CREATING SUSTAINABLE ASPHALT PAVEMENTS

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ABSTRACT

Sustainability and durability are key items regarding the quality of road pavements. For that reason technical aspects of durability and sustainability which can lead to improved durability and sustainability of asphalt pavements are important parameters for pavement performance.
The predominant failure modes of asphalt pavements are: rutting, thermal cracking, fatigue, stripping, fretting, ageing and mixture design failures. Improvements in durability whereby the onset of any of the above failure modes can be extended will also improve the sustainability of the pavement.
The main elements that can influence durability of pavements will be described in this paper with a focus on examples of premature failures and an analysis of contributing factors, examined with reference to current available lab evaluations. The short and long term ageing behaviour and the correlation with ageing of asphalt and bitumen will be described.
Good practices to improve durability will be given by describing best practice for building durable roads and by describing how premature failures due to ageing can be avoided or reduced
Based on the evaluation of long-term ageing studies an appropriate regime for evaluation of durability will be suggested.

Keywords: Durability, Ageing, Fatigue Cracking, Permanent Deformation

1. INTRODUCTION

Sustainability and durability are key items regarding the quality of road pavements. For that reason technical aspects of durability and sustainability which can lead to improved durability and sustainability of asphalt pavements are important parameters for pavement performance.
The predominant failure modes of asphalt pavements are: rutting, thermal cracking, fatigue, stripping, fretting, ageing and mixture design failures.
The occurrence of these failure modes can be influenced by many elements, for example, insufficient compaction of the asphalt layer during the paving operation can lead to rutting at an early stage. To avoid premature failures of asphalt pavements attention should be paid to details in each step from the design through to the completion of construction.
This paper gives an overview of the main elements influencing the durability of the asphalt pavement and it will give a summary of good practices for the improvement of durability.

By avoiding premature failures the durability of asphalt pavements will improve and this will contribute to sustainability.

2. MAIN ELEMENTS INFLUENCING DURABILITY OF PAVEMENTS

There are many elements influencing the durability of pavements. Elements that can influence durability of pavements are listed here:

Pavement design

- Thickness of asphalt pavement/layers
- Bonding between the different layers
- Design of the unbound sub base layers
- Drainage
- Homogeneity of the substrate (the under laying structure / foundation)

Asphalt mix design

- Aggregate type(s)
- Asphalt mixture / aggregate grading
- Bituminous binder content
- Filler type
- Binder – aggregate interaction additives like anti-stripping agents and fibres
- Specialised additives for requirements like fuel resistance
- Processing additives like Warm Mix additives such as Zeolites, waxes, foaming and surfactants
- Bitumen binder choice or formulation regarding:
    - Resistance to permanent deformation (expressed through Zero Shear Viscosity, Complex shear modulus and phase angle)
    - Resistance to thermal cracking expressed as low temperature fracture toughness, or through stiffness strength balance using DTT and BBR-Resistance to fatigue cracking expressed as Fracture toughness, force ductility or breaking energy at selected temperature
    - Resistance to ageing in plant processing (short term ageing) or in its service life (long term ageing)
    - Workability and processability from the temperature, shear and viscosity profile assessed in direct and proxy tests
    - Storage stability

Asphalt production

- Production temperatures
- Homogeneity of coating in the mixture, related to equipment, process conditions and sequencing

Transport of asphalt mixture from plant to paver

- Mixture segregation
- Covering and insulation of trucks transporting the mixture
- Even temperature distribution (homogeneous temperature in the mixture)
- Transport distance

The paving operation

- Continuous material supply
- Temperature of the mixture
- Material segregation / remixing
- Speed of the paver
- Compaction of the asphalt layer
- Weather conditions.
- Hand-work
- Joints / avoiding joints
- Bonding between the layers / bond coat formulation and good spread
- Use an effective release agent

A description of the influence of these elements on the durability of pavements can be found in Road Note 42 [1].
In the above list several examples of "Binder properties" and "Asphalt mixture properties" were given. As it is impossible to address all of these properties in this paper, it will mainly focus on the bitumen and asphalt mixture properties that are related to the long term behaviour/ageing of asphalt mixtures and bitumen.

