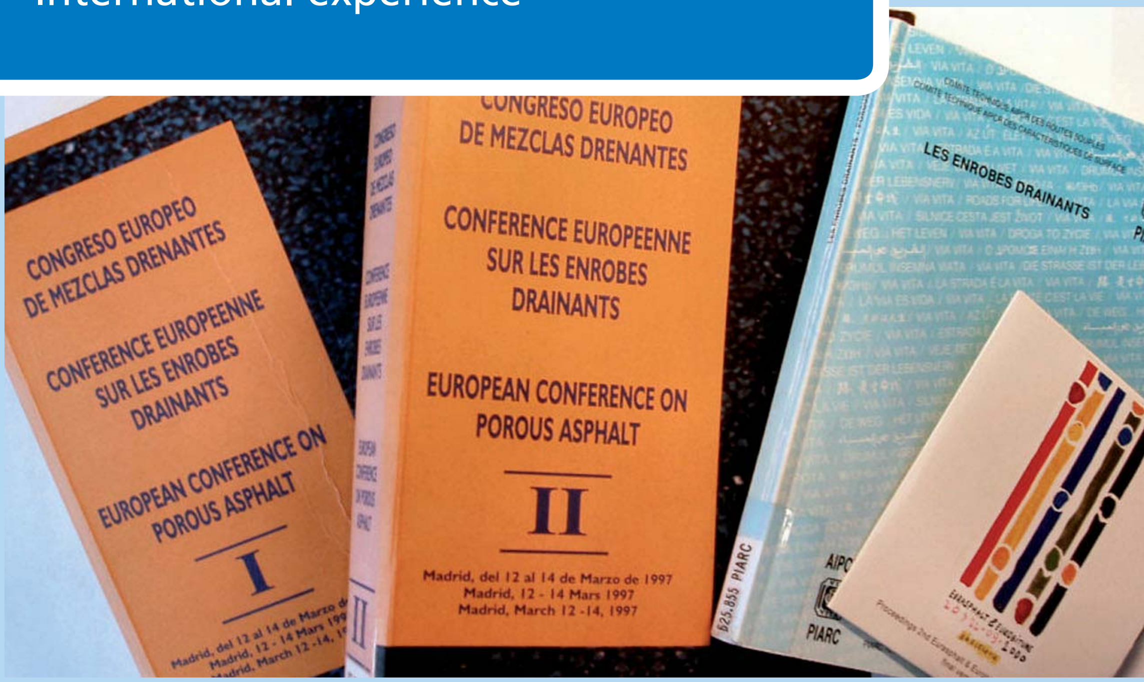
Durability of porous asphalt

- International experience



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Road Directorate
Ministry of Transport and Energy

Road Directorate
Guldalderen 12
DK-2640 Hedehusene
Denmark

Telephone +45 4630 7000
Telefax +45 4630 7105
www.Roadinstitute.dk

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Authors	Carsten Bredahl Nielsen
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Contents

Preface

The DRI-DWW Noise Abatement Programme was started in the beginning of 2004. It is a joint cooperation between the Road and Hydraulic Engineering Institute (DWW) in the Netherlands and the Danish Road Institute (DRI) for research and development in issues related to abatement of road traffic noise. The cooperation is carried out within the framework of the Dutch Noise Innovation Program (the IPG programme) [9]. The projects *Ravelling of porous Pavements* and *Modified bitumen used for porous pavements* are two of the seven themes included in the cooperation.
The present note is the milestone M3 "International Experience" mentioned in the project description as of July 2004. Since the two subjects have much in common it was decided to combine the two notes on international experience into one.

Forord

Vejteknisk Institut og Road and Hydraulic Engineering Institute (DWW) i Holland samarbejder under det Hollandske Noise Innovation Programme (IPG) i en række projekter relateret til støjbekæmpelse. Projekterne *stentab i drænasfalt* og *modificeret bitumen i drænasfalt* er to af de syv projekter, som samarbejdet omfatter. Dette notat er milepæl M3 *Internationale erfaringer* omtalt i projektbeskrivelsen fra juli 2004. Da de to projekter har meget til fælles blev det besluttet at samle de internationale erfaringer i et notat.

Summary and conclusions

The DRI-DWW Noise Abatement Programme is a joint cooperation between the Road and Hydraulic Engineering Institute (DWW) in the Netherlands and the Danish Road Institute (DRI) carried out within the framework of the Dutch Noise Innovation Programme. The project ravelling of porous pavements and modified bitumen used for porous pavements are two of the seven themes included in the cooperation. The overall aim of these studies is to understand the ravelling process from the microstructure of porous asphalt and to relate this to the performance of porous pavements on the roads.

The present literature research is focused on the use and durability of porous asphalt in general, the mixture design and the use of modified bitumen for porous asphalt. The main objective being to assess whether ravelling is a general problem and what could be done to improve durability from a mix design point of view.

