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EARN

Effects of constituent materials, recycled and secondary sources materials and construction conditions on pavements durability derived from literature and site data review - D3

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CEDR Call 2012: Recycling: Road construction in a post-fossil fuel society

EARN
Effects on Availability of Road Network

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Executive summary

The service lifetime of road materials and pavement structures depend on numerous parameters. Some of them can be controlled by material and pavement engineering (e.g. mix design, raw material selection, and pavement design) while others are ancillary conditions which cannot be modified during road design and construction (e.g. weather conditions). Because of its effects on the frequency and extend on maintenance road works, the durability plays an important role on the environmental life-cycle performance of the road structure as well as on its life-cycle costs.

A high number of parameters affect the durability of road materials and the service lifetime of the pavement structure. A list of parameters for conventional asphalt materials was evaluated. Additionally a list of asphalt additives was established showing the high number of various techniques for reducing the energy consumption of asphalt paving works. For evaluating additional effects on service lifetime yet not considered in life-cycle assessment (LCA) and life-cycle cost assessment (LCCA), European databases on structural and performance properties of the road network were assessed in detail. Unfortunately, due to lack of reliable structural data on road network databases and inhomogeneously referred localisation of detailed material databases no conclusions could be drawn for the effect of recycled materials or secondary materials on the service lifetime of the road structure.

However, it has been shown from international literature that the use of reclaimed asphalt (RA) in new hot-mix asphalt results in adequate material durability performance in most of the cases. However, some researchers have also identified reduced durability for mixtures containing RA. Altogether, the application of RA in new hot-mix asphalt inhibits additional procedures in mix design as well as asphalt mixture production on industrial scale. Because the sole number of production steps increases which individually affect the durability properties of the resulting asphalt mixture, the risk of reduced durability will increase in general. When all procedures were conducted in high quality (as is usually the case in laboratory research as well as test section studies), no adverse durability effects were observed in most publications. Nevertheless, if there is any general adverse long-term performance, as indicated by database analysis in every-day paving industry, the higher risk will result in reduced durability for some of the projects. The increased use of various additives will further increase this development due to additional risks (e.g. incompatibilities to specific binders).

When considering the durability effect of asphalt mixture composition as well as the use of additives and or recycled materials, feasible laboratory conditioning procedures is needed in order to allow the estimation of long-term properties already during mix design. Based on these results, durability effects can be implemented into LCA and LCCA in comparison to traditional asphalt mixtures with known durability properties.

For the construction conditions analysed in this report, durability effects were found which can be implemented to LCA and/or LCCA calculations.

For the effect of construction season, the paving during adverse weather conditions will slightly increase the risk for insufficient compaction and interlaying bonding. These independently occurring effects result in significant reductions of pavement ad/or road material service lifetime. These reductions can be summed up to a service lifetime decrease of -2,2 % for pavements constructed in winter months (October until January):

- due to risk of insufficient compaction: -1,7 %
- due to risk of insufficient interlayer bonding: -0,5 %

The splitting of larger construction sites into smaller patches, which may be necessary when using times of low traffic volume for conducting pavement maintenance works, incorporate the disadvantage of an increase in the number of joints. These areas of pavements often inhibit inadequate compaction properties and, therefore, a significantly decreased durability. Based on published research results, the effect of reduced compaction degree on estimated service lifetime combined with the risk of inadequate joint design could be estimated to a reduced service lifetime of -14,4 %.

1 Introduction

The service lifetime of road materials and pavement structures depend on numerous parameters. Some of them can be controlled by material and pavement engineering (e.g. mix design, raw material selection, and pavement design) while others are ancillary conditions which cannot be modified during road design and construction (e.g. weather conditions). Because of its effects on the frequency and extend on maintenance road works, the durability plays an important role on the environmental life-cycle performance of the road structure as well as on its life-cycle costs.

This report summarises the results addressed in EARN project work package 1. In section 2 the state of the art on service lifetime approximations as being applied in pavement management systems are discussed.

In section 3 parameters affecting the durability of asphalt pavements are discussed. A list of parameters with even more sub-items indicate that the modelling of durability and service lifetime would account for extensive parameter evaluation by means of laboratory tests at various loading conditions, validation efforts based on several detailed site survey and high computational effort. Additionally a large number of additives increase the variety of parameters, indicating the impossibility to evaluate adequate model input parameters from all types of materials which would enable the comparison between products and techniques on a life-cycle assessment (LCA) basis.

In order to derive service lifetime assumptions linked with specific material properties, existing databases on European road network are being assessed:

- Surface conditions / PMS databases: In recent years, high effort was made to develop pavement management systems (PMS) for predicting the road maintenance needs. Therefore, the road surface conditions (skid resistance, rutting, and cracking) are monitored in regular intervals for the main road network. The associated databases include some data on road structure on various levels of detail and accuracy. However, data on detailed road material composition is usually not available.
- Trial section reports: Databases exist on experimental / trial road section, in which innovative road materials and road structures were initially tested. Usually these sections are well documented and a lot of tests were made after construction. However, investigations on these sections after several years in service are less common. Another issue to consider is that engineers and road workers usually know that their work is being monitored in close detail, which may have an influence on the accuracy of their work. This improved workmanship may lead to better performance of these materials compared to the properties reached in day-to-day practice.
- Databases on material properties: Some databases may exist where data on material properties (e.g. from control tests) are stored. These databases will contain information on detailed road material composition (e.g. binder content, recycled material) but generally do not contain data about the road structure for which the material was applied. In order to evaluate the influence on given material properties on the durability, these material databases have to be combined with other databases by means of geo-reference.

In addition to this published research, data and results from the database evaluation are applied for estimating effects from construction conditions (working season, night construction / early trafficking) on the service lifetime.

2 Durability of pavements - State of the art

2.1 General

Asphalt pavement durability is a key factor in determining the performance of a pavement material and, as such, the pavement service life together with the pavement maintenance requirements during that service life. Therefore, it plays an important role regarding the environmental life-cycle of the road structure.

The durability of a pavement involves many relevant parameters that can be categorised as:

- The effects from traffic and weather as well as environment and sub-base soil conditions.
- The parameters for unbound base layers, hydraulically bound base layers and bituminous bound base and finally surface layers.

A summary has been produced (Mollenhauer *et al*., 2013). However, many data sets are required to evaluate the effect of one parameter on the service lifetime of the pavement. Furthermore, the modelling of a pavement's service life is only possible if most of the parameters are known; otherwise, it is subjected to a wide range of uncertainty.

2.2 PMS-approach based on service lifetime estimation

In pavement management systems (PMS), service life and qualitative functions for relevant pavement distresses are already incorporated. One approach considers a general design life of the pavement structure of a defined time (e.g. 20 or 30 years) for a design traffic loading. For pavement management, the actual known traffic loading from the beginning of the service life is used for the service life prognosis. This approach considers the pavement structure as a whole without consideration of the layers and/or materials. Another approach is that some national guidelines already contain service life for selected pavement materials which are applied in PMS. In Table 1, these assumed service lives derived from various sources are summarised for different pavement materials.

While this approach does work on network level, it is not possible to estimate the service life of a specific road section. The unique loading conditions are not considered – or only in very broad terms.

Table 1. General service life assumptions given in guidelines and specifications for pavement management systems

Road layer	Pavement material	Germany (FGSV, 2001)		Netherlands (IVON, 2012)		UK (SWEEP Pavements, 2013)	
		≥ 300 ESAL/day	< 300 ESAL/day	Right hand lane	Full width	surface life	structural life
Surface asphalt layers	Asphalt concrete (AC)	12	18	12	18	8	–
	Very thin layer asphalt concrete (BBTM)	–	–	–	–		
	Hot rolled asphalt (HRA)	–	–	–	–		
	Stone mastic asphalt (SMA)	16	22	11	17		
	Mastic asphalt (MA)	19	26	–	–		
	Porous asphalt (PA)	–	–	10	18		
Asphalt base layers	Asphalt concrete (binder layer)	26	30	–	–	–	20
	Asphalt concrete (base layer)	55	75	*	*		
	Other base layers						
	Hydraulically bound base layer	60	80	*	*		
	Unbound base layer	55	75	*	*		
Rigid pavement	Concrete surface layer	26	30	*	*	10	40
	Hydraulically bound base layer	55	70	*	*		
	Asphalt concrete base layer	50	65	*	*		
	Unbound base layer	45	60	*	*		
Maintenance materials	Slurry surfacing	6	8	–	–	8	–
	Micro-surfacing	5	8	–	–		
	Thin hot-mix asphalt layer on sealing	8	10	–	–		

* Highway maintenance in the Netherlands aims at timely strengthening the AC base layers and (sub)bases and thus, never has to be replaced.

2.3 PMS-approach based on design traffic loading

In order to predict the actual maintenance needs for specific pavements more accurately, procedures were developed taking into account the specific traffic loads on the specific road section. In several research projects, a system was developed with which the actual pavement surface characteristics can be predicted (Hinsch *et al*., 2005; Rübesam *et al*., 2005; Ressel, 2013). Based on the results of monitoring the surface condition that was conducted regularly, the development of relevant surface performance conditions were plotted against the traffic loading between the monitoring and the pavement construction.

Based on these network-wide data plots, regression functions were calculated which show that all surface characteristics, relevant for service life performance of the road as well as for the structural performance, could be described with a common 3-parameter function (equation 1) from the actual traffic loading. The traffic loading from the time of road construction or the last structural maintenance works is applied in terms of the number of equivalent 10-t-axle loads.

$$z_{i,k} = a_{i,k} + b_{i,k} \cdot ESAL_{10-t}^{c_{i,k}} \quad (1)$$

where $z_{i,k}$ is the surface characteristic considered (e.g. rut depth, proportion of cracks), $ESAL_{10-t}$ is the number of equivalent 10-t-standard axle loads since pavement construction or maintenance and $a_{i,k}$,$b_{i,k}$,$c_{i,k}$ are the regression parameters for the surface characteristic *j* and the homogenous pavement group *k*.

As an example, in Figure 1 the rut depth for pavements with a mastic asphalt surface course is shown. Based on these data, regression functions could be evaluated which are added to the figure. The data exhibit a large scatter and, therefore, can show large differences concerning the calculated surface properties, especially when extrapolated for large traffic loads. Nevertheless, the estimation of differences in the maintenance requirements and service lives from the derived regression formulae will allow the comparison of various pavement structures as well as materials applied.

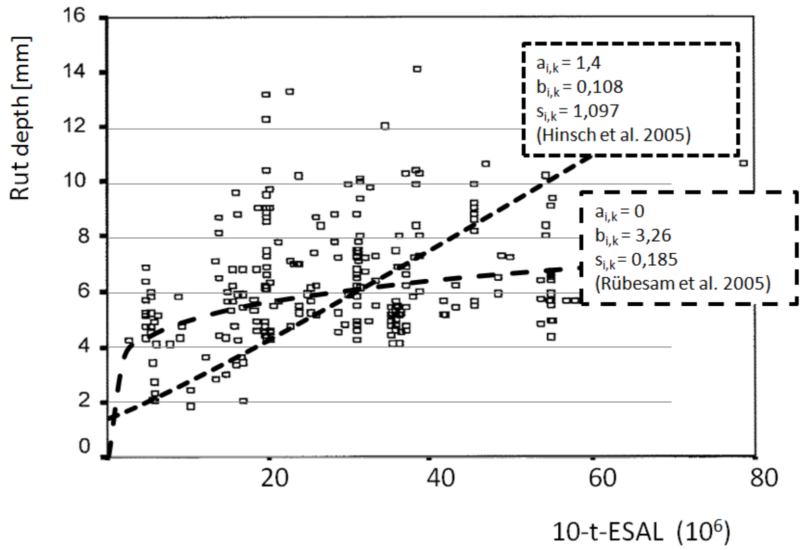

Figure 1. Evaluation of surface condition equation from pavement survey data (Rübesam *et al.*, 2005)

For the structural pavement conditions (evenness, cracking, repair patches), the network data from the German road network were evaluated in which analysis the various road structures were classified and regression functions were calculated for the specific road structures. For the structural pavement properties found to be significant, regression functions could be calculated for specific types of pavement materials. As an example, in Figure 2 the area of alligator cracking is shown plotted against the cumulated traffic loading. Specific differences can be observed for the selected pavement structures. For a given area of alligator cracking (e.g. 20 %), pavements with mastic asphalt as the surface course can endure higher traffic loading compared to asphalt concrete (AC) and stone mastic asphalt (SMA) layers. Further, asphalt pavements with a hydraulic road base ("rigid base") inhibit higher resistance against alligator cracking compared to asphalt pavements on pure flexible road base (unbound base layers). The distinct equations allow specific graphs to be plotted but these equations are based on road condition survey data which will exhibit a large scatter. For the shown functions, the coefficient of correlation, R^2, varied between 1 % and 10 % and, therefore, indicates a very low statistical accuracy of the data. The prediction of specific service lifetimes will not be possible by this approach.

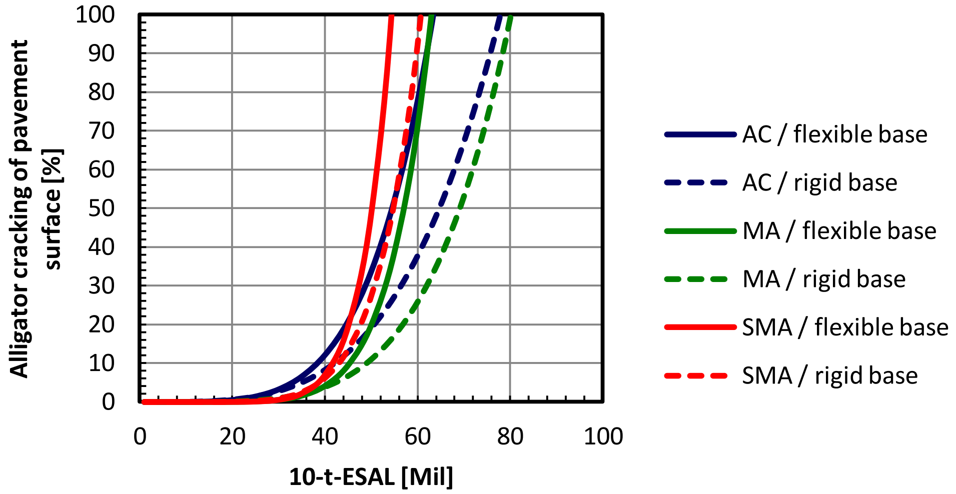

Figure 2. Development of pavement alligator cracking versus traffic loading depending on structural pavement properties (Hinsch *et al*., 2005)

Nevertheless, differences between the durability of specific road structures found from network survey data may allow the evaluation of trends for comparing the service lives of the different road structures and materials. Therefore, threshold values for the various pavement condition parameters were defined by Kunze & Rübesam (2007) based on the mean parameters of pavements just before maintenance works were applied. The surface condition parameters, which made maintenance work necessary and which were proposed for the application in PMS, are summarised in Table 2. These values are considerably lower than the values which are usually applied for the introduction of a fast repair needed after condition surveys. This difference is because, for the motorway network, road maintenance and rehabilitation works should be limited to relatively large areas. Between highly damaged road sections, lesser damaged sections will occur and, therefore, the mean pavement quality just before rehabilitation should be better than expected.

Table 2. Surface condition parameters defining the end of service lifetime

Pavement surface condition indicator	Condition survey: traffic safety issues	Mean end of service life condition	
		Asphalt	concrete
longitudinal unevenness ("AUN")	9000 mm³	1500 cm³	2500 cm³
rut depth	20 mm	7,5 mm	7,5 mm
alligator cracks / patches	10% / 15%	Σ 15 %	-
cracks / rupture	35 % / 35 %	-	Σ 40 %

Based on these data, Ressel *et al*. (2013) applied the approach to evaluate differences in service lives for selected pavement structures and road materials. As shown in Figure 3, little difference is found for the mean service lifetime based on these data for various types of pavement structures or road materials. However, different ranges of scatter can be observed for specific pavement parameters.

