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QUIET PAVEMENT TECHNOLOGIES

Technical Committee D.2 – Road Pavements

WORLD ROAD ASSOCIATION
MONDIALE DE LA ROUTE
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STATEMENTS

The World Road Association (PIARC) is a nonprofit organisation established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport.

The study that is the subject of this report was defined in the PIARC Strategic Plan 2008 – 2011 approved by the Council of the World Road Association, whose members are representatives of the member national governments. The members of the Technical Committee responsible for this report were nominated by the member national governments for their special competences.

Any opinions, findings, conclusions and recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of their parent organizations or agencies.

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EXECUTIVE SUMMARY

This report explains the conceptual framework for managing road noise and the tyre-pavement noise fundamentals (mechanisms, main systems which act as source, mechanisms complexity and practical needs). Practical solutions (asphalt rubber friction course, poroelastic road surface, porous asphalt-single-layer, porous asphalt– two-layer, stone mastic asphalt, thin and ultrathin surfacing, surface dressing, porous concrete, exposed aggregate concrete, drag textures, diamond grinding, longitudinal tining). Finally, national and multi-national quiet pavement initiatives (European and multi-national overview, United States overview) were described.

The key conclusions drawn from this analysis are the following.

There are a number of national/international projects and research programs looking at reducing the physical impacts of environmental noise, developing innovative reduction measures and/or assessment schemes and/or reducing costs.

There is a strong focus on source-related mitigation measures and an increasing emphasis on cost-effectiveness. Many solutions are proprietary products.

It still remains crucial that knowledge and experiences be shared in order to permit that innovations and products developed for use within specific member states may be equally beneficial/valid for use in a wider area.

There is the need for the standardisation of components and acoustic labeling to help achieve the selection of the appropriate products.
Due to the evolution of traffic spectrum, it becomes more and more relevant to include truck tyre noise in mitigation research.

Infrastructure sustainability is growing in interest, in the sense of a development that meets the needs of the present without compromising the ability of future generations to meet their own needs. The fact implies the opportunity of considering, in future projects, the combination of noise, air pollution and other environmental issues.

1. MANAGING ROAD NOISE

1.1 ROAD NOISE CONTEXT

Highway agencies around the world are facing an increase in noise from automobile traffic. Noise pollution takes different forms (pavement/tyre noise, motor noise, speed, etc.) and has negative impacts on those living near highways. It can even cause mental illness and cardiac disorders, and therefore has social costs. Highway agencies and governments must deal with this problem, which pits economic development against people's quality of life.

In a recent report, the World Health Organization (WHO) reviewed and demonstrated the effects of environmental noise on annoyance and health, including cardiovascular disease, cognitive impairment, sleep disturbance, physiological stress reactions and tinnitus [WHO 2011]. It is estimated that at least one million healthy life years are lost every year from traffic related noise in the western part of Europe. Annoyance and sleep disturbance, mostly related to road traffic noise, are the main nuisance due to environmental noise. Compared with other stressors, road traffic noise pollution mostly shows an increasing trend, due to the combination of growing urbanisation, increasing demand for motorized transport and inefficient urban land planning.

In addition to health related costs, noise pollution induces devaluation in house prices, productivity losses, costs related to premature death. The social costs of road and railway traffic noise across the European Union were estimated around 40 billion Euros per year, out of which 90% were attributed to passenger cars and heavy goods vehicles [den Boer & Schroten, 2007].

Road traffic is the main source of environmental noise. The assessment relating to the first round of noise mapping in Europe showed that almost 67 million people (i.e. 55%) living in agglomerations with more than 250,000 inhabitants are exposed to daily road noise levels exceeding 55 dB Lden (noise indicator for day, evening and night periods) (*figure 1, next page* from [EEA 2009]). With almost 48 million people exposed to levels exceeding 50 dB Lnight, road noise is also by far the largest source of exposure to night-time transport noise. Large numbers of people still live in "*hot spots*" where transport noise levels are likely to have severe effects on human health. Here again, road traffic is the main source of noise exposure. Outside agglomerations, major roads are responsible for the exposure to daily noise above 55 dB Lden of 34 million people and for the exposure to night noise above 50 dB Lnight of 25 million people [EC 2011].

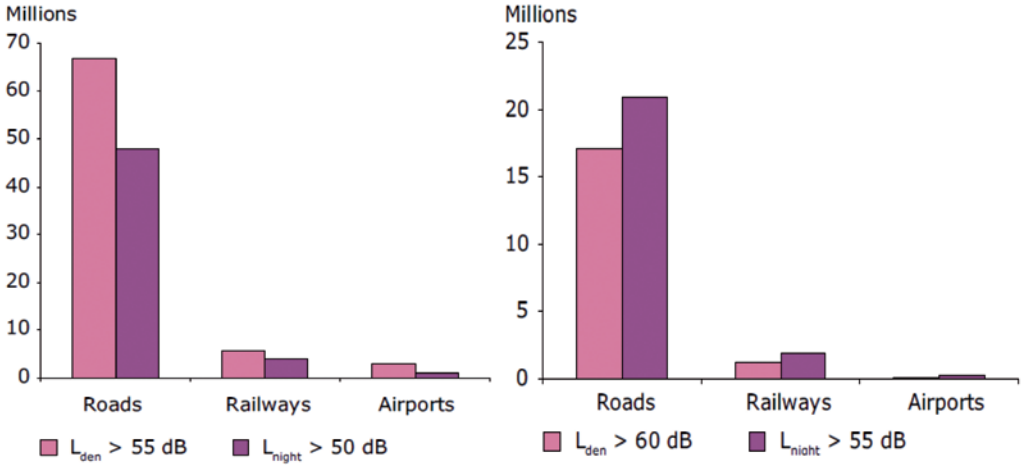


FIGURE 1 - PEOPLE EXPOSURE TO TRANSPORT NOISE

Note. agglomeration > 250.000 inhabitants in EU-27: people affected (left) and people living in "hot spots" (right) (source : EEA report n°3/2009)

The level of noise pollution is influenced by several factors, such as traffic density, vehicle speed, and the presence of heavy vehicles, as well as highway quality and configuration. Other factors influence the perception of noise by those living near highways, such as atmospheric conditions, the proximity of highways to houses, topography or the type of environment (wooded area, industrial park, etc.) that the highway goes through. Sound propagation is not the same along a body of water or around a large parking lot compared with an environment with tall buildings or a very heavily wooded area. The level of noise pollution also varies at different times of the day and depends on traffic levels.

Among road traffic noise abatement measures, source orientated actions are preferable because their effect is wider and not limited to restricted areas. They are also often recognised to be more cost-effective. A legal framework and national or international standards are necessary to reduce the impact of noise on communities. The WHO recommends the following steps to improve noise management:

- monitor human exposure to noise;
- obtain reductions in noise emissions and not just in the number of noise sources;
- take into account the consequences of noise in the planning of transportation networks and land use;
- introduce systems to monitor the harmful effects of noise;
- evaluate the effectiveness of noise policies in reducing harmful effects and exposure as well as in improving soundscapes;

- adapt WHO directives on noise in individual communities to create intermediate objectives for the improvement of human health;
- adapt precautionary measures to favour the sustainable development of soundscapes.

1.2 NOISE MITIGATION POLICIES

There are two distinct approaches for reducing the problems caused by noise pollution. First, governments can adopt an approach called "*integrated planning*", which consists in preventing noise pollution problems by an integrated planning approach to transportation and land use. This approach requires concerted action at all levels of government so that the measures taken meet community needs. For road traffic noise abatement, this includes an efficient land planning system, the introduction of noise mitigation criteria in traffic management systems, incentives to develop, optimize and use quiet low noise technologies regarding vehicles, tyres and road surfaces. This global approach is expected to be the most efficient and cost effective one. It can be achieved through the support of research/development, the development of standards, or through adapted regulations.

Second, a corrective approach can be used to correct the main problems through abatement measures (low noise pavements, anti-noise screens, berms, traffic management such as speed limit or optimised crossroads, improvement of façade insulation, etc.). This approach is well adapted to noise pollution problems caused by an existing highway network. In the case of new developments near existing highways, the corrective approach can also be relevant if all the interested parties take steps to control noise sensitive areas.

In order to monitor the management of highway noise, transportation agencies must adopt indicators and set limits that take into account community needs. Some highway agencies limit themselves to corrective measures while many others adopt noise management policies and regulations.

In the U.S., two laws cover highway noise management. The National Environmental Policy Act (NEPA) empowers authorities to evaluate and mitigate negative environmental effects, including highway noise. Procedure 23CFR772, "*Procedure for Abatement of Highway Traffic Noise and Construction Noise*", defines a procedure for noise analysis and mitigation measures for the purpose of protecting public health. It also sets criteria that authorities must respect in the planning and development of highways.

In Canada (with the exception of Québec), few provinces regulate highway noise. Most provinces limit themselves to corrective measures for existing highways and the use of anti-noise paving or anti-noise screens in situations where highway planners think such steps are needed. Some cities (e.g., Edmonton, Alberta) have developed a policy aimed at reducing the effects of highway noise.

In Québec, there are some rules that cover actions to be taken in the field of highway noise management. In 1990, the Québec government published its Politique sur le bruit routier (policy on highway noise). In that policy, the government commits to working with cities to reduce the level of noise pollution associated with highway traffic. The policy refers to both the corrective and the integrated planning approaches mentioned above. It also specifies that noise abatement measures (corrective measures) will be implemented in noise sensitive areas throughout the highway network under the purview of the Ministère des Transports where outdoor noise levels have reached a threshold of B 5 dBA Leq (24h).

In terms of integrated planning, the policy sets out the responsibilities of municipal organizations and provides for a review of land-use plans in order to reduce the impact of noise pollution.

Different countries in Europe (e.g. Denmark, Germany, the Netherlands, France, Italy) have well elaborated legal rules and procedures to regulate noise in all phases of planning, construction and exploitation. Required by law, measures must be taken and maintained to obey maximum noise levels. In the Netherlands, for all main motorways an anti noise pavement as porous asphalt is the standard wearing course to be used.

In Europe, the European Union (E.U.) is greatly concerned about noise control. In 2002, it adopted the directive 2002/49/EC relating to the assessment and management of environmental noise. The purpose of the Directive is to "*define a common approach intented to avoid, prevent or reduce on a prioritised basis the harmful effects, including annoyance, due to the exposure to environmental noise*". The directive refers to the corrective and integrated planning approaches. It requires the EU Member States to carry a number of actions, in particular:

- to determine the exposure to environmental noise through noise mapping. Noise maps should be made in main agglomerations (over 100.000 inhabitants) and around main transport infrastructures: airports (over 50.000 movements per year), roads (over 3 million vehicles per year) and railways (over 30.000 trains per year). Not only noise levels are estimated but also the population exposed to these level. Noise maps must be updated every 5 years;
- to adopt action plans based upon the noise mapping results;
- to ensure that the information on environmental noise is made available to the public;
- The EU Directive does not set noise limits or targets. Such limits are part of national legislation in some EU countries.

A survey of the literature indicates that a similar trend can be observed in Asian countries.

In summary, noise has harmful effects on human health, and governments must be concerned about that. They must implement well-defined policies, regulations and standards with short-, medium- and long-term objectives that will make it possible to reduce noise levels and their impact on communities.

1.3 SHARING KNOWLEDGE ON ROAD NOISE MANAGEMENT

Road traffic noise problems are acute in many countries in the world. However, if concerns are similar, situations, legislations, management practices are different. Under these conditions, sharing knowledge and experience can bring a significant step forward to raise awareness and to possibly improve the practice for road noise mitigation.

In Europe, the Conference of European Directors of Roads (CEDR) appointed a working group on "*noise*" in 2006-2007, with objective to facilitate knowledge sharing on noise management and abatement issues among the European national road administrations (NRAs). The group carried out a survey questionnaire and reported the analysis in a comprehensive report in May 2008 [19]. Various issues were considered, including noise regulations, integration of noise in road maintenance, noise abatement measures, communication of noise related matters to the public. The study noted that despite many regulations, noise limits, or guidelines exist they are not easily comparable due to different indicators and different calculation models. Furthermore, although the noise reducing pavements are available on the marked in 80% of the EU member states, the noise criteria is almost never used in the pavement management system. A number of recommendations for good governance regarding noise management and abatement were made.

In the meantime, a similar questionnaire was circulated with European countries in the frame of the TYROSAFE EU-project [Nitsche & Spielhofer, 2009]. This questionnaire was more focused on the way road surface properties are considered in policies or regulations regarding all road networks, not only noise properties but also skid resistance and rolling resistance, whereas the questionnaire of CEDR concentrated on national road network and noise only.

At PIARC level, a supplementary survey was made within worldwide Road Authorities by the "*Noise mitigation group*" in 2010. Five questions were asked:

1. What are the main concerns your country has about the potential impact of (rural/urban; new/existing) road noise?
2. Is anything being done in your country to assess and/or address the consequences of (rural/urban; new/existing) road noise? Are there legal requirements? Is there a list of best practices?
3. If nothing is being done, why not?

4. If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?
5. Can you please list road pavement-specific issues associated with road noise that in your opinion would require more work?

The answers from twelve countries were received and analysed: nine European countries (Austria, Denmark, France, Germany, Italy, Norway, Slovenia, Spain and United Kingdom), three American countries (Canada, Canada-Quebec and Mexico) and one Asian country (Japan). The following conclusions can be made:

- Concerns about road noise are mainly driven by health related issues. Economical reasons are also explicitly mentioned, either directly (e.g. 20% of the budget for new road infrastructure to be dedicated to road noise mitigation measures) or indirectly (e.g. noise impact on land price).
- In some countries (Canada, Spain), the main focus is on urban road noise, whereas in most other countries, all types of road networks are of concern.
- Two countries (Mexico, Slovenia) mentioned specific concerns related to the transit of heavy goods vehicles. Nuisance due to noise from construction and maintenance work is also a concern in UK.
- Many countries have developed legal requirements or targets in terms of road noise levels. Most of them apply to outdoor noise levels at façade or close to residential buildings. A legal maximum indoor noise level was mentioned in Norway. In this country, a National goal is set for 2020 in terms of reduction of a Noise Annoyance Index by 10% compared to 1999. In Japan, roadside noise levels are also part of the standard.
- In many countries, noise impact assessment is required for road construction projects and noise mitigation measures must be assessed (Austria, France, Slovenia, Japan?). This implies noise predictions by calculation and in some cases assessment by measurements.
- Several countries have set up an exhaustive legal frame for road noise mitigation, including legal noise limits for new roads, regulations on minimum sound insulation for new building, classification of noisy roads, development of transportation noise monitoring centers, identification of "*hot spots*" (France, UK, Italy, Canada-Quebec, etc.). Remedial measures to eliminate road noise hot spots are also organised in some countries.
- The main practical tools to tackle road noise are an appropriate highway design and the use of noise reducing technologies: earth mounds, noise barriers, low noise road surfaces and in some cases building insulation. For noise barriers specifications, standards are available in Europe. For low noise road surfaces, several countries have defined and apply a national procedure to specify the acoustic requirements.
- Two countries mentioned that they do not have regulations related to road noise. In Denmark, noise reduction measures are frequently taken although noise limit

values are specified in Guidelines and are not mandatory. In Mexico, only the vehicle noise emission (cars and motorbikes) is regulated. The implementation of noise mitigation measures is regulated only for airport surroundings and other stationary sources.

- All European countries have transposed the EU directive 2002/49/EC in their legislation and have realised noise maps for major road infrastructures.
- Guidelines for road noise mitigation are developed in most countries. On the contrary, lists of best practice do not seem very used.
- All the countries that responded have conducted number of studies, research studies or pilot studies on road noise impact, quiet pavements optimisation, reduction of noise annoyance, etc.

Among the road pavement specific issues associated with road noise, convergent views were expressed on the further works to be performed:

- The most often quoted issue is the long-term performance of low noise road surfaces. Research needs were expressed on a better understanding on the life span and durability of low noise road surfaces, on the optimization of maintenance and rehabilitation of porous pavement, and on the balance of noise reducing durability and structural performance. In particular, the need for an improved understanding on the effects of weather on low-noise surfaces was expressed, particularly as climate change may lead in some places, to increased precipitation which may affect noise generation and structural durability. Systematic monitoring of low noise pavements was suggested.
- The development of regulations, harmonized procedures or policies is needed in some countries: application policy for low noise pavements and other noise reducing measures; regulation of environmental noise assessment; definition of environmental noise indicators; definition and implementation of harmonised procedures for classification, check of conformity of production of road surfaces.
- The development of further noise reducing materials by improving their mix design, or ultimately the development of next generation low noise surfaces were also quoted in five cases. The development of low noise dense surfaces for urban areas is also of interest.
- A specific interest on low noise concrete pavements was expressed by Canada, both in terms of technical optimisation (including comparison with bituminous mixes) and discomfort felt by the population (i.e. acceptability).
- Needs were expressed for a better acceptability or performance of porous asphalt pavements, in particular in terms of cleaning, winter maintenance and within a recycling system.
- There is an interest expressed twice for a combined consideration of noise and rolling resistance properties. Further work seems to be needed to establish robust relationships between rolling resistance, noise and texture in order to develop silent surfaces with low rolling resistance.

- Finally, more research seems to be needed on the combined effect of low noise pavements with other noise mitigation measures such as noise barriers and sound insulation of buildings.

2. TYRE-PAVEMENT NOISE FUNDAMENTALS

2.1 STAKES OF TYRE-PAVEMENT NOISE REDUCTION

Road traffic noise (mainly caused by power unit and tyre-road contact) affects densely populated areas all over the world and decreases the health and the quality of life of residents (Haider et al, 2007).

Regulations and research in the past mainly focused on engine, power train and exhaust system and were successful in reducing the average engine's noise power output. However, despite vehicle noise emission limits have been gradually tightened over the years (e.g. by a reduction of more than 10 dB(A) in 15 years for certain vehicles in Europe), no effectiveness on overall road traffic noise reduction could be observed. This can be explained by a significant increase in road traffic volumes and a trend towards larger, heavier and more powerful vehicles. Furthermore, it was recognised that the test cycle for vehicle certification on noise levels was not representative of normal driving conditions, especially for typical urban stop-star situations at lower speeds, where engine noise is dominant. As a consequence, the test cycle was revised in 2006 to better integrate the contribution of tyre noise emission.

In the mid- to high-speed range (approximately $v > 40$ km/h for passenger cars and approximately 70-80 km/h for trucks) the main contributor to traffic noise is tyre/road noise (*figure 2, next page*). This fact is very relevant and it is strictly linked to the outstanding role that low noise pavements can achieve in terms of road traffic noise abatement measures. Based on the above mentioned facts, the tyre/road surface combination must be optimized in order to achieve noise reductions.

Tyre/road noise may vary by more than 15 dB depending on the tyre/road combination at a given speed, ranging from block pavements to low-noise porous asphalt. In the tyre contact patch the tyre tread pattern interacts with the texture of the top road surface layer which generates complex vibrations of the tyre as well as aerodynamic effects and resonances within the cavities, which are called air pumping.

The following main mechanisms are involved: mechanical vibrations, air vibrations, stick-slip and stick-snap effects, and amplification systems. They are described in the *section 2.1*. The mitigation of this part of noise depends on the control of the above mentioned mechanisms, through the main systems which are responsible for this: tyres and road surfaces. This problem is briefly summarized in the section 2.2.