3. PREMATURE FAILURES

Premature failures are considered to be major distress that appears much earlier than expected, e.g. severe rutting or surface cracking within a few years.

Section 2 gave an overview of the main elements influencing the durability of pavements. By taking these main elements into account it should be possible to build longer lasting pavements. In practice there are some premature failures that cannot be explained easily, which might be related to ageing of bitumen / asphalt. Ageing in the pavement is related to the asphalt application and will be influenced by the aggregate and filler. Open graded mixes will show different behaviour than dense mixes. The bitumen recovered from a failed asphalt pavement will be aged, in part, because the elements, air and water, have penetrated the asphalt. For that reason EAPA and Eurobitume created a Task Force to investigate the long term ageing behaviour of asphalt and bitumen, the TF started with a literature review.

The Transportation Research Board produced an information circular on bitumen oxidation [2] which contained several relevant conclusions, which indicated that the ageing behaviour of the bitumen is an important item for the pavement durability. Similar conclusions were drawn in [3] where a long term ageing protocol was evaluated.

4. SHORT AND LONG TERM AGEING BEHAVIOUR OF BITUMEN AND ASPHALT MIXTURES

Ageing contributes to pavement embrittlement which can result in pavement cracking. Some properties however improve due to ageing, like the resistance to rutting.

Within CEN TC336, WG1 "Bituminous Binders" Task Group 3 is responsible for evaluating binder conditioning regimes to simulate short and long term ageing. Their most recent update is shown in [4]. The next paragraphs give a short summary of the conditioning procedures available for bitumen and for asphalt mixtures.

4.1. Ageing of bitumen

The European philosophy on laboratory simulation of binder ageing follows the principle that short term ageing should represent the mixing and laying of hot mix asphalt, therefore a dynamic procedure is required.

Long term ageing represents the ageing during the pavement service life and therefore in theory a static procedure may be appropriate. Both static and dynamic procedures have been developed.

It should be noted that all ageing conditioning methods currently used were either validated using surrogate characteristics such as softening point, ring and ball or needle penetration of the binder examined being compared to those of a binder recovered from an aged road pavement, or against those of binders conditioned in existing ageing procedures. Only occasionally, the changes in the chemistry of the binder were the basis for recommendations and conclusions.

4.1.1 Short term ageing (STA)

EN 12607 “Determination of the resistance to hardening under the influence of heat and air” consists of three parts and describes short term bitumen conditioning methods using the Rolling Thin Film Oven Test (RTFOT), the Thin Film Oven Test (TFOT) and the Rotating Flask Test (RFT). Short-term conditioning can also be performed according to EN 15323 “Accelerated long-term ageing/conditioning by the rotating cylinder method (RCAT)”.

European bitumen specifications commonly call up the RTFOT @ 163°C for short term ageing. In the scope of all three parts of EN 12607 a statement is made that the procedure simulates hardening during mixing and laying of the asphalt. The research for this conditioning was performed in 1962 using Paving Grade bitumen and, whilst RTFOT may simulate mixing of asphalt with paving grade bitumen, it is not necessarily valid when using Hard Grades, PMBs, soft binders or Warm Mix solutions. The protocol could be carried out at different, equi-viscous temperatures (EVT) to accommodate other binders, but the effects have not been reported.

4.1.2 Long term ageing (LTA)

There are several long term ageing protocols used in Europe and conditioning is described in two European test method standards, EN 14769 for the Pressure Ageing Vessel (PAV) and EN 15323 for the RCAT. Other long term ageing protocols have been proposed, but the methods are not yet standardised in Europe. These include repeated (3x) applications of the RTFOT or modified RTFOT using a lower temperature and a longer time period. These protocols are used mainly for collecting information and for research and development.

There has been discussion about the practicality and the relevance of the different long term ageing protocols used in Europe. It is recognised that some methods are simpler and produce more binder for further testing, but the protocol should give results representative of ageing in the field.