It seems that there are two trends or directions in the design of low noise pavements;

- Considerations mainly on noise abatement on the account of durability. Porous elastic pavements as developed in Japan is an example of this but also the further improvements of the durability of porous asphalt and the high void mixes (up to 30 %) are examples;
- Considerations mainly on pavement management and practical maintenance on account on noise abatement. Ultra thin dense layers such as the French 0/6 mixes and the UK strategy are examples of this.

Summarising the international experience on ravelling of porous asphalt it seems that large stone mixes should be avoided in countries with wet weather conditions like UK (0/20 mm mixes) and partly the Netherlands (0/16 mm mixes). The overall development is towards finer mixes with higher binder contents (0/8 mm or 0/6 mm mixes) and void contents of 22 – 30 %. In general all countries state that ravelling is a serious problem but France states that the durability of well designed porous asphalt is identical to that of conventional asphalt. In Germany it was decided only to use porous asphalt if extremely expensive noise barriers could be avoided, but the public demand for noise abatement has lead to new developments and new generations of porous asphalt and this development should be closely watched.

The general tendency in Europe in resent years is towards the use of modified binders in porous asphalt on a routine basis. Modifiers are believed to increase the lifetime of porous asphalt by increasing the cohesion and adhesion in the asphalt mixes and by increasing the binder film thickness without the risk of segregation of the binder (binder drainage). They are also believed to increase the resistance to ravelling due to the higher viscosity at higher temperatures and higher flexibility at lower temperatures.

1. Methodology

International experiences on ravelling and aging of porous pavements is mainly collected in a literature research and partly by personal contacts within FEHRL and other international contacts. The literature search is conducted as a general search in international databases and a specific search in selected, resent international conferences. These are:

- European Conference on Porous Asphalt (1997).
- Eurasphalt & Eurobitumen Congresses (1996, 2000, 2004).
- ISAP International conference on Asphalt Pavements (2002).
- TRB annual meetings (2004, 2005).

The search is concentrated on resent publications since the focus on noise abatement and the use of porous pavements has increased considerably in the last 5-10 years and the experiences from the use therefore has not been published earlier. Selected references and the work by selected authors in these publications are also assessed.

The references are organised in accordance with the relevance to the present study. The subjects of interest are:

- Durability of porous asphalt in general (state of the art, field evaluation, maintenance).
- Mixture design, laboratory experiments, models for and field observations of the durability of porous asphalt.
- Modified bitumen used for porous asphalt.

Each reference is classified according to these subjects being relevant to one or several subjects. After this initial classification each subject is assessed in separate paragraphs summarising all experiences within this subject. In a final assessment of the international experiences some knowledge gabs are identified.

It is the intention to keep the present note as brief as possible only including the most relevant statements from literature which is of interest for the final assessment. It should also be noted that only selected references referred to in the present note are included in the reference list. This selection is made from a broader assessment of international literature. Only references in English language are included since these are easy accessible to most people but other selected references has been scanned. The reference lists in the selected references has been scanned but references only included if the subject was not covered by a newer reference. The reference list is sorted in alphabetic order by the first author and referred to with a number in square brackets according to this order.

References available in electronic form will be included on a CD when the final report from the DRI-DWW noise abatement programme is published.

2. Experiences with porous asphalt

A brief historic summary of the development of porous asphalt is provided by Kraemer at the opening of the European Conference on Porous Asphalt in Madrid in 1997 [17]. Originally developed to prevent skidding on wet pavements in the thirties in the US porous asphalt was ready for general applications on highways and airports in the seventies. This was the basis for the European development of porous asphalt in the early eighties based on the research at the University of Cantabria where a mix-design method for porous asphalt was established. In 1985 the operational use on motorways and major roads began and a rapid development took place especially when the noise reducing benefits was recognised.

The research has been reported at several workshops and seminars and Kraemer highlights:

- Seminars in Farnham (1977) and Bruising (1981) in the Netherlands.
- TRB annual meeting (1990).
- PIARC seminar in Marrakech (1991) and publication of Porous asphalt (1993).

He concludes that the progress made in resent years and the road user satisfaction with porous asphalt are forcing a change in attitude and will lead to a general use of porous asphalt.

Corté [8] states that the main advantage associated with porous asphalt are related to the safety and comfort of the road users and the reduction of rolling noise, which is confirmed by almost all literature on porous asphalt.

Ruiz [41] states that the main objective of porous asphalt is to attain a large amount of interconnected voids which permit the evacuation of surface water from the carriageway. This is a change in the traditional concept having a waterproofing wearing course. In order to achieve a high percentage of voids the fine aggregate content is lowered and the mortar content must be drastically reduced compared to dense asphalt concrete. Lower mortar content results in mixtures with higher sensibility towards aging, particle losses and water action. The design of porous asphalt mixtures thus is a balance between a **minimum binder content** assuring:

- an adequate resistance to disintegration;
- a thick binder film to avoid aging;
- an adequate resistance against the action of water

and a **maximum binder content** in order to:

- assure a minimum void content for drainage of water and reduce rolling noise;
- avoid binder drainage in the mixing, handling and laying.