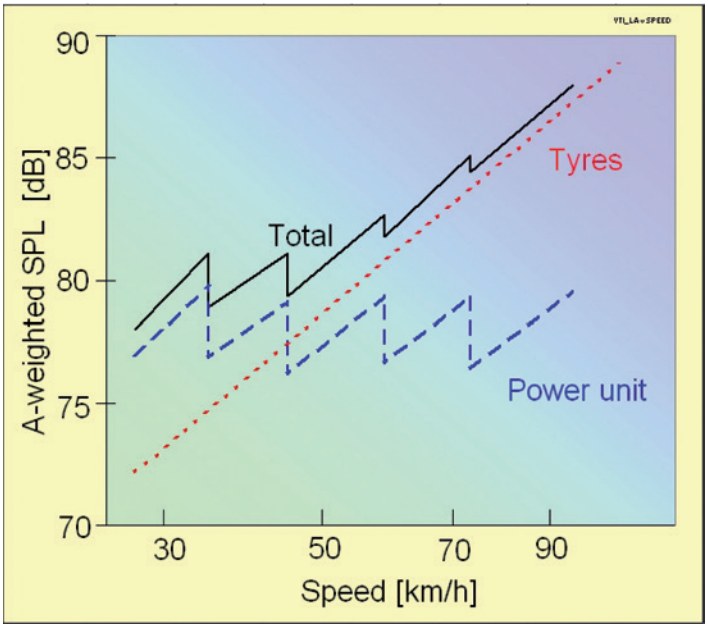


FIGURE 2 - POWER UNIT NOISE, TYRE/ROAD NOISE AND OVERALL NOISE VS. SPEED [AFTER SANDBERG AND EJSMONT, 2002].

2.2 MECHANISMS

The concept "*tyre-pavement noise*" requires the understanding of basic terms related to acoustics and pavements. A summary can be found in Sandberg et al., 2010.

The interaction between a pavement and a tyre generates acoustical pressures, which are responsible, according to Weyl-Van Der Poel's equation, for the loudness experienced outside the vehicle by a human receptor [Attenborough 1983; Praticò 2001].

The generation of such acoustical pressures depends on a few complex mechanisms which can be differently combined. An interpretation is given in *figure 3, next page*.

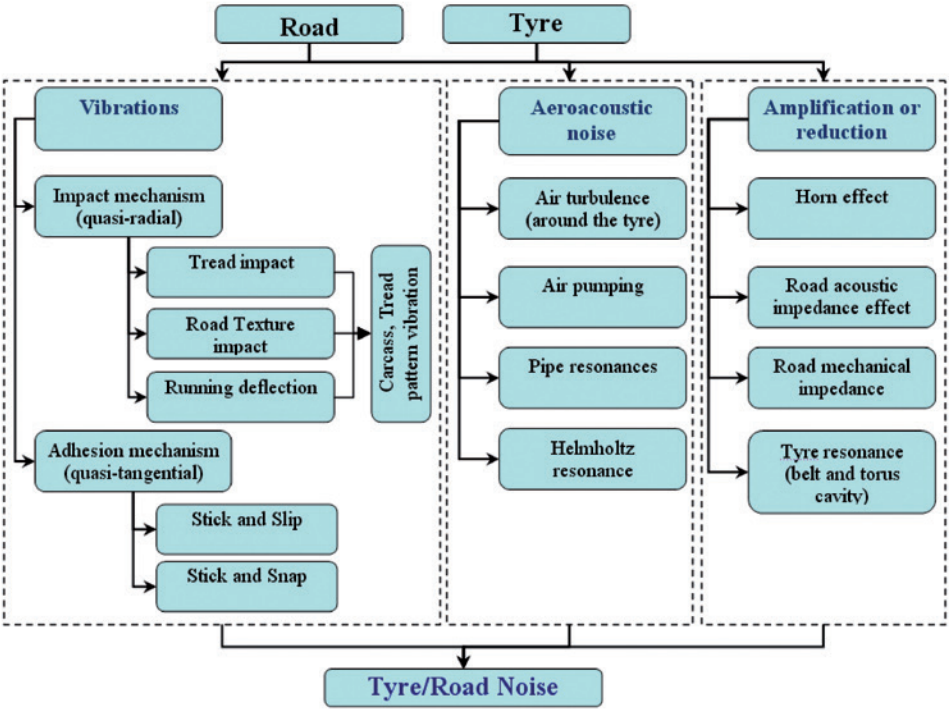


FIGURE 3 - TYRE/ROAD NOISE AS A RESULT OF VIBRATIONS, AEROACUSTIC NOISE AND AMPLIFICATIONS (AFTER HAIDER ET AL. 2007)

2.2.1 Mechanical Vibrations

These are generated through impact between tyre tread pattern and pavement surface. There is also an influence from the deformation of the tyre around the contact area. In summary, this mechanism is strongly related to features of tyre tread patterns and pavement texture. A practical example of this mechanism could be the effect of thousands of small hammer strokes occurring every second, each generating sound. *Figure 4, next page* depicts this practical example of mechanical vibrations [Rasmussen 2007].

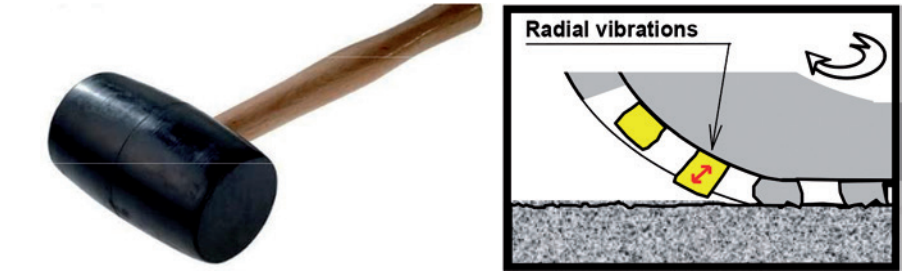


FIGURE 4 - MECHANICAL VIBRATIONS BETWEEN TYRETYRE-PAVEMENT (HAMMER EFFECT)
(SOURCE: RASMUSSEN 2007)

2.2.2 Air Vibrations

These are generated between the road surface and the tyre grooves. As the tyre rolls along the pavement, air is squeezed out, and some is trapped and compressed. Later, as the tyre loses contact with the pavement, what was trapped air is now forced out and in some cases, air is sucked back in. This happens hundreds or thousands of times per second. A practical example is clapping hands, where much of the sound that is heard is air being pushed away quickly. Another very common example of air vibration is whistling, where air is forced out of a small opening, generating sound as a result. *Figure 5* displays the air vibration mechanism [Rasmussen 2007].

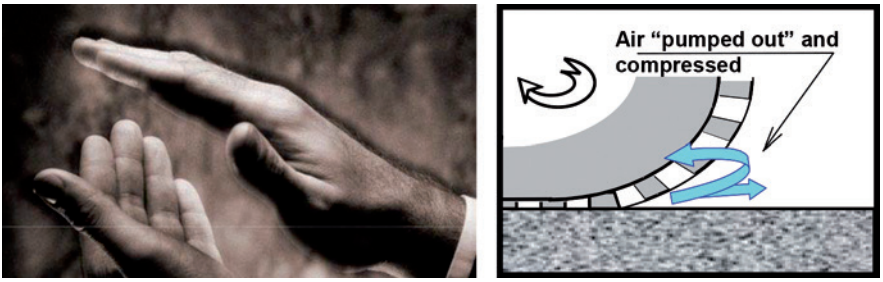


FIGURE 5 - AIR VIBRATIONS BETWEEN TYRE-PAVEMENT (CLAPPING EFFECT)
(SOURCE: RASMUSSEN 2007)

2.2.3. "*Stick-Slip*" Effect

This mechanism is generated by the shifting adhesion (stick) and gliding (slip) of the tyre tread pattern. The tyre is subject to horizontal forces in the contact area between tyre and pavement surface which generate vibrations. As the tyre is continually deformed and distorted, it will mostly stick, but also periodically slip once a critical limit is reached. These "*corrections*" under each tread block happen thousands of times a second, thus generating high frequency sound. A practical example of this effect can be observed at a basketball game, where the sound of sneakers squeaking

on the court can be heard. This same type of sound is produced as a tyre rolls along the pavement. *Figure 6* shows a simulation of the tangential motions observed at the tyre-pavement contact area and also shows the "*sneaker effect*" [Rasmussen 2007].

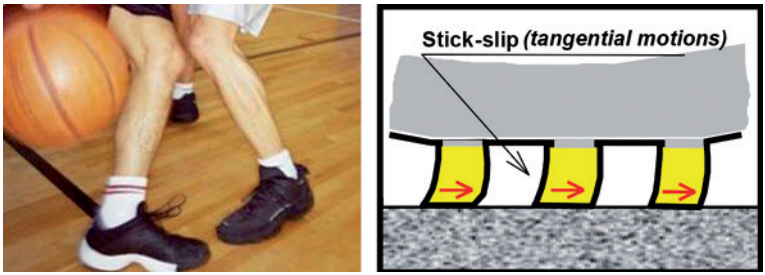


FIGURE 6 - STICK-SLIP MECHANISM BETWEEN TYRE-PAVEMENT (SNEAKER EFFECT)
(SOURCE: RASMUSSEN 2007)

2.2.4 "*Stick-Snap*" Effect

This mechanism is also known as suction pad effect, and is generated when the tread pattern abruptly leaves the pavement surface at the rear of the tyre-pavement contact area, which leads to radial vibrations. A practical example is a suction cup that sticks to a smooth surface because of both adhesion and a vacuum that is created when the air in the cup is pushed out. As tread blocks interact with some pavements, a similar effect can occur, generating sound. *Figure 7* displays this effect [Rasmussen 2007].

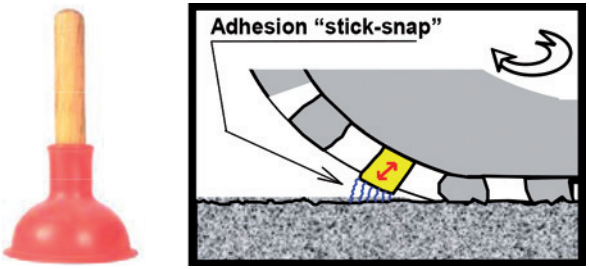


FIGURE 7 - STICK-SNAP MECHANISM BETWEEN TYRE-PAVEMENT (SUCTION CUP EFFECT)
(SOURCE: RASMUSSEN 2007)

2.2.5 Amplification Mechanisms

The mechanisms previously described are hypothesized sources of tyre-pavement noise. However, there are a number of amplification mechanisms that can possibly increase these noise levels. These amplification mechanisms are indeed complex and should be targeted if overall noise is to be reduced. Identified amplification mechanisms include acoustical horn, Helmholtz resonance, pipe resonance, sidewall vibrations, and cavity resonance.

Acoustical Horn

This effect is generated by the geometry of the tyre and the pavement, which when in contact forms a wedge-shaped segment of open air. This air creates multiple reflections of sound similar to those reflections that occur within a musical horn or megaphone. However, in the case of the tyre, the horn is poor as it is open on two sides. This results in significant amplification in the forward and aft directions and distortion of some frequencies [Rasmussen 2007]. *Figure 8* displays the acoustical horn amplification mechanism.

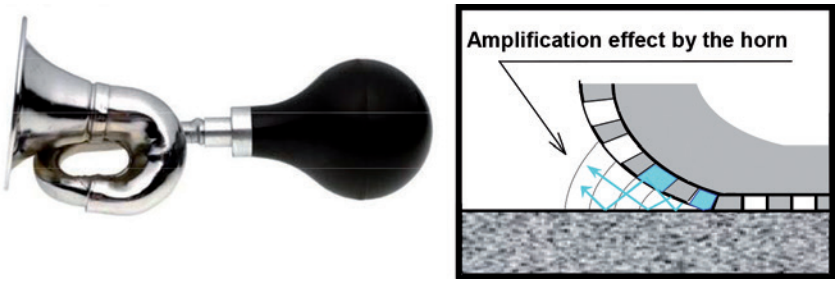


FIGURE 8 - ACOUSTICAL HORN AMPLIFICATION MECHANISM
(SOURCE: RASMUSSEN 2007)

Helmholtz Resonance

When air is blown across the top of a bottle, a distinct tone can be heard. This occurs as the air in the neck of the bottle (acting as a mass) vibrates up and down on the pillow of air inside the bottle (acting as a spring). By itself, blowing creates very little sound. However, blowing across the bottle significantly amplifies the frequency that is distinct to that bottle (resonance). A similar effect can be found close into the wedge where the tyre and pavement meet. In this case, the mass and spring are side-by-side. The result is an amplification of some frequencies unique to the geometry of the tyre and the pavement [Rasmussen 2007]. *Figure 9* depicts the Helmholtz amplification mechanism.

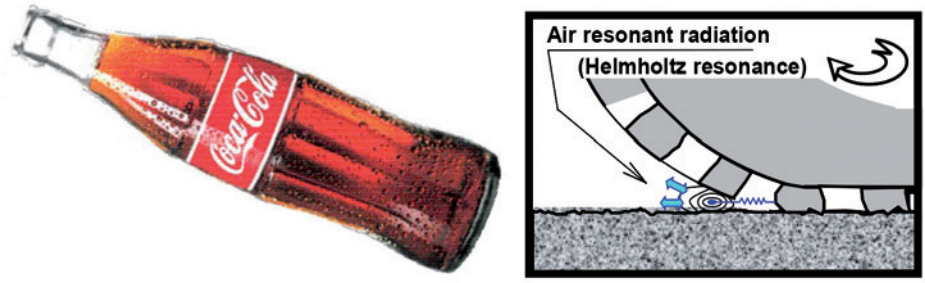


FIGURE 9 - HELMHOLTZ RESONANCE AMPLIFICATION MECHANISM (SOURCE: RASMUSSEN 2007)

Pipe Resonance

This effect is similar to that produced when air is blown across an organ pipe, a sound will be amplified that is unique to the length of the pipe and how many openings are in the pipe. In a tyre, similar "*pipe*" geometries can be found as the various grooves in the tyre are pinched-off and opened-up at various points underneath the contact area. Sound that is generated elsewhere can be amplified within these pipes [Rasmussen 2007]. *Figure 10* shows how pipe resonances generate.

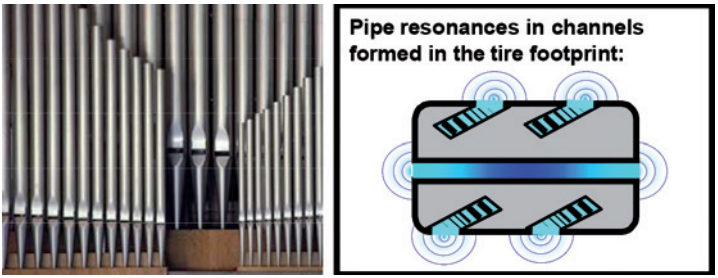


FIGURE 10 - PIPE RESONANCE AMPLIFICATION MECHANISM (SOURCE: RASMUSSEN 2007)

Sidewall Resonance

This is also known as the pie plate effect because if this plate is placed upside-down, the vibrations produced by a vibrating object (e.g., cell phone or electric shaver) placed on top of it will amplify, while the vibrating object does not make much sound by itself. The deformation of a tyre sidewall when in contact with the pavement has a similar effect. Many of the small vibrations described as generating mechanisms will be amplified as vibrations of the tyre sidewall. *Figure 11* presents a diagram that represents sidewall vibrations between tyre and pavement.

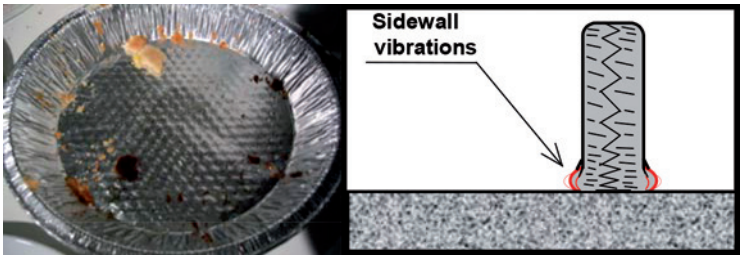


FIGURE 11 - SIDEWALL VIBRATIONS AMPLIFICATION MECHANISM SOURCE: RASMUSSEN 2007)

Cavity Resonance

This is known as "*The Balloon*" effect and is created when a balloon is thumped, then a distinctive ringing sound can be heard. The same is true when a tyre is kicked.

The resonance can actually be better heard inside the vehicle. Therefore, this amplification mechanism is less important than the previous mechanism for noise heard outside the vehicle. The air inside the vehicle itself tends to further amplify this frequency. *Figure 12* shows an example of this mechanism.

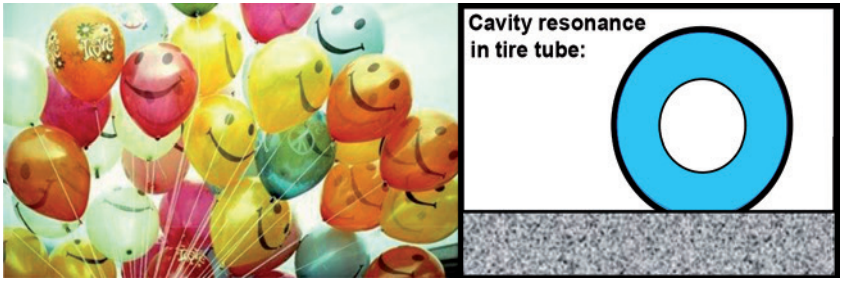


FIGURE 12 - CAVITY RESONANCE AMPLIFICATION MECHANISM (SOURCE: RASMUSSEN 2007)

2.3 VEHICLE/TIRE/PAVEMENT OPTIMISATION

Vehicles (tyres) and road surfaces are the main systems which act as a source. In reference to tyre-pavement noise the potential for future noise reduction utilizing tyres is estimated to be 1-2 dB for cars and up to 2 dB for heavy vehicles. (Dimitri, 2008) The influence of tyre on road noise generation is further described in *section 2.2.2*.

On the contrary, the influence of road surfaces, for dense surfaces ranges from 4 dB(cars) to 2 dB (heavy vehicles), is around 6 dB for optimized dense surfaces, and ranges from 8 dB(cars) to 4 dB (heavy vehicles) for porous surfaces. Road surfaces influence is analyzed in *section 2.2.3*.

2.3.1 Vehicles

As is well known (Haider et al, 2007), road vehicles are designed to comply with regional and national regulations regarding type approval which include maximum noise levels during a certain operation (Haider et al, 2007). In the European Union, the relevant regulation is Directive 70/157/EEC. Outside the EU, both within and outside Europe, many countries honour the UNECE regulation R51 which is issued by WP29 of the United Nations Economic Commission for Europe (UNECE).

Vehicle noise emission limits are intimately connected to the measurement method and mode of vehicle operation during the noise test. There are two different modes of operation: one for light and the other for heavy vehicles. However, common to both is that the measurement is conducted with the test vehicle approaching the test area at a constant speed. The test area in the EC or UNECE shall have a surface

meeting the requirements of ISO 10844 Edition 94. When a position 10 m ahead of the microphones is reached by the front of the vehicle, the throttle is opened totally and the vehicle drives by the microphones at full acceleration, closing the throttle when the end of the vehicle has passed 10 m behind the microphones. The maximum A-weighted sound level is measured with two microphones 7.5 m to the left and right of the vehicle path. The measurement method prescribed in the regulations is almost identical to that of ISO 362 (see reference ISO 362 Edition 98).

For light vehicles, the test is performed with the vehicle approaching the test area at a given speed, then accelerating on the 2nd gear. The test is repeated when using the 3rd gear and the final result is the average noise level of the tests, which is compared to the limit value. Powerful vehicles may be required to use the 3rd and 4th gears instead in order to avoid excessive tyre slip. Heavy vehicles need to be tested at a great number of gear settings to determine the maximum noise levels and the approach speed is generally lower. The heavy vehicles are tested unloaded, which means that considerable tyre slip might occur.

Before 1996 (EU and UNECE), the test procedure and the limit values put the emphasis of noise reduction on the power unit, whereas the present limits create a need to select tyres for the test that have low noise emission during conditions of medium or high torque. For cars, this has led to attempts to find tyres which emit noise during the test which is 3-5 dB lower than the legal limit for the whole vehicle. For trucks, the tyre noise is not as critical as for cars, but one must avoid tyres which produce large slip and excessive noise at this slip.

