Long-Life Asphalt Pavements

Technical version

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Content

1. Introduction

An important goal in the pavement industry is to provide constructions at ever lower life-cycle costs, a goal requiring continuous development in areas such as design, material characterization and production, as well as maintenance techniques and management. During the last couple of years, the concept of Long-life pavements[1] (LLP) has been established in Europe and America. The main purpose of this concept is to develop a framework, in which more cost-effective pavements are produced. The LLP-concept is to some extent based on earlier concepts, such as full-depth, stage-by-stage and deep-strength designs, but mainly on more recent advances in material technology, design and functionality. In practice, the intention of the LLP-concept is to significantly extend current pavement design life by restricting distress, such as cracking and rutting, to the pavement surface. Common distress mechanisms such as bottom-up fatigue cracking, rutting in the unbound layers and frost heave should, in principle, be completely eliminated.
When the availability of road lanes and the road user delay costs are taken into account in the cost-benefit analyses of pavements it will show that a number of highways in densely populated areas require low maintenance pavements. That means a total reconstruction of a road pavement is hardly possible or even impossible.
This is one of the reasons for developing the Long-Life Pavement concept.

The purpose of this paper is to provide a state-of-the-art review of developments in long-life asphalt pavements.

1.1 Background

All elements of long-life pavements are not by any means new and some have been circulating in different forms for a considerable time. For example, several countries have utilised so-called full-depth asphalt pavements consisting of relatively thick bitumen-bound layers directly constructed on the sub-grade or placed on relatively thin granular base courses. One of the main arguments for this type of design is that the overall pavement thickness can be kept relatively thin compared to conventional designs consisting of relatively thin bitumen-bound layers on relatively thick granular layers. In addition to this obvious advantage, during the years it has been recognized that full-depth and deep-strength pavements often have shown design lives significantly longer than initially expected [1.]. Similar experiences to those mentioned have been recognised in the UK, where investigations on motorways suggest that fatigue cracking and structural deformation are not prevalent in pavements which are constructed with sufficient strength (above a certain level). The main conclusions suggest that well-constructed flexible pavements show very long service lives provided that distress mechanisms such as rutting and cracking are confined to the pavement surface, which significantly facilitates maintenance [2. and 3.].

During 1998/1999, the Conference of European Directors of Roads (CEDR) declared, as suggested by the UK Highways Agency, that so-called Long-Life Pavements were an appropriate area for co-operative research. Subsequently, a working group called

[1] It should be emphasised that the term *long-life pavements* given in this paper is a collective name incorporating many of the features shared by concepts such as perpetual, long-lasting, heavy duty and maintenance free pavements.

ELLPAG (European Long-Life Pavement Group) was established as a focal group for determining the way forward. The objectives of ELLPAG include producing state-of-the-art reports on European knowledge on the design and maintenance of long-life pavements. In the long run, a user-friendly comprehensive Best Practice guidance document for all types of pavements is intended to be produced [4.].

In the USA, the concept termed "Perpetual pavements" has rapidly gained acceptance following workshops on the concept held in the first years of the new millennium. One of the publications arising from these is a synthesis published by the Asphalt Pavement Alliance (APA), a coalition of the National Asphalt Pavement Association (NAPA), the Asphalt Institute (AI) and the State Asphalt Pavement Associations (SAPA) [5.]. Relevant material presented at the Transportation Research Board (TRB) Annual Meeting in 2001 was published in Transportation Research Circular 503 "Perpetual Bituminous Pavements" [6.]. This long-life approach aims at extending the 20-year life expectancies of hot-mix asphalt pavements to greater than 50 years [6.]. The term Perpetual Pavements is to some extent a rewriting of long-life pavements, but focuses on resisting specific distresses in the each bound layer. In this case, the surface course, binder course and base courses are selected, designed and performance tested in accordance with deterioration mechanisms such as permanent deformation and fatigue cracking. In addition to long-life and perpetual pavements, several other approaches have been used, each comprising different parameters and techniques.

As indicated in this section, the long-life concept is not a single coordinated drive towards improved pavements. The common feature among different approaches within the long-life pavement concept described here is the objective to gather knowledge regarding design, material characterization and production, as well as maintenance techniques and management methods to produce pavements with long life in order to achieve low life-cycle costs. Consequently, even though the long-life concept may appear homogenous, many significant differences arise between different organisations and researchers regarding design, material selection and production methods. In addition to the two approaches mentioned (long-life pavements and Perpetual Pavements, respectively), some countries, including France, Germany, USA and the UK, already permit design periods in excess of the frequently used 20 years [4.]. However, it should be emphasised that in Europe, solely the UK states that their pavements are designed for 40 years [4.]. In countries such as the Netherlands, flexible pavements of motorways are designed in such a way that structural damage will be avoided. In the past they used the "Stage-by-stage" concept; the existing pavement was overlaid to become a long-life-pavement. Now the structural design is based on long life taking into account expected functional use of the road. In the Netherlands the traffic intensities are very high and therefore the disruption to traffic has to be avoided. The availability of the road is of utmost importance. The repair of structural damage is too costly and too time consuming. In other countries, e.g. France, pavement design life is guided by an economic strategy, which usually is carried out over 30 years. Since most countries possess national pavement design methods, based on local materials and local experience, only a general strategy for long-life pavement design and construction will be described in this document.

1.2 Definition

In the literature several definitions of long-life pavements have been given. In the USA, perpetual pavements has been closely connected to thick asphalt pavements comprising a three-layered asphalt pavement including a wear-resistant and renewable top layer, a rut-resistant and durable intermediate layer and a fatigue-resistant and durable base layer [6.]. This concept represents an operational definition, or example of a long-life pavement, but it restricts long-life pavements to a certain design. The synthesis presented by the Asphalt Pavement Alliance (APA) defined a perpetual pavement as an asphalt pavement designed and build to last longer than 50 years [5.].

ELLPAG [4.] uses a similar functional definition:

> *A long-life pavement is a type of pavement where no significant deterioration will develop in the foundations or the road base layers provided that correct surface maintenance is carried out.*

The ELLPAG definition above came from the intention to avoid limiting the concept to a specific life (e.g. 30, 40 or 50 years), which has done in some studies (e.g. [7., 3. and 1.]). In this paper, the functional definition of ELLPAG has been adopted, which consequently implies that all pavement layers, except the surfacing, are considered as permanent. To maintain the overall objective, it is necessary to successively monitor pavement performance in order to ensure that all distress mechanisms are limited to the surface layer.