4.1.3. Recommendations regarding ageing of bitumen

Long term ageing is related to the asphalt application and the ageing behaviour of the bitumen is an important characteristic for the durability of asphalt mixtures. There is a need to address long term ageing because contractors are more often requested to take the responsibility for the durability of the asphalt surface layers for a longer time periods. The long term ageing protocol should be able to reflect the bitumen ageing process in the field equivalent to the design service life of the asphalt.

4.2 Ageing of asphalt mixtures

To build durable and sustainable asphalt pavements, many elements play an important role as described in paragraph 2. One of them is the ageing behaviour of the asphalt mixture itself.
Ageing of asphalt mixtures depends on many factors such as void content of the mix, type of aggregate and filler used as well as bitumen (film) properties. This paragraph gives on overview of the existing conditioning procedures to age asphalt mix samples.

4.2.1 Long term ageing of asphalt mixtures

The most relevant properties of the bituminous binders for the aggregate / binder interaction are cohesion, adhesion and ageing. The cohesion describes the binder’s inner bonding forces and the adhesion the bond strength of the binder with the aggregates. Ageing characterizes the changing of chemical-, physical- and rheological properties of the binder which is caused by the external influence factors of using the bituminous binder (bitumen) in the asphalt mixture. This ageing process of the bitumen starts already during asphalt production and leads finally to a change of the material properties of the compacted asphalt material.

For these reasons a good ageing procedure (a conditioning procedure to simulate ageing) is important. Such a procedure is not only important to study the change in bitumen properties due to the ageing of mixtures, it would also be very helpful to have a procedure to age asphalt samples in order to be able to do asphalt mixture tests on aged asphalt mixture samples.

In 2009 CEN TC227, WG1 “Bituminous Mixtures” discussed test methods that are needed for asphalt mixtures in the future. Here also a conditioning method needed for ageing samples to define aspects that contribute to ageing (weather e.g. sun, UV, water, frost) for Resistance to Ageing (due to weather influences) was discussed.
It was agreed that such a conditioning method is needed, but at that moment (in 2009) there were proven suitable conditioning methods available.

So CEN TC227 WG1 decided to wait for the results of the following projects:

- RILEM Committee ATB: “Advanced Testing and characterization of Bituminous materials” Task Group 5 “Recycling” working on an ageing procedure.
- The Re-Road project (of FP-7) was also looking at a conditioning method for both short and long term performance of asphalt pavements produced with Reclaimed Asphalt Pavements.

At this moment several research institutes or research groups are developing or have developed procedures. Table 1 [5] gives an overview of published ageing procedures for asphalt.

Table 1: Overview of published ageing procedures for asphalt [5]

Alterungsmethode	Temperatur [°C]	Dauer [h]	Probenart	DIN EN	Veröffentlichung
Short-Term Oven Ageing (STOA)	135	8-36	loses Material	-	NCHRP 1988
Long-Term Oven Ageing (LTOA)	85	120	verdichtete PK	-	NCHRP 1988
Low-Pressure Oxidation (LPO)	60, 85	120	verdichtete PK	-	SHRP 1989
Rotating Cylinder Aging Test (RCAT)	70-100	144	Asphalt-mastix	15323	Verhasselt & Choquet (1991)
Long-Term Ageing	60	48	verdichtete PK	-	NCHRP 1988
	60	120-240	verdichtete PK	-	NCHRP 1988
	107	72	verdichtete PK	-	NCHRP 1988
Bitutest-Protocol	135	2	loses Material	-	Scholz (PhD-Thesis) Nottingham
	85	120	verdichtete PK	-	Scholz (PhD-Thesis) Nottingham
Ottawa Sand Mixtures	163	verschie-den	verdichtete PK	-	AAPT 1952
	60	1200	verdichtete PK	-	AAPT 1982
Plancher et al.	150	5	verdichtete PK	-	AAPT 1976
Hugo & Kennedy	100	96, 168	-	-	AAPT 1985
Khalid & Walsh	60	bis 600	verdichtete PK	-	EE Congr. 2000
Kumar & Goetz	60	24-240	verdichtete PK	-	AAPT 1977
Kim et al.	60	24-120	verdichtete PK	-	Oregon 1986
Pressure Ageing Vessel	100	72	verdichtete PK	14769	EE Congr. 1996
Saturation Ageing tensile stiffness conditioning Test (SATS)	85	65	verdichtete PK	12697-45	Transport 157 2004
Modelltopf nach Potschka	140	1	loses Material	-	FA 07.121 G85 E
Braunschweiger Alterung (BSA)	80	96	loses Material	-	FE 07.208/2004/BGB 2007
Warmboldscher Alterungstisch	40	720-1440	verdichtete PK	-	Diss. Warmbold 1996
Alterung im Wärmeschrank	135-175	4-24	loses Material	-	Bitumen 2/1999

