.

One of the most important requirements of a wearing course is good skid resistance, which is dependent on the aggregate embedded in the surfacing. For a long-life surface layer, it is essential to choose an aggregate with superior polishing resistance. Based on wide experience, calcined bauxite is recognised as one of the best aggregates available. However, calcined bauxite is also an expensive material, with limited suppliers: its unit cost may range from 30 to 40 times that of ordinary aggregates. Therefore, if it is to be used, there would be value in the surface dressing having only a single layer of aggregate particles. Among the aggregate sizes available, a 3-7 mm size was chosen, because a maximum aggregate size of around 6 mm tends to be the optimum size when a combination of adequate skid resistance and limited noise emission is required.

Next is the design of the binder, the key function of which is to ensure the calcined bauxite chippings stick to the pavement. When the option of using a hydraulic binder is taken, it is important to develop a fine material with the maximum tensile strength that is obtainable on site. From the experience gained with ultra-high performance concretes[1], it follows to design a mix of sand, Portland cement, silica fume, superplasticiser and water, with a low water/binder ratio. As in the ultra-thin white topping technology[2], a good bond is essential between the cementitious mortar and the bituminous substrate. However, due to the shrinkage of the mortar which will be restrained by the pavement structure, cracking is likely to occur. To limit the crack openings, some sort of reinforcement is needed, but, given the thinness of the mortar layer, only fibres added to the mix may play this role. The thickness of this fibre-reinforced mortar layer should be minimal for reasons of cost. However, it should be thick enough to allow for good penetration of the chippings in the fresh mortar. Moreover, the chippings/mortar composite should form a strong surface layer protection to the lower pavement layers. Taking all these considerations into account, a thickness of 8 mm was adopted for the mortar. Figure 5.1 summarises the concept adopted for the HPCM[3].

This chapter also outlines the various tests performed to develop and to characterize the innovative hydraulic HPCM surfacing. Sections 5.2-5.5 deal with the choice of constituents, mix-design and plain mortar shrinkage measurements. Section 5.6 details the HPCM application procedures used in the laboratory and outdoor tests. In sections 5.7-5.9, the cracking behaviour of the HPCM composite is investigated at various scales. Sections 5.10-5.14 help assess the likelihood of chipping loss under the action of traffic and/or climatic exposure. Sections 5.15 & 5.16 cover the fatigue behaviour of HPCM for the material and structure levels. The noise generation at the tyre/wearing course interface is predicted in section 5.17 and the risk of delamination and buckling is studied in section 5.18. Finally, the preliminary conclusions of this series of tests are set out in section 5.19.

Figure 5.1. **Principle of the HPCM solution**



Source: Laboratoire Central des Ponts et Chaussées (France).

5.2 Choice of constituents [HPCM Report 1, 2]

At the beginning of the project, in order to get a consistent set of data, the members of the HPCM Group decided to use the same constituents and mixtures in their tests which were undertaken in national testing laboratories in the seven different countries involved. The following constituents were included in the original mixture designs:

- Possibly 3-7 mm calcined bauxite.
- Aeolian siliceous fine sand.
- Portland cement CEM I.
- Light grey silica fume.
- Polycarboxylate-type superplasticiser in powder form.
- Commercially available retarder in liquid form, in order to limit the slump loss phenomenon.
- Steel fibres with a length of 13 mm and a diameter of 0.2 mm.
- Alternatively, PVA (polyvinyl alcohol) fibres with a length of 15 mm and a diameter of 0.33 mm.

After the development of a basic mix-design for the mortar (see next section), a premix incorporating all dry constituents (including the superplasticizer) was prepared by the commercial supplier (SIKA France), and delivered on order to the national laboratories of the project's HPCM group participants, in their respective countries.

5.3 Mix-design, production and characterization of the mortar (LCPC, France) [HPCM Report 3, 12]

The original mix-design of the mortar was developed taking into account the following considerations:

- *Soft consistency*

The mortar had to be easy to spread, but it should not be self-levelling, since pavement surfaces always exhibit a certain slope (from 1-2 % to 6 % or more). A slump value around 10-11 cm was initially selected. After the second series of cracking tests, it was decided that a higher slump value (about 20 cm) would improve the bond between mortar and binder course.

- *Large dosage of superplasticizer*

This type of admixture is essential in any High Performance Concrete (HPC), especially at very low water/binder ratio. The saturation dosage is a good starting point, if the next point is correctly managed.

- *No crust at the surface*

It is a peculiarity of many HPCs that a thin crust of fine material forms at the top surface quickly after finishing, even when there has been careful curing. Such a crust should be avoided, since chippings have to be embedded with a good bond to the mortar layer.

- *Possible use of 3/7 chippings*

It is important for the coarse aggregate to be able to penetrate the surface of the soft mortar. This means that the mortar should not be too dense, and should be able to flow between coarse aggregate particles, to a certain extent. In other words, the original mortar was designed assuming that the mix of mortar with half of the chippings could be placed with a normal level of compaction.

- *Water/cement ratio = 0.20*

A Water/cement ratio of 0.20 is typical of most Ultra-High Performance Concrete (UHPC) produced commercially. Using a Water/Cement ratio of 0.20 ratio ensures that the material will be among the best performing cementitious materials. Adopting a lower value would have created difficulties in the rheology of the fresh mix, which means a material difficult to apply industrially.

- *Silica fume/cement ratio = 0.20*

This value is also typical for a Ultra High Performance Concrete (UHPC). A higher value would mean a higher cost with little improvement of the material, if any.

After some trial batches, the recipe presented in Table 5.1 was obtained – and called Plain Mortar A. Such mixtures require a long mixing time and a carefully optimised sequence encompassing moistening of the mixer, introduction of dry materials, first mixing stage, addition of the water containing admixtures, second mixing stage, addition of fibres, third mixing stage and discharge from the mixer. Total mixing time ranged from 5 to 15 minutes, depending of the type and volume of the mixer. The main properties of Plain Mortar A and Mortar A mixed with 1% steel fibres appear in Table 5.2 (the specimens were cured at 20°C and at 100% relative humidity (R.H.) after demoulding).

Table 5.1. **Mixture-proportions of plain mortar A**

Components	Kg/m³
Siliceous coarse sand 0.2/1	432
Siliceous fine sand 0.08/0.315	432
CEM I Portland cement	991
Silica fume	198
Superplasticizer (dry powder)	2.93
Water	198
Water/cement (w/c[4])	0.20

Table 5.2. **Properties of plain mortar A and mortar A with 1% steel-fibre (SF)**

Wet and hardened properties of the mix	Plain (A)	A plus 1% SF
Slump (cm)	11.5	14
Air content (%, as measured with a pressure mortar airmeter)	6.3	5.8
Compressive strength at 28 days (MPa, as measured on 4 × 4 × 16 cm specimens)	138	172
Flexural strength at 28 days (MPa, as measured on 4 × 4 × 16 cm specimens)	24.9	23.5
Elastic modulus at 28 days (GPa, as measured on 11 × 22 cm specimens)	–	42.5

During the preliminary cracking test series (see section 5.6), it was realised that the mixture was subject to early slump losses. Therefore, a retarder was added to the original mix, and the following Mortar B mix-design was obtained (see Table 5.3).

Table 5.3 **Mixture proportions of the plain mortar B**

Components	Kg/m³
Siliceous coarse sand 0.2/1	429
Siliceous fine sand 0.08/0.315	429
CEM I Portland cement	985
Silica fume	197
Superplasticizer (dry powder)	2.91
Retarder	4.95
Water	195
w/c	0.2
Slump after mixing (cm)	9.5
Slump after one hour (cm)	9

Later in the project, it was found that the mix consistency had to be more fluid, with lower slump losses. Therefore, another mix-design for the plain mortar was recommended (Mortar C), with more superplasticizer and water. The composition of this third plain mortar is given in Table 5.4. As well, following the first results of the strip cracking tests, a tentative selection was made for a solution incorporating 4% of PVA fibres. Table 5.5 presents the main properties of this fibre-reinforced mortar. This last mixture was used in most of the HPCM performance tests in the project, with some local adjustment of the water-cement ratio, which ranged from 0.21 (in the original mixture) to 0.27 (in the PTF test – see section 5.16).

Table 5.4. **Mixture-proportions of the plain mortar C**

Components	Kg/m^3
Siliceous coarse sand 0.2/1	429
Siliceous fine sand 0.08/0.315	429
CEM I Portland cement	985
Silica fume	197
Superplasticizer (dry powder)	4.40
Retarder	4.95
Water	207
w/c	0.21
Slump (cm)	21

Table 5.5. **Properties of the hardened mortar C with 4% of PVA fibres**
(fresh state properties: slump 23 cm, air content 4.5%)

Dimensions of specimens (cm)	Curing regime	Type of test	Mean value (MPa)
Prisms 4 × 4 × 16	28 days at 20°C, 100% R.H.	Flexural	28.5
Prisms 4 × 4 × 16	28 days at 20°C, 100% R.H.	Compressive	164
Prisms 4 × 4 × 16	56 days at 20°C, 100% R.H.	Flexural	35.7
Prisms 4 × 4 × 16	56 days at 20°C, 100% R.H.	Compressive	182
Prisms 4 × 4 × 16	28 days at 20°C + 28 days at 60°C, 100% R.H.	Flexural	31.5
Prisms 4 × 4 × 16	28 days at 20°C + 28 days at 60°C, 100% R.H.	Compressive	190
Cubes 10 × 10 × 10	28 days at 20°C, 100% R.H.	Compressive	148
Cylinders Ø11 × 22	28 days at 20°C, 100% R.H.	E-modulus	43 000
Cylinders Ø11 × 22	28 days at 20°C, 100% R.H.	Compressive	129

A water sensitivity analysis was performed by Dansk Beton Tecknik (DBT) since the water/cement ratio was increased during some tasks. The results of this laboratory study appear in Table 5.6.

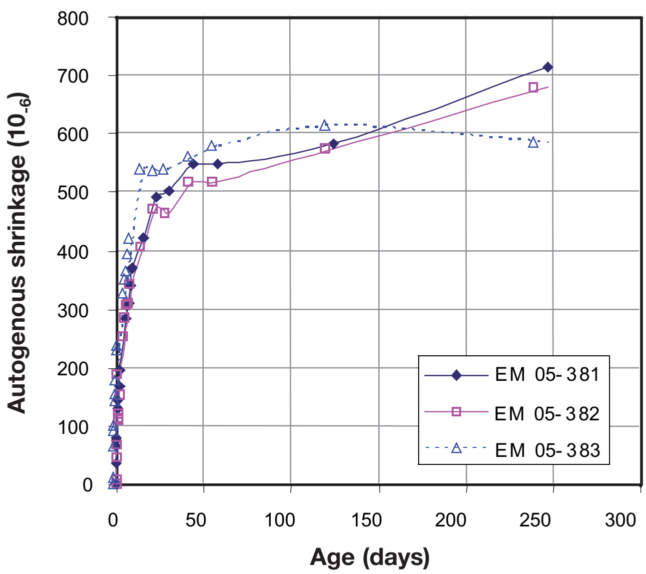
Table 5.6. **Effect of water dosage on compressive and flexural strength of mortar C with 2.5 % of steel fibres (as measured on 4 × 4 × 16 cm prisms according to EN 1097-1)**

w/c	Compressive strength at 28 days (MPa)	Flexural strength at 28 days (MPa)
0.21	188	41
0.23	171	35
0.25	132	29

5.4 Shrinkage tests (LCPC, France) [HPCM Report 6]

Since some cracking tendency was anticipated, shrinkage measurements were carried out at the beginning of the Phase II project work. Shrinkage tests were performed on 7 × 7 × 28 cm prisms, using plain mortar A. Six samples were cast and sealed, then demoulded at 24 hours. Three specimens were cured at 20 ± 2°C, 50 ± 10% R.H., for total shrinkage measurement, while the three other specimens were sealed with an adhesive aluminium sheet, for autogenous shrinkage measurement. The samples were weighed in order to monitor their water loss.

Figure 5.2. **Autogenous shrinkage of the HPCM mortar, vs. time after demoulding**

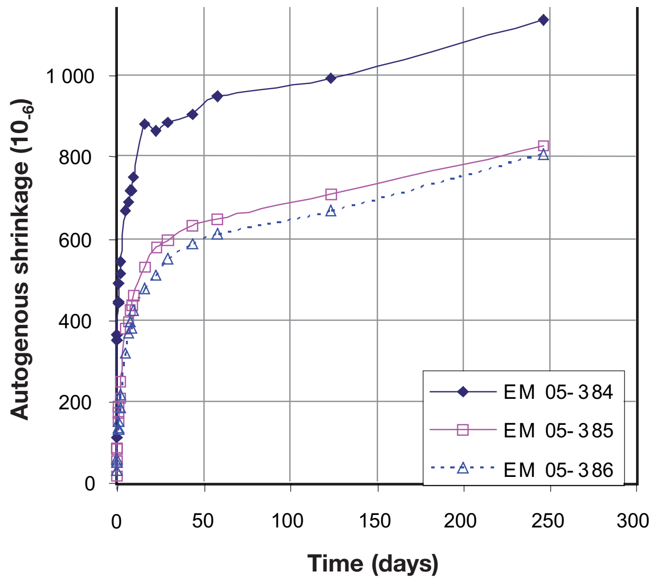


Source: Laboratoire Central des Ponts et Chaussées (France).

The HPCM mortar phase exhibited a quite strong autogenous shrinkage, as shown in Figure 5.2, which is a classic result for a very low water/cement ratio material. The final value was about 600-700 µm/m. The water loss obtained (about 2 g, or 0.8% of the initial water content) showed the good quality of the vapour tightness provided by the aluminium sheet.

As for total shrinkage, two specimens were consistent with each other, while the third one exhibited a much higher value (see Figure 5.3). However, it is likely that the very first length measurement for EM05-384 was erroneous. Therefore, we can assume that a total shrinkage of about 800 µm/m is reached after 8 months. The water loss at the same age yields 17 g per specimen. This value is much higher than in the case of the sealed specimen, but remains low with regard to the total water content of the sample. Hence, very low water-cement ratio materials keep a small amount of free water; moreover, the drying process is slow due to the very low porosity of the hardened material.

Figure 5.3. **Total shrinkage of the HPCM mortar, vs. time after demoulding**



Source: Laboratoire Central des Ponts et Chaussées (France).

Finally, the shrinkage of the HPCM mortar is essentially autogenous, and the most significant part takes place in the first two months. It should be noted that part of the shrinkage occurs between the set point and 24 hours, i.e. before demoulding, and was not measured.

5.5 Coefficient of thermal expansion (FHWA, USA)

A *Coefficient of Thermal Expansion* (CTE) is defined as 'the change in unit length per degree of temperature change' and depends on the concrete composition, age and moisture state.

The individual CTE of the components of concrete can vary significantly. The mineralogical differences among aggregates are reflected in different CTEs, and cement paste CTE may be several times higher than the aggregate.

CTE is a very important property in concrete pavement design as it can affect the curling stresses and displacements and axial stresses and movements and, as a consequence, has an impact on the performance and the serviceability of the pavement structure. The CTE can influence the early age cracking, fatigue cracking, faulting, and joint spalling[3].

A provisional test method to determine the CTE of concrete (AASHTO TP 60) was developed at the US FHWA's Turner Fairbank Highway Research Centre (TFHRC) as part of the Long Term

Performance Pavement (LTPP) test protocol. Under this test, a saturated concrete core or cylinder is subjected to temperature cycles (segments) from 10°C to 50°C and from 50°C to 10°C and the change in length is measured for each segment (see Figure 5.4). The reported CTE is the average of the two segment measures, corrected for any length change of the measuring apparatus – once the length change for each is within a required tolerance of each other.

The influence of the moisture condition on the CTE can be significant and the CTE of concrete in both dry and saturated condition is lower than when the paste is partially saturated. The value at 100 percent relative humidity (RH) is 20 to 25 percent less than the maximum, which occurs at 60 to 70 percent RH.

In order to eliminate the effect of the moisture condition variation, the test is performed in a water bath and the specimens are maintained in a saturated condition, which is considered to be achieved when two successive weighings of the surface-dried sample at intervals of 24 hours show an increase in weight of less than 0.5 percent.

As achieving saturation of the HPCM may be problematic due its low permeability, CTE tests performed on HPCM under the conditions specified – *i.e.* when the two successive weighings of the surface-dried sample at intervals of 24 hours show an increase in weight of less than 0.5 percent – do not necessarily mean that the specimen was saturated.

Table 5.7 shows the CTE of the three HPCM mixes prepared as reported in section 5.3 (mix-design C with 4% of PVA fibres). The results are very consistent. The average of the three mixes was $17.2 \times 10^{-6}/^{0}C$, which is considerably higher than previously found at TFHRC for a commercially available UHPC (Ductal®).

Table 5.7. **Coefficient of Thermal Expansion**

Mix Number	**CTE ($\times 10^{-6}/^{0}$ C)**
6061	17.2
6062	17.1
6063	17.2

An Energy Dispersive X-Ray Fluorescence (EDXRF) analysis for the elements in the mix showed a significant difference in the Si and Ca peaks of the two materials, which could explain the higher CTE value for the HPCM (Table 5.8).

Table 5.8. **EDXRF of HPCM and Ductal,**

Element	**Weight %**	
	HPCM	**Ductal®**
Al	11.74	1.44
Ca	25.63	15.05
Fe	–	1.03
Mg	–	0.79
O	46.68	49.44
S	1.39	1.04
Si	24.58	31.24

Figure 5.4. **CTE frame and LVDT dilatometer device**

The CTE frame and LVDT are placed in a water tank

Source: Turner-Fairbank Highway Research Center / Federal Highway Administration (United States).

The CTE is definitely a property that has to be taken into account, especially when the material is expected to be used in an overlay. The CTE of regular concrete ranges normally between $6 \times 10^{-6}/^{0}C$ and $12 \times 10^{-6}/^{0}C$, which is much lower than for the HPCM.

However, outdoor strip cracking tests reported in section 5.7 show that cracking tends to be more pronounced at high temperature. This means that HPCM has a lower CTE than the surrounding asphalt material. Therefore the high CTE value of HPCM could be a moderating factor as far as cracking of the material is concerned.

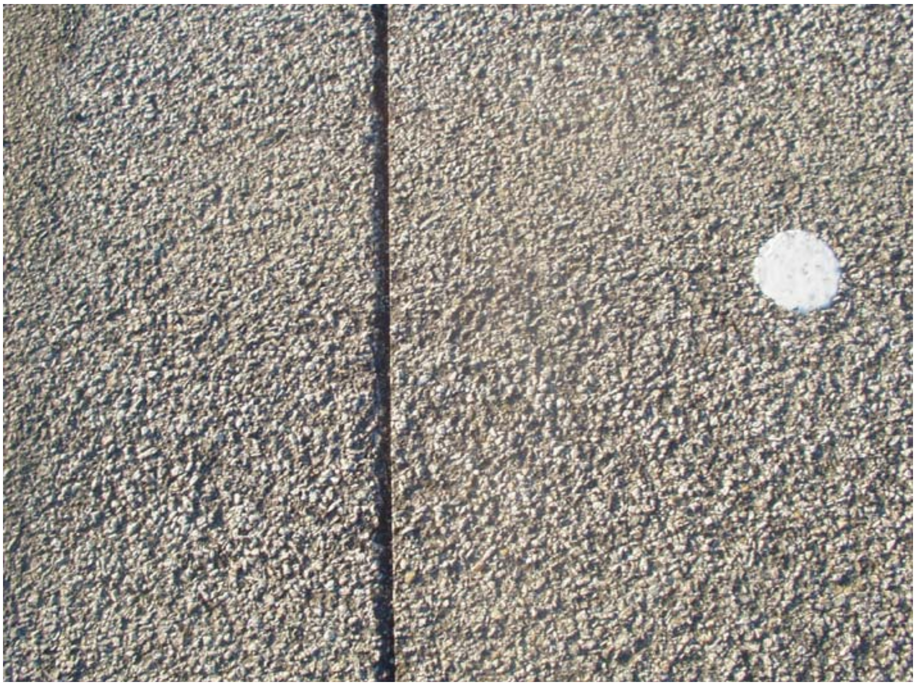
5.6. Asphalt preparation and HPCM application procedures [HPCM Report 4, 12]

After the second series of cracking tests (reported in 5.4), it was concluded that the asphalt layer required some special preparation:

- The macrotexture needed to be high enough to promote a bond between the mortar and the asphalt concrete top aggregate particles. Shotblasting was suggested and carried out in a number of tests. The required macrotexture, when measured by the sand patch method (EN 13036-1), was 2.5 mm. Values obtained in the various tests ranged from 1.0 to 2.5 mm.
- The surface had to be humid and clean, with no dust or water pockets.
- For semi-industrial tests, 10 × 10 mm trenches had to be saw cut along the edges of the test pads, in order to avoid shrinkage-induced end slip of the HPCM.

Figure 5.5 shows a typical aspect of a well-prepared asphalt layer prior to HPCM application.

Figure 5.5. **Aspect of asphalt surface after treatment (shot blasting + anchorage trench)**



Source: Laboratoire Central des Ponts et Chaussées (France).

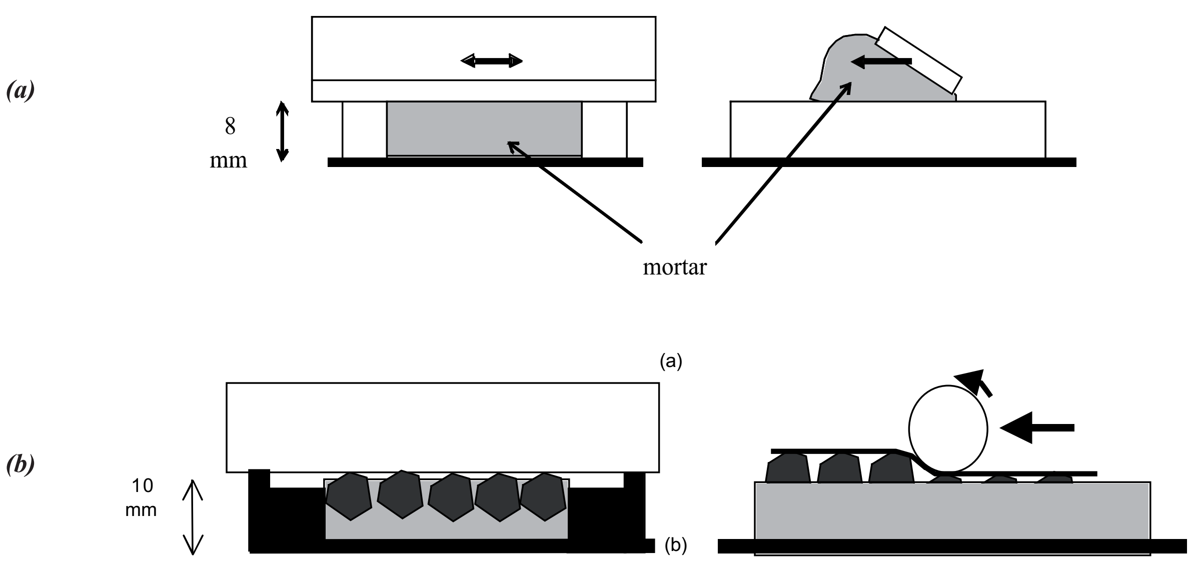
The next stage of the procedure dealt with the placement of HPCM onto an asphalt surface. Timber 8 mm deep was used as formwork, on which a straight edge, in this case a rule, was applied to spread the fresh mortar, as indicated in Figure 5.6a.

To insert the chippings, a first method (procedure A) involved spreading a dense bed of chippings on the fresh mortar. This bed was then rolled with a wooden cylinder after 10mm deep timber formwork had been placed (see Figure 5.6b). Then, loose chippings were removed. The typical amount of chippings inserted with this process was around 6 kg/m^2. However, it was realized during the first stripping tests that many particles were only loosely bonded to the mortar. As a result, the procedure was subsequently adapted.

In the second method (procedure B), an adhesive aluminium foil was placed on the particles, resulting in most of them sticking to the foil. The foil, together with the particles, was then placed onto the fresh mortar surface, and rolled as in the previous procedure. The foil was kept on the specimens for 48 hours (acting as a curing membrane), then removed.

Later in the project, it was found that the placement of chippings was being performed in a 'blind' manner, sometimes resulting in poor embedment of the chippings. As well, it seemed that the mortar surface could be subject to rapid desiccation, damaging the bond with the chippings. As a result, a new method (procedure C) was developed, which involved moistening the chippings in order to reach the 'saturated-surface dry' state, then dispersing manually the same amount of particles on the fresh mortar. The surface was rolled and gently finished with a trowel, ensuring that the particles were embedded up to about half their diameter.

Figure 5.6. **Laboratory application process of the HPCM (procedure B)**



Source: Laboratoire Central des Ponts et Chaussées (France).

The laboratory specimens produced with procedure A or C were cured by applying a wet burlap for 48 hours; then the specimens were kept in the ambient conditions for 28 days. For semi-industrial applications, a polyethylene sheet was applied on the HPCM surface for two or three days, or a curing compound was sprayed after the placement of the chippings.

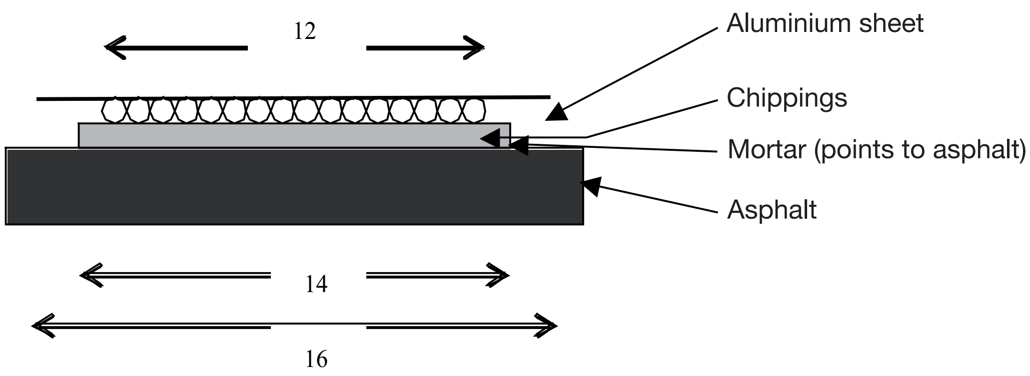
5.7 Strip cracking tests (LCPC, France) [HPCM Report 6, 7, 13]

Cracking tests were carried out to determine the optimum type and amount of fibres. HPCM was applied outdoors in 14 cm wide strips, on an existing old pavement, and the natural cracking process was monitored for some months. Preliminary tests showed that 6 m long strips were more useful than 3 m strips in displaying a cracking pattern typical of a long pavement. Afterwards, two series of strips were laid, the first one in 2005, the second one in 2006.

2005 test series

The same laying process as the one used in the laboratory was employed and procedure B was applied to embed the chippings (see Figure 5.7). The two types of fibre (steel and PVA) were incorporated in mortar B, with a percentage volume in the mortar of 0, 1, 2 and 3%. Figure 5.8 shows the test site at LCPC. This 30-year old pavement was made of 5 cm of asphalt concrete over 20 cm of cement-treated base material, on a granular sub-base layer. The strips were applied on a solid section of this pavement, between two transverse cracks. For this series, the asphalt surface was only washed with water, with no treatment to increase the surface roughness.

Figure 5.7. **Transverse dimensions (in cm) of the cracking strips**



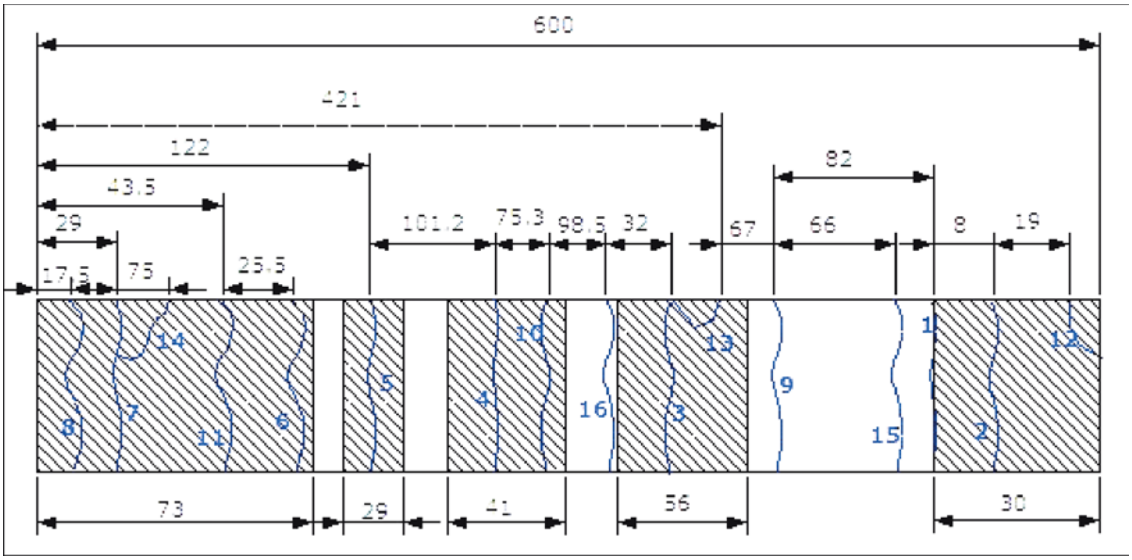
Source: Laboratoire Central des Ponts et Chaussées (France).

Figure 5.8. **Testing site for the cracking strips at LCPC centre of Nantes (France)**

Source: Laboratoire Central des Ponts et Chaussées (France).

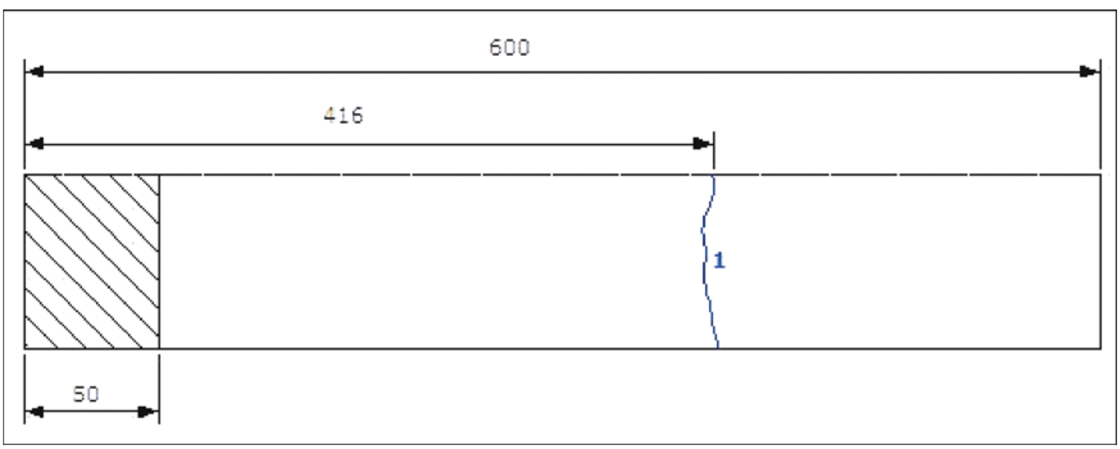
The strips were cured with an aluminium sheet and a polyethylene sheet for the first 48 hours after casting. Then the strips were exposed to ambient conditions. Most cracks appeared during the first month, because of the rapid development of shrinkage (see section 5.4). In the vicinity of the cracks, a certain degradation of the bond with the asphalt layer could be detected by gently tapping the strips with a hammer; debonded parts produced a lower frequency noise. Examples of cracking and delamination patterns are shown in Figures 5.9 and 5.10, where the cross hatching indicates delaminated zones.

Figure 5.9. **Cracking pattern of the control strip (lengths are given in cm)**



Source: Danish Board of Technology (Denmark).

Figure 5.10. **Cracking pattern of the strip with 3 % of steel fibres (lengths in cm)**



Source: Danish Board of Technology (Denmark).

The control strip was heavily cracked and delaminated. However, incorporation of 3% steel fibres almost suppressed the cracking and the delamination process.

Delamination only occurred from one of the two ends of the strip, and the crack was only 5-6 cm long. Cracking data for all strips, as measured at 28 days, are summarised in Table 5.9.

These results – although useful – were not found to be fully satisfactory. As a result, another series of tests was launched the following year.

Table 5.9 **Cracking data (2005 test series)**

Strips	**Number of cracks**	**Cumulated opening (mm)**	**Mean opening (mm)**	**Maximum opening (mm)**	**% of delaminated length**	**% of delaminated length (excluding ends of the strips)**
Control	11	2.95	0.27	0.6	38	32
Pre-cracked	2	0.4	0.20	0.2	65	62
1% steel	4	0.65	0.16	0.2	17	11
2% steel	5	1.25	0.25	0.5	20	20
3% steel	1	< 0.1	< 0.10	< 0.1	8	0
1% PVA	3	1.3	0.43	0.5	35	29
2% PVA	4	0.9	0.23	0.3	52	50
3% PVA	6	0.7	0.12	0.2	16	7

2006 test series

For this new series of tests, the following parameters were adopted:

- The asphalt surface was shot-blasted with steel balls, in order to increase the macro- and micro-texture, thus improving the bond at the HPCM/asphalt interface.
- The plain mortar was made softer at the fresh state by slightly increasing the superplasticizer and water dosages (development of mortar C).
- Strips were cast with 3% of steel fibres, and 0, 3, 4 & 5% of PVA fibres.

After 42 days, the first survey was carried out, which showed no cracks for the strips incorporating 4-5% of PVA fibres, nor for the steel fibre strip. Also, no delamination was found on any strip, including the control strip without fibres. These observations led the project partners to choose the 4% PVA solution for the rest of the tasks, most of which dealt with performance characterization, corresponding to Sections 5.8, 5.10, 5.12 and 5.14 of this report.