Figure 1 illustrates how the goals of the LLP-concept can be approached. The figure illustrates important quantitative components which have been identified by researchers to achieve long-life performance. In addition to the guiding components, some requisites are important to consider when designing a LLP. Pavement network funding normally comes from the government by budget allocations and effective network management requires that the budget levels are at least sufficient to keep the core road assets in stable condition in the long term. In the case of LLP, the expected increased construction costs associated with improved materials and construction constitute financial restraints even though lower life-cycle costs are obtained in time (see Section 3). In addition, the final design of a LLP depends on local conditions such as sub-grade type, present and future traffic volumes and materials available. From these so-called prerequisites, the ultimate goal of low life-cycle costs can be obtained based on optimizing maintenance activities, delay and environmental costs.

Figure 1. Prerequisites, components and goals of long-life pavements concepts

Prerequisites	**Components**	**Goals**
• Sufficient financing • Knowledge regarding local conditions - *Subgrade types* - *Traffic volumes* - *Available materials*	• Design - *Design life, e.g.>40 years* - *Conservative design criteria* • Performance specifications - *Wear-resistant top layer* - *Rut-resistant layers* - *Fatigue-resistent base course* • Periodical resurfacings	• Low life-cycle costs - Few maintenance activities - Low delay costs - Low environmental costs

2. Construction of new pavements

Today, most countries regard the public road transportation system as an essential pre-condition for economic development and welfare. It is therefore important that the asset is managed professionally through all stages including design, construction and maintenance.

2.1 The pavement structure

A flexible pavement consists of the road structure above the formation level, which normally comprises bitumen-bound and unbound materials. The pavement structure should be able to resist the traffic and environment to which it will be exposed in such a way that structural distress mechanisms are avoided. Normally, pavements are designed as layered structures with relatively low strength in the lower layers and materials with progressively increasing strengths towards the top (see Figure 2). The rationales for this arrangement are both technical and economic.

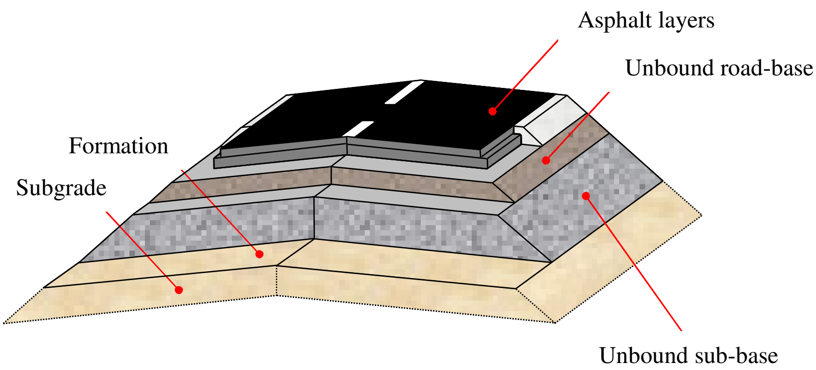

Figure 2. Schematic illustration of flexible pavement structure.

In general, the asphalt layers are laid on a bound or unbound road base layer. Starting at the road surface, the first layer is called the surface course. The second layer is the binder course and the lower layers are the base courses.
For a good bearing capacity of the whole road structure it is important that there is a good bond and interlock between all the (bituminous) bound pavement layers and a good interlock between the unbound pavement layers. It of course also applies to the interlock between the first asphalt layer and the unbound base beneath it.
For the durability of the asphalt structure, it is also essential to have a good bond between the asphalt layers that can avoid water penetrating between asphalt layers.

2.1.1 Surface course

The surface course constitutes the top layer of the pavement and should be able to withstand high traffic- and environment-induced stresses without exhibiting unsatisfactory cracking and rutting in order to provide an even profile for the comfort of the user and at the same time possessing a texture to ensure adequate skid resistance. Depending on local conditions, functional characteristics such as skid resistance, noise reduction and durability are often required for surface courses. In some cases, rapid drainage of surface water is desired through a porous surface while in other cases the surface course should be impermeable in order to keep water out of the pavement structure. As indicated, the surface layer is important for the pavement performance but no single material can provide all the desired characteristics (e.g. porous and impermeable at the same time). A wide range of surface layer products can therefore be considered appropriate depending on specific requirements:

- Asphalt Concrete (AC)
- Béton Bitumineux Mince (Thin Layers Asphalt Concrete – AC-TL)
- Asphalt Concrete Very Thin Layers (AC-VTL)
- Ultra Thin Layer Asphalt Concrete (UTLAC)
- Stone Mastic Asphalt (SMA)
- Hot Rolled Asphalt (HRA)
- Porous Asphalt (PA)
- Double layered Porous Asphalt (2L PA)
- Mastic Asphalt (MA)
- Soft Asphalt (SA)

In the end, the selection of the surface course is a matter of identifying the most appropriate material during the design process. The functional requirements can conflict. For example, noise reduction could require the use of a double-layered porous asphalt and that conflicts with the requirement of a very durable surface layer. The durability of surface layers can be improved by using higher quality materials. The higher costs of these will be compensated by the lower costs of traffic measures and user costs.
In Appendix A the durability of these surface layers is shown.

2.1.2 Binder course

Under the assumption that a particular layer solely is subjected to a mode of deterioration, long-life pavements are usually designed by preventing permanent deformation in the bound layers using an appropriate binder course. Binder courses are frequently adopted on the assumption that the highest shear stresses will occur about 50 – 70 mm below the asphalt surface. The binder course is therefore placed between surface course and base courses to reduce rutting by combining qualities of stability and durability. Stability can be achieved by sufficient stone-on-stone contact, combined with stiff and/or modified binders.