A European agreement on design procedures was never reached since the first developments at the University of Cantabria. Ruiz concludes that this has not stopped the development of porous asphalt mixes and presents a European state of the art on the selection of components, test and design methods.
The experiences with porous asphalt as reported in literature are summarised below country by country. Durability has always been a matter of concern since this is one of the disadvantages due to the open mix design of porous asphalt. Kraemer [17] states that it is important not to regard the reduction of hydraulic and acoustic surface properties as a failure when it would simply mean that such asphalt gradually turns into non-porous surfacing and still affords good surface characteristics. From a road engineers perspective this is true but as the benefits of reduced rolling noise becomes more and more important for the public one also has to consider the acoustic durability. Other drawbacks often reported in literature is the special considerations regarding maintenance and repair and strategy for winter maintenance.

2.1 The Netherlands

Swart [48] reports on the experience with porous asphalt in the Netherlands. Porous asphalt was introduced in the early eighties and in 1987 it was decided to start applying porous asphalt wearing courses on a larger scale, and three years later the decision was made that the entire main highway network (3.200 km) qualified for porous asphalt. On heavy trafficked roads mostly porous asphalt 0/16 mm in a layer thickness of 50 mm is used. In general modified binders are only used for special purposes.
The typical deterioration is ravelling and rapid aging of the binder is considered to be a problem. Due to ravelling the average service life is about 10 years. Padmos [30] reports five year later that the design and composition has not really changed after 1990 and that ravelling in about 76 % of the cases is the cause for maintenance or renewing of the top layer. The average service life is 10-12 years and in narrow curves ravelling is a problem already after three years.

Bochove [3] reports that since 1990 test tracks with two layered porous asphalt has been constructed in the Netherlands as part of a large scale research project.
The benefit from a fine graded upper course is the prevention of clogging in the coarse graded porous asphalt layer below. In this way the hydraulic conductivity is kept intact. The good experiences from the research project lead to creation of new test sections on the Motorway A-17 in 1995 and several other locations later. Battiato [1] also reports that two layered porous asphalt has been applied in Italy in 1995-96.
Bendtsen et al. [2] and Larsen et al. [18] reports that a trail section with two layered porous asphalt was constructed and monitored in Denmark since 1999. Schäfer [44] reports that this concept will be used for the first time in Germany on a larger motorway section in spring 2004. Schäfer [43] also presents the compact module paving machine for laying twin-layer porous asphalt.

2.2 France

Bonnot [4] reports that in France the use of porous asphalt started in 1976, increased from 1984 until 1990, then stabilised and later decreased mainly related to the specific recommendations for winter maintenance. In 1995 more than 60 % of the total porous asphalt surface area in France was laid on conceded motorways and 15 % of those were covered with porous asphalt. Most frequently a 40 mm thick course of 0/10 mm mix is used with pure 50/70 penetration grade bitumen. On conceded motorways polymer modified or fibre modified bitumen is almost exclusively used. Bonnot states that the French 8-years of experience (in 1997) have not indicated that porous asphalt with unmodified binders is more susceptible to ravelling than mixes with modified binders. Also, the binder film of pure bitumen causing reduced skidding resistance in the early life of porous asphalt is more rapidly removed (3-6 months) by traffic than the binder film of modified bitumen (8-18 months).

French contractors have conducted trails with 0/6 mm mixes with very high void contents (between 25 % and 28 %) with no (or very low) sand fraction. These mixes are all highly modified since they are extremely sensitive to horizontal stresses (and following ravelling). The benefits from such fine graded courses are low rolling noise and high skid resistance (due to the microtexture). Spillemaecker [46] presents the genesis of these new asphalt products from the viewpoint of their mix design, their application and their observed behaviour on the most significant sites. Bonnot [4] states that the durability of well designed porous asphalt is identical to that of conventional asphalt. The high voids content causes rapid aging of the binder, but the binder film thickness prevents this from resulting in an abnormal tendency of ravelling. Bonnot concludes that porous asphalt mainly should be used on high-traffic motorways and urban express roads with a design speed of 80 or 100 km/h in level terrain and with no or only a few curves with R<300 m.

2.3 United Kingdom

Bowskil et al. [5] reports that in the United Kingdom the specifications for porous asphalt is based on trails over a period of about 20 years starting with the firs trails in 1967. Most frequently a 50 mm thick course with 20 mm maximum size high quality aggregate is used. The first trails pointed out that the lifetime of porous asphalt is limited by clogging and the hardening of the binder. It was observed that there was a 20 per cent reduction in penetration per year and brittle fracture occurred when penetration of the binder was less than 15. The later trails were designed to solve the hardening of the binder by thickening the binder film but at the same time reducing binder drainage. In the UK specifications it is concluded that the binder should be either 100 or 200 penetration grade and a variety of modifiers is permitted. In 1992 it was decided to allow limited use of porous asphalt on trunk roads and motorways where the benefits can be shown to outweigh the drawbacks. This has lead to selected use in the UK of porous asphalt in some sensitive locations. Bowskill concludes that the greater cost of UK porous asphalt has limited the use and as new types of thin surfacings combine many of the beneficial properties of porous asphalt without the drawbacks, these surfacings is expected to be used. This strategy is confirmed by Wright [58].