Table 5.10. **Cracking data ('2006 test series) after 218 days**

Strips	**Number of cracks**	**Cumulated opening (mm)**	**Mean opening (mm)**	**Maximum opening (mm)**	**% of delaminated length**
3% steel	0	0	0	0	0
3% PVA	7	2.3	0.33	0.6	0
4% PVA	10	2.0	0.20	0.5	0
5% PVA	4	0.7	0.18	0.2	0

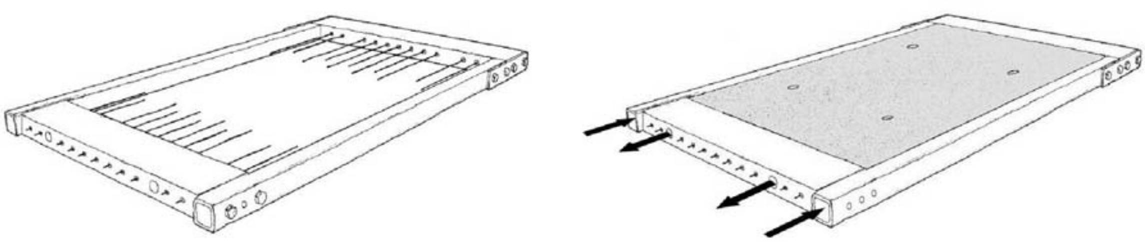
Five months after casting, the test site was exposed to high temperatures due to prevailing meteorological conditions. These temperatures either increased the shrinkage rate of the mortar or induced a swelling of the surrounding layers. Another possible consequence was a certain softening of the PVA fibres (although the temperature did not seem to influence the strength – see Table 5.5 in section 5.3). The result was a sudden increase in the amount of cracking. Finally, all the new strips were cracked, except the one incorporating 3% of steel fibres (see Table 5.10). Notably, no delamination appeared, in spite of the numerous cracks found in some of the strips.

Based on these results, the original selection of PVA fibres appeared to have been the wrong choice: among the options investigated, only the 3% steel fibre HPCM seemed able to provide a continuous wearing course, with no visible cracks.

5.8 Cracking under restrained shrinkage and imposed elongation (DBT, Denmark) [HPCM Report 19]

As a complement to the above cracking tests, it was decided during the project to also carry out laboratory tests, in which the mortar would be submitted first to restrained shrinkage until 28 days, and then to an imposed elongation up to 0.3%. The absence of a bond with a stiff base course, the thickness of the plate and the lack of inserted chippings made this test quite severe. However, a material passing this test, *i.e.* having no crack wider than 0.2 mm at the maximum elongation, would provide a very robust solution.

Figure 5.11. **Sketch of steel frame (30x500x800 mm) before casting and during testing**

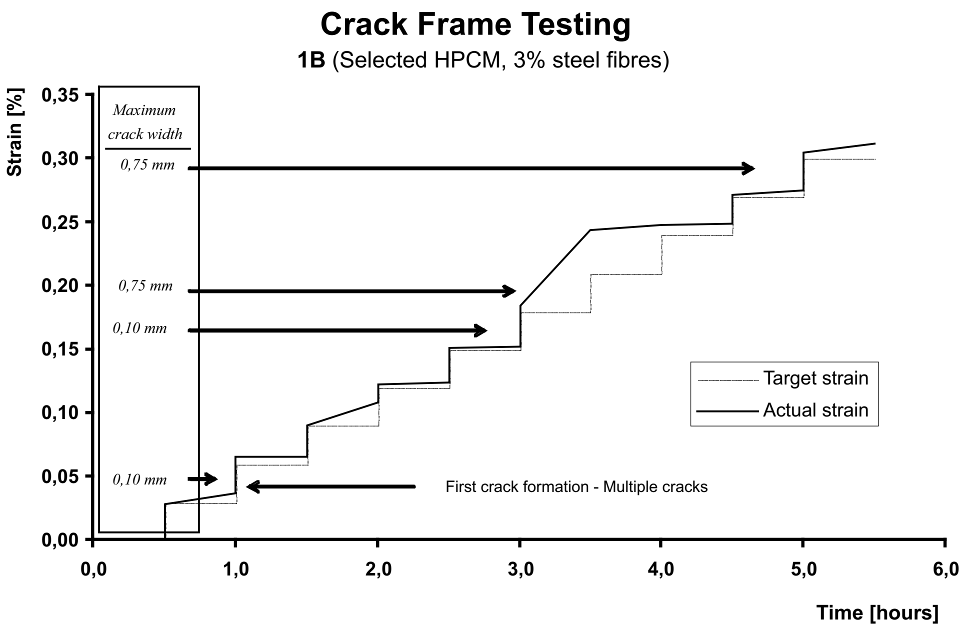


Source: Laboratoire Central des Ponts et Chaussées (France).

A cracking bench was used, in which the mortar was anchored to the ends through a series of thin bars (see Figure 5.11). The mean elongation was measured in the mid-zone during the loading cycle. HPCM mortar C with a slight water addition (w/c = 0.22) was used with steel (2, 3 and 4%) or PVA (2, 4 and 6%) fibres. A lower strength mortar, with a target compressive strength of 50 MPa, was also tested in case the HPCM had too high a tensile strength to be able to demonstrate distributed cracking. Figure 5.12 shows a typical loading program, where the strain of the specimen is increased step by step, creating progressive development of cracks. The results of the HPCM tests are given in Table 5.11.

A well distributed cracking pattern, as shown in Figure 5.6, was obtained only with 3 or 4% steel fibres in the HPCM mortar. For many other specimens, a localized failure occurred before the end of the test, especially with the lower strength mortar, in which fibres were apparently not well anchored. In all cases, the maximum crack opening was higher than the original expectation of 0.2 mm. These tests tended to promote the HPCM solutions with a high percentage of steel fibres (3 or 4%), for which the crack opening in the field could be lower than measured in these tests.

Figure 5.12. **Strain over time during the cracking test, for the 3% steel fibres HPCM**

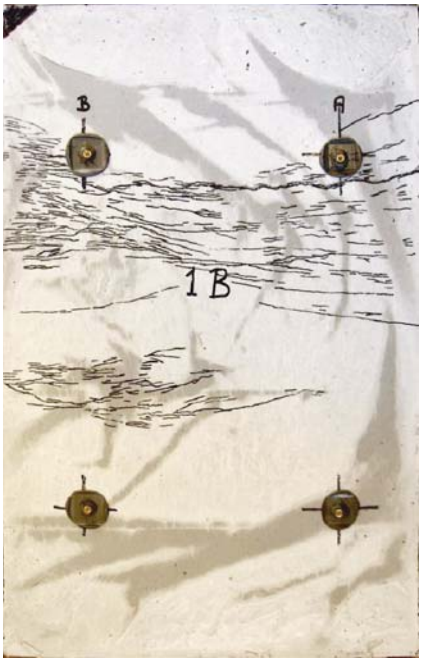


Source: Laboratoire Central des Ponts et Chaussées (France).

Table 5.11. **Summary of test results (HPCM matrix)**

Test No.	Matrix	Steel fibres [%]	PVA fibres [%]	Number of cracks	Max. crack width (*) [mm]	Remarks
1A	HPCM	2	–	Multiple cracks in a narrow zone	1.4	
1B	HPCM	3	–	Multiple cracks in a large area	0.75	
1C	HPCM	4	–	Multiple cracks in a large area	0.70	
1D	HPCM	–	2	3 crack-zones developed at end of the load transferring threaded steelbars	No cracks developed before failure of the specimen	Failure of specimen outside the measuring area at 0.03% strain
1E	HPCM	–	4	4 crack-zones developed at end of the load transferring threaded steelbars. Some fine cracks at the edge of the measuring area.	No cracks developed before failure of the specimen	Failure of specimen outside the measuring area at 0.03% strain
1F	HPCM	–	6	Multiple fine cracks at the edges of the measuring area	1.10	Failure of specimen outside the measuring area at 0.15% strain

Figure 5.13. **Final crack pattern obtained for the 3% steel fibres HPCM**



Source: Roads and Traffic Authority (Australia).

5.9 Full Scale cracking test [HPCM Report 15]

After the laboratory cracking tests reported above, it was important to assess the cracking tendency of the HPCM material at Full Scale, using a test model representative of a real pavement. Following liaison with the New South Wales Roads and Traffic Authority (RTA), it was decided to build a 20 × 2 m test pad near Sydney, Australia. Consistent with the original schedule of the project, the pad should have been cast in the Australian summer (end 2005/early 2006), and monitored for six months, which would have allowed observation of the effect of the temperature drop. However, due to some delays in the previous tasks and material deliveries, the pad was finally cast during the Australian winter. A purpose-built asphalt lane, consisting of a 20 cm thick asphalt concrete, was laid over 15 cm of dense grade granular base material (see Figure 5.14). The asphalt surface was shot blasted, and the macrotexture ranged between 1 and 1.5 mm. The evenness of the surface could not be fully controlled, which later caused some scatter in the thickness of the HPCM.

Mortar C with 4% PVA was produced and applied on the asphalt layer (see Figure 5.15). The water dosage was increased up to a water/cement ratio of about 0.24, in order to increase the mix fluidity and to accelerate the mixing process (which could not be shorter than 15 minutes per batch). This water addition probably increased the free shrinkage of the mix, and the measured cylinder strength at 28 days was about 76 MPa (as compared to 129 MPa for the original mix, see Table 5.5). However, these strength measurements cannot be directly compared to the reference ones, because of differences in the curing regime and possibly on the cylinder testing conditions. A compressive strength drop of 30% could have been anticipated according to Table 5.6.

The pad was cast in successive 2.5 m-long sections (see Figure 5.16) separated by ‘cold joints’. Chippings were embedded using procedure C. A commercial curing compound was sprayed three hours after the HPCM mixing, and cracking was monitored on a weekly basis. Between the months of August and November, 2006, the temperature ranged from 3 to 39°C, and the evaporation rate ranged from 0.5 to 8 mm per day.

Figure 5.14. **View of test site at RTA's St Marys work depot with the completed asphalt trial pad**

Source: Roads and Traffic Authority (Australia).

Figure 5.15. **View of batches 1 (left) and 2 being spread immediately after mixing was completed**

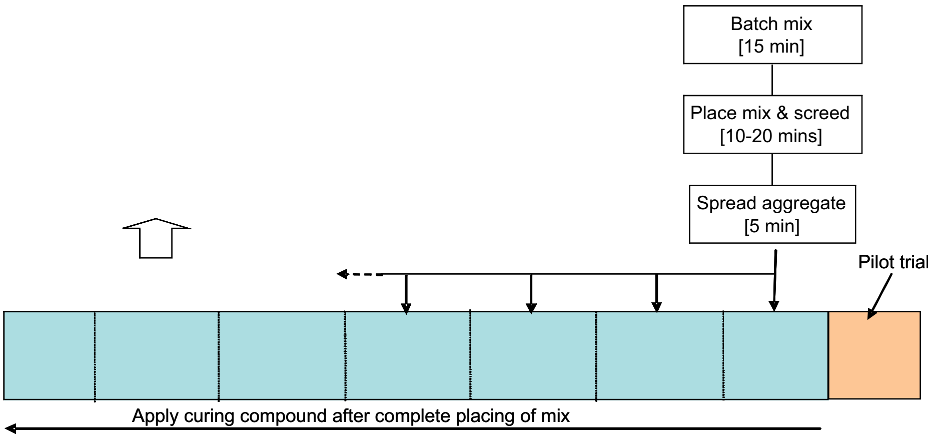
Source: Roads and Traffic Authority (Australia).

Given the final results of the narrow strip cracking tests with the 4% PVA mix-design (see Table 5.8), it could be anticipated that there would be some transverse cracking. In fact, such cracks appeared quite soon. Their early appearance was probably related to the warm temperatures of the Australian test site, compared to those of the French site. However, the width of cracks obtained (0.4 to 1.2 mm) was more surprising.

Several factors, which clearly made the solution not acceptable for a long-life pavement, may explain this result, viz:

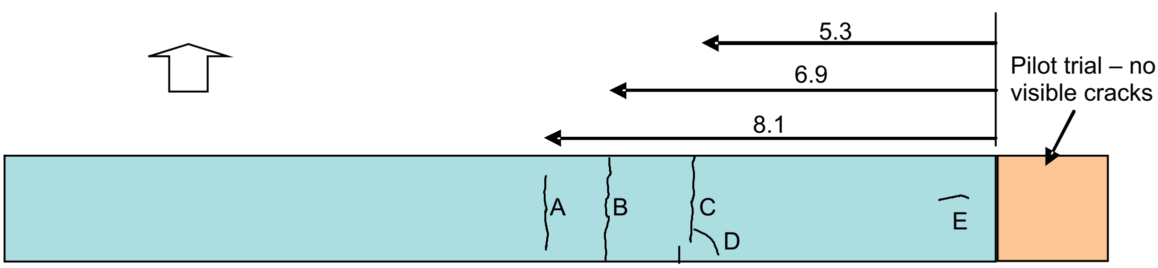
- The water dosage of the mixture.
- The presence of cold joints, which may explain the 'A' crack (in Figure 5.17).
- A certain unevenness in the thickness of the HPCM layer, which may have led to stress concentrations in the thinnest zones of the pad.
- The presumably softer character of the asphalt concrete, as compared to the one of the LCPC pad, where the asphalt concrete was thirty years old when the HPCM was applied; its modulus and tensile strength were probably high, due to ageing of bitumen over such a long period.

Figure 5.16. **Construction sequence adopted for trial showing the average duration for each event**



Source: Roads and Traffic Authority (Australia).

Figure 5.17. **Diagrammatic view of crack patterns on test pad [Ref]**



Source: Roads and Traffic Authority (Australia).

Table 5.12. **Crack observation details recorded to 25th September, 2006 [Ref]**

Crack Designation	Timing[1] (wks)	Description
A	1.5	A 0.7 mm wide crack over the full width of the pad.
B	1.5	The most visible crack is about 1.0 mm wide for at least 400 mm of its length. This crack shown in Figure 5.18 consists of about 4 separate cracks which stop and start but represents cracking over the full width of the pad.
C	1.5	This crack starts at the northern edge and meanders down a transverse path, crack stops & starts. The maximum width of the crack is 1.2 mm.
D	3	This crack appeared 350 mm east of crack C and this crack joins Crack C at 400 m from edge.
E	3.5	A 300 mm long crack appeared 600 mm from north edge and 500 mm from the start of placing the pad. Crack width varies but is about 0.4 mm wide.
F, G	8 < T < 28	Later thin cracks, 0.1-0.3 mm wide. (not shown)

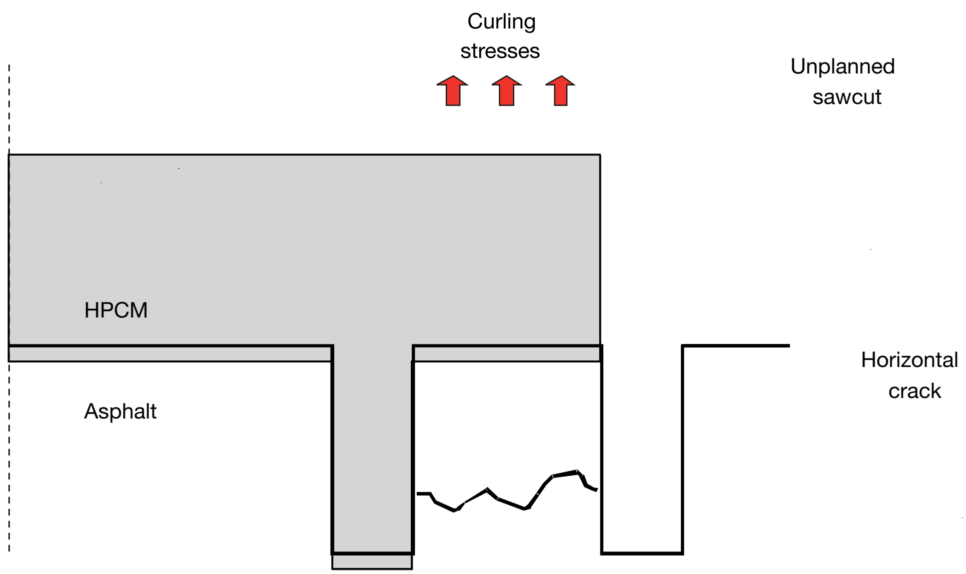
1. Timing refers to the first appearance of the crack after placing the HPCM.

Apart from the vertical cracking, some horizontal cracking (in the top zone of the asphalt) took place around the pad (see Figure 5.18). This was probably related to a curling tendency of the HPCM, which created some vertical tensile stresses in the base course. The asphalt edge zones were weak because of limited compaction, and because of a second saw cut, parallel to the interior one required for anchoring the HPCM in the asphalt, which was carried out by error. Apart from these edge zones, no delamination was detected on the test pad.

Some important conclusions can be drawn from this semi-industrial scale experiment:

- HPCM with 4% PVA fibres cannot resist shrinkage-induced cracks without strain localisation, as already found in the two previous cracking test series.
- It is important to use below the HPCM layer a stiff-enough asphalt concrete as a binding course, with homogenous compaction and quality.
- HPCM thickness should be as regular as possible, to avoid stress concentrations in thinner zones.

Figure 5.18. **Horizontal cracks at the pad edges**



Source: Roads and Traffic Authority (Australia).

5.10 Preliminary stripping tests (LCPC, France) [HPCM Report 11]

The aim of the Preliminary Stripping Tests was to get a first appraisal of the behaviour of the HPCM when subjected to truck traffic, by using a conventional rutting machine (see Figure 5.19). Sandwich specimens were produced (mortar composition A with 1% of steel fibres, procedure A and B for placement of chippings) and submitted to a number of cycles (see Figure 5.20) at ambient temperature. For some sequences, the wheel was angled at 5°, in order to create a certain level of shear stress which could simulate the effect of traffic in curves or during vehicle braking. Unfortunately this loading programme was limited in time by the degree of wear of the wheel rubber, due to the unusually strong abrasive effect exerted by the strong and resistant calcined bauxite chippings, which was quite severe after 3 000 passes.

Figure 5.19. **The LCPC rutting machine**

Source: Laboratoire Central des Ponts et Chaussées (France).

Figure 5.20. **Typical sandwich samples of HPCM cast over an asphalt concrete prism**

Source: Laboratoire Central des Ponts et Chaussées (France).

Two control materials were evaluated in parallel with the HPCM: a typical French asphalt concrete for wearing course (BBTM) and an epoxy-asphalt surface dressing. The results of the tests appear in Table 5.13.

From these results, the following conclusions were drawn:

- No debonding was noted between the HPCM and the asphalt concrete.
- Procedure B was much better than procedure A in terms of prevention of chipping loss. Later, procedure C was adopted, with (presumably) even better performance (see Section 5.6).
- The loss of material was higher with HPCM (procedure B), as compared to some existing asphaltic materials. However, conventional bitumen emulsion surface dressing was not included in the test programme. Such field materials commonly present aggregate losses around 5-10% after some weeks of traffic.

The test results were difficult to fully interpret, because the loading programmes differed among the various materials. Also, the ambient temperature was favourable to asphalt materials, since bitumen is temperature sensitive, unlike Portland cement. Finally, the equivalence between this test and the effects of real traffic is not known.

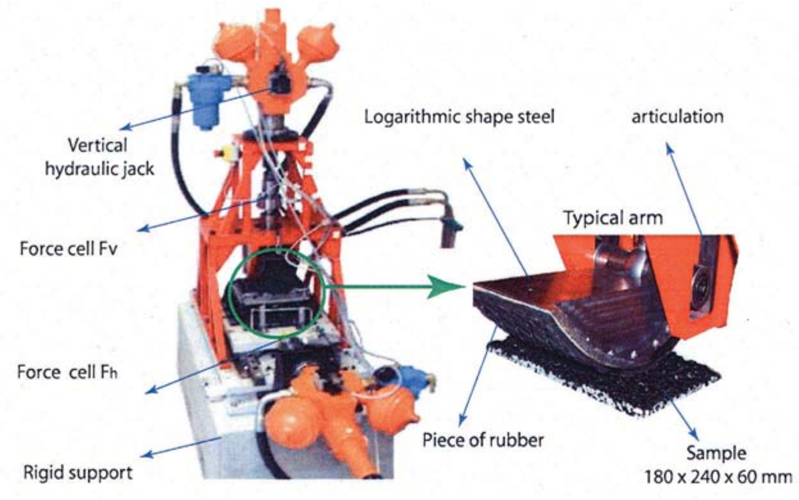
Table 5.13. **Results of preliminary stripping tests**

Material	**HPCM (procedure A)**	**HPCM (procedure B)**	**BBTM asphalt concrete**	**Epoxy-asphalt surface dressing**
Loading program	1 000 c. at 0° + 2 000 c. at 5°	1 000 c. at 0° + 2 000 c. at 5°+ 8 000 c. at 0°	1 000 c. at 0° + 10 000 c. at 5°	1 000 c. at 0° + 3 000 c. at 5°
Original macrotexture (mm)	1.77	1.63	2.25	1.88
Final macrotexture (mm)	2.01	1.57	1.38	1.89
Loss (kg/m^2)	1.08	0.31	0.11	0.18
Loss (% of total chippings)	18.2	7.5	–	4.5

5.11 Tribometer tests (LCPC, France) [HPCM Report 18]

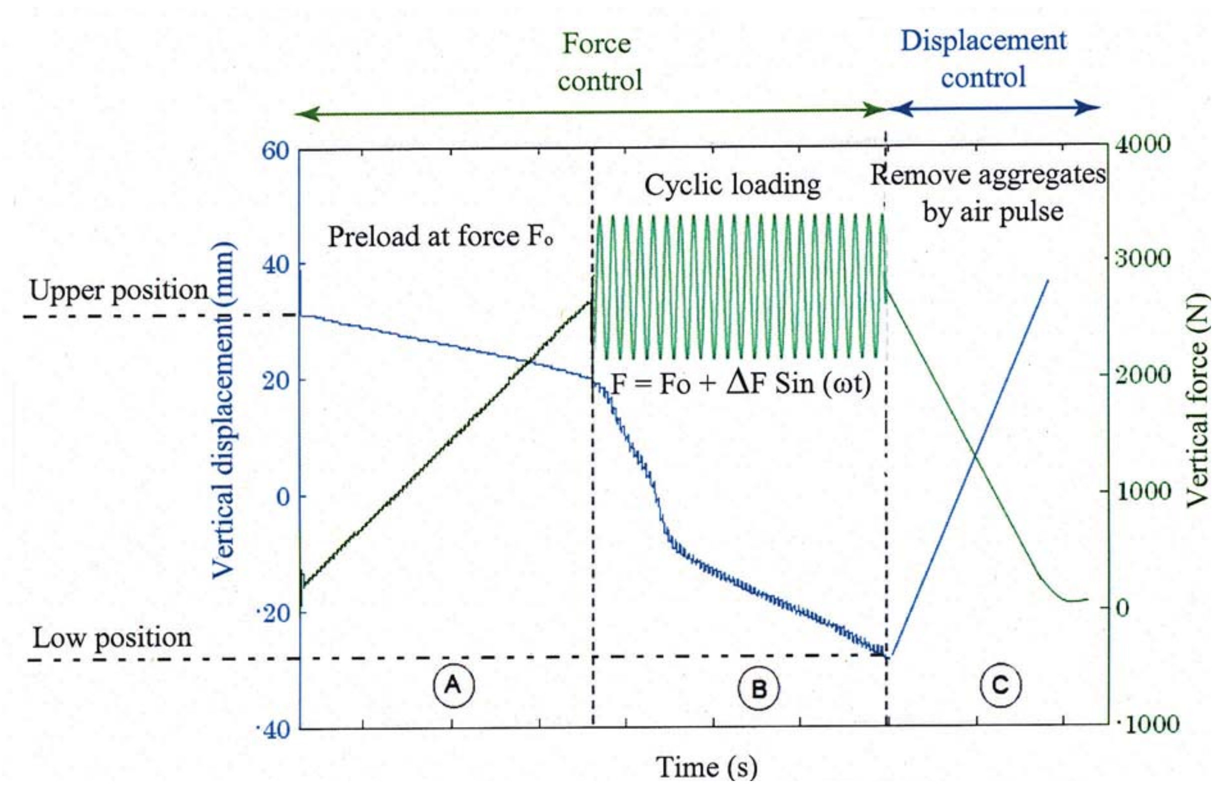
A new Tribometer test had recently been developed at LCPC in order to reproduce the degradation process of a wearing course in a laboratory. The way the Tribometer operates is as follows. A steel arm having the shape of a logarithmic spiral is coated with rubber having a shore hardness of 68°. The arm applies a controlled load onto the specimen surface, with a constant angle, simulating the action of a braking truck tyre which would slip on the pavement surface. Figure 5.21 shows the test set-up, and the loading programme is presented in Figure 5.22. The mean force F0 of 2.5 kN is equivalent to the typical pressure exerted by truck tyres, while the amplitude DF is equal to F0/3. In the test program, 3 000 cycles are applied during phase B. For each test specimen the programme is applied twice, which makes a total of 6 000 cycles for each test. The mass of the sample and the macrotexture are measured three times: before starting the test, between the two programmes and at the end.

Figure 5.21. **The LCPC Tribometer**



Source: Laboratoire Central des Ponts et Chaussées (France).

Figure 5.22. **The Tribometer test protocol**



Source: Laboratoire Central des Ponts et Chaussées (France).

Two asphalt prisms were produced and coated with HPCM (mortar C with 4% PVA fibres, procedure C for the chippings placement). A series of asphaltic materials were tested with the same procedure:

- BBTM 0/10 pure bitumen'. This is nowadays the standard material for a highway wearing course in France, and it is supposed to last 7-10 years when subject to high traffic.
- 'BBTM 0/10 BmP SBS cross-linked', similar to the previous one except in the nature of the bitumen. This material is often used for heavy-duty wearing courses as in roundabouts.
- 'BBTM 0/10 Epoxy asphalt', the other candidate for long-life wearing courses highlighted in this project.
- Epoxy-asphalt surface dressing. This commercial material, as outlined in the previous section (section 5.10), is comparable to HPCM apart from the nature of the binder (which is epoxy-bitumen mixture instead of hydraulic mortar).

The results of the tests appear in Table 5.14. The following observations can be made:

- The HPCM lost about 10% of its total mass of chippings. Most particles were worn during the first series of 3 000 cycles.
- Among bituminous materials, only those containing epoxy-bitumen binder showed a better behaviour.
- As in the case of the stripping test, the test temperature (20°C) favoured asphaltic materials. As an illustration of this, the tribometer test was recently carried out on another BBTM 0/10 up to 1 800 cycles, at two temperatures. At 19°C, the amount of material loss was about 4 kg/m². This quantity increased to 11 kg/m² at 24°C.

Keeping in mind that the surface temperature of a wearing course may reach 50°C in summer, one may expect a lifespan of several decades for HPCM, at least if traffic action is the only distress mechanism.

Table 5.14. **Results of the Tribometer tests**

	Mass loss per unit area (Kg/m²)	
	After 3 000 cycles	**After 6 000 cycles**
HPCM/F10-6	0.34	0.39
HPCM/F10-7	0.38	0.42
BBTM 0/10 Pure bitumen pen 35/50	0.87	5.09
BBTM 0/10 BmP SBS cross-linked	1.73	3.14
BBTM 0/10 Epoxy asphalt	0.03	0.08
Surface dressing – EA/F20-4	–	0.03

5.12 Abrasion tests (FHWA, USA)

Asphalt slabs were prepared and overlaid with 8 mm of the HPCM mortar (mix-design C with 4% PVA fibres) in abrasion tests undertaken in the US. Three batches were prepared (6061, 6062 and 6063) on three different days. For each batch, one slab and three cylinders were cast. Each slab was cut into three specimens that were used for the abrasion tests. Cylinders were used to determine the compressive strength and the coefficient of thermal expansion.

Different methods were used to insert the calcined bauxite aggregate chips (chippings). For mix 6061, procedure B was applied.

It was observed that the chippings were pulled out during the abrasion tests, so the aluminium foil procedure was eliminated. For mixes 6062 and 6063 chippings were manually placed on the mortar, one by one (according to procedure C, modified as explained hereafter). A paper sheet was placed on the slab and the chippings were forced into the mortar with hand pressure. The pressure applied to mix 6063 was higher than the one applied to mix 6062. The difference in the embedment of the particles, obtained in mixes 6062 and 6063, is shown in Table 5.15.

After casting, the slabs were covered with wet burlap and sheet plastic for 48 hours before being exposed to ambient conditions.

Their compressive strength was determined at 28-days in accordance with ASTM C39 on two 75 × 150 mm cylinders per batch. The measurements varied from 121 MPa to 125 MPa, giving a range close to reference values (see section 5.3).

In accordance with the ASTM C 944 procedure, abrasion resistance was measured by the amount of concrete abraded off a surface – the mass loss – over a given time period by a rotating cutter at 200 rpm, under a constant force of 98 kN. Figure 5.23 shows the set up.

The specimens tested did not comply with the test requirement that their surface be either formed or finished. The specimens had exposed chippings, so their surface was not even, which created some issues during testing. As a result, it was not possible to use double the pressure (197 kN) as recommended for highly resistant concretes.

The abrasion was carried out for 2 minutes. Then the specimens were cleaned with a soft brush and the mass loss determined. The specimens were tested at different ages. All specimens from mix 6061 were tested only at 7 days.

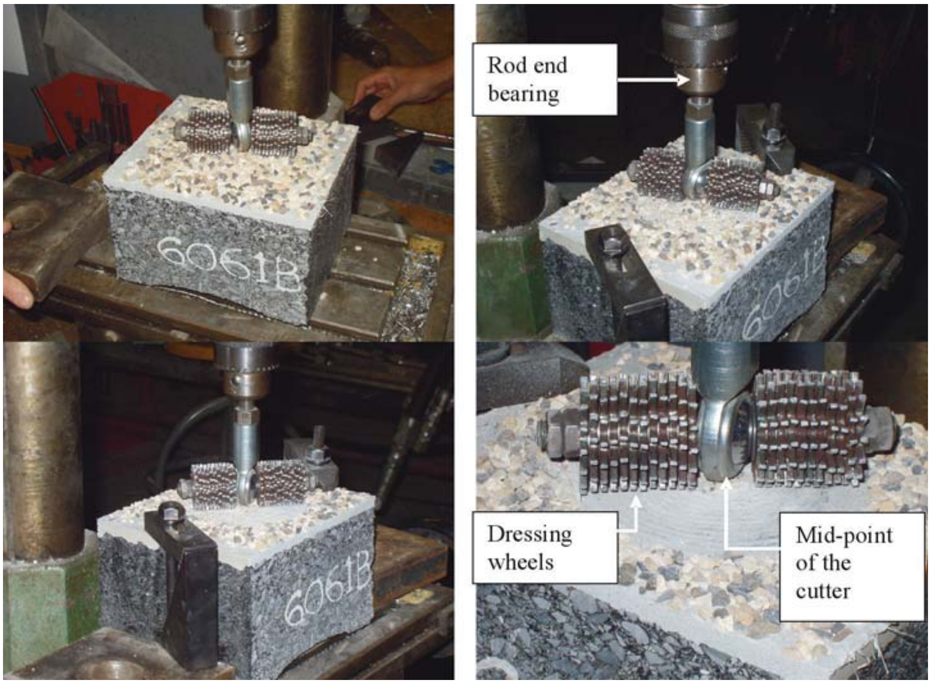
Not enough specimens were tested in order to draw firm conclusions but some trends were observed. Figure 5.24 shows a strong correlation between the depth of chipping embedment and mass loss (not necessarily abrasion). Table 5.15 shows the mass loss and the estimated depth of embedment of all specimens. It also seems that there is a relationship between age and abrasion: Figure 5.25 shows the difference in mass loss between mixes 6062 and 6063 at age 14 and 28 days.

Table 5.15. **Abrasion of HPCM**

PCCP I.D.	Age (days)	Mass loss (g)	Depth of Embedment, through Visual estimate (%)	Comments
6061A	7	33.8	20	OECD pre-mix, calcined bauxite chippings. Chippings were lightly forced into the mortar.
6061B	7	34.0	25	
6061C	7	33.4	20	
6062A	14	25.7	40	OECD pre-mix, calcined bauxite chippings. Chippings were moderately forced into the mortar.
6062B	14	20.0	45	
6062C	28	14.7	50	
6063A	14	8.8	70	OECD pre-mix, calcined bauxite chipping. Chippings were heavily forced into the mortar.
6063B	28	5.7	75	
6063C	28	4.3	80	

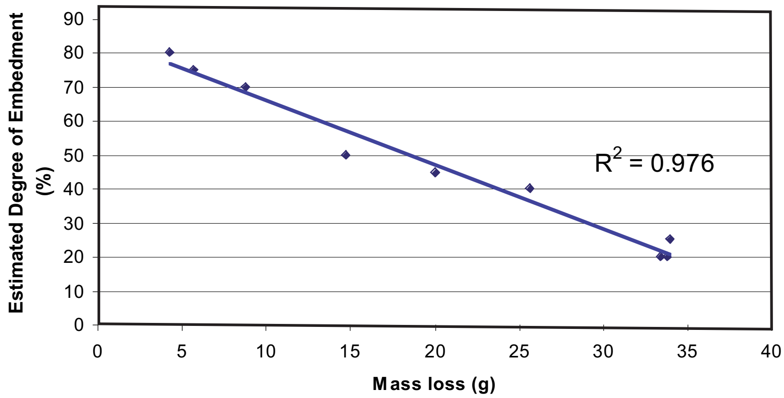
Figure 5.23. **Rotating cutters: set up used for abrasion test**

The figure shows different stages of the same tests, during a period of 2 minutes



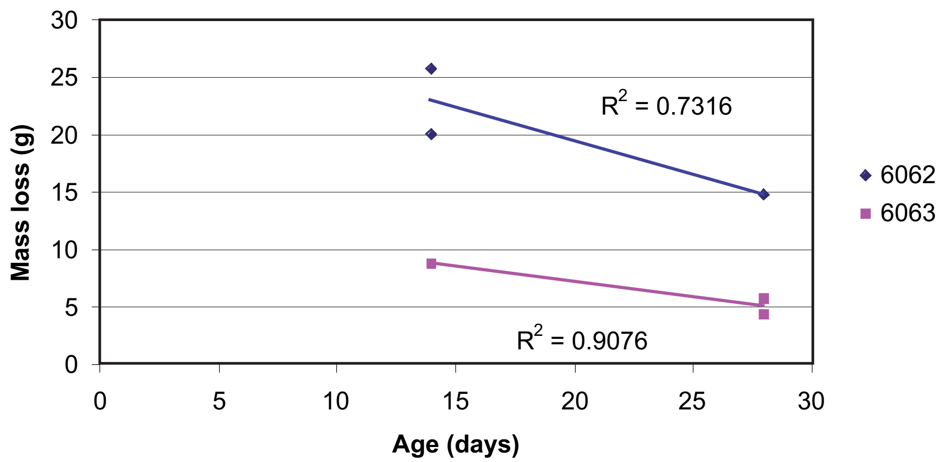
Source: Federal Highway Administration (United States).