2.1.3 Base course

The base course is perhaps the most important structural layer of the pavement, which is intended to effectively distribute traffic and environmental loading in such a way that underlying unbound layers are not exposed to excessive stresses and strains. This often implies comparatively high stiffness of the base course. However, following the principle of performance-specific design of each layer, the base course should primarily show adequate fatigue resistance. Consequently, it is often assumed that for an asphalt mixture, there exists incompatibility between stiffness and fatigue-resistance. This assumption is based on the fact that a stiff base course can be obtained using either relatively course aggregate or stiff bitumen, which both increase the sensitivity to high strain levels [8.]. In principle, a base course material is affected by all material-related factors including grading, additives as well as air void and binder contents. In practice, relatively fine grading [9.], low void content [10.] and high binder contents are strived for. According to APA [5.], there are several possible strategies to achieve a base course exhibiting long-life characteristics. One approach to ensure good fatigue life, as determined by a given laboratory test and a given pavement construction, is to restrict the tensile strain at the bottom of the base course below a certain fatigue limit, under which no damage develops. However, the identification of such a limit is in practice very difficult.

2.1.4 Unbound materials and foundation

Since the formation and sub-soil often constitute relatively weak materials, it is of utmost importance that the applied loadings are effectively eliminated by the layers above. Especially, high vertical strains may require relatively thick layers. In this case, unbound road-base or sub-base layers consisting of uncrushed aggregate or crushed aggregate can be suitable. Generally, unbound materials originate from locally available sources, such as native soil, crushed/uncrushed granular materials and re-used (secondary) material. The type and thickness of the unbound materials used for the unbound road base layers technically depend on the structure to be designed (traffic loading) and the stiffness of the sub-grade. In some countries, climatic conditions may also require relatively thick pavement structures in order to avoid frost-related heaves. Furthermore, economic factors, such as availability and transportation costs, also have a significant impact on the amount of unbound materials desired in a pavement. In some cases adequate bearing capacity can be achieved using different stabilization techniques. For example, different types of cement- or lime-stabilization can be used to improve clays.

2.2 Design

Today, pavement design is normally represented by so-called semi-mechanistic methods, implying that they partly are based on fundamental engineering principles. Semi-mechanistic procedures consist in principle of a structural response model and associated performance models (see Figure 3). Response models relate traffic loading to stresses and strains in the pavement structure, while performance models relate calculated stresses and strains to rate of deterioration. As indicated in Figure 1, the actual design life is an essential feature of the LLP-concept. In most European countries, a design life of 20 years is adopted. Only in the UK is it explicitly stated that pavements should be designed for 40 years when economically viable [4.].

Even though a number of potential deterioration mechanisms exist, the two main distresses considered in semi-mechanistic methods are rutting, originating in the sub-grade, and fatigue cracking, initiated in the bottom of the asphalt layer. Structural rutting originating at the sub-grade is considered by limiting the compressive strain induced at the top of the sub-grade, normally as a function of the expected number of load applications during the design period and the thickness and stiffness of the pavement layers. These two traditional design criteria were originally based on laboratory testing and field performance of pavements whose layers were relatively thinner than pavements designed for current relatively high traffic levels.

According to a recent European investigation [11.], the importance of traditional fatigue cracking and rutting in the sub-grade is nowadays questionable. In this investigation, fatigue cracking and rutting in the sub-grade were only considered to be ranked as numbers 6 and 9, respectively. Other deterioration mechanisms such as rutting in the bituminous layers and surface-initiated cracking were considered far more important: ranked as number 1 and 2, respectively. However, even though distress mechanisms associated with cold climate such as frost heave, wear due to studded tyres and low-temperature cracking, achieved low ranking (number 10, 11 and 12, respectively), they may be significant in some countries such as Sweden.

In contrast to traditional fatigue cracking and rutting in the sub-grade, the other deterioration mechanisms (such as rutting in the bituminous layers, crack initiation in the surface layer), are difficult to address in (the 'old') semi-mechanistic design methods. One way of including these mechanisms is therefore to prescribe functional demands using different simulation methods (functional laboratory tests).

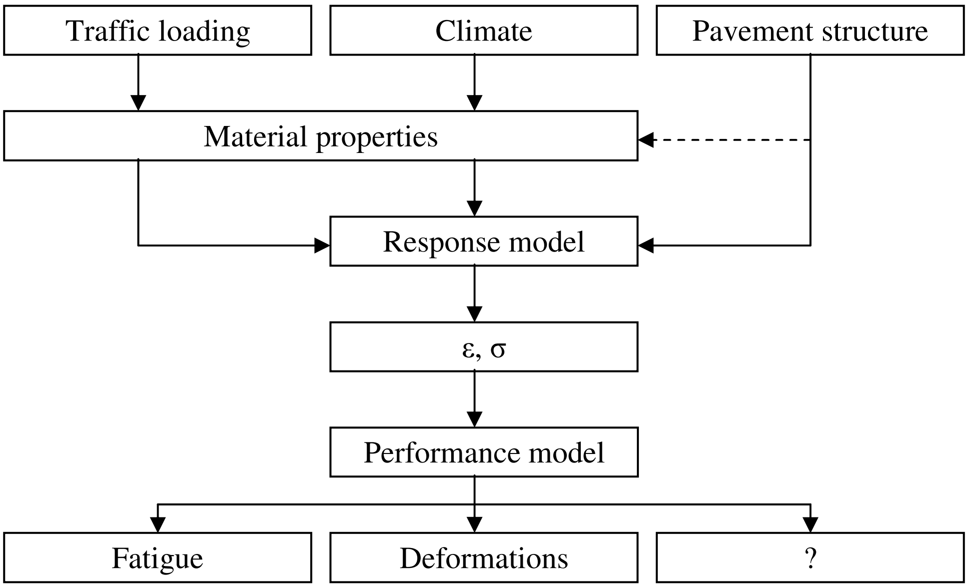

Figure 3. Schematic illustration of semi-mechanistic design method.