2.4 Germany

Reichelt [37] reports that in Germany a research programme were conducted from 1986-93 to find the noise reducing potential of porous asphalt. The result was that coarse mixes (0/16 mm) and a void content below 15 per cent had good structural lifetime but poor noise reducing properties. Fine mixes (0/8 mm) had better noise reducing properties but poor structural lifetime. New trails in 1993 with fine, high void mixes indicate a service life of only 5-7 years. In order to improve service life different modified binders, compaction work and the effects of evenness are tested but it seems that ravelling occurs already after five years. The German Transport Ministry therefore has decided only to use porous asphalt if extremely expensive noise barriers can be avoided.

Suss [47] reports that to obtain a longer structural lifetime in the revised German guidelines for the construction of porous asphalt the minimum binder content was raised and only polymer modified binders is allowed.

Ripke [40] refers to five generations of porous asphalts in Germany; the first and second generations (1986-93) being those referred to by Reichelt; the third generation (1996-2004) with void contents above 22 %; the fourth generation (1998 – 2004) being twinlay pavements as reported by Bochove [3] and the fifth generation (2003-) with variable thickness are on trail in a large-scale research project. In all cases the structural durability is characterised as sufficient or on trial as all porous pavements are susceptible to ravelling. Ravelling is mainly related to the hardening of the binder and an increase in softening point of 1.5 – 2 °C per year is reported. A dense surface is expected to harden approximately 1 °C per year. Renken [38, 39] also reports on increased softening points from trail sections in Germany and other test results related to the performance of seven different mixes after 4-6 years in service.

Schäfer [44] reports some experiences of the third generation of porous asphalt in Germany since 1996 consisting of 40 mm 0/8 mm mix with void content of minimum 22 % and a binder with high polymer content. He expects a noise related service life of more than 6 years and a structural service life of more than 10 years. He also mentions the German practice of sealing with 2.5 kg/m^2 with the same binder as used for the porous pavement.

2.5 Austria and Italy

Litzka [20, 21] reports that porous asphalt was introduced in Austria in 1984, and in 1992 18 % of the main road network was paved with porous asphalt. Since then the use of porous asphalt has declined substantially mainly due to an observed rapid decline in serviceability once a first damage (ravelling) has occurred. In general the performance is considered quite satisfactory but the sensitivity to ravelling has lead to the use of non-porous pavements which is less sensitive. The most commonly used porous pavement consists of a 40 mm 0/11 mm mix with a binder content of at least 5.2 %. Only modified binders are used.

Pasetto [31] reports that in Italy porous asphalt is consolidated as a construction practice, especially for motorways. Durability is also a problem in Italy and Pasetto therefore has conducted research on the contribution of polypropylene, polyacrylonitrile and cellulose fibres to the performance of porous asphalt. It was found that fibres greatly improved the behaviour in the Cantabro test, especially for the mixtures with higher binder contents.

2.6 Spain and Portugal

According to Ruiz [41] the most commonly used mix en Spain is a 0/12 or 0/10 mm with 4.5 % binder content. Soto et al. [45] reports that porous asphalt mixes have been applied in Spain since the beginning of the eighties. Overall the only maintenance on a larger scale has been to clean the pavements to restore the permeability. Recently several problems has appeared amongst others ravelling. Soto suggest a new maintenance technique using warm (80 °C) open graded mixes with polymer modified emulsions.

Luis [22] reports that porous asphalt was introduced in Portugal in 1991 on the motorway network mainly applied as a 40 mm thick 0/15 mm mix with 4.8-5.0 % polymer modified binder and 20-25% air voids. No experiences on the durability are reported.

2.7 Japan

Motomatsu et al. [27] reports that porous asphalt was introduced in Japan in 1987. The first trail sections were applied with normal SBS modified bitumen and due to very heavy traffic and severe climatic conditions the mixes was scattered in a few years. Therefore a special polymer modified bitumen was developed containing more than 9 % SBS. The main reason for using porous asphalt was to increase traffic safety and to avoid rutting of the pavement. In 1998 it was decided to use porous asphalt for all highways as a standard surface mix. This concept was very successful and at the end of 2002 more than 40 % of the Japanese highways are paved with porous asphalt. According to EAPA in 2003, in total 152 million m^2 are covered with porous asphalt in Japan. In comparison 50 million m^2 are covered with porous asphalt in the Netherlands in 2003. The paper contains no information on mix design or performance of the mixes on the road.