Figure 5.24. **Correlation between mass loss and estimated degree of embedment of the calcined bauxite chipping**



Source: Federal Highway Administration (United States).

Figure 5.25. **Correlation between mass loss and age**



Source: Federal Highway Administration (United States).

No control material was used, so it is difficult to interpret these results. The chippings mass originally placed in the surface by the brush was about 21 g. This means that most particles were removed for the 6061 and 6062 specimen series, while about two thirds remained for the third series. Converted in abraded depth, this last series performed as a level 3 High-Performance Concrete, according to American FHWA classification[6]. This category stands for HPC with a 28 day compressive strength in excess of 69 MPa. In other countries, *e.g.* Belgium, concretes used for high-traffic highway surface courses with a compressive strength in the range of 50-70 MPa have shown satisfactory performance and required no maintenance for more than 30 years.

Finally, these test results reinforced the importance of having sufficient chipping embedment in the mortar, as also concluded from the other surface resistance tests.

5.13 Freeze-and-thaw tests (DRI, Denmark) [HPCM Report 8]

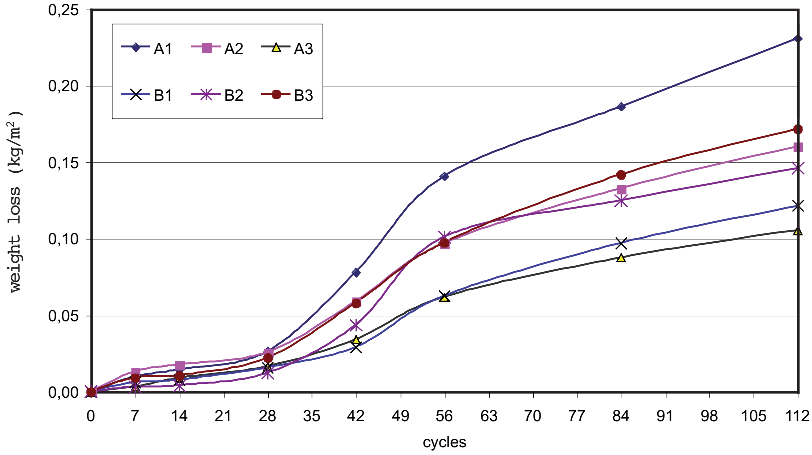
An HPCM wearing course must be able to withstand freeze-thaw cycling without any significant deterioration. In particular, it should be ascertained whether the chippings stay in place and also if the matrix material does not scale off during repeated freeze-thaw cycles. A total of six sandwich (HPCM on asphalt) specimens were subjected to the Swedish frost scaling test SS 137244, using a NaCl-solution as the freezing medium. The specimens were exposed to 112 freeze-thaw cycles with temperatures ranging from +20°C to –20°C. These samples had previously been used for the stripping test (see section 5.9), *i.e.* the loosest chippings had already been worn off. The mortar was type A, and the chippings were inserted through procedure B.

The frost scaling losses (kg/m^2) from the six test specimens during 112 frost cycles are illustrated in Figure 5.26. There was some indication of an accelerating scaling from 28 to 56 cycles, but in the last part of the exposure period the increase of scaling was less dramatic. There was no visible change to the surfaces after 112 frost cycles except for some corrosion of steel fibres near the surface.

Practically all bauxite chippings stayed in place during testing, and the scaling loss from the mortar was very limited. According to the method statement a scaling loss of less than 0.10 kg/m^2 after 56 cycles is "very good", and with an average value of 0.09 kg/m^2, the surface material tested just fell within this category.

Figure 5.26. **Cumulated weight losses from six test specimens**

(A1, A2 and A3 are taken from prism A, B1, B2 and B3 from prism B)



Source: Danish Road Institute (Denmark).

Generally, this frost scaling test did not give rise to any serious concern about the scaling resistance of the HPCM.

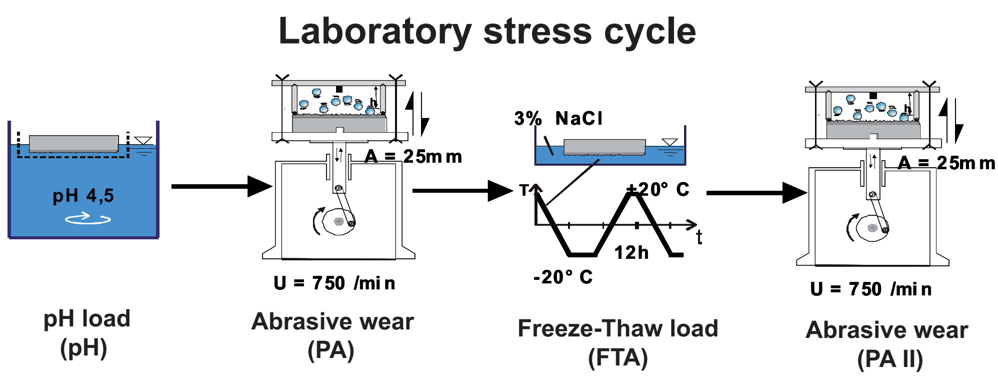
5.14 Combined acid-freeze/thaw-abrasion tests (BASt, Germany) [HPCM Report 21]

A combined acid-freeze/thaw-abrasion test represents a newly developed 'total' test devoted to assessing the durability of a concrete pavement surface under the successive action of acid, mechanical shocks, freeze/thaw and then mechanical shocks again, as shown in Figure 5.27. In this test, 150-mm diameter disks of HPCM (mortar C without or with 4% PVA fibres, chippings placement procedure C) were first soaked in pH 4.5 acetic acid solution at 20°C for one hour.

After weighing for material loss, a series of twelve 5-minute abrasion tests were applied on the central 105 mm-diameter surface of the disks, in a machine where 30 mm-diameter polyurethane balls were shaken at an amplitude of 25 mm and a frequency of 750 cycle/min. Between each 5-minute test, the material loss was monitored. Then, the specimens were submitted to 28 cycles of freeze/thaw in the presence of a 3% sodium chloride solution, which provoked further material loss.

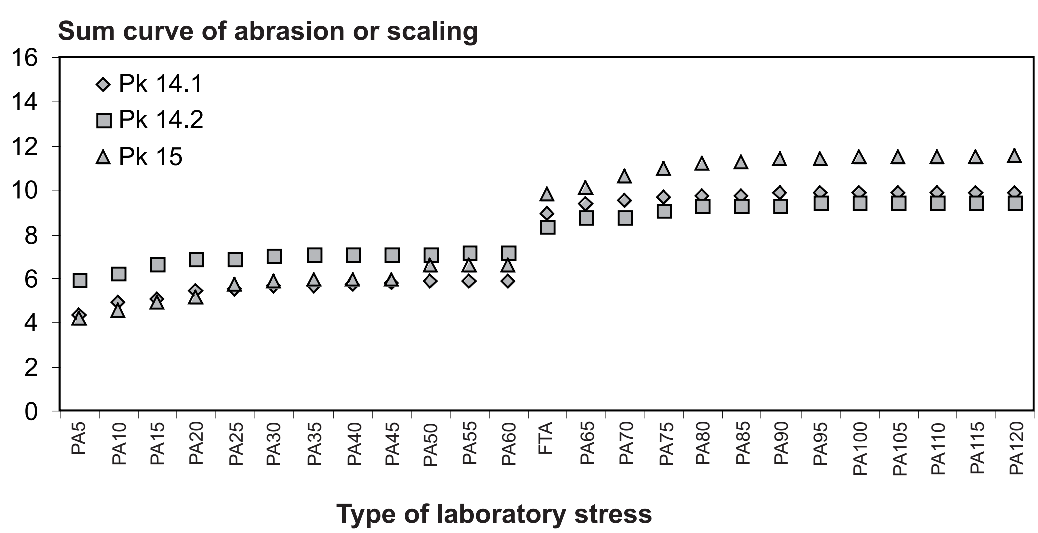
Finally, a second series of twelve shock cycles, identical to the first one, was applied, and the final material loss was measured. The total number of shock cycles within this 'total' test was 90 000. The results obtained from the 4% PVA fibre specimens appear in Figure 5.28.

Figure 5.27. **Sequence of individual loads in the laboratory stress cycle**



Source: Federal Highway Research Institute (BASt) (Germany).

Figure 5.28. **Material loss against time in minutes, for three fibre-reinforced specimens.**



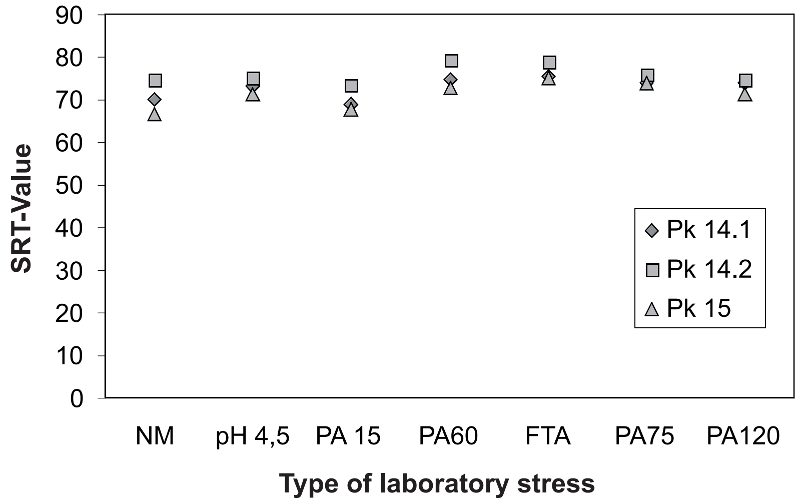
Source: Federal Highway Research Institute (BASt) (Germany).

Note: First measurements reflect the action of acid, while the gap in the middle correspondsto the effect of freeze/thaw cycles.

The mean values of the mass losses over the different stages were as follows: 5 g (7% of the exposed surface) by the acid attack, 2 g (3% of the exposed surface) by freeze/thaw, and about 3.5 g (10% of the exposed surface) by the two series of shocks. Therefore, the acid attack appears quite harmful for HPCM. (It is difficult to find confirmation of these figures in the graphics unless the latter are accumulative.)

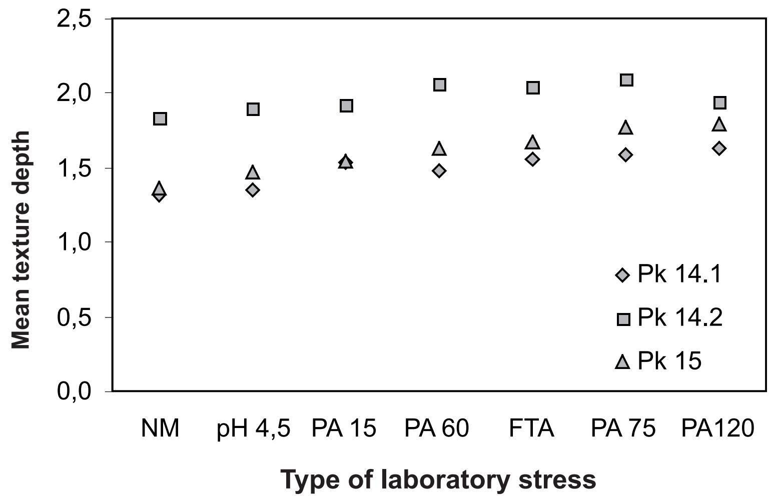
The skid resistance (measured with the SRT pendulum) was monitored during the test (see Figure 5.29), as was the mean texture depth (sand patch method EN 1036) shown in Figure 5.30.

Figure 5.29. **Evolution of skid-resistance, as measured with the SRT pendulum, during the test series**



Source: Federal Highway Research Institute (BASt) (Germany).

Figure 5.30. **Evolution of the mean texture depth (EN 1036), during the test series**



Source: Federal Highway Research Institute (BASt) (Germany).

Despite this being a very severe test, it was difficult to evaluate the durability of the HPCM, given the lack of a control material such as a conventional exposed aggregate concrete in the test programme. It can be noted that the mechanical action of shocks results in a material loss comparable to the one obtained in the stripping test (see section 5.10), while the action of freeze/thaw creates some additional loss, unlike in the Swedish test reported in section 5.13.

However, it is remarkable that, up to a total material loss of 20% of the exposed chippings mass, the mean texture depth and the skid resistance did not evolve markedly. This finding was also valid for the more precise macro- and micro-texture measurements performed during this research with a texture double triangulation sensor. Therefore, an important conclusion is that, while HPCM will probably lose some chippings in the field, as long as this loss is less than 20%, there should be no effect on skid resistance nor on user safety.

5.15 Fatigue tests (DBT, Denmark) [HPCM Report 9]

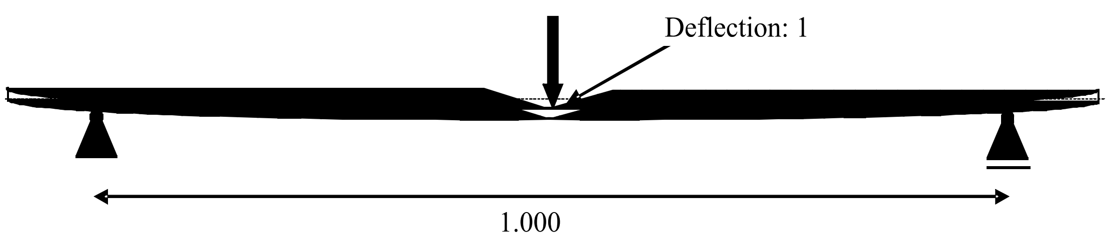
A series of bending tests on mortar beams were performed in the laboratory to test the rather thin wearing course for resistance to a large number of repeated deflections. Another goal of this task was to compare the performance of the two types of fibres in providing fatigue resistance to the HPCM.

Two types of surface courses were tested, *i.e.*:

- HPCM mortar A with 2% of steel fibres.
- HPCM mortar A with 2% of PVA fibres.

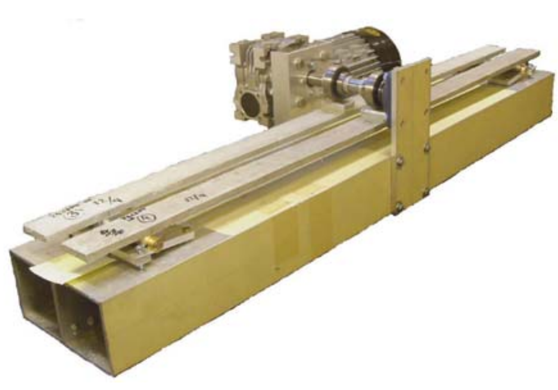
The fatigue tests were carried out on specimens with dimensions of 10x50x1000 mm, and the beams were given a deflection in mid span of 1 mm. This deflection represents about three times the average deflection which may be expected in roads of the type/classification under consideration. The principle of the test is presented in Figure 5.31 and the test set-up appears in Figure 5.32.

Figure 5.31. **Principle of the fatigue tests**



Source: Danish Board of Technology (Denmark).

Figure 5.32. **Fatigue test set-up**



Source: Danish Board of Technology (Denmark).

The aim of the test was to determine the integrity of the material and particularly the performance of the fibres in response to a large number of cyclic loads. The results are presented in terms of the development of the equivalent modulus of elasticity as a function of the number of loads cycles. The initial elastic modulus at 28 days maturity was recorded as follows:

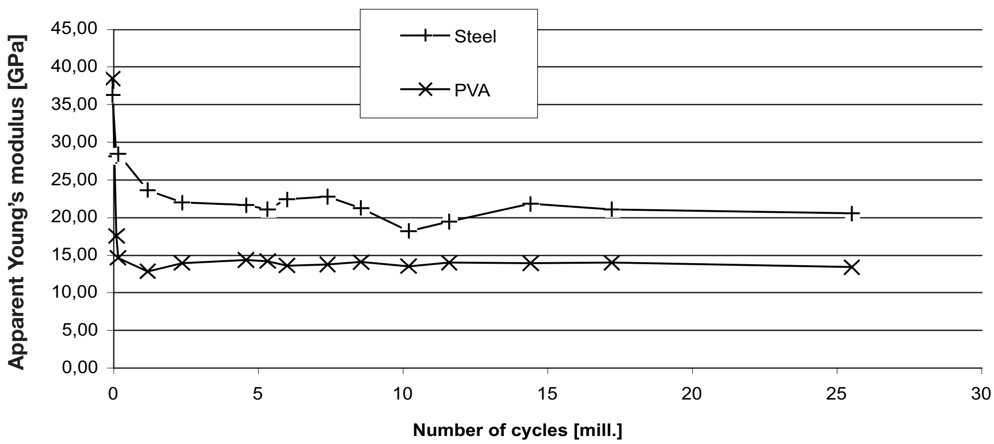
- HCPM, 2% (vol.) steel fibres: 36 Gpa.
- HPCM, 2% (vol.) PVA fibres: 38 Gpa.

These values are lower than those measured on cylinders under compression (see Table 5.2), which were about 42-43 GPa, but the difference may be due to the curing as well as the type of loading. After 25 million cycles of imposed 1-mm deflections, these figures were reduced to the following:

- HCPM, steel fibres: 21 GPa.
- HCPM, PVA fibres: 14 GPa.

In both types of material only an insignificant reduction was recorded after the first million cycles of imposed deflections. It was concluded that following the initial formation of micro cracks in the pavement, no further deterioration of the modulus of elasticity will occur during the service life of a HCPM wearing course. As for the two types of fibres, the higher E-modulus of steel as compared to PVA probably explains that the same ranking was found between the two corresponding composite materials. However, the stability of apparent modulus after some millions of cycle demonstrated that both types of fibres are suitable to produce a durable HPCM layer. The results of the tests are illustrated in Figure 5.33.

Figure 5.33 **Results of the fatigue tests**



Source: Danish Board of Technology (Denmark).

5.16 Full Scale fatigue test (TRL, UK) [HPCM Report 14]

One of the key test tools of the project was in the Pavement Testing Facility (PTF) (see Figure 5.34), a large device allowing the application of fatigue cycles on a Full Scale pavement model at controlled temperature.

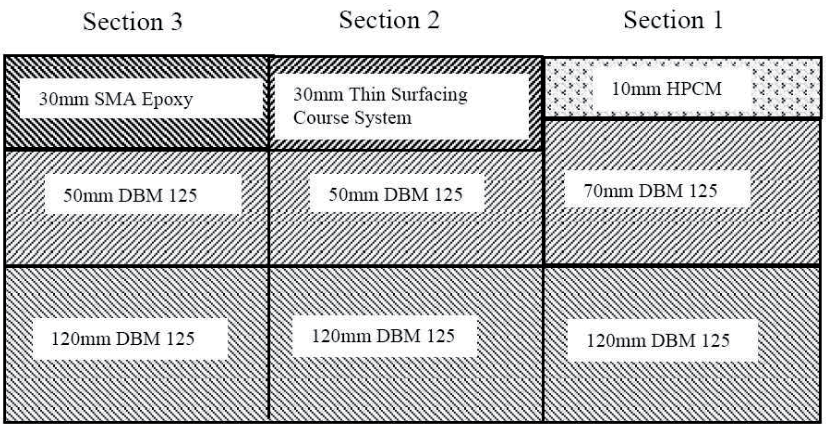
Figure 5.34. **The TRL Pavement Testing Facility**

Source: Transport Research Laboratory (United Kingdom).

Although fatigue is not seen as the main failure mode for a wearing course, any candidate for a long-life top layer must pass this type of loading, where two wheels simulate typical heavy truck traffic. Therefore it was decided to test the two project materials (namely the epoxy-asphalt concrete and the HPCM), and to compare their behaviour with a conventional SMA (stone mastic asphalt).

Three 25 × 10 m test pads were built, with a total depth of 3 m. The nature and thickness of top layers appear in Figure 5.35.

Figure 5.35. **Thickness of the bound layers (DBM stands for Dense Bitumen Macadam)**



Source: Transport Research Laboratory (United Kingdom).

The structure was designed to support equivalent traffic without fatigue failure, but the base course material was chosen to allow some deformation, in order to test the top layer material and the interface with the base course.

Figure 5.36 shows the various steps in constructing the HPCM pad. The mean texture depth of the base layer (in dense bitumen macadam) was 2.0 mm, a value close to the specification. The 4% PVA fibres mortar C was batched with a water-cement ratio of 0.27, giving a slump value of 24-25 cm. At 28 days, the compressive and flexural strengths were equal to 86.1 and 25 MPa, respectively.

Figure 5.36. **Construction of the HPCM test pad**

Source: Transport Research Laboratory (United Kingdom).

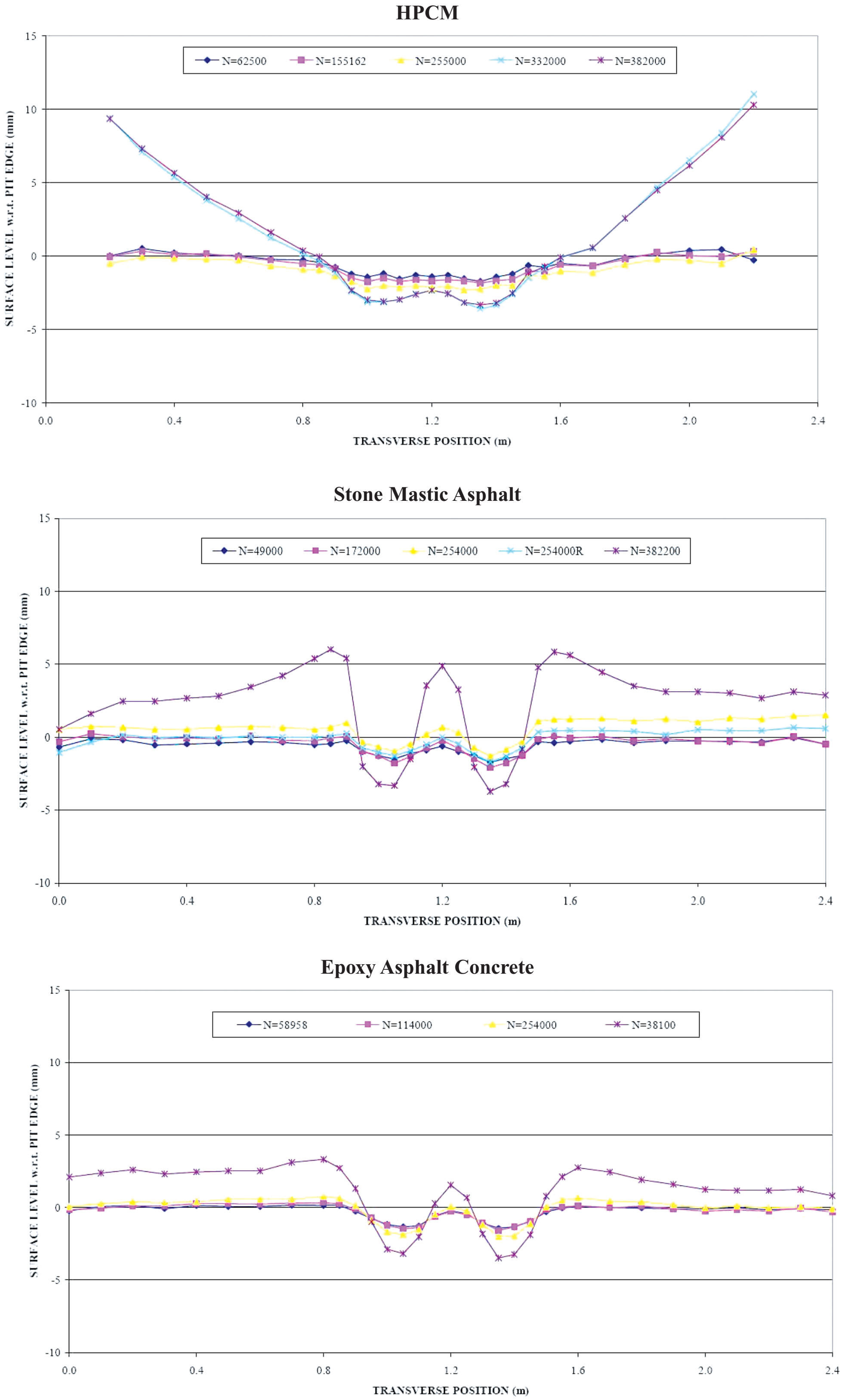
In the PTF test, a total of 255 500 wheel passes – corresponding to one million of standard axles (MSA) – were applied to the samples at 20°C, followed by a further series of half this number at 35°C.

The loading sequence at ambient temperature provoked little distress on the structures, limited to some rutting. However, after 0.5 MSA at 35°C, the rutting reached higher values (8,6 and 1.5 mm in SMA, epoxy-asphalt and HPCM, respectively, see Figure 5.37).

The SMA surface did not exhibit any cracking. As for HPCM, some random ‘hairline’ cracks were found away from the central place where chippings made such fine cracks invisible.

Also, one fine longitudinal crack developed in the axis of the pad, between the two wheel tracks. Such a crack, with a larger width of about 1 mm, was also visible on the epoxy-asphalt section.

Figure 5.37. **Evolution of surface profiles for the three pavement sections**



Source: Transport Research Laboratory (United Kingdom).

An unexpected type of distress appeared in the HPCM section, namely a delamination of the base course material along the edges of the test pad (see Figure 5.38). At first glance, this failure could be a consequence of the HPCM curling, provoked by a higher drying shrinkage at the surface of the material as compared to the bottom zone. However, it can be seen in section 5.4 that the part of shrinkage after some weeks due to drying is quite low for HPCM. Moreover, the curvature of the de-bonded parts of the HPCM layer looks minor in Figure 5.37. More likely, the rutting in the base layer led to a certain curvature in the HPCM submitted to the wheel loads. This curvature generated a certain flexural moment in the HPCM layer. To balance this moment, and the induced vertical stresses in the base layer, a residual tensile strength was necessary in the Dense Bitumen Macadam (DBM).

After the test was completed, the residual bond between HPCM and the base layer was assessed through a series of in-place tensile tests performed after a superficial coring of the hydraulic layer. The failure always occurred in the DBM, at stress levels of 0.26-0.45 MPa (for the tests performed at ambient temperature), the strength becoming lower near the edges. But the strength was nil at 35°C. According to later measurements (where parts of the HPCM layer were put on another asphalt course), the temperature in the shoulder zones of DBM should have reached a level of 38-40 °C, corresponding to an E-modulus of about 200 MPa for this material.

Figure 5.38. **Delamination of the dense bitumen macadam below the edges HPCM pad**

Source: Transport Research Laboratory (United Kingdom).

In terms of surface properties, the mean texture depth of the HPCM pad was about 2.2-2.3 mm, although the placement procedure C was used. This texture did not change significantly after the 1.5 MSA. The skid resistance slightly decreased from 97 to 92 (SRT values), but remained higher than for the two other materials.

Finally, apart from the delamination problem, the HPCM composite performed quite well during the PTF test, providing a very low level of rutting and keeping its surface integrity. The delamination was linked directly with the tendency of DBM to rut (a characteristic which should be avoided in a long-life pavement) and with its thermal susceptibility. As already concluded after the Full Scale cracking tests (see section 5.9, it is essential to place HPCM on a stiff and strong asphalt binder course which offers the prospect of very little rutting and maintains a certain level of tensile strength in hot weather.

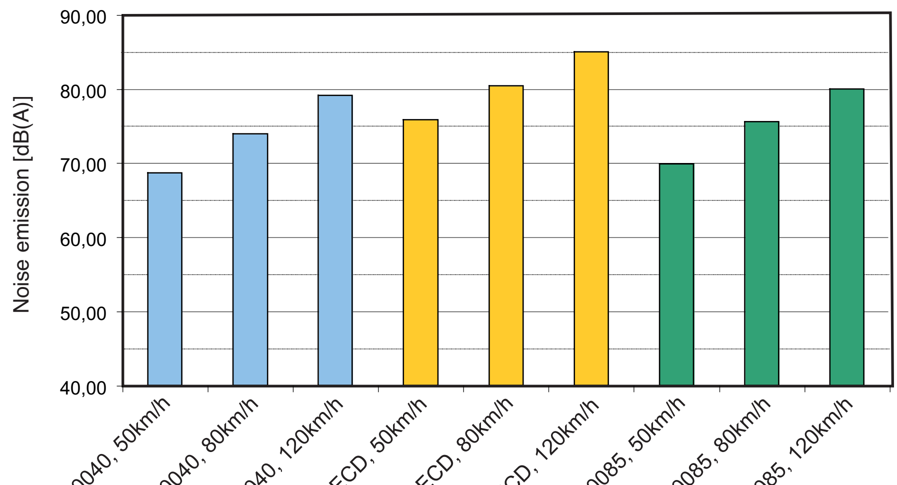
5.17 Evaluation of noise generation (BASt, Germany) [HPCM Report 17]

Noise generation at the pavement/tyre interface is one of the key issues in modern pavement engineering. In order to assess a pavement's noise characteristics, tests are normally carried out with vehicles passing on a pavement test section at various speeds, the noise level being recorded either at a fixed place near the pavement or by a microphone attached on the vehicle. However, no test section of sufficient size was built during this project to allow such measurements. Therefore it was decided to use a computer model called SPERoN (Statistical Physical Explanation of Rolling Noise). This model simulates the acoustic effect of rolling tyre vibration, accounting for the texture of the road and the tyre properties. The model is also able to provide the noise spectrum in the range of 300 to 2000 Hz.

The texture of the 4% PVA HPCM strip cast at LCPC (see section 5.6) was acquired with a laser device, and processed by the computer. The mortar was Type C (cf. Section 5.3), and for the chippings placement method 'B' (cf. Section 5.6) was used. Although the mean texture depth was not measured on the test site, the values obtained on prisms produced with the same procedures and used in the stripping tests (see section 5.10) was about 1.6 mm. The results of noise simulations appear in Figure 5.39.

Figure 5.39. **Comparison of the computed noise of HPCM (yellow bars) used in LCPC strip and computed noise from two exposed aggregate cement concrete pavements (blue and green bars) with different texture depths**

Noise emissions can be compared to typical results of the statistical pass-by method ISO 11819-1



Source: Bundesanstalt für Straßenwesen (BASt) (Germany).

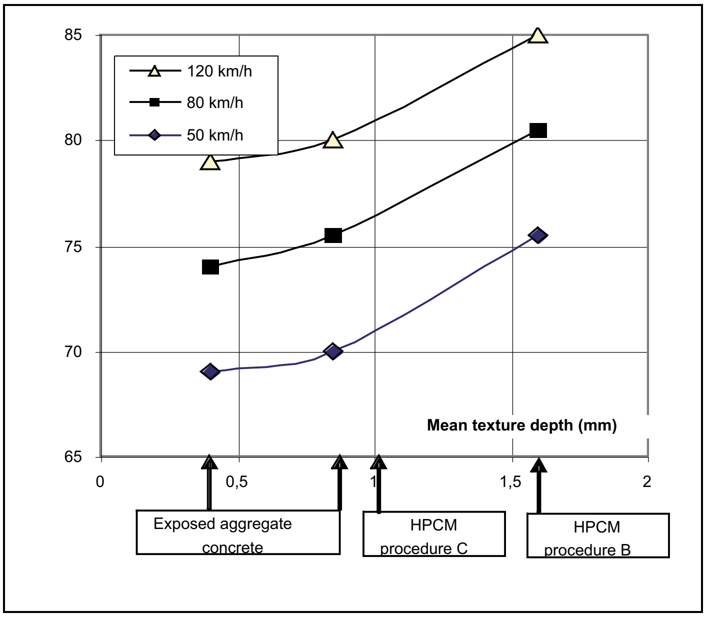
As compared to two exposed aggregate concrete surfaces, the expected noise generation of HPCM is about 5 dB (A) higher. However,

- The chippings were placed using method B with a mean texture depth of about 1.6 mm. When method C was adopted later in the project with a mean texture depth of 1.0-1.1 mm, the expected noise emission is much lower, as evident in Figure 5.40.

- The control materials' texture depth were very low, owing to the German skid resistance requirements. French specifications require an exposed aggregate concrete to have a mean texture depth of at least 1 mm.

From these simulations, it can be concluded that it will important to control the mean texture depth of HPCM, not only to limit the material loss but also to ensure an acceptable level of noise generation.

Figure 5.40. **Noise emissions against mean texture depth**



Source: Bundesanstalt für Straßenwesen (BASt) (Germany).

5.18 Evaluation of delamination and buckling hazards (DBT, Denmark and LCPC, France) [HPCM Report 5]

In addition to the numerous material tests performed on the HPCM, some calculations were carried out to evaluate the likelihood of some additional degradation phenomena, particularly the extent to which traffic loading could promote delamination and possible buckling in hot weather.

5.18.1 Elastic analysis

The goal of the elastic analysis was to see the extent to which traffic loading could promote delamination.

As a preliminary estimation of the elastic behaviour of a thin cementitious wearing course installed on an asphalt base, a first analytical assessment was performed based on an assumption of linear elastic behaviour of the asphaltic material. (However, it should be noted that this assumption may not be correct as asphalt at certain temperature levels exhibits a visco-elastic behaviour even when exposed to short-time loads).

The elastic analysis indicated a risk of longitudinal cracking along the edges of the pavement in the two materials, *i.e.* asphalt and concrete. Further studies are being carried out but it seems as though state-of-the-art data are not readily available for a complete and reliable finite element analysis. As a consequence, one of the recommendations in performing full-scale trials is to assess and thereby confirm or reject the assumptions and indicative analysis.

5.18.2 Buckling analysis

Consideration was given to the extent of possible buckling in hot weather using buckling analysis.

Since the HPCM layer is very thin, it may be wondered whether compression might appear in this layer during hot weather, and to what extent this compression could be high enough to generate elastic instability.

If it is assumed that the temperature at the material setting is θ_0 and may rise up to θ_{max} during a summer day, the equivalent swelling is then

$$\varepsilon_S = \alpha\,(\theta_{max} - \theta_0) \qquad (1)$$

where a is the coefficient of thermal expansion. With $\theta_0 = 15°C$, $\theta_{max} = 55\ °C$ and $\alpha = 1.2 \times 10^{-5}\ /°C$, it is found that. $\varepsilon_S = 480 \times 10^{-6}$. This value is equal to the strain corresponding to the cumulated crack opening obtained on plain mortar after 28 days (see section 3.2).