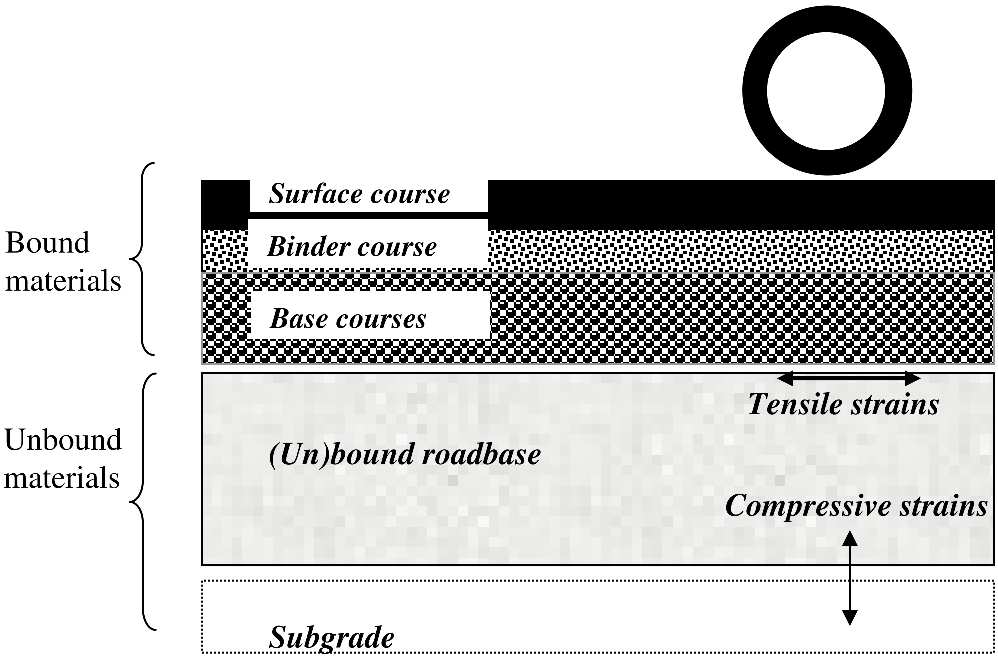

Figure 4. Example of pavement structure and the two traditional design criteria.

In general, deterioration, such as fatigue, is within the semi-mechanistic framework generally obtained from laboratory testing, which is assumed to represent field conditions. Fatigue testing is usually performed by applying a cyclic loading (strain- or stress-controlled), often at a given test temperature and frequency, to an asphalt mixture specimen. The fatigue results obtained at laboratory testing are subsequently related to the strain response obtained from the structural model. Consequently, the life of a given pavement structure subjected to repetitive traffic loading can be calculated when the strains in the structure as well as the relationship between the strains and deteriorations have been established.

2.2.1 Fatigue cracking

Fatigue is one of the main distress mechanisms considered in flexible pavement design and is generally considered to be caused by excessive tensile strains due to repetitive traffic loading. The loading results in growth and coalescence of pre-existing or initiated microscopic defects, which finally cause the asphalt layer to crack. Eventually, the entire bearing capacity of the pavement structure may be jeopardized. An increased asphalt thickness reduces the traffic-induced strains in the bottom of the bituminous base layer and, consequently, increases the fatigue life.

In principle, the design philosophy of long-life pavements does not differ significantly from traditional semi-mechanistic design methods. However, due to the aim of restricting structural deterioration to the pavement surface, conservative design criteria should be employed. In the UK, the design traffic for 40 years is determined in a similar manner to that of a 20 year life with enlarged traffic multiplier to account for the greater growth in traffic over the extended period. Pavements design above a traffic level of 80 million standard axles (80 kN) are said to be designed as long-life pavements [4.]. The rationale for this traffic level is supported by empirical and analytical studies [2. and 4.].

In order to eliminate structural deterioration, some investigations have suggested that conventional transfer functions (i.e. performance models, cf. Figure 3) should be replaced by explicitly expressed conservative thresholds for allowable strain values. For example, Monismith and Long [12.] suggested that the maximum tensile strain at the bottom of the asphalt layer should be restricted to 60×10^{-6}. It should be emphasised that the threshold level given by Monismith and Long may not be universally applicable since they are derived using a given pavement system, design method, bituminous mix and laboratory test equipment. However, in principle it should be possible to derive corresponding threshold values for other pavement configurations and values in the range of $50\text{-}70\times10^{-6}$ m/m have been reported as fatigue thresholds [13., 14. and 15.]. For the sake of convenience, it should be emphasised that any design parameter and criterion given should not be taken out of context since they are closely linked to a specific design guide and testing method used.

2.2.2 Permanent deformation

The other major deterioration mechanism considered in semi-mechanistic design is rutting, originating in the sub-grade. As in the case of fatigue cracking (see Section 2.2.1), most semi-mechanistic methods are equipped with performance models for calculating permanent deformations using transfer functions.

In order to eliminate structural deterioration, some investigations have suggested that conventional transfer functions (i.e. performance models, see Figure 3) should be replaced by explicitly expressed conservative thresholds for allowable strain values.

For example, Monismith and Long suggested that the maximum vertical compressive strain at the top of the sub-grade should be restricted to 200×10^{-6} m/m.

2.2.3 Other mechanisms

Traditionally, fatigue cracking has been viewed as initiated in the bottom of the asphalt layer to propagate up through the layer (bottom-up cracking). However, there are other forms of fatigue-related cracking than traditional bottom-up cracking, such as *reflective cracking*. The latter deterioration mechanism is caused by repetitive shearing, e.g. when a new asphalt layer is laid upon an already cracked layer. With time, the crack will propagate through the new layer. A third type of fatigue is *surface initiated (top-down) cracking*. This type of fatigue cracking is considered to be caused by a complex combination of pavement structure, load spectra and material characteristics. Even though still disputed, this deterioration mechanism motivates a certain fatigue-resistance of the surfacing. In addition to fatigue cracking and rutting, some semi-mechanistic methods also take *low-temperature cracking* and *frost heave* into account. Another deterioration mechanism which should be accounted for is *ageing*. This distress mainly affects the bituminous layers and is manifested by increased stiffness and decreased flexibility. According to Nunn et al [2.] a road is more susceptible in its early life before the structural properties have been increased by curing. In this case, curing implies increased bearing capacity due to gradual increase in asphalt stiffness. However, whether or not increased stiffness is desirable depends on whether, or not, the stiffening extends pavement life and lowers overall life-cycle cost. In certain cases, it is not unlikely that ageing will result in low temperature cracking but also complicates recycling. Consequently, it will in many cases be desirable to minimize ageing by reducing the air void content of the mixture.

A common denominator of the distress mechanisms mentioned in this section is that they are difficult to take into account using semi-analytical methods. Some of the distresses are considered to require more advanced response and/or performance models (see Figure 3). In the case of top-down cracking and permanent deformations in the bitumen-bound layers, new and improved design methods may take this into account in the future.