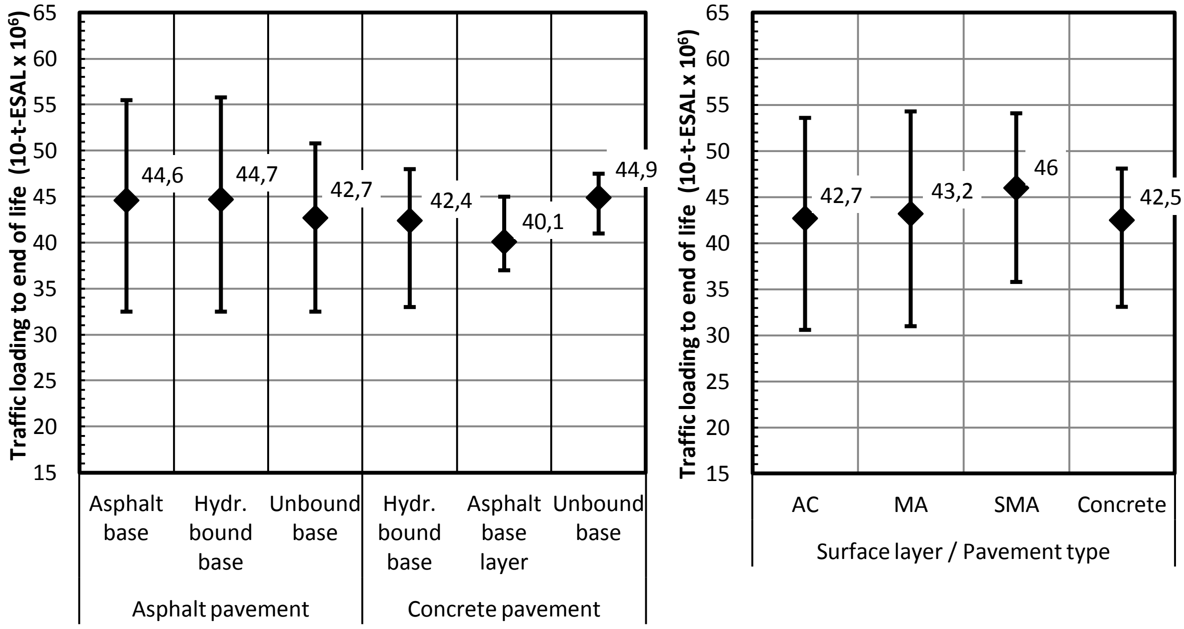

Figure 3. Service lifetime for specific road structures (left) and pavement materials applied in surface courses (right) (Ressel *et al*., 2013)

In order to improve the prediction quality for pavement management systems on project level (i.e. for specific road sites), results of laboratory performance tests can be introduced into PMS as demonstrated by Wistuba *et al*. (2013) during ERA-Net road project InteMat4PMS. This approach should improve the prediction quality and provide the link between laboratory-assessed road material properties and the predicted service life of the road structure built of the road materials (Figure 4). In InteMat4PMS, the approach was demonstrated for the fatigue resistance of asphalt base layer.

Therefore, the results of laboratory performance tests can be used for estimating the effect of road material composition on the service life of the road structure. This approach has been applied for the analysis of international research projects and additional literature regarding the effects on asphalt material performance of reclaimed asphalt use or low-temperature asphalt mixtures as presented in Section 3.

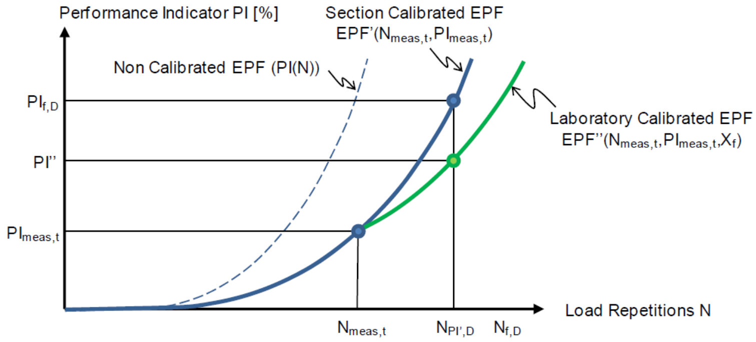

Figure 4. Calibration of performance indicator for PMS application based on laboratory material performance tests (Wistuba *et al*., 2013)

3 Effects on durability

3.1 Construction materials

3.1.1 General

Low-temperature asphalt mixtures were developed in order to reduce the paving temperature and the energy used and greenhouse gases emitted. The development of low-temperature asphalt mixtures has been driven by the aim to reduce the temperature effect on asphalt pavement production, laying and compaction, in order to improve effect of asphalt production on the environment. Furthermore, low-temperature mix asphalts have been utilised to allow the recycling of existing pavements at the end of their service life with reduced demand for material transport, heating energy and raw-material consumption.

However, the low-temperature asphalt pavements may often result in shorter service life in comparison to equivalent standard hot mix asphalt pavements. It is believed that this reduction occurs because the different mixing and paving technologies used in the production of low-temperature asphalt result in weaker mechanical material properties as well as its resistance against cracking.

The WMA technologies can be classified in several ways. One is to classify the technologies by the degree of temperature reduction. Figure 5 shows the classification of asphalt mixtures according to the production temperature. Warm asphalt mixtures are separated from half-warm asphalt mixtures by the resulting mixture temperature. Specifically, for the warm and half-warm asphalt mixtures the mixing, laying and compaction are usually undertaken at 100 ºC to 140 ºC and at 70 ºC to 100 ºC, respectively, whereas for the hot asphalt mixtures the temperatures can reach 138 °C to 160 °C depending on the bitumen grade used.

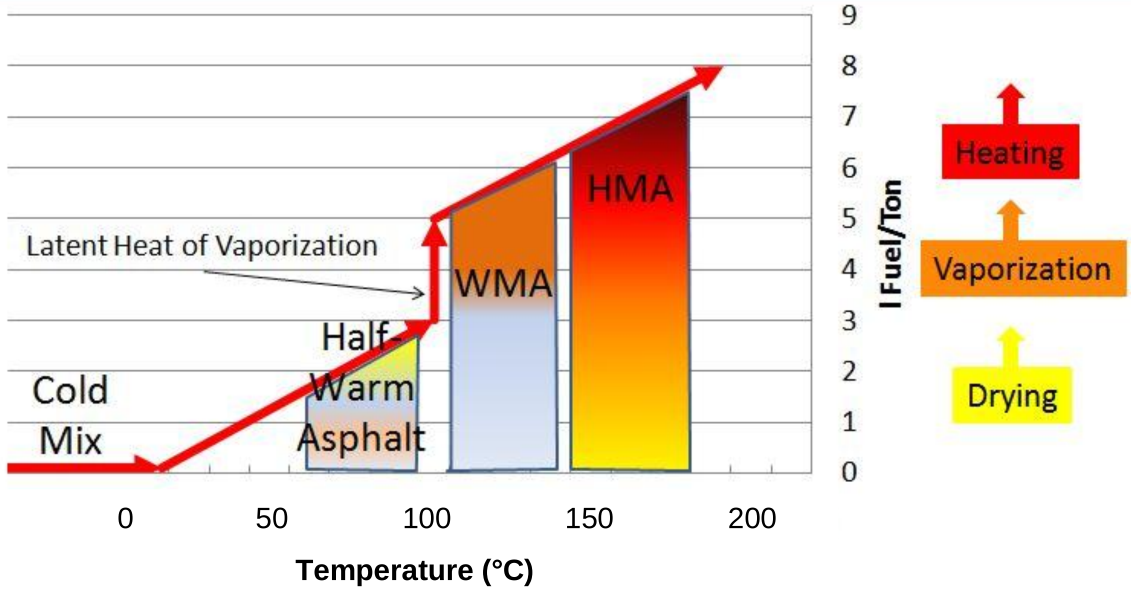

Figure 5. Definition of low-temperature asphalt mixtures (Prowell, 2007)

The following sections summarise important findings on material properties of low-temperature asphalt mixtures. Suitable test procedures for evaluating the durability characteristics are discussed.

3.1.2 Hot-mix asphalt

Asphalt pavement durability is a key factor in determining the performance of a pavement material and, as such, the pavement service life together with the pavement maintenance requirements during its service life. Therefore, it plays an important role regarding the environmental life-cycle of the road structure.

Relevant parameters affecting the pavements service life are summarised in Table 3. As a bottom-up approach, the order of review is:

- The effects from traffic and weather as well as environment and sub-base soil conditions.
- The parameters for unbound base layers, hydraulically bound base layers and bituminous bound base and finally surface layers.

This summary is used to identify parameters which will be addressed during the research work in the EARN project.

The items identified are labelled as follows:

1. Parameters which are of importance for the pavement service life and which are likely to be available within various national road databases are <u>underlined</u>. These characteristics will be evaluated in the database acquisition subsequently.
2. Parameters which are important for the pavement service life but the acquisition of which will be more problematic are marked in *italics*.
3. Parameters for the pavements durability that are considered to be outside the scope of the EARN project are not highlighted.

In several cases, there are correlations between relevant parameters, such as the temperature effect on asphalt stiffness. If one parameter is significantly affected by another parameter, this relationship is identified by a superscript reference to the relevant row number.

The data presented in Table 3 show the effects on pavement durability and its service life. A high number of data values are required to evaluate the effect of one parameter on the service lifetime of the pavement. Furthermore, the modelling of a pavement's service lifetime is only possible if most of the parameters are known; otherwise, it is subjected to a wide range of uncertainty, i.e. error.

Table 3. Summary of effects on service lifetime and durability of pavement structures

No.	Parameter	Description of effect on durability[a]	Relevance for EARN and way of evaluation[b]
1	**Environmental effects**		
1.1	Air Temperature, sun exposure, wind speed	Temperature effect on pavement surface temperature: - temperature-dependent asphalt stiffness, - rutting.	Different international approaches for material choice and composition will be validated against the general climatic conditions.
1.2	Sun exposure	UV radiation affects surface asphalt ageing.	
1.3	Precipitation, humidity	Effect on water sensitivity: Stripping, reduction of strength, adhesion failure of aggregate/bitumen-interface.	
1.4	Frost-Thaw-Cycles	Frost damages by volume-increase of water in material voids, surface damage[1.1,1.2,1.3].	
1.5	High-depth frosting	Damages of entire structure by frost-heaves[1.1].	No - distress is independent on construction material properties.
2	**Traffic loading**		
2.1	Tyre/Axle load; weight and number	Traffic data is considered by calculating ESAL.	ESAL is the controlling factor for traffic loading: calculated according to 4^{th} power law. For the EARN project, a standard axle load of 10 t will be used.
2.2	Traffic Speed (distribution)	Effect on loading intensity: slow loads increase distress (e.g. rutting).	*Will be considered for the effect of various designs for construction work sites.*
2.3	Axle configuration	Effect on loading shape and rest periods between loads.	No data will be available.

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[a] cross-interfering parameters will be identified by superscript reference to table row numbers

[b] underlined letters: will be considered; *italic letters: will be considered if possible;* normal letters: will not be considered because they are considered outside the scope of EARN project or no data are availability

Table 3. Summary of effects on service lifetime and durability of pavement structures (Cont.)

No.	Parameter	Description of effect on durability[a]	Relevance for EARN and way of evaluation[b]
3	**Sub-base characteristics**		
3.1	Bearing capacity	Bearing capacity of sub-base is one key factor for the pavement load distribution. The actual mechanical loads depend highly on the sub-base quality.	*Bearing capacity will be considered in database analyses. Data may be available from original pavement design.*
3.2	Sub-base moisture / drainage properties	High content of water-filled voids will reduce the bearing capacity. Water content is influenced by weather parameters[1.3,1.4] and permeability of pavement structure.	*Sub-base moisture effect on durability can be estimated by considering type of soil, and season of distress observed.*
4	**Pavement type and structure**		
4.1	Type of pavement	Different bearing systems regarding flexible (asphalt) or rigid (cement concrete) pavements.	Only flexible pavements are considered.
4.2	Number of structural layers	Number, thickness and quality of structural layers affect the load and distress distribution.	For database acquisition the pavement structural parameters (number, type and thickness of layers) will be considered in most possible detail.
4.4	Layer thickness	The layer thicknesses have an important effect on the load and distress distribution in the pavement. The greater the thickness, the higher is the layers contribution to the overall bearing capacity but the higher is the effect of permanent strain distress on rutting.	
4.3	Interlayer bonding	The interlayer bonding characteristics affect the loading of each construction layer. The better the interlayer bonding, the less is the loading for each layer.	*Effect can be considered from quality control test data. Construction of HMA at cold weather or rain can provoke bad interlayer bonding.*

Table 3. Summary of effects on service lifetime and durability of pavement structures (Cont.)

No.	Parameter	Description of effect on durability[a]	Relevance for EARN and way of evaluation[b]
5	**Unbound base layers**		
5.1	Composition (type of aggregates, grading)	Grading will influence the materials deformation characteristics (shear strength, stiffness and resistance to plastic deformation).	Identification of layer type may allow conclusion regarding some material characteristics and can be drawn from structural databases. *Details from mix design data.*
5.2	degree of compaction	Influence on stiffness properties and resistance against rutting.	*Effect can be considered from quality control test data.*
5.3	Moisture	Effect on bearing capacity for dense grading and high content of fines[1.3].	*Data possibly available from pavement design data (problematic groundwater conditions).*
5.4	Bearing capacity	Bearing capacity is a combined effect of sub-ground and layer properties[3.1, 5.1-5.3].	*Data possibly available from databases or pavement design data.*
6	**Hydraulically base layers**		
6.1	Construction type	Mixed in plant (lean concrete) or mixed in place material (cement-stabilised soil).	Data available from structural databases or pavement design data
6.2	Grading of aggregates	Composition will affect the stiffness and strength properties.	*Data possibly available from databases, pavement design data or quality control tests.*
6.3	Binder type		
6.4	Binder content		
6.5	Void content		
6.6	Stiffness	Stiffness properties affect the layer's contribution to the overall load distribution and distress[6.2-6.5].	
6.7	Strength	The strength properties determine the layer's resistance against single loads and fatigue[6.2-6.5].	
6.8	Construction conditions: Shrinkage / cracking	Shrinkage cracks (or notches) affect the bearing properties of the layer as well as the danger of reflective cracking to surface layers[1.1,1.2,1.3,6.3,6.4].	*Data on construction details possibly available (with/without notches).*

Table 3. Summary of effects on service lifetime and durability of pavement structures (Cont.)

No.	Parameter	Description of effect on durability[a]	Relevance for EARN and way of evaluation[b]
7	**Bitumen stabilised base layers (Cold recycling mixtures)**		
7.1	Type of mix (foam or emulsion; site or plant mixed)	Type of mix affects the materials stiffness and strength.	Data available from structural databases or pavement design data.
7.2	Aggregate grading	Composition will affect the stiffness and strength properties.	*Data possibly available from databases, pavement design data or quality control tests.*
7.3	Binder content (bitumen)		
7.4	Binder content (cement)		
7.5	Void content		
7.6	Curing conditions	Curing affects the strength and stiffness as well as the shrinkage properties[1.1,1.2,1.3,7.1-7.5].	
7.7	Stiffness	Stiffness properties affect the layer's contribution to the overall load distribution and distress[1.1, 7.1-7.6].	
7.8	Strength	The strength properties determine the layer's resistance against single loads and fatigue[1.1,7.2-7.6].	

Table 3. Summary of effects on service lifetime and durability of pavement structures (Cont.)

No.	Parameter	Description of effect on durability[a]	Relevance for EARN and way of evaluation[b]
8	**Asphalt layers (hot, half-warm and warm mix asphalts)**		
8.1	Type of mix	Type of mix (according to EN 13108) may have an effect on the durability.	Data available from structural databases or pavement design data.
8.2	Aggregate grading	Aggregate grading reflects the type of mixture and will have an influence on the binder needed, the air voids content and the performance properties	*Data possibly available from databases, pavement design data, construction protocol or quality control tests.*
8.3	Binder type	Binder viscosity affects the performance properties.	
8.4	Binder content	Binder content affects the binder film thickness, air voids content and, therefore, the performance properties.	
8.5	Air voids content and volumetric properties	The air voids content results from the asphalt mixture composition[8.2-8.4] and the paving/compaction conditions. The air voids content is a main parameter affecting the material's performance properties and durability characteristics (ageing / water accessibility)	
8.6	Type and content of additives	Additives affect the performance characteristics.	
8.7	RA type, quality and content	The effect of RA in asphalt mixtures is key topic addressed in EARN. The quality (in terms of properties[8.1-8.6] and homogeneity of properties) may influence the performance properties.	
8.8	Construction conditions	Asphalt mixture properties are highly dependent on the mixture temperature and weather conditions during construction[1.1,1.3] as well as the paving conditions (mix segregation) and compaction.	

Table 3. Summary of effects on service lifetime and durability of pavement structures (Cont.)