Except if the hot weather appears in the first month (in which case the assumed initial temperature is probably too low), the temperature-induced swelling will be less than the material shrinkage, which means that no compressive stress is likely to appear in the HPCM layer. Therefore, the buckling risk, at least in mild climates, seems negligible.

5.19 Preliminary conclusions

This section presents the preliminary conclusions drawn from the extensive HPCM testing undertaken and reported in this chapter.

Clearly, considerable progress has been made in developing and testing the innovative concept of High Performance Cementitious Material, a hydraulic surface dressing proposed as a potential candidate for a long-life wearing course.

An initial mix-design, which was developed based on early research, evolved through a number of stages and was improved during the project. Importantly, the improved mix design took into account the results of the extensive materials testing undertaken by national testing laboratories under the guidance of members of the HPCM Group.

The development and testing of the HPCM material helped address a series of questions identified at the beginning of the project, viz:

- How to produce and to apply the material on a base layer?
- Will the wearing course suffer cracking due to restrained shrinkage?
- Will the wearing course remain stuck to the base layer?
- Will the wearing course loose its chippings under the action of traffic load or exposure to climatic conditions?
- Will a pavement covered with an HPCM surfacing face some unexpected distress which threatens its essential long-life character?

Procedures were proposed and implemented that allowed all the laboratory testing participants to produce and successfully use materials delivered from a single source. Apart from the water content, the same material was used by all the participants involved in the laboratory testing, ensuring a quite consistent set of experimental data. Although the tests performed by the participating laboratories were quite different, they helped in drawing a consistent picture of the HPCM's behaviour.

The fibre reinforcement was designed to prevent shrinkage-induced cracking. Two types of fibres were pre-selected, and the dosages were varied in order to find the minimum amount necessary to prevent any visible cracking in the wearing course. At an intermediate stage of the project, one solution was emphasized, based upon the use of 4% (by volume) of synthetic (PVA) fibres. However, later observations showed that this reinforcement could not overcome macro-cracking in the long run. Steel fibres seem a preferable approach, with a minimum dosage of 3%.

Some improvements were also made in the mortar mix-design (leading to a more fluid consistency when freshly mixed) and in the procedures for application of the material (shotblasting and trench along the section edges of the asphaltic binding course). Where these improvements and new application procedures were used, there was no debonding of the HPCM layer in any of the tests, including in the fatigue tests encompassing 1.5 Million Standard Axles. It seemed that the combination of strength and roughness of the asphalt surface on one hand, and strength of the HPCM on the other hand, is able to develop a high resistance to debonding. However, it should be stressed that the limitation of available fatigue testing machines and the relatively short duration of the project did not allow application of a loading that could reproduce the effects of high-traffic during 20 or 30 years, a typical case for a long-life wearing course. As well, the effect of ageing of the asphalt substrate on the interface bond is unknown.

Following the measurements for chipping loss, it was quite obvious that such a phenomenon will take place in a real pavement, to an extent which can be expected to vary between 5 and 20% of the original dosage. Importantly, however, it was concluded that such an outcome does not seem to change markedly the pavement's skid resistance. Nevertheless, good insertion of chippings during wearing course construction is essential to limit both chipping loss under traffic and the level of noise generation.

Finally, although a debonding between HPCM and asphalt is unlikely to appear, at least in the short term, some delamination of the asphaltic binding course may take place along the edge zones, particularly due to hot weather. It is therefore critical to build a sound and stiff base course, which ensures low rutting and is compatible with a thin top layer of high modulus.

Acknowledgements

The HPCM sub-group gratefully thanks SIKA France (with a special mention to Isabelle Lallemant-Gamboa) for advice in the choice of the HPCM constituents, and for the packaging and delivery of HPCM lots to the various involved laboratories.

LIST OF HPCM TECHNICAL REPORTS

[HPCM Report 1] HPCM Material Source – Author: F. de Larrard, LCPC, France

[HPCM Report 2] Selection of Constituents. Revised Report – Author: F. de Larrard, LCPC, France

[HPCM Report 3] Mix Design of the Matrix, thin solution, – Author: F. de Larrard, LCPC, France

[HPCM Report 4] Production of Sandwich Samples – Author: F. de Larrard, LCPC, France

[HPCM Report 5] Buckling Analysis – Author: F. de Larrard, LCPC, France

[HPCM Report 6] Preliminary Cracking Tests – Authors: F. de Larrard and O. Garcin, LCPC, France

[HPCM Report 7] Series of Cracking Tests – Authors: F. de Larrard - O. Garcin, LCPC, France

[HPCM Report 8] Behaviour at Cold Temperature – Author: Finn Thogersen, Danish Road Institute, Denmark

[HPCM Report 9] Fatigue Behaviour of Matrix + Fibres – Author: Anders Henrichsen, Dansk Belaegnings Teknik, Denmark

[HPCM Report 10] Abrasion/Wear Resistance. Skid Resistance Measurements – Author: Nina Sliwa, BASt, Germany

[HPCM Report 11] Resistance to Stripping Cement Matrix with Fibre – Authors: F. Hammoum, F. Travers, C. de la Roche, O. Burban, LCPC, France

[HPCM Report 12] Final Mix-Design and HPCM Application Procedures – Author: F. de Larrard, LCPC, France

[HPCM Report 13] Series of Cracking Tests – Authors: F. de Larrard and O. Garcin, LCPC, France

[HPCM Report 14] Application of HPCM Wearing Course on an Asphalt Pavement - semi-industrial scale – Author: J. Chandler and A. Badr, TRL, United Kingdom

[HPCM Report 15] In Situ Cracking – Author: G. Vorobieff, Roads & Traffic Authority, Australia

[HPCM Report 16] Total Lab Test - Combined Laboratory Stress Cycle Test – Nina Sliwa, BASt, Germany, and Patrick Wenzl, TU Munich, Germany

[HPCM Report 17] Evaluation of Noise Emission – Author: Nina Sliwa, BASt, and Manuel Männel, Germany

[HPCM Report 18] Surface Resistance under Traffic – Authors: F. Hammoum, J-P Terrier and O. Burban, LCPC,

[HPCM Report 19] Crack-frame Testing of Restrained Contracting – Authors: Anders Henrichsen and Jacob Gulstad, DBT Engineering A/S, Denmark

[HPCM Report 20] Evaluation of Noise Emission – Authors: Nina Sliwa and Manuel Männel, Germany

[HPCM Report 21] Total Lab Test - Combined Laboratory Stress Cycle Test – Authors: Nina Sliwa, BASt, and Patrick Wenzl, TU Munich, Germany.

NOTES

1. De Larrard F., Sedran T. (1994), "Optimization of Ultra-High Performance Concrete by Using a Packing Model", Cement and Concrete Research, Vol. 24, No. 6, pp. 997-1009, RICHARD P. *et al.* (1995), "Les bétons de poudres réactives (BPR) à ultra-haute résistance (200 à 800 MPa)", Annales de l'ITBTP, N° 532, pp. 81-143, Mars-Avril.

2. Rasmussen R. O., Rozycki D. K. *et al.* (2004), « Thin and Ultra-Thin Whitetopping – A Synthesis of Highway Practice", NCHRP synthesis 338, TRB, Washington, 96 pp.

3. De Larrard F., Garcin O., Hammoum F., Travers F. (2005), « Essais préliminaires d'un enduit hydraulique pour couche de roulement a longue durée de vie », Technical note, Bulletin des Laboratoires des Ponts et Chaussées, No. 258-259, pp. 121-128, October-December. http://www.lcpc.fr/en/sources/ blpc/pdf/bl258-259-121-en.pdf.

4. Total water/Portland cement.

5. The ° indication stands for the cornering angle. 0° means free rolling.

6. http://www.fhwa.dot.gov/BRIDGE/hpcdef.htm#1.

6. PERFORMANCE ASSESSMENT AND EXTRAPOLATION OF RESULTS

6.1 Introduction

The testing and test results presented in Chapters 4 and 5 focussed on the basic characteristics of Epoxy Asphalt and HPCM materials as well as their resistance to external factors such as environment and traffic. This chapter reviews the findings of the laboratory and accelerated pavement testing in areas important for longevity/durability and draws conclusions, where possible, on the likely long term performance of Epoxy Asphalt and HPCM surfacings under conditions likely to be encountered in the field.

The Epoxy Asphalt and HPCM surfaces will have to perform extremely well across a range of functional properties to be able to achieve the goal of a practically maintenance-free 30 year service life. Such wearing courses will also have to perform well enough to compete not only with today's standard solutions, but also with best practice 20-30 years from now.

Clearly, these two products are currently at different stages of development:

- Epoxy Asphalt is much more advanced, being a modified version of a standard asphalt wearing course which has been quite widely used in the field in particular situations (principally on rigid bridge decks).
- An HPCM wearing course is an innovative new system which needs more development before its debut for commercial applications. Consequently, the HPCM material can be expected to have – and does have – more uncertainties and unknowns at this stage of its development.

The assessments and evaluations in this chapter assume that the two surfacing materials can be paved on a large scale to a quality that at least matches the various specimens tested in the laboratory and in the field (as outlined in earlier chapters) – *i.e.* after any desirable or necessary construction advances have been made. Further consideration is given in Chapter 8 to practical construction issues that need to be addressed.

6.2 Epoxy Asphalt

The use of Epoxy Asphalt as a paving material is not new. It has an established record of development and use for the surfacing of significant road bridges over many years.

The first recorded use was on the San Mateo-Hayward Bridge in San Francisco in 1967 where the Epoxy Asphalt has provided over 40 years of satisfactory service. The material has since been used on other long-span bridges in many other countries, where its superior properties have been acknowledged.

Road administrations have not used Epoxy Asphalt for regular road pavement surfaces as cheaper materials have been available which, although they may not last as long, could be replaced relatively easily at moderate cost each time. The Phase II work provided an opportunity to test the properties and suitability of Epoxy Asphalt for use in such highway environments.

6.2.1 General overview

The many tests performed on the epoxy asphalt materials covered all the important questions regarding the properties which are known to be critical for the durability and service life of a pavement under heavy traffic.

From the testing done in this project, Epoxy Asphalt has been found to be a premium material, superior to current conventional asphalt surfacing materials. Its increased strength makes it more resistant to all the deterioration mechanisms that normally effect road paving materials. As can be seen from the discussion on the material's properties in the following sections, there is considerable confidence in the material. The previous experience with this material on long-span bridges – including its superior resistance to rutting and fatigue cracking – supports this view.

6.2.2 Modulus and Tensile Strength

Modulus and Tensile Strength tests are especially important properties for paving materials. Modulus or stiffness properties address permanent deformations or rutting, and the tensile strength becomes important when looking at low temperature cracking and fatigue. In terms of pavement design, an improved stiffness (load spreading ability) at design temperature would normally facilitate a reduction in pavement thickness for an equivalent traffic level. As well, a reduced temperature susceptibility at elevated temperature (less change in stiffness with temperature) compared with conventional asphalt materials would extend these beneficial properties to higher ambient temperatures.

Epoxy asphalt mixtures immediately *after manufacture* were found to have moduli comparable to those of the control mixtures, indicating that the early-life load spreading ability of the epoxy materials is similar to that of conventional mixtures. The moduli of both acid and amine cured epoxy asphalts *after curing*, were found to be relatively temperature independent and at least 2-5 times greater than that of the respective controls (up to two orders of magnitude higher at very low frequencies).

The epoxy asphalt performed well because it is a cross-linked system whereby some of the cross-linking or chemical reaction may be with the aggregate. As the epoxy asphalt reaction proceeds, the binder effectively becomes more cross-linked which leads to greater stiffness, and improved cohesive and adhesive properties. This curing process can take differing times depending on the type of epoxy being used. Although full strength may not be gained for some time, there will normally be sufficient integrity in the material to support traffic, in the same way as for a conventional asphalt material that gains its strength after cooling.

Due to the increased tensile strength of Epoxy Asphalt compared with conventional surfacing materials, there are strong indications that this material would provide a long and lasting surface, with its strength making a major contribution to it resisting all normal forms of deterioration. Its performance on rigid bridge decks is consistent with these conclusions. On this performance indicator, the laboratory testing supports the use of Epoxy Asphalt to provide long-lasting highway surface treatments.

6.2.3 Fatigue Resistance

Resistance to fatigue is essential for a paving material where the load is particularly repetitive and localised. Although deterioration on heavily trafficked roads due to fatigue cracking associated with bottom up cracking is less likely in thicker pavements, it remains important that the material has a good resistance to fatigue. Extensive studies were made into the fatigue resistance of cured epoxy asphalt mixtures using tests that apply repetitive loads and measure the resulting total movement.

At high strains, it was found for HRA and SMA mixtures that the fatigue resistance of the epoxy materials was only marginally better than that of the controls. At the PTF trials, no significant distresses were evident in the epoxy asphalt surfacing despite the lowers layers not being particularly thick. Since the Epoxy Asphalt is much less susceptible to ageing, it also experiences less embrittlement. It is less likely to experience top down cracking and is expected to exhibit better fatigue resistance.

The research and testing drew attention to the importance of the underlying pavement layers being strong enough to provide a long-life structure that is resistant to movement and any deterioration.

In general terms, it was shown that Epoxy Asphalt is less susceptible to fatigue deterioration and thus should not suffer in this mode in the long-term. Without actual full scale trials, it is difficult to predict time scales but it is clear that an Epoxy Asphalt surfacing must have a sound long-life pavement to provide support if the benefits and longevity are to be realised.

6.2.4 Rutting Resistance

Deterioration due to rutting is a major cause of maintenance works. Rutting tests are an important part of any routine set of tests for paving materials and have been an important element in the testing of Epoxy Asphalt. With testing being carried out over a variety of temperatures, it was likely that Epoxy Asphalt with its thermosetting characteristics would have very good resistance at elevated temperatures compared with conventional asphalt materials.

Permanent deformation and rutting associated with moisture damage were evaluated using various wheel tracking devices and the Simple Performance Test. These tests were conducted at temperatures between 40°C and 64°C. In APT tests, rutting of cured epoxy asphalt was found to be reduced compared to controls.

On the basis of the tests undertaken, HRA and SMA epoxy mixtures would be considered suitable for use on most of the heavily stressed sites requiring very high rut resistance – on the UK trunk road network, for example those up to at least 135 msa [Million Standard (80 kN) Axles)], or 80 000 AADT (both directions) where the proportion of heavy goods vehicles is 15%. Similarly the amine cured BBSG epoxy mixture would be suitable for even the most heavily trafficked situations.

With good resistance to rutting, particularly if temperatures rise, Epoxy Asphalt demonstrates that in relation to this indicator it can be expected to provide good service performance over a long-period. It is unlikely to deteriorate or soften in the long-term and should provide a rut-resistant long-life surfacing. The accelerated loading tests also emphasised the importance of the quality of the binder course/bituminous base beneath the long life surface layer (level of compaction, rut resistance, durability in general). Epoxy asphalt is not recommended for pavements with studded tyres.

6.2.5 Surface Shear Resistance

Resistance to shearing is important for any construction material but is particularly important for a flexible pavement material which must have the ability to retain the integrity of the material and the aggregate particles as part of the matrix. Loss of aggregate through surface abrasion from vehicle tyres leads to a rough, uneven surface and dislodged aggregate particles pose a safety hazard and can reduce skidding resistance. This type of damage is particularly common for open graded asphalts as the high percentage of air voids (typically about 20%) results in rapid oxidation of the binder compared to dense asphalts.

Resistance to surface abrasion was evaluated in the laboratory using the Cantabro test and the Triboroute test machine (sections 4.6 and 4.8.1 respectively) and a full scale accelerated loading trial.

- Results from the Triboroute testing showed that, under loading conditions that replicate loading forces expected from heavy vehicle tyres, loss of mass from the epoxy asphalt was very small compared to that from control mixtures (including an SBS polymer modified asphalt).
- Under the Cantabro test, the test results indicate that early life (freshly cured) cohesive properties of the epoxy asphalt should be comparable to that of standard open graded asphalt at 25°C. At 10°C however the epoxy material is markedly superior. By contrast with the control, mass losses from the epoxy asphalt were unaffected by the oxidation treatment.

The severe abrasive testing carried out on the Epoxy material has shown that there is good resistance to shear and to loss of aggregate and that, on these indicators, the performance of the material is consistent with a wear resistant long-life surfacing.

6.2.6 Moisture Resistance

Resistance to moisture and durability are closely associated when considering asphalt paving materials. Resistance to moisture is also related to the type of aggregate used so it is essential that materials undergo moisture resistance tests especially if durability is a key issue.

The amounts of rutting measured in the wheel tracking investigation were negligible; damage from water induced stripping on the basis of this test was considered insignificant. Similarly Lottman type tests on both freshly prepared (uncured) and cured epoxy HRA and SMA materials indicated that the epoxy materials were not susceptible to moisture damage, even at early age *i.e.* before the chemical setting process was complete, when compared against the Strategic Highway Research Programme (SHRP) criterion of 80% retained tensile strength.

Although the results presented indicated no significant likelihood of epoxy asphalt susceptibility to water damage, it should be recognised that there is no universally accepted method for this assessment. In particular, the understanding of water damage in real life trafficking situations is poor, and it would be useful to evaluate the performance of an Epoxy Asphalt surfacing at a larger scale by trafficking a flooded APT test section.

6.2.7 Low Temperature Behaviour

Any surfacing material must be able to perform at all possible temperatures. Low temperature performance is essential for counties like Canada and the Nordic countries. Conventional asphalts will have a tendency to crack at low temperatures as they become brittle and shrinkage forces increase. Epoxy Asphalts are thermosetting and expected to show greater stiffness at lower temperatures than temperature-sensitive conventional asphalts. Loading tests at reduced temperatures which were carried out, some of them down to –30°C, were used to check the performance of Epoxy Asphalt over a full range of temperature conditions (down to –30°C).

Results from thermal stress restrained specimen tests carried out on cured dense epoxy asphalt showed that under rapid cooling the material had a fracture temperature of –26°C, considerably lower than that specified in the Superpave binder criteria. Measurements of fracture energy and fracture toughness at -10°C and -30°C also showed the epoxy asphalt to have significantly larger resistance to crack initiation and fracture propagation compared to conventional asphalts. Similarly good low temperature performance was observed for epoxy HRA and SMA during bending (flexural) tests at 5°C.

However, the ductility/flexibility of the epoxy materials was reduced compared to that of the controls. This behaviour is consistent with the high strain characteristics predicted from the fatigue measurements made on the epoxy HRA and SMA and may place some restrictions on the practical use of epoxy asphalt. Stiff foundations may be needed in order to minimise the level of deflection (or tensile strain) within the epoxy material.

Simulation tests of two layer combinations (epoxy asphalt over different stiffness foundations) are required, either in the laboratory (for example using a Thermal Crack Simulation apparatus), or in APT Facility tests in order to assess the likely long term performance of these materials on different substrates.

Clearly, Epoxy Asphalts can provide good performance even at low temperatures and thus will be resistant to deterioration over a wide range of temperatures. Indications are that durability should not be compromised by changes in temperature and also should not be affected by any possible climate change.

6.2.8 Skid Resistance

Maintaining adequate skid resistance is an essential property for any pavement especially as increased safety for the road user is the continuing goal for all road owners. Ultimately the skid resistance of epoxy asphalt surfacings will depend on the properties of the aggregates used, as for conventional asphalts. In many situations skid resistance may be the factor limiting the lifetime of epoxy asphalt rather than the properties of the epoxy bitumen itself. Tests were carried out to measure skidding resistance and aggregate loss in a variety of ways to ascertain if aggregate retention was improved over that for conventional materials. Tests carried out on APT sections demonstrated that the skid resistance of epoxy asphalt was not significantly different from that of conventional asphalt. Of course, the skid resistance of an epoxy asphalt surface will lessen in time and may need a restoration treatment within the structural life of the surface layer, as is the case for conventional (reference) surfacings.

6.2.9 Noise

Concern over traffic noise has become a serious issue in many countries, particularly in Europe, where increasingly heavy traffic both day and night has now become commonplace. All modern surfacing materials should, if possible, be less noisy that older established materials. Noise generation from the pavement surface is related specifically to aggregate size and to texture depth associated with the evenness of the upper layer of the material. The way the pavement is laid and compacted as well as the consistency and temperature of the material will all add to the resultant noise profile of the material.

The work undertaken indicated that, in order to meet noise requirements while giving primacy to initial cost, there would be incentives to give priority to Open Graded Porous Asphalt (OGPA).

Traditional OGPA surfacing is typically chosen for its good water draining qualities and its ability to reduce traffic noise. By comparison with such lower cost OGPA surfacing, tests showed that OGPA with Epoxy Asphalt binder can be expected to increase the long-life /durability of this type of pavement, while there is no evidence that it may be able to improve on the noise levels achieved with the bitumen bound OGPA pavements.

6.2.10 Delamination

As the proposal for long-life surfacing considers a thin layer of the material over an existing long-life pavement structure, it is essential to examine the possibility of delamination of the material. Full testing really requires full scale trials but some testing has been carried out as part of this project.

The limited testing done was somewhat inconclusive but indicated the need for a durable underlying pavement and an adequate tack coat.

6.2.11 Durability

Although long-term durability of the material can only be fully tested in long-term trials, results from a wide range of laboratory tests all indicate exceptional long-term performance from epoxy asphalts. Epoxy Asphalt has been shown to resist many of the avenues of deterioration to which conventional materials are subject – and has been shown to be relatively inert to oxidation and embrittlement in particular, which is very significant for long-term durability. The abrasive tests carried out on the material were also very positive enhancing the view that its durability will be good or even very good.

6.2.12 Other Factors

While the tests performed on the acid-based epoxy asphalt materials addressed the properties known to be critical for long service life, there are other important factors in some regions that may also be important. In some countries (eg Finland, Sweden an Norway, use is made of studded tyres in winter. The Epoxy Asphalt surfacings may not deliver long life if subjected to vehicles using studded tyres. As well, further testing would be needed to ascertain whether use of de-icing chemicals would have any impact on the longevity of such surfacings.

6.2.13 Conclusions

Epoxy Asphalt was found to result in asphalt mixtures with significantly improved performance compared to conventional mixtures. In particular compared to conventional asphalts, cured epoxy asphalts are:

- Significantly stiffer (higher modulus) at service temperatures with greater load spreading ability.
- Highly resistant to rutting.
- Significantly more resistant to low temperature crack initiation and propagation.
- Significantly more resistant to surface abrasion from tyre action, even after oxidation.
- Significantly more resistant to fatigue cracking (although the benefits are less marked at higher strain levels).
- Less susceptibility to water induced damage.
- More resistant to oxidative degradation at ambient temperatures.

Although curing of acid based epoxy systems is slow (weeks or months) at ambient temperatures, in all cases the behaviour of uncured epoxy asphalts was at least comparable or better than that of the respective control mixtures. The curing process is thus unlikely to have any major effect on the overall life of the material – except the delay in developing early rutting resistance could lead to some early rutting, unless curing periods are modified.

Nearly all the testing indicated that acid-cured Epoxy Asphalt should provide a durable long lasting material in the most heavily trafficked road situations. There must be close consideration of the type of epoxy materials to be used and great care in the choice of aggregates if the best performance is to be achieved.

Epoxy Asphalt needs close supervision at the time of production and laying to ensure full mixing is carried out and that time and temperature are carefully monitored. If all aspects of the process are handled correctly, it has been shown that Epoxy Asphalt should be able to provide a surfacing material that has a considerably longer life than other materials used currently.

6.3 High Performance Cementitious Materials

6.3.1 General

High-Performance Cementitious Material (HPCM) is an innovative product which was developed and tested for road surfacing applications for the first time during the present project. This pavement consists of a layer of ultra-high performance, fibre-reinforced fine mortar, in which hard, polish resistant aggregate particles are embedded, forming a 10 mm composite layer.

Like all paving materials, HPCM needs strength to resist vehicle loading and environmental stresses. Due to its nature and the ultra-thin layer in which it is laid, there are other areas where the HPCM layer needs resistance to ensure that it has the ability to act as an advanced surfacing.

As an indication of the design considerations, one of the most important requirements of a wearing course is good skid resistance, which is dependent on the aggregate embedded in the surfacing. Another is the design of the binder, the key function of which is to ensure the aggregates adhere to the pavement. As well, a good bond is essential between the cementitious mortar and the bituminous substrate.

A thin cementitious surface layer is likely to develop discrete cracks unless this layer is restrained by the underlying pavement structure. However, regardless of the restraint provided by the bond to the underlying structure, micro cracks will inevitably be developed to compensate for natural shrinkage and temperature strains. To assure that the crack opening in this system remains at micro level, some reinforcement is needed and – given the thinness of the mortar layer – the research indicated that only steel fibres added to the mix could fully meet this requirement.

The aim of the testing was to perform an analysis primarily at laboratory scale to facilitate an assessment and extrapolation of results, addressing the feasibility of an ultra-thin HPCM wearing course with long life properties. The testing therefore focussed on the following main performance issues:

- General physical properties of HPCM particularly in regard to bond to substrate and capability to establish a lasting bonding of chippings to the matrix.
- Ductility and fatigue properties.
- Durability under environmental impact.
- Surface properties, noise and skid resistance.

As reported in Chapter 5, the range of testing carried out on the material provided some favourable indications of its performance in terms of the properties required of an advanced surfacing – and also highlighted areas where construction methods need to be refined to ensure satisfactory performance.

6.3.2 Shrinkage Cracking and Delamination

Because HPCM is both cementitious – and therefore non-flexible by nature – and also laid in an ultra-thin layer like a carpet, it could be susceptible to shrinkage and cracking and also to delamination from the existing substrate. Testing to minimise these effects was essential to ensure its performance and involved adjustment of the mixture and the type of fibre incorporated into the mix. Because the cementitious material and the underlying asphalt behave in different ways, it is particularly important that the HPCM has sufficient strength, integrity and 'stick', to resist shrinkage and delamination. The series of tests described in Chapter 5 enabled the mix proportions to be adjusted to reduce these problems to a minimum.

The initial outdoor (untrafficked) tests of the plain mortar laid on untreated asphalt surfaces were unsatisfactory due to excessive shrinkage cracking and de-bonding from the substrate. But further samples were cast and observed with a number of outdoor strips with 1, 2 and 3% steel and PVA fibres. From these strips, the best performance was achieved with the 3% steel fibres with very little shrinkage cracking. The other strips all suffered from cracking and delamination of varying severity.

To eliminate these early problems, in the next series of cracking tests the bond between the asphalt substrate and the mortar was improved by reducing the yield stress of the mortar and increasing the surface texture of the asphalt. New strips with 3% steel fibres and 3, 4 and 5% PVA fibres were laid out and observed. After 42 days, only the strip made with 3% PVA fibres developed two fine cracks, whereas the other strips had not developed any cracks or delamination. Later observations found that all the strips with PVA fibres had developed cracking whereas the strip with 3 % steel fibre was still in a perfect condition. At this late stage of the project it was therefore decided that a matrix material with 3 % steel fibre should be recommended for future trials.

As a supplement to the outdoor tests, it was decided to evaluate crack formation under controlled laboratory conditions by testing two different matrix materials and different fibre types and contents in the crack frames (see section 5.8). These rather severe tests were undertaken without the restraint that would normally be supplied by the substrate. The best performance was achieved with the standard matrix material and a minimum of either 3% steel fibres or 6% PVA fibres.

Performance of the HPCM in a climate with high summer temperatures was investigated by construction of a trial in New South Wales, Australia. A 20 m long un-trafficked section was laid with a matrix with 4% PVA fibres and observations started in the Australian winter season. In this trial, the surface texture of the substrate was only approximately 1 mm, i.e. significantly less than the suggested 2 mm requirement. During the first four weeks, a few transverse cracks appeared in the HPCM wearing course.

In summary, it is essential for the HPCM to be able to resist cracking and delamination if it is to be suitable as an advance surfacing. It has been shown that with the right mixture and most suitable fibres that cracking and delamination can be kept to a satisfactory level. Although, as yet, testing over a number of years has not been carried out at the same time to replicate the effects of being trafficked, the evidence and performance indicates that HPCM can resist cracking and delamination over the long term.

6.3.3 Surface Wear Resistance

As the surface of HPCM has chippings embedded in it to provide the skidding resistance required for the trafficked surface, it is vital that the material retains chippings and does not lose its integrity under vehicle wear or from environmental changes. The surface wear resistance and susceptibility to chipping loss of the HPCM material was evaluated by a number of different tests. These tests were undertaken in a number of laboratories in different countries and the specimens prepared by different organisations.

Chipping loss was found to be greater than for both an epoxy bitumen surface dressing and a standard thin bituminous surfacing. However, the amount of chippings required per square metre of surfacing has been reduced since these original tests.

As with the epoxy asphalt surfacing, the HPCM surfacing was subjected to Triboroute testing in order to evaluate the surface shear resistance. After 3000 load cycles about 9% of the chippings were lost, and after a further 3000 loads a total of around 10% were lost. These results indicate that less firmly bonded chippings wear off in the beginning, but then chipping loss is stabilised and the majority of the chippings will stay in place for the full pavement life. When comparing mass loss results for the HPCM surfacing with results for surface dressings made with other binders, the conclusion was that the HPCM surfacing performed much better than a surface dressing made with modified bitumen, but not as well as a surface dressing with epoxy bitumen.

In relation to longevity, retention of chippings and maintenance of the surface characteristics is essential if HPCM is to be able to perform as an advanced surfacing. Retention of skidding resistance will depend on chippings not being worn or plucked out from the cementitious matrix. Testing over a period of years has not yet been possible but early indications are that long term retention is possible. Chipping loss was shown to be not as high as for other reference materials and the ability to retain chippings was shown to be very good. Small adjustments to the mix may be necessary to ensure the high performance necessary for an advanced surfacing. The wear effects on the actual cementitious matrix were found to be minimal, due the integral strength of the material.

6.3.4 Buckling

As suggested in Chapter 5, because of its nature, HPCM could be particularly subject to thermal movements and therefore its resistance to bucking (as well as to cracking) will be an essential property. The integral strength of the material and the effect of the fibres included in the mix will provide the resistance both to cracking and to bucking. Although this was tested as part of the cracking tests, calculation of the likely thermal expansion of the HPCM during extremely hot weather (55°C) indicates that buckling and delamination are unlikely in temperate climates. Expansion of the material is offset by the shrinkage occurring during curing.

Although no long-term tests have been carried out, the indications from the tests undertaken were that HPCM should continue to be able to resist thermal movements and not deteriorate for a considerable length of time.

6.3.5 Fatigue Resistance

As was highlighted when considering epoxy asphalt, pavement loadings come mainly from exceedingly high numbers of repetitive loadings as vehicles travel over sections of the pavement. Deterioration caused by low fatigue resistance is of primary concern when considering new pavement materials. Tests involving over 25 million strain cycles conducted on the steel and the PVA fibre-reinforced HPCM mortar found that the applied deflection was about three times the average value that would be expected for roads of this type. The tests indicated that the HPCM with both fibre types has very high fatigue resistance. After initial micro-crack formation during the first few thousand load applications no further reduction of the elastic modulus would be expected during the service life of an HPCM wearing course. From the tests carried out, it was shown that HPCM has good fatigue resistance and – although there may be initial minimal cracking – that there is no further deterioration. This gives reassurance that the material will be able to provide good service as an advanced long life surfacing.

6.3.6 Freeze/Thaw Resistance

In a similar manner to other concerns about thermal movements, it is important that a paving material can resist the changes in temperature that may occur over short periods of time. Testing has been carried out as described in Chapter 5 that incorporates changes of temperature together with a sequence of loading. Freeze/thaw cycling (-20 to 20°C) of HPCM cast on asphalt specimens indicated that delamination or scaling of the material from the substrate during winter conditions was unlikely to be significant in practice. Similarly, losses of bauxite chippings from the surface of the specimens were negligible even after 112 freeze-thaw cycles and should not pose a significant problem in the field. Following the testing, indications are that HPCM would continue to be able resist temperature changes, to maintain its integrity and would continue in a fully serviceable condition.

6.3.7 Noise

Concerns over noise are particularly relevant for HPCM, where embedded chippings provide the surface and the size of chippings, the resultant texture and evenness of the surface have to be absolutely right for noise emissions to be as low as possible. The noise emission from the HPCM surface was evaluated by model calculations based on surface texture measurements made on one of the strips at LCPC. Indications from the work carried out suggest that, with the right embedded chippings and with the most appropriate texture depth, noise emissions will not be dissimilar to current conventional surfacings. This had not yet been fully tested but previous work with exposed aggregate concrete surfaces indicate that with due care and attention satisfactory noise levels can be achieved. Other work has shown that texture depth and chippings can be retained in the long-term so it is unlikely that noise emissions would increase over long periods of time.

6.3.8 Resistance to climate and mechanical action

Resistance to environmental effects is an essential property of any pavement material and although difficult to fully test in the laboratory, testing of HPCM was carried out in a fairly rigorous manner. The combined effects of mechanical, climatic and chemical actions was tested by a total laboratory test, encompassing cycles of repeated impacts of balls on the surface wear, freeze/thaw cycling with NaCl solution and finally low pH immersion. Different surface characteristics like chipping loss, skid resistance and the texture depth were measured during and after these tests.

The skid resistance and the texture depth, in practical terms, did not change during the testing. The total chipping loss during this severe test amounted to about 20%. Although, chipping loss was recorded under this very abrasive testing regime, other properties were retained so it is considered that the material has very good resistance to environmental effects. Although not a full scale test or carried out in live traffic conditions, the test, because of its robust nature, is a significant indication that the material will survive considerable climatic interference over a long period of time.

6.3.9 Traffic effects

The HPCM surfacing is by its nature rut resistant, but the thin layer must also be able to resist rutting tendencies from the underlying asphalt at elevated temperatures.

Rutting resistance of the HPCM was evaluated and compared with epoxy asphalt and a reference material in the PTF trials. During the application of the first 1 million standard axles, rutting was insignificant and only about half the value of the epoxy asphalt rutting. After a further 500.000 standard axles at an elevated temperature of 35 °C in the PTF, rutting was still insignificant and much smaller than for epoxy asphalt and the reference surfacing. Friction measurements performed in the PTF indicate that the skid resistance decreased slightly after trafficking but still remained at a very high value determined by the good friction properties of the bauxite chippings. Although some random cracking occurred in the HPCM, all the cracks were classified as hairline or fine, less than 0.5 mm in width, and were held tightly closed by the fibres at the end of the trial.