However, functional demands may be used to take these mechanisms into account. For example, the adequacy of a binder course can be evaluated using a simulation method. If a material shows superior resistance against a certain distress mechanism simulated by the test it may be judged appropriate to be used in the design.

2.2.4 Improved design methods

Today, there are several design methods available for pavement design.
At the National Center for Asphalt Technology (NCAT) at Auburn University in conjunction with the Asphalt Pavement Alliance (APA) a procedure was developed for the mechanistic-based design of flexible long-life or perpetual pavement structures. This is a program called PerRoad. [19.]

The design software utilizes layered elastic theory to compute critical pavement responses under axle load spectra. Monte Carlo simulation is used to model the uncertainty corresponding to material, loading and construction variability. The program can be used as a design and analysis tool to assess the likelihood that critical pavement responses will exceed a threshold set by the analyst. Additionally, transfer

functions may be used to determine a damage accumulation rate for pavement responses exceeding the threshold.
This software uses "U.S. customary units, commonly known in the United States as English units"**.**

2.3 Construction

Like traditional pavement construction, the construction of LLP should at least be executed in accordance with public requirements. In this case, technical and functional requirements on LLP should in general be higher compared to traditional pavements. One way of ensuring higher quality is to prescribe functional demands instead of technical specifications. This emphasises the contractor's roll in achieving long-life performance compared to when technical specifications are used. When functional demands are used, it is up to the contractor to show that a solution meets the requirements. At least two benefits can be identified:- improved flexibility, meaning that several solutions may be considered, and an increased concern from the contractor to optimize the production, e.g. compaction.

The transportation of the asphalt mixture from the asphalt plant to the construction site is important for the durability of the pavement. During transport the temperature of the asphalt mixture should not drop too much and one should be aware of possible segregation. During transportation there could occur temperature segregation and/or mixture segregation. Material Transfer Vehicles that remix the mixture could be used to avoid temperature and mixture segregation. Adequate quality control during construction is essential too. In this way all the relevant issues will be monitored.

One of the most important construction-related aspects is mixture composition. An optimal recipe should result in a homogenous material structure which facilitates adequate compaction. Results presented in [7, 21] indicate that 3 percent more compaction results in 15 percent less thickness needed due to improved fatigue behaviour (in this case 8% air voids versus 5% air voids). Low void and high binder contents will also improve fatigue characteristics as well as enhance resistance against moisture-related damage, which is important since the base course layer often is in prolonged contact with water. Perhaps the most advocated material-related improvement is to modify the bitumen using different polymers. Many studies have indicated that polymer modified bitumen produces pronounced improved fatigue behaviour of a given mixture type (e.g. [16.]). The combination of a thick well-constructed pavement and a fatigue-resistant base course is considered sufficient to guard against traditional fatigue cracking.

In the context of long-life pavements, it is still necessary to periodically replace the surface course in order to fulfil the aim of avoiding structural deterioration. In the UK, two quite different routes have occurred [2.]. In order to improve durability, thicker asphalt layers have been introduced in order to achieve improved compaction. On the other hand, UK has experienced an increased interest in the use of relatively thin hot-mix surface courses (Thin Layers of Asphalt Concrete). Investigations on motorways in the UK have suggested that fatigue and structural deformation do not occur in pavements which have been constructed with sufficient strength to resist structural deterioration. The main conclusions suggest that well-constructed flexible pavements show very long service life provided that distress mechanisms such as rutting and cracking are confined to the pavement surface [2. and 3.].Asphalt mixtures are viscoelastic composite materials which show significant time- and temperaturedependence. At high temperatures and/or low loading rates (vehicle speed), asphalt mixtures are relatively soft, while the opposite applies at low temperatures and/or high loading rates. Another characteristic of asphalt mixtures is the gradual stiffening with time, ageing. The adequacy of asphalt mixtures in flexible pavement design depends on the quality and composition of the main constituents: bitumen and aggregates. Binder properties, such as stiffness and ductility, have a well-documented effect on mixture performance since the stiffness of the binder largely influences the stiffness of the mixture. The bituminous binder should be chosen taking into consideration the prevailing conditions concerning aggregate type and regional climate since they collectively influence mixture performance. In some respects, asphalt binder and mixture properties can be improved using certain additives, e.g. polymers. In addition to binder properties, binder content shows a major impact on mechanical properties of asphalt mixtures. The aggregate should exhibit adequate properties regarding mainly stability and wear resistance.

2.4 Maintenance

In the past, the preoccupation of road engineers has been mostly with construction of new roads. However, as road networks in many countries have been completed, the emphasis has gradually turned to maintenance of the existing network [17.]. In contrast to relatively short-duration construction projects, maintenance is characterised as an on-going long-term process over a relatively widespread area.

Maintenance of traditional roads normally covers a wide range of activities aimed at reducing the rate of pavement deterioration and in the end achieve low vehicle-operating costs. As more advanced maintenance activities, such as reconstruction, are significantly more expensive than resurfacing, it is important to continuously carry out adequate activities in order to avoid an increased deterioration rate. A third reason for carrying out maintenance is to keep the road open continuously. Any failure to keep a highly trafficked road open will lead to serious social and economic consequences.
For this reason structural damage has to be avoided; repairing structural damage is costly and time consuming. In contrast to traditional pavements, long-life pavements are defined as pavements, which do not show any structural deterioration. Consequently, the end of a pavement's life will not be reached as long as correct surface maintenance is carried out.
For motorways with a very high traffic intensity the availability of the road is of utmost importance and therefore disruption to traffic has to be avoided. The maintenance or the renewing of the surface layer has to be done in a short time period to minimise the hindrance to the traffic. Besides that the cost of traffic management measures during maintenance works on motorways are high and can be more then 50% of the total job costs.
The lower need for more extensive structural maintenance activities with LLP certainly affects the pavement's overall life-cycle costs.