No.	Parameter	Description of effect on durability[a]	Relevance for EARN and way of evaluation[b]
8.9	Performance properties	Performance properties are a key factor for asphalt layer durability and affected by material composition and layer temperature[1.1,8.1-8.8]: - stiffness modulus determines the layers contribution to load and distress distribution[2.2], - fatigue distress, - rutting resistance, - ageing[1.2], - aggregate-binder adhesion[1.3], - skid resistance.	*Data possibly available from databases, pavement design data, construction protocol or quality control tests.* *Some characteristics can be modelled roughly from mixture properties (e.g. ageing affected by void content).* *Skid resistance is not directly linked to pavements durability but can be a major reason for road maintenance.*

3.1.3 Half-warm and warm mixtures

Hot Mix Asphalt (HMA) is a well-established, durable road construction material worldwide. HMA can be designed to accommodate a wide range of traffic loading for any pavement application. However, during the mixing process, a significant amount of heat is required to reduce its binder viscosity (i.e. increase its ability to flow). The amount of energy/fuel used during the heating process increases the amount of CO_2 emitted. The development and implementation of lower temperature asphalt technologies in EU road construction will assist the EU governments, the National Roads Authorities and the highway construction industry to meet their environmental commitments as set by the European Construction Technology Platform Vision 2030, the EU White Paper on Transport Policy, the EU Lisbon Agenda and the Kyoto Protocol. These policies oblige the national governments and the construction industry (ECTP, 2005; EAN, 2004; EC, 2001; UN, 1998) to:

1. Reduce manufacturing and construction costs by 30 % to 40 %,
2. Reduce the cost of maintaining the transport infrastructure by 10 %,
3. Reduce the lead-in time for the development of all transport modes by 25 % to 30 %,
4. Reduce CO_2 emissions and
5. Improve road user safety.

Warm Mix Asphalt (WMA) is a technology that allows asphalt mixtures to be produced and placed on-site at lower temperatures. WMA is produced at temperatures of between 20 °C and 55 °C lower than typical Hot Mix Asphalt (HMA) (EAPA, 2010; Vaitkus *et al*., 2009; D'Angelo *et al*., 2008). The reduction of the asphalt production temperature should deliver cost and energy savings and emission reductions at the various stages of the production and road construction process. Its use should also result in safer working conditions for construction crews and lower construction and (potentially) life-cycle costs.

Currently, European Standards for bituminous mixtures (EN 13108 1 – 7) do not explicitly preclude the use of Warm Mix Asphalt. The standards include maximum temperatures for particular mixtures; however, they do not specify minimum temperatures. The minimum temperature of asphalt mixtures at delivery is declared by the manufacturer (EAPA, 2010).

The standards also contain provisions for dealing with mixtures containing additives, subject to a demonstration of equivalent performance. The European Asphalt Pavement Association (EAPA) in its position paper on the use of WMA (2010) stated that: "*European Standards do not preclude the use of WMA and they should not be seen as a barrier to the introduction of WMA*".

Denmark, Finland, Germany, Ireland, Netherlands, Norway and UK, as signatories to the Kyoto protocol, agreed to lower greenhouse gas emissions to 5 % below the 1990 level by 2012 (UN, 1998). WMA technology offers the NRAs and the EU road construction industry an opportunity to reduce the CO_2 emissions at the road production. The overall benefits of using WMA in road construction (EAPA, 2010; Vaitkus *et al*., 2009; D'Angelo *et al*., 2008) are:

1. Reduced CO_2 emissions,
2. Reduced noise level on the work sites,
3. Improved working conditions for construction and maintenance crews, due to reduced mix temperatures and
4. Financial benefits derived through lower production and transport costs.

WMA technology consumes 30 % less energy, reduces CO_2 emissions by 30 % and reduces dust emissions by between 50 % and 60 % compared with HMA (EAPA, 2010; Vaitkus *et al*., 2009); D'Angelo *et al*., 2008). It has been estimated that, if production temperatures are reduced by 28 °C, fuel consumption to heat and dry the aggregate will be reduced by 11 %. Theoretical calculations for WMA indicate a greater than 50 % reduction in fuel consumption to heat and dry the aggregate (D'Angelo *et al*., 2008).

The use of WMA technologies is also consistent with the ideals of sustainable development (Soderlund, 2007). The United Nation's Brundtland Commission defined sustainable development as "*Development that meets the need of the present without compromising the ability of future generations to meet their own needs*", (UN, 1987). The concept of sustainable development embraces the ideas of:

i. reduced consumption of raw materials (aggregates, bitumen and fuel),
ii. reduced emissions and
iii. the possibility of increased recycling.

The Greenroads sustainable project rating system is a metric project rating system for sustainable performance of road design and construction (Soderlund, 2007), developed by the University of Washington and CH2M HILL that has been adopted by the Washington State Department of Transport (WSDOT). It considers WMA technology as an ideal technology for the promotion of sustainable practices in road construction. It offers the opportunity to reduce consumption of raw materials and increase recycling. This reduction is achieved by increasing the amount of reclaimed asphalt included in WMA mixtures to between 45 % and 100 % (D'Angelo *et al*., 2008).

When compared with HMA technology, WMA technology presents an improvement in working conditions for the construction crew. Reductions in pavement mix temperature reduce the fumes that workers are exposed to and provide a cooler working environment. The improvement in working conditions should results in increased productivity, greater employee retention and a reduction in work related injuries.

Reduced mixing and compaction temperature of WMA offers potential for the expansion of paving season, it can also be beneficial during cold-weather paving or when mixtures must be hauled long distances before placement (Vaitkus *et al*., 2009; Brosseaud and Saint Jacques, 2008; Manolis *et al*., 2008; Tušar *et al*., 2008; Kristjansdttir, 2006). The smaller differential between the mix temperature and ambient temperature results in a slower cooling rate. Because WMA can be compacted at lower temperatures, more time should be available for compaction. The mechanisms that allow WMA to improve workability at lower temperatures also aid compaction. Improved compaction or in-place density tends to reduce permeability and binder hardening due to ageing, which tends to improve performance in terms of cracking resistance and moisture susceptibility (Hurley and Prowell, 2006).

However, the most common classification differentiates warm mixes by the technology used, and divides them into three categories (Zaumanis, 2010):

- Foaming techniques;
- Addition of organic or wax additives;
- Addition of chemical additives (usually emulsification agents or polymers).

Foaming techniques are utilized to introduce water into bitumen in a direct (water-containing processes) or in an indirect manner (water-based processes). When water comes in contact with the hot bitumen, it turns into steam and results in a volume expansion of the bitumen thus reducing its viscosity. Among other parameters that affect the degree of bitumen volume expansion, the most important are the amount of water added and the temperature of the bitumen (Jenkins, 2000).

Water-containing foaming technique involves direct injection of water into the bitumen via a foaming nozzle. This injection results in a temporary increase of the volume of the bitumen which enables coating of the aggregates at lower temperatures and reduces the viscosity and, hence, facilitates compaction. This technique can result in a temperature reduction of about 20 °C to 30 °C. Alternatively, water-based techniques can use water bearing chemical additives or minerals, which introduce moisture into the mixture, causing it to vaporise and create foam. The most commonly used materials are hydrophilic zeolite minerals, which contain approximately 20 % water by weight, which is released upon temperature increase (above 100 °C). This release of water creates a restrained foaming effect, which improves the workability of the mixture for a 6 to 7 h period, or until the temperature drops below 100 °C.

The organic and wax additives include products that modify the rheological properties of the bitumen. At high temperatures above the melting temperature of the additives, the viscosity is reduced and, therefore, aggregate coating and compaction is improved. At temperatures below the melting temperature of the additives, the binder’s viscosity is increased and the resistance to rutting and permanent deformation of the asphalt mixture is improved. However, for some additives, the low-temperature cracking resistance is reduced by the viscosity increase as well.

The addition of chemical additives has a negligible effect on the rheological properties of the bitumen. This technique focuses in controlling and reducing the frictional forces at the bitumen-aggregate interface and, therefore, enhancing the spreading of the bituminous film over the aggregate at lower temperatures.

3.1.3.1 Selection of additives used for half-warm and warm mixtures

A large number of different products that can be used in Warm Mix Asphalt technologies are currently available in the market. The additives and/or processes used to produce warm or half-warm mix asphalt tend to be proprietary products that may not necessarily have data available that is comparable with that of other products. A list of half-warm and warm asphalt mix production processes and additives used is given in Table 4.

This list comes from a literature survey of half-warm and warm asphalt mix production processes and additives used in Europe and North America. Therefore, this list does not include all of the options available Worldwide, nor does the inclusion of any system on the list give any assurance that the additive / system works as may be claimed by the promoter of a particular system.

Table 4. Summary of Warm and Half-Warm Systems

(after D'Angelo *et al*., 2008; Zaumanis, 2010, Bonaquist, 2011 Rubio *et al*., 2012; Nicholls and James, 2012; Lewis *et al*., undated)

Product	Company	Description	Dosage of additive	Country used	Production Temperature or reduction ranges	Website
Zeolite additives						
Advera	PQ Corporation	Water containing using Zeolite	0.25 % of mixture by mass	USA	(10-30) °C	www.pqcorp.com/products/AdveraWMA.asp
Aspha-Min	Eurovia and MHI	Water containing Zeolite	0.3 % of mixture by mass	Worldwide including France, Germany and USA	(20-30) °C	www.eurovia.fr/en/produit/135.aspx?print=y
Organic (Wax) additives						
Asphaltan A Romonta N	Romonta GmbH	Montan wax for mastic asphalt	(1.5-2.0) % of bitumen by mass	Germany	20 °C	www.romonta.de/ie4/english/romonta/i_wachse.htm
Asphaltan B		Rafined Montan wax with fatty acid amide for rolled asphalt	(2-4) % by mixture by mass	Germany	(20-30) °C	
Sasobit	Sasol	Fischer-Tropsch wax	(2.5-3.0) % of bitumen by mass in Germany; (1.0-1.5) % of bitumen by mass in USA	Worldwide including EU, RSA and USA	(20-30) °C	www.sasolwax.us.com/sasobit.html
Sasolwax Flex		Fischer-Tropsch wax plus polymer (choice of type)	Unspecified		At least 28 °C	www.sasolwax.com/More_about_Sasolwax_Flex.html

Table 4. Summary of Warm and Half-Warm Systems (Cont.)

(after D'Angelo *et al*., 2008; Zaumanis, 2010, Bonaquist, 2011 Rubio *et al*., 2012; Nicholls and James, 2012; Lewis *et al*., undated)

Product	Company	Description	Dosage of additive	Country used	Production Temperature or reduction ranges	Website
Fatty acid derivative additives						
Hypertherm	Coco Asphalt Engineering	Fatty acid derivative	Unspecified	Canada	Unspecified	www.cocoasphaltengineering.com/warm_mix.aspx
Licomont BS 100	Clariant	Fatty acid amide wax	3 % of bitumen by mass	Germany	(20-30) °C	http://clariant.com/C12576850036A6E9/A0F44E23B922E21CC12576BF00484894/$FILE/20100203_Clariant_LowEmissionModifierBoosts.pdf
Chemical additives						
Cecabase RT	CECA Arkema group	Chemical package	(0.2-0.4) % of mixture by mass	France and USA	120 °C	www.cecachemicals.com/sites/ceca/en/business/bitumen_additives/warm_coated_material/warm_coated_material.page
Ecoflex or 3ELT	Colas	Unspecified additive	Unspecified	France	(30-40) °C	www.colas.com/en/innovations/products/products-list/fiche-produit-1101193.html%26product=73
Evotherm DAT	Mead-Westvaco	Chemical package plus water	30 % of binder by mass	Worldwide including France and USA	(85-115) °C	www.meadwestvaco.com/Products/MWV002106
Evotherm 3G or REVIX		Water-free chemical package	Unspecified	USA	(15-27) °C	
Qualitherm	QPR ShopWorx	Unspecified additive	Unspecified	Canada and USA	Unspecified	www.qprshopworx.com/products/asphalt-engineering/qpr%C2%AE-qualitherm/
Rediset WMX	Akzo Nobel	Cationic surfactants and organic additive	(1.5-2) % of bitumen by mass	Norway and USA	≥30 °C 126 °C	www.surfactants.akzonobel.com/asphalt/pdf/Rediset%20Brochure_0907.PDF
Sübit VR	GKG Mineraloel Handel	Unspecified additive	Unspecified	Germany	Unspecified	www.gkg-oel.de/fileadmin/gkg-oel/Dokumente/Produktbeschreibung.pdf

Table 4. Summary of Warm and Half-Warm Systems (Cont.)

(after D'Angelo *et al*., 2008; Zaumanis, 2010, Bonaquist, 2011 Rubio *et al*., 2012; Nicholls and James, 2012; Lewis *et al*., undated)

Product	Company	Description	Dosage of additive	Country used	Production Temperature or reduction ranges	Website
Other specified additives						
Thipoave	Shell	Sulphur plus compaction aid	(30-50) % of bitumen by mass	Worldwide	20 °C	www.shell.com/home/content/sulphur/your_needs/products/in_roads/
TLA-X	Lake Asphalt of Trinidad and Tobago	Trinidad Lake Asphalt plus modifiers	Unspecified	Worldwide	Unspecified	www.trinidadlakeasphalt.com/home/products/tla-x-warm-mix-technology.html
Emulsions						
ECOMAC	SCREG	Cold mix warmed before laying	Unknown type or quantity	France	c.45 °C	www.colas.com/en/innovations/products/products-list/fiche-produit-1101193.html%26product=75
Evotherm ET	Mead-Westvaco	Chemical bitumen emulsion	Delivered in form of bitumen emulsion	Worldwide including France and USA	(85-115) °C	www.meadwestvaco.com/Products/MWV002106
Foaming technology						
Accu-Shear Dual Warm Mix Additive System	Stansteel	Water-based foaming process	Unnecessary	USA	Unspecified	www.stansteel.com/sip.html
Adesco/Madsen Static Inline Vortex Mixer	Adesco/ Madsen	Water-based foaming process	Unnecessary	USA	Unspecified	www.asphaltequipment.com/documents/Static%20Inline%20Vortex%20Mixer%20Brochure.pdf
Aquablack WMA	MAXAM equipment	Water-based foaming process	Unnecessary	USA	Unspecified	http://maxamequipment.com/AQUABlackWMA.htm
AquaFoam	Reliable Asphalt Products	Water-based foaming process	Unnecessary	USA	Unspecified	www.reliableasphalt.com/Default.asp

Table 4. Summary of Warm and Half-Warm Systems (Cont.)

(after D'Angelo *et al*., 2008; Zaumanis, 2010, Bonaquist, 2011 Rubio *et al*., 2012; Nicholls and James, 2012; Lewis *et al*., undated)

Product	Company	Description	Dosage of additive	Country used	Production Temperature or reduction ranges	Website
Double Barrel Green	Astec	Water-based foaming process	Optional anti-stripping agent	USA	(116-135) °C	www.astecinc.com/index.php?option=com_content&view=article&id=117&Itemid=188
ECO-Foam II	Aesco / Madsen	Water-based foaming process	Unnecessary	USA	Unspecified	www.asphaltequipment.com/documents/EcoFoamII.pdf
NA Foamtec	Foamtec International	Water-based foaming process	(1.5 - 3.0) % by mass of binder	RSA and USA	Unspecified	www.aapaq.org/q/2011st/docs/110909_Lewis_Discussion_with_Aussie_delegation_WMA.pdf
HGrant Warm Mix System	Herman Grant Company	Water-based foaming process	Unnecessary	USA	Unspecified	www.hermangrant.com/warm-mix.htm
LEA (Low Energy Asphalt)	LEACO and McConnaughay	Water-based hot coarse aggregate mixed with wet sand	±0.5 % of bitumen by mass of coating and adhesion additive	France, Italy, Spain and USA	≤100 °C	–
LEAB	BAM Wegen bv	Water-based mixing of aggregates below water boiling point	0.1 % of bitumen by mass of coating and adhesion additive	Netherlands	90 °C	www.bamwegen.nl/sites/www.bamwegen.nl/files/site_images/LEAB%20-%20Asphalt%20English.pdf
LT Asphalt	Nynas	Water-based binder foaming with hygrophilic filler	Hygroscopic filler at (0.5-1.0) % of mixture by mass	Worldwide including Italy and Netherlands	90 °C	http://nyport.nynas.com/Apps/1112.nsf/wpis/GB_EN_LT-Asphalt/$File/LT-Asphalt_GB_EN_PIS.pdf
Meeker Warm Mix Asphalt System	Meeker Equipment	Water-based foaming process	Unnecessary	Spain	Unspecified	www.meekerequipment.com/new_warmmixad1.html
Ultrafoam GX	Gencor Industries	Water-based foaming process	Unnecessary	USA	Unspecified	http://gencorgreenmachine.com
Warm Mix Asphalt System	Terex Roadbuilding	Water-based foaming process	Unnecessary	USA	<32 °C	www.terexrb.com/default.aspx?pgID=308

Table 4. Summary of Warm and Half-Warm Systems (Cont.)

(after D'Angelo *et al*., 2008; Zaumanis, 2010, Bonaquist, 2011 Rubio *et al*., 2012; Nicholls and James, 2012; Lewis *et al*., undated)

Product	Company	Description	Dosage of additive	Country used	Production Temperature or reduction ranges	Website
Other processes						
Low Emission Asphalt	McConnaughay Technologies	Combination of chemical and water based foaming technology	0.4 % of bitumen by mass	USA	90 °C	www.mcconnaughay.com/lowemissionasphalt_intro.php
WAM-Foam	Shell, Kolo Veidekke	Foaming process using two binder grades	Anti-stripping agents can be added to soften binder	Norway, France, Canada, Italy, Luxemburg, Netherlands, Sweden, Switzerland, UK and USA	(110-120) °C	www.shell.com/home/content/bitumen/products/shell_wam_foam/

3.1.3.2 Organic (Wax) additives

Sasobit is a Fischer-Tropsch (FT) wax. FT paraffin waxes are produced by treating hot coal with steam in the presence of a catalyst. FT waxes are long-chain aliphatic hydrocarbon waxes with a melting point between 85 °C and 115 °C and that have a high viscosity at lower temperatures and a low viscosity at higher temperatures. They solidify in asphalt at between 65 °C and 115 °C into regularly distributed, microscopic, stick-shaped particles. They may be used to modify the binder or added directly to the mixture (D'Angelo *et al*., 2008).