The main problem observed during the PTF trials was an upward displacement (curling) of the HPCM wearing course along the edges of the slab. It is believed this was the result of the high temperature, 35 °C, as no problem occurred when testing at 25 °C. This indicates the need for a good quality substrate on which to place the HPCM wearing course.

It was shown that rutting of the HPCM will be minimal but will depend absolutely on the nature of the material on which it is laid. It has been a basis of all the current work on long-life surfacing that the material below the advance surfacing must have a strong long-life structure but also have sufficient strength to resist rutting and other forms of deterioration. Concerns raised during PTF testing should be resolved if the HPCM is laid to full widths over a substantial and long lasting substrate. All the indications are that if the material is well-laid as described, it should be able to resist traffic effects for a considerable time.

6.3.10 Other Factors

While the tests performed on the HPCM addressed the properties known to be critical for long service life, there are other important factors in some regions that may also be important. As an example, in some countries (*e.g.* Finland, Sweden and Norway, use is made of studded tyres in winter. Studded tyres are not likely to be compatible with HPCM surfacings. As well, further testing would be needed to ascertain whether use of de-icing chemicals would have any impact on the longevity of such surfacings.

6.3.11 HPCM Conclusions

Contrary to the Epoxy Asphalt, where the technical properties can easily be compared to a reference asphalt wearing course, the HPCM surfacing is a new development with no obvious reference material. It can be described as an attempt to introduce a durable and tough cementitious binder in the conventional surface dressing technology as a substitute for bitumen. An evaluation of the HPCM wearing course therefore had to be more focused on the actual test results.

Overall, the thickness of the fibre-reinforced mortar layer needed to be minimised for cost reasons. At the same time, it needed to be thick enough to allow for good penetration of the chippings in the fresh mortar, where the presence of fibres exerts an elastic reaction, lessening, in many cases, the direct contact of the chippings with the base course. As well, the chippings/mortar composite had to form a strong surface layer that protected the lower pavement layers.

The HPCM wearing course also needed to be able to stay intact with no discrete cracking or delamination taking place while at the same time delivering superior functional properties for a period of 30 years. With the choice of extremely durable and wear resistant bauxite chippings, texture and friction were considered unlikely to be a problem provided the chippings stay in place.

Because of the nature of the material and the way that it is laid in thin layers, the testing was particularly concentrated on the results of thermal effects and the material's ability to remain adhered to the substrate – together with the ability of the material to retain the embedded chippings that provide the all-important skidding resistance and running surface.

The test results suggested that well-embedded chippings (probably 1/2 to 2/3 submerged) will not be lost, but some of the less firmly bound chippings may wear off early in the pavement life. With a suitable chipping placement method and curing process, it may be expected to keep 80-90 % of the total mass of chippings, which is expected to be enough to preserve the pavement skid resistance.

The durability and fatigue strength of the matrix material seemed to be very good. With the choice of steel fibres some near-surface corrosion may take place, however this will not have any effect for the long-term performance.

There are two main concerns remaining for the HPCM surfacing:

- The first one is a possible de-lamination tendency along the edges. At elevated temperatures, the tensile strength of the asphalt substrate may not be sufficient to keep the high stiffness wearing course in place, as it was indicated by the PTF experiments. It will then be necessary to specify an asphalt base course material with a suitable rutting resistance and a limited thermal susceptibility.
- Secondly, it needs to be confirmed in larger scale trials that a mixture containing 3% steel fibre reinforcement effectively eliminates discrete transverse cracking. If either of these two possible failure modes occur, it is likely to happen in the early life of the wearing course.

In summary, testing has shown that HPCM has great strength and integrity. Where there have been indications of less-than-perfect performance, the reasons have been discussed and improvements proposed. It is clear that certain conditions need to be in place including a strong lower layer (ie base course) and careful embedding of chippings to ensure maximum performance. From the testing and consideration of the results and performance in the tests, it is considered that, if the HPCM layer performs well for the first 1-2 years, then it is unlikely to fail in the following years. The expectation is that this surface, based on further trials, can be developed into a final product characterised by high safety, comfort, durability and limited noise emission.

7. FUTURE RESEARCH AND TESTING

7.1 Introduction

Great efforts have been made during the second phase of this project to research the properties of the two candidate materials, making maximum use of the testing undertaken in the national testing laboratories involved. A lot of knowledge has been gathered but the research has also revealed some new facets to be assessed and certain aspects and points to be studied in greater detail.

This chapter highlights a number of aspects and issues that will need further research and testing. These are presented in the following three major sections:

- Issues common to both materials
- Specific issues for Epoxy Asphalt.
- Specific issues for High Performance Cementitious Material.

In general, on the basis of the work undertaken (as reported in Chapters 4 and 5) and the assessments of the materials and their performance characteristics (as presented in Chap 6), it is clear that the Epoxy Asphalt is closer to being ready for the demonstration projects planned for Phase III than is the High Performance Cementitious Material.

One reason for this is the difference in the availability of suitable production/laying equipment. While Epoxy Asphalt applications can utilise normal asphalt production and paving equipment without any major modifications, existing production and laying equipment are not well suited to commercial applications of HPCM. These would need some time for their development, an aspect that is discussed in greater detail in Chapter 9.

A second reason is that Epoxy Asphalt simply replaces one binder with another whereas the most appropriate mixture for HPCM still requires further research and development.

Another consideration is that both materials are intended for use in thin surface layers which calls for special knowledge and awareness by all the parties involved in pavement design and construction.

7.2 Issues common to both materials

7.2.1. Accelerated loading tests

There is a need for further Accelerated Loading Tests (ALTs) for both materials. Some ALT investigations have been undertaken – *e.g.* at the Pavement Test Facility at TRL (see 4.7.1), the Canterbury Accelerated Pavement Testing Indoor Facility in New Zealand (see 4.7.2) and the Danish Asphalt Rut Tester at DRI (see 4.7.3). Other ALTs are planned or being undertaken *e.g.* at the Accelerated Loading Facility at FHWA (see 4.7).

However, in order to strengthen confidence in the performance and longevity of the HPCM and Epoxy Asphalt solutions, which utilise very thin sections compared to the loads they are expected to carry, their interaction with the substrate or underlying layer is very important and needs further investigation.

Questions that need to be researched include:

- Will the thin surface solutions demand special or expensive underlying pavement layers in order to cope with the bonding conditions under thermal and traffic action?
- Will there be a need for special surface preparation prior to applying the long life surface layer in order to achieve the optimal pavement conditions?
- How strong, durable and free from defects do the underlaying layers need to be to provide a suitable base for an advanced surfacing?

Such questions were raised in the Industry consultations in Denmark in 2006. Even with the tests undertaken at TRL and DRI, the information available on these aspects was quite limited – and will continue to be until the issues are more thoroughly researched.

7.2.2 Properties of the aggregates

Both Epoxy Asphalt and HPCM will be exposed over long periods to the polishing action of the tyres on the aggregate used. The polishing action from traffic is especially important to consider when selecting aggregates (artificial or natural) for inclusion in Epoxy Asphalt. The friction required is especially important for aggregates to be included in HPCM. Selecting the right aggregates is therefore crucial to obtaining longevity of the pavements using these materials.

The HPCM concept has the advantage that specially selected aggregate particles can be partially embedded in the thin surface to provide adequate skid resistance. Because only one layer of such aggregates is needed for an HPCM wearing course, the volume of aggregates required is reduced. It will therefore be easier to afford a very high quality aggregate. An artificial aggregate like bauxite, for example, would prove to be a more expensive solution for Epoxy Asphalt.

Of course, for the initial demonstration projects under consideration in Phase III, aggregates other than bauxite could be utilised, because the principal aims will not be a demonstration of the long term effects but rather of the matrix of the material and solutions to the production and quality control issues at hand.

In the case of the fully developed final products, whatever aggregates are chosen – whether from artificial or local natural sources – they will need to withstand some 30 years or more of the deteriorating effects of traffic and climate, which if not adequately addressed would have a severe and unacceptable adverse impact on traffic safety.

In the case that there is not a natural aggregate that could withstand such a long service life without polishing, another strategy for consideration would be to contemplate a restoration of micro texture after 10 to 20 years. This could be performed through a shot, water or other blasting process, to restore the skid resistance by improving the aggregate macro- and micro-texture. However the possible costs and impacts of any such restoration work on the original requirements for economic viability of the long life wearing course need to be recognised and assessed.

A further area for research is the potential for recycling of both Epoxy Asphalt and HPCM.

7.3 Epoxy Asphalt

7.3.1. Optimisation of curing rate and handling time

The main difference when producing and handling epoxy asphalt compared to conventional asphalt is that the working process (mixing, transportation, installation and compaction) has to be adapted to the curing characteristics of the epoxy binder. Due to the thermosetting nature of the material, extra care is required in the timing of manufacturing and construction phases to ensure the product is not over-cured before compaction.

The solution will include optimising the chemical composition in such a way that these requirements can be best fulfilled. Needless to say, it is important to get the mix design correct. The asphalt producer will need to be well informed and aware of the important issues involved. Possible disturbances at the mixing plant during the course of the process itself could lead to the material being of no use if the subsequent pavement laying time schedule cannot be maintained. The risk of construction failures and damage to plant is greater than with conventional bitumen.

Recognising the time critical nature of the activities, careful planning and management of the downstream processes will be required, *e.g.* by:

- Keeping the transport routes from the mixing plant to the site as short as possible and minimising the risk of delays due to traffic jams.
- When the material is being installed on site, making sure supply levels correspond to the quantity of mixture that can be processed at the time.
- Ensuring that, in general, the construction process is as smooth, continuous and trouble-free as possible.

The construction processes will need to be tailored to the time within which the curing of the epoxy takes place after laying and the time available for compacting of the mixture; it will therefore be important to explore this sufficiently in trials before actual use in the epoxy asphalt applications. The time after which the road can be opened to traffic can only be established with certainty after this process has been completed.

7.3.2. Low temperature curing and energy conservation

The rapid curing epoxy systems have shown the ability to cure rather quickly at a lower temperature than might be expected. Prospects exist for some energy cost savings when using rapid curing epoxies if they can be processed at lower temperatures. In fact, epoxy systems in general should offer energy conservation at least comparable to current warm-mix technology.

7.3.3. In depth material modelling of epoxy asphalt

Despite recent advances in computational sciences and engineering, simulation of pavement behaviour remains one of the most challenging problems in civil engineering. The difficulties are twofold. First there is the need for a better mechanistically-based characterization of the material behaviour of new materials for wearing courses. Secondly there is the need to develop models that can handle time-dependent reactions in the material as well as physical aspects associated with traffic loading.

Any new material needs adequate research on its long term behaviour. The extension of available methods to very long time scales is critically important to predictions on expected life of wearing courses using new materials. In this case, researchers may usefully pursue new approaches based on probability and take advantage of the knowledge of other materials in helping to define the likely behaviour of epoxy-asphalt in the long term.

Normally models account for the long term effects of ageing phenomena and changing environmental conditions including the combination of climatic changes and traffic loading. Epoxy Asphalt materials call for models that can also handle the many interesting physical change processes that take place at relatively short time scales and explore their consequences on long term behaviour of the pavement. The understanding of these relationships is currently inadequate.

Modelling of the material behaviour in ways which capture both ageing phenomena and the influence of environmental/climatic conditions is important but will also pose a further challenge.

7.3.4 Environmental impacts

7.3.4.1 Chemical/environmental assessment of epoxy types

Different epoxy systems might have different environmental impacts. Both handling and transport of uncured components requires special care. Once the system is cross-linked, health and safety issues generally disappear.

Experience with bridge decking applications indicates that the main period of worker safety concern is during work at the hot mix plants. Nevertheless, leaching studies should be conducted to ascertain the environmental friendliness of the material.

During mixing and handling at the asphalt plant, the reactive components need to be handled only by skilled, instructed personnel. From the time it is transported to the job site for installation and during mixing and compaction, the workers immediately involved should use adequate heath and safety protection. Precautions and awareness are necessary until reaction in the material is complete.

It is important for any such impacts to be understood and accepted – particularly by authorities responsible for Workers' Occupational Health and Safety and the Environment – before these advanced surfacing materials are widely used. These issues are discussed further in Chapter 8.

7.3.4.2 Recyclability potential

If Epoxy Asphalt is used for long life pavement wearing courses, consideration needs to be given to the alternative scenarios for the end of their useful life and to their recycling potential. It is technically possible to recycle the epoxy asphalt as an 'aggregate'.

Assessments will be required on whether or not it will be possible to recycle the asphalt material, with the addition of conventional or new epoxy binder, in a hot or cold process, taking into account any environmental/health and safety considerations. In the unlikely worst case, the material could be used as a 'flowable fill'.

Should any jurisdiction ban recycling, a detection method will be needed to assess the presence of epoxy asphalt. Of course, there will be impacts on the asphalt producers and costs if such assessments require them to screen the reclaimed asphalt material for contents of epoxy in addition to other testing.

7.4 High Performance Cementitious Material

HPCM is an innovative product which was developed and tested for road surfacing applications for the first time during the present project. It is clear that certain requirements need to be met – including a strong and even lower layer and careful embedding of chippings – to ensure maximum performance. By comparison with Epoxy Asphalt, the HPCM solution needs more development, including operational laying techniques, before being ready for commercial introduction as a long life surfacing.

7.4.1 Asphalt base course specification

ALT and full scale testing have shown that the substrate must be stiff and strong enough to resist the vertical stresses induced by HPCM shrinkage (*i.e.* to avoid a 'curling' phenomenon) and, more importantly, those induced by flexural moment forces accompanying the asphalt and bottom layer rutting.

A minimum tensile strength at temperatures up to 40°C and a maximum permissible rutting level should be specified for the asphalt material, which should be matched on site, particularly at the edges of road pavements.

7.4.2 Effect of water dosage on HPCM properties

The original HPCM mortar proposed in the project had a water/(Portland) cement ratio of 0.20-0.21. However, due to the difficulty in mixing and laying the product at the laboratory scale, this ratio was increased up to 0.24-0.27 during some tasks.

In future, it will be important to know the effect of water dosage on the most significant mortar engineering properties, such as:

- Ease of mixing (at the industrial scale).
- Workability (just after mixing and evolution).
- 'Extrudability' (see next section).
- Shrinkage.
- Chippings loss.
- Bond with asphalt.

Based upon the knowledge gained about such properties, a range of acceptable water to cement (w/c) ratios could be defined for on-site quality control.

7.4.3 Industrial application technology

During the phase II work, all the HPCM research was undertaken on sections laid manually. For future industrial/commercial applications, a suitable road paving machine would have to be developed for laying HPCM wearing courses on actual road pavements.

Such an HPCM pavement machine would need to perform four distinct functions. It should successively (in one single pass) do the following:

a. Lay the mortar layer with a controlled thickness (*e.g.* 8 ± 2 mm).

b. Evenly spread the chippings at a controlled rate (*e.g.* 4.0 ± 0.5 kg/m^2), whatever the machine speed.

c. Roll the chippings at a controlled height, to provide an even, flat surface and in order to ensure a specified macrotexture (*e.g.* 1.2 ± 0.2 mm).

d. Apply a curing compound at a controlled rate (depending on the product).

Some on-site equipment already exists that may perform part of the application process:

- Conventional slipform pavers, currently used to build concrete pavement.
- Pavers for applying asphalt microsurfacing, that currently lay very thin layers of materials which have a consistency comparable to that of HPCM mortar.
- Machines devoted to the application of surface dressing, which spray a bitumen emulsion and spread a bed of aggregate particles.

Therefore, it is considered an HPCM pavement machine could probably be developed by adapting and combining such existing devices.

7.4.4 Two-dimension cracking tendency

A successful cracking test was performed at LCPC. But it was a one-dimension test using narrow strips, which cannot be considered as fully representative of a real pavement. Therefore, a test is required which is similar to the one performed by the New South Wales Roads and Traffic Authority in Australia, in which a 20 × 2 m^2 strip was cast and observed during several months,.

The new test should be performed with the definitive mix-design – that is a water-cement ratio in the acceptable range and 3% of steel fibres – and the test strip should be laid on a sufficiently stiff asphalt material.

7.4.5 End-of-life removal and recycling

In the framework of the Innoconcrete Eurêka project (2003-2006), LCPC has shown that an ultra-high performance concrete, *similar to* HPCM, was easily recyclable[1]. This material, which incorporates steel fibres and calcinated bauxite aggregates, can be crushed with conventional quarry facilities, producing on the one hand a good quality sand, and on the other hand the fibres separated from their cementitious matrix. Both products can be re-used in new mixtures to produce materials of similar or lower properties. However, in the case of HPCM itself, a remaining open question is the behaviour of the composite material under a conventional grinding or planing machine.

Although modern facilities are extremely powerful and accurate in terms of efficient grinding depth, the possibility of grinding HPCM to crush it and to separate the various phases would need to be checked through full scale tests.

7.5 Immediate Research needs

The different needs for research and testing mentioned in the previous paragraphs can be divided into a few groups and the more urgent summarised as follows:

- For Epoxy Asphalt, some further studies need to be performed in the local laboratory prior to the demonstration projects in order to optimise the curing profile with the desired rate of reaction, which is dependent on local conditions (time for curing, distance of transport and laying etc).

- For HPCM, the adaptation of existing equipment or the practical development of new pavement laying equipment needs to be given a high priority in order to support the demonstration projects in the Phase III field testing proposed (see Chapter 9).

Energy conservation and modelling of Epoxy Asphalt together with common aggregate issues are more in the nature of long term matters and are not critical for the demonstration projects under consideration in Phase III.

NOTES

1. Sedran T., Durand C., Recycling an ultra high performance fiber-reinforced concrete, Sixth International Symposium on Cement & Concrete CANMET/ACI International Symposium on Concrete Technology for Sustainable Development, Xi An, China, 19-22 September, 2006.

8. CONSTRUCTION ISSUES, ECONOMIC ASPECTS AND RISK ASSESSMENT

8.1 Introduction

The research and testing reported in Chapters 4 and 5 and the assessments of these results in Chapter 6 have confirmed the potential of Epoxy Asphalt and High Performance Cementitious Material for use as long life wearing courses. This chapter examines the state of the art in production of the material mixes in commercial quantities and potential methods for construction of advanced surfacings using these materials. In doing so, the chapter explores some anticipated construction issues and risks, as well as indicative cost estimates for the use of these materials.

In relation to *construction*, consideration needs to be given to a range of factors including: the role and interests of the user agency or owner; the materials involved and their particular needs for processing within a reasonable construction time; transportation; laying procedures; testing for quality and performance; work zone safety and traffic control; and training. Lessons learned from placement of the materials for the accelerated testing reported in Chapters 4 and 5 can help those responsible identify with industry the construction issues, risks and processing requirements involved.

From an *economic perspective*, the Phase I study highlighted that, for economic viability, long life surfacings would most likely only be viable on highly trafficked roads, would need to have costs within a defined cost envelope (typically around 3 times the cost of conventional wearing surfaces) and would need to be evaluated over the 30-40 year project life cycle, using 'reasonable' discount rates (*e.g.* around 6 per cent).

Following the testing undertaken, further consideration needed to be given to indicative costs of the candidate materials, taking into account the experience gained with the preparation and testing during the Phase II work.

Consideration also needed to be given to any *health and safety* risks associated with use of the candidate materials as well as to *environmental aspects* including recyclability of the materials at the end of their useful life.

These aspects are discussed in some detail for Epoxy Asphalt and HPCM in the following individual sections. Aspects common to both Epoxy Asphalt and HPCM are addressed after the individual Epoxy Asphalt and HPCM sections.

8.2 Epoxy Asphalt Wearing Courses

8.2.1 Background and previous use of Epoxy Asphalt

The use of Epoxy Asphalt as a paving material is not new. It has an established record of development and use for the surfacing of significant road bridges over many years.

The Shell Oil Company developed Epoxy Asphalt in the late 1950's as a jet fuel and jet blast resistant specialty pavement for airfield applications. In 1967, Epoxy Asphalt was supplied for its first commercial roadway application on the deck of the San Mateo-Hayward Bridge across San Francisco Bay. This first application is still meeting performance requirements, after 40 years of service. Over time, Epoxy Asphalt has been more widely used for stiff bridge decking applications in a number of other countries. Recently, it has been used extensively on bridge decking in China, following a rigorous assessment process completed for the first bridge in 2000 that proved its advantages of resistance to fatigue and rutting together with its ability to withstand extreme temperatures. Ten bridge decks projects have recently been completed in China and at least another six are expected to be undertaken in 2007[1].

Although its use on long-span bridges is well established, these are considered to be specialist applications favoured by particular conditions (e.g. the rigidity of the supporting bridge deck surface). The possible use of this material for regular road pavements has previously not thought necessary as cheaper materials were available that may not last as long but could be replaced relatively easily at moderate cost each time.

It can be seen that the properties of the material are well understood and there is experience that addresses many of the construction issues. However, the transfer of this material technology to general road pavement construction remains to be done.

8.2.2 Construction

Epoxy asphalt is a material with high stiffness that can be applied in thin surface layers. Production experience to date is not widespread although Epoxy Asphalt has been used quite extensively for bridge decking in some countries.

Trials using a continuous mix drum plant have shown that full-scale production of "acid curing" epoxy bitumen asphalt is feasible with only minor modifications required to plant, machinery or construction practice. Accurate metering and in-line blending of the two components are essential, but easily achieved using conventional pumping equipment. Some countries – for different reasons (ease of switching between mixes, smaller jobs sizes etc.) – predominantly use batch plant. Batch plants give good control of the mixing time which is an important part of the subsequent curing and later properties of the asphalt. Experience gained with continuous drum mix plant should be easily applied and be valid for asphalt batch plants.

Existing local sources will continue to be used for the selection of aggregates whenever possible, while ensuring that the mix designs developed will support expected traffic loads under a wide range of conditions. Importantly, mixes with epoxy asphalt demand natural aggregates with certain essential properties. More angularity in the coarser fractions and clean, angular fine aggregate will be required to obtain mixes that will provide the target objective of extended performance under increasingly heavy traffic loads for a long life pavement. Of course, high quality aggregates with high resistance to polishing will not always be available locally and this will be an important concern in some geographical areas.

The basic components of today's hot mix plants are essentially the same as those of many years ago. However, the plants have become larger, more productive, and more sophisticated , which will assist in the production of Epoxy Asphalt in commercial quantities.

Existing paving equipment can be used to lay mixes with epoxy asphalt but particular care is required to ensure the epoxy formula chosen is compatible with the construction time needed or available. Such an approach, where possible, is likely to be more cost-effective and convenient than the development of new construction equipment for epoxy asphalt mixes.

Improved plant control will be a great help to be able to check, in situ, the proportions of two-part epoxy asphalt and produce high quality epoxy asphalt mixes. Control could be assisted by using improved materials management and monitoring systems. The following advances in plant management will assist in improved mix control:

- Ferromagnetic tagging.
- Monitoring of binder viscosity.
- Automatic belt sampling of aggregates.
- Automatic asphalt content.
- Automatic mix temperature monitoring.
- Automatic binder content monitoring.

As well as good control at the mixing plant, it is essential that good control is in place during transport, placing and compaction. The timing of these operations and the relationship to the mix temperature are very important. Sufficient time has to be provided to ensure the chemical reaction has proceeded to some extent and the binder viscosity has increased to an acceptable level before placement and compaction. Although mixing temperatures are not as high as for conventional asphalt, sufficient temperature must be maintained to ensure good compaction. It follows that good site practice together with good control of transport arrangements must be in place if this technology is used for large-scale highway pavements.

Due to the thermosetting nature of the material, extra care is required in the timing of manufacturing and construction phases to ensure the product is not over-cured before compaction. As well, the risk of construction failures and damage to plant is greater than with conventional bitumen. For both these areas, the perceived risk is likely to diminish in importance as experience with the material grows.

8.2.3 Economic Aspects of Construction and Maintenance

Construction and maintenance is always difficult where traffic congestion is very high. Nevertheless, public works agencies need to be able to repair or replace deteriorated wearing courses and increasingly need to do so while maintaining the traffic flows on often congested roadways. Urban intersections typically pose particular construction problems in ensuring that traffic flows are maintained.

In the past, public agencies may have decided that epoxy asphalt would not be an appropriate choice due to perceived constructability problems and the increased cost of materials and related construction costs. However by incorporating a holding period for the hot mix to allow curing to begin before placement and compaction, Epoxy Asphalt can be opened to traffic once the material has cooled to near ambient temperature, providing quick public access to a high-quality, long life pavements with greatly reduced maintenance needs. On bridge decking, road pavements are typically opened in around 2 hours.

The costs for the binder element of Epoxy Asphalt surfacing will be higher than for conventional materials. It is considered likely that some of the cost premium will disappear as use of the material grows and volumes increase, suggesting some reduction in the additional costs over time. Other materials (aggregates, filler etc) should have no significant extra cost, nor should mixing plant costs be significantly different, although initial changes may be necessary to allow for the addition of a two-part binder. Transport, laying and compaction costs should be the same as for conventional materials although initially there may slight additional costs for small quantities and some element of learning. More costing information is provided in the following section.

It has always been understood that the skid resistance of an epoxy asphalt surface will lessen in time and may need a rejuvenation treatment within the structural life of the surface layer. This treatment was considered within the economic analysis carried out in Phase 1 of this work but has not been included within the initial works costs that are included in this chapter. The types of possible mid life treatment are discussed briefly in chapter 7.

Environmental issues together with worker health and safety concerns need careful attention, noting these may vary depending on the formulation of the epoxy resin and curing agent used. There are not thought to be significant cost implications related to this issue which is addressed in Section 8.2.5.

8.2.4 Materials and paving costs

The cost for Epoxy Asphalt for use on a high traffic road is likely to be very variable depending on the amount used, and a range of other factors including the experience of the contractor and supplier involved and the location and country/region concerned. However, given the importance of initial costs for the economic viability of long life surfacing, an indication of likely costs would be valuable. While experience is limited, it should be possible to make an indicative price estimate based on the price of natural aggregate materials and the epoxy asphalt materials required, and a typical price for mixing, transport and paving stages, assuming the use of current production technology.

Accordingly, indicative cost estimates for Epoxy Asphalt surfacing were sought from countries with active members of the working group. Because experience is very limited, only a few countries were able to provide cost estimates, in response to the Questionnaire distributed. In terms of Epoxy Asphalt itself, as this is supplied mainly as a proprietary material, cost indications from suppliers were generally only available on a 'laid per sq m' basis. In assessing costs on a per square metre basis, it was recognised the total cost will depend amongst other things, on the quantity of Epoxy Asphalt needed per square metre and the total tonnage to be supplied.

The estimates provided for Epoxy Asphalt have been brought together and the results for Western Europe are shown in Table 8.1.

Table 8.1. **Indicative Costs of Epoxy Asphalt Surfacings**

Epoxy Asphalt Surfacing (30 mm thick)	**Indicative Cost* (Euros per sq m)**
Milling	0.75-1.25
Binder course	6-10
Tack/bond coat	0.25
Wearing course materials	
Sub-Total costs of mixed material incl mixing, transport & laying	18-33.5
Indicative Total Costs of EA Wearing Course	25-45

* Indicative costs as at April 2007.

The indicative total price for milling an existing surface course and relaying with *Epoxy Asphalt surfacing* can be taken as being from €25 up to around €45 per sq metre.

Comparison with costs of Traditional surfacing

The Phase II Questionnaire also sought current costs for conventional surfacing using standard reference materials, assuming typical 30mm thin surfaces or SMA type wearing course as used in each country.

Responses indicated that current costs for conventional surfacing could now be taken as around 20 per square metre – allowing for the recent significant price rises, particularly in Western Europe. (The equivalent cost is $US27 at currency exchange rates [1 EUR ≈ 1.35 USD] applicable in April 2007). The actual range was from €13-25, depending on location.

Comparison with Phase I Estimates for Traditional Treatments

The costs of traditional surfacing had previously been identified in Phase I of the study as a basis for the whole life costing work and evaluations of the economic feasibility of advanced surfacings in the Phase I report. The earlier cost estimates were based on a Phase I questionnaire and the results presented in the Phase I report included the following advice on the estimates provided:

> *"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 i.e.*
>
> ***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".*

This traditional surfacing cost estimate of $US8 per square metre was used for the assessments of economic feasibility of advanced long life surfacings included in the Phase 1 report. Costs in the Phase I report are in $US in December 2002 [average exchange rate: USD 1 ≈ EUR 0.98]. At that exchange rate, the estimated traditional surfacing cost of $US8 per square metre in 2002 was equivalent to around 8 per square metre (2002 prices).

Clearly, the costs of conventional surfacings using traditional materials have risen significantly in Europe since 2002 – *i.e.* from around € 8 to around € 20 per square metre – and the increase in prices in Euros appears even larger when converted to US dollars at prevailing exchange rates.

The significance of the current cost levels in relation to the analysis undertaken in Phase 1 and a comparison with the costs for HPCM are discussed further in Section 8.4.

8.2.5 Environmental and Life Cycle Issues

8.2.5.1 Health and safety considerations

Currently, epoxy asphalt can be used both for wearing courses and for surface dressing. The epoxy material contains a variety of components that will depend on the type of asphalt and the actual constituents being used, some of which can cause skin irritation. These chemicals can include amines and epoxy resins, bitumen, tar (which is also carcinogenic), pitch and natural asphalts and as well as a variety of organic solvents.

The chemicals used can vary and the *fatty-acid* cured systems used in much of the testing for this report did not entail significant additional risks over conventional asphalt testing with few additional precautions necessary over usual good practice.

When *uncured*, some epoxy materials are characterised as strong allergy provoking compounds and can cause an allergic contact eczema when used. Experience with bridge decking applications indicates that the main period of worker safety concern is during work at the hot mix plants. Workers handling uncured epoxy products need to be made aware of possible problems and would need protective clothing – certainly gloves, as for similar asphalt products but other protective clothing may be required.

In some countries, occupational safety concerns over the use of epoxy compounds are a more sensitive point and special regulations apply[3]. It is essential that these requirements are checked before epoxy asphalt is used and the handling requirements necessary for the materials to be used are assessed and the necessary precautions put into place. Any reservations by the health authorities should therefore be prompted and cleared at this stage.

8.2.4.2 Life Cycle Assessment – Environmental considerations

Recycling of conventional asphalt pavements is a great asset to the road industry but there has been little experience of the recycling of Epoxy Asphalt. There are some questions that may need answering with respect to environmental impacts although if removed from the road using cold, mechanical means (milling or planing), then the material can be considered for re-use as a crushed product with no harmful effects.

As the material is thermosetting and does not soften on heating, it is more difficult to use it for hot recycling as is done currently for conventional asphalt. If the loose material is heated and used as an aggregate source for new material, then further work may be necessary to examine for possible harmful emissions. If the material is stored for reuse or disposed of as waste, the possibility of harmful leachates should also be examined.

8.3 High Performance Cementitious Material Wearing Courses

8.3.1 Construction

The High Performance Cementitious Material with fibre reinforcement that has been developed and tested in the Phase II work is a material with high stiffness and requires good adhesion to the substrate when applied in thin surface layers. The research has shown that such a material with a calcined bauxite high friction aggregate surface can be used to produce wearing courses with enhanced potential to withstand climatic stresses and traffic loading. The material has been designed and the testing so far carried out based on using an existing asphalt surface as a substrate.

The construction issues that are important for this material include:

a. *Availability of constituent materials.* Requirements on the composition of the constituent materials are strict, particularly as regards the gradation of the very fine particles (below 75mm). Currently it seems that suitable materials can be obtained in most geographical areas. However, in recent years, there has been a shortage of micro-silica (MS) for use in the construction industry. At present, this shortage has only had an impact on the market price of this mineral additive. In future, a shortage of micro-silica may be problematic. Alternative strategies could be available in such circumstances, *e.g.* production of silica fume from silica rock (*e.g.* quartz) or use of some natural rock microfillers as substitutes for silica-fume (their performance may not be as satisfactory).

b. *Mixing.* During the laboratory testing it was observed that the cementitious mix is very sticky and that an extended mixing time – up to 15 min. – is required to establish complete dispersion of the ultra fine particles. This dispersion is required to achieve the flow, workability and bonding properties of the matrix and is well known from the mixing of other high-density cementitious materials. It seems that the material may be produced in any high quality pan mixer. Another aspect, which has to be addressed when moving to full scale production, is the procedure for cleaning the mixing equipment and probably a cleaning sequence during a production day will need to be established.

c. *Workability.* Experience with mixing and paving at TRL indicated that the originally proposed mix was too stiff. After the initial trial mix, more water was added to the mix to produce a more workable material. Although some loss of strength was noted, this did not appear to be sufficient to be detrimental, at least in the short term.

Additional construction issues that need to be addressed in order to take forward an HPCM wearing course would include:

- In order to get a good and lasting bond of the bauxite chippings to the cementitious matrix, the chippings will need to be well embedded, ideally probably 1/2 to 2/3 of the aggregate size to provide a texture depth of 1.0-1.5 mm.

- Paving should not be undertaken in rain or at temperatures below 5 °C and the chippings need to be in a saturated, surface dry condition when spread.

- The application of the chippings should ideally take place immediately after placing the thin mortar layer, i.e. with the same machine or with a chip spreader. A light rolling or tamping action is required to ensure the desired embedment of the chippings.

- To minimise noise from the completed surface, the chippings should be finished to a flat, even, level surface. Since the chippings are rather expensive, excess chippings could be collected by a vacuum cleaner after the machine, as it is done for surface dressing. Curing compound needs to be applied after application of chippings.

- Suitable paving equipment for these operations may not exist at present, but will have to be developed or modified from existing equipment.

8.3.2 Economic aspects – Construction and Maintenance

The frequent maintenance required on some wearing courses has made reconstruction with High Performance Cementitious Material a feasible alternative. However, many construction issues need to be addressed in order to realise the full potential of this alternative.

Consideration needs to be given to three activities to ensure that this form of paving is not slower than any other and these are:

- Methods to accelerate the rate of strength gain.
- Methods to minimize the construction time depending on the setting time of mortar.
- Traffic control strategies to minimize user delay.