2.8 USA and New Zealand

In the US they have just started to adapt the European porous pavement technologies. A recent FHWA/AASHTO scanning tour of Europe reviewed Quiet Pavement technologies and practices in five European countries amongst those Denmark and the Netherlands. Open graded friction courses (OGFCs) was originally developed to prevent skidding on wet pavements in the thirties in the US and was generally applied on highways and airports in the seventies. OGFCs, used in the US in the past, differ from porous asphalt mixes. In general, OGFCs have had lower void percentages (10-15%) than porous asphalt mixes. Porous asphalt mixes generally have strongly gap-graded gradations to yield higher air voids (18-22 percent). Watson et al. [55] reports on a mix design study of OGFCs based on Cantabro tests and recommend a minimum air void content of 18 %. McDaniel et al. [24] reports on a field evaluation of a 0/12 mm size porous friction course (PFC) laid in 2003 in Indiana. The Gyratory Compactor and the Cantabro test was used for mix design and obtained air voids was 23 % with 5.7 % modified binder. McDaniel reports no experiences with durability of the PFCs.

Patrick et al. [32] reports that porous asphalt is widely used in New Zealand and was introduced in 1975 with a specified total air void content greater than 14 %. In the eighties the specification was revised to an air void content greater than 20 % but due to an observed poor effective life a research was conducted to maximise the void content (up to 30 %) and applying modified bitumen to ensure adequate strength. Standard mixes in New Zealand are either a 20 mm or a 14 mm size mix. Jackson et al. [14] reports on trails with new 70 mm thick twin-layer pavement based on European developments consisting of a 0/16 mm lower layer and a 0/8 mm upper layer.

3. Porous asphalt mixture design

The mixture design is as stated earlier a balance between minimum and maximum binder content for a specific (open) aggregate grading. Large maximum aggregate sizes and low fine aggregate content increases the risk of aggregate losses. If only the resistance to disintegration (ravelling) is considered the binder content should be as high as possible as long as binder drainage in the mixing, handling and laying could be avoided. This will give a thick binder film to avoid aging and an adequate resistance against the action of water. In this relation it is also important to ensure an adequate affinity between the binder and the aggregate which is also improved by the use of adhesion agents (amines, limes and others). The use of modified bitumen and fibres stabilize the mastics and makes it possible to increase the binder content. Good quality filler improves the adhesion and the resistance to aging.

Ruiz [41] summarizes the state of the art of the porous asphalt mixture design in Europe. Since the beginning of the eighties different design procedures were discussed especially which mechanical test to be used. A European agreement was never reached and different procedures are used. Basically the maximum binder content that allow for the specified voids content are selected. Some countries supplement this with binder drainage tests, water sensitivity tests and particle loss tests. Samples for testing are usually compacted with the Marshall equipment but in France the Gyratory machine are used.

The most commonly used mechanical test is the Cantabro test which is carried out with Marshall samples placed in a Los Angeles machine without the steel balls. After 300 revolutions the particle loss is measured. The test result is very sensitive to the ambient temperature and therefore the particle loss is always specified at a specific temperature. The test results correlates well with the binder hardness as observed by Nielsen et al. [29] and basically it measures the resistance to impacts of the mix. The Cantabro test is also used to measure the susceptibility to water testing the samples after a period of immersion in water and comparing with non-submerged samples. Results from such testing are also reported by Nielsen et al [29].

The Cantabro test has been criticized by several countries by it lack of correlation with ravelling on roads, specifically since it favours modified binders which according to these countries do not correspond to practical results. Tolman et al. [50] presents an alternative to the Cantabro test namely the Cyclic Tensile Test (CTT) which is connected to a model of the mechanical damage of porous asphalt. He finds the CTT more discriminating than the other test, though a relation to actual road conditions are still lacking. The model is further developed by Tolman et al. [51] but he still misses the aimed verification to literature. Voskuilen et al. [53] has found no relation between the results of the indirect tensile test, Cantabro test, cyclic direct tensile test and the field behaviour (ravelling) of porous asphalt on 26 trail sections from the late eighties and early nineties in the Netherlands.

Molenaar et al. [25] investigates the resistance to ravelling using the Wheel Fretting Test (WFT) and the California Abrasion Test (CAT). He states that a definitive choice for a definition of the mechanical strength of porous asphalt relevant to ravelling has not been made. He concludes that the mass loss in WFT and CAT seems to be related to the penetration of the binder at the test temperature.

According to Ruiz [41] a new test has been developed by the Nynäs company, the Nynäs immersion wheel tracking test applying friction forces with an 6 °angled wheel. The results of the test seem to be well related to the experience with ravelling. Bochove [3] suggest a new test method to investigate the mechanical stability of porous asphalt, the Rotating Surface Abrasion Test (RSAT). The progress of stone loss during test is observed and is taken as an indicative of the durability of the mix. Hagos [13] suggest applying cyclic shear stresses to a porous asphalt slab to simulate the action of traffic to test the resistance to ravelling.