Recent research projects are:

- Re-Road project
- Delft University “The Effect of Aging on Binder Properties of Porous Asphalt Concrete” project
- Bochum Ageing Procedure

Re-Road [6]

For the long term performance the Re-Road project will develop and test laboratory procedures for artificial ageing. They will look at available laboratory procedures for characterizing the ageing. Also a climatic chamber (of LCPC) with UV rays to reproduce, in laboratory, the in-situ ageing conditions of asphalt will be used.

In the Re-Road project (WP2) the following four ageing procedures will be compared [6]:

- RILEM TG 5 method:
  Here the asphalt material is spread on a plate and subjected for 4 hours to a temperature of 135°C for simulating short-term aging. Afterwards the plate is stored at 85°C for 9 days in a heating chamber for simulating long-term aging. (First results indicate the possibility of reaching a high comparability with this ageing procedure)
- BRRC-method

It consists in spreading the loose mix in bulk to a thickness of 2 or 3 cm in a cake pan and placing it in an open-air ventilated oven at 60°C for about two weeks.

- PAV with loose mix
- BRRC-method with additional UV radiation

In this Re-Road study a SMA with a SBS modified binder and an Asphalt Concrete with unmodified binder will be used. The asphalt mixtures will be mixed in the laboratory. After applying a short term ageing simulation (flat storage for 4 hours at 135°C) the long-term aging procedures will be applied.

Delft University - "The Effect of Aging on Binder Properties of Porous Asphalt Concrete"
In the Netherlands a method was developed to simulate the weathering process to represent field ageing of materials in the road. They used the Weather-Ometer (which was developed to test the ageing of exterior paint coatings) to age Porous Asphalt. The method can simulate the first three years of ageing in the field accurately, but further research is needed to simulate field ageing of up to 13 years, equivalent to the current average service life of a durable porous asphalt on a motorway [7 and 8].

Bochum Ageing Procedure (Bochumer Alterungsverfahren - BAV) [5]
The Ruhr-University of Bochum in Germany did research within the framework of a dissertation research study [5] to analyse the factors that affect ageing using identical binder and aggregate types while varying the mixture composition and ageing conditions.
The ageing process of asphalt is affected by multiple factors and can result in early damage of the pavement by rapid ageing. Therefore the knowledge of these factors is important for creating a durable asphalt pavement.
Many research studies already analyzed such factors on different asphalt mixtures.
In [5] the effect of binder film thickness, voids in the asphalt as well as the type of binder and aggregates were identified.

In Bochum they used specific aggregate and binders to get mixture variations for quantifying their effect on the thermal-oxidative ageing behaviour of bitumen in asphalt. For this study, they choose porous asphalt (PA 11) and asphalt concrete (AC 11) mixtures in combination with three types of aggregates (dense Diabase, porous Quartz Porphyry and hydrated Limestone Filler) and two binders (20/30 and 70/100). For the ageing process under laboratory conditions they used a new kind of asphalt ageing method (Bochumer Alterungsverfahren - BAV) [5].
For the thermal-oxidative ageing of compacted porous asphalt slabs they stored the slabs in a basin which was equipped with an air entrance on the top and a perforated plate on the bottom. The samples were aged by pumping continuously heated air with a temperature of 100 °C through the slab for three days. For the ageing of dense graded asphalt mixtures slightly compacted asphalt slabs were used. The conditioning procedure of three days is reported to be equivalent to 10 years of natural aging in the road.
The ageing of the mixture itself was determined by comparing 8 bitumen properties of the fresh bitumen, after the production of the bituminous mixture with the same properties after the mixture ageing process.