There would be obvious advantages if HPCM wearing courses could be used for re-surfacing existing bituminous and cementitious pavements as well as for new pavements. Consideration would need to be given to the following matters before HPCM could be considered a feasible alternative:

- The existing pavement would need to have a high bearing capacity (residual life at least corresponding to expected life of the new wearing course) and be free from visible cracks.
- The surface of the old pavement would need to be prepared – either by removal of a certain thickness due to rutting and use of a suitable fill material; or by milling, shot blasting etc – to ensure a good bond is possible between the HPCM wearing course and the underlying asphalt or concrete.
- Very strict surface evenness requirements would need to apply to the surface to be overlaid, *e.g.* similar to normal wearing course requirements, since the HPCM wearing course has a thickness of only about 8-10 mm.

8.3.3 Materials and paving costs

The production and laying costs for HPCM wearing course are more difficult to evaluate than for Epoxy Asphalt as there has, as yet, been no supplier experience with the material. It should be possible to assess the price principally on the basis of the price of constituent materials and the prices of mixing, transport and paving. Material, mixing and transport costs can be evaluated based on current practice, but paving costs may be more difficult to assess if new or modified paving equipment has to be developed.

As was done for the Epoxy Asphalt surfacing, indicative costs estimates for providing a new surface using HPCM were sought from countries with active members of the Working Group. The following table is thought to be a realistic assessment of indicative costs as may be appropriate in Western Europe. Preparation and asphalt layers below can be taken as being similar to those taken for Epoxy Asphalt.

Table 8.2a **Western Europe – 2006 prices**

HPCM matrix with chippings		**Cost**
Materials	**Quantity and cost (kg per m³) (€/t)**	**(€ per m³)**
Silicious sand	890 kg @ 15 /t	13.35
Cement, CEM I	1.020 kg @ 90 /t	91.80
Microsilica	205 kg @ 270 /t	55.35
Water	220 kg @ 10 /t	0.22
Superplasticiser	3 kg @ 6 /kg	18.00
Steel fibres	230 kg @ 3 /kg	690.00
Contingency for waste, etc.		868.72
		31.28
Cost of material per m³		900.00

Table 8.2b **Western Europe – 2006 prices** *(continued)*

HPCM production costs per m²	
Production cost categories	**(€ per m²)**
HPCM Materials 0.01 × 900 (as above at 10mm thick)	9.00
Mixing HPCM, 0.01 × 50	0.50
Transportation, 0.01 × 20	0.20
Paving incl. Chippings	5.00
Total direct cost per m²	14.70
Overhead, site management, risk and profit	€ 3.30-7.30
Estimated cost per m²	€ 18.00-22.00

Note: While material costs may not be too dissimilar in different countries in the developed world, labour costs are likely to vary considerably.

Although these figures suggest that HPCM might be available at a lower cost than Epoxy Asphalt, this is partially because it would be laid considerably thinner. It should also be realised that there will be less certainty about HPCM materials and costs until larger quantities are produced and laid.

8.3.4 Environmental and Life Cycle Issues

8.3.4.1 Health and safety considerations

The handling of the materials, and the mixing and laying of the HPCM will need similar precautions as for any cementitious material. The cement, the other fine materials and the fibres used in the mix may be an irritant to eyes, breathing and skin and so appropriate protection will be necessary.

Following the mixing process when water has been added, the material can still be irritating to skin and so gloves will still be necessary as for handling conventional concrete. Operatives should wash their hands and faces after working with the material. Any chemical additives used in the European Union may require registration under REACH (See Paragraph 8.2.4.2).

8.3.4.2 Life Cycle Assessment

Recycling of conventional cementitious material is a great asset to the road industry as crushed concrete is a valuable resource for many construction projects. The issues that affect the recycling possibilities for an HPCM layer relate to both practical and to environmental considerations, some aspects of which were raised in Chapter 5.

As the material is firmly bonded to an asphalt substrate, any material for recycling would be available as a mixed asphalt/cementitious material – that could be used as a mixture or separated into its two parts. If the material were removed from the road by cold mechanical means then it should be treated in a similar manner to broken concrete and there would be few environmental considerations. If the material were heated (possibly to remove the bonded asphalt) then the same considerations for emissions would apply as for recycling the asphalt on its own.

Given the material is likely to contain steel fibres, further consideration would need to be given to handing. Recently, it was found that when crushing a fibre-reinforced ultra-high performance concrete similar to HPCM, it was easy to separate the fibres from the matrix, and to reuse the fibres in a new material, with the same reinforcement effect as with new fibres. This raises the prospect that recycling fibre reinforced concrete would not be different or require special measures.

8.4 Comparative Cost Estimates –Epoxy Asphalt and HPCM Wearing Courses

Indicative estimates of EA and HPCM surfacings have been provided individually in the previous sections.

This section provides a comparison between the indicative costs of these materials. It also compares these indicative estimates with current surfacing costs using conventional (reference) surfacing materials.

The same qualifications should be made about the indicative cost estimates for Epoxy-Asphalt and HPCM solutions as made previously, viz:

- The cost for Epoxy Asphalt for use on a high traffic road is likely to be very variable depending on the amount used, and a range of other factors including the experience of the contractor and supplier involved and the location and country/region concerned.

- In assessing costs on a per square metre basis, it was recognised the total cost will depend amongst other things, on the quantity of Epoxy Asphalt needed per square metre and the total tonnage to be supplied.

- The indicative costs of HPCM wearing courses are assessed by extrapolation of material, mixing and transport costs for current cementitious pavements and on estimated paving costs, which will be higher – although how much higher will depend on any new or modified paving equipment that has to be developed. Preparation and asphalt layers below can be taken as being similar to those taken for Epoxy Asphalt.

Cost estimates for conventional surfacing, provided for several countries, assume typical 30mm thin surfaces or SMA type wearing course as used in each country.

Responses to the Questionnaire indicated that current costs for *conventional surfacing* – which had risen significantly particularly in Western Europe – could now be taken as around €20 per square metre. The actual range was from €13-25, depending on location.

Table 8.3 shows indicative costs for Epoxy Asphalt, HPCM and conventional asphalt 30mm ‘thin surfacing’ which has used as a typical standard base material. The figures in the table are thought to be realistic assessments of indicative costs as may be appropriate in Western Europe.

Table 8.3 suggests that the cost of an advanced surfacing could be between 2 and 3 times the cost of a conventional resurfacing treatment. The indicative cost premiums for the Epoxy and HPCM wearing courses, by comparison with conventional (reference) surfacing costs, are probably less than assumed for Phase I of the study. In part, this is due to having a better understanding of the costs and production processes involved (as a result of the work undertaken), but is also due in part to the significant increase in the cost of asphalt surfacing, particularly in Western Europe, in recent years.

Table 8.3. **Comparison of costs between materials**

Typical surfacing costs in €/m² for Western Europe			
Description	**Epoxy Asphalt 30mm wearing course**	**HPCM 10mm wearing course**	**Conventional 30mm asphalt solution**
Expected Lifespan	**~30 years**	**~30 years**	**7-15 years**
Milling 50-100mm	0.75-1.25	0.75-1.25	0.75-1.6
Binder course (50mm)	6-10	8-12	6-12
Tack/bond coat	0.25		0.1
Wearing course	18-33.5	18-22	6-12
Total costs	25-45[1]	27-35	13-25[2]

Notes: 1. Cost of restoration (once) of skid resistance during the service life not included.
2. Costs of minor repairs during 15 years of service not included.

The whole life costing exercise completed in Phase I showed that the use of advanced surfacing on high-traffic roads would result in net benefits when the discount rate used in the analysis is below about 6 % p.a. and when the advanced surfacing does not cost more than about three times as much as conventional materials. These benefits were estimated on a whole life cost analysis over a period of at least 30 years and take user delay costs during maintenance into account. The indicative cost estimates set out in Table 8.3 would appear to be broadly consistent with this envelope of costs.

8.4.1 Life-cycle Maintenance Costs

For economic viability, the additional material costs of using advanced materials for pavement surfacing need to be offset by the benefits from greatly increased intervals between maintenance interventions as well as reduced maintenance-related impacts on users in terms of delay time, fuel consumption, emissions and other environmental impacts such as noise.

Laboratory and accelerated pavement testing has indicated that advance surfacings can be expected to have increased strength and a much longer life than conventional surfacing, thereby greatly reducing maintenance requirements. However, no controlled and monitored trials have yet been carried out for heavily trafficked road pavements. Previous experience of the use of epoxy asphalt on bridge decks is considered to provide useful experience and confidence but, given the different conditions, cannot be taken as proof of performance, including reduced maintenance, on highway pavements. Although a surfacing life of 30 years might be anticipated, until further trials are completed any estimation of time to maintenance is bound to be uncertain.

However, as congestion increases on many roads to the stage where carrying out any maintenance is viewed as unacceptable either to the road user or by the road owner, the additional cost of using advanced surfacing materials may no longer be such a significant issue when repairs need to be carried out. As well, the continuing increase in the amount of traffic and the resulting congestion, the pressure from road users through to highway authorities and political leaders may lower the resistance to higher initial costs for the advanced surfacing.

A further consideration is that, although it has previously been assumed that the cost of advanced surfacings would be considerably higher than for conventional treatments, it appears that the gap may have been narrowed due in part to a better understanding of construction techniques and equipment required and in part due to recent prices rises for traditional surfacings.

Of course, any analysis carried out for any individual country should consider all the wider impacts and the advantages of using these materials as well as including the costs to the users which should always be the basis for any whole life cost analysis. The costs of both maintenance works and delays to road users vary considerably between nations and the political incentives and policy approaches adopted in relation to acceptable maintenance on busy roads are developed in different ways.

In these circumstances, it is clearly for each country to consider, using their own analysis with their own national data and to decide on a case-by-case basis when advanced surfacing could be appropriate and whether the long term benefits including reduced maintenance costs and associated user cost savings outweigh the increased initial costs.

NOTES

1. For further information, see the Chemco Systems website: www.chemcosystems.com/epoxy.html.

2. Greater attention is being paid to stockpile management aimed at reducing segregation. In addition, there is a trend toward the use of plant enclosures to maintain uniform moisture in the aggregate and eliminate neighbourhood complaints about dust, particularly in urban areas. Placement of the various sizes of aggregate into multiple feeder bins (to provide the desired proportions to the rotating drum dryer or other drying equipment) also requires efforts to control segregation. In future, current vibrating, reciprocating and belt feeders will be enhanced with better controls and electronic weighing systems.

3. For countries in the European Union, the Commission adopted a directive (Regulation (EC) 1907/2006, OJ L396,) in December 2006, on the Registration, Evaluation and Authorisation of Chemicals (REACH), which affects all chemicals produced or imported in quantities larger than 1 ton per year and so the addition of chemicals/additives to bituminous binders. For further details, see: http://ec.europa.eu/environment/ chemicals/reach/reach_intro.htm

9. PHASE III TRIALS

9.1 Next step in the innovation process

When this project was first proposed and accepted on the 2001-2003 Programme of Work for the OECD Road Transport Research Committee, a three phase process was clearly envisioned. The first phase was expected to focus on exploring technical and economic feasibility, the second on materials development and testing and the third phase on trials which could test the best candidate materials on the ground.

Having completed Phase II, a comprehensive research phase including laboratory testing and trials in various accelerated pavement testing machines, the project has progressed to the point where limited field trials under traffic – either on the road network or off-road – are the logical next phase.

The transition to real life testing is a critical moment for any innovative process, including this project. The small-scale and limited-cost activities of the research phase are completed and have confirmed with some caveats that the two very different pavement concepts deserve the attention of decision makers who are responsible for the cost-effective management of roads. Further progress towards large scale implementation is necessary if the potential economic benefits of these materials and techniques are to be realised. It is also obvious that – as always with such larger-scale trials of new materials and techniques – there are risks.

The expectations for the durability and long-life capabilities of the materials are based on extrapolations of the observations made during the phase of the project which is reported here. Consequently, the behaviour of the materials cannot be guaranteed over the greatly extended time periods required for long life pavements. This is business as usual for pavement research and it is part of the explanation why improvements have always been incremental and slow. It also partly explains why such improvements have generally been based on developments of known pavement types with proven performance. A third issue is that no matter how good the material and design, inadequate placement and poor construction operations can compromise its performance.

This project is, however, aiming for non-incremental improvements based on materials which are distinctly different from any of the pavement types that until now have been in common use on the roads of our nations. If this aim is to be pursued, and if the high probabilities delivered through the research phase are to be moved closer towards proof, then some future users must take them through the next phase – with a tangible risk that the actual pavement performance does not meet the levels now envisaged.

It is assumed that some road authorities, perhaps in partnership with industry, will be prepared to take this step. This chapter develops a framework for the coordination which may then be established for such initiatives and for the cooperation between them which could pursued in order to maximise the overall gains in experience.

9.2 The setting for coordinated trials

It is a long established practice of national road authorities to introduce new technologies individually and then later, after considerable delays, to collect and exchange information about their experiences from these innovations – important steps which then contribute to the assessment and recognition of best practice. While this will always be a way to disseminate technological advances among cooperating countries, jointly planned and coordinated trials and demonstrations offer shortcuts to a broad based establishment of better practices for all. That is the approach suggested in this report and outlined in the following sections.

9.3 Programme opportunities

The framework conditions seem to be favourable for launching cooperative field tests and demonstrations of the long life surface paving materials which have been tested and developed in this project.

Major international and regional research programmes have long demonstrated the added value of international cooperation and are increasingly assuming some responsibility for the critical passage from research to routine usage, *i.e.* precisely for the "field test and demonstration" phase of the innovation process. In a parallel move, national or state road authorities have generally established frameworks for formal cooperation and exchange of knowledge, which increasingly include the joint pursuit of strategic aims that call for research and technological development.

Such cooperative research programmes include:

- The 7th Framework Programme for Research and Technological Development (FP7) in Europe, which has been authorised from 2007 through 2013 to direct major funding to road infrastructure research as a critical element in its road transport programme.
- The Second Strategic Highway Research Programme (SHRP-2) in the United States.
- The ERANET Road Programme in Europe, in which 12 National Road Authorities have joined forces to co-ordinate and increasingly co-fund items on their respective national strategies for research that have the same objectives.
- AUSTROADS, which promotes cooperation and exchange of knowledge between Australian state road authorities and with New Zealand road authorities.

9.4 The aims

The overall aim of a coordinated programme of field trials of the Epoxy Asphalt and HPCM surfacings – which offer real prospects for use on long life pavements – is as follows:

- To demonstrate that the performance envisaged on the basis of the laboratory tests and the accelerated testing will hold within the period of the trial under real traffic and environmental conditions.

Collateral aims are to:

- Utilise the practical and economic opportunities provided by the trials for developing manageable and safe practices for producing and handling the pavement materials in larger amounts.

- Develop construction methods (in particular substrate preparation requirements) that are compatible with the properties of the materials and the volume and quality specifications of the resulting pavement.
- Improve the basis for realistic estimation of construction costs using these materials.
- Study variations in performance under varying loading and environmental conditions, underlying asphalt quality, and to suggest some limitations to this approach.
- Study the effects of limited variations in aggregate properties insofar as these are important for long-term friction properties and for aggregrate gradation and mix design.
- Measure the noise properties of the test pavements under real traffic.
- Develop methods of construction repairs due to non-compliance or unforeseen damage to the surface or supporting substrate.
- Study the recycling properties and usage of the materials.
- Increase the comfort level of contractors experienced principally in conventional pavement materials by providing opportunities for them to gain experience with these advanced paving materials.

The last of these is especially important since currently there is a lack of such experience and the possibility of unnecessarily high costs *e.g.* a high premium placed on construction with epoxy asphalt (EA) due in part to fear of premature setting of the EA or not having adequate time for proper placement. As contractors move up the learning curve, it can be expected that construction practices will adapt as necessary and the paving costs of advanced surfacings will ultimately drop as experience and volumes increase.

Further collateral aims are dependent on which of the two types of materials are involved, and are further detailed in 9.4.2 and 9.4.3.

In order to have quantitative confirmation of the achievements of the trials with respect to pavement performance – as compared with previous studies and the coordinated trials by other participants – a limited common instrumentation will be required.

9.4.1 Specific conditions and aims for field trials of the two materials

The results of the laboratory and accelerated testing of Epoxy Asphalt and HPCM materials carried out by this project have differing implications for the scope of the field trials that may be undertaken for each of these materials.

Basically, the Epoxy Asphalt material is ready for large scale demonstrations on the roads, and the challenges of producing and laying this material are considered as moderate. The major practical issue is linked to the potential health effects of the uncured epoxy asphalt binder, which has resulted in serious restrictions to use in some countries.

The fibre reinforced High Performance Cementitious Material is not thought to have such a problem, but presents some real challenges in terms of the rapid and accurate placing of the thin layer of pavement and in terms of adding within the same machine-pass the surface dressing of durable friction aggregates. Further, although the testing of this material has supported the expectations that steel fibres can prevent severe cracking, there is still some uncertainty regarding this behaviour when the pavements are constructed in larger areas that are exposed to traffic. The ability of the very thin and plate-like pavement to remain attached to the underlying pavement without provoking de-lamination of the base layer in the edge zones is not yet ascertained. Accelerated testing is continuing at the time of writing and will give better indications with regard to these phenomena, but it is the opinion of the group that these residual uncertainties, once the accelerated testing opportunities are completed and the results disseminated, are best addressed in some form of limited field trials on real roads.

9.4.2 Trial aims specific to the Epoxy Asphalt pavement

There are a number of EA-specific trial aims. Given the time periods anticipated for such trials and the expected durability of the surfacings, it is unlikely much new information will be gathered on their performance in the short term. The main focus of Epoxy Asphalt field trials will more likely be on consistency in construction/laying and cure characteristics – especially quality control, good consistency of depth, how to enhance curing etc. Any reservations by the health authorities should be prompted and cleared at this stage. In the short term, there may also be a focus on crack propagation as well as on the durability of Epoxy Asphalt as an Open Graded Friction course.

Over a longer period, the field trials could also be expected to produce information on:

- Testing of locally available materials as opposed to material from one supplier.
- Determining performance of Epoxy Asphalt materials having different chemical formulations.
- Determining the impact of aggregate type on long life surface characteristics.
- Testing of various Epoxy Asphalt layer thicknesses to determine the best lift thickness.
- Testing of several asphalt base courses in various climatic regions to evaluate thermal and moisture effects on the composite pavement.

Testing of several PCC base courses in various climatic regions to evaluate the propensity for crack propagation and de-bonding.

9.4.3 Trial aims specific to High Performance Cementitious pavement

There are also a number of HPCM-specific trial aims. With HPCM, there will be greater likelihood of getting improved performance data in a short time period. The trials could also study the stresses in the HPCM, different Coefficients of Expansion (COE) on the hot mix pavement and how wet the pavement can be.

Over a longer period, the field trials could also be expected to produce information on:

- Use of locally available materials as opposed to material from one supplier.
- Development of techniques for laying the mortar and inserting the chippings (which may require development of currently available equipment or development of new equipment).
- Testing of several asphalt base courses, of varying stiffness.
- Testing of several mixtures with water-cement ratios ranging from 0.20 to 0.30, in order to find a reasonable compromise between the ease of mixing/handling/placing and the performance of the hardened material.

- Testing of methods for preventing loss of moisture and monitoring of actual shrinkage on non-restrained samples from the pavement.
- Verifying the finite element calculations and the input to these, i.e. recording the temperature profile in HPCM and asphalt, actual deformation along edges and monitoring micro crack development through petrographic testing.

9.5 Time schedule

Given the programme will involve cooperative international research, the road map for the coordinated field trials activity must schedule sufficient time for the involvement and coordination of activities across the countries and bodies involved. The programme should include the following steps and timings:

No.	Field Trial Programme Steps	Timing
1.	Provision of information to potential participants (dissemination of this report) and its consideration by potential participants.	Sep '07-Mar '08
2.	Preparation of a suitable framework for the joint activity and identification of possible common sources of funding.	Jan '07-Sept '08
3.	Preparatory meeting for committed participants and agreement on common protocol, periodical reporting and final reporting.	Apr '08-Jun '08
4.	Initiation of trials.	Sep '08-May '09
5.	Conduct of trials and midterm review of the activity.	Sep '08-May '11
6.	Finalisation of trials and delivery of individual final reports.	Sep '10-Jul '11
7.	Writing of final report for the joint activity.	Aug '11-Dec '11

Although the field trials of course will need careful planning, at this stage it may be helpful to administrations and potential participants to outline the proposed content of the steps in this road map. These are described in some detail below:

Step 1: Begins with the publication of this report and continues through a suitable period to give sufficient time for interested road authorities to discuss it internally and externally and to include it in their planning. While not planning to be involved in the coordination of the trials, the JTRC is prepared to register during this period the agencies that announce their interest in joining the activity.

Step 2: A group of participants in the project are working to establish a suitable framework for the planned trial phase with a view to finding opportunities in large national and international innovation programmes.

Step 3: If this solicitation for joint trials results in a minimum of 3 trial offers with any one material, then a meeting will be called by the host organisation (cf. section 9.6 below), but chaired and summarised by a representative appointed by the potential participants. The preparatory meeting(s) must appoint a project coordinator and discuss and agree on the fundamental plans and principles for the trials. Anyone joining later must accept the established principles for participation.

Step 4: Participants may begin trials whenever it suits their plans after the preparatory meeting and no later than May 2009.

Step 5: The trials must last for a minimum of 2 years and initial results available by May 2011.

Step 6: Participants will be expected to deliver their final reports within 3 months after their trials have been completed and no later than in July 2011.

Step 7: The project coordinator for each series of trials will write the draft final report based on the documentation from the participants and a final meeting will be held to edit and finalise the report.

9.6 The host organisation

In order for the LLP Phase III project to have the credibility and authority needed to attract serious and committed partners, it must be conducted under the auspices of an international organisation which is acknowledged and respected by the road community.

Conversely, the host organisation should feel confident that it will be credited with the results of an international project having far reaching implications for the construction and maintenance of high traffic roads.

Importantly, the project should be organised and financed in such a way as not to have serious resource repercussions for the host organisation, although it is foreseen that it must carry the cost of the final report.

Phases I and II of the JTRC (initially OECD) Long Life Pavement project have attracted interest and participants from Europe, North America, Australasia and East Asia. It seems therefore appropriate to look for international host organisations which cover at least these regions of the World and are internationally recognised for high quality contributions to the development of the road transport sector.

Two organisations are immediately visible as fulfilling these requirements.

One is the OECD/ITF Joint Transport Research Centre with its strong link to the International Transport Forum, which starting in 2008 will become a very visible and authoritative institution with global reach.

The other is PIARC World Road Association with its strong links to road administrations in 107 developed and developing countries and its membership from road sector stakeholders in an even larger number of countries. PIARC does not have research as an important objective, but has nevertheless through its Technical Committees supported and conducted research, notably in the fields of tunnel safety and road/vehicle interaction.

Recommendation

With the past and present phases of the LLP project linked to JTRC, it is the preferred choice of the current Working Group to recommend that JTRC assumes the role of host organisation for a possible phase III, while maintaining the precondition that the consequences for the resources of the JTRC must be negligible.

10. FINDINGS, CONCLUSIONS AND RECOMMENDATIONS

10.1 Context

"Long life pavements" have a great deal to offer on highly trafficked roads where road works are increasingly constrained and undesirable because of traffic impacts on congested roads and delays to road users. In such environments, long life pavements are expected to show high quality performance without the need for significant repair for more than 30 years. It is also in such environments that the benefits of avoiding major repairs and re-pavements become large enough to justify the higher initial costs of such pavements.

It has been demonstrated that long life as just described is achievable for the subsurface pavement layers, but the surface layer or wearing course, which is critical for safe and comfortable driving, remains the Achilles' heel of the Long Life Pavement concept. This thin uppermost pavement layer is more than any other part of the structure exposed to air, sun and weather, and to the wear, tear and deformation of the traffic it sustains.

10.2 Phase I Report

The Phase I report explored the economic feasibility of long life surfacings and identified possible candidate materials.

10.2.1 Phase I Findings

The Phase I report drew the following conclusions on economic viability[1]:

"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 80000 or more.

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."

Two prospective candidate materials – epoxy asphalt and high performance cementitious materials (HPCM) – were identified for further research as possible innovative long life wearing courses.

10.3 Phase II Work – Findings

This report documents and provides analyses of the results of a major coordinated research effort involving staff and research facilities from 8 countries (AU, DE, DK, FR, NZ, UA, UK and US), as well as comments and advice from 10 other countries (cf. annex B). The draft Final Report was reviewed by external reviewers from Canada and Finland. This research was launched after the positive outcome of the economic analysis in Phase I.

The Phase II work aimed to strengthen current knowledge about the potential and the limitations of these two promising candidate materials (Epoxy Asphalt and High Performance Cementitious Materials). It was recognised that the Epoxy Asphalt and HPCM surfaces will have to perform extremely well across a range of functional properties to be able to achieve the goal of a practically maintenance-free 30 year service life.

The next two sections set out the findings of the laboratory scale tests undertaken and assessments made of the performance and suitability of Epoxy Asphalt and *High Performance Cementitious Materials* for advanced, long life surfacings. Later sections set out the Summary Conclusions and Recommendations.

10.4 Epoxy Asphalt

Epoxy Asphalt has been used for many years as a road surface on stiff bridge decking. The first such application, in San Francisco, is still meeting performance requirements, after 40 years of service. Over time, Epoxy Asphalt has been more widely used for stiff bridge decking applications in a number of other countries (*e.g.* recent extensive use in China).

Administrations have not used Epoxy Asphalt for regular road pavement surfaces as cheaper materials have been available which, although they may not last as long, could be replaced relatively easily at moderate cost each time. The Phase II work provided an opportunity to test the properties and suitability of Epoxy Asphalt for use in such highway environments.

The many tests performed on the acid-based epoxy asphalt materials in this project covered all the important questions regarding the properties which are known to be critical for the durability and service life of a pavement under heavy traffic. The testing focussed in particular on the *fatigue* and *fracture* properties which are crucially important for longevity. The effect of oxidation on the binder properties and condition of the surface dressing was also considered to be crucial.

By comparison with acid-based Epoxy Asphalt, the rapid curing amine and amino based epoxy asphalts were somewhat problematic in that the systems cured too quickly to allow proper compaction under the curing and setting conditions used; this resulted in higher air voids of the compacted specimens. Consequently the rapid setting epoxies will require some adjustment in the operation of a conventional hot mix plant and may limit their use to placement in closer proximities to the plant.

10.4.1 Main findings of Phase II testing

On the basis of the comprehensive testing undertaken, acid-based Epoxy Asphalt mixtures were found to have greatly improved performance compared to conventional mixtures. In particular compared to conventional asphalts, cured epoxy asphalts are significantly:

- Stiffer (higher modulus) at service temperatures, with greater load spreading ability.
- More resistant to rutting.
- More resistant to low temperature crack initiation and propagation.
- More resistant to surface abrasion from tyre action, even after oxidation.
- More resistant to fatigue cracking (although the benefits are less marked at higher strain levels).
- Less susceptible to water induced damage.
- More resistant to oxidative degradation at ambient temperatures.

A limited accelerated pavement testing (APT) trial of epoxy Open Graded Porous Asphalt (OGPA) resulted in early signs of surface abrasion in the control section but not in the epoxy. Tests on the APT sections demonstrated that the skid resistance of epoxy asphalt was not significantly different from that of conventional asphalt.

In short, the tests undertaken confirmed that epoxy asphalt is a premium material that outperforms conventional binders. Test performance of the epoxy asphalts studied in this phase was considered greatly superior when compared with conventional materials on the important indicators central to assessment of the potential for long service life.

10.4.2 Conclusions on performance expectations

Performance expectations for the longevity and durability of Epoxy Asphalt surfaces were built up during the project taking into account the results of the tests undertaken and experience with their relationship to longevity in the field. Nearly all the testing indicated that Epoxy Asphalt should provide a durable long lasting surfacing, even in the most heavily trafficked road situations.

There must be close consideration of the type of epoxy materials to be used and great care in the choice of aggregates if the best performance is to be achieved. Epoxy asphalt needs close supervision at the time of production and laying to ensure full mixing is carried out and that time and temperature are carefully monitored to achieve the best performance outcomes.

If all aspects of the process are correctly handled, Epoxy Asphalt should be able to provide a surfacing material that can be expected to meet the aim for a much extended practically maintenance-free service life, i.e. 30 years or more.

10.4.3 Issues for future research and testing

Important issues for consideration in future research include:

- *Curing and construction time.* Further laboratory studies are needed prior to any demonstration projects to optimise the curing profile with the desired rate of reaction for the local conditions (time for curing, distance of transport and laying etc).
- *Curing period.* It is important to establish when after the initial blending of the epoxy asphalt the curing reaction is complete.

- Curing temperature. Some epoxy systems have shown the ability to cure rather rapidly at a lower temperature than might be expected. The prospects for lower temperature curing – and the related potential for energy and cost savings during production – need further research.

10.4.4 Construction issues

Epoxy Asphalt is a material with high stiffness that can be applied in thin surface layers. Production experience to date for the relatively small quantities used has almost exclusively been with a batch plant that gives good control of mixing time – an important part of its subsequent curing and post-curing properties. However, the test section used in New Zealand was constructed from Epoxy Asphalt produced in a continuous mix drum plant without problems.

Due to the thermosetting nature of the material, extra care is required in the timing of manufacturing and construction phases to ensure the product is not over-cured before compaction. The risk of construction failures and damage to plant is greater than with conventional bitumen. For both these issues, the perceived risk is likely to diminish in importance as experience with the material grows.

When uncured, certain epoxy materials are strong allergy provoking compounds. These were not used for the Epoxy Asphalts in this project. However, if such materials are used, special equipment and safety precautions would be required for all involved in handling them while uncured.

10.5 High Performance Cementitious Materials (HPCM)

High-Performance Cementitious Material (HPCM) is an innovative product which was developed and tested for road surfacing application for first time during the present project. The aim was to assess the feasibility of its use as an ultra-thin HPCM wearing course.

The HPCM surfacing under consideration consists of a layer of ultra-high performance, fibre-reinforced fine mortar, in which hard, polish resistant aggregate particles are embedded, forming a 10 mm composite layer. As a new surfacing material with no obvious reference material, considerable work was undertaken on the development of HPCM mixes with the most suitable properties and evaluation of the HPCM needed to focus principally on the actual test results.

The initial mix-design developed based on early research was improved during the project. It evolved through a number of stages which included: selection of constituents, mix-design and laboratory application processes and assessment of behaviour. It was assessed against critical properties such as: skid resistance; binder function; protection of lower pavement layers; resistance to freeze/thaw and acid attacks; cracking behaviour; and bond between the cementitious mortar and the bituminous substrate.

Overall, the thickness of the fibre-reinforced mortar layer needed to be minimised for cost reasons. At the same time, it needed to be thick enough to allow for good penetration of the chippings in the fresh mortar.

The improved mix design took into account the results of the extensive materials testing undertaken by national laboratories. A thin cementitious surface layer is likely to develop discrete cracks unless the layer is restrained by the underlying pavement structure. However, regardless of the restraint provided by the bond to the underlying structure, micro cracks will inevitably develop to compensate for natural shrinkage and temperature strains. To ensure that crack openings remain micro level, some reinforcement is needed and – given the thinness of the mortar layer – the research indicated that it required steel fibres added to the mix to fully meet this need.

10.5.1 Main findings in Phase II testing

The test programme was undertaken primarily at laboratory scale and focussed on the main performance issues:

- General physical properties of HPCM particularly in regard to bond to substrate and capability to establish a lasting bonding of chippings to the matrix.
- Ductility and fatigue properties.
- Durability under environmental impact.
- Surface properties, noise and skid resistance.

Testing of the HPCM matrix for compressive strength, tensile strength and modulus of elasticity indicated the material can be characterised as High Strength/High Modulus. The results indicate HPCM wearing courses will have good bonding properties as well as durability confirming these objectives have been achieved.

Testing at medium scale demonstrated that a durable bond between the asphalt substrate and HPCM can be established provided the asphalt surface prior to paving of HPCM has been carefully cleansed and where required scarified. It is also critical for this asphalt to be in the high-range regarding E-modulus and temperature resistance. While a loss of chippings in the order of 10% could be expected, primarily in the very early stages of the pavement service life, the bonding between matrix and chippings appeared to be of a sufficiently high quality to indicate that the majority of the chippings will stay in place for the full service life of the pavement.

10.5.2 Conclusions on performance expectations

Testing has shown that HPCM has great strength and integrity. It is clear that certain requirements need to be met – including a strong and even lower layer and careful embedding of chippings – to ensure maximum performance.

By comparison with Epoxy Asphalt, HPCM needs more development, including operational laying techniques, before being ready for commercial applications as a long life surfacing.

However, the tests undertaken in Phase II at the same time the HPCM mix-design was being developed indicate there is a high probability that the current uncertainties about HPCM applications will be overcome.

From the testing and performance in the tests, it is considered that, if the HPCM layer performs well for the first 1-2 years, then it is unlikely to fail in the following years. It is the expectation that this surface, based on further trials, can be developed into a final product characterised by high safety, comfort, durability and limited noise emission.

10.5.3 Issues for future research and testing

A number of issues were identified for future research and testing, including:

- *Effect of water dosage on HPCM properties*. The water dosage has a significant impact on mortar engineering properties, such as: ease of mixing (at industrial scale) and workability; chippings loss; and bond with the asphalt.

- *Industrial application technology.* The adaptation of existing equipment or the practical development of new pavement laying equipment needs to be given a high priority to support the proposed Phase III field testing.
- *Two-dimension cracking tendency.* The test pad chosen for testing two-dimension cracking tendency needs to be fully representative of a real pavement and laid on a sufficiently stiff asphalt material.

10.5.4 Construction issues

Production of HPCM is seen as a manageable process using existing know-how and equipment. However, some modification of existing equipment or development of new equipment will be required for laying the HPCM mortar and inserting the chippings. Construction factors that are important include the availability of constituent materials, the mixing process and the workability of the freshly mixed material. The application of the chippings should ideally take place immediately after placing the thin mortar layer, i.e. with the same machine or with a chip spreader. A light rolling or tamping action is required to ensure the desired embedment of the chippings and a flat, even running surface.

10.6 Summary Conclusions from the Project

The project reflects the concerns of road owners for the slow and limited innovation during many years in road pavement technology as compared with other significant material technologies.

On the basis of the extensive work undertaken, it is concluded that both materials, Epoxy Asphalt and High Performance Cementitious Material with steel fibre reinforcement, are likely – at high levels of probability – to be able to provide long life solutions to the demand for surface pavements which can be placed on new pavements or existing pavements if these have a long remaining life.