Renken [38] presents methods to predict the influence of the temperature on the compaction effort and the dependency between void content and compaction degree during mix design. He concludes that it is strictly unacceptable to obtain a high void content by the reduction of the compaction degree, because a high compaction degree is decisive for the resistance against deformation and particle loss (ravelling). Therefore a high compaction degree enhances the service-life of porous asphalt surface courses.

Research conducted by Voskuilen et al. [54] demonstrates that premature ravelling was caused by the quality of the construction materials, especially of the crushed rock, and manufacturing and laying. Ravelling was attributed to the presence of too high amount of weak rock material which was not detected by the test methods used. Other factors causing premature ravelling are too high or too low mixing temperature (causing segregation respectively poor mixing and crushing of rock) and lower percentages of lime (causing increased aging). In general Voskuilen [53] states that a higher initial stiffness of the binder reduces the initial loss of stones, which is usually the cause of premature ravelling. He considers the higher initial stiffness of the binder as the primary effect of modified bitumen.

Molenaar et al. [25] states that short term ravelling is assumed to be caused by intense shearing force in the tyre/pavement contact area. Long term ravelling is assumed to be caused by gravity segregation of the mastic during the service life followed by stripping at the pavement surface. He hypothesises that the resistance to ravelling of porous asphalt can be enhanced by increasing the number of stone to stone contacts per element of volume of asphalt mixture.

Kneepkens et al. [16] describes the ravelling process as slow starting, but after 7 till 9 years an increasing domino-like effect of gap growing develops; after the first stones are removed, more stones will follow at a higher rate. When the first stone is removed by a car wheel, the remaining stones around the gap lack support from at least one direction. Therefore, it is rather easy to remove the subsequent stones in the gap. Also, from the start there is sometimes less binder in the upper half of the PA, because the binder drains to the lower part. To prevent this domino effect Kneepkens suggests a new maintenance technique for porous asphalt as an alternative to a complete replacement consisting of about 10 mm thick fine cold mixed asphalt with voids content of 25-30 % put on top of porous asphalt. He concludes that further development is needed but it seems possible to stop the ravelling process and maintain the performance of the porous asphalt at an acceptable level.

Soto et al. [45] suggest using a warm (80 °C) mix with a polymer modified emulsion as binder for the maintenance of porous asphalt as an alternative to a dense or open graded hot mix or an open cold mix. The main problem is to find a mix to use in operations with small quantities for patching with satisfactory mechanical properties and drainage capacity. Soto states that the solution to this problem implies the use of a mix combining the cohesion of a hot mix with the workability of a cold mix.
The mix has low flux content, is easily workable even at summer ambient temperature and with the advantage of being storable for a minimum of 24 hours.

4. Modified bitumen used for porous asphalt

The general tendency in Europe in resent years is towards the use of modified binders in porous asphalt on a routine basis. Modifiers are believed to increase the lifetime of porous asphalt by increasing the cohesion and adhesion in the asphalt mixes and by increasing the binder film thickness without the risk of segregation of the binder (binder drainage). They are also believed to increase the resistance to ravelling due to the higher viscosity at higher temperatures and higher flexibility at lower temperatures. The modifier used is rubber from recycled tyres, SBS and EVA the choice depending on the contractor's experience.

As stated by Ruiz [41] the main reason for not using modified binders is cost-benefit considerations. France and the Netherlands find a general lack of data proving a better durability of porous asphalt with polymer modified binders and also highlights that the initial friction due to the superficial binder film is low for a longer period of time with modified binders.

From a research of the service life of 26 porous asphalt test sections Voskuilen et al. [53] concludes that PMB do not provide a longer service life in itself; the main benefit seems to be in the initial stage when initial damage is reduced. He suggests that the higher mixing and compaction temperatures of PMB and the higher initial strength reduce damage in the first months, which is one of the causes of short service lives. PMB enables the increase of the binder content and hence the resistance to ravelling but he recommend to use drainage inhibitors because of lower costs. He finds that PMB and thicker bitumen films do not noticeably increase the resistance to aging. He observes that trail sections with PMB have lower particle losses in the Cantabro test but poorer performance in practice compared to porous asphalt with standard bitumen and fibres.

Nielsen et al. [29] concludes from a laboratory study of 18 different porous asphalt mixes that the most durable mix is obtained using slightly reduced voids content in the mix and a highly modified SBS binder developed from a soft virgin binder. The conclusion is based on Cantabro tests and is not confirmed by trail sections.

Wegan et al. [56, 57] presents a technique (optical and UV fluorescence microscopy) to examine the polymer structure of the modified binder in an asphalt mix. She assumes that the structure of the polymer phase in the asphalt mix can be related to the performance of the asphalt mix. She has observed that variations in the mineralogy of both the filler and the coarse aggregate have resulted in large differences in the distribution of the polymer phase in the bituminous mixture. She concludes that it is important to investigate the parameters which influence the structure of the polymer modified binder in order to be able to improve the performance of the bituminous mixture.