The present system has been criticised for using driving operations which are not typical of common traffic flow. Therefore, a new method is being developed internationally. It will include testing heavy vehicles with a reasonable load and testing light vehicles both at constant speed (i.e. where tyre-road noise is important) and full throttle operation (i.e. where engine noise is predominant). The results will be normalized to correspond to a moderate acceleration commonly appearing in real traffic. For light vehicles, it will become very important to reduce tyre noise, whereas their power units will face less stringent requirements than today. There are also attempts to work out a supplementary method to take into account engine noise low-speed situations, typical at stop-lights and intersections.

Some experts are dissatisfied with the mixing of requirements on tyres and power units and would prefer to keep them separate. Some politicians would probably not be satisfied with the fact that the stepwise reduction of noise limits in the period 1970-1996 has stopped and no progress has been made for the last decade and will not occur in the next few years. This new type approval system is not likely to be in force for vehicles before 2012.

2.3.2 Tyres

In explaining tyre influence on tyre/road noise the most important tyre design characteristics are tread area features, casing construction features and the rubber compound. These are the results of a number of balanced objectives (price, skid resistance, rolling resistance, wet traction, hydroplaning, snow traction, comfort, noise, weight, etc.). The contribution of the different noise generation mechanisms to the total tyre/road noise can be analysed by simulations using tyre models.

The tread pattern influences all noise generating mechanisms (*table 1*, in which □ refers to lower noise levels, Haider et al, 2007); in practice aggressive treads lead to marginal noise level increases of 1-2 dB. Nonetheless, owing to the fact that sound radiation is generated even by smooth tyres, only a limited reduction in the tyre/road noise can be achieved by changing the tread pattern. The influence of the blocks and ribs depends on their geometry and on the road texture. On one hand, the presence of the tread blocks may cause higher noise levels in the low-frequency range on very smooth roads. On the other hand, smooth tyres emit more noise than standard tyres on rough-textured pavements. The worst examples are tyres with a constant pitch, which generate a very unpleasant noise of tonal character. Therefore treads are usually randomized.

TABLE 1 - NOISE EMISSION EFFECTS OF DIFFERENT TYRE/ROAD COMBINATIONS

Tyre	Smooth road	Rough road
slick tread (smooth)	□	□
patterned tread	□	□

Tyre design and condition affect the noise emission in several ways:

- tyre wear and ageing influence tyre/road noise;
- in general harder rubber compounds cause higher noise levels than softer ones, especially for aggressive tread patterns. The elastic modulus of the tread has often a much larger influence than that of the sidewall;
- studded winter tyres show very significant increases in noise levels compared to the same tyres without studs;
- in general, noise emission increases with tyre width;
- the tyre's inner structure influences tyre/road noise. Radial tyres are somewhat less noisy than bias tyres. A decrease of the belt stiffness can increase tyre/road noise. Increases of carcass stiffness of truck tyres can result in reductions of tyre/road noise;
- the tyre's sidewall affects the whole tyre vibration due to road megatexture. The sidewall design can also change the level of the sound that radiates away from the tyre;

- non-uniformities (tyre run out, unbalance) can cause a noise level increase for the interior noise and at low frequencies;
- tyre load and inflation pressure can also influence the tyre/road noise.

Some new developments are low rolling resistance compounds and run-flat tyres. Run-flat tyres are designed to retain their stability even when a perforation and loss of inflation pressure occurs. This is achieved by increased stiffness of the sidewalls, which may lead to increased noise emission.

The type approval testing of tyres with regard to rolling noise emission in the EU is carried out according to Directive 2001/43/EEC (see reference Directive 2001/43/EC) or UNECE Reg. 117 and uses two microphones at 7.5 m distance of a coasting vehicle with the tyres under test rolling on an ISO 10844 Edition 94 surface. The pertinent limit values were reviewed recently and strengthened on the basis of a technical review that showed that most tyres already met the standards before they came into force [FEHRL 2006]. In more detail, the pertinent limit values have been reviewed in EC Regulation 661/2009 and the amendment of UNECE Reg. 117 with effect on November 2012 for new tyre types. Furthermore, a large proportion of tyre already have performances much below the limits (up to 8 dB). The review also showed that tyre noise emission can be lowered without compromising safety or energy consumption.

In addition the EC regulation N°122/2009 of the European Parliament on the labelling of tyres and its subsequent amendment shall introduce labelling requirements on tyres for fuel efficiency (rolling resistance), wet grip and external rolling noise and shall apply on the first of November 2012.

The labelling information requirement or the tyre must be in accordance with *figure 13, next page*.

The external rolling noise measured value (N) must be declared in decibels and calculated in accordance with UNECE Regulation No 117 and its subsequent amendment.
The external rolling noise labelling class must be determined on the basis of the limit values (LV) for tyre rolling noise set out in Part C of Annex II of Regulation (EC) No 661/2009 as indicated in *figure 14, next page*.

Other Tyre Parameters
There are some tyre parameters that influence tyre-pavement noise and that might be worth further research. These parameters include optimization of tyre construction, which would look into increasing the stiffness of the tyre carcass by increasing the number of ply sheets, adding reinforcement rubber, and/or using steel ply materials. Also, the tread radial vibration could be improved by modifying the tread shape,

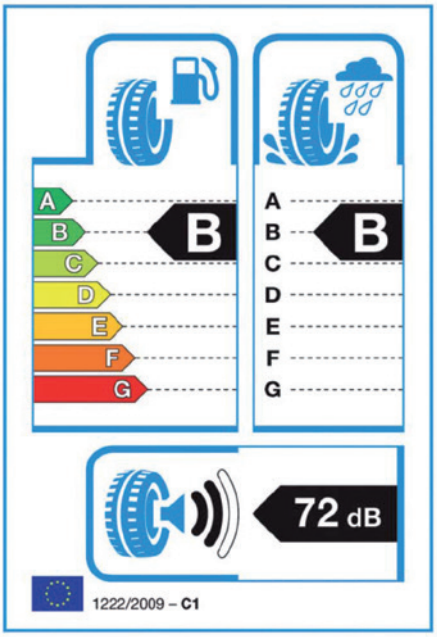


FIGURE 13 - TYRE LABELLING

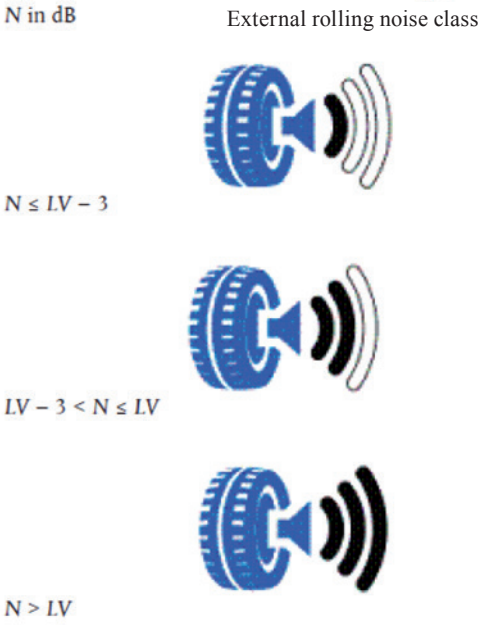


FIGURE 14 - TYRE LABELLING (EXTERNAL ROLLING NOISE)

arrangement and size and by utilizing circumferential-oriented grooves, also by reducing the hardness of tread rubber [IPG 2005].

2.3.3 ROAD SURFACES

Surface texture and bulk properties govern the contribution of road surfaces to tyre-road noise [Domenichini et al 1998; Boscaino and Praticò 2001]. Surface texture is usually described in terms of micro-, macro- or megatexture, in relation to the texture wavelength, i.e. the quantity describing the horizontal dimension of the irregularities of a texture profile. These terms are defined in the international standard ISO 13473-2 (2002):

- **microtexture** refers to texture wavelength smaller than 0.5 mm and typical peak amplitudes between 0.001 and 0.5 mm;
- **macrotexture** refers to texture wavelength between 0.5 and 50 mm and typical peak amplitudes between 0.1 and 20 mm;
- **megatexture** refers to texture wavelength between 50 and 500 mm and typical peak amplitudes between 0.1 and 50 mm.

There are a few basic rules for designing a silent road surface. For bituminous surfaces these include [Haider et al 2007]:

- the surface must be provided with sufficiently deep macrotexture (minimum texture depth: 0.5 mm) making up a random, closely packed, homogeneous array of small to medium size aggregates (maximum size: 10 mm) in order to prevent air pumping;
- or, the role of macrotexture can be played by a porosity made of pores connected to the surface and to one another (minimum voids content: 20%) which moreover will provide some favourable sound absorption if the layer is sufficiently thick (minimum thickness : 40 mm);
- megatexture and large-wavelength macrotexture must be minimised by ensuring in all cases that macrotexture is fine and homogeneous. This holds for porous surfaces also.

In addition, as either macrotexture or porosity provide water drainage at the interface between tyre and road surface, they are beneficial to pavement friction as well.

For additional information on this chapter see also the references SANDBERG, SILVIA, FEHRL and ISO 11819-1.

2.4 TOOLS FOR EXPERIMENTAL ASSESSMENT

Although significant efforts have been devoted to the development of modelling tools over the past decades, the optimisation of road surfaces in terms of noise generation is still empirical and widely based on experimental assessment. In-laboratory experimental methods are mostly based on drums facilities: either the drum moves around a fixed wheel or a rotating wheels rolls on a fixed drum surface. These laboratory facilities are not so many in the world. They are usually very expensive, the engine must be acoustically optimised so that the tyre/surface noise dominates and the realism of the road surface on the drum is often questionable. In situ methods are generally preferred and a several methods are available for outdoor tyre/road noise measurements.

These simple and robust methods are used to evaluate the noise performance of a road surface and possibly to label/classify it. The following acoustic noise performance indicators for road surfaces can be listed:

- *Statistical Pass By Method* (SPB, ISO 11819-1): the maximum pass-by noise levels of a large amount of vehicles in a free flowing traffic are measured on the road side. The statistical analysis provides an average noise level representative of the road surface acoustical properties. Distinction can be made between passenger cars and heavy trucks. The test site must be free from obstacles (buildings, barriers,

hills, etc.). However a variant of the SPB method using a backing board has been proposed recently (to be included shortly in ISO 11819).

- *Controlled Pass By Method* (CPB) is a variant of the SPB method using a set of test vehicles driven in controlled conditions. It is used when the road is not opened to traffic (before opening, test tracks, etc.), mainly for research/development purposes. The results obtained are assumed to be equivalent to those provided with SPB.
- *Close Proximity Method* (CPX, ISO/CD 11819-2): noise level is measured in the vicinity of the contact patch between a test tyre rolling on the road surface. This test tyre can be mounted on a test trailer or on a self-powered test vehicle. There is almost no site restriction and longitudinal homogeneity of the road surface can be checked. Most existing equipments are designed for passenger car tyres.
- *On Board Sound Intensity* (OBSI, AASHTO TP76): the principle of the method is close to CPX, but sound intensity is measured instead of sound pressure. One of the main advantage is the better immunity to external noise sources (surrounding traffic, noise from the test vehicle other than the tyre noise, wind noise).

Auxiliary measurement methods of noise-relevant surface characteristics are sometimes used as complements to tyre-road noise measurements. These characteristics are texture and in the case of porous pavements, sound absorption. Mechanical impedance or dynamic stiffness is a relevant parameter for very elastic pavements (e.g. poro-elastic road surfaces), however experimental characterisation methods adapted to road pavements are still under development (see PERSUADE project in *chapter 4*).

Surface texture (ISO 13473 series): the relevant texture information to be correlated with noise must be expressed in spectral terms and covers complete macro and mega-texture ranges. Measurements of texture profiles are performed continuously by contactless systems (laser sensors) mounted on test vehicles operating within the traffic.

- Acoustic absorption (on site extended surface method according to ISO 13472-1, or laboratory method with impedance tube according to ISO 10534.): The sound absorption coefficient is the fraction of sound energy absorbed by a material when a sound wave is reflected by its surface. Most low-noise pavements produce sound absorption. The extended surface methodology (ISO 13472-1) is static and the road has to be closed to traffic. An alternative, is a laboratory measurement on a core sample of the road surface in an impedance tube (or standing wave tube or Kundt tube) as described in ISO 10534-1 or -2.
- It is sometimes expected that auxiliary methods, because they are accurate and easier to implement, could be used as "*proxi*", and thus replace tyre-road noise measurements for the evaluation of noise performances of road surfaces. However, considering that up to now, no relationships between road characteristics and tyre/road noise has been clearly and unanimously established, such expectation is premature.

3. OPTIMISED PAVEMENT TECHNOLOGIES

3.1 PREMISES

This chapter provides information about different types of quiet surfaces and their characteristics and is organized into two main sections: bituminous road surfaces (thick, thin, ultrathin and bituminous surface treatments) and cement concrete road surfaces.

The following preliminary considerations are worthwhile: i) the boundary between the different classes and types of pavements is often not well defined; ii) below some possible solutions are described but many other solutions are possible; iii) one problem of comparing acoustical properties between countries is that different countries use different methods to measure the noise reduction and that references to which the reduction is compared are different. One has to take this into account realizing that the different acoustical performance between countries may not be readily compared.

These premises precede both the chapters, aiming at providing a general conceptual framework. Information related to the different solutions is displayed in an outlined format that is the same for all pavements. By doing this, the reader will have a better understanding of the pavements and might be able to compare one technology to others.

Usually road surfaces act as a part of flexible, rigid or semi-rigid pavements and herein they are organized in the form of a catalogue. Note that the term "*semi-rigid pavement*" is mostly used in European countries, while the term "*flexible pavement*" is commonly found in the literature in the United States and in Latin American countries. In either case, this type of pavement consists of a system of various layers, with or without a stabilized base with an asphaltic wearing course.

The term "*rigid pavement*" is more universal and refers to a pavement in which a Portland cement concrete slab is used as the main structural support and wearing layer in the pavement system.

Surface layers are a crucial part of every type of pavement solution, due to the fact that they can often offer quite different performance and characteristics, such as friction, texture, quietness, reduction of splash and spray, sufficient reflectivity, drainability, chemical resistance, etc. Such performance has to be linked to a satisfactory level of mechanical resistance.

This latter is a mandatory requirement but the relative contribution sometimes is not considered in terms of (traditional) pavement design (e.g. non-structural overlays).

From a noise-related standpoint, the following main classes of solutions can be considered:

- thick (thickness >40 mm) bituminous surface courses: asphalt rubber friction courses (ARFC); rubberized asphalt concrete, open (RAC(O)); rubberized asphalt concrete (RAC), gap-graded (RAC(G)); poro-elastic road surfaces (PERS), porous asphalt (PA); two–layer porous asphalt (TPA); dense-graded friction courses (DGFC) or dense asphalt concrete (DAC); hot rolled asphalt (HRA);
- thin (e.g. 0/9.5; 30 mm < thickness < 40 mm), very thin (20 mm < thickness < 30 mm) and ultra thin (e.g.0/5mm; 10 mm < thickness < 20mm) bituminous wearing courses: stone mastic asphalt (SMA); BBTM;
- surface dressings or bituminous surface treatments (epoxy-bound, slurry seal, etc.);
- cement concrete road surfaces: porous concrete, exposed aggregates cement concretes, drag textures, diamond grinding, longitudinal tining.

Thick layers such as PA, TPA, SMA, and DAC (*table 2, page 31*) are often considered in traditional (mechanical-oriented) pavement design.

Regarding noise, one can argue that thick layers range from being as quiet as porous asphalt to noisier than ordinary dense asphalt concrete surfaces.

As for thin surfacing in recent years the use of thin layers or thin surfacings has grown very rapidly in popularity for pavement maintenance operations [Haider et al., 2007]. Usually, these surfaces are thin (15-40 mm) bituminous layers, coated at the plant and hot rolled. Low noise types of these thin surfaces are gap-graded, and typically, the grading is 0/6, 0/8 or 0/11 with a gap at the medium aggregate sizes and the binder is bitumen modified with elastomers. Recently, products with 0/4 grading were developed, showing particularly low noise properties. They exhibit a surface texture visually similar to porous asphalt and mostly appear on the market under proprietary names. Thin layers have largely replaced the classical surface dressings as a maintenance technique, especially in urban areas where noise problems can be critical.

The crucial factor which identifies surface dressing with respect to thin surfacing is the fact that surface dressing usually has a single layer of aggregates. As a consequence, on average, the thickness of surface dressings is usually lower than the one of the thin layers. However, unlike asphalt concretes in which the aggregates are coated in the mixture, the aggregates in surface dressing are sprayed over the bituminous layer, resulting in a significantly rougher texture of the surface which generally favours noise generation.

Regarding noise, one can conclude that thin layers range from being as quiet as porous asphalt to about the same as less noisy dense asphalt concrete surfaces.

The rather low tyre/road noise emission on thin layers, as compared to classical surface dressings (e.g. chip seal, often termed bituminous surface treatments, BST) is due to the smoothing action of roller compaction and to relatively favourable possibilities for stones to orient themselves with flat and smooth sides towards the top without filling the voids between the stones. This has the effect of aligning them with relatively flat, horizontal sides upwards. Hence very little megatexture is created.

This is in some contrast to the stones embedded in dense mixes, the orientation of which is more restricted (*figure 15*).

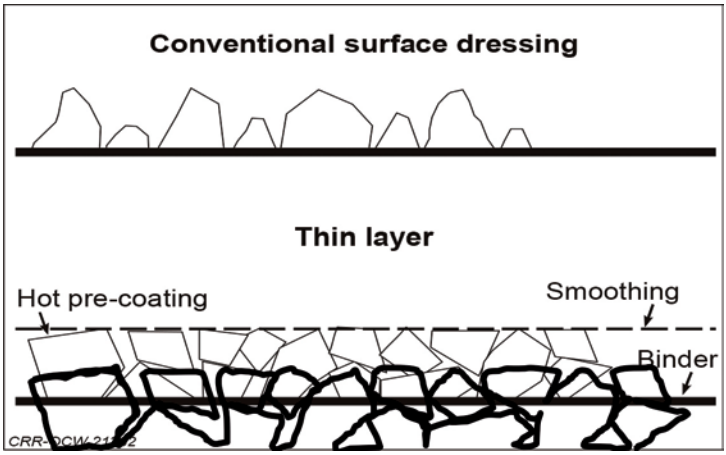


FIGURE 15 - SURFACE DRESSING VS. MODERN THIN LAYERS [ADAPTED FROM HAIDER ET AL 2007]

Porous or semi-porous thin layers are often less resistant against tangential stresses; therefore, they are often not recommended for use in e.g. crossroads or roundabouts. On the other hand, bituminous surface treatments can eventually involve some amount of loose aggregate.

Table 2 provides a tentative list of solutions and their main characteristics.