Montan wax is a combination of nonglyceride long-chain carboxylic acid esters, free long-chain organic acids, long-chain alcohols, ketones, hydrocarbons, and resins. It is a fossilized plant wax. *Asphaltan A* and *Romonta N* are Montan waxes with the congealing points at 78 °C and 125 °C, respectively; in *Asphaltan-B*, the refined Montan wax is blended with a fatty acid amide. They are hard waxes obtained by solvent extraction of certain types of lignite or brown coal. They have a similar effect on asphalt as FT-waxes. The stiffness is increased after cooling, as with fatty acid amide. They have been used as an additive for mastic asphalt in Germany, because of the possibility to modify the consistency of the binder and improve the adhesion between binder and aggregate particles (D'Angelo *et al*., 2008; Zaumanis, 2010).

Licomont BS 100 is a fatty acid amide. Fatty acid amides are produced synthetically by reacting amines with fatty acids. Typically, the melting point is between 141 °C and 146 °C. Similar products have been used as viscosity modifiers in asphalt for several years and are available in various forms from a number of suppliers. Fatty acid amides have been used in roofing asphalt since the late 1970s to early 1980s (D'Angelo *et al*., 2008).

3.1.3.3 Foaming processes

Aspha-min is a synthetic zeolite composed of aluminosilicates of alkalimetals. It contains about 20 % water of crystallization, which is released by increasing temperature. Typically 0.3 % zeolite by weight of mixture is added to the mixture shortly before or at the same time as the binder. The zeolite releases a very small amount of water, creating a controlled foaming effect that leads to a slight increase in binder volume and reduces the viscosity of the binder (D'Angelo *et al*., 2008).

Advera is a synthetic zeolite similar to Aspha-min zeolite, described above. Advera has a finer gradation than Aspha-min, with 100 % passing the 0.075 mm (No. 200) sieve. PQ Corporation is working on a process to blend Advera with the binder as it is being introduced into a plant instead of simply blowing it into the mixing chamber like a fibre. This process is believed to provide a more consistent WMA (D'Angelo *et al*., 2008).

Little is known about the *Ecomac* process. It appears that a traditional cold mix is prepared using an emulsion. The cold mix is stored until it is ready to be laid. At that time, it is warmed to improve compaction and the overall mechanical properties (D'Angelo *et al*., 2008).

Low Energy Asphalt (LEA) uses wet fine aggregate to foam the bitumen. The main reason for energy savings in this process is that it takes five times more energy to turn water into steam than it takes to heat aggregate from 0 °C to 100 °C. The coarse aggregate and a portion of fine aggregate are heated to normal HMA temperatures (approximately 150 °C) and mixed with the binder containing coating and adhesion additives. After the coarse aggregate is coated with the binder, it is mixed with the cold, wet fine aggregate. Ideally, the fine aggregate should contain about 3 % moisture. This moisture turns to steam and causes the asphalt on the coarse aggregate to foam, which in turn encapsulates the fine aggregate. The resulting (equilibrium) mix temperature is less than 100 °C. This method has been used widely for the last few years and, although the results are promising, the suitability for colder areas such as the Nordic countries still has to be verified because the use reports are mostly from countries with slightly warmer climate (Zaumanis, 2010).

The *LEAB* process is a commercialization of the half-warm foamed asphalt work (Jenkins, 2000). To date, this process has been used only in batch plants. The virgin aggregate is heated to about 95 °C and RA is heated in a separate dryer drum to between 110 °C and 115 °C. During trials to assess the moisture content of the aggregate, it was noted that the moisture content of the fines/filler going to the baghouse was high, about 2.2 %. Therefore, the contractor who developed the mix, BAM, added an extra burner (after the pugmill) to heat the air going into the baghouse. An additive is added to the binder immediately before mixing to promote coating and adhesion. This additive also tends to extend the life of the foam, which increases workability (Jacobs *et al*., 2010).

LT-Asphalt technology foams the binder with special nozzles just before adding to mixture chamber with the heated (at about 90 °C) aggregates. Between 0.5 % and 1.0 % of hydrophilic filler is added to hold and control the latent moisture from foaming (D'Angelo et al., 2008; Zaumanis, 2010).

WAM-Foam technology differs slightly from the others. It is a process, not an additive or material. It uses two component binder systems that add a soft binder and a hard foamed binder at different times in the mixing cycle during production. The aggregates are heated at about 130 °C and then coated with the soft binder, which is typically 20 % to 30 % of the total binder. The hard binder is then foamed into the mixture by adding cold water (2 % to 5 % by mass of the hard bitumen) at about 180 °C. This combination of soft binder and foamed hard binder reduces mix viscosity to provide the necessary workability (D'Angelo *et al*., 2008; Rubio *et al*., 2012; Zaumanis, 2010).

Double Barrel Green, *Ultrafoam GX*, *Aquablack WMA* and *Warm Mix Asphalt System* are using some type of nozzle to inject water into asphalt binder stream. Each technology uses equipment developed by the individual company. A small amount of water is added in order to microscopically foam the binder. The water creates steam which is encapsulated in the binder resulting in foaming and large volume increase of the binder. Consequently, the viscosity is decreased allowing the aggregates coating at lower temperatures (D'Angelo *et al*., 2008; Rubio *et al*., 2012; Zaumanis, 2010).

3.1.3.4 Chemical additives

Evotherm ET is an emulsion mixed with hot aggregates to produce a resulting mix temperature between 85 °C and 115 °C. The emulsion is produced using a chemical package designed to enhance coating, adhesion and workability. The majority of the water in the emulsion flashes off as steam when the emulsion is mixed with the aggregates (D'Angelo *et al*., 2008; Rubio *et al*., 2012; Zaumanis, 2010). Evotherm ET has been replaced by *Evotherm DAT* and *Evotherm 3G*.

Evotherm DAT is injected into liquid asphalt at the mix plant using low-cost metering equipment. For batch plant production, a spray bar is used to deliver the additive into the pug mill. Evotherm DAT decreases the viscosity of the binder at lower mixing temperatures, which leads to fully coated aggregates. This process reduces the production temperature by 30 % (D'Angelo *et al*., 2008; Rubio *et al*., 2012; Zaumanis, 2010).

Evotherm 3G is a water-free form of Evotherm. It promotes adhesion at lower temperatures by acting as both a liquid antistrip and a warm mix additive. It can replace hydrated lime with an easy to handle, pumpable liquid. Because this is a relatively new product, there is no information available from independent research about its properties (D'Angelo *et al*., 2008; Rubio *et al*., 2012; Zaumanis, 2010).

Rediset WMX is a combination of cationic surfactants and organic additive based rheology modifier. It chemically modifies the bitumen and encourages active adhesion that improves the wetting of aggregates by binder. Other components of the additive reduce the viscosity of the binder at production temperature. It is in pellet form, does not contain water and allows a production temperature reduction of 15 °C to 30 °C compared to HMA (D'Angelo *et al*., 2008; Zaumanis, 2010).

3.1.3.5 Parameters influencing the durability

Extensive quantities of several warm and half-warm mix asphalt mixtures have been installed across the world in all road layers of both motorways and non-trunk roads under different climatic conditions from the warm Mediterranean climate through to places which experience extremes of both hot and cold weather conditions. However, most such systems have not been in general service for long enough to assess their actual long-term durability (Nicholls and James, 2012). Certain test results, such as those from the saturated ageing tensile stiffness conditioning test, have indicated good durability, but there is still a concern among many engineers about the potential durability of warm and half-warm mix asphalt mixtures (Prowell *et al*., 2007).

All the long-term environmental and economic benefits arising from the use of warm and half-warm mix asphalt are of little worth if the mechanical performance of warm and half-warm mixtures is not as good as, or is even significantly worse than, that of standard hot asphalt mixtures. Because WMA is a relatively new technology, there is little information on the long–term field performance of warm asphalt mixtures. Furthermore, the variety of WMA processes along with the great number of products utilized to achieve lower mixing, laying and compaction temperatures necessitates a more in-depth investigation on the durability characteristics of warm and half-warm mixtures.

Despite the variability of WMA technologies and the fact that specific methods can have particular weaknesses, there are certain parameters that may commonly influence the mechanical performance characteristics of the mixture and hence affect its durability.

The main concern associated with WMA is the moisture damage susceptibility. Moisture damage, causing a loss of bond between the binder or the mastic and the aggregate under traffic loading, can result in a decrease of strength and durability in the asphalt mixture and, ultimately, affect its long-term performance.

Many WMA processes utilize water into the mixture as part of the manufacture process or the use of moist aggregate (D'Angelo *et al*., 2008; Zaumanis, 2010). In case of incomplete evaporation of the water during the mixing and laying process, water can be present in the final mixture. In general, moist aggregates can have an adverse effect on the integrity of the bond between the bituminous film and the aggregate, because moisture diffuses from the aggregate towards the bonding interface (Kringos, 2007). This presence of moisture may result in premature rutting and ravelling on the pavement surface. Therefore, finding the appropriate amount of water to be introduced in the warm and half-warm mixtures, as well as determining the type and dose of anti-stripping agents used in WMA, is important.

The retention of the water introduced for the foaming processes is a potential concern to the traditional approach of keeping all moisture out of the mixture. The presence of water in the mixture after compaction has been found even in other types of systems with the lower mixing and compaction temperatures not completely drying the aggregate (Nicholls and James, 2012). Therefore, the moisture susceptible of warm and half-warm mix asphalt mixtures needs to be checked with water-sensitivity testing being an integral step when developing a mix design procedure for mixtures with additives. However, moisture sensitivity can be different for warm and hot mix asphalt mixtures designed using the same aggregates and binder (Bonaquist, 2011). Anti-strip additives have proved effective with warm and half-warm mix asphalt mixtures with systems using them generally having reduced moisture susceptibility (Hodo *et al.*, 2009).

An additional issue, associated with the reduction of temperature in WMA is whether a reduced amount of bitumen is absorbed by the aggregates during the mixing process (Chowdhury and Button, 2008). Generally, the amount of absorption was found to be less with increased bitumen viscosity; therefore, the mixing temperature plays an important role in durable bitumen film thickness creation (Lee *et al*., 1990). The formation of thin aggregate coatings may lead to premature failure of the paving mixture due to premature age hardening, erosion of the bituminous film as a result of water action (pumping action caused by traffic over a wet pavement) and/or suppression of the bitumen by water at the binder/aggregate interface.

Age hardening is caused mostly by the presence of oxygen, ultra-violet radiation and by changes in temperature. The effect of ageing can be classified in two major groups: short-term and long-term ageing, where the first involves loss of volatiles and oxidation during the mixing and placement phase and the latter refers to oxidation during the service life of the asphalt mixture. Lower mixing temperatures in WMA can cause less short-term ageing during the production process and, thus, the pavement can be prone to permanent deformations if this effect is not taken into account.

Generally, low-viscosity binders show higher ageing effects compared to high viscosity binders because of higher volatility. The extent to which the aged binder of any reclaimed aggregate mixes with, and is rejuvenated by, that of fresh added binder is a concern for some with hot mix asphalt, but is further exacerbated when the mixing is undertaken at reduced temperature. A binder mixing analysis using dynamic modulus and recovered binder testing on plant mix validated that aged and new binders can mix at warm mix asphalt process temperatures (Bonaquist, 2011). Nevertheless, there is potential for reduced durability from this cause when warm or half-warm mix asphalt is produced with reclaimed asphalt if good practice is not followed.

Not obtaining adequate coating of all the aggregate particles is another risk associated with the lower mixing temperature. For the wide range of warm and half-warm mix asphalt processes, mixing and compaction temperatures based on viscosity cannot be used to control coating and it was found that the degree of coating obtained in the laboratory depends on the type of mixer that is used (Bonaquist, 2011). The lack of adequate coating will worsen moisture sensitivity and promote binder stripping, both of which will have an adverse effect on mix durability. Therefore, there is considerable potential for this affect to influence the durability, although it has been found not to occur with many of the systems.

Mixing and compaction temperatures based on viscosity cannot be used in to ensure workability or compactibility of warm and half-warm mix asphalt processes (Bonaquist, 2011). The combination of reclaimed asphalt and low production and compaction temperatures has been found to make some warm and half-warm mix asphalt mixtures more sensitive to changes in temperature than similar hot mix asphalt mixtures, with that sensitivity having implications for the durability.

Research reports have also shown that WMA exhibits better compactibility characteristics than standard HMA (Hurley and Prowell, 2006), which is considered to be an advantage during paving. However, it can also lead to higher mixture densities and, thus, lower air voids contents in the asphalt mixtures and, as a result, lower levels of long-term ageing. Basically, limiting long-term ageing is desirable because it is likely to result in longer pavement service life. On the other hand, reduced bitumen hardening due to reduced ageing can increase the rutting potential of WMA. For that reason, it may be essential to choose lower grade bitumen when working with WMA.

Cold mix asphalt (also commonly called *bitumen-stabilised material* and *cold recycling mixtures*) are bituminous bound road materials where the mixing, laying and compaction are usually undertaken at < 70 ºC. Cold mixed road materials are most often applied for recycling high proportions of reclaimed road materials and/or for strengthening existing base layers. Particularly for the recycling of environmental problematic road materials (such as tar-containing road layers and asbestos-polluted material), cold mixtures are commonly applied in Europe, particularly central Europe.

3.1.4 Cold-mix asphalt

Cold mix asphalt can be achieved by various technologies. The most common technologies are:

- Bitumen emulsion technology.
- Foamed bitumen technology.

In both cases, hydraulic binders can be added during the mixing process.

Pure hydraulic-bound road layers, often referred as cold mixtures, as well as cold mixtures of slurry surfacing and other veneer overlays that are applied for road maintenance, are not discussed within this report because they are outside the focus of the EARN project.

Cold bitumen-stabilised mixtures resulting in structural layers are discussed in the following section. Most often, the cold mixtures are applied for strengthening existing road base layers. By these means, high recycling rates are reached (> 80 %). Usually, the cold mixtures are produced on site by milling existing layers, mixing them with additional aggregates and binders and laying in the same working stage.

The resulting material property depends on type and content of binder applied. Cold mixtures are either mixed with hydraulic binders only, resulting in lean concrete mixtures for stiff (rigid) road courses and/or with bitumen emulsion or foamed bitumen. In later cases, usually hydraulic binders are added to the mixtures in order to reduce the content of free water from the emulsion after breaking or from the foaming process and to increase the early-life stiffness. For these mixtures, the material properties depend highly on the content of bituminous and hydraulic binder. As indicated by Figure 6, the resulting material properties range between the plastic properties of unbound road materials (for low contents of binders) to predominant brittle and stiff properties for cement-dominant mixtures to flexible road layers with improved cohesion (Wirtgen, 2012).