The results show [5] that the bitumen film thickness, the void content, the bitumen type and aggregate type are the main factors influencing the ageing behaviour.
The air void content of the mixture during laboratory ageing is one of crucial factors affecting the ageing behavior.
A small change in the asphalt mixture recipe can lead to significant changes in the ageing behaviour.
Also the (initial) stiffness of the unaged binder as well as the bitumen content, the bitumen film thickness, the mastic film thickness do influence the ageing behaviour of the mixture.
The mixtures with porous aggregates aged faster than the mixtures with dense aggregate.
The use of the hydrated limestone delayed the long term ageing process.

4.2.2. Recommendations regarding ageing of asphalt mixtures

Conditioning procedures to simulate ageing of the asphalt mixture for loose mixtures or slightly compacted mixtures are available, but these are not representative for the behaviour of (dense / compacted) mixtures as they are used in the road.

When new mixtures are being developed, their long term behaviour is important. To be able to test this long term behaviour, a long term ageing procedure is needed.
Therefore a good conditioning procedure for asphalt mixtures is needed to be able to age asphalt samples or plates in order to characterise the long term behaviour of asphalt mixtures (for instance regarding ravelling resistance).

5. GOOD PRACTICES FOR IMPROVEMENT OF DURABILITY

Good practice is important for building durable roads. By paying attention to the details, premature failures can be avoided or reduced.

5.1. Asphalt mix design

Asphalt binder and mixture properties can be improved using certain additives, e.g. polymers and fibres.
In addition to binder properties, binder content and binder content homogeneity show a major impact on mechanical properties of asphalt mixtures. The binder content in surface layer mixtures should not be too low in order to promote durability, but should not be too high as to have a negative influence on texture, skid resistance and rutting resistance. So in the asphalt mix design a right balance should be sought to avoid rutting, skid resistance problems or fatting up (bleeding) on one hand and durability on the other.

5.2. Asphalt production

During the production of an asphalt mixture, the right procedures should be followed as described in the Factory Production Control Standard (EN 13108-21). Too high production temperatures can have a negative effect on the bitumen properties and on the durability of an asphalt layer.
Recently, the use of Warm Mix Asphalt has started to increase. Due to its lower production temperature (20 - 30 °C reduction or even lower) there is less ageing during the production and laying phase, so less short term ageing of the bitumen [9.].

5.3. Transport of asphalt mixture from plant to paver

Transport conditions for the asphalt mixture from the asphalt plant to the construction site is important for the durability of the pavement. During transport of the asphalt mixture the temperature should not drop too much and the temperature homogeneity should be maintained. Also during transportation mixture segregation could occur.
For that reason the mixture in the truck should be covered during transport and the trucks could be insulated. Material Transfer Vehicles that remix the mixture before transfer to the paver can be used to minimise the effect of temperature and mixture segregation.
For a good end result the temperature of the mix during placement and compaction should be the right one.

5.4. The paving operation

During the paving operation, segregation in the paver should be avoided.
Segregation can occur [19] in particular in coarse and gap graded mixtures. A larger maximum particle size is more prone to segregation.

A continuous material supply avoids the need for the paver to stop and wait for the next truck. Stopping the paver can result in an uneven surface. The use of a Material Transfer Vehicle can be a solution. The use of a Material Transfer Vehicle also avoids the potential influences which the delivery trucks might have on the (constant) speed of the paver by avoiding “bumping” which can lead to a better smoother layer.
The speed of the paver should be constant and not be too high.
Hand-work, for example in tight curves at junctions and around ironwork, might affect the quality.

The temperature of the mixture in the paver should checked frequently.

The weather conditions can have a big impact on the compactability of the asphalt mixture and therefore on the pavement properties. The paving operations should therefore be abandoned when minimal conditions are not met The impact of weather is dependent on many aspects:

- the asphalt layer thickness being paved
- the temperature of the mixture
- the type of asphalt mixture (hence ease of compaction)
- ambient temperatures, wind speed, dampness or rain.