TABLE 2 - LIST OF SOLUTIONS AND THEIR MAIN CHARACTERISTICS

	Example of			
Type	Thickness (mm)	Maximum aggregate size or NMAS (mm)	texture (mm) or/ and air voids content (%)	noise reduction (dB)(1)
poroelastic road surface (PERS)	30	2 mm (rubber) 8 mm (aggregates)	30-35%	5~15 (vs. DAC)
RAC (O)	30	12 (as OGFC)	14-20%	6
RAC(G)	30	12 (as DGFC)	4%	
SMA 0/16	30-50	16 mm	4%	-1~ -2
SMA 0/11	30-50	11	4%	0
SMA 0/8	30-50	8	4%	1
SMA (general)	30-50	5-16 mm	0.5-1.5 mm 4%	-2~ 1
DAC0/11 or DAC 0/8	30	8/11	0.8 mm 4%	0
porous asphalt concrete 0/16 (PAC),	45	16	25%	3
porous asphalt concrete 0/11 (PAC),	45	11	25%	4
porous asphalt concrete 0/8 (PAC),	45	8 mm	25	5
Two-layer porous asphalt (TPA)	25 (top) + 45 (bottom)	8 (Top); 16 (bottom)	20% (top); 25% (bottom)	4~6 (vs. DAC)
Thin layers	5~8 mm	5~8 mm	5~15%	3~7
bardon	25 - 35 - 50 mm c.a	14	SH=2 mm	3 (vs. HRA)
masterflex (Note: it is not a registered trademark)	(15~50 mm)	6-10-14	2 mm	5~ 6 (vs. DAC)
Novachip	(12~25 mm)	6 mm; 9 mm; 12 mm; (1/4 - 3/8 - 1/2)	Texture similar to PAC	1 (vs.PCC/ DAC)
MASTERpave	(20 mm ~50 mm~ 75 mm)	6 - 14 - 20 mm	1.5-2	4
UL-M	20-50 mm	6 mm - 10 mm - 14 mm	1.5 mm	5~7 (vs.DAC)
MicroFlex	20 mm	6 mm	AV=13%	3.9~4.9 (vs. DAC)

TABLE 2 - LIST OF SOLUTIONS AND THEIR MAIN CHARACTERISTICS

	Example of			
Type	Thickness (mm)	Maximum aggregate size or NMAS (mm)	texture (mm) or/ and air voids content (%)	noise reduction (dB)(1)
Colsoft	20-30 mm	6 mm-10 mm	2 mm	3 ~5 (vs. DAC)
Rugosoft	20-50 mm	Unknown	unknown	5~7 (vs. DAC)
Nanosoft,	25-40 mm	4 mm	Unknown	9
MICROVIA	10-30 mm	6 mm	0.8 mm	Unknown
Rollpave	30 mm	6 mm	Unknown	4.3
Nobelpave	NA			
Surface dressing	3 ~ 20 mm	3 ~ 20 mm		+ 2~-3 dB (A)
porous cement concrete	80	9.5 mm	20-25%	4~8
Portland cement concrete – general			4%-25%	-2~8

(1) the figures in this column are provided as indicative values or ranges. They are either provided by the manufacturers or come from specific studies found in the literature.

Regarding the duration of noise mitigation, it is important to remark that this factor interacts with the expected life, this latter based on mechanical (bearing properties) and functional (surface properties) performance. The issue of the sometimes insufficient duration of noise-related performance caused in the past a progressive optimisation of silent technologies.

Table3, next page illustrates several examples related to the loss of noise performance during the expected life. The method used was usually the SPB (statistical pass-by), while the initial noise reduction was referred to the traditional DACs (dense asphalt concretes, see IPG report). Note that the durability and the evolution over time of surface performance (such as noise reduction) is a key-issue in terms of pay adjustment and contract administration in the acceptance procedures of premium surfaces such as porous European mixes [Praticò 2007].

TABLE 3 - DURATION OF NOISE MITIGATION (SPB METHOD)			
Solution	**Expected lifetime (years)**	**Initial noise reduction (db(A))**	**Final/minimum noise reduction (db(A))**
DAC	Variable	0	-2
PA	10-12	4	<3
TPA	9	6	4
SMA-like thin layers	9.5	4.7	3
Porous-type thin layers	8.5	5	3
DAC: dense asphalt concrete; PA: porous asphalt concrete; TPA: two-layer porous asphalt; SMA: stone mastic asphalt.			

As for cost, note that what follows refers to production costs (agency costs).

Relationships with other characteristics and other points of view (delay and cost reduction), maintenance, monitoring and innovation, climate change aren't described.

Asphalt concrete pavements

This section (from *3.2 to 3.8*) provides an overview of quasi-bituminous road surfaces, often part of the flexible and/or semi-rigid pavement types that have been used mostly in some European countries, in Asia and in the United States to reduce tyre-pavement noise. These materials have also often aimed to improve the surface characteristics of the pavement in different ways. Each pavement type starts with a definition of the pavement and then continues with information related to acoustical effectiveness, structural performance, friction, texture and splash and spray properties. Finally, in some cases, material costs are presented when found in the literature.

3.2 POROUS ASPHALT– SINGLE-LAYER

3.2.1 Definition

Porous asphalt is mostly used as single porous layer. In the U.S. hot mix asphalts with a high content of air voids are termed open-graded friction course (OGFC).

A conventional OGFC is a layer of asphalt that incorporates a skeleton of uniform aggregate size with a minimum of fines. In the past, these pavements typically had a void content as low as 12% and as high as 15 or 16%. In the U.S. this material rarely exceeds 20% of voids content [Sandberg 2009], while in the other countries 15% to 30% air voids for porous asphalt are used [DRI-DWW, 2006].

Most open-graded friction courses are 0.75-inch thick, and usually no thicker than 2 inches in the U.S. The layer thickness of porous asphalt in the other countries is 40 to 50 mm (2 in.) [DRI-DWW, 2006].

The OGFC should be elevated above the shoulder, as the water drains onto the shoulder and hence to a roadside ditch [Kuennen 2003]. A new generation of OGFC called porous friction course (PFC) has been built in several countries in Europe and in the U.S. *Figure 16* displays a construction operation of an OGFC in the Netherlands.

FIGURE 16 - OPEN GRADED POROUS ASPHALT PAVEMENT
(SOURCE: IPG NOISE INNOVATION PROGRAM, MINISTRY OF TRANSPORTATION, THE NETHERLANDS)

3.2.2 Acoustical Effectiveness and Durability

The experiments conducted in the State of Arizona in the U.S. show that OGFCs offer superb noise attenuation and durability properties [Kuennen 2003]. Over 70% of the agencies that use OGFC report service life of eight or more years. Also, nearly 80% of the agencies using this pavement type have standard specifications for design and construction. It seems to be that the key component to a longer-life success is polymer modification of the asphalt binder.

Porous asphalt has been tested within the SILVIA project on Motorway E18 west of Stockholm in Sweden. The experimental section was quite successful, achieving a 5 dB or more of noise reduction over several years and has kept this noise-reducing capacity constant. This noise reduction of the pavement is in reference to a conventional SMA 0/16 [Sandberg 2009].

In Germany, air voids below 15% 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 [DRI-DWW, 2006].

In the Netherlands porous asphalt has been applied on the main motorway since the 80's. At this time more than 90% of the main motor network has been covered with porous asphalt. The average service life was 10-12 years and in narrow curves raveling is a problem already after three years [DRI-DWW, 2006]. By increasing the bitumen content the service life is increased to 13 years for the riding lane and to 16 for passing lanes. Porous asphalt is nowadays the standard wearing course for motorways.

The acoustical durability has been monitored on the motorway. It was found out by CPX measurements that the reduction in time is about 2 dB, only sharply increasing at the end of the lifetime as raveling becomes important (*figure 17*).

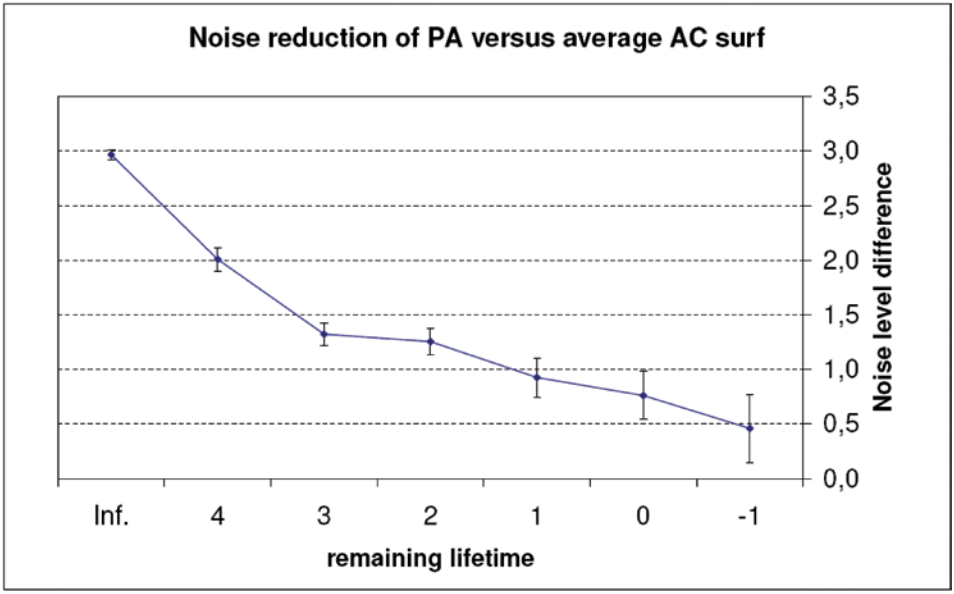


FIGURE 17 - DECREASE IN NOISE REDUCTION I THE NETHERLANDS
AS A FUNCTION OF THE REMAINING LIFE OF POROUS ASPHALT
(-1 MEANS MAINTENANCE SHOULD HAVE BEEN PERFORMED THE YEAR BEFORE)

Bonnot states that the French 8-years of experience (in 1997) have not indicated that porous asphalt with unmodified binders is more susceptible to raveling 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) [DRI-DWW, 2006].

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 raveling) [DRI-DWW, 2006].

As for Austria and Italy, the most commonly used porous pavement consists of a 40-50 mm 0/11 or 0/15 mm mix with a binder content of at least 5.0 %. Only modified binders are used [DRI-DWW, 2006]. In South Italy around ten millions of square meters of PA (often termed PEM, porous European mixes) are going to be laid (A3 motorway). A national project [PRIN 2008] is underway on surface performance of recycled PEMs.

In the Japanese motorways it was reported that porous asphalts sustained 3 dB lower noise than neighboring dense grade pavements, even 3 years after construction. Also porous asphalts showed less rutting increase than dense-graded [Asahi 2000 REAAA]. This is thanks to the use of highly polymer modified bitumen to be used for porous asphalt [Nakanishi 2000 REAAA]. A special PMB with more than 9% SBS content was developed for snowy areas [Motomatsu 2004 E&E].

3.2.3 Material and Structural Performance

OGFCs can be (but this is not needed as the 30 years experience in the Netherlands have showed) polymer-modified and can include mineral or cellulose fibers for binder stability during laydown. The polymer modifier stiffens the asphalt binder, while adding flexibility, helping it resist raveling of the top layer of aggregate. Several transportation agencies in the U.S. and in Europe have obtained good performance with their OGFCs; some others have stopped using them due to poor results. It is a general consensus that improvements have been achieved by relying in good design and construction practices [Kuennen 2003]. On the downside, OGFC pavements might clog with roadway fines, reducing their drainage abilities. In Europe, equipment has been developed that applies high pressure into the pavement, forcing out fines, and vacuuming them out in a single pass. These machines have not been evaluated in the U.S. In Japan a high speed performance recovery machine for porous asphalt was developed. Masuyama reported that the amounts of clogging materials at 10 km/h can be the same as at 1km/h by increasing the number of machine passes [Masuyama 2000 REAAA].

On heavy trafficked roads in the Netherlands 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 raveling and rapid aging of the binder is considered to be a problem. Due to raveling the average service life is about 12-15 years [DRI-DWW, 2006].

In France, 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 fiber modified bitumen is almost exclusively used [DRI-DWW, 2006].

In Germany, Schäfer reports some experiences of the third generation of porous asphalt since 1996 consisting of 40 mm 0/8 mm mix with void content of minimum 22 % and an asphalt binder with high polymer content. A noise related service life of more than 6 years and a structural service life of more than 10 years are expected [DRI-DWW, 2006].

According to Ruiz the most commonly used mix in Spain is a 0/12 or 0/10 mm with 4.5% binder content. Soto et al. report that porous asphalt mixes have been applied in Spain since the beginning of the eighties [DRI-DWW, 2006].

Luis reports that porous asphalt was introduced in Portugal in 1991 on the motorway network and mainly applied as a 40 mm thick 0/15 mm mix with 4.8-5.0% polymer modified binder and 20-25% air voids [DRI-DWW, 2006].

In Japan a special polymer modified bitumen with more than 9% SBS content has been implemented to increase the life of porous asphalt in snowy areas [Motomatsu 2004 E&E].

3.2.4 Friction Properties

New generation OGFC or "*porous friction course*" has been used in the State of Texas in the U.S. with great success. For instance, in San Antonio, Texas this material has substantially reduced noise levels and improved ride quality by 61% of a project located on Interstate Highway IH-35. This material has increased the skid resistance by 200%, according to State DOT representatives [Kuennen 2003].

Instead, experts recommend that OGFCs be used on high-volume, high-speed roadways such as interstate highways, where the suctioning action of the tyres on the pavement tend to pull detritus from the porous lift. Open-graded pavements on lower-volume, slower-trafficked local roads have been less successful.

Friction of porous asphalt in time is not a problem provided the right quality stone is used. In the Netherlands stone with a PSV of 58 is desired for the high traffic volume roads (main motorway network). Friction of new laid material can be a problem. In The Netherlands, it was observed that on new porous asphalt braking with blocked

wheels (emergency stop) can cause "*bitumen planing*" due to the melting of bitumen in the interface between the wheel and the road service. For this reason braking measurements are performed on new porous asphalt (*figure 18*) and if necessary speed limitations are in place until the deceleration valued is above a certain limit (6.5 m/s^2)

FIGURE 18 - FRICTION MEASUREMENTS WITH BLOCKED WHEELS IN THE NETHERLANDS

3.2.5 Texture Properties

OGFC texture is such that allows for a reduction in noise levels and increases skid resistance of the pavement (especially in wet conditions and for high speeds). Aqua-planning probability is strongly reduced.

3.2.6 Splash and Spray Properties

OGFC shows very good to excellent splash and spray properties given that voids are not clogged with fines.

3.2.7 Cost

The cost of OGFC is variable. In the State of Arizona (USA), this type of material costs between 30 to 40% more than conventional asphalt mixes [Kuennen 2003]. Studies conducted in the Netherlands indicate that the costs of porous asphalt are higher than dense asphalt concrete, but they also show that OGFCs can compete with other means of noise abatement in cost and on actual and perceived effects [Larsen,

Ellebjerg and Bendtsen 2001]. In some European countries the cost of OGFCs can be up to 50% more than conventional dense asphalt concrete mixes. In other European countries cost difference can be lower, the use of modified bitumen being the main difference.

3.3 POROUS ASPHALT– TWO-LAYER

3.3.1 Definition

A two-layer porous asphalt (usual total thickness in the range 50-90 mm) consists of a coarser underlying porous layer with a finer porous surface layer on top [Goubert et al 2005]. Normally, the underlying layer has a maximum aggregate size on the order of 12.5 mm (0.5 in.) to 19 mm (0.75 in.) and the layer is about 35 to 60 mm thick. Usually the top layer is comprised of a maximum aggregate size of less than 9.5 mm (0.375 in.), and it is 15 to 30 mm thick. In the Netherlands, the layer thicknesses are 45 mm for the bottom layer and 25 mm for the top layer. Regarding the composition of these materials, in the U.S. air voids between 15% and 19% are typical, while in Europe and Japan air voids can be as high as 20% to 30%. *Figure 19* shows core samples of two-layer porous asphalt mixes built with different coarse aggregates.

FIGURE 19 - CROSS-SECTION OF TWO-LAYER POROUS ASPHALT PAVEMENTS
(SOURCE: NATIONAL ASPHALT PAVEMENT ASSOCIATION)

Because sufficient inter-layer bonding seems difficult by separately paving two layers materials, a new type of asphalt paver (multi-asphalt paver, MAP) is used in Japan. The MAP allows simultaneous spreading of two different types of asphalt mixtures as upper and lower layers. By compacting the two layers at a time, sufficient bonding between the layers and appropriate physical properties can be ensured even when the layers are thin. An external view of the MAP is given in *figure 20, next page* [Tsukamoto 2003 REAAA]. Similar machines are being applied in Europe (Germany, Netherlands). In the Dutch noise innovation program for road and rail traffic (IPG) fundamental research has been performed on two-layer porous asphalts.

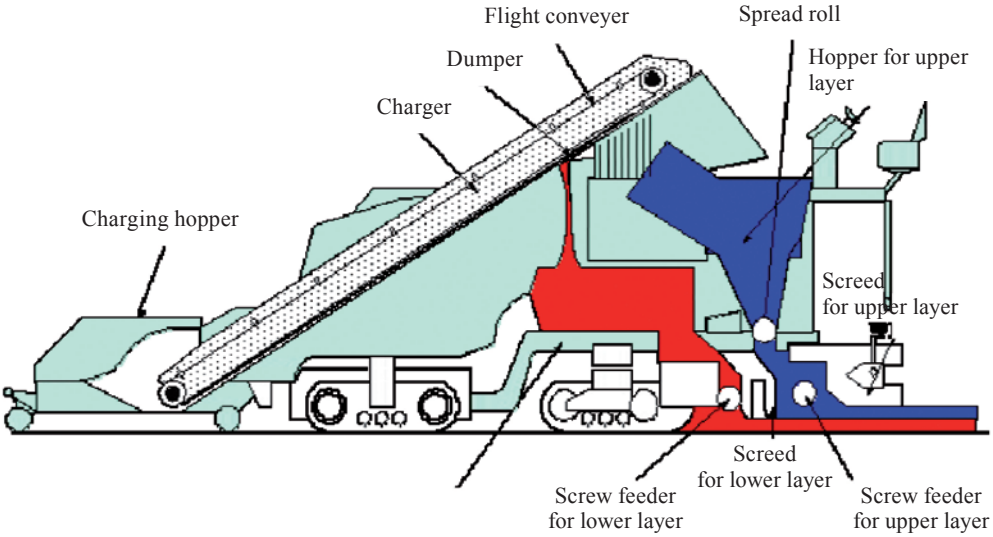


FIGURE 20 - CONSTRUCTION OF TWO-LAYER BY MULTI-ASPHALT PAVER

3.3.2 Acoustical Effectiveness and Durability

This porous two-layer pavement type is very effective in reducing noise in pavements; however, it is more complex to produce than a single layer system. Here, two layers have to be placed in rapid succession to avoid using an adhesion coat that would reduce the draining and noise-attenuating effectiveness of the system [Giavarini 2004]. Danish studies on two-layer porous asphalt surfaces on urban roads showed noise reductions of 4 to 6 dBA (compared to a reference surface of dense asphalt concrete). Dutch studies of two-layer porous asphalt with very small chipping size in the top layer revealed noise reductions from 3 to 4 dBA at 50 km/h up to 5.5 dBA at 100 km/h. For motorways for a mixed volume of traffic two layer porous asphalt has a reduction of 6 dBA against the reference dense asphalt concrete wearing course.

In terms of durability, the two-layer system life varies from only 3.3 years to more than 10 years. The most durable pavements have been built in The Netherlands, which have served for more than 10 years [Goubert 2005]. On the average the technical durability in the Netherlands is app. 8 years, during that time the acoustical reduction is minimized with app. 2dBA

Finally note that Note durability, repair and rejuvenation, cleaning, winter maintenance are well known technical aspects related to low noise pavements which still call for research, as assessed in many reports [Goubert et al 2007].

3.3.3 Material and Structural Performance

In general, a two-layer or twin-layer surface consists of a bottom layer with a large chipping size and a top layer with small chipping size. The top layer with the small chipping size 4 to 8 mm (0.16 to 0.31 in.) ensures an even surface as required for low rolling noise. This layer acts like a filter keeping out some of the dirt. The large chipping size of the bottom layer 11 to 16 mm (0.4 to 0.6 in.) ensures that dirt and water penetrating the top layer can be drained off without clogging the pores. The void content of both layers is in the range of 25% [Rust 2003].

The load capacity of the thick porous pavement is higher than that of a 30 mm (1.2 in.) thick dense asphalt concrete (DAC) pavement, so the foundation for a road with PA8/PA16 can be 30 mm (1.2 in.) thinner than for one with DAC [Larsen, Ellebjerg and Bendtsen 2001]. *Figure 21* shows a two-layer porous asphalt pavement.