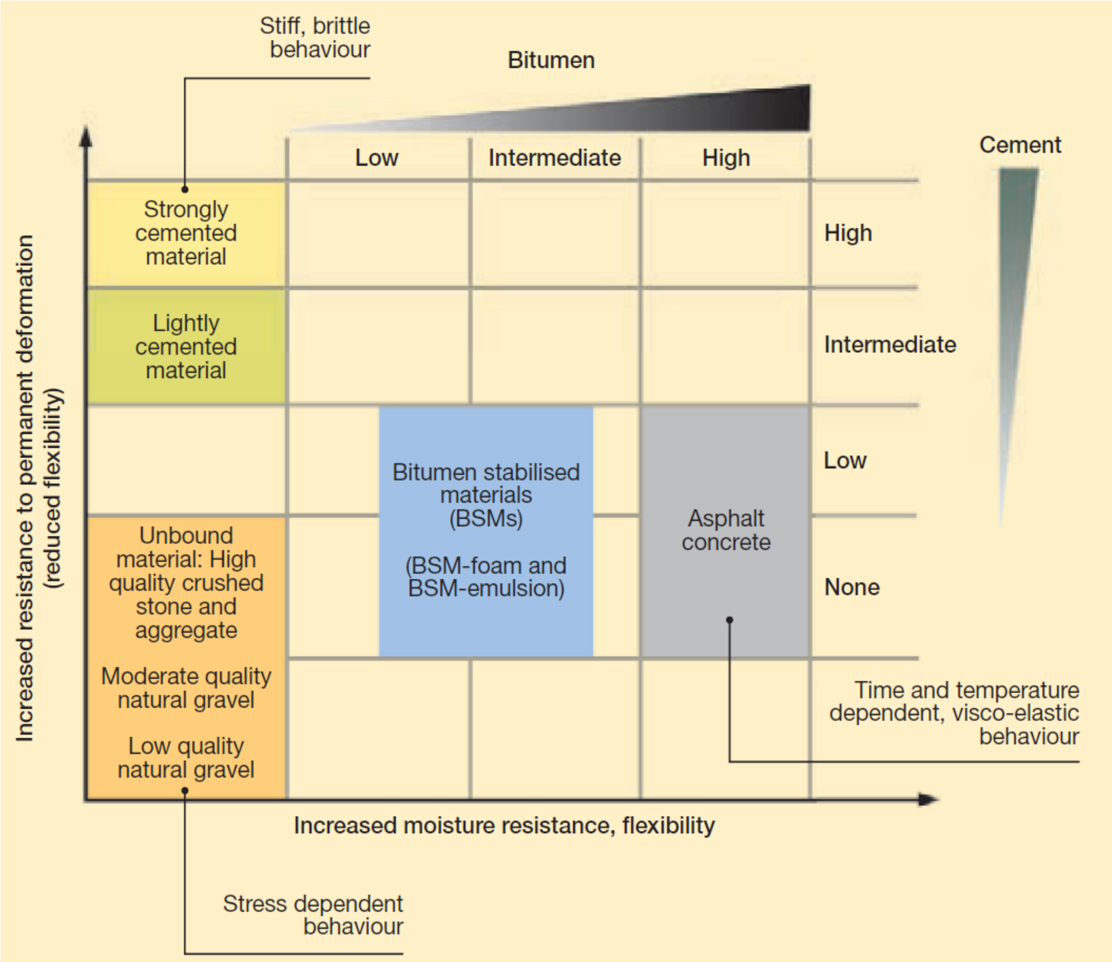

Figure 6. Classification of cold mixtures according to content of binders (Wirtgen, 2012)

3.1.4.1 Parameters influencing the durability

Compared to hot mix asphalt, warm and half-warm asphalt mixtures, the moisture content plays a dominant role for the mix design of cold recycled mixtures. The cold-mix compactibility is dependent on moisture content similarly to that of unbound road layers. The overall moisture of the mixture is based on the aggregate moisture, content of bitumen emulsion or foamed bitumen and added water. For foamed bitumen mixtures, additional water is needed for improving the foam distribution in the mixture (Jenkins, 2000).

Curing plays an important role for the cold mix asphalt performance properties. The term curing refers to the reduction of moisture in the material. During compaction, water is pressed from the mixture. After the compaction, moisture is removed from the mixture by evaporation. Therefore, the content of air voids is generally larger in cold mix asphalt compared to HMA base layers. Forming a continuous binder coating of the aggregates, especially emulsion mixtures, requires considerably longer curing time, which can be up to several months (Doyle *et al*., 2013; Thanaya *et al*., 2009). During curing, the material's stiffness and strength will increase. Early life traffic loading can provoke premature failure of the cold recycled layer as well as other pavement courses because the cold-mix stiffness has not reached its required value. To reduce the curing time, hydraulic binders can be added to the cold-asphalt mixtures. However, for large additions of cement, the material properties may shift towards rigid pavement properties and, therefore, may provoke early-life shrinkage cracking.

The aggregate temperature plays an important role for the curing effects and the durability of cold asphalt mixtures (Jenkins, 2000).

The high air voids content, as well as the incomplete coating of the aggregates by bitumen, risks the moisture susceptibility of cold asphalt mixtures. Furthermore, despite the comparatively high mix design air void contents, cold asphalt mixtures exhibit a high resistance against compaction. Therefore, durable cold asphalt pavements require the use of heavy rollers during compaction. Because of the high bitumen viscosity after breaking and defoaming at low temperatures, dynamic compaction should be prevented in order to avoid the aggregates cracking under the heavy rollers.

The dominant failure modes determining the durability of cold asphalt depend highly on the content of bituminous and hydraulic binder. For mixtures containing relatively low binder contents (i.e. ~2 % bitumen), the material properties are similar to those of unbound base layers. For these types of mixture, pavement failure often occurs as permanent deformation. The beneficial cohesion effect of the binder is reduced by moisture affecting the bond between the binder and the aggregate particles.

With increasing bitumen content, the moisture susceptibility is reduced by better binder coverage of the aggregate particles and the material will reach a higher stiffness. Simultaneously, the pavement performance will be more similar to that of hot-mix asphalt, shifting the predominant failure mode from permanent deformation to (fatigue) cracking.

The addition of hydraulic binder will increase the stiffness of the material and strengthen the material in order to allow early life traffic loading. However, an increased content of hydraulic binder will increase the shrinkage of the material, resulting in the need for joints or notches to control the shrinkage cracking. The long-term performance and durability is, therefore, similar to that of hydraulic bound base layers.

3.1.4.2 Test procedures for evaluating durability

As discussed in section 3.1.4.1, the durability of cold asphalt mixtures is affected by:

- type of failure (rutting, cracking, shrinkage)
  - binder type (foamed bitumen / bitumen emulsion / hydraulic binder)
  - binder contents
- aggregate composition
- void content (after compaction)
- moisture
- curing time and conditions.

Because of the comparatively high moisture contents of the mixtures as well as the partly incomplete bitumen coverage of aggregates, the water susceptibility plays an important role during mix design. The most frequently applied test is the indirect tensile test conducted on dry and water-saturated specimen in order to evaluate the ITSR-value (Batista *et al*., 2012).

Further quality requirements are based on the material stiffness modulus and material strength.

The curing plays an important role for the development of long-term pavement properties. In order to accelerate the on-site curing, a wide variety of curing procedures are applied worldwide. Even throughout Europe, the accelerated curing procedures applied vary in temperature, conditions and time of storage considerably. Table 5 summarizes cold asphalt mix design, compaction and mechanical testing procedures.

Table 5. Mix design approaches for cold asphalt mixtures in Europe (Batista *et al*., 2012)

Country / Institution	Optimum water content determination	Optimum binder content determination		Mechanical testing
		Compaction	Test specimen curing	
Germany	Static compaction (50 kN)	Static compaction (50 kN)	2 days @ 20 ºC and 95 % relative humidity + 26 days 20 ºC, (55 ± 15) % rel. hum.	Air voids content; Indirect tensile strength (5 ºC) after 7 days and 28 days; Water sensitivity; Stiffness modulus (indirect tensile test)
Ireland	–	Static compaction (120 kN)	14 days @ 35 ºC and 20 % relative humidity	Compactibility; Resistance to compression; Wet strength; Indirect tensile stiffness modulus (dry); Indirect tensile strength (wet and dry); Unconfined compression strength
Portugal	Modified Proctor	Static compaction (21 MPa / 8 MPa)	1 day @ room temperature + 3 days @ 50 ºC (after 2009)	Water sensitivity; Uniaxial compression strength (*v* = 5,08 mm/mm)
Spain	Modified Proctor	Static compaction (170 kN / 60 kN); Gyratory	3 days @ 50 ºC	Water sensitivity; Uniaxial compression strength (*v* = 5,08 mm/mm); Indirect tensile strength
UK	Proctor	Proctor	3 days @ 60 ºC	Indirect tensile stiffness modulus to EN 12697-26 and EN 12697-45
Wirtgen	Modified Proctor	Impact compactor (2 x 75 blows)	3 days @ 40 ºC	Indirect tensile stiffness modulus (dry); Indirect tensile strength (wet and dry); Unconfined compression strength

3.2 Results from literature review

The Direct-Mat Project established a database containing details on road construction projects that had applied various kinds of recycling techniques. Although data from a high number of projects were gathered, generally the information on the actual long-term performance reached by the partly innovative recycling procedures is still missing. The incorporated literature review indicated the performance for several applications of RA in new hot mix asphalt (HMA), but the comparable material performance is in terms of rutting and crack resistance (Figure 1).

Mixture type		***HMA with x % RA has the same or better properties than comparable mix without RA***		***HMA with x % RA has worse properties than comparable mix without RA***	
		Laboratory study	***Full-Scale study***	***Laboratory study***	***Full-Scale study***
Surface course asphalt	AC	20%(DRF4.2) 40%(DRF4.6) 50%(DRF4.1)			
	SMA	20%(DRF4.162) 30%(DRF4.14) 30%(DRF4.51)		30%(DRF4.162)[3]	
	ACTL		30%(DRF4.229)		
Binder course asphalt	AC	25%(DRF4.2); 30%(DRF4.15); 30%(DRF4.155);		30%(DRF4.155)[1]	
Base course asphalt	AC	30%(DRF4.12); 15%(DRF4.154)			
	HRA				
General HMA		30%(DRF4.222) 30%(DRF4.224) 35%(DRF4.160) 40%(DRF4.158) 45%(DRF4.159) 40%(DRF4.163) 50%(DRF4.225) 50%(DRF4.51) 70%(DRF4.181) 70%(DRF4.223) 100%(DRF4.228)	45%(DRF4.159)	30 % (DRF4.222)[3] 70%(DRF4.223)[3] 50%(DRF4.225)[4]	45%(DRF4.159)[2]
Life-Cycle Analysis / Pavement performance			(DRF4.161) 30%(DRF4.164) 20%(DRF4.165)		
[1] higher moisture sensitivity [2] more cracking [3] reduced fatigue resistance [4] reduced rutting resistance					

Figure 7. Experience of performance of hot-mixed asphalt containing reclaimed asphalt compared to control sections (Mollenhauer *et al*., 2011)

Whereas most of research projects found better or the same performance properties for asphalt materials with RA compared to asphalt mixtures containing only virgin constituent materials, some studies did find decreased resistance of mechanical properties which would lead to reduced service lives for these pavements. When looking in detail at these specific reports, reasons for the different findings can be found for DRF4.162 (Watson *et al*., 2008). Reduced resistance against fatigue was evaluated by four-point bending tests for two strain amplitudes. The closer evaluation of the report showed that, for increased RA contents, the viscosity of the added virgin binder was not reduced in order to compensate for the aged RA binder as is standard practice in Europe mix design procedures.

Since the Direct-Mat project (which ended in 2011), new data on service lives or material performance effects of RA addition to HMA have been published.

During Re-road project, comparative site monitoring of existing test sites were conducted (Carswell *et al*. 2012). As a result for plant-produced hot mix asphalt containing up to 40 % of RA, the medium and long-term performance on site was found comparable to control sites without RA. For hot-in-place recycling, Swedish long-term performance data was evaluated. For very high recycling rates of above 90 %, the service lifetime of pavements is reduced compared to conventional asphalt layers.

In 2011, the long-term pavement performance data from 18 road sections was reported, in which HMA overlays were paved with virgin constituent materials as well as with 30 % of RA addition. After 20 years, West *et al*. (2011) evaluated the surface condition data for estimating the long-term effect of RA application in HMA. The result of the statistical analysis is shown in Figure 8, where the assignment of the three possible differences between virgin material and material containing RA are shown. Except for IRI and rutting, the highest proportion of test sections shown no significant difference between RA and virgin asphalt mixtures. However, for all surface condition parameters except for ravelling, the proportions of test sections where 30%-RA asphalt mixtures performed significantly worse than virgin asphalt mixtures is higher than the proportions of test sections where RA mixtures showed better performance. In particular, the risk for fatigue cracking increases when HMA with 30 % of RA is applied.

The same long-term pavement performance (LTPP) database was assessed by Gong *et al*. (2012) to assess the effectiveness of pavement rehabilitation methods. The average service lifetime between rehabilitation activities were assessed. It was found that the use of 30 % of RA had no effect on the service lifetime (9,7 years) compared to (9,3 ± 1,1) years for the same structure but virgin material only. These results, though, are only based on two road sections (where 30 % of RA was added to HMA).

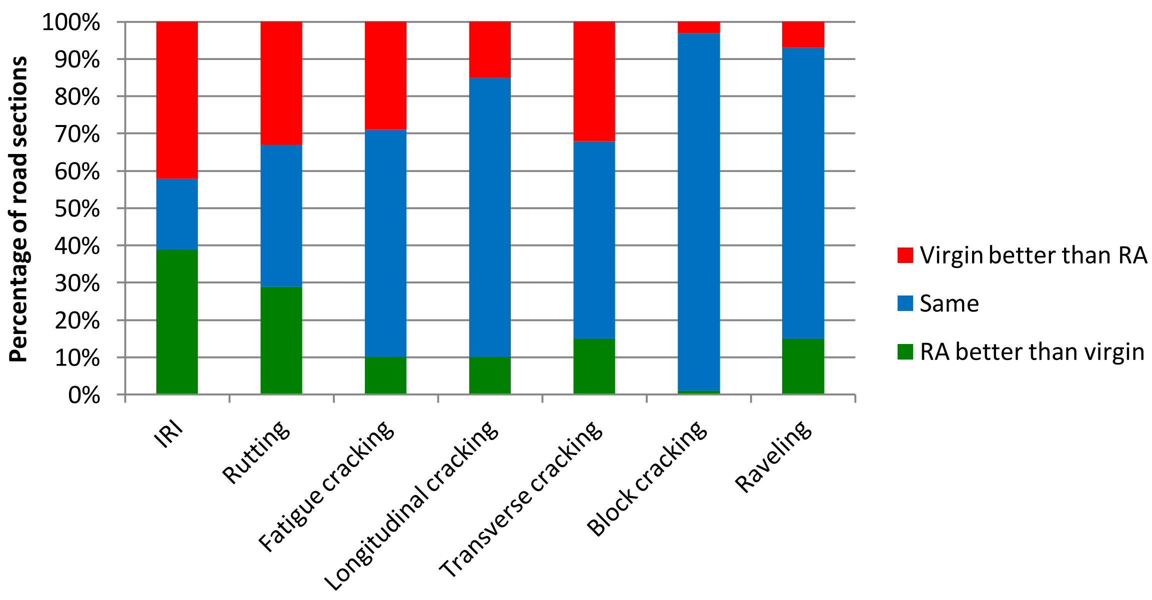

Figure 8. Performance of road sections with and without RA in hot-mix asphalt (West et al. 2011)

3.3 Results from site data review

In order to evaluate the effect of various pavement materials on the service lifetime of the road structure, existing databases containing structural and material properties may be evaluated. In the frame of EARN project, two databases were assessed.

3.3.1 UK data on service lifetime of road structures (HAPMS)

The UK road asset management database HAPMS was addressed in order to derive the effect of service life of various structures and road materials. The HAPMS database contains the structural data history of the UK primary road network from 1950 to today. For EARN assessment, datasets were evaluated which contained the actual service life of road structures or layers which were rehabilitated. The datasets contain information on the structure and some pavement materials. From these data, the mean service life of the pavement structures registered in the database can be evaluated. In Figure 9, the mean service lifetimes evaluated from HAPMS datasets for structures with total pavement length of more than 100 km are depicted. Only for the pavement sections which were identified as "green" pavements, shorter structural lengths were considered. The colour indicates the type of material:

- light grey: rigid pavements
- light red: bituminous pavements
- green: pavements based on recycled materials
- dark grey: unbound structures / not specified
- red: tar pavements.

Specific differences for the mean service life can be evaluated. Specifically, the following statements can be drawn for the three "green" pavement materials:

- Cold-recycling (foamed bitumen) seems to provide only a short service life (5,8 years); however, these data are based on 26 km of sections only.
- Cold-recycled (lean concrete) has a shorter service life than other rigid pavements (based on 75 km)
- Wet-mix recycled Macadam have a relatively long service life (based on 10 km)

However, what is not considered in this data evaluation is the effect of different traffic loading between the datasets. This difference can be one reason for the high scatter in the single structural groups, indicated by the error bars between the minimum and maximum service lives. Another item to be considered is the large time span which is covered by the analysis because, from 1950, the pavement materials have changed. In particular for younger developments (which may also contain the "green" pavement structures of special interest), this database only consists of the sections which have already failed. The road network may contain additional sites where innovative road materials are still working well and, therefore, are not considered in this dataset.