3. Economical aspects

As discussed in Section 1, the overall purpose of LLP is to achieve lower annual costs by increased pavement life and fewer and more cost effective maintenance activities. In order to assess the economic benefits of LLP, the full financial consequences should be considered using Cost/Benefit Analysis (CBA) [4.]:

- Initial construction costs
- The loss of pavement capital due to pavement deterioration
- Agency costs due to periodic maintenance and traffic management at road works
- Road user costs, primarily due to delays at road works
- The costs due to accidents involving road users and workers at road work sites
- The environmental economical impacts of road construction and maintenance

Intuitively, a LLP probably results in an increase in construction cost compared to traditional pavements, but lower maintenance-related costs. Some of the costs included in CBA are relatively simple to determine while others are relatively difficult. In the case of pavement deterioration, only limited information regarding costs has been published. The most likely explanation is that present Pavement Management Systems (PMS) mostly do not include residual value of pavements [4.]. Costs associated with road user delays can be obtained using models based on measured traffic flows and road capacities. Road safety costs are more difficult to appreciate, primarily due to lack of relevant data. The three main areas of concern for environmental costs are recycling of pavement materials, pollutant impacts related to fuel consumption and noise impacts related to maintenance work. The agency costs consist mainly of direct costs including maintenance and traffic management costs but also indirect costs in terms of administration. The review presented by FEHRL [4.] showed that only the UK takes special account of the economic aspects of LLP. Using CBA, UK experience has shown that pavements classified as LLP are expected to be more cost-effective than traditional road pavements since the small increase in construction cost is compensated by lower direct maintenance costs and indirect disruption-related costs. For a 10 year period, the total savings by adopting the LLP principal in the UK, are expected to reach 350 Million Euro [4.].

However, even though many costs associated with CBA are abstract and difficult to establish, there are simpler ways of estimating the economic benefits of a LLP. Perhaps the easiest way is to compare the construction and maintenance costs of two (or more) types of pavement structures, one being a LLP and the other being a conventional one. This in turn requires that the design models used are capable of taking into account the different parameters responsible for the deterioration.

The traditional Life Cycle Cost Analyses (LCCA) can be used for calculating the present worth of costs for pavement alternatives and it is the primary tool used for economic comparisons.
For these LCCA studies the time span that is taken into account is mostly between 20 and 40 years. When dealing with Long Life Pavements this time span should be longer and might have to go up to 100 years.

In [20.] Haas et al. suggest a framework for LCCA applications which recognizes short, medium and long term cycle periods, functional class of highway, public and private sectors and likely or preferred LCCA method. Reasonable life cycle periods for short, medium and long term analysis are in the order of 25, 50 and 100 years respectively. This paper [20.] also gives a numerical example which shows how an agency could calculate an internal rate of return (IRR) for a base investment alternative involving a long life pavement design.

4. Future developments

4.1 Procurement and specifications

An important aspect, which affects the final result in the field, is the means by which quality is defined, measured, controlled and ensured. In recent years, performance specifications for pavements have been debated intensively. Performance specifications are often considered to recognize the relationship between construction quality and long-term performance. By rationally controlling variables that impact long-term performance, the quality of the final product can be improved. In order to achieve long-life performance, aspects such as these should be considered in addition to the technical demands.

4.2 Improved economic models

As indicated in Section 3, improved economic models are necessary to show the benefit of alternative designs and materials. Perhaps the most significant obstacle is the need to develop a model which is capable of illustrating the relation between investment cost and life-cycle costs. Today, most pavements are purchased primarily based on investment cost, which consequently, often leads to high life-cycle costs since the procurement procedure rewards the lowest bidding price.

5. Summary and conclusions

During the last couple of years Long-Life Pavements- and Perpetual Pavement concepts have been established in Europe and in the USA. The main purpose of these concepts is to develop a framework, in which more cost-effective pavements can be produced.
When the availability of road lanes and the road user delay costs are taken into account in the cost-benefit analyses of pavements it will show that a number of highways in densely populated areas require low maintenance pavements. That means a total reconstruction of a road pavement is hardly possible or even impossible.
This is one of the reasons for developing the Long-Life Pavement concept.

A long-life pavement is defined as a type of pavement where no significant deterioration will develop in the foundations or the road base layers provided that correct surface maintenance is carried out.

This definition implies that all pavement layers, except the road surface layer are considered as permanent pavement layers.

The LLP-concept is to some extents based on earlier concepts but mainly on recent advances in material technology, design and functionality.
In practice, the intention of the LLP-concept is to significantly extend current pavement design life by restricting distress, such as cracking and rutting to the pavement surface. Common distress mechanisms such as bottom-up fatigue cracking, rutting in the unbound layers and frost heave should, in principle, be completely eliminated.

For design and construction of new pavements this concept means that the pavement has to be designed and constructed in such a way that

- bottom-up fatigue cracking should be prevented
- rutting in the pavement layers should be avoided by using adequate asphalt mixtures
- rutting in the unbound layers and frost heave should completely eliminated.

The choice of the surface layer depends on the functional requirements. This could be a combination of comfort, durability, stability, skid resistance and noise reduction. There might be even additional requirements like surface water drainage or water impermeability.
A wide range of bituminous surface layer products can be considered appropriate depending on specific requirements. The selection of surface course is a matter of identifying the most appropriate materials during the design life.
The bituminous binder courses should be able to withstand high shear stresses and the bituminous base layer should be thick and stiff enough to distribute the traffic loadings to the substrate and to withstand fatigue.

The resistance to fatigue depends on the fatigue resistance of the bituminous mixture and the tensile strain at the bottom of the asphalt base course. The tensile strain should be below a certain fatigue limit, under which no damage accumulates.
There are two approaches to achieve a sufficient low strain level. On approach is based on a certain number of Equivalent Standard Axle Loads in the design and the other approach is to limit the tensile stain at the bottom of the bituminous base layer to a certain number:

- Pavements design above a traffic level of 80 million standard axles (80 kN) are said to be designed as long-life pavements.
- Threshold values for tensile stain in the range of $50\text{-}70 \times 10^{-6}$ m/m have been reported as fatigue thresholds.

In practice both approaches will lead to a tensile stress level at the bottom of the bituminous base layer that is low enough to avoid crack initiation / crack propagation.

It should be emphasised that any design parameter and criterion should not be taken out of its context since they are closely linked to a specific design guide, test methods used, materials used and the construction of the pavement, etc.
In the same way the maximum tensile strain at the top of the sub-grade could be mentioned (200×10^{-6} m/m) to avoid rutting in the top of the subgrade.

In general the technical and functional requirements for LLP will in general be higher compared to traditional pavements. A way to achieve this is by prescribing functional specifications instead of technical specifications. Then it is up to the contractor to show that a solution meets the requirements. In this way several solutions may be considered by the contractor and the contractor will optimize the construction.