FIGURE 21 - TWO-LAYER POROUS ASPHALT PAVEMENT IN THE NETHERLANDS (SOURCE: AASHTO/FHWA)

3.3.4 Friction Properties

As in single layer OGFC two-layer porous asphalt reduces noise levels and improves the ride quality of pavements. Two-layer porous asphalt pavements have been tested within the SILVIA project on motorway E18 west of Stockholm, in Sweden. The two-layer porous surface was efficient only during early ages, but after four years of operation it lost its award- winning acoustic and friction properties [Sandberg 2009]. In The Netherlands, friction is not a problem during the technical life time as indicated above. For two layer porous asphalt the same initial skidding problems occur as has been reported for porous asphalt.

3.3.5 Texture Properties

Two-layer porous asphalt texture allows for a reduction in noise levels and increases skid resistance of the pavement at least in the short-term. There is still debate on the long-term performance of this material.

3.3.6 Splash and Spray Properties

Two-layer porous asphalt shows very good splash and spray properties during the first years of life; however, voids get clogged with fines after four or five years. Also this is depending on the type of road, the maintenance to be performed and the amount of traffic. The tyres of the wheels in general have a cleaning effect.

3.3.7 Cost

In the Netherlands, the top layer of 25 mm (1 in.) PA8 costs 5.4 Euros/m^2, the 45 mm (1.8 in.) thick PA16 bottom layer costs 9.7 Euros/m^2. Comparatively, a 30 mm (1.2 in.) thick of DAC (the alternative to porous asphalt) costs 5.6 Euros/m^2 [Larsen, Ellebjerg and Bendtsen 2001].

3.4 STONE MASTIC ASPHALT (SMA)

3.4.1 Definition

There are many types of SMAs. This material can be classified as a gap-graded friction course with voids filled with a considerable amount of asphalt binder, stabilizer and finer aggregate. In general, SMAs contain crushed materials. In Europe, SMAs originate from Germany and are also used in many other countries (e.g. throughout the United Kingdom, the eastern and mountainous portions of France, the Netherlands, Denmark). *Figure 22* depicts a sample of an SMA cut and extracted from an actual pavement section.

FIGURE 22 - CROSS-SECTION OF STONE MATRIX ASPHALT STRUCTURE
(SOURCE: WASHINGTON STATE DOT)

3.4.2 Acoustical Effectiveness and Durability

Results of pavement texture observations and noise measurements on Highways M18 and A50 in the United Kingdom show that SMA is a surface treatment that offers a very promising option to reduce tyre-pavement noise, especially when looking at 4 or 5 years after placement. Data on noise, texture measurement methods, and skid resistance in these pavements showed very good results [Chandler, J. W., et al, 2003]. The noise levels measured on SMA sections on these highways in the United Kingdom were lower than the values measured on pavement sections were exposed aggregate concrete surface (EACS) was used.

Similar studies in the United Kingdom show that SMA reduces tyre-pavement noise in 3 to 4 dBA, as compared to a brushed cement concrete. This reduction is referred to light vehicles traveling at 90 km/hr (44 mph) and 110 km/hr (68 mph). Noise measurements were taken for different road surfaces using the close proximity method (CPX) method, and for SMA, noise levels were around 101 dBA at 80 km/hr (50 mph) for a new pavement, then after one year that noise level increased about 1 dBA, later at year 2, the increase was negligible [FEHRL 2006].

In the EU project SILENCE, work has been carried out to optimize the noise reduction of different types of pavements for urban roads. Danish Road Institute/

Danish Road Directorate (DRI) found an initial noise reduction for passenger cars of 4.3 dB in relation to a DAC 11 reference pavement of the same age [Bendtsen, 2009].

3.4.3 Material and Structural Performance

This material is used very frequently as roadway surface course in the U.S., often resulting in tyre-pavement noise level reductions, when compared to traditional 12.5 mm (0.49 in.) or 19 mm (0.74 in.) dense-graded HMA. SMAs are also very popular in various countries in Europe; however, the structural composition and performance of SMAs in either part of the globe is different [Gibbs 2005].

By referring to coarse aggregate, SMA appears similar to porous asphalt and both pavement types consist of an aggregate structure of relatively coarse aggregate. However, the level of voids filled with mastic is different. The voids content in as-built SMA after filling the aggregate structure with mastic is around 3 to 6%, while for porous asphalt is around 20% or more. Nevertheless, SMA can offer great noise reducing properties [EAPA 2007].

The new generation of SMA has a very small maximum size aggregate, generally about 5 or 6 mm (~0.2 in.). It has a gap-graded coarse aggregate, with the gap occurring in the range of 2 to 4 mm. The aggregate is 100% crushed material that is very cubical with good polish resistance values. Fibers are used in the mix and polymers or powdered crumb rubber may be employed in the binder. New generation SMAs have design air void contents between 5 and 10%, much higher than the normal 3 or 4% design air void content for conventional SMAs.

In the EU project SILENCE, DRI optimized for noise reduction by using small aggregate size of 4 to 6 mm and a relatively high percentage of built-in air voids as well as by using a small proportion of oversize aggregate [Bendtsen, 2009].

3.4.4 Friction Properties

SMAs have shown better friction properties than conventional dense asphalt concrete pavements and other concrete pavement textures. Nevertheless, it is worthwhile to remark that in general friction properties over the time depend on the type of stone, traffic and climatic circumstances.

3.4.5 Texture Properties

SMA has a combination of good resistance to deformation and fatigue. This is achieved by its stone skeleton and relatively high percentage of mortar or binder, which at the same time provides adequate texture [FEHRL 2006].

3.4.7 Splash and Spray Properties

This material provides a negative texture (indented texture) which results in lower tyre-pavement noise generation than other traditional materials. Besides generating lower noise levels, the texture and configuration of the surface layer results in less spray than a more traditional surfacing material [FEHRL 2006]. Thus, SMA provides very good to excellent splash and spray properties.

3.4.8 Cost

The cost of SMA is higher than a conventional dense graded asphalt mix. Projects developed in the State of Washington in the U.S. showed that the cost of SMA could be around 20 to 25% more than a dense graded asphalt mix [WSDOT 2000]. Those numbers are for the initial SMAs built in the state, where void contents were around 3 to 4%. Newer SMAs with higher void contents could be possibly around 10 to 15% more expensive than conventional mixes.

3.5 THIN, VERY THIN AND ULTRA THIN SURFACING

These techniques with layers of small thickness were developed to better fit to urban specificities: laying down is easy and quick, thus limiting traffic hindrance and costs. Surface properties are homogeneous and can be good in terms of noise reduction and often excellent in terms of skid resistance [Anfosso & Brosseaud, 2009]. Open-graded thin layer are becoming very popular for noise reduction in urban areas, where porous surface are banned because of clogging problems and low shear resistance. The characteristics of Very Thin Asphalt Concrete are described in a European standard (standard EN 13108-2). A distinction is made between dense surfaces (class 1) and open-graded surfaces (class 2) which are usually used for road noise reduction purposes. A VTAC of class 2 is typically an open asphalt mixture, half way between a open porous asphalt and traditional very thin asphalt concrete, with a very thin layer (2 to 2.5 cm thick), a higher void content than a traditional VTAC of class 1, but lower than PAC. To limit noise generation, the use of small aggregates is sought, typically 0/10, 0/6 or even 0/4 (however, this later has been developed recently as a proprietary product and is not part of the European standard). The characteristics of mix designs are summarized in *table 4, next page* for thin asphalt concretes and compared to dense and porous asphalts. Void contents are measured in laboratory with a gyratory shear compactor, after 25 rotations. They are between 20 and 25% for VTAC 0/6 and between 18 and 25% for VTAC 0/10. This porosity is obtained with intermediate granular fractions between PAC and traditional VTAC class 1. The proportioning in sand (maximum size 2 mm) is generally between 15 and 25% and most often around 20%. A clear gap appears in the grading curve: between 4 and 6 mm for the VTAC 0/6 and between 2 and 6 mm for the VTAC 0/10. The fine content are rather high (6 to 8 %) in order to stiffen the bituminous mastic

that coats the great number of aggregates. The use of modified bitumen with polymers prevents the binder from flowing and enhances the mechanical properties and the durability of the mix. The proportion of binder for a VTAC 0/6 of class 2 is usually between 5.0 and 5.4%. Some additives such as fibers or special aggregates (rubber chips, artificial porous aggregates) can be introduced in the mix in order to improve mechanical or acoustical properties.

TABLE 4 - DEFINITION OF ASPHALT CONCRETE MIXTURES

Name	Thickness (mm)	Max chipping size (mm)	Void Content (%)	Sand content (%)**
DAC	50 - 80	10 or 14	4 - 9	28 - 35
PAC	40	10 or 6(*)	20 – 30	10 – 14
VTAC class 1 ("*traditional*")	20 - 30	10 or 6	10 – 20	22 – 35
VTAC class 2 ("*low noise*")	20 - 30	10 or 6(*)	18 – 25	17 – 22
UTAC	10 - 20	10 or 6(*)	not significant	15 - 22

(*) with gap grading
(**) order of magnitude

Cuts of VTAC of class 2 compared to dense asphalt concrete (DAC) and PAC show that DAC is a mix with aggregates of continuous grading, PAC is a discontinuous mix with a lack of medium and small aggregates, and open graded VTAC is an intermediate mix with a lack of medium aggregates (*figure 23*).

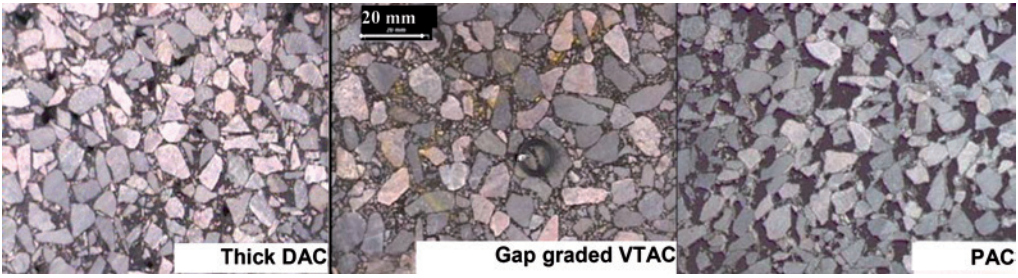


FIGURE 23 – CUTS OF ASPHALT CONCRETE MATERIALS OF 10 MM MAXIMUM AGGREGATE SIZE.

Below only some examples of proprietary products of thin and ultrathin surfaces are described, based on the available information. It appears relevant to preliminary observe that: i) an overall separation in open and dense mixes with different acoustics properties can be considered; ii) often these types of bituminous surfaces are patented products; iii) few experiments have been carried out in order to test their performance over the time (see however [Anfosso, 2008]); iv) there is an European

standard for defining Asphalt concrete for very thin layers [EN 13108-2 (2005)]; v) a technical agreement is currently being prepared by CEN for ultrathin layers; vi) there are many competing products which can guarantee high performance. As a consequence it is possible that a product below mentioned has performance worse than another product we did not mention. Furthermore, experience shows that these commercial products sometimes have a limited existence on the market. This fact yields the potential for making obsolete some information contained in the report.

3.5.1 First example

Definition
Bardon is a thin surfacing system comprised of polymer-modified binder or penetration grade asphalt with cellulose fibers, limestone filler, coarse and fine aggregates that is used in highways. This surfacing system is produced using different coarse aggregate sizes, BARDON HITEX 14 mm (0.6 in.), BARDON THINPAVE 10 mm (0.4 in.), BARDON SMATEX 14 mm (0.6 in.) [Aggregate Industries UK Ltd 2003; Sandberg 2009].

Acoustical Effectiveness and Durability
Bardon Hitex provides a durable pavement surface suitable for all classes of road. According to noise testing conducted in the United Kingdom, this material is capable to reduce tyre-pavement noise by 3.6 dBA (statistical pass-by method), in comparison to a theoretical hot-rolled asphalt surface. Other Bardon Hitex products are capable of reducing noise levels up to 7.8 dBA. These noise reductions were achieved after 2 to 3 years of operation test sections [Aggregate Industries UK Ltd 2003]. This material has been measured to have a very high noise reduction in the United Kingdom. It was tested on the A38 Devon Expressway at Heathfield in Devon and provided great results as an overlay of an old Portland cement concrete pavement, where it gave a -7.8 dB noise reduction at an age of 30 months [Sandberg 2009].

Material and Structural Performance
According to the literature, BARDON HITEX and BARDON SMATEX have been used in the United Kingdom since 1994 with great success [Aggregate Industries UK Ltd 2003]. The overall performance of the product will depend on the types of coarse aggregate materials used. Among the approved materials for use with BARDON are gritstones, granites, and dolerites.

Friction Properties
No friction values are provided for this proprietary product.

Texture Properties
The texture properties of BARDON are comparable and equivalent to the texture created by a hot rolled asphalt surface with 2 mm of texture depth. According to the

producers (see the references), stopping distance (urban braking conditions at 40 m.p.h.) results lower than SMA or HRA with chippings (*figure 24*).

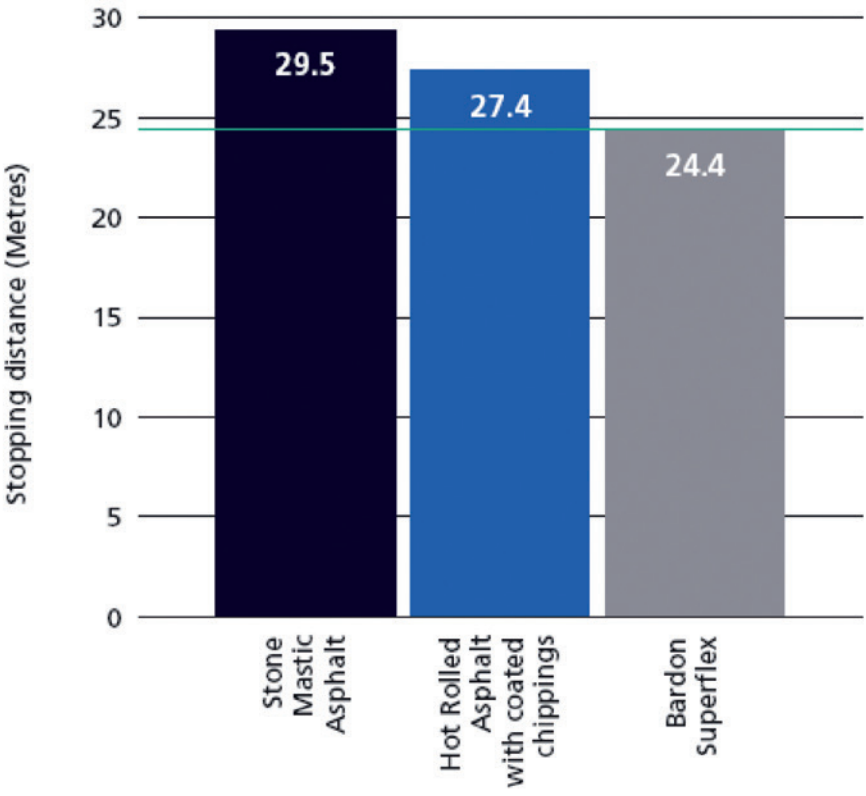


FIGURE 24 - STOPPING DISTANCE FOR DIFFERENT BITUMINOUS MIXES

Splash and Spray Properties
No splash and spray characteristics are provided for this proprietary product.

Cost
No cost information is available for this proprietary product. Further information may be found contacting the producer.

3.5.2 Second example

Definition
MASTERFlex is a machine-laid surfacing system that consists of an asphalt mix a polymer modified asphaltic material, limestone filler and coarse aggregate, and fine aggregates. This system is placed on top a substrate treated with an emulsion or a polymer-modified asphalt and is usually placed in lifts ranging from 15 mm (0.6 in.) to 40 mm (1.6 in.) of thickness [Tarmac Limited 2002; Sandberg 2009].

Acoustical Effectiveness and Durability
According to a certificate issued by the British Board of Agreement (BBA), when this material is prepared and laid according to the specifications it provides a "*durable*" surface carrying traffics of up to 5,000 commercial vehicles/lane/day [Tarmac Limited 2002]. Noise measurements indicate that this thin surface treatment can reduce as much as 5.0 to 5.9 dBA compared to a hot rolled asphalt surface with 2 mm of texture depth [Tarmac Limited 2002]. This information is based on tests conducted on a three-month old pavement.

Material and Structural Performance
This material has been used in the United Kingdom since 1994 and according to the technical information available; there is evidence that MASTERFlex provides a durable pavement surface suitable for all classes of road [Tarmac Limited 2002].

Bitumens approved for use in MASTERFlex include Cariphalte M, Cariphalte TS, and Nypol TS. Emulsion coatings approved include K1-40, K1-60 and K1-70. Polymer-modified asphalts include Mastertack, Aquagrip 60 and Colbond 50 [Tarmac Limited 2002].

Friction Properties
No friction values are provided for this proprietary product.

Texture Properties
The texture properties of MASTERFlex are comparable and equivalent to the texture created by a hot rolled asphalt surface with 2 mm of texture depth.

Splash and Spray Properties
No splash and spray characteristics are provided for this proprietary product.

Cost
No cost information is available for this proprietary product. Further information may be found contacting the producer.

3.5.3 Third example

Definition

Novachip consists of an "*ultrathin, open graded, hot mixed asphalt friction course placed over a heavy application of polymer-modified asphalt emulsion [Sandberg 2009]. The material is laid using specially built equipment (termed novachip, see figure 25), which spreads both the asphalt emulsion and hot mix asphalt in a single pass.*" NOVACHIP is placed with a nominal maximum aggregate size of 9.5 to 19 mm (0.375 to 0.75 in.) [Keiter 1993]. *Figure 26* displays a NOVACHIP applied on top of an aged asphalt concrete pavement.

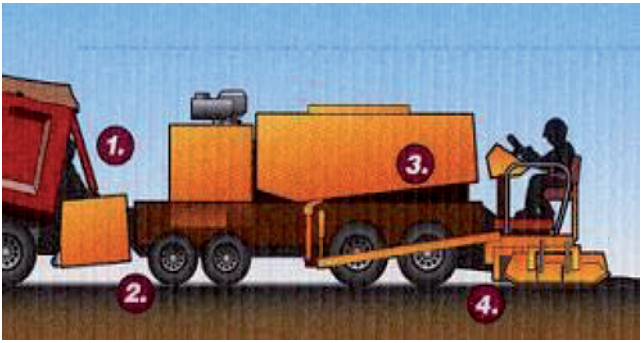


FIGURE 25 - THE "*NOVAPAPER*" (LAYDOWN OF NOVACHIP) (FROM PRODUCERS)

FIGURE 26 - NOVACHIP SURFACE (SOURCE: BORAL ASPHALT)

Acoustical Effectiveness and Durability

Excellent performance over a 5 year period. Evaluation included a visual performance for raveling, weathering, delamination, in addition to skid resistance testing, surface macrotexture depth testing, surface roughness (International Roughness Index), and transportation related noise measurements.

Based on results obtained from tests performed in the State of Pennsylvania, NOVACHIP appeared to reduce noise levels in about 1.4 dB on both existing bituminous and Portland cement concrete pavements. That reduction was obtained by measuring noise levels before and after construction [Keiter 1993].

Information from a report from the Forum of European National Highway Research Laboratories (FEHRL), noise levels measured on Highway E18 in Sweden, where NOVACHIP was used, were lower than those measured on pavements where SMA and single-layer porous asphalt were used. These measurements were made using the close proximity method (CPX) [FEHRL 2006]. Likewise, tests in the Netherlands claim the ability of NOVACHIP to reduce tyre-pavement noise in 1.3 dB, as compared to a dense asphalt concrete pavement.