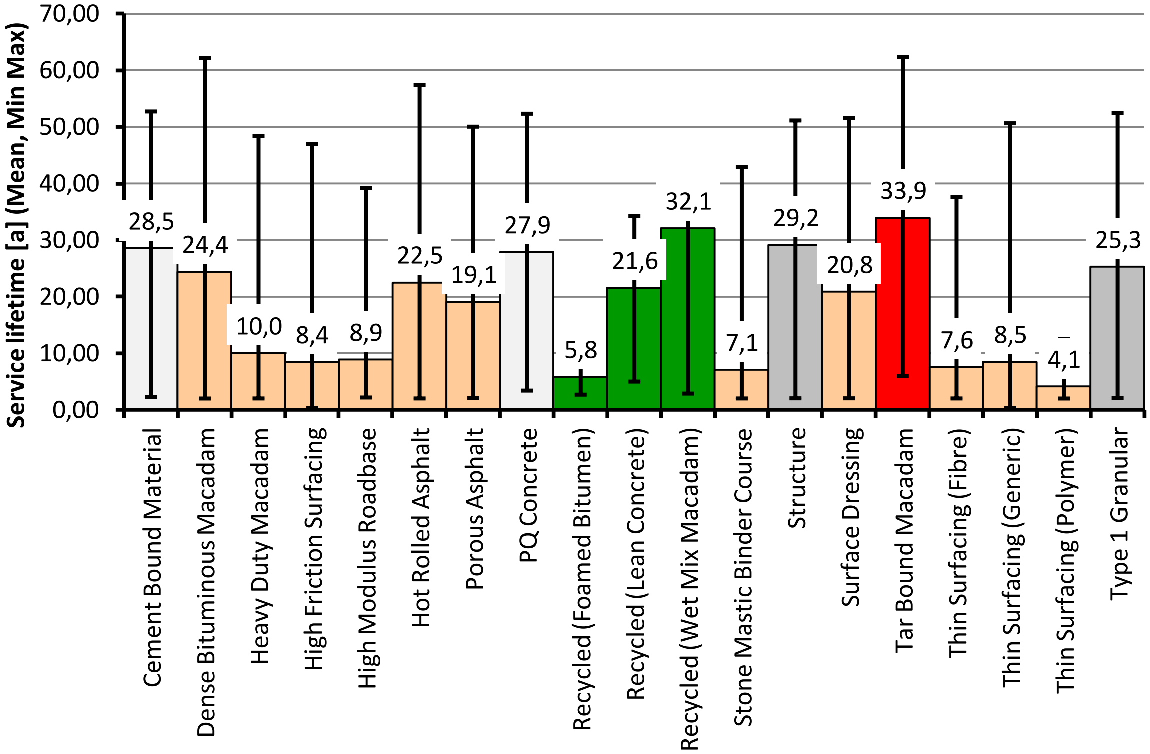

Figure 9. Mean service lifetime for specific road structures / materials and range of service lifetimes derived from UK HAPMS database

3.3.2 German data on asphalt material composition and pavement surface condition

Usually, data on the actual pavement materials applied on German road structures are stored for contractual reasons for up to 10 years but not analysed further on a network-wide basis. The data is only collected by the federal state highway agency of Lower Saxony in northern Germany where a database was developed and applied which contains the asphalt mix design properties of asphalt pavements constructed since 1989 as evaluated for contractual control tests. In this database, the actual composition is stored together with some further information on the initial mix design. For example, the mixtures which contain RA are given but the RA content is not recorded in the database. The database contains more than 80.000 data sets on asphalt mixtures that have been applied on federal roads in Lower Saxony since 1989.

From this data, the change in mix design in terms of the inclusion of RA during the years can be evaluated (compare Figure 10). The addition of reclaimed asphalt to new asphalt mixtures started in the1980s in Germany. Initially, RA was applied in asphalt base layers only. In the early 1990s, more than half of all asphalt base mixtures produced contained reclaimed asphalt.

The use of RA in asphalt mixtures for asphalt binder course layers started in 2004, initially for lightly-trafficked roads and then also for heavily-trafficked road sections from 2005. Nowadays, more than 80 % of all asphalt mixtures for asphalt binder courses are mixed with the addition of RA.

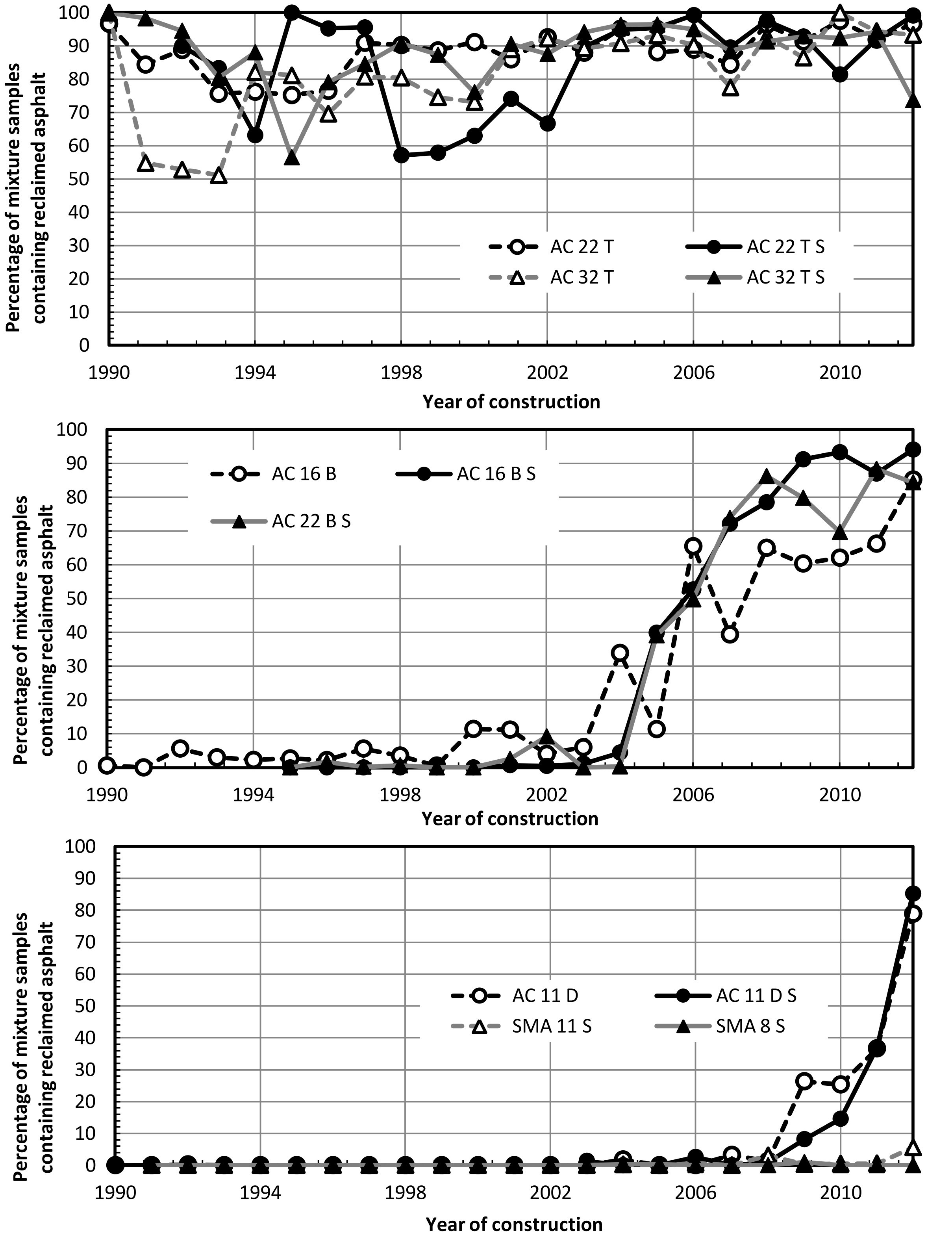

Figure 10. Proportions of newly paved asphalt layers containing RA at various rates for base (top), binder course (middle) and surface course(bottom) mixtures "S-mixes" are used for heavy-traffic roads (≥ 3,2 Mill. 10-t-ESAL)

For asphalt mixtures applied in surface courses, wide application started in 2009. However, whereas most asphalt concrete mixtures are currently produced with the addition of RA, only 5 % of SMA contains RA.

As Figure 10 shows, in surface asphalt layers, the addition of RA started late in 2008 which is too short to evaluate durability effects from existing databases. Therefore, in the following section, the asphalt binder courses were further evaluated. The addition of RA started about 2004 and, therefore, the evaluation of surface quality properties in 2012 will be applied in order to analyse if durability-related effects can be identified.

The material database containing the information of RA use for specific pavement works was combined with surface condition database of Lower Saxony measured in 2012. One problem occurring during the database evaluation was the non-homogeneous identification of locations of pavement works. Because the material database is filled by test laboratories rather by the road authorities, data from sample locations were filled as station data regarding construction-site positioning. On the other hand, the surface quality database uses network-wide, harmonised positioning system. In order to combine these two databases, each material dataset had to be evaluated manually and the eventually given information of sample or site location had to transferred to network positioning system. Because of this necessary effort, only 250 datasets could be evaluated for durability effect of RA application. From these 250 sets of data, 52 samples contained RA.

The results for the durability-relevant surface parameters "area of cracking" and "longitudinal evenness" of the comparison of sites with and without RA application are shown in Figure 11 and Figure 12.

The age or traffic loading and RA use in asphalt binder course does not have significant effects on the durability-relevant pavement surface characteristics cracked surface area or longitudinal evenness. For both characteristics large scatter can be observed.

If the scatter is analysed by regression lines, for cracking surface area larger areas of cracked surface can be observed for surfaces on top of asphalt binder courses with RA compared with the surface on top of asphalt binder layers without RA.

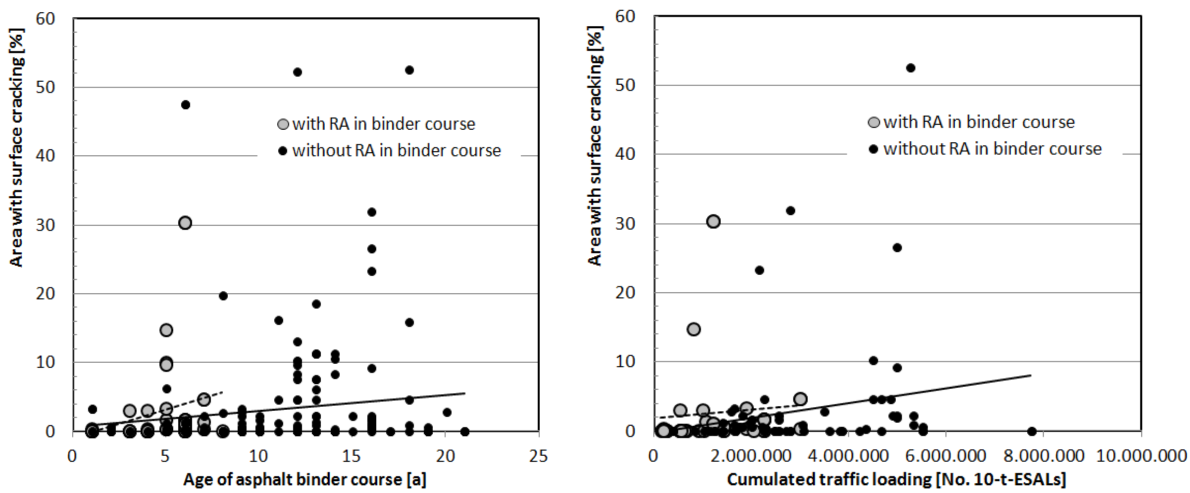

Figure 11. Surface characteristic "Area of cracking" versus asphalt binder layer age and accumulative traffic loads (ESAL)

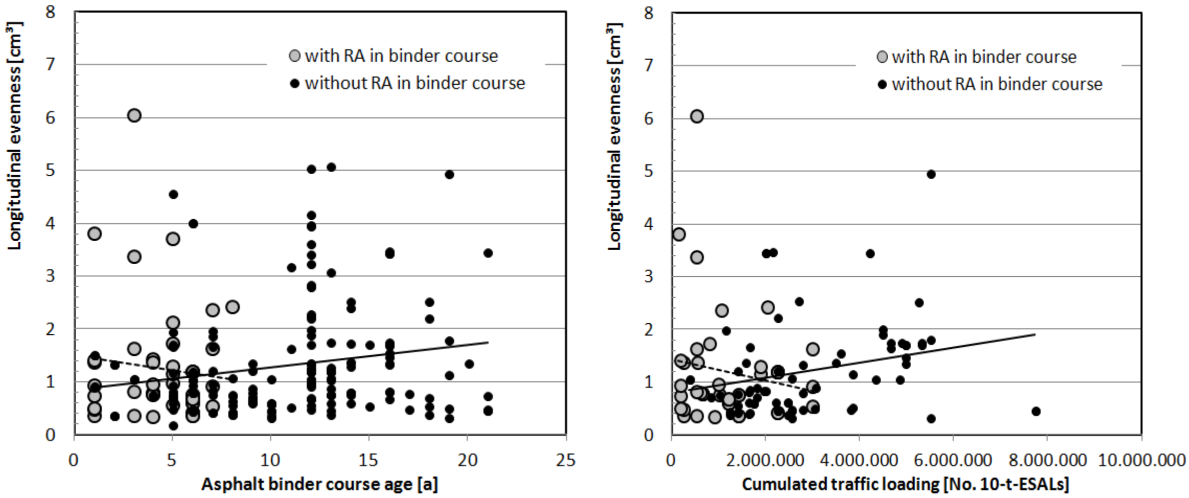

Figure 12. Surface characteristic "Longitudinal evenness" versus asphalt binder layer age and accumulative traffic loads (ESAL)

For the longitudinal evenness measured on the asphalt pavement surface, similar results are obtained for asphalt binder layers both with and without RA application.

The data available allowed an assignment of locations with control test samples of the surface quality, but the greatest age of asphalt binder courses with RA was only 9 years, which is a period too short to evaluate the durability of asphalt binder courses.

Also, for other pavement surface characteristics, similar data scatter could be observed which does not allow a clear conclusion about the effect of RA application on the pavement performance. Here it has to be taken into account that the non-consistent identification of locations of (a) material characteristics and (b) surface characteristics did not allow for the evaluation of more pavement sections.

As a conclusion to this evaluation it has to be stated that existing databases on material properties and actual pavement service lifetime and service characteristics cannot easily be compiled because of non-consistent localizing format. To enable the development of material-specific service lifetime estimations, road asset databases are needed which allow for the network-wide comparison of pavement performance data (e.g. assessed during surface serviceability monitoring) and valid material data. Current pavement management systems still do not assess the actual pavement material properties in required detail.

3.3.3 Existing national test section evaluation

3.3.3.1 German test site B32 1989-2008

In 1989, a test site on the federal road B32 in southern Germany to evaluate the durability of asphalt binder and surface asphalt concrete containing RA was paved.

Additional to control fields without RA addition, the site contained test fields in which the asphalt binder layer was prepared with 25 % of RA. For the surface asphalt concrete course, 20 % of RA was added. For both the asphalt binder and asphalt surface course layers, the asphalt mixtures were produced in two variations. For one option, RA was added cold into the asphalt mixer whereas aggregates were superheated and, in the other case, the RA was heated separately in a parallel drum (Charif, 1992).

After construction of the test fields and again in 2008, cores were taken from the test sections and following performance properties were evaluated:

- low-temperature cracking by TSRST (EN 12697-46)
- fatigue by 4-point-bending tests (1989) and CIDT (2008) (EN 12697-24)
- resistance against rutting by uniaxial cyclic compression tests (EN 12697-25).

For all evaluated performance-properties, the asphalt materials containing RA showed statistically the same results compared to the control sites without any RA addition both after construction in 1989 as well as after 19 years of traffic loading in 2008. The test field indicated feasible surface characteristics without any cracks or rutting. The traffic loading during 19 years resulted in approximately 2,6 million 10-t-ESAL (Roos & Karcher, 2012).

3.3.3.2 Dutch perpetual pavements study 1997-2006

In the A12 motorway, various pavement structures were paved for long-term performance evaluation. The structures were varied in terms of the binder course and base mixtures whereas all sections were surfaced with porous asphalt mixture ZOAB 0/16 or ZOAB 0/16 III with polymer-modified binder as summarised in**Fehler! Verweisquelle konnte nicht gefunden werden.** (Dekkers and Van der Ven, 2007). Considering that the surface asphalt course was the same in all sections, quality differences will result from the varied binder course and base structures below the porous asphalt surface course.

All pavements were constructed in 1997 and, in 2000, 2002 and 2005, the rut depth and longitudinal evenness were measured (Figure 13). Furthermore, the necessary maintenance works between 1997 and 2006 were registered.

For Section 5, the porous asphalt had to be replaced at several locations after lifetimes of between two to seven years of traffic loading due to ravelling of the porous asphalt layer. In this section, reinforced concrete was applied as a base below the asphalt surface course. Obviously, the stiffer base layer increases the loads for the surface course. If polymer-modified binder is applied in the porous asphalt surface, as applied in comparative Section 6, the surface course can withstand the increased loads. This difference can also be confirmed by the rut depth and evenness, which is worse for Section 5 than Section 6.

However, the use of polymer-modified binder does not automatically improve the performance of the asphalt layer, as can be seen when comparing the rut depth and evenness of Section 4 (unmodified binder) and Section 7 (polymer-modified binder).