The traditional Life Cycle Cost Analyses can be used for calculating the present worth of costs for pavement alternatives and it is the primary tool for economic comparisons. For Long-Life Pavement the recommended life cycle periods for short, medium and long term analysis are in the order of 25, 50 and 100 years respectively.

6. Literature

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Appendix 1

Durability of surface layers in Europe

A.1. Introduction

Long-life Pavements or Perpetual Pavements mean building roads in such a way that fatigue at the bottom of the asphalt pavement layer is not a critical parameter. This also means that the total thickness of the pavement layers should be enough to avoid fatigue starting from the bottom.
Consequently, for maintaining the road in a good condition it is sufficient to replace the surface-layer only. In this way the durability of the surface layer is now the dominant factor for the pavement surface life.

To get an insight into the service life of surface layers the EAPA Technical Committee investigated the durability of the surface layers used in Europe.

This annex gives an overview of the different asphalt mix types that can be used for surface layers and their expected durability. The data are based on a questionnaire and a panel discussion of experts.

A.2. Asphalt mixtures

In the descriptions of the asphalt mixtures (1 to 7) the definitions are from the European Asphalt Standards EN 13108 – 1 to 7 and they are quoted with inverted commas.

1. **Asphaltic Concrete (AC)**
   "Asphalt in which the aggregate particles are continuously graded or gap-graded to form an interlocking structure". Dense asphalt concrete is often used as the 'basic' surface layer.

2. **Asphalt Concrete for very thin layers (AC-TL)**
   "Asphalt for surface courses with a thickness of 20 mm to 30 mm, in which the aggregate particles are generally gap-graded to form a stone to stone contact and to provide an open surface texture". This mixture is often used in France and is called BBTM (Béton Bitumineuse Très Mince).

3. **Soft Asphalt (SA)**
   "Mixture of aggregate and soft bitumen grades". This flexible mixture is used in the Nordic countries for secondary roads.

4. **Hot Rolled Asphalt (HRA)**
   "Dense, gap graded bituminous mixture in which the mortar of fine aggregate, filler and high viscosity binder are major contributors to the performance of the laid material". Coated chippings (nominally single size aggregate particles with a high resistance to polishing, which are lightly coated with high viscosity binder) are always rolled into and form part of a Hot Rolled Asphalt surface course. This durable surface layer was often used as a surface layer in the UK.

5. Stone Mastic Asphalt (SMA)
"Gap-graded asphalt mixture with bitumen as a binder, composed of a coarse crushed aggregate skeleton bound with a mastic mortar". This mixture is of often used as a surface layer in case high stability is needed. The surface structure also has good noise reducing properties.

6 Mastic Asphalt (MA)
"Voidless asphalt mixtures with bitumen as a binder in which the volume of filler and binder exceeds the volume of the remaining voids in the mixed". This mixture is very durable and was often used as surface layer in certain countries.

7. Porous Asphalt (PA)
"Bituminous material with bitumen as a binder prepared so as to have a very high content of interconnected voids which allow passage of water and air in order to provide the compacted mixture with drain and noise reducing characteristics".

8. Double layered Porous Asphalt (2L-PA)
The top layer with a grain size 4/8 mm is about 25 mm thick and the second/bottom layer is porous asphalt with a course aggregate (11/16 mm). The total thickness is about 70 mm. Because of the finer texture at the top (that gives less tyre vibrations), it gives a better noise reduction than a single layer porous asphalt.

9. Asphalt Concrete for ultra thin layers (UTLAC)
Asphalt for surface courses with a thickness of 10 mm to 20 mm, in which the aggregate particles are generally gap-graded to form a stone to stone contact and to provide an open surface texture. Several varieties of this layer are often used to provide a good, new noise reducing surface layer.

The difference between the mixtures with regard to structure and skeleton are also illustrated in figures 5, 6 and 7.

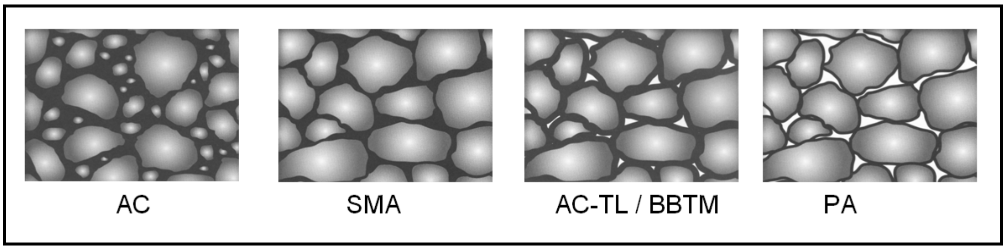

Figure 5: Difference in structure between AC, SMA, BBTM and PA.

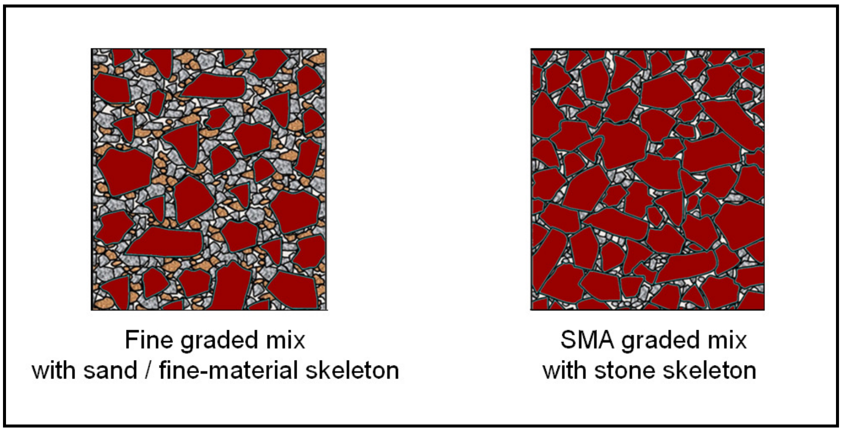

Figure 6: Difference between sand skeleton and stone skeleton mixtures

Figure 7: Structure of double- layered Porous Asphalt

A.3. Basic assumptions for determining the durability of the surface layers

The expected durability is based on the best practice. This means that surface layers are expected to be laid on a properly designed road where the durability of the surface layer is not determined by bottom-up fatigue cracking.
Also, it is assumed that the mix is properly designed and well compacted. As an example, a SMA surface layer that shows rutting in the SMA is an improperly designed mixture.