Material and Structural Performance

The first NOVACHIP project was built in France in 1988. Applications in the U.S. took place in the States of Texas and Alabama in 1992, and the performance in both states was reported successful. Research was then conducted in the State of Pennsylvania in the U.S. to investigate the potential success of this material as an alternate maintenance option for state roads. The performance for the first six months after construction was good and no adhesion problems of NOVACHIP were found [Keiter 1993].

Four of the projects built in the State of Pennsylvania were monitored at regular intervals over a five-year period. The evaluation included a visual performance for raveling, weathering, delamination, in addition to skid resistance testing, surface macrotexture depth testing, international roughness index (IRI) and noise measurements. The results of the evaluations showed that the overall performance results of NOVACHIP were excellent [Knoll and Buczeskie 1999].

Friction Properties

Friction values for NOVACHIP are average.

Texture Properties

The texture of NOVACHIP is similar to the one of porous asphalt concrete (PAC) and it improves the skid resistance of the pavements, compared with conventional asphalt concrete pavements.

Splash and Spray Properties
NOVACHIP provides very good splash and spray properties.

Cost
For the three projects built in the State of Pennsylvania in the U.S. the cost of NOVACHIP was USD2.40 per square yard (1sqyd= 0.836 m^2). Additional information about costs states that information on the costs of NOVACHIP in the U.S. depends on the region, but in general they range from USD3.50 to USD4.00 per square yard [Uhlmeyer 2003].

3.5.4 Other Proprietary products

Definition of Products
At the present time, there is a great variety of products that are used as pavement surface treatments [Sandberg 2009]. Most of these products are the result of materials interaction and research conducted to investigate the benefits that would enhance or rejuvenate the properties of existing aged pavements. Most of the products offered are proprietary and their application might be more common in some areas or countries than in other. This section summarizes the information gathered for some of the most commonly found surface treatments in Europe and in the U.S.

Colsoft is a proprietary road surfacing material developed by Colas Limited. It is also known as the French Two-layer system. This material consists of crumb rubber obtained from recycled tyres, crushed aggregate, asphalt, and asphalt modifiers. It has been used in pavements located in urban areas mainly for noise reduction purposes [Abbott and Watts 2003]. Colsoft is conventionally placed in layers of 20 mm to 30 mm and uses certain aggregate sizes [Phillips 2003]. In 1995, Colsoft was awarded the Golden Decibel Prize by the French Ministry of the Environment because of its major reductions in traffic noise in urban areas. *Figure 27* shows the field operations during the placement of a Colsoft layer. The chipping size can be 0/6 or 0/10.

FIGURE 27 - APPLICATION OF COLSOFT PRODUCT (SOURCE: COLAS)

Rugosoft is another road surfacing material developed by Colas in France, it was previously known as "*Le Ruflex FG*." Rugosoft was awarded the 2005 Golden Decibel Prize by the French Ministry of the Environment. This material uses a polymer-modified asphalt that enhances adhesion, durability and noise reduction [COLAS S.A.]. According to the literature this material offers good drainage properties that minimize hydroplaning and splash and spray conditions in wet pavements. *Figure 28* displays a close-up of a finished Rugosoft. Maximum chipping size is 6 or 10 mm and layer thickness is between 20 and 30 mm as for other VTAC.

FIGURE 28 - RUGOSOFT MATERIAL (SOURCE: COLAS)

Nanosoft is one of the surface treatments for which experiments were conducted lately to measure friction and noise. It is produced by Colas in France with a **maximum aggregate size of 4 mm** and optimized grading curve, which allow optimum sound absorption [Gautier and Ballie 2008]. Nanosoft is probably the first pavement materials for which laboratory design was guided by a theoretical performance based approach [Gautier and Ballie 2008]. Layer thickness is between 20 and 30 mm as traditionally for VTAC.

MASTERpave is applied in nominal layer thicknesses ranging from 20 mm (0.79 in.) to 75 mm (3.0 in.). Maximum aggregate size could be 6, 10, 14, or 20 mm; however, the 14 mm aggregate size is the material that has given the best results in terms of noise reduction. This material meets the required performance for rutting and rut depth and can significantly reduce traffic noise levels [Tarmac 2007]. MASTERpave has been successfully installed on various highway projects in the United Kingdom.

Due to its high thickness and due to the ratio thickness/MAS, it cannot be considered a surface dressing. Note that the thickness to MAS ratio, t/MAS, is around 3.5 (20/6-75/20).

UL-M is a thin surface pavement developed in France by Eurovia. UL-M is made of a series of thin surfaces that contain Evatech, a polymer-modified binder. All this thin surfaces are approved by the Highway Authorities' Product Approval Scheme (HAPAS). UL-M has been used in England over the last ten years with good results. This material improves pavement characteristics such as durability, skid resistance, reduced water spray, lower noise levels, and smooth riding quality. According to the literature this material has been laid at over 2,000 sites, including urban roads and motorways in the United Kingdom [Sandberg 2009].

MicroFlex is a thin layer of pavement constructed and offered by Heijmans Infrastructuur in the Netherlands. Microflex contains approximately 13% of air voids when constructed and has a maximum aggregate size of 6 mm (0.24 in.) (MicroFlex 0/6) [Sandberg 2009].

MICROVIA is a proprietary product developed in France by Eurovia. It consists of a modified binder, crushed chips, and crushed aggregates to obtain a coarse gap grading. It is usually laid over a bond coat, most often a polymer modified bitumen emulsion to ensure impermeability of the substrate layer and to provide an excellent bonding, which will improve the service life of the wearing course [Eurovia 2003]. Two types of MICROVIA are used, MICROVIA TM used in thicknesses between 2 to 3 cm (0.78 in. to 1.2 in.) and MICROVIA UM used in thicknesses between 1 to 2 cm (0.39 in. to 0.78 in.). Maximum aggregate size is 6 mm or 10 mm

Rollpave is a futuristic quiet pavement material. It is a prefabricated 30 mm (1.18 in.) thick rollable porous asphalt concrete pavement which is rolled up on reels, brought out to the site, and rolled out on the base layer. This concept was developed based on Nobelpave, another thin proprietary product. Rollpave can be either bonded or unbounded to the base by inducing electromagnetic waves. One of its main advantages is that repaving projects can be finished faster than when using conventional paving methods. Other advantages are less traffic disruptions and a more uniform and homogeneous surface [Sandberg 2009].

High Friction Surfacing (HFS) treatments are surface dressings produced with a variety of binders, both thermosetting and thermoplastic which are intended for application where exceptional skid resistance is required [Sandberg 2009]. There are a number of proprietary HFS products that are commonly used in various areas in Europe; those include Suregrip, Spraygrip, Safetrack, Duragrip, Truegrip, and Tyregrip. Also, in Italy and the United States Italgrip has been used in some projects. *Figure 29, next page* illustrates a high friction surface application.

FIGURE 29 - CLOSE-UP OF HFS AGGREGATE (SOURCE: THE TRANSTEC GROUP)

Acoustical Effectiveness and Durability

A common feature of many surface treatments discussed here is that they their noise-reducing capabilities are less efficient for heavy trucks than porous asphalt layers, mainly due to lower texture of surface treatments [Sandberg 2009].

Colsoft gives a reduction of road traffic noise between 3 and 5 dBA compared with conventional dense asphalt surfaces [Phillips 2003]. In the United Kingdom, A 35 mm (1.38 in.) thick layer was built in 1999 and a noise reduction of about 5 dB measured with the SPB method at 64 km/h was reported, in comparison to the normal UK HRA surface [Sandberg 2009]. Trials in other countries, using other reference pavements, have failed to show such high noise reductions for Colsoft.

Nanosoft, in new condition, allows reducing rolling noise by about 9 dBA when compared to traditional reference asphalt pavement, this is using the SPB method, but considering only light traffic [Gautier and Ballie 2008].

MASTERpave made with 14 mm maximum aggregate size has given the best results in terms of noise reduction on surface with 14 mm size aggregates, achieving a reduction of 3.7 dB at two months of age [Sandberg 2009].

UL-M might be able to provide a durable thin surface treatment under certain conditions of traffic and weather. A pavement section in London in the United

Kingdom that carries severe traffic stresses and is subject to continuous stop and go operations has shown signs of deterioration. Based on this experience, it can be concluded that in wet conditions with intensity sufficient to saturate the pavement wearing course, UL-M, is ineffective. At three months of age, the material was already showing signs of deterioration [Sandberg 2009].

MicroFlex provides a noise reduction of 4.3 dB for light vehicles at 50 km/h, but also 3.9 dB at 40 km/h and 4.9 dB at 70 km/h. Depending on the aggregate characteristics (size) this material offers a good balance between high durability and noise reduction [Sandberg 2009].

MICROVIA is used in suburban and urban areas because of its low rolling noise properties and its aesthetic appearance related to the small size of the aggregates used [Eurovia 2003].

During the first Rollpave full-scale trial laid in June 2006 on Motorway A35 in Hengelo, in the Netherlands noise testing findings were below expectations. The material gave a 4.3 dB noise reduction when new and 3.4 dB after one year, compared to the Dutch reference pavement [Sandberg 2009]. The reported expected lifetime of Rollpave is about 10 years.

High Friction Surface (HFS) treatments are not essentially designed for noise reduction; however, it has been found that they may actually provide a substantial noise reduction if they are laid on a smooth base layer [Sandberg 2009].

Material and Structural Performance

The structural performance of surface treatments is limited to that offered by a very thin layer of material. It should be understood that the main objectives of surface treatments are to provide a quieter pavement, better skid resistance and texture; however, these parameters are greatly affected by the structural conditions of the pavement underneath, traffic and weather conditions. Generally, the surface treatments described here have a performance that is particular for each case studied. It is very possible that such performance of the treatment could be different if used in different conditions or in a different project.

Friction Properties

Surface treatments provide enhanced friction properties that usually justify their use. Although those friction properties vary from product to product it is important to learn from previous projects to estimate the feasibility of using one material or alternatives. Also, the effect of time and traffic conditions has an effect on the friction properties of surface treatments.

According to the literature, Nanosoft offers a tyre-pavement grip higher than that of traditional pavements. Furthermore, its mechanical characteristics and its aesthetical aspect are very well fitted to urban environments [Gautier and Ballie 2008]. UL-M offers high skid resistance and ultra-smooth riding quality [Sandberg 2009]. High friction surface (HFS) treatments have a high skid resistance that makes them viable for use in areas where slippery pavements are an issue. Locations where HFS can be used include pedestrian crossings, junctions, islands and bus stop bays.

Texture Properties

All surface treatments have a particular texture that makes them different from other treatments and more suitable for application in certain conditions. For instance, Colsoft has a granular composition that uses chopped rubber from scrap tyres. In addition to low road noise, it has a matte appearance, which improves visibility by reducing reflections from light sources. Colsoft is laid to a depth of 20-30 mm (0.8-1.2 in.) using crushed gap aggregate grading of either 0/6 mm (0.24 in.) or 0/10 mm (0.39 in.) An average texture depth of 2 mm (0.08 in.) was found at the first Colsoft trial in the UK [Phillips 2003].

Another treatment, MasterPave, is capable of retaining its texture on traffic volumes up to 5,000 commercial vehicles/lane/day. It has shown excellent deformation resistance. Other surface treatments have textures that reduce noise levels or enhance wet pavement conditions. For instance, high friction surface (HFS) treatments have a macrotexture that could be capable of achieving some tyre-pavement noise reductions. Although, at present time there are no noise measurements where those reductions are shown and approved by HAPAS [Sandberg 2009].

Splash and Spray Properties

The splash and spray properties of surface treatments can be quite different from each other and even for the same material, these conditions change over time and traffic conditions. Surface treatments usually offer better properties than conventional pavements when wet; however, those properties may or may not last longer. Therefore, it is important to know what these conditions are for different materials.

Among the surface treatments aforementioned Rugosoft and UL-M have been found to offer very good drainage, reduced splashing in wet conditions, and high skid resistance. All the other products have had limited application and therefore the splash and spray properties have not been fully observed.

Cost

The costs of surface treatments are very variable, not only because of the regional availability, but also because of the costs that result from different contractors. These costs could range from as low as EUR 6.0 to as high as EUR 25 per square meter for Rollpave in Europe.

Rollpave has a projected cost of EUR 25 per m², which is significantly higher than for a thin layer or one-layer porous asphalt [Sandberg 2009]. However, it is thought that this may be justified in cases where traffic congestion due to repaving may be critical and when faster repaving is needed. Other potential uses of Rollpave include bridge decks, temporary pavements and emergency repairs.

3.6 ASPHALT RUBBER FRICTION COURSE

Definition

An asphalt rubber friction course (ARFC) is usually a wearing surface layer that is built using either a gap-graded or open-graded asphalt mix and which contains from 15 to 20% of crumb rubber in it [Fickes 2003], by weight of liquid asphalt cement. This pavement has been used in different countries for constructing surface layers and performance results have differed accordingly, but the overall experience has been positive, with more research being conducted in the area of tyre-pavement noise [Gibbs 2005]. The one-inch thick ARFC surfacing used in the State of Arizona in the U.S. consists of a 3/8 open-graded aggregate. Typical asphalt-rubber binder contents range from 9 to 9.4% by total mix weight. This overlay strategy was used for most of the Portland cement concrete pavement (PCCP) overlay placements since 1988. [Scofield and Donavan 2003]. *Figure 30, next page* below displays an image of the texture of an ARFC.

FIGURE 30 - ASPHALT RUBBER FRICTION COURSE IN ARIZONA (SOURCE: DANISH ROAD INSTITUTE)

Acoustical Effectiveness

Regarding these characteristics, results have been reported in different studies. For instance, in the State of Arizona, noise reductions of up to 6.7 dBA were achieved in a project located on Highway I-19. This reduction was achieved at a distance of 10.6 m away from the roadway. In other studies in the same State of Arizona, noise measurements compared to tined concrete surfaces have shown reductions of 7.3 dB

and 13.1 dB. These results were obtained for longitudinally tined and random transverse tining concrete, respectively [Scofield and Donavan 2003].

The overall performance of the material has been as good as the one used in the State of Arizona. The State of Texas commonly uses asphalt rubber, and the states of Nevada, Washington, and Nebraska in the United States are starting to use ARFC in some experimental sections in highways. In a study conducted in Belgium, an open-graded asphalt rubber hot-mix asphalt reduced noise by 8 to 10 decibels or 75% when applied to the Brussels Loop [Fickes 2003].

Data from studies conducted in the State of Arizona indicate a weak, positive relationship between noise level and pavement age. The studies revealed that ARFC surfaces might have attained a value of approximately 93 dBA at construction and would increase approximately 5.5 dBA over ten years. Likewise, the pavements' acoustic life typically ranged between 94 and 98 dBA. [Scofield and Donavan 2003]. State of Arizona's Quiet Pavement Pilot Program (QPPP) main objective is to evaluate the durability of the noise reduction of the ARFC. Preliminary data shows that a reduction of 6 or more dBA in noise levels can be achieved for 10 or more years; however, more supporting data is needed to confirm these results [Fickes 2003].

Material and Structural Performance
Rubberized asphalt has also been used in the State of California in the United States. It is commonly termed as RAC(O) which means rubberized asphalt concrete, Type O for open or RAC(G), which refers to gap graded. In the case of RAC(O) air voids contents are around 14-20%, while for RAC(G) air voids contents are similar to dense graded AC and Optimum Bitumen Content (OBC) corresponds to that yielding 4% air voids.

Friction Properties
ARFC usually possesses average friction properties, depending on aggregate and job mix formula.

Texture Properties
ARFC texture longevity is variable and relates directly to the structural performance of the pavement.

Splash and Spray Properties
ARFC, especially if open-graded, usually shows good splash and spray properties.

Cost
"*The higher cost of asphalt rubber mixes will likely limit wider use of the material for the time being – unless, of course, the driving public starts making noise about wanting quieter roads*" [Fickes 2003].

In the State of Arizona, assuming a pavement with fatigue failure with alligator cracking, "*an asphalt rubber overlay could cost USD60,000 per lane mile.*" "*The rehab might cost USD200,000 or more per lane mile*" [Fickes 2003].

3.7 POROELASTIC ROAD SURFACE

Important Note

This section deals with the poroelastic road surfaces, PERS. Altough the PERS have an outstanding role from a scientific standpoint, note that PERS are mainly futuristic solution for the time being. Although promising, PERS are not really currently available on the market.

Definition

The POROELASTIC ROAD SURFACE, PERS, is defined as a mix that contains from 20 to 40% of air void content and is made of rubber, usually from scrap tyres. The rubber content is about 20% in volume of the mix. Aggregates and rubber are bound by a polymer modified asphalt or polyurethane binder. Virtually, any type of good performance binder could be used; however, only bitumen and polyurethane binders have been used to the present time [Rasmussen 2004]. This type of material provides a very elastic surface which is beneficial to the vibration-excited rolling noise produced by vehicle tyres. According to Swedish-Japanese studies, poroelastic road surface provides an effective reduction of tyre-pavement noise between 5 and 15 dBA compared with conventional dense asphalt surfaces [Rust A., 2003]. *Figure 31* displays a couple of samples of poroelastic asphalt.

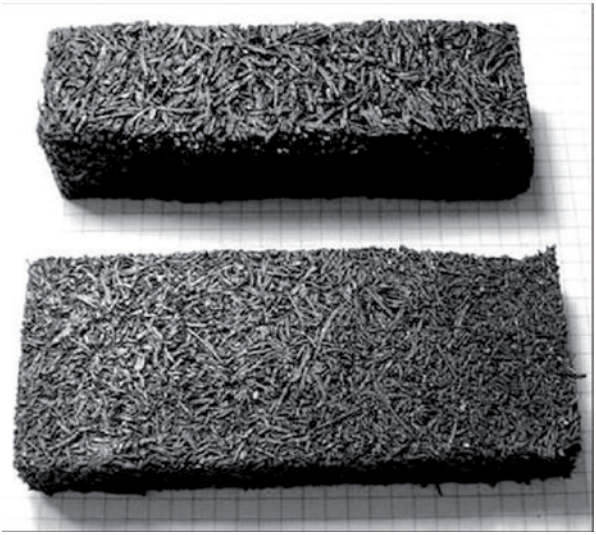


FIGURE 31 - POROELASTIC SURFACE USED IN SCANDINAVIA (SOURCE: ULF SANDBERG)

Acoustical Effectiveness and Durability
This type of surface can provide an effective reduction of road traffic noise. The reduction of noise levels could be between 5 and 15 dBA compared with conventional dense asphalt surfaces, as shown by the results of Swedish studies [Meiarashi 2006]. Research conducted in Japan shows that the durability of noise reduction seems to be around 3 years, but research is being conducted to improve this feature.

Work conducted by Meiarashi in Japan focuses on developing an improved poroelastic road surface or PERS. This researcher estimates that the potential noise reduction levels in Leq could exceed 10 dBA. Likewise, in the Japanese experience, some problems with this material have been solved such as insufficient adhesion between the pavement and the base course, low skid resistance, and poor fireproof performance.

Material and Structural Performance
The mix design of PERS is patented. Nevertheless, the following possible, tentative composition (in weight) can be supposed (thickness=30mm):
- rubber 0/2: circa 37% (this paving material has a high content of granules or fibers of rubber - at least 20% of the volume which can be obtained from scrap tyres);
- binder (polyurethane): circa 7.5%;
- aggregates 0/8: circa 55.5%.

Although research results show promising results further research and development is still needed to make the poroelastic surfaces sufficiently durable and safe. This might be achieved in the coming years through the European project "*PERSUADE*". PERS has been used in Japan on top of inter-locking block (ILB) pavements, but its rate of success has not been as expected, thus, more research was going to be conducted to investigate other more adequate pavement construction methods. Also in the Netherlands trial test sections have been laid with this product.

Friction Properties
PERS typically possesses lower than average friction properties.

Texture Properties
PERS texture longevity is variable and relates directly to the structural performance of the combination of the binder and rubber aggregate.