5.5. Joints

All joints are potential weak spots where the asphalt mix is likely to be less well compacted and therefore an increased potential for water ingress [1]. For this reason the number of longitudinal and transfer joints should be minimised.
If joints are needed paving in echelon is the best solution.
If ‘cold’ joints are permitted, provision should be made to ensure that the vertical face of the joint can be adequately bonded to the new material and that joints are compacted to a level similar to that of the rest of the asphalt layer [1] gives several recommendations to create durable joints.

5.6. Compaction of the asphalt layer

Adequate compaction of asphalt layers is essential. The optimum compaction level will increase the resistance to permanent deformation and improve the fatigue behaviour (compared to a lower degree of compaction) [10.].

Better compaction of the asphalt layer also results in an improvement in stiffness and will enhance the resistance against moisture-related damage as it will keep water out of the pavement layer(s). Better compaction (of dense mixtures) also leads to less ageing.

Optimal compaction of the asphalt mixture is facilitated by good mixture design with a homogenous material structure. Also a robust Quality Control System during construction is essential.

5.7. Bonding between the layers

Bonding between asphalt layers is essential for several reasons and therefore a bond coat should always be used.
An inadequate bond can allow water to penetrate between the layers from the side or from longitudinal joints.
Where an insufficient bond between layers exists the pavement layers can bend independently under load reducing its inertia compared to one thick layer. This leads to higher stresses at the bottom of each of the layer leading to premature further delamination and cracking .

To obtain a good bond between the layers, the substrate (the surface to be paved) should be clean. The application rate of the bond coat depends on the surface to be paved.
A dry, aged pavement requires a higher application rate than a newer pavement. A milled surface also requires a higher application rate because of the increased surface area (from the grooves left by the cutting teeth on the milling machine) typically in the range of 20 to 30 percent. Bond coat selection and formulation as well as thickness applied has a substantial impact on their functionality in the overall pavement design ranging from hard, brittle and stiff to elastic and tough.

5.8. Other important items

Some other important items are mentioned by PIARC. The main conclusions of the PIARC study on ‘success stories’ [11] mention:

- The pavements should be designed wide enough to avoid traffic edge loading [12].
- The asphalt / single seal surfacing should be well designed and constructed to avoid ingress of water into the lower layers. [13].
- It is important to have a good homogeneity within the individual pavement layers in all directions, by using homogeneous materials and equal (homogeneous) compaction levels. A chain is as strong as the weakest link [12].
- For durability of a road it could be desirable to minimize ageing of the pavement by reducing the air void content of the mixture and by selecting a binder [12 and 13] that does not age quickly. This will also contribute to preventing fatigue cracking and stripping of the surface layer.
- The thickness of asphalt pavement is a very important parameter for the pavement life. A conservative design giving an extra thickness added to the theoretical design will lead to a much longer pavement life [14 and 15]. Increased thickness can also be regarded as an additional safety margin in the design.
- The use of modified asphalt with higher quality can be justified in the case of severe conditions (climatic, traffic) [16]
- A good asphalt mix gradation is essential for obtaining a rut resistant asphalt mixture [16].

By taking all these conclusions into account when designing and building a road, the probability of creating a success story will definitely increase. Many case studies showed that well designed and constructed asphalt pavements are very durable.

6. CONCLUSIONS AND RECOMMENDATIONS

Current European bitumen standards address the short term ageing of bitumen but the long term ageing is not addressed. When contractors are becoming responsible for the long term durability of asphalt surface layers there will be a need to address long term ageing. For most binders long term behaviour can be predicted from short term ageing, but complex binders may require more assessment. This long term ageing protocol should reflect the bitumen ageing process in the field over the design life of the asphalt.

There are several conditioning procedures available for long term ageing of bitumen and CEN TC336 is evaluating procedures for incorporation into European bitumen standards.