The project has therefore succeeded in demonstrating the scope for significant advances available in materials which are not normally considered in the traditional thinking of pavement development.

There is of course a cost to this, which must be considered, and which is summarised in the next section and the associated table.

10.6.1 Indicative Costs for EA, HPCM and conventional wearing courses

This section provides a comparison between the indicative cost estimates for EA and HPCM surfacing. It also compares these indicative estimates with current surfacing costs using conventional (reference) surfacing materials.

It must be kept in mind that the actual costs for both types of surfacing are, of course, likely to vary depending on the amount used, and a range of other factors including the experience of the contractor and supplier involved and the location and country/region concerned.

Epoxy Asphalt costs and risks

The indicative costs set out in the Table below were estimated based principally on the price of natural aggregate materials and of epoxy asphalt materials, and a typical price for mixing, transport and paving, assuming use of current production technology. Because experience is very limited, only a few countries were able to provide cost estimates.

The skid resistance of an epoxy asphalt surface will lessen in time and may need a restoration treatment within the structural life of the surface layer. Such a treatment was considered in the economic analysis carried out in Phase I but has not been included within the initial works costs that are included in Table 10.1.

HPCM costs and risks

As there are yet no commercial applications, there is currently greater uncertainty about HPCM surfacing materials and costs than about EA surfacing costs, which will remain until larger quantities are produced and laid.

The indicative costs of HPCM wearing courses are assessed by extrapolation of material, mixing and transport costs for current cementitious pavements and on estimated paving costs, which will be higher – although how much higher will depend on any new or modified paving equipment that has to be developed.

Conventional (reference) surfacing

Cost estimates were provided by several countries and assume typical 30mm thin surfaces or SMA type wearing courses as used in each country. Responses indicated that current costs for conventional surfacing which had risen significantly – particularly in Western Europe – could now be taken as around € 20 per square metre. The actual range was from € 13-25, depending on location.

Comparison of indicative costs

Table 10.3 shows indicative costs for Epoxy Asphalt, HPCM and conventional (reference) asphalt 30mm 'thin surfacing' which has been used as a typical standard base material. The figures in the table are thought to be realistic assessments of indicative costs, as may be appropriate in Western Europe.

Table 10.1. **Comparison of indicative costs between materials**

Typical surfacing costs in €/m² for Western Europe			
Description	**Epoxy Asphalt 30mm wearing course**	**HPCM 10mm wearing course**	**Conventional 30mm asphalt solution**
Expected Lifespan	**~30 years**	**~30 years**	**7-15 years**
Milling 50-100mm	0.75-1.25	0.75-1.25	0.75-1.6
Binder course (50mm)	6-10	8-12	6-12
Tack/bond coat	0.25		0.1
Wearing course	18-33.5	18-22	6-12
Total costs	25-45[1]	27-35	13-25[2]

Notes: 1. Cost of restoration (once) of skid resistance during the service life not included.
2. Costs of minor repairs during 15 years of service not included.

The estimates in Table 10.1 suggest that the cost of an advanced surfacing could be between 2 and 3 times the cost of a conventional resurfacing treatment. The indicative cost premiums for the Epoxy and HPCM wearing courses, by comparison with conventional (reference) surfacing costs, are probably less than assumed for Phase I of the study. In part, this is due to having a better understanding of the costs and production processes involved, but is also due in part to the significant increase in the cost of asphalt surfacing, particularly in Western Europe, in recent years.

The whole life costing exercise completed in Phase I showed that the use of advanced surfacing on high-traffic roads would result in net benefits when the discount rate used in the analysis is below about 6 % p.a. and when the advanced surfacing does not cost more than about three times as much as conventional materials. The benefits were estimated on a whole life cost analysis over a period of at least 30 years and take user delay costs during maintenance into account. The indicative cost estimates set out in Table 10.1 would appear to be broadly consistent with this envelope of costs.

In these circumstances, it is clearly for each country to consider, using their own analysis with their own national data to decide on a case-by-case basis, when advanced surfacing could be appropriate and whether the long term benefits including reduced maintenance costs and associated user cost savings outweigh the increased initial costs. However, the indications are that there are reasonable prospects that this will be the case.

Having now demonstrated the real potential for using alternative materials, it is expected that industry and road owners together can move towards the implementation of these innovations. It is also obvious that both materials now need to be tested under traffic in limited trials after using realistic production and laying methods. This is discussed in the final section.

10.7 Recommendations for Phase III Trials

The research in Phase II has provided comprehensive results from laboratory testing and trials in various accelerated pavement testing machines.

The expectations for the durability and long-life capabilities of the materials are based on extrapolations of observations made during the testing reported here, but nobody can give full guarantees for the behaviour of materials in the extrapolated time domain. Therefore, if the potential economic benefits of these advanced technology pavements types are to be realised, then the innovation process must be taken to the next phase, in which the materials are tested in larger scales under real traffic on roads or off roads.

The project has therefore progressed to the point where such limited field trials are the logical next phase. It is also obvious that – as always with such larger-scale trials of new materials and techniques – there are risks. Still, it is assumed that some road authorities, perhaps in partnership with industry, will be prepared to take this step.

While such steps could be taken individually, jointly planned and coordinated trials and demonstrations offer shortcuts to a broader based and earlier establishment of better practices for all.

Such a coordinated trials programme would aim to demonstrate that the performance assumed from the laboratory tests and the accelerated testing will hold within the period of the trial under real traffic and environmental conditions – and that a large number of collateral aims and the material-specific aims described below will also be achieved.

10.7.1 Overall aims of the trials

The overall aim of a coordinated programme of field trials of the Epoxy Asphalt and HPCM surfacings – which offer real prospects for use on long life pavements – is as follows:

- To demonstrate that the performance envisaged on the basis of the laboratory tests and the accelerated testing will hold within the period of the trial under real traffic and environmental conditions.

Collateral aims include to:

- Develop construction methods (in particular substrate preparation requirements) that are compatible with the properties of the materials and the quantum and quality specifications of the resulting pavement.
- Improve the basis for realistic estimation of construction costs using these materials.
- Study variations in performance under varying conditions of traffic, the effects of limited variations in aggregate properties which can affect long-term friction properties and the noise properties of the test pavements under real traffic.
- Increase the comfort level for contractors by providing opportunities for them to gain experience with these advanced paving materials.

The last of these is especially important. As contractors move up the learning curve, it can be expected that construction practices will adapt as necessary and the paving costs of advanced surfacings will ultimately drop as experience and volumes increase.

10.7.2 Specific targets for Epoxy Asphalt Phase III trials

The Epoxy Asphalt material is ready for large scale demonstrations on the roads, and the challenges of producing and laying this material are considered as moderate. The major practical issue is linked to the health effects of the uncured epoxy asphalt binder, which has resulted in serious restrictions to use in some countries. Any reservations by the health authorities should therefore be prompted and cleared at this stage.

There are a number of EA-specific trial aims, including: testing of locally available materials; determining the performance of EA materials having different chemical formulations – and the impact of aggregate type on long life surface characteristics; testing of various EA layer thicknesses; and testing in various climatic regions.

10.7.3 Specific targets for HPCM trials

There are a number of HPCM-specific trial aims, including: use of locally available materials as opposed to material from one supplier; development of techniques for laying the mortar and inserting the chippings; and testing of several asphalt base courses and several mixtures with water-cement ratio ranging from 0.20 to 0.30 to achieve the best balance between mixing/handling/placing and the performance of the hardened material.

10.7.4 Proposed Phase III Field Trials: Summary of Recommendations

Field trials are recommended to: allow the new surfacing materials to be tested on the ground in real traffic and environmental conditions; promote improved production and laying techniques and the development of new equipment where needed; and to focus on quality control.

It is recommended that:

- Interested road authorities be invited to register with the JTRC Secretariat their interest in joining the proposed trials as soon as possible after the publication of this report and before a year has passed.
- When a minimum of three trial offers have been received with any of the materials, a preparatory meeting be called by the host organisation. Such preparatory meetings must appoint a project coordinator and agree on the fundamental plans and principles for the management of the trials.
- Participants may begin trials whenever it suits their plans after the preparatory meeting, but not later than May 2009. The trials must last a minimum of 2 years and must be terminated no later than May 2011.
- Participants must be prepared to deliver their final report within 3 months after their trials have been completed and no later than in July 2011. The two consolidated reports, one for each type of material, are drafted by the coordinators for the two series of trials and final meetings are held to edit and agree the final versions of the reports.

It is further recommended that:

- The JTRC assumes the role of the host organisation and responsibility for calling the meetings of the participants in this Field Trial phase.
- The responsibility for the funding and management of the field trials as well as recording and disseminating of the results of the trials rests with the sponsoring organisations, the participants and the project coordinators.

NOTE

1. Note: The typical costs of roadworks referenced in the findings of the Phase I report are specified in US dollars and take into account exchange rates applicable at the time the Phase I report was being prepared.

APPENDIX A
(RELATED TO CHAPTER 4)

A1. Laboratory and field performance histories of United States and New Zealand reference materials

A1.1 Reference Material used by Turner Fairbank Highway Research Centre (TFHRC)

During the summer and fall of 2002, the Federal Highway Administration (FHWA) in partnership with 16 State Highway Agencies (SHA) and over 30 Industry groups constructed 12 full-scale test sections of pavements with various modified asphalt binders at FHWA's Pavement Test Facility in McLean, Virginia. The 12 test sections were loaded using FHWA's two Accelerated Loading Facility (ALF) machines to evaluate permanent deformation (rutting) and fatigue cracking response. The ALF performance results are linked to a comprehensive laboratory binder rheological, physiochemical, and mixture characterization study.

The layout of the lanes as well as a listing of the materials evaluated are noted in figure A1.1. A job-mix formula was submitted by the paving contractor for a Superpave mixture with the unmodified PG 70-22 asphalt binder and the primary 12.5-mm NMAS gradation. The optimum asphalt binder content was 5.3% by total mass of the mixture, based on a 4.0% design air-void content at 75 gyratory revolutions. Although mixture designs with the other binders suggested slightly higher binder contents, the targets for all except the CR-AZ mixture were also set at 5.3%.

Figure A1.1. **Layout of the 12 as-built pavement lanes (not to scale)**

Lane 1	2	3	4	5	6	7	8	9	10	11	12
CR-AZ PG 70-22	**PG 70-22**	**Air-Blown**	**SBS LG**	**CR-TB**	**Ter-polymer**	Fiber	**PG 70-22**	**SBS 64-40**	**Air-Blown**	**SBS LG**	**Ter-polymer**

Removed 100 mm Of Existing CAB (lanes 1–7)

100 mm of New No. 21A CAB Under All 12 Lanes

Removed 50 mm of Existing CAB (lanes 8–12)

Existing VDOT No. 21A Crushed Aggregate Base (CAB)
(25-mm Nominal Maximum Aggregate Size)

Bottom of CAB to Pavement Surface is 660 mm
Re-compacted AASHTO A-4 Subgrade Soil

Notes: PG 70-22 = Unmodified Asphalt Binder Control (Intermediate Grade Temperature TIS = 26.1°C); CR-AZ = Crumb Rubber Asphalt Binder, Arizona DOT Wet Process; CR-TB = Crumb Rubber Asphalt Binder, Terminal Blend (TIS =17.9°C); Terpolymer = Ethylene Terpolymer Modified Asphalt Binder (TIS = 14.3°C); SBS LG = Styrene-Butadiene-Styrene Modified Asphalt Binder with Linear Grafting (TIS = 18.1°C); SBS 64-40 = Styrene-Butadiene-Styrene Modified Asphalt Binder Graded PG 64-40 (TIS =8.6°C); Air-Blown = Air-Blown Asphalt Binder (TIS = 22.6°C); Fiber = Unmodified PG 70-22 Asphalt Binder with 0.2% Polyester Fiber by Mass of the Aggregate.

Source: Turner-Fairbank Highway Research Center (United States)

A1.2 Reference OGPA mix used in New Zealand Work

A standard aggregate grading conforming to the Transit New Zealand P11 OGPA specification was used for both the epoxy and control mixtures (see Table A1.1). The bitumen content was 4.7%. Compaction of 100 mm diameter cylindrical specimens was by gyratory compactor, giving air voids of 20.4 ±1.2% (95% confidence limits) for all the specimens used in the study. This type of mix, usually manufactured with 80-100 or 60-70 penetration grade bitumen has a typical service life in New Zealand of 10-11 years and usually fails due to embrittlement and surface fretting resulting from oxidation of the binder.

Table A1.1 **Grading of aggregate used in epoxy and control mixtures**

Sieve size (mm)	13.2	9.5	6.7	4.75	2.36	0.60	0.075
Passing (%)	100	98	66	36	25	13	6.3

Note: Binder content: 4.7%.

A2. Manufacturers' recompmendations for acid-cured epoxy asphalts

Chemco Systems Manufacturers' Recommendations

Chemco Systems[1] (US) provides the following recommendations for acid-cured epoxy asphalts:

Can local asphalts be used as the asphalt in Epoxy Asphalt?

Epoxy Asphalt is formulated using a blend of materials from a particular domestic oil field. The asphalt derived from this crude has unique properties that make it compatible with the epoxy resins and curing agents that make up the total binder and balance the working life, cure time, strength and flexibility of the system. Other asphalts do not provide all these properties and most are not compatible with the epoxy resin and curing agents.

What are requirements of the time and temperature when mixing epoxy asphalt concrete?

The epoxy resin component is maintained at 80-85°C prior to mixing. The asphalt/curing agent component is maintained at 150-155°C prior to mixing. The aggregate temperature is controlled to be about 113-124°C. The mixed batch as it leaves the pug-mill (asphalt plant mixing chamber) is controlled to be between 110 and 121° C.

What are the optimum aggregate properties for Epoxy Asphalt?

Since the aggregates make up about 94% of the paving mix it is essential to use the best available aggregate to obtain a durable pavement with good flexural life. Aggregate should be hard, tough, resistant to wear and polishing and have 100% crushed faces. Elongated particles with an aspect ratio of greater than 1 to 3 should be no more than 5 % of all aggregate particles by weight.

A typical gradation for a paving course 25 mm thick is:

Sieve Size		Percent Passing
inches	mm	
3/4	19.0	100
1/2	12.5	95-100
3/8	9.5	80-95
No. 4	4.75	58-75
No. 30	.0006	20-35
No. 200	.000075	7-14

A3. Methods for evaluating curing charateristics

Various approaches for assessing the curing characteristics of epoxy asphalt binders are given in Table A3.1.

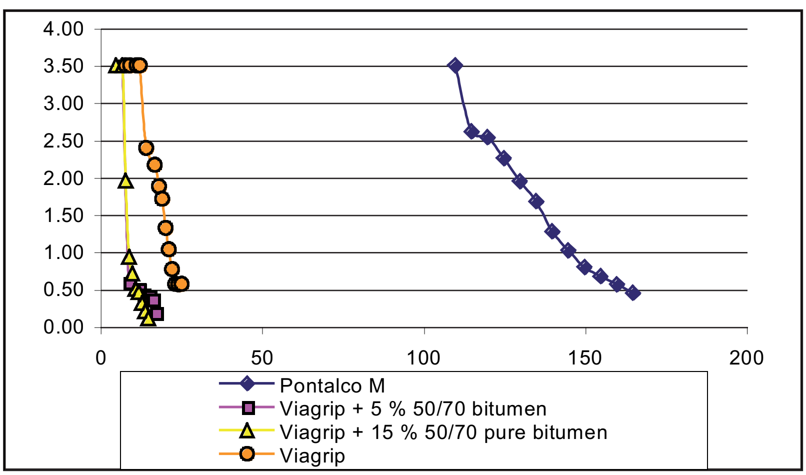
Table A3.1 **Approaches used to assess the curing characteristics of the epoxy asphalt binders**

Laboratory	Approach	Property Measured
France	Differential Scanning Calorimetry Penetration Test	Enthalpy of reaction (extent of polymerization) Pen Number
USA	Dynamic Shear Rheometer Pull-off Test	Rheology of epoxy asphalt beams Cohesive strength of epoxy asphalt film

Of the four approaches, the empirical Penetration Test is the most expedient way to evaluate the onset of curing. Results for two different epoxy systems using the Penetration Test are shown in Figure A.3.1.

Figure A3.1. **Evaluation of Curing Characteristics Using the Penetration Test**

Penetration [Vertical axis] vs Curing Time (hours) [horizontal axis]



Source: Nelly Vulcano-Greullet, LRPC Autun.

The Viagrip binder was found to have a very short setting time – in the order of minutes. This uses an amine curing agent and reacts considerably faster than the Pontalco M epoxy which uses an acid based curing agent.

Such short curing times are not practical for application in conventional hot mix plants or even workability of the loose hot mix.

The other approaches are more fundamental and provide insight as to the cured or nearly cured state. Differential Scanning Calorimetry (DSC) was used to monitor heat evolution associated with the polymerization of the epoxy.

The setting time was estimated as the time to attain 30% polymerization. Dynamic Shear Rheometer (DSR) was used to evaluate cast beams of cured epoxy asphalt. These results are discussed in section 4.3.2.

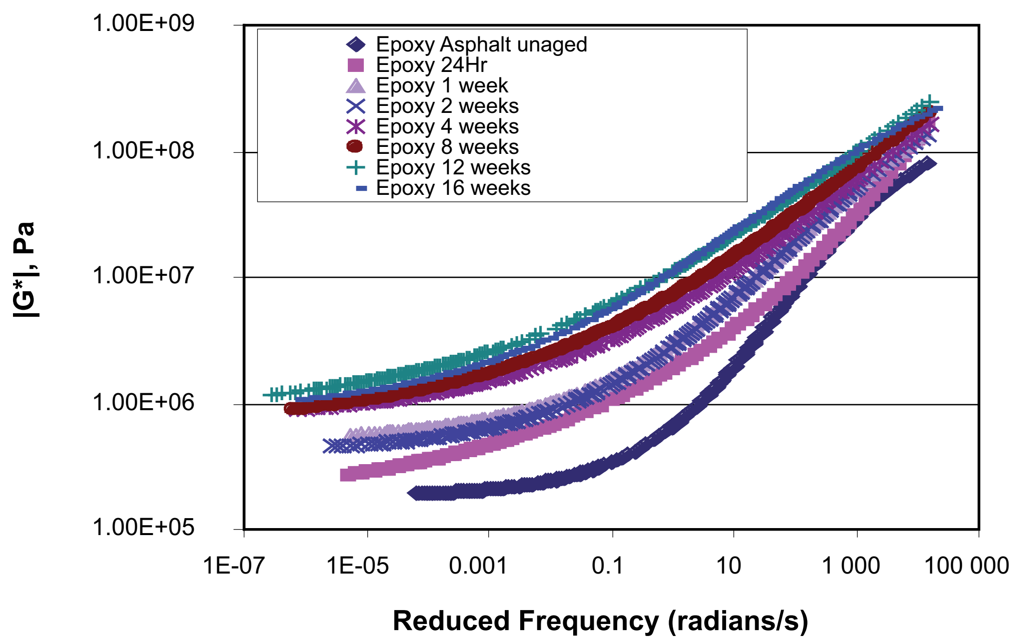
The Pull-off Tester was used to measure the cohesive strengths of epoxy asphalt films as means to provide insight as to curing history of asphalt-epoxy system. The results were similar to those reported by Scott Wilson.

Overall, cohesive strengths were found to be significantly greater than those of conventional and polymer modified binders.

A4. Binder rheological properties at different aging conditions

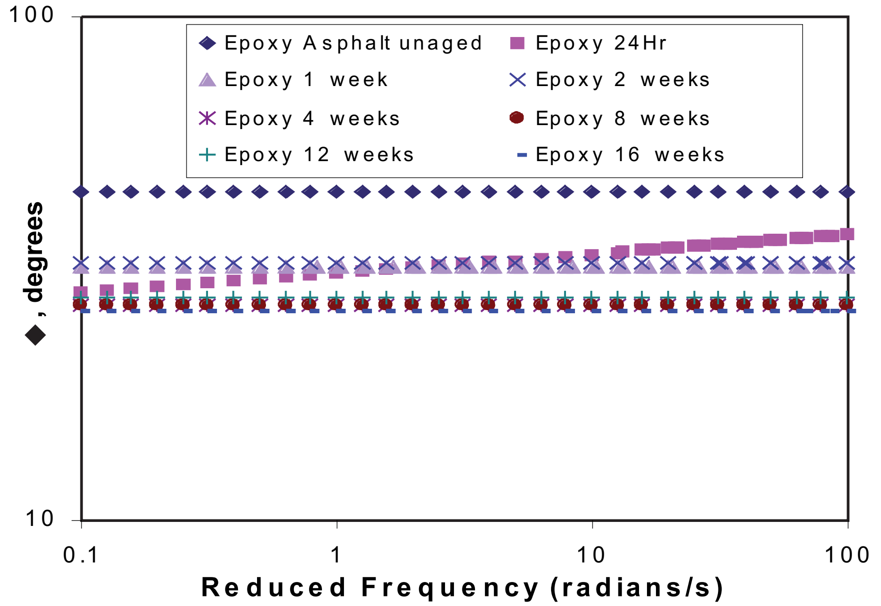
The changes that occur to three rheological parameters – the complex modulus |G*|, the phase angle δ, and the Superpave parameter |G*|/sinδ at various aging conditions (see section 4.3.3) are shown in Figures A4.1, A4.2 and A4.3 respectively.

Figure A4.1 **Master Plot of the Complex Modulus (|G*|) vs. the Reduced Frequency Curves at Reference Temperature of 28°C for Epoxy Asphalt Ultraviolet (UV) Aged for Different Intervals**



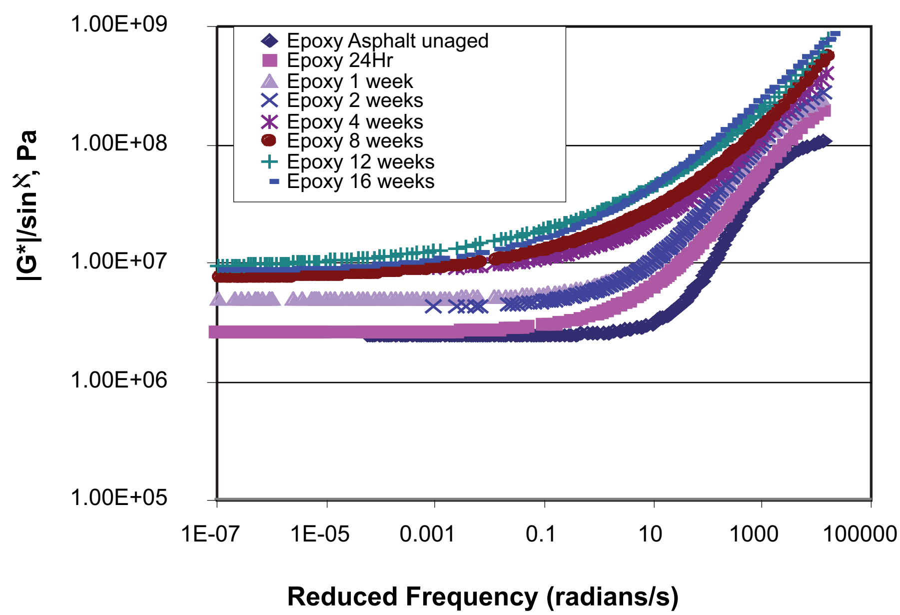
Source: Materials and Construction Team, Turner-Fairbank Highway Research Center (United States).

Figure A4.2. **Master Plot of the Phase Angle (δ) vs. the Reduced Frequency Curves at a Reference Temperature of 28°C for Epoxy Asphalt UV Aged for Different Intervals**



Source: Materials and Construction Team, Turner-Fairbank Highway Research Center (United States).

Figure A4.3. **Master Plot of the Superpave Parameter |G*|/sinδ vs. the Reduced Frequency Curves at Reference Temperature of 28°C for Epoxy Asphalt UV Aged for Different Times**



Source: Materials and Construction Team, Turner-Fairbank Highway Research Center (United States).

Three times over this aging interval, a recognizable major change in the properties takes place. The first change occurs after a week of aging, which is most likely the period when the epoxy has gone through the final stages of curing, consistent with observed curing times at 85°C (see section 4.4.2).

Following two weeks of aging, the epoxy does not appear to show any difference from the 1-week of aging; the next radical change occurs after four weeks of UV conditioning. The epoxy shows virtually no or very little change from that time onwards even after 16 weeks of UV conditioning – which equates to over 30 years exposure in Florida, USA.

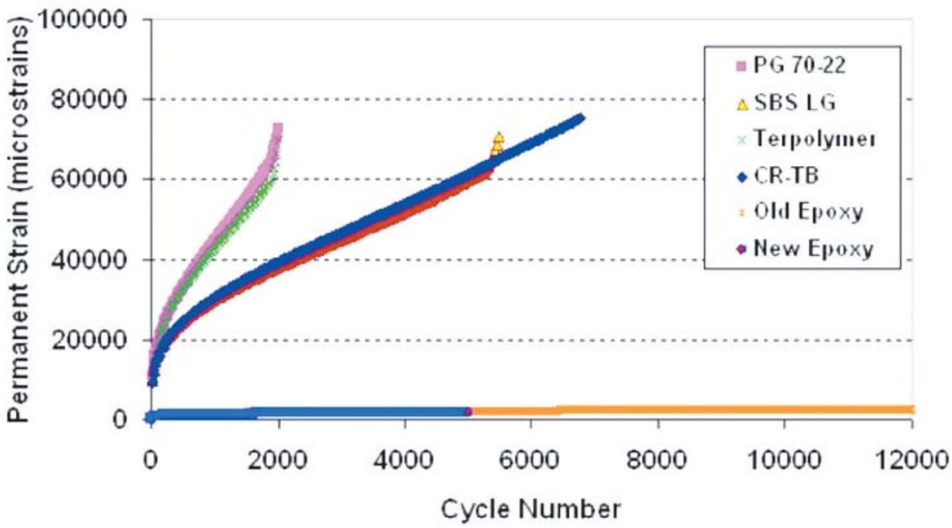
A5. Mixture properties

A5.1 Mixture Properties: Deformation Resistance

The Simple Performance Test (SPT) protocol for Flow Number test [6]. was carried out at 64oC on epoxy and various reference asphalt mixtures. This test applies repeated haversine loads with rest periods. This test is intrinsically designed to characterize the viscoplastic properties of the mixture intended for a rutting performance evaluation. The results, accumulated permanent strain as a function of loading cycle, are shown in Figure A5.1.

The reference mixtures experience much higher permanent deformations than the epoxy asphalt mixtures. The figure also demonstrates the significant differences between the unmodified mixtures (PG 70-22) and the modified mixtures (CR-TB and SBS LG), [23] as well as between the modified mixtures and those with epoxy asphalt.

Figure A5.1. **Accumulated Permanent Strains vs. Load Cycles for Reference and Epoxy Asphalt Mixtures from the Simple Performance Test Flow Number**

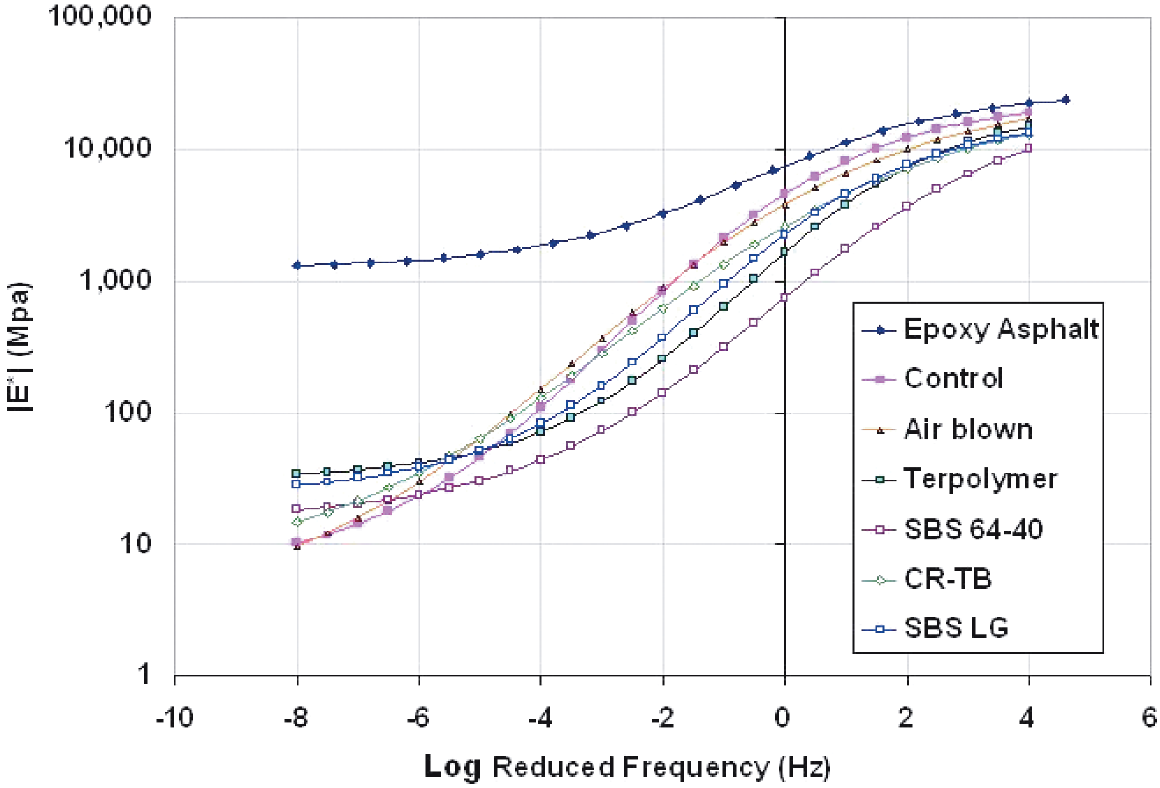


Source: Materials and Construction Team, Turner-Fairbank Highway Research Center (United States).

A second type of SPT test protocol for Dynamic Modulus (E*) was completed on the reference and epoxy asphalt mixtures. Here testing was conducted over a range of temperatures/frequencies.

As can be seen in the master curves in Figure A5.2, epoxy asphalt is significantly stiffer at all temperatures and frequencies. The implications of this again reflect that negligible rutting would be expected with this material. However, one must take caution when using these properties in any existing mechanistic empirical models such as those in the NCHRP 1-37A methodology [7].

Figure A5.2. **Comparison of Dynamic Modulus (|E*|) for Epoxy Asphalt and Reference Mixtures**



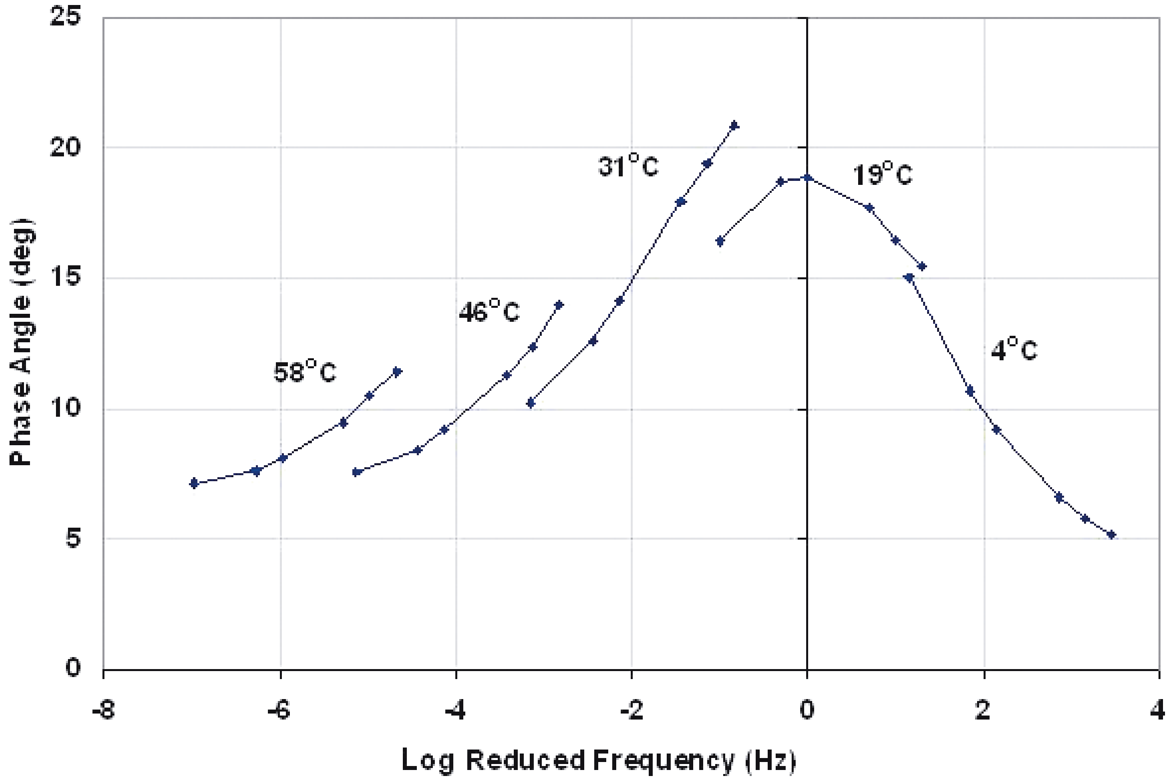
Source: Materials and Construction Team, Turner-Fairbank Highway Research Center (United States).

While the dynamic modulus follows the time temperature superposition concept, another fundamental viscoleastic property – the phase angle – does not, as shown in Fig A5.3. This indicates a degree of cross-linking in the polymer matrix of the epoxy. The implications of this have few ramifications toward secondary distress or rutting prediction, but any advanced viscoelastic material characterization and prediction across multiple temperatures will rely upon the inherent viscoelastic relaxation modulus.

Kim *et al.* [8] through a large series of experiments on fatigue damage of mastics and assorted binders, found the slope of the viscoelastic modulus master curve to be strongly associated (R2=0.82), with a material property related to the viscoelastic crack speed and energy release rate.

Hence the maximum slope of the dynamic modulus master curve (in log-log space) indirectly indicates that epoxy asphalt mixtures may be less susceptible to damage and fracture development than conventional, unmodified or modified, asphalt concrete mixtures.