Mouillet et al. [28] presents a supplementary technique to UV fluorescence microscopy, the infrared microscopy (FTIR). FTIR micro imaging can be used to complement other usual imaging techniques and to correlate the microstructure (visible image) with the chemical composition (spectroscopic characteristics). Mouillet concludes that the knowledge of parameters related to the polymer swelling and dispersion, and the changes in bitumen composition, gives guidelines to optimise PmB formulation with respect to their functional properties. This technique could also possibly be used to study structural changes of PMBs during aging.

Potgieter et al. [34] reports on the long term performance of bitumen rubber (B-R) asphalt in South Africa. Porous B-R asphalt was laid in the South Africa as early as 1985. The high viscosity of bitumen rubber binders, combined with good adhesive properties and the presence of carbon black, antioxidants, amines and aromatic oils as part of the modified binder (which contribute to the improvement of durability and resistance to ageing and to stripping) makes bitumen rubber binders ideally suited for use in porous asphalt mixes. With these binders, coarser porous asphalt mixes can be designed with greater void contents (in excess of 22 %) with good durability and resistance to abrasion. He concludes that B-R asphalt outperformed conventional asphalts (penetration grade bitumen) and other modified binder asphalts (SBS, SBR, EVA, etc.) and is the more economical asphalt when assessed over its full life cycle.

Punith et al. [35] reports on the results of a study in India comparing structural performance of porous asphalt mixtures containing cellulose fibres, crumb rubber modified binder or reclaimed polyethylene modified binder. The effect of binder type and binder content on the performance parameters is evaluated. Punith concludes that the abrasion loss of the porous asphalt mixtures resulting from aging can be reduced significantly with the addition of modifiers or additives. The use of polymeric asphalt makes it easier to obtain a greater thickness of the binder film, which improves the cohesion, resistance to cracking, friction and durability of the porous asphalt mixtures. The investigation was limited to a laboratory study and the findings have not been related to actual field performance.

Molenaar et al. [26] presents the feasibility of performing a quantitative analysis of polymer modified bitumen (PMB) in asphalt mixtures and of polymer in PMB. He finds that it is not yet clear how bitumen properties contribute to the durability (resistance to raveling) of porous asphalt and consequently whether polymer modification of porous asphalt is cost-effective. In the Netherlands it is therefore required that polymer modifications are identifiable and determinable. The paper reviews analytical techniques to determine the polymer type and concentration in PMB.

Motomatsu et al. [27] reports on new types of highly modified SBS bitumen (9-12%) requiring a new testing method to evaluate the properties. This very high polymer content is used for porous asphalt applied in heavy trafficked mountain regions with snow chain usage. The paper presents a Binder Bending Test suitable for this. It is found that bending toughness and stiffness of the binder and Cantabro test at low temperatures is related to the performance of the porous asphalt mix. The homo genization of the polymer and the base bitumen is very important and it is found that poorly homogenized PMB with high polymer content performs the same or worse than well-homogenized PMB with lower polymer content.

Rayner et al. [36] reports on the long term aging of polymer modified bitumen (Starfalt) in Austria in different types of asphalt. He finds no correlation between age and aging in general. For each asphalt type (e.g. porous asphalt) retained penetration and age are (roughly) correlated but difference in softening point does not correlate to the age. It is observed that after nine years the softening point decreases due to the decomposition of the SBS modifier.

Hagos [12] has conducted a literature review of the effect of aging of bituminous mortars on ravelling of porous asphalt. The use of PMB in porous asphalt is recommended since the modified binder is assumed to coating the aggregate with relatively thicker binder films and thus enhancing the aging susceptibility. The rheological changes of modified binders due to aging are dependant on the combined effect of bitumen oxidation and polymer degradation, which varies with types of bitumen and polymer, as well as polymer content.

Valdés-Hevia et al. [52] propose a procedure to measure changes in the chemical composition of polymer modified bitumen due to aging in laboratory. He concludes that bitumen oxidation is more dominant than the degradation of the SBS-polymer.

5. Assessment of international experience

The present literature research is focused on the use and durability of porous asphalt in general, the mixture design and the use of modified bitumen for porous asphalt. The main objective being to assess whether ravelling is a general problem and what could be done to improve durability from a mix design point of view.

It is obvious that the choice of porous asphalt as wearing course is not due to durability; in fact durability is the main disadvantage of porous asphalt on account of several well known advantages. The easy access of air and water is the main reason for the good performance related to drivers comfort and noise abatement and at the same times the reason for the relative short service life. Realistically it seems not possible significantly increasing durability without counteracting on drivers comfort and noise abatement.