Splash and Spray Properties
PERS shows good splash and spray properties.

Cost
No costs were found for this pavement type, but have been reported by the authors as much higher than any conventional.

3.8 SURFACE DRESSING

Definition
A surface dressing or bituminous surface treatment (BST, e.g. seal coat or chip seal) is a protective wearing surface that is applied to a pavement or base course. The main components are emulsion and aggregates. The main steps of construction are: surface preparation; asphalt emulsion application; aggregate application; aggregate embedding (through a roller into the asphalt material, against the underlying pavement).

It can provide a waterproof layer, protect the underlying pavement, increase the skid resistance, fill for existing cracks or raveled surfaces, provide an anti-glare surface during wet weather, increase the reflectivity of the surface for night driving. Surface dressings are have been primarily used on low volume roads.
Overall, surface dressings do not have a structural objective.

Note that beyond single surface treatments, also double or triple surface treatments are sometimes constructed. Furthermore, it appears relevant to precise that slurry seal, microsurfacing and high friction surfaces have in common several compositional and construction aspects. Slurry seal (a combination of asphalt emulsion, well-graded fine aggregates and filler, cement and water) is mixed on the truck in transit and is placed. Friction surfacing is available as hot (application of a hot pre-mixed material consisting of binder and calcined bauxite) or cold (application of a tough liquid binder onto the road surface followed by the application of calcined bauxite aggregate)

Acoustical Effectiveness and Durability
Surface dressing are never used for noise mitigation purposes. However, different studies about acoustical effectiveness of surface dressing have been carried out in different countries. For instance, in the United Kingdom surface dressing has been compared to chipped hot rolled asphalt (HRA) surface courses, indicating that surface dressing produced a greater noise level. This high noise level, combined with the deterioration of the surface dressing and the poor ride quality associated with differential settlements, resulted in an "*excessively*" noisy carriageway.

Tests conducted in the Netherlands and Germany showed that there is a linear correlation between noise levels and mean profile depth (MPD) values. For surface dressing the noise level increased by 4.5 dB per mm with increasing MPD values [Steven and Küppers 2000].

In Spain measurements of noise levels with CPX comparing dense hot mix asphalt and one aggregate size surface dressing with the same maximum aggregate size in both cases indicate that surface dressing surfaces are 2-3 dB (A) louder than dense hot mix asphalt.

Surface dressing layers may last up to 10 years (6 to 8 years normally), assuming a pavement with adequate structural capacity is underneath. In order to achieve an appropriate durability or in roads with a high volume of heavy traffic use of modified binder is necessary.

It is widely recognized that weather-related factors are often responsible for the failure of a newly constructed surface dressing, because the performance of emulsions depends on evaporation for developing their adhesion characteristics, environmental and pavement temperatures, relative humidity, wind velocity, and precipitation. Ideal surface dressing weather conditions are those with low humidity, without wind, and with sustained high temperatures.

Material and Structural Performance

Materials needed for a surface dressing are emulsion (usually modified) and aggregates (natural gravel or crushed stone). One aggregate size is often preferred because of a convenient interlocking and a better skid resistance. When a slurry is placed over dry and ravelling pavement, a tack coat should be done before the slurry seal.

It is possible to apply one layer or multiple layers. Two layers are referred to as a double and three as a triple layer. If multiple layers are applied, smaller aggregate sizes are used in each successive layer. For example, in a double layer, the largest size stones are placed in the first course and these determine the surface layer thickness. The second course serves to fill the voids in the first course. When using multiple layers, the first layer should be cured before the application of the second layer.

BSTs are usually applied through spray emulsions at a high rate followed by an aggregate application. The aggregate is rolled immediately after spreading with either a steel-wheeled tandem or a rubber-tyred roller.

The thickness of these asphalt mixtures often varies from 10 to 20 mm (0,4 to 0,8 in.). Maximum aggregate size is 19 mm (0,8 in.) and application rate/layer vary between 12 to 30 kg/m^2 (1kg=9.8N). Normal applications have a thickness between 12 and 16 mm (0,5 to 0,67 in.) per layer, while the maximum aggregate size is between 6 to 12 mm (0,25 to 0,50 in.), and application rate/layer varies between 16 and 25 kg/m^2.

The ratio MAS (maximum aggregate size, mm) on weight of emulsion (kg per squared meter) is 1/8 to 1/10. For a surface dressing in which the maximum aggregate size is 9 mm and 12 kg/m^2 of aggregate is applied, about 1.2 kg/m^2 of emulsion is necessary.

Friction Properties
Friction properties mainly depend on macrotexture, microtexture and mineralogy. Independently of the type of aggregate used in a surface dressing, an improvement of friction properties is often achieved due to the good macrotexture.

Texture Properties
A comprehensive study was conducted in the Netherlands and Germany, where various pavement surfaces were tested to validate the close proximity method (CPX). This international project was performed in the summer of 1998 by TÜV Automotive GmbH and M+P Raadgevende Ingenieurs bv. In this "*International CPX Validation Experiment Project*", eight test vehicles from different countries participated. The measurements for the project were carried out on 13 acoustically different road surfaces in The Netherlands and Germany [Steven and Küppers 2000].

Among the pavements tested, a surface dressing 0.625 in. (16 mm) treatment was used on one of the tracks and the test results showed that this material had some significant non-homogeneity issues, which could have been probably caused by irregular spreading of stones, together with some stone loss in the wheel tracks [Steven and Küppers 2000].

Splash and Spray Properties
Surface dressings provide good splash and spray properties. Not so good as the ones obtained with SMA or porous asphalt, but better than the ones obtained with dense and semi-dense hot mix asphalts.

Cost
The cost of surface dressing depends on the material used and on its thickness. It usually varies from 1.00 €/m^2 to 2.50 €/m^2.

Cement concrete pavements
This section (from *3.9 to 3.13*) deals with cement concrete pavements and related surface treatments.

3.9 POROUS CONCRETE

Definition
Porous concrete is a paving material with large-void contents intentionally built in by using a gap- or open-graded mix. The resulting permeability allows for water (and air) to flow readily through this material. This type of concrete is currently used as a top layer (wearing course) in pavements, and provides both low noise emission and good drainage capacity [Rasmussen 2004]. *Figure 32, next page* displays an image of a two-layer porous concrete pavement.

FIGURE 32 - CROSS-SECTION OF A TWO-LAYER POROUS CONCRETE PAVEMENT (SOURCE: RASMUSSEN, ET AL., 2004)

Acoustical Effectiveness and Durability

The rolling noise on porous concrete is theoretically improved compared to dense concrete pavements. When the pavement preserves its acoustical characteristics for over three years it can be qualified as a noiseless pavement. However, it is desirable that this material maintains low tyre-pavement noise levels in the long-term.

One study in Belgium reported a 5 dB reduction in a porous concrete pavement that contained only 19 percent porosity compared to a conventional concrete pavement [Sandberg and Ejsmont 2002.] In additional studies conducted in Belgium it was consistently found that porous concrete lost its noise reducing characteristics because of the clogging of the pores [Caestecker 1999]. ModieSlab a one-to-two-layer porous concrete developed in the Netherlands allows an actual noise reduction of 6-7 dB compared to a dense-graded reference mix. ModieSlab is a modular pavement solution that is still being researched [Gibbs 2005] for the long term performance. Nevertheless based on the results of test sections, in the Netherlands the use of Modieslab has been accepted for the main motorway network.

It was reported by Japan Cement Association (JCA) that newly paved porous concrete with its 18% air voids showed noise reduction of 6-7 dB using 5mm maximum aggregates and that of 2-3dB using 13mm, compared with neighboring dense pavements. This reduction gradually disappeared in 5 to 10 years. A hydro-pressuring test for air void recovery revealed that soil particles mainly caused clogging [JCA 2007, R22].

Note that in pervious concrete pavement designs usually the pavement itself acts as pretreatment to the stone reservoir below. Because the surface serves this purpose, periodic maintenance of the surface is an important factor in optimal performance.

Material and Structural Performance

Porous concrete surfaces have been built in at least two countries in Europe, showing clogging of the pores. In a technical discussion at the PIARC 8th International Conference on Concrete Roads in Lisbon, it was indicated that the performance of porous concrete sections was poor. Overall, optimal results with this material were obtained in the Netherlands, where a test section lasted about seven years [Chandler, J. W., et al, 2003].

In the U.S., the United States Environmental Protection Agency (EPA) reports that porous concrete has been known to have a high rate of structural failure – about 75%. "*Poor design, inadequate construction techniques, soils with low permeability, heavy vehicular traffic, and resurfacing with nonporous pavement materials*", have all shown to be attributing factors to the pavement's failure [EPA, 1999].

However in Japan, no structural damage in one national and five prefectural highway projects has ever been reported for 7 to 10 years. This is probably due to the use of high strength cement materials [JCA 2007, R22].

As for porous concretes and exposed aggregate concretes, the following information on materials and design are relevant (*table 4*)

TABLE 4 - POROUS CONCRETE AND EXPOSED AGGREGATE CONCRETES: BASIC INFORMATION ON COMPOSITION

	Porous concrete (example)		Exposed aggregate concretes (example)	
	kg/m^3	m^3	kg/m^3	m^3
Air		0.20		0.04-0.06
Cement	350 (270-415)	0.12	375	0.12
Aggregates	1,345 (1,190-1,480)	0.58	1,910	0.67
Water	105 (80-140)	0.10	150	0.15
Sum	1,800 (1,600-2,000)	1.00	2,400	1.00

Friction Properties

This material was used as early as 1983 in Japan for pedestrian areas and parking lots. However, the first pavement application was built in the Netherlands. Among the inconveniences found for this pavement were low initial friction and excess megatexture [Descornet 2000].

In Japan, sufficient skid resistance was measured using Dynamic Friction Tester at both times just after construction and 5 years in service [JCA 2007, R22].

Texture Properties

In an experimental design in Belgium, different pavement sections were built using various materials. One section was built using a thin fine concrete 0/7 layer 4 cm (1.6 in.) cast wet on wet and was built on top of a CRCP (Continuously Reinforced Concrete Pavement) 18 cm (7 in.) thick [Caestecker 1999]. Compared to other materials, the porous concrete lost its texture properties and noise reducing features. *Figure 33* shows the open texture of a porous concrete pavement.

FIGURE 33 - POROUS CONCRETE IN BELGIUM (SOURCE: THE TRANSTEC GROUP)

Splash and Spray Properties

Porous concrete shows good splash and spray properties, but clogging of the concrete pores is still an issue that needs to be solved.

Cost

In Belgium, reports show that the cost of a porous concrete wearing surface placed on top of a CRCP was about 40% greater than the reference pavement, consisting of a 22 cm (8.7 in.) thick CRCP. The document concludes that if polymers were added to porous concrete, the cost would increase 25% more [Caestecker 1999].

3.10 EXPOSED AGGREGATE CONCRETE

Definition

This pavement type is one where the surface of the concrete is sprayed with a set retarding agent and then the mortar is washed away. The concrete mix is usually prepared using a high quality aggregate with a polished stone value (PSV) over 50 [Rasmussen 2004]. The PSV value is a measure of the resistance of an aggregate to polishing. Thus, the aggregate is exposed on the surface of the pavement. Exposed aggregate concrete (EAC) can be constructed in one-layer or two-layer systems;

however, the two-layer systems is considerably more difficult to construct [van Keulen and van Leest]. *Figure 34* depicts the open texture of an exposed aggregate concrete pavement.

FIGURE 34 - EXPOSED AGGREGATE SURFACE IN BELGIUM (SOURCE: AASHTO/FHWA)

Acoustical Effectiveness and Durability

Research studies have shown that good aggregates with PSV over 50 provide better durability and lower tyre-pavement noise levels [Rasmussen 2004]. Likewise, using smaller aggregates provide better noise reduction levels. Experiences in Germany and Austria showed that EAC decreases noise levels in about 4 dBA when compared to longitudinal tined concrete [Larson 1993], although the used standards and conditions were not described. In Sweden, EAC with aggregate size of 8 mm showed a noise reduction of 3.0 to 3.5 dBA. EAC with aggregate size of 16 mm showed a reduction of 1.0 to 1.5 dBA, in both cases the close proximity (CPX) test method was used and the control pavement type was conventional dense graded hot mix asphalt. Other research studies have shown that EAC noise performance are roughly comparable to the ones of dense asphalt concrete 0/16 (Dutch calculation scheme for traffic noise, Inventory study of basic knowledge on tyre/road noise, DWW-2005-022).

Material and Structural Performance

EAC pavement can be constructed in one or two layers. When two layers are used, the quality of the aggregate in the bottom layer is lower than that of the aggregate in the upper layer, which saves in materials costs. Recycled materials could be even used in the bottom layer of this pavement. The experiences in Germany and Austria estimate that this type of pavement can last up to 30 to 40 years, assuming that studded tyres are not used that accelerate the deterioration of the pavement [Larson 1993].

Friction Properties

A test section was constructed in the U.S. in Detroit, State of Michigan. This project looked at the effectiveness of EAC pavement concept, which was brought over to the

U.S. as a result of a European Scanning Tour on Concrete Pavements. The pavement was constructed in two layers using a wet-on-wet procedure. A transversely tined section was built nearby for comparison purposes. Friction levels were not too different between tests conducted one and five years after construction; however, noise levels were not as low as expected after year one of constructing the EAC pavement. It was found that the sand used in the concrete mix was not adequate and therefore increased tyre-pavement noise levels [Rasmussen 2004].

The Austrian Cement Research Institute conducted experimental research in the U.K. and Austria and it was found that two-layer EAC pavement systems worked adequately, reducing noise, and retaining skid resistance [British Cement Association 1999].

Texture Properties

Austrians have probably more experience with noise-reducing EAC surfaces than any other country in the world. EAC is very common in Vienna and has been laid on many roads. This pavement type is also common in Belgium, but the Belgians use larger aggregates and thus have not achieved considerable noise reductions. Those experiences were transferred and applied in the United Kingdom, where the surface became known as "*whisper concrete*" [Sandberg 2009]. Pavements built in different countries have provided different results because of the different textures of the finished pavements. *Figure 35* shows a close-up view of an exposed aggregate pavement built in Belgium.

FIGURE 35 - CLOSE-UP VIEW OF EXPOSED AGGREGATE SURFACE (SOURCE: THE TRANSTEC GROUP)

Splash and Spray Properties

EAC shows average splash and spray properties.

Cost

EAC pavement is seen as an "*advantageous method*" to produce a low-noise concrete pavement [Rasmussen 2004]. In Germany, costs are reportedly about 10% higher than they are for conventional concrete pavements. In Austria, EAC costs around $2 to $3 per square meter [Larson 1993].

3.11 DRAG TEXTURES

Definition

Drag textures are created by dragging a tool along the surface of the pavement. Many times hand or mechanical brooms are used to provide the texture to the concrete. Common drag textures include carpet drag, broomed surface and burlap. These are all considered shallow textures with grooves between 1.5 to 3 mm (0.06 to 0.12 in.) deep, either longitudinally or transversely [Rasmussen 2004]. *Figure 36* displays a PCCP (Portland Cement Concrete Pavement) with burlap drag texture.

FIGURE 36 - BURLAP DRAG TEXTURE ON CONCRETE PAVEMENT (SOURCE: THE TRANSTEC GROUP)

Acoustical Effectiveness and Durability

The durability of drag textures is directly linked to the properties of the concrete material used in the pavement. It is important that the pavement surface is not overworked during construction, otherwise, the durability of the texture is jeopardized. Evaluations conducted in the State of Minnesota in the U.S. have shown that the use of artificial drag texture provides comparable noise levels and surface friction to conventional hot-mix asphalt (HMA) pavements [Rasmussen 2004].

Material and Structural Performance

Drag textures seem to provide an economical method to provide adequate friction and improved wear resistance. In fact, these might be among the best alternatives for concrete pavements placed at lower speed roads [Rasmussen 2004].

Friction Properties

The use of shallow drag textures is usually linked to quiet pavements; however, there is a concern about sufficient friction, particularly for high-speed facilities. Some studies have shown that drag textures are good for roadways with speeds less than 72 km/hr (45 mph) [Rasmussen 2004].

Texture Properties

Drag textures can be applied to concrete pavements using different methods. For instance, broomed drag is achieved by simply brooming the unhardened surface of the pavement with a broom designed for that purpose. An artificial turf drag is created by dragging an inverted piece of artificial turf along the surface of the concrete. This technique is constructed by a device controlling the time and rate of texturing.

Burlap drag or hessian drag is created by dragging a moistened, coarse burlap across the surface of the concrete, creating the grooves [Rasmussen 2004]. In Europe, different methods and textures have been used over the years, for instance, in Germany and Austria burlap drag was found to be effective; however, there is always a possibility that friction will diminish with time if the coarse aggregate in the concrete polishes [Larson, Vanikar, and Forster 1993]. *Figure 37* shows a burlap drag texture on fresh concrete.

FIGURE 37 - BURLAP DRAG TEXTURE ON A FRESHLY PLACED CONCRETE PAVEMENT IN WISCONSIN (SOURCE: THE TRANSTEC GROUP)

Splash and Spray Properties
Drag textures show poor to good splash and spray properties.

Cost
Drag texturing concrete pavements is one of the lowest cost methods to reduce tyre-pavement noise levels; however, the long-term performance of these methods needs to be improved by better technology, materials, and construction procedures. It is a consensus that drag textures offer their best in roadways where speeds are below 72 km/hr (45 mph). For high speed highways, the use of other materials might need to be considered as an alternative.

3.12 DIAMOND GRINDING

Definition
"*Diamond grinding consists of removing surface irregularities from concrete pavements that are often caused by faulting, curling, and warping of the slabs*" [Correa and Wong 2001]. This technology has been used for different purposes in pavements; it has been used to restore the smoothness of existing pavements and has also been used to reduce tyre-pavement noise levels and to increase pavement friction. In some instances, diamond grinding has been considered as a possibility to comply with smoothness specifications in newly placed concrete pavements.

The American Concrete Pavement Association has developed a refinement to conventional diamond grinding called Next Generation Concrete Surface or NGCS. NGCS differs from conventional diamond grinding in that the entyre surface is ground with diamond blades to remove all macrotexture and megatexture. An additional step is added to construct longitudinal grooves to provide macrotexture. [Scofield 2010]. *Figure 38* below depict NGCS and conventional diamond grinding.

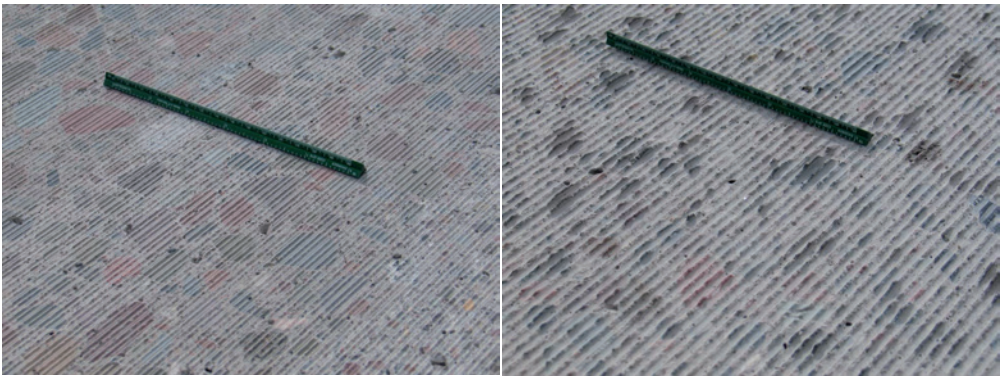


FIGURE 38 - NEXT GENERATION CONCRETE SURFACE (NGCS) PRIOR TO GROOVING (LEFT) AND CONVENTIONAL DIAMOND GRINDING (RIGHT) (SOURCE: MARK SWANLUND, FHWA)

Acoustical Effectiveness and Durability

In general, diamond grinding does not affect the durability of concrete pavements, unless the coarse aggregate is a soft stone subject to polishing [Correa and Wong 2001]. A study conducted in the State of Arizona in the U.S. demonstrated that different cutting blade spacings produced very different results, for instance, wide spacings and shallow depth textures achieved greater noise reductions than other saw configurations. The findings of this study concluded that diamond grinding may achieve noise reductions between 3 to 6 dBA [Rasmussen 2004]. In the State of Wisconsin in the U.S., studies were done to evaluate the effectiveness of diamond grinding of a heavily faulted transversely tined concrete pavement and it was found that noise levels were reduced by 3 dBA using the controlled pass-by method (CPB) [Kuemmel, Jaeckel, and Satanovsky 2000]. Tyre whining (high frequency pure tone noise) commonly produced by transverse tining of concrete pavements can be significantly reduced by diamond grinding , which removes the uniformly spaced tines from the pavement [Wolf 2008]. *Figure 39* shows an image of a grinding head commonly used in concrete pavements.