Table 6. Pavement structures in A12 perpetual pavement study

# Road section	Distance (from-to in km)	Layer type	Layer thickness (mm)	Composition	Binder type/content	Air voids
1	64.36-64.53	Surface	50	ZOAB 0/16		
		Binder course	60	STAB 0/22	Pen 40/60, 4.8%	8
		Base course	80	STAB 0/22	Pen 40/60, 4.8%	8
		Sub-base	90	STAB 0/22 I	Polymer mod. binder	8
		Sub-grade	250	AGRAC		-
2	64.53-64.70	Surface	50	ZOAB 0/16		
		Binder course	60	STAB 0/22	Pen 40/60, 4.8%	8
		Base course	80	STAB 0/22	Pen 40/60, 4.8%	8
		Sub-base	90	STAB 0/22 I	Polymer mod. binder	8
		Sub-grade	250	AGRAC		-
3	64.70-65.00	Surface	50	ZOAB 0/16		
		Binder course	60	STAB 0/22 II	Polymer mod. binder	8
		Base course	80	STAB 0/22	Pen 40/60, 4.8%	8
		Sub-base	90	STAB 0/22	Pen 40/60, 4.8%	8
		Sub-grade	250	AGRAC		-
4	65.00-65.18	Surface	50	ZOAB 0/16		
		Binder course	60	STAB 0/22	Pen 40/60, 4.8%	8
		Base course	80	STAB 0/22	Pen 40/60, 4.8%	8
		Sub-base	90	STAB 0/22	Pen 40/60, 4.8%	8
		Sub-grade	250	AGRAC		-
5	65.18-67.14	Surface	50	ZOAB 0/16		
		Binder course	250	DGB		
		Base course	60	GAB 0/32		4
		Sub-grade	250	AGRAC		-
6	67.14-67.44	Surface	50	ZOAB 0/16 III	Polymer mod. binder	
		Binder course	250	DGB		
		Base course	60	GAB 0/32		4
		Sub-grade	250	AGRAC		-
7	67.44-67.66	Surface	50	ZOAB 0/16 III	Polymer mod. binder	
		Binder course	60	STAB 0/22		
			80	STAB 0/22		
		Base course	90	STAB 0/22		4
		Sub-grade	250	AGRAC		-
ZOAB: porous asphalt; STAB: asphalt concrete; DGB: continuously reinforced concrete; GAB: gravel asphalt concrete						

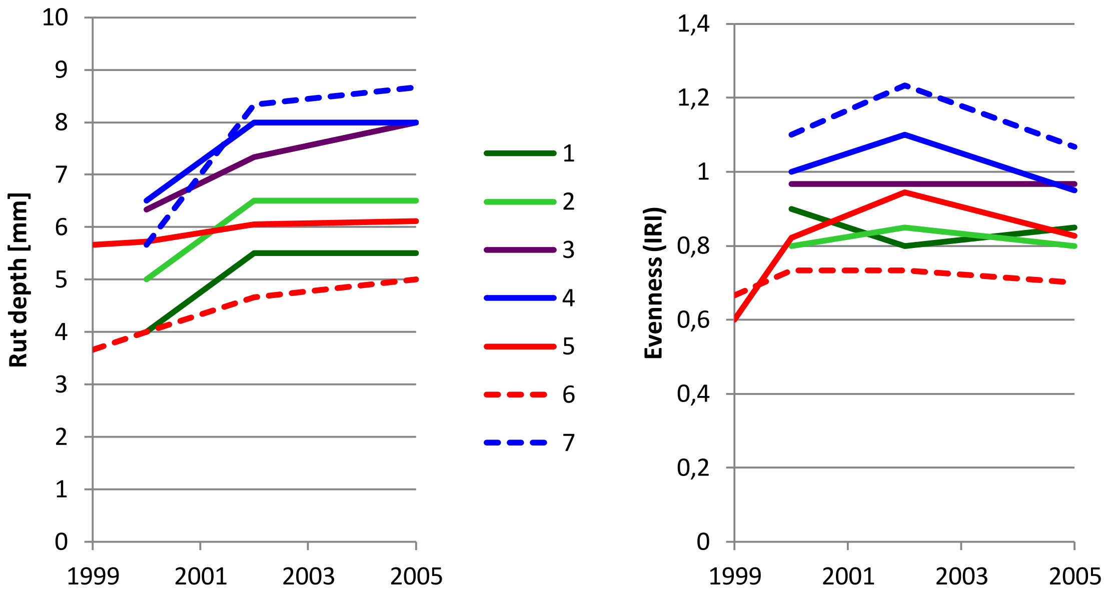

Figure 13. Surface condition of road sections in A12 perpetual pavement study

3.4 Construction conditions

The durability of road structures is affected by the pavement material properties. In addition to the composition of the construction materials - specified by EN 13108 - their properties are strongly influenced by on-site construction conditions (laying and compaction). The construction conditions can only partly be controlled by the road engineer which generates a risk for failing the target durability. Nevertheless, during the planning of road construction specific aspects can be considered, which will affect the construction condition:

- The seasonal climatic conditions can be considered in order to avoid construction time with high risk of inadequate weather situation.
- The construction during times of low traffic volume (e.g. at night) in order to reduce traffic disruption may affect the construction quality due to inadequate light conditions.
- The length of construction sites will affect the pavement performance because of the reduction of joints which often are the weakest parts of a pavement structure due to inadequate compaction or non-waterproof seal. The benefit of small construction length linked to reduced traffic disruptions are counter weighted by the higher number of joints.
- The minimum timespan between laying and trafficking is specified in some asphalt pavement regulations due to structural viscosity of asphalt materials. Early trafficking of freshly-paved asphalt courses can provoke early rutting.

In the following section, these aspects are analysed by literature review. A focus of this study is laid on the current specifications applied for these topics.

3.4.1 Construction season / weather aspects

The weather condition during paving strongly affects the risk for inadequate pavement quality, because of the fast cooling due to low base and air temperature, rainfall and/or wind chill will reduce the available timespan for compaction. Further, wet bases may result in inadequate interlayer bonding and, thus, reduced the bearing capacity of the pavement.

In several national specification documents on asphalt pavement construction, inadequate weather conditions are defined (see Table 7). Obviously, in winter months these weather conditions may be failed more often compared to summer season.

Table 7: Required weather conditions for asphalt pavement works (FGSV, 2014)

Country	Minimum allowed air temperature for paving of							Rainfall
	AC base layer	AC binder layer	asphalt surface ≥ 30 mm	asphalt surface < 30 mm	PA	MA ≥ 30 mm	HRA & PCC	
Germany	-3 °C	0 °C	+5 °C	+ 10 °C	+10 °C*	0 °C	-/-	allowed, no closed water film
The Netherlands	-**	-**	-**	-**	T_{air} ≥ W+5 (°C)***	-**	-**	
UK and Ireland	Combination of wind and rainfall for layers less than 50 mm to Figure 14						0 °C	-/-

* Paving of PA is restricted at high wind velocities (not further defined)

** There are no specific requirements for other types of asphalt pavements than PA. However, the contractor is obliged to monitor and report on the conditions during construction and indicate how the quality of the paving work was ensured.

*** PA pavements can only be constructed when the air temperature is above 5°C plus the wind velocity (T is the air temperature in °C; W is the wind velocity in m/s).

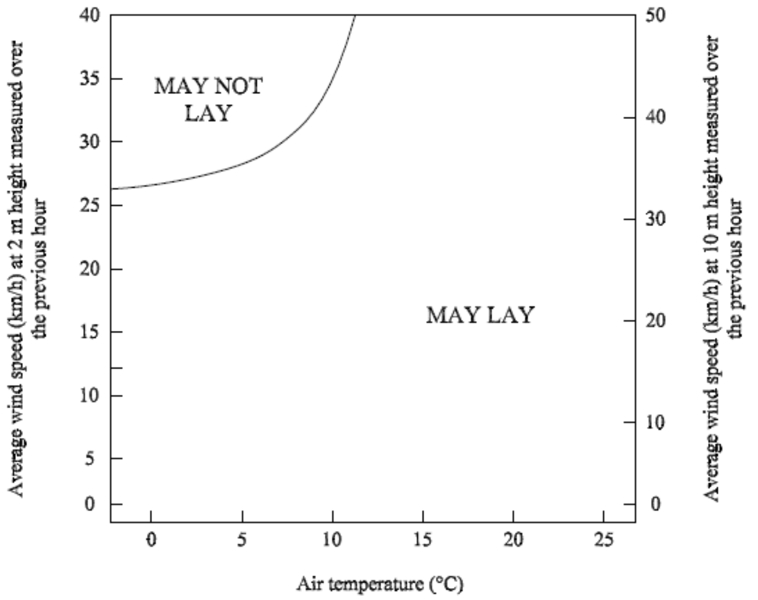

Figure 14: UK wind speed and air temperature laying restrictions for layers less than 50 mm thick

3.4.1.1 *Seasonal effect on compaction quality*

The adequate compaction is an important factor controlling the durability of asphalt pavements. According to results obtained by Leutner et al. (2000), the compaction degree of an asphalt layer significantly affects its resistance against rutting as well as fatigue and low-temperature cracking. As shown by Mollenhauer *et al*. (2010) and Walter *et al*. (2010) by mechanical-empirical pavement design calculations, an insufficient degree of compaction (< 97 %) can reduce the predicted service lifetime by 50 % of the expected lifetime. When further evaluating the data presented by Walther *et al*. (2010), a linear regression is found between the air void content difference (resulting from varied compaction energies applied) and the design lifetime calculated based on laboratory-measured stiffness and fatigue properties (see Figure 15).

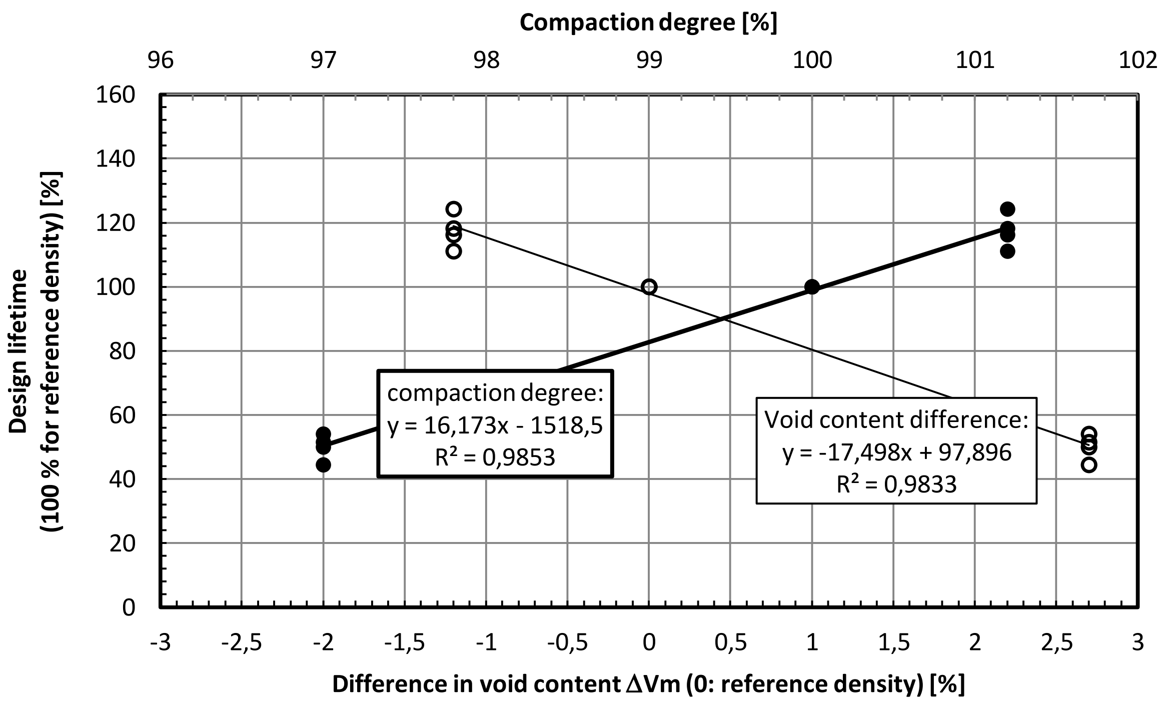

Figure 15. Effect of compaction degree and resulting void content difference on design lifetime

The compaction properties are strongly affected by asphalt course temperature and, therefore, by weather conditions during paving.

The already mentioned database of control test results obtained from northern Germany (Section 3.3.2) allows the evaluation of the risk for inadequate compaction for different construction times. The risk for failing to reach the required degree of compaction can be evaluated by comparing the compaction results obtained from core samples versus the time of sampling, which is usually done shortly after construction. From this evaluation, the risk for failing the required degree of compaction (which was 97 % in Germany until 2012), as an important property predetermining the durability, can be analysed.

In Figure 16, the mean results of degrees of compaction obtained are indicated for three types of surface asphalt courses versus the construction month. The evaluated standard deviation is added as error bars. All mean values of degree of compaction are higher compared to the German requirement (until 2012) of 97 %. Generally, no clear trend can be observed of significant lower compaction degrees during winter months (January - March).

Nevertheless, the requirement for degree of compaction is not reached for several construction works as indicated by the standard deviation error bars.

Therefore, the parts of samples failing the compaction requirement are plotted versus the construction month in Figure 17. On average, the rate of samples with inadequate compaction is around 10 %. A small increase of the rate of inconsistent samples can be observed from summer months (May to July) to winter months (November to January). High rates of inconsistent compaction degree can be observed for SMA 8 courses (which are usually applied in layers of reduced thickness) in January as well for PA 8 courses paved in autumn months. Here should be noted that the rates of SMA in January and of PA in December are based on a low number of samples (~ 20).

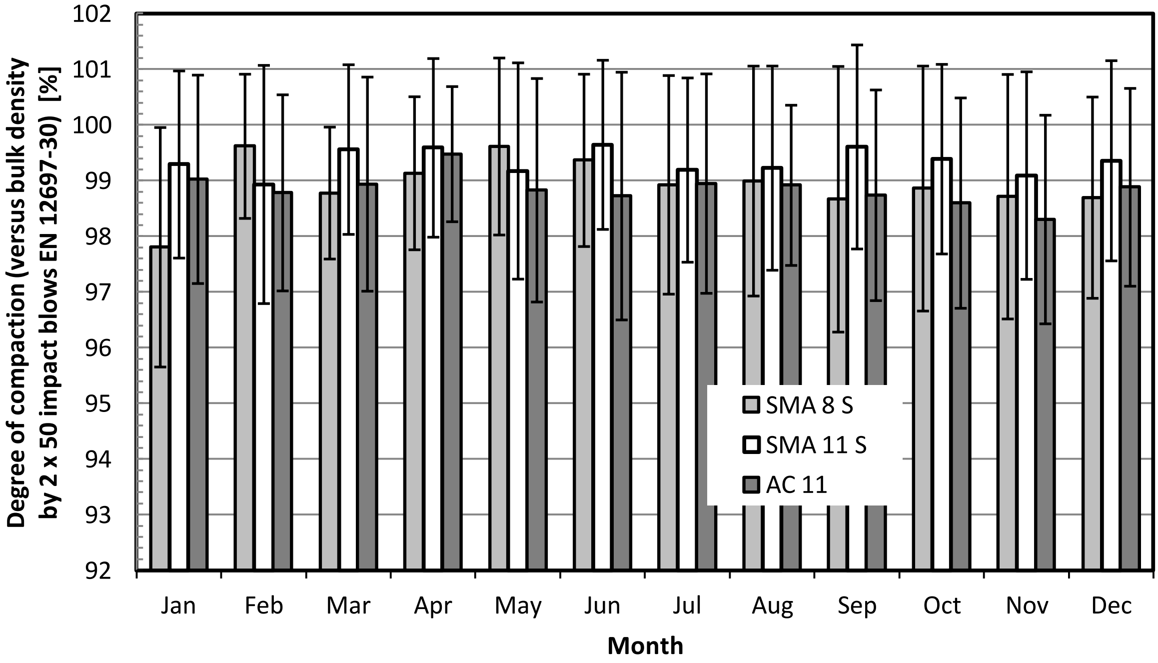

Figure 16. Mean degree of compaction and standard deviation for surface asphalt layers composed of SMA 8, SMA 11 and AC 11

As depicted in Figure 18, the rates of insufficiently compacted asphalt binder and asphalt base courses are lower when compared to those of surface courses. Also, for these layers of higher thickness, an increased failure rate can be observed for pavements constructed late in the construction season (December and January).

On average, it can be concluded that the risk for insufficient compaction degree will increase in the winter months in Germany (October to January). For just February and March, a limited number of samples could be analysed which reperesents the usual annual construction break during these months.