Historically the use of porous asphalt was initiated by the need to prevent skidding on wet pavements followed by the benefits of drivers comfort and later noise abatement. The good experiences lead to an increase in the use of porous asphalt during the eighties, a recess in the nineties in several countries when problems with winter maintenance and durability became a serious practical and political problem and overtaken by environmental concerns in the new millennium. Today the public demand for noise abatement attract increasing political attention and a new balance between noise abatement and practical pavement management has to be established. For this purpose cost-benefit analysis including the costs of noise annoyance, maintenance and drivers delay is developed.

It seems that there are two trends or directions in the design of low noise pavements;

- Considerations mainly on noise abatement on the account of durability. Porous elastic pavements as developed in Japan is an example of this but also the further improvements of the durability of porous asphalt and the high void mixes (up to 30 %) are examples;
- Considerations mainly on pavement management and practical maintenance on account on noise abatement. Ultra thin dense layers such as the French 0/6 mixes and the UK strategy are examples of this.

In the first methodology innovation and new thinking plays an important role; new materials, new combinations of well known materials and development of new technology is important and the price and durability is initially of minor interest. From this innovation should lead to lower prices and better durability.

In the second methodology innovation and new thinking also is important but the price and durability of the pavement is the principal interest. From this innovation should lead to still better noise reduction. Kraemer [17] states that the impact of porous asphalt has proved to be an incentive to improve the surface characteristics of other kinds of surfacing, in respect either of drainabillity, such as porous concrete wearing courses or of good noise and surface drainage properties, as in the case of microasphalt gap grades mixes.

Summarising the international experience on ravelling of porous asphalt it seems that large stone mixes should be avoided in countries with wet weather conditions like UK (0/20 mm mixes) and partly the Netherlands (0/16 mm mixes). The overall development is towards finer mixes with higher binder contents (0/8 mm or 0/6 mm mixes) and void contents of 22 – 30 %. In general all countries state that ravelling is a serious problem but France states that the durability of well designed porous asphalt is identical to that of conventional asphalt. In Germany it was decided only to use porous asphalt if extremely expensive noise barriers could be avoided, but the public demand for noise abatement has lead to new developments and new generations of porous asphalt and this development should be closely watched.

Another problem stated by UK is the expensive use of high quality aggregates due to the applied thickness of porous asphalt. This also point towards the use fine mixes in thin layers either as in twinlayer porous asphalt or as single layers.

Based on the international experience the use of modified binders is recommended. Most countries recommend the use of modified binders from a mix design point of view and claim the possible effect on the increased binder film thickness due to a higher binder content and better resistance to aging. Those countries considering the actual field performance (France and the Netherlands) find a general lack of data proving a better durability of porous asphalt with polymer modified binders, but it is recognised that the higher initial strength might reduce damage in the first months which could be of vital importance to avoid the initiation of ravelling. The very fine 0/6 mixes in France are all highly modified since they are extremely sensitive to horizontal stresses (and following ravelling). Experiences from Japan demonstrates that it is possible to use SBS contents as high as 9-12%, but then it is very important that the polymer is well-homogenized. At such high polymer contents it could also be considered to use a pure synthetic binder.

An important effect from using modified binders are the higher binder content possible. In the Netherlands it is recognised that increasing the binder content from 4.5 % to 5.5 % increases durability by 2-3 years. In Germany it is specified to use 6.2 – 6.8 % polymer modified bitumen in a 0/8 mm mix. It is of course also possible to use other stabilising additives to obtain high binder content if this is more cost effective. Using modified binders, though, one could obtain both increased binder content and a higher initial strength.

The simplest criterion for the initiation of long term ravelling is the binder penetration and several references states that this often gives the same answer than more advanced and performance based rheological parameters. It generally observed that a brittle fracture occurs when penetration of the binder is less than 15 – 20. Once a first damage (ravelling) has occurred a rapid decline in serviceability is observed. This is explained by the increasing domino-like effect of gap growing; after the first stones are removed, more stones will follow at a higher rate.

The Cantabro test, also observed to correlate with the penetration of the binder, is still the most widely used test to determine the mechanical strength of porous asphalt relevant to ravelling even though some references states that here is not a direct correlation with field performance, especially for polymer modified binders.
The problem is that there is still no simple, proven alternative. Suggested alternatives are the Cyclic Tensile Test, the Nynäs immersion wheel tracking test, the Rotating Surface Abrasion Test and the Cyclic Shear Test. The advantage of the Cyclic Tensile Test is that it is connected to a suggested model of the mechanical damage of porous asphalt.

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Road Directorate
Niels Juels Gade 13
P.O. Box 9018
DK-1022 Copenhagen K
Denmark
Telephone +45 3341 3333
Telefax +45 3315 6335

Road Directorate
Guldalderen 12
DK-2640 Hedehusene
Denmark
Telephone +45 4630 7000
Telefax +45 4630 7105

Road Directorate
Thomas Helsteds Vej 11
P.O. Box 529
DK-8660 Skanderborg
Denmark
Telephone +45 8993 2200
Telefax +45 8652 2013

vd@vd.dk
Roadinstitute.dk