The data shown are not valid in the case of using studded tyres.
The durability of surface layers also depends on the local conditions, the local climate, the mix formula, the types of bitumen and aggregate used, the maximum allowable axle loads and the actual axle loads used (because excessively high axle loads have a strong negative influence on the service life of the pavement surface layers). In some cases or countries the skid resistance of the surface layer is the dominant factor for determining the service life, so the durability depends on the required friction level and the PSV-value of aggregate that has been used.

A distinction has been made between major roads (motorways and heavily traffic roads) and secondary roads.

A.4. Results

Table 1 and Figure 8 show the Durability of Surface Layers is expressed in years of service life for major roads / motorways / heavily trafficked roads.

Table 2 and Figure 9 show the Durability of Surface Layers is expressed in years of service life for secondary roads.

Major roads / motorways / heavily trafficked			
Type	15% Lowel level	European average	85% Higher level
AC	8	14	18
AC-TL 30-40 mm	8	12	18
AC-VTL 25-30 mm	8	10	12
UTLAC	8	10	12
PA	8	10	14
2L-PA [1])	9	11	12
SMA	14	20	25
HRA	17	21	25
Mastic-A	18	21	24

Soft-A is not used here

[1]) Only based on Dutch results

Table 1: Durability of surface layers on major roads

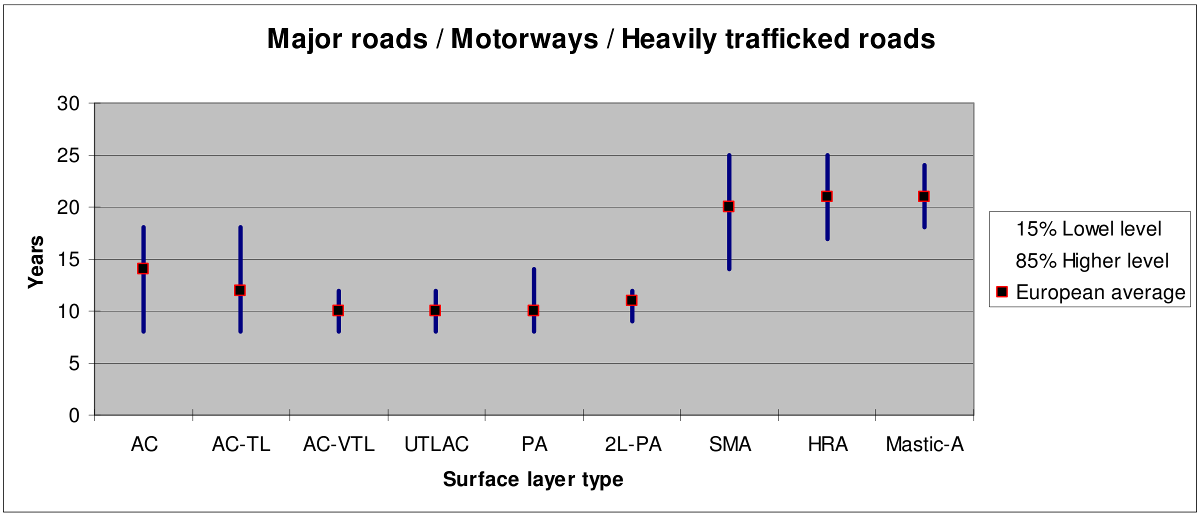

Figure 8: Durability of surface layers on major roads

Secondary roads			
Type	15% Lowel level	European average	85% Higher level
AC	10	15	20
AC-TL	10	15	20
AC-VTL	10	12	14
2L-PA [1])	10	11	12
SMA	16	20	25
HRA	20	25	30
Mastic-A	18	24	30
Soft-A	8	12	25

PA and UTLAC are not used here

[1]) Only based on Dutch results

Table 2: Durability of surface layers on secondary roads

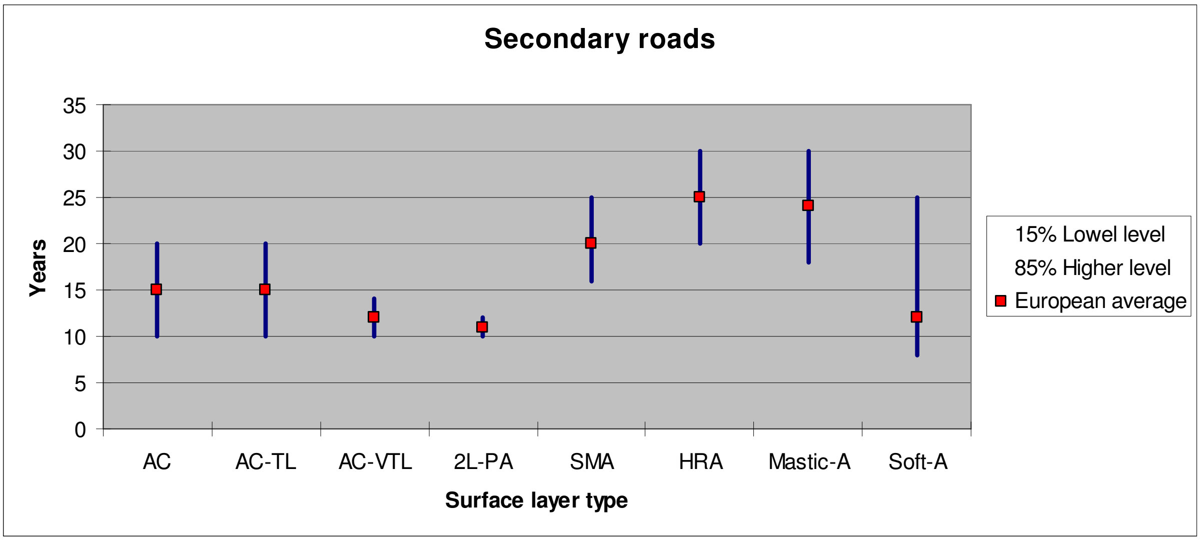

Figure 9: Durability of surface layers on secondary roads