In order to quantify the seasonal effect on compaction degree for service lifetime calculations, the results published by Walther *et al*. (2010) and shown in Figure 15 will be further analysed. For this evaluation it is assumed, that all samples not meeting the requirement of compaction degree of 97 % will suffer a reduced service life by -50 %. Therefore, for LCA and LCCA calculations, the mean effect of adverse weather in terms of construction season on the service lifetime due to improper compaction can be calculated by multiplication of the service lifetime effect (-50 %) with the risk of not meeting the compaction requirement. This results in following service lifetime effects for surface asphalt courses:

- mean risk of insufficient compaction in winter (Oct - Jan): 14,1 %
- mean risk of insufficient compaction in summer: (Apr - Sep): 10,7 %
- Increased risk in autumn and winter months: 3,4 %
- Resulting service lifetime effect:
  3,4 % * -50 % service lifetime reduction = -1,7 %

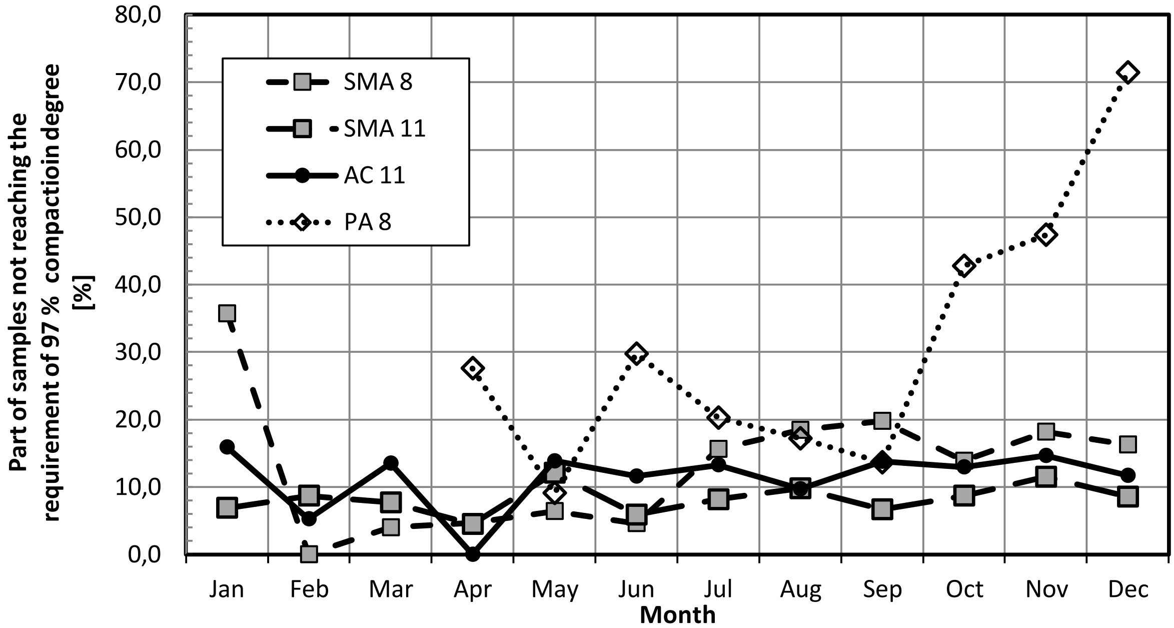

Figure 17. Rate of samples failing the 97-%-degree-of-compaction requirement (1989 - 2007) for surface asphalt courses

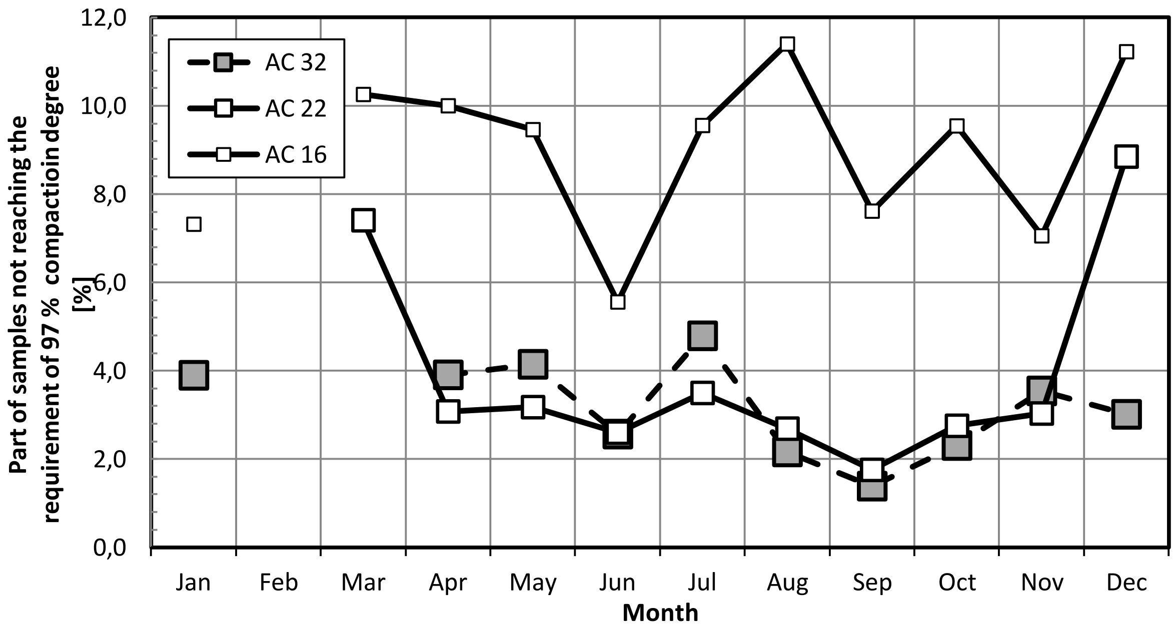

Figure 18. Rate of samples failing the 97-%-degree-of-compaction requirement (1989 - 2007) for base and binder asphalt courses

3.4.1.2 Seasonal effect on interlayer bonding

The bearing capacity of an asphalt pavements is controlled by the joint bearing of all asphalt layers as a monolithically structure. Therefore, if the interlayer bonding between layers is not adequate, the bearing capacity is significantly reduced and the loading of the asphalt layers by stress and strain will increase which results in reduced durability. Besides a clean surface and a suitable treatment of the bottom layer before the laying of the top layer, the temperature of the bottom surface affects the bonding properties at the interlayer. Furthermore, water on the surface has to be evaporated which decreases the asphalt temperature at the interlayer and, further, may prevent adequate bonding.

The bond between pavement layers significantly affects the loading conditions as well as the stress/strain distribution in the pavement. Therefore, insufficient bonding will reduce the service lifetime of the road structure as well as that of the surface layer due to increased rutting (Wellner *et al*. 2012). Based on mechanistic-empirical pavement design calculations, lacking interlayer bonding between asphalt surface and asphalt binder layer will decrease the calculated service lifetime of the structure for -33 % and between asphalt binder and asphalt base layer for -75 %. Because of higher loads resulting from lack of interlayer bonding, the surface layer itself can have a reduced service lifetime of - 70 % due to increased rutting.

The quality of interlayer bonding is assessed during construction control tests. For the control test database, the rate of tested interlayer bonding with inadequate bond is plotted for the interlayer between asphalt surface and asphalt binder course in Figure 19. It can be clearly observed that the risk of inadequate bonding between asphalt layers increases significantly during winter construction time, especially for thin layers constructed late in the year that indicate high potential for insufficient bonding to the substrate.

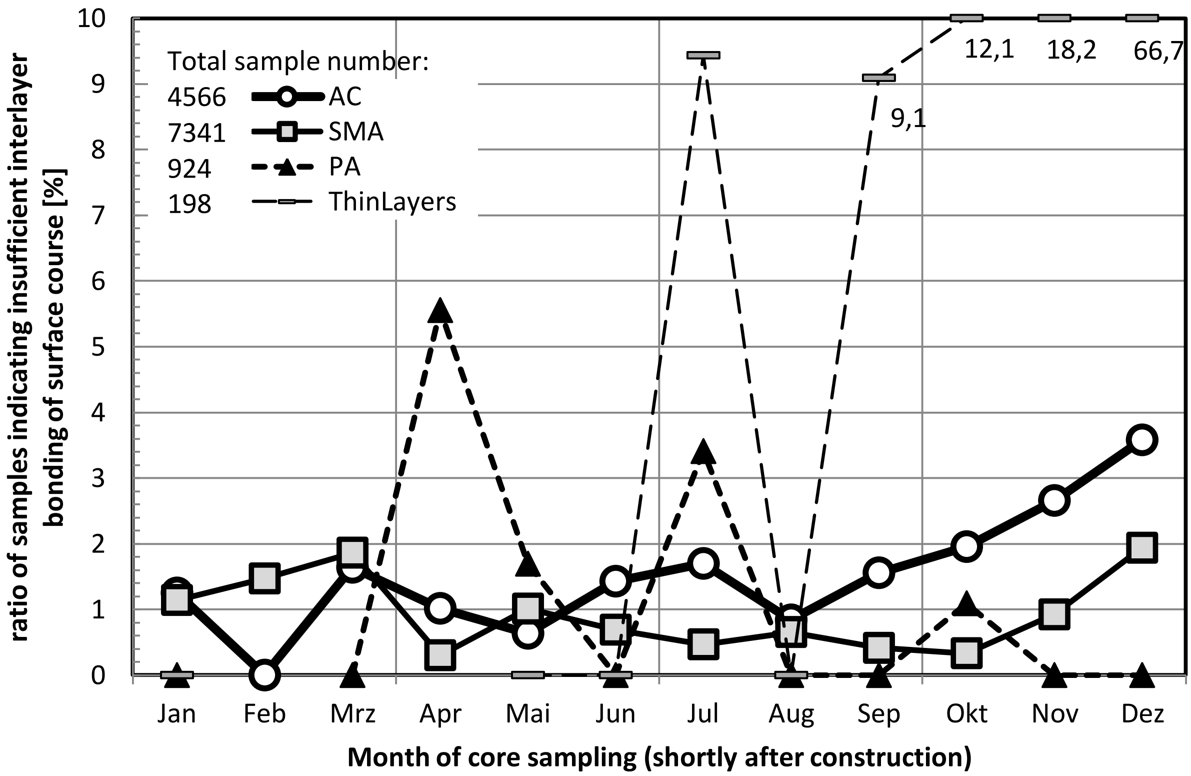

Figure 19. Rate of samples with insufficient interlayer bonding (1989 - 2007)

By combining the seasonal-dependent risk of insufficient interlayer bonding and the pavement design calculations, the following service lifetime effects can be quantified about the seasonal effect for paving works in Germany:

- mean risk of insufficient interlayer bonding in winter (Oct - Jan): 1,7 %
- mean risk of insufficient interlayer bonding in rest of year: (Feb - Sep): 1,0 %
- Increased risk in autumn and winter months: 0,7 %
- Resulting service lifetime effect:
  0,7 % * -70 % service lifetime reduction = -0,5 %

3.4.2 Effect of night construction and small paving lengths

Night construction is a feasible mean in order to reduce traffic congestion during day time hours with high traffic volumes. In particular for small rehabilitation schemes, these effects are already applied in pavement management systems where costs of the road users are considered for rehabilitation work planning (see Norkauer 2004, Rübesam & Hellmann 2005, Hess 2005).

Hopwever, for larger pavement rehabilitation works, the partition of the construction schemes into several small rehabilitation patches increases the number of joints in the pavement. The joints always incorporate high risks of insufficient compaction, higher air void contents and inhomogeneous pavement material by segregation of the asphalt mixtures during paving.

There is general acceptance about the adverse effects of joints on pavement durability but no calculation tools have been developed as yet which would allow the calculation of the risk for a reduced service life. Because of the known inhomogeneities of asphalt properties near joints, these areas are not considered for contractual control tests and, therefore, reduced data is available from standard construction sites.

Several researchers report of these observations and various technical procedures for improving the joints were analysed by Benson & Scherocman (2006). Seebaly *et al*. (2008) found significant density differences in cores taken from the joints and the middle area of a paved lane. Depending on the compaction procedure for the preparation of longitudinal joints (hot mix next to existing lane), significant lower densities were found in 9 of 20 cases next to the joints, the air voids content of the compacted asphalt layer was significantly higher compared to the central region of the asphalt course (differences were between 1,0 % and 2,2 % with a mean of 1,7 %). Williams (2011) showed correlations between the bulk density and absorption, permeability and infiltration characteristics of compacted asphalt courses in the vicinity of longitudinal joints. Therefore, the higher air voids content near to joints will increase the accessibility of the asphalt course to moisture and air, both of which will decrease the durability of the pavement material.

Based on the published results, the service life of pavements areas in the vicinity of joints can be roughly estimated. Therefore, the effect of air voids content (or compaction degree) on the fatigue resistance can be used for appraising the durability effects of joints.

The mean air voids content difference found by Seebaly *et al*. (2008) of 1,7 % for the asphalt course in the vicinity of the joint compared to that in the middle part of the lane (which is usually assessed). Using this reduction in the pavement design calculations (as already applied for the evaluation of adverse weather effects) would result in a lifetime decrease to 68 % of the initial design lifetime (-32 %), see Figure 15. This reduces service lifetime would be valid for 9 of 20 joints. Thus, for the evaluation of the service lifetime effects of an increased number of joints which would result from splitting larger road maintenance sites into smaller patches (e.g. for night-time construction), the discussed results allow the assumption of a service lifetime decrease of 14,4 %[3]. This assumption is based on a very limited number of research results and does not take into account the deteriorating effect of moisture and binder ageing, which were both not evaluated in the pavement design study.

3.4.3 Effect of early trafficking

Early trafficking of freshly-paved asphalt courses can provoke early rutting due to elevated temperature and/or structural-viscosity effects in the bitumen. This potential damage is the reason for specifications on the minimal timespan between paving and compaction and the road opening for traffic as applied in national regulations.

Table 8: National specification on traffic opening of freshly paved roads

Country	Specification on early trafficking	Document
Germany	• timespan ≥ 24 h (for surface layers), • in specific cases timespan < 24 h but at least over one night	FGSV, 2014
UK, Ireland	• temperature in middle of paved layer < 40 °C	

Nevertheless, early trafficking may be possible but requires special attention to the structural viscosity development of the bitumen.

4 Conclusions

For the implementation of the various durability-effects into LCA and LCCA, the general observations and findings as discussed in Section 3 has to be specifically quantified. Therefore, some assumptions are proposed which are based on the discussed results.

As discussed in Sections 3.1 to 3.3, so far no databases exist to identify the influence of the use of recycled construction materials or secondary by-products on the durability of the road pavements. The high number of parameters affecting the pavements durability (see Table 3) will not allow a comprehensive model for calculating the durability in near future. At the same time, reliable data on the structural properties of the road network is still lacking which prohibits the empirical evaluation of long-term performance of various pavement material parameters on network level. What can be concluded from a database evaluation conducted (see Section 3.3.2) is that the application of RA in hot-mix asphalt can reduce the expected service lifetime. Nevertheless, the evaluation shows large scatter and, therefore, no distinct statement can be drawn. From international literature, it has been shown that the use of RA in new hot-mix asphalt mixtures results in adequate material durability performance in most of the time. However, some researchers have also identified reduced durability for mixtures containing RA. Altogether, the application of RA in new hot-mix asphalt requires additional procedures in mix design as well as in asphalt mixture production on an industrial scale. Because the number of production steps increases which individually affect the durability properties of the resulting asphalt mixture, the risk of reduced durability will increase in general. However, if all procedures are conducted in high quality (as is usually the case in laboratory research as well as test section studies), no adverse durability effects have been

[3] 32 % service lifetime reduction near joints * 9 joints out of 20: 32 % * 9/20 = 14,4 %

observed in most publications. Nevertheless, the general adverse long-term performance in every-day paving industry, as indicated by database analysis (see Figure 11 and Figure 12), the higher risk will result in reduced durability for some of the projects. The increased use of various additives will further increase this development due to additional risks (e.g. incompatibilities to specific binders).

For considering the durability effect of asphalt mixture composition as well as the use of additives and or recycled materials, feasible laboratory conditioning procedures are needed in order to allow the estimation of long-term properties during the mix design. Based on these results, durability effects can be implemented into LCA and LCCA in comparison to traditional asphalt mixtures with known durability properties.

For the construction conditions analysed in this report, durability effects were found which can be implemented to LCA and/or LCCA calculations.

For the effect of construction season, the paving during adverse weather conditions will slightly increase the risk for insufficient compaction and interlaying bonding. These independently occurring effects result in significant reductions of pavement and/or road material service lifetime. These reductions can be summed up to a service lifetime decrease of -2,2 % for pavements constructed in winter months (October to January):

- due to risk of insufficient compaction: -1,7 % (see section 3.4.1.1)
- due to risk of insufficient interlayer bonding: -0,5 % (see section 3.4.1.2)

The splitting of larger construction sites into smaller patches, which may be required in order to use times of low traffic volume for conducting pavement maintenance works, incorporate the disadvantage of an increase in the number of joints. These areas of pavements often result in inadequate compaction properties and, therefore, a significantly decreased durability. Based on published research results, the effect of reduced compaction degree on estimated service lifetime combined with the risk of inadequate joint design could be estimated to a reduced service lifetime of -14,4 % (see Section 3.4.2).

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