Figure A5.3. **Dynamic Modulus (|E*|) Phase Angle of Epoxy Asphalt Mixture**



Source: Materials and Construction Team, Turner-Fairbank Highway Research Center (United States)

A5.2 Mixture Properties: Moisture Damage

Two moisture damage torture tests were used to evaluate the susceptibility of the epoxy asphalt HMA. Rutting induced by the Hamburg Wheel Tracking Device run at 64°C for 40,000 passes was less than 2 mm; these conditions were 6°C higher and 20 000 passes longer than for typical tests [9,10]. Rutting induced by the second test, the Pine Wheel Tester at 60°C for 40 000 passes was less than 1 mm. Essentially negligible amounts of rutting and moisture damage were observed.

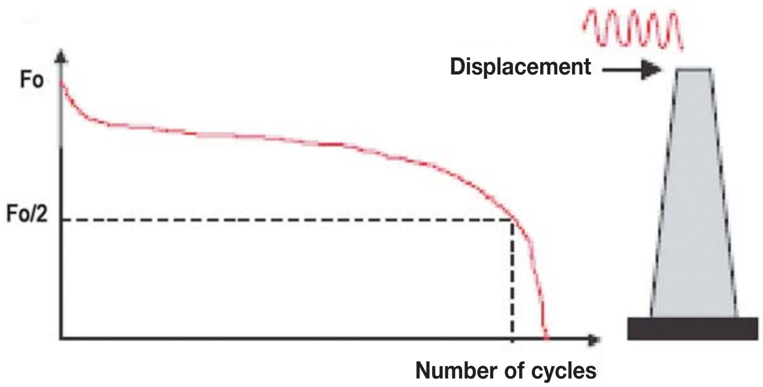
It can be inferred that stripping and rutting distresses are of little concern with epoxy asphalt concrete mixture, although further confirmation is required with additional aggregate types and gradations.

A5.3 Mixture Properties : Fatigue

A5.3.1 Principle of French fatigue test

The reason for conducting fatigue tests on mixes is to compare the computed bending tensile strains at the base of the layers of mix with the maximum strain values tolerated by a specimen of mix in the course of a laboratory fatigue test. In France, laboratory characterization is performed by means of a two-point bending test conducted on a trapezoidal specimen of bituminous mix to the top of which a continuous sinusoidal displacement is applied. The specimen is fixed at the bottom on a piece of steel by epoxy resin as shown in Figure A5.4. Failure is deemed to have occurred when the reaction force at the top of the specimen has been halved.

Figure A5.4. **The principle of the sinusoidal displacement test**



Source: Laboratoire Central des Ponts et Chaussées.

The laboratory fatigue test provides a means of determining the strain ε6 that leads to fatigue failure in a specimen under certain test conditions (frequency and temperature) after 1 million loadings. The result of this test provides the basis for the design of bituminous pavements in France and it is therefore of prime importance for a fatigue test to be indicative of real performance within a pavement.

The Fatigue test on trapezoidal specimen was performed on BBSG made with the conventional and epoxy asphalt binders. The results presented in Table A5.1 are shown in terms of ε6 and life duration at different imposed displacements.

Table A5.1. **Comparison of fatigue life between conventional and epoxy asphalt mixtures**

Sample	**Life duration (average value)**				**ε6**
Displacement level (µm)	**150**	**170**	**203**	**250**	
BBSG 0/10 – Epoxy-bitumen	–	–	11 436 000	2 856 000	267
BBSG 0/10 – 10/20 pen	1 031 400	457 500	250 200	–	147

The life duration obtained for the BBSG mix made with epoxy-bitumen indicate that the epoxy asphalt is superior to the conventional bitumen mix. While the epoxy asphalt exhibited an extremely larger fatigue life duration than the conventional mixture it does not necessarily correlate to an extremely larger fatigue life in the field and suggests a more relevant lab test or tests may be needed to confirm enhanced fatigue performance. The next section addresses several such tests.

A5.3.2 Fatigue up to Fracture Initiation

Direct axial, reversed tension-compression, cyclic loading can be used to evaluate an asphalt mixture's susceptibly to fatigue damage – see Figure A5.5. These tests were performed at 19oC on 150mm tall by 71mm diameter cylindrical specimens with specially designed grips and deformation characterization very similar in spirit to that advanced by other researchers [11].

As part of initial stages of fatigue characterization under the FHWA ALF research program, these tests were preformed on the epoxy asphalt and also the terminal blended crumb rubber mixture (CR-TB) from the ALF for comparison as well. This particular test applies a prescribed strain from platen to platen controlled by the actuator. Three external LVDTs are glued 120 degrees apart on the outer edge of the sample with the gauge length over the centre of the specimens height. The gauge length was the diameter of the sample, 75 mm.

The purpose of the external LVDTs is to measure strain in a more appropriate 'on-specimen' manner such that the strain over the centre portion of the sample is not influenced by edge effects from the restrained ends glued at the platens. Both the CR-TB and Epoxy asphalt mixture were controlled at a platen-to-platen strain level of about 1300 microstrains to target an on-specimen strain of 1 000 microstrains, corresponding to the mean transverse and longitudinal tensile strain level observed at the bottom of the Asphalt Concrete layer under the ALF. The CR-TB mixture achieved an on-specimen strain level of about 1 000 microstrains and fracture was induced in the specimen at about 6 200 loading cycles whereas the epoxy asphalt specimens achieved a strain level of only 250 microstrains. The fatigue hysteresis loops of the stress-strain for both the CR-TB and the epoxy asphalt mixtures are shown in Figure A5.6.

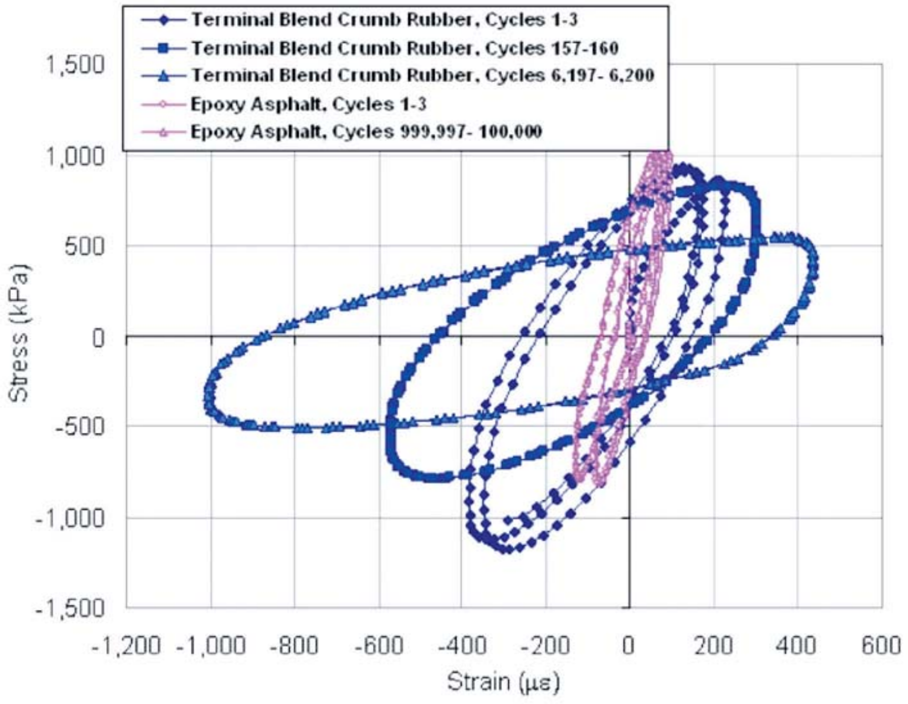
Figure A5.5. **Push-Pull Axial Fatigue Set-up**

Source: Materials and Construction Team, Turner-Fairbank Highway Research Center (United States).

The CR-TB experiences some fatigue deterioration at 6 200 loading cycles as noted by the changes in the hysteresis loop as the test progresses. On the other hand, the hysteresis loop of the epoxy mixture at 100 000 loading cycles is identical to that at the beginning of the fatigue test, which indicates from Figure A5.7 that the epoxy mixture is not showing any fatigue deterioration. Negligible reduction in stress was observed at 100 000 loading cycles. This indicates a significant strain is tolerated by the epoxy asphalt. However, it is difficult to make estimations of fatigue properties of the epoxy asphalt mixture when comparing it to the laboratory result of the CR-TB or its fatigue cracking performance under the ALF.

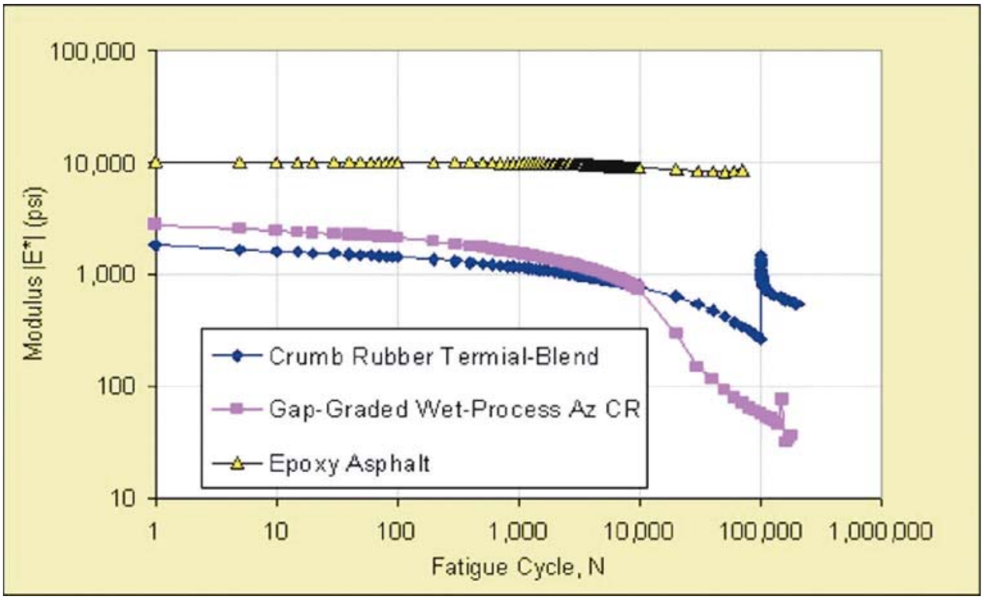
Figure A5.8 shows a plot of the cumulative crack length versus the number of ALF wheel passes for various reference mixtures [23]. Qualitatively, it can be said that the epoxy asphalt mixture should have fatigue performance better in magnitude than the polymer modified mixtures given that no damage can be ascertained in the mixture under 100 000 cycles of 250-microstrain loading; conditions under which non-epoxy asphalt mixtures normally sustain damage, *i.e.* any reduction in modulus. Much more intensive fatigue characterization continues with further laboratory experiments.

Figure A5.6. **Fatigue Hysteresis Loops of Epoxy Asphalt and Terminally Blended Crumb Rubber mixtures (Same Aggregate and Volumetric Properties)**



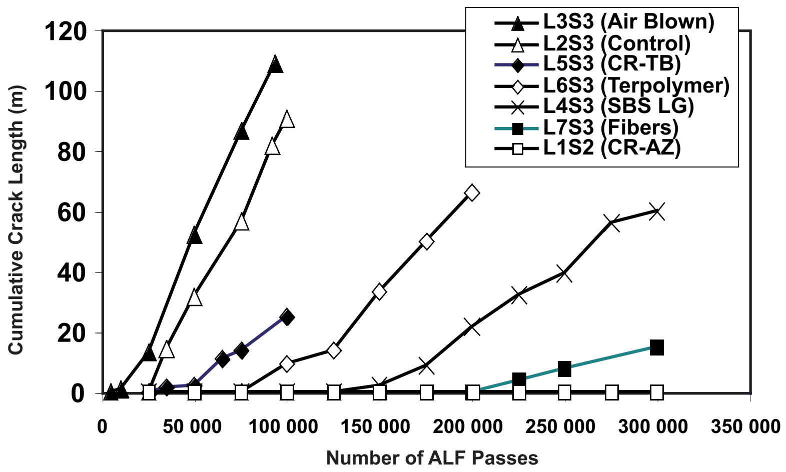
Source: Materials and Construction Team, Turner-Fairbank Highway Research Center (United States).

Figure A5.7. **Comparison of Push Pull Fatigue Results for Epoxy Asphalt and Crumb Rubber Modified Asphalts**



Source: Materials and Construction Team, Turner-Fairbank Highway Research Center (United States).

Figure A5.8. **Cumulative Crack Length vs. Number of Accelerated Loading Facility (ALF) Passes**



Source: Materials and Construction Team, Turner-Fairbank Highway Research Center (United States).

Indirect tensile (IDT) strength and resilient modulus tests were completed on the ALF reference mixtures used in the ALF trial (cores directly taken from the ALF lanes) and the epoxy asphalt mixture at 19oC. Fracture energy ratios [13] are the objective for this analysis. The fracture energy of the epoxy asphalt mixture essentially sustains until the point of fracture initiation. The total energy is calculated from the total area under the stress-strain curve. The fracture energy is less than the total energy and is calculated from the area enclosed by the stress strain curve rising up to the point of fracture initiation then returning to zero stress along a line at the slope of the resilient modulus of the mixture.

While strength values in the range of 550 to 1 350 kPa were achieved with the ALF polymer modified reference mixtures, the tensile strength of the epoxy asphalt mixture oxidised by heating reached the capacity of the test machine (a load of 5 000 lb) reaching a stress of 1 885 kPa without failure.

The maximum tensile strain reached in the epoxy asphalt mixture before reaching the machine load capacity was on the order of 865 microstrains whereas the reference mixtures reached fracture between 1 250 and 2 000 microstrains. This is consistent with tension-compression axial fatigue tests indicating that the epoxy asphalt can sustain larger stresses and strains before fracture localization appears in the mixture. This lends itself to, qualitatively, significantly better fatigue life and fracture properties than conventional modified and unmodified asphalt mixtures.

A5.4 Mixture Properties : Low Temperature Cracking Tests

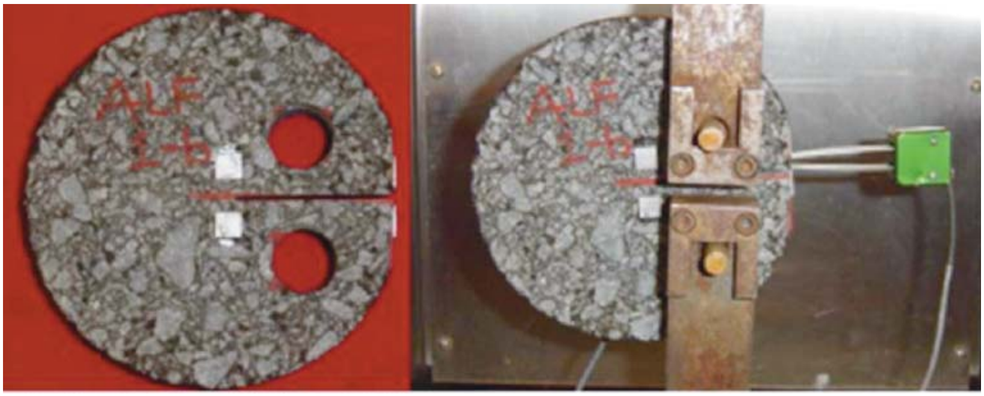
Three different laboratory characterization tests were performed on the epoxy asphalt mixture.

- TSRST.
- Compact Tension Tests.
- Semicircular Bending Tests.

Thermal Stress Restrained Specimen Tests (TSRST) were performed on the epoxy asphalt mixture following AASHTO TP 10-93 [14] as a means to understand the material's performance under extreme cooling events where low temperature thermal cracking becomes an issue. A cooling rate of 15°C/hr was used. The TSRST finding for epoxy asphalt mixtures shows a lower fracture temperature of -26°C. This is considerably lower than that expected from the Superpave binder criteria from m and S values which, based on m and S values, grade the unaged cured epoxy asphalt as PG X-10 (see section 4.3.2).

The disc-shaped compact tension test takes cues from established metal fracture test procedure and was pioneered in its application to asphalt by the work of Wagoner, Buttlar [15], and Paulino and Wagoner et al. [16]. An overview of the test specimen geometry is shown in Figure A5.9.

Figure A5.9. **Disc Shaped Compact Tension Sample and Test Configuration**

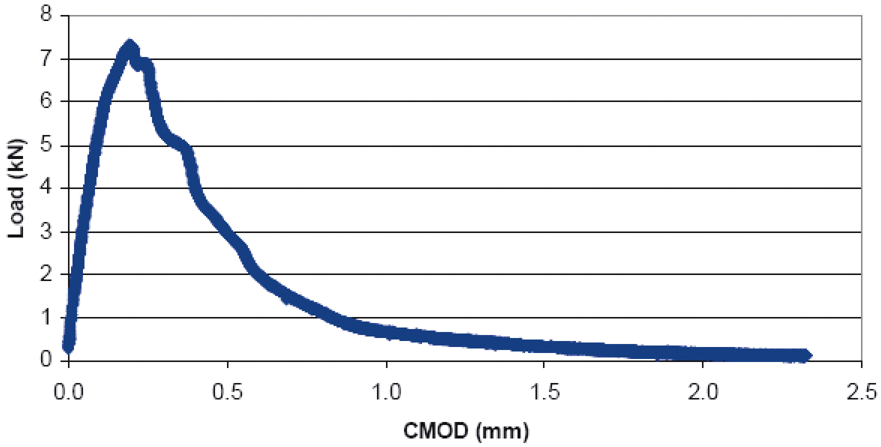


Source: Bill Buttlar, University of Illinois.

Fracture occurs as a pre-cut notch in the specimen is pulled apart. Load and crack mouth opening displacement are measured. The fracture energy is calculated as the area under the load-crack mouth opening displacement curve divided by the area of the fracture surface.

The tests were performed over a range of temperatures; typical test results showing the effects of loads on crack mouth displacement openings are shown in Figure A5.10.

Figure A5.10. **Typical Disc Shaped Compact Tension Test Data**



Source: Bill Buttlar, University of Illinois.

The tests are summarized in Table A5.2. As can be seen the fracture energy decreases with decreasing temperature. The magnitudes of the epoxy asphalt fracture energy at -18°C are compared to those from a field section studied by Wagoner *et al.* [16]. Mixtures with PG 64-22, PG 58-28, and PG 58-34 binder used in the different sections indicated fracture energies at -20°C of about 220 J/m^2 to 190 J/m^2 (PG 64-22 mixtures), about 305 J/m^2 (PG 58-22), and about 305 J/m^2 to 350 J/m^2 (PG 58-34).

The epoxy asphalt mixture at -18oC exhibited fracture energies on the order of 610 J/m^2, which is significantly larger than conventional mixtures indicating an indeed better resistance to low temperature thermal cracking. A proprietary, high-binder content, high-elasticity interlayer was used in the study and exhibited fracture energy of 1 400 J/m^2 at -20°C, but at -10°C the mixture did not truly fracture as a single crack did not propagate but smaller distributed cracking or blunting occurred ahead of the notch. Similar behavior was observed for the epoxy asphalt at relatively warmer temperatures. The tests are summarized in Table A5.2.

Table A5.2. **Test Results from Compact Tension Tests on Epoxy Asphalt Mixtures (Courtesy Bill Buttlar, UIUC)**

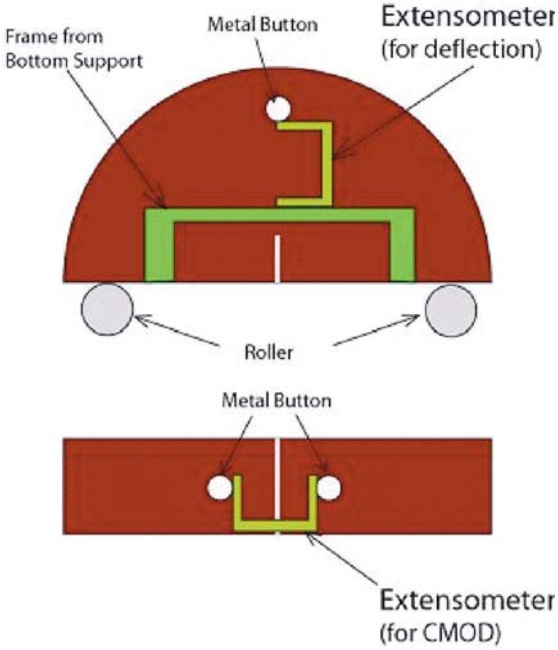
Test Temperature (°C)	Fracture Energy (J/m^2)	Peak Load (kN)	Notes
+19	Did not fracture, no data collected		
+10	4354.3	5.08	Crack mouth opening displacement gage reached maximum value stopped test early, one test.
-6	931.4	7.24	One sample hit load limit, had to restart test, did not include in this summary.
-18	610.9	7.74	Two good tests.

When the epoxy asphalt truly fractured the bond between the aggregate and the epoxy asphalt binder is very strong as indicated by the visual observation of the fracture face showing aggregate fracturing with little epoxy asphalt binder debonding from the bare face of stones.

The straight fracture of the epoxy asphalt indicated only Mode I or opening type of fracture occurred, which is important for performance prediction models.

Semicircular bending tests on asphalt concrete have recently been studied [17] to evaluate asphalt concrete's resistance to fracture at temperatures below -20°C. A schematic of the test is shown in Figure A5.11 where the specimen can be created from Superpave gyratory compactor specimens or field cores, much like the disc shaped compact tension specimen. A semicircular specimen is fabricated with a pre-cut notch.

Figure A5.11. **Schematic of Semicircular Bending Test**



Source: Mihai Marasteanu, University of Minnesota.

The specimen is loaded vertically in a direction parallel to the crack propagation. This is in contrast to the disc shaped compact tension test where the specimen is loaded perpendicular to the crack.

Based on the specimen size and geometry and the peak load, the critical stress intensity factor (fracture toughness) can be calculated.

From the load versus load line displacement the PG 64-28 asphalt concrete for temperatures of –30°C. SCB testing was also completed at -18°C.

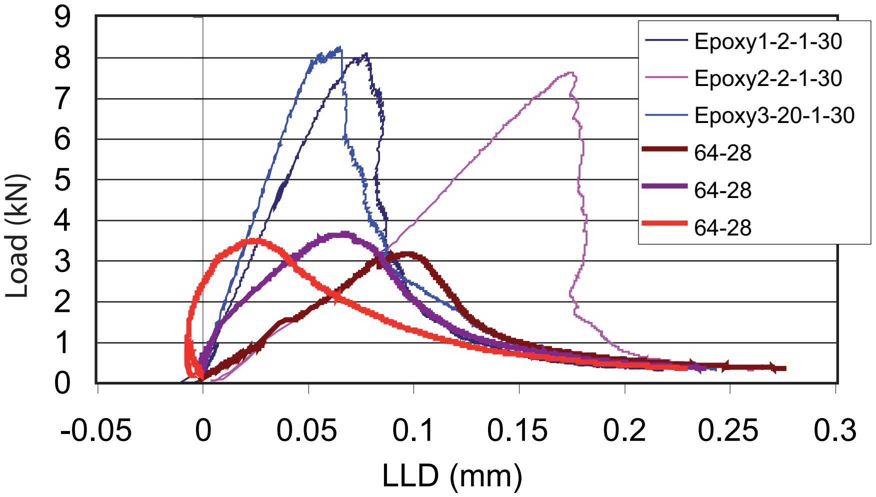
Test results are summarized in Table A5.3.

Table A5.3. **Summary of SCB Test Data (Courtesy Mihai Marasteanu, UMN)**

Temperature (°C)	**Mixture**	**Fracture Energy (N/m) [COV %]**	**Fracture Toughness, K_{IC} (MPa $=\overline{m}$) [COV %]**
-18	Epoxy Asphalt	690 [19%]	2.3 [10%]
-18	PG64-22	506 [22%]	0.92 [7%]
-30	Epoxy Asphalt	447 [14%]	2.4 [4%]
-30	PG64-22	274 [6 %]	1.0 [3%]

For the two mixtures compared, the fracture toughness tends to offer a more discriminative material property and less variation than the fracture energy, shown in Figure A5.12 which is also seen graphically amongst the three examples.

Figure A5.12. **Semicircular Bending Test Results at -30°C**



Source: Mihai Marasteanu, University of Minnesota.

These tests qualitatively support the findings of the other tests that epoxy asphalt mixture is much more resistant to low temperature thermal cracking than conventional asphalt concrete mixtures.

NOTES

1. See Chemco Systems web site for further details: http://www.chemcosystems.com/epoxy_faqs.html

APPENDIX B
(RELATES TO CHAPTER 7)

General long term needs in pavement research

Pavement construction of thin surface layers

The knowledge of quality and quantity characteristics of the process of dynamic loading of the pavement is crucial for dimensioning, operational use and current estimation of the condition of a road pavement.

The above mentioned issues define the need for research on the physical phenomena occurring in the pavement under the influence of impacts and vehicles moving along it.

Mechanical waves propagating inside the pavement cause variable stress and strain conditions generating mini fatigue effects of the materials in particular pavement layers.

The results of dynamic actions depend not only on stiffness moduli and expansion coefficients of pavement materials, but also to a significant extent on such parameters as:

- Velocity of propagation of waves in layers.
- Poisson's ratio.
- Wave impedance.
- Inter-layer connections.
- Friction coefficient between a wheel and the pavement.

The influence of the above mentioned factors on the pavement needs to be understood and requires future research.

The factors which have a qualitative and quantitative influence depend on the design method of the structure of the layered pavement, characteristics of used materials, technology of their production and also on appropriate construction of the pavement.

Elaboration of new methods to design diagnostics and new construction technologies and their implementation require extensive research in the field of modeling, description and methods to solve the thermo-mechanical subjects in the layered pavements.

Continuing research is required on new materials for pavement construction, directed towards practical evaluation of not only the basic parameters (e.g. elastic moduli) but also of other material characteristics having important effects, such as Poisson's ratio, velocity of waves inside the pavement (mass density) etc.

Such research will allow the development and construction of pavements with optimal features adjusted to real traffic loads, water-soil conditions and ambient conditions.

APPENDIX C

LABORATORY TEST REPORTS PUBLISHED ON THE JOINT TRANSPORT RESEARCH CENTRE WEBSITE

General

In the course of the research and testing, Epoxy Asphalt and HPCM Group members were encouraged to prepare Laboratory Test Reports as a basis for sharing the results of their research with other Group members and staff in each participating national laboratory.

The Long Life Pavements Editorial Group agreed that these Laboratory Test Reports should be published but decided that they could not be published in this Report – for reasons of space, cost and the desirable length of the report.

Instead, it was agreed that they should be published on the Joint Transport Research Centre's website.

Final versions and titles of all the Laboratory Test Reports were not available at the time the English version of this Report was finalised and sent for translation.

Epoxy Asphalt Laboratory Test Reports

A complete listing of the *Epoxy Asphalt Laboratory Test Reports* is available on the Joint Transport Research Centre's website, at the following address:
www.internationaltransportforum.org/infrastructure/index.htlm

Copies of all these Laboratory Test Reports will be posted to the JTRC's public web site, so they are available for consultation and downloading after this Report is published.

HPCM Laboratory Test Reports

A complete listing of the *HPCM Laboratory Test Reports* is available on the Joint Transport Research Centre's website, at the following address:
www.internationaltransportforum.org/infrastructure/index.htlm

Copies of all these Laboratory Test Reports will be posted to the JTRC's public web site, so they are available for consultation and downloading after this Report is published

Participating Organisations

Working Group members and National Laboratories in each country that coordinated and/or participated in the laboratory testing are listed in Annex B and Annex C to this Report.

ANNEX A

LIST OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
ALF	Accelerated Loading Facility
APT	Accelerated Performance Test
BASt	Bundesanstalt für Strassenwesen (German road research institute)
BBTM	Very Thin Bituminous Pavement Material
BBR	Bending Beam Rheometer
BBSG	Semi Coarse Bituminous Pavement Material
CAPTIF	Canterbury Accelerated Pavement Testing Indoor Facility(New Zealand)
CTE	Coefficient of Thermal Expansion
DART	Danish Asphalt Rut Tester
DBM	Dense Bitumen Macadam
DerzhdorNDI	Ukraine State Road Scientific Research Institute
DRI	Danish Road Institute
DSR	Dynamic Shear Rheometer
DTT	Direct Tension Test
FHWA	Federal Highway Administration (US)
FPRT	French Pavement Rutting Tester
HMA	Hot Mixed Asphalt
HPCM	High Performance Cementitious Material
HRA	Hot Rolled Asphalt
LCPC	Laboratoire Central des Ponts et Chaussées (French Road Research Institute)
LVDT	Linear Variable Differential Tranducers
MSA	Million Standard Axles
OGPA	Open Grade Porous Asphalt
PCC	Portland Cement Concrete
PG	Performance Graded
PTF	Pavement Test Facility (ALF machine at TRL)
PVA	PolyVinyl Alcohol
RAP	Recovered Asphalt Pavement
SBS	Styrene Butadiene Styrene (an asphalt modifier)
SHRP	Strategic Highway Research Programme
SMA	Stone Mastic Asphalt
SRT	Skid Resistance Tester (also known as the "pendulum")

SWPE	Scott Wilson Pavement Engineering (English company)
T2R	LCPC device used to evaluate shear stress resistance in asphalt mixes
TFHRC	Turner Fairbank Highway Research Centre (US road research institute)
TRL	Transport Research Laboratory (UK transport research institute)
UHPC	Ultra High Performance Concrete
UV	Ultra Violet

ANNEX B

JOINT OECD/ITF TRANSPORT RESEARCH CENTRE PROJECT ECONOMIC EVALUATION OF LONG-LIFE PAVEMENTS: PHASE II

Working Group Members

A number of countries participated actively in the Phase II project with a high level of involvement of their Working Group members and active involvement of their national testing laboratories viz: Australia, Denmark, France, Germany, New Zealand, Ukraine, United Kingdom, United States.

The following is a listing the most active group of countries and Working Group members:

Country	Working Group Members
Australia	Mr. George VOROBIEFF NSW Roads and Traffic Authority (RTA)
Denmark	Mr. Jørgen CHRISTENSEN Chair of the Working Group and the Editorial Group Danish Road Institute (DRI) Mr. Anders HENRICHSEN Danish Concrete Company (Dansk Beton Teknik) Mr. Erik NIELSEN Danish Road Institute (DRI) Finn THOEGERSEN Danish Road Institute (DRI)
France	Dr. François DE LARRARD TECHNICAL COORDINATOR, HPCM GROUP Laboratoire Central des Ponts et Chaussées (LCPC) Ms. Nelly VULCANO-GREULLET Laboratoire Régional des Ponts et Chaussées (LRPC Autun) Mr. Ferhat HAMMOUM Laboratoire Central des Ponts et Chaussées (LCPC)
Germany	Mr. Stefan LUDWIG Federal Highway Research Institute (BASt) Miss Nina SLIWA Federal Highway Research Institute (BASt)
New Zealand	Greg ARNOLD Transit New Zealand Phil HERRINGTON Consultant to Transit New Zealand Opus Central Laboratories
Poland	Dr. Miroslav GRACZYK Road and Bridge Research Institute (IBDiM)

Ukraine	Ms. Tatiana HIMERIK State Road Scientific Research Institute (DerzhdorNDI) Ms Kateryna KRAYUSHKINA State Road Scientific Research Institute (DerzhdorNDI) Valery VYROZHEMSKY State Road Scientific Research Institute (DerzhdorNDI)
United Kingdom	Mr. John CHANDLER Transport Research Laboratory (TRL) Ltd Mr. Richard ELLIOTT Scott Wilson Pavement Engineering Mr. Wyn LLOYD UK Highways Agency
United States	Dr. Jack YOUTCHEFF Technical Coordinator, EA Group Turner Fairbank Highway Research Center Federal Highway Administration
OECD/ITF Secretariat	Mr. John O. WHITE Joint OECD/ITF Transport Research Centre Mr. Ceallach LEVINS OECD Consultant, Londonderry

Editorial Group Members

The following were members of the Editorial Group that finalised the draft Report:

Country	Editorial Group Members
Denmark	Mr. Jørgen CHRISTENSEN Chair of the Working Group and the Editorial Group Danish Road Institute (DRI) Mr. Anders HENRICHSEN Danish Concrete Company (Dansk Beton Teknik)
France	Dr. François DE LARRARD TECHNICAL COORDINATOR, HPCM GROUP Laboratoire Central des Ponts et Chaussées (LCPC)
United Kingdom	Mr. Wyn LLOYD UK Highways Agency
United States	Dr. Jack YOUTCHEFF Technical Coordinator, EA Group Turner Fairbank Highway Research Center, Federal Highway Administration
OECD/ITF Secretariat	Mr. John O. WHITE Joint OECD/ITF Transport Research Centre

External Reviewers

The following two experts accepted a request from the Editorial Group to act as External Reviewers of the draft Final Report.

Canada	Mr. Michael F. OLIVER Ministry of Transportation
Finland	Mr. Heikki JÄMSÄ Finnish Asphalt Association

Other Working Group Members

Working group members nominated by a number of countries who participated less actively or by correspondence and/or whose laboratories were not involved in laboratory testing, were:

Austria	Professor Johann LITZKA Technische Universität Wien Institut für Strassenbau und Strassenerhaltung
Australia	Mr. David MANGAN Southern Australian Asphalt Pavement Association Mr. Kieran SHARP ARRB Transport Research Ltd
Belgium	Ms. Anne BEELDENS Belgian Road Research Centre
France	Mr. Jean-Michel PIAU LCPC Mr. Thierry SEDRAN LCPC
Greece	Dr. Andreas LOIZOS National Technical University of Athens (NTUA)
Italy	Mr. Mario ARATA ANAS S.p.A.
Japan	Mr. Masahide ITO Public Works Research Institute
New Zealand	Mr. David ALABASTER Transit New Zealand
Poland	Professor Dariusz SYBILSKI Road and Bridge Research Institute, Warszawa
Portugal	Mrs. Helena Maria LIMA Instituto de Estradas de Portugal (IEP)
Russian Federation	Mr. Nikolay BISTROV State Moscow Automobile and Highway Technical University (MADI)
Sweden	Dr. Marianne GRAUERS National Road and Transport Research Institute (VTI) Mr. Safwat SAID National Road and Transport Research Institute (VTI)
Switzerland	Mr. Markus CAPREZ Swiss Federal Institute of Technology (ETH)

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These surfaces use new materials that cost more than conventional asphalt and require special handling.

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