Also a good conditioning procedure for asphalt mixtures is needed. This is a more complex issue. There are conditioning procedures to simulate ageing of the asphalt mixture for loose mixtures or slightly compacted mixtures, but these are not representative for the behaviour of (dense / compacted) mixtures as used in the road.

A good procedure to age asphalt samples or plates is important to be able to test the long term behaviour of asphalt mixtures (for instance to test the ravelling resistance of asphalt mixtures). When new mixtures are being developed the long term behaviour is important and to be able to test this, a long term ageing procedure is needed.

Next to the tests that are needed to characterise the ageing of bituminous binders and asphalt mixtures, the application of good construction practices is essential in creating durable and thereby more sustainable asphalt pavements.

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8. LITERATURE

[1] Nicholls, J.C. ; McHale, M.J.; Griffiths, R.D.; Best practice guide for durability of pavements; Road note 42, TRL 2008; UK.
[2] A Review of the Fundamentals of Asphalt Oxidation Chemical, Physicochemical, Physical Property, and Durability Relationships, Transportation Research Circular E-C-140, October 2009, TRB, Washington D.C., USA.
[3] SPIEGL, M.; STEIDL, H.; WEIXLBAUM, M.; Alterungsbeständigkeit von Straßenbaubitumen; Gestrata Jounal, April 2008, Folge 120.
[4] Besamusca, J.; Sörensen, A.; Southwell, C.; Addressing Ageing Characteristics of Bituminous Binders in Europe; Paper of CEN TC336 WG1 TG 3 prepared for the Eurasphalt & Eurobitume Congress 2012, Istanbul, Turkey.
[5] Reha Çetinkaya, R.; Analysis of the influence factors on the thermal-oxidative ageing of bitumen in asphalt (in German), PhD dissertation, Fachbereich Bau- und Umweltingenieurwissenschaften der Ruhr-Universität Bochum, Bochum, 2011.
[6] State of the art on existing laboratory methods (sampling, characterization) linked to Reclaimed Asphalts study; Deliverable 1.1 of the (FP-7) Re-Road project, 2010.
[7] Van der Zwan, J.T., Developing Porous Asphalt for Freeways in the Netherlands, TR News, Transportation Research Board, USA, Number 272, 2011.
[8] Hagos, E.T. The Effect of Ageing on Binder Properties of Porous Asphalt Concrete. Dissertation of Road and Railway Engineering, Faculty of Civil Engineering and Geoscience, Delft University of Technology , Delft, Netherlands, 2008
[9] Warm-Mix Asphalt: European Practice, Publication no.: FHWA-PL-08-007, February 2008, FHWA/US DOT, Washington DC, USA.
[10] Harvey, J.; "Long-Life AC Pavements: A Discussion of Design and construction Criteria Based on California Experience"; International Symposium on Design and Construction of Long Lasting Asphalt Pavements, Auburn USA, 7-9 June 2004.
[11] PIARC Report on Success stories of PIARC TC 4.3.1 (2007)
[12] Litzka, J.; "Analysis of road pavements with long term reliability in Austria, Institute for Road Construction and Maintenance", TU Vienna, Vienna, 2006.
[13] Steyn, W.J.v.d.M., Jones, D., and Sadzik, E.; Analyses of the Performance of a Long Life Pavement in South Africa – N12 Experimental Section 2.
[14] Andersen, R.J, Ertman Larsen, H.J., Thau, M.; Long-life pavement (LLP)- the Danish experience, 2006.
[15] Laurent, G. ; Analyse des chaussées construites avec succès dans l'ouest de la France / Analysis of pavements built with success in the West of France, CETE de l'OUEST, Ministère de l'Equipement, Nantes
[16] Kobayashi, T.; A case of Long Life Pavement observed on an Expressway in Japan, Japan Highway Public Corporation (JH)
[17] EAPA Paper Long-Life Asphalt Pavements, EAPA, Brussels, 2007.
[18] Newcomb, D.E., D'Angelo, J.; Perpetual Hot Mix Asphalt Pavements in the US.
[19] Hensley, J.; Eliminate 12 segregation snarls, Asphalt Institute, USA.