Initial installations of the NGCS in the State of Arizona in the U.S. show the noise performance of the NGCS is approximately 3 dBA reduction over conventional diamond grinding and 5 dBA reduction compared to longitudinal tining of concrete pavements [Scofield, 2010].

FIGURE 39 - IMAGE OF DIAMOND GRINDING HEAD (SOURCE: IOWA CONCRETE PAVING ASSOCIATION)

Material and Structural Performance

According to a research study conducted in the U.S. a survival analysis was conducted to quantify the effectiveness of diamond grinding to extend the life of concrete pavements. This analysis showed that "*the probability that diamond-ground pavements will have to be overlaid or reconstructed before the pavement reaches 30 years of age is less than 15%.*" [Correa and Wong 2001]. Based on this same study, a diamond ground surface may be expected to last at least 8 to 10 years, before requiring another treatment.

Friction Properties

The study performed in the State of Arizona in the U.S. concluded that diamond grinding can significantly reduce the roughness of concrete pavements and increase their friction. A test section where this texture was applied produced the smoothest and quietest concrete pavement in Arizona [Rasmussen 2004]. In this study, diamond grinding improved friction numbers in all 4 test sections tested, ranging from 15 to 41% increment and overall improvement of 27% [Scofield, Larry, 2003].

Texture Properties

Concrete pavement diamond grinding produces such a macrotexture that provides a more controlled directional stability to drivers, when compared to longitudinal tining [Rasmussen 2004]. *Figure 40* shows a macro-picture of a diamond ground pavement taken in Europe. Texture results reported by Scofield in 2010 indicates that both NGCS and conventional diamond grinding produce surfaces with high Mean Profile Depth (1.5 mm) compared to dense graded asphalt surfaces (0.65 mm).

FIGURE 40 - CONCRETE PAVEMENT WITH DIAMOND GROUND SURFACE
(SOURCE: THE TRANSTEC GROUP)

Splash and Spray Properties
Diamond grinding produces good splash and spray properties in concrete pavements.

Cost
Information collected in the U.S. estimates that diamond grinding costs between USD2.00 and $8.00 per square meter of pavement (USD1.70 and USD6.70 per sy; 1sy=1 yd² = 0.836127 m²). This cost may increase up to USD12/m² or $10/sy depending on factors such as aggregate type, PCC mix properties, depth of removal, and smoothness requirements [Correa and Wong 2001]. The cost of diamond grinding has dropped in the last few years. Increased competition and better diamond blade performance may help lower prices even more the future. State DOT's have found that the cost of diamond grinding is generally lower than the cost of an asphalt concrete overlay. Much of the cost savings can be attributed to the fact that diamond grinding can be applied only to lanes that need the corrective treatment. In Europe, diamond grinding costs are around 1 EURO per square meter and per mm depth [Descornet, G., et al., 2000].

3.13 LONGITUDINAL TINING

Definition
This texturing method is created by using a tining head that moves longitudinally along the pavement. This texture is not used as frequently as transverse tining possibly because the longitudinal grooves have resulted in lower friction numbers when compared to transverse tining and other textures. In contrast, longitudinal tining has shown to prevent vehicle skidding and improved safety and has shown to be quite successful in drier climates where surface drainage is adequate [Rasmussen 2004]. *Figure 41, next page* shows how longitudinal tining is applied on a fresh concrete pavement.

Acoustical Effectiveness and Durability
Optimal noise emission performance of longitudinal tining requires that the geometry of the grooves and their spacing conforms to that objective. It has been found that a uniform tine spacing of 19 mm (0.75 in.), tine width of 3±0.5 mm (0.12±0.02 in.), and an individual tine depth of 3 to 6 mm (0.12 to 0.24 in.) provides good results [Rasmussen 2004]. Likewise, it is commonly reported that deeper tining will exhibit more noise, regardless of the orientation of the texture. In terms of durability, mixture design and the use of studded tyres have shown to have a negative impact on the pavement, diminishing its life expectancy.

The results from studies developed in the State of Arizona in the U.S. indicate that uniform longitudinal tining produced approximately a 5 dBA reduction over the standard texture used in Arizona's highways, which is a uniform one inch transverse texture. Additionally, it produced between 8 to 9 dBA noise reduction over a random

FIGURE 41 - LONGITUDINAL TINING EQUIPMENT
(SOURCE: THE TRANSTEC GROUP)

transverse tining project built in the State of Wisconsin, in the U.S. [Scofield and Donavan 2003].

Material and Structural Performance

Research conducted in the State of Colorado in the U.S. has shown that longitudinal tining results in comparable noise levels to ground surface and 9.5 mm (3/8 in.) stone matrix asphalt (SMA). However, skid numbers were higher for the SMA than for the tined concrete, which were adequate anyway [LaForce and Schlaefer 2001].

Friction Properties

To enhance the friction conditions of pavements where longitudinal tining is used, the properties of the concrete are fundamental. First, it is vital that the mortar is durable, so it withstands the traffic; also high strength and low permeability are desired in the concrete and cementitious materials will help increase durability and workability of the mixture. It has been found that the use of siliceous sand increases the friction numbers [Rasmussen 2008]. The performance of longitudinal tining in wet weather has not been documented in any recent study; therefore, research is needed in this area. The FHWA indicates regular use of longitudinal tined pavement in the State of California in the U.S.; in contrast, the United Kingdom has prohibited longitudinal tining because it does not meet the required friction standards [Kuemmel 2000]. *Figure 42, next page* shows a longitudinally tined concrete pavement.

FIGURE 42 - LONGITUDINAL TINED CONCRETE PAVEMENT (SOURCE: THE TRANSTEC GROUP)

Texture Properties

From a constructability standpoint, longitudinal tining usually produces more consistent surfaces than transverse tining. Longitudinal tining allows texturing and curing to be applied in a continuous and more consistent pace than it is done in transverse tining. Additionally, a single texture-cure machine can be used for longitudinal tining, whereas in transverse tining two machines perform these operations independently [Rasmussen 2008].

Splash and Spray Properties

Longitudinal tining provides fair splash and spray properties in concrete pavements. Water retention in the tines or grooves might pose a safety concern, especially if surface drainage is inadequate. Tests which consisted of a skid test trailer towed along the roadway at 60 mph (96 km/h) while spraying water on the surface just ahead of the test wheel and then locking it, showed a 16% reduction in the wet weather skid resistance of the longitudinal tining when compared with the transverse tining [Kuemmel 2000]. Splash and spray on longitudinal textures has been reported to be greater than on transverse tined pavements. *Figure 43* shows a uniformly spaced longitudinal tining concrete pavement surface and curing compound being applied.

FIGURE 43 - UNIFORM LONGITUDINAL TINING
(SOURCE: THE TRANSTEC GROUP)

Cost

The cost associated with tining a concrete pavement is usually implicit in the pavement cost, which is usually budgeted per square yard of a given thickness and pavement type. Thus, this texturing technique is one of the most cost-effective methods to reduce tyre-pavement noise levels.

4. AN OVERVIEW OF NATIONAL AND MULTI-NATIONAL QUIET PAVEMENT INITIATIVES

4.1 PIARC QUESTIONNAIRE

The following main questions were posed:

- What are the main concerns your country has about the potential impact of (rural/urban; new/existing) road noise?
- Is anything being done in your country to assess and/or address the consequences of (rural/urban; new/existing) road noise? Are there legal requirements? Is there a list of best practices?
- If nothing is being done, why not?
- If you are aware of studies that have been conducted or are currently being conducted in your country or region, can you please list those and provide references as to where more information can be obtained?
- Can you please list road pavement-specific issues associated with road noise that in your opinion would require more work?

Many countries answered to the questionnaire (Austria, Canada- British Columbia, Canada- Quebec, Denmark, Norway, France, Germany, Italy, Japan, Mexico, Slovenia, Spain, United Kingdom, etc.). Concerns dealt with heath impacts and urban roads resulted often considered more vulnerable. Available budget emerged as a critical factor and in some cases up to 20% of the budget for new roads was noise-oriented.

4.2 EUROPEAN AND MULTI-NATIONAL OVERVIEW

The topic of quiet pavements has been mainly researched in some countries in Europe, Australia, and Japan [Sandberg, 2009]. Various initiatives have taken place and some of them have been very successful in the sense that lots of valuable information has been obtained through data collection, evaluation, analysis, and interpretation. There are also several examples of widespread use of these pavements for noise reduction purposes, as part of national, regional or local policies.

Among the most relevant initiatives for quiet pavement research are the Sustainable Road Surfaces for Traffic Noise Control (SILVIA), which over the three active years

developed a series of guidelines to optimize the selection of road surfaces to reduce noise levels in roadways. The objective of SILVIA was to help decision makers on the selection of sustainable road surfaces for noise reduction. The initial vision of SILVIA focused on obtaining a cost/benefit analysis, sustainable solutions, integrated noise measurements, and ultimately overall guidance and advice on performance measures of different wearing course materials.

Another initiative includes HARMONOISE, which was a 4-year project initiated in 2001 and aimed to develop a noise prediction model that could be used in Europe for an accurate assessment of noise generated from roads, railways and industrial areas. As part of this project, special concern was devoted to the integration of pavement effects in the noise prediction method and a comprehensive database of pavement noise characteristics was compiled.

SILENCE was a 3-year project that aimed at developping "*an integrated system of methodologies and technologies for an efficient control of urban traffic noise.*" This integrated system would combine inputs and considerations of city authorities, road traffic, and mass transport (rail and road) in various traffic noise facets focused on urban noise scenarios, individual noise sources (vehicles), traffic management, noise perception and annoyance [Ripke 2005].

As for the so far mentioned projects, the European Commission sponsored the project "*CALM II – Coordination of European Research for Advanced Transport Noise Mitigation*". This project ran until the end of 2007 and aimed at enhancing and coordinating the European transport noise research. It involved stakeholders and facilitated the networking of different organizations to conduct activities and exchange and disseminate knowledge [Sandberg 2009].

These and other multinational initiatives conducted around the world are briefly described in the following sections.

4.2.1 Sustainable Road Surfaces for Traffic Noise Control (SILVIA)

In 2006, SILVIA finalized a manual, titled "*Guidance Manual for the Implementation of Low-Noise Road Surfaces*". This document introduced the common concept "*Conformity of Production*", or COP, also into the pavement sector, which aimed to investigate the properties of a given surface that was used routinely, so that the end results of that surface could be anticipated in terms of performance. Throughout this initiative, data were collected and analyzed and tolerances for acceptance (or rejection) of acoustic performance of materials were defined.

The objectives of SILVIA, as conceived initially included the following [SILVIA, 2009]:

- "*To develop a classification procedure for noise reducing road surfaces combined with a conformity-of-production testing method*". This procedure would evolve and new methods would be developed.
- "*To test and specify road construction and maintenance techniques that would achieve satisfactory durability of the acoustic performance while complying with other requirements for safety, rolling resistance and maintenance*".
- "*To develop a procedure for cost/benefit analysis of noise abatement measures*".
- "T*o issue a "European Guidance Manual on the Utilization of Low-Noise Road Surfacings*" to help decision-makers to rationally plan noise abating or preventing measures integrating low-noise surfaces with other noise control measures.

Participants in the SILVIA project included research institutes, transportation institutes, material producers, and academia, all of them from various countries in Europe.

4.2.2 Sustainable Road Surfaces for Traffic Noise Control (HARMONOISE)

The HARMONOISE project started at the end of 2001 and ran through 2005 and its objective was to develop a European prediction model that could be used all over Europe. At that time there were several fairly accurate standard methods for the prediction and assessment of noise generated from roads, railways and industrial sites in various countries in Europe, but there was no common method to the entire Union. In the same time, an effort was initiated by the European Commission to develop comprehensive noise policies, including noise maps that would benefit the general public [van Leeuwen 2002]. As part of this, the Commission decided that a common advanced prediction method be produced.

The main objective of the HARMONOISE project was to develop prediction methods for environmental noise from roads and railways. The project would deal with physical noise sources and with acoustic propagation concepts. Ultimately, this project would become the reference model that could be used for everyday projects over all member states in the European Union.

The HARMONOISE project included four main work packages; Package 1 was related to the noise sources (e.g., road vehicles and rail vehicles). Package 2 included the development of a model considered the "Golden Standard" for noise measurement. Package 3 combined the acoustical propagation paths with the propagation and the noise sources, resulting in an engineering model. Finally,

Package 4 dealt with the validation of the engineering model and of some of the individual components of the source description and the propagation. The main object of this package was to collect data from measurements. Other packages dealt with dissemination, exploitation, coordination and project management [van Leeuwen 2002].

Partners in the HARMONOISE project included research centers, laboratories, transportation institutes, material producers, and academia, all of them from various countries in Europe.

During this project there were numerous deliverables and technical reports that contain the core of HARMONOISE. An advantage of the outcome of the project was that the methods developed herein were methods compared to other existing methods with good accuracy. In the end, HARMONOISE came out with more suitable methods of noise mapping and detailed computations in noise assessment studies.

4.2.3 SILENCE

SILENCE was a research project funded by the Sixth Framework Programme of the European Commission. The project ran from February 2005 until January 2008 and had a budget of approximately EUR 16 million. SILENCE aimed to develop an integrated methodology and technology for improved control of surface transport noise in urban areas. Some specific goals included noise control at the source, noise propagation, noise emission, and the human perception of noise. The project also aimed to provide world-leading technologies for efficient control of surface transport noise, innovative strategies for action plan for urban transport noise abatement and practical tools for their implementation. Some new quiet pavement concepts were developed and tested, as well as special concerns of pavements in urban areas having substantial non-uniformities and their maintenance were addressed. Another important topic for this report was compilation of the deterioration of acoustical properties of pavements over their lifetime [Sandberg 2009].

4.2.4 CALM

The overall objective of the project was "*the synchronisation and encouragement of European transport noise research through a holistic system approach involving all related research areas*". Based on networking, the main thrusts of CALM II were initially:

- to optimize research efforts,
- to identify synergies between noise research and development in the different transport modes,

- to strengthen the coherence of future noise research objectives, and
- to identify new technology requirements and remaining research needs.

4.2.5 SIRUUS

The project SI.R.U.US. – "*SIlent Road for Urban and extra-urban Use*" was conducted in the period 1998-2002. Partners in the project included Argex (BE), BRRC (BE), INRETS (FR), LNEC (PT), Pavimental (IT), SACER (FR) and Autostrade (IT) as project coordinator [Sandberg 2009]. The main goal of SIRUUS was to develop low noise multi-layer pavements with different surface and structural functions. Other objectives included full scale implementation of innovative solutions to reduce traffic noise mainly by optimizing the texture, roughness, hydraulic conductivity and sound absorption characteristics in the pavement. It also aimed to find a balance between the structural and acoustical performance of the pavements over time and their life-cycle costs.
SIRUUS aimed to design and implement innovative concepts for pavement surface and lower layers. It introduced the use of light expanded clay aggregates and other non traditional mixes and concepts. The most spectacular one was a concrete pavement with Helmholtz resonators built-in to absorb the sound, and with a porous asphalt pavement as wearing course. Short test sections were constructed during this project, which provided good results.

4.2.6 QCITY

QCITY or "*Quiet City Transport*", was a project running in parallel with SILENCE and having similar objectives. The project ran from February 2005 until January 2009 and had a budget of approximately EUR 14 million. QCITY aimed to develop an integrated technology infrastructure for the efficient control of road and rail ambient noise. Activities within QCITY supported a policy to eliminate harmful effects of noise exposure and decrease levels of transport noise creation. Another objective of the project was to provide municipalities with tools to establish noise maps and actions plans with validated technical solutions for their problems. Of special interest to this report was the development and trials with asphalt rubber pavements with a very high proportion of rubber; up to 10% by weight as opposed to the 2% which are common in the United States version of asphalt rubber. The project did not produce any durable surface of this type (none lasted two years), but it demonstrated that the extra noise reduction potential with such high rubber content is significant [Sandberg 2009].

4.2.7 IMAGINE

This project was a direct continuation of the HARMONOISE project; and was conducted from 2004 to 2006 with a budget of EUR 4.4 million. IMAGINE stands

for "*Improved Methods for the Assessment of the Generic Impact of Noise in the Environment*". This project extented prediction procedure to include industrial noise and aircraft noise, but it also addressed several details in the road noise prediction procedure. Not least, comprehensive guidelines were developed for a skilled use of the models developed in HARMONOISE and IMAGINE, for noise mapping purposes in practical applications. Thus, IMAGINE "*provided the link between HARMONOISE and the practical process of producing noise maps and action plans*". [Sandberg 2009].

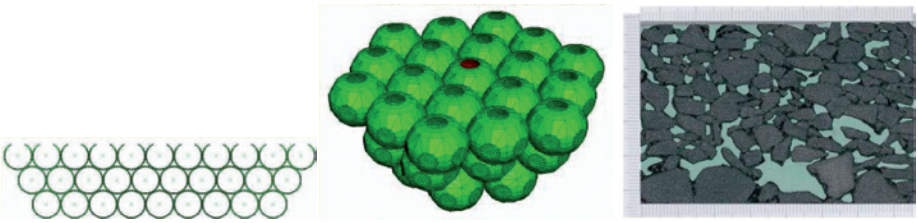
4.2.8 IPG Research to improve performance of (two-)layer porous asphalt

In the Dutch Noise Innovation Programme for Road and Rail Traffic (Innovatie Programma Geluid - IPG) fundamental research has been performed into a better understanding of failure mechanisms and noise production. This research dealt with the development of a life time optimisation tool, in order to improve mixtures for a better durability, and an acoustic optimisation tool for a better understanding of the mechanism related to noise and the possibility to optimise mixtures for acoustic performance.

The Lifetime Optimisation Tool (LOT)

An important part of the IPG was improve the structural durability of TPA (two-layer porous asphalt). Much of the work has focused on understanding the processes and mechanisms that are responsible for ravelling (the loss of stones from the top surface of the pavement). The outcomes from this investigation have been combined into a model, referred to as a Lifetime Optimisation Tool (LOT), which is specifically developed for porous asphalt pavements (Huurman M (2007).

The LOT consists of several parts. A relevant part is a discrete physical model, comprising 2-D and 3-D mathematical models of the aggregate in the pavement, and a 2-D model which derives cross-sections of the aggregate from photographs of test cores, which can be used to examine the forces between the aggregate particles that would be generated by loads on the pavement (*figure 44*).



(a) Simple 2-D model of aggregate (b) simple 3-D model of aggregate (c) Complex 2-D model of aggregate

FIGURE 44 - ILLUSTRATION OF AGGREGATE MODELS USED IN THE LOT

The data inputs for the model are those parameters that the surface contractor can physically control during the manufacturing process. The results from the model predict the type of failure that occurs in the surface (adhesive or cohesive) and the number of vehicle passages required to cause that failure.

This provides a surfacing contractor with information on which physical properties should be changed to obtain a better structural performance. However, it is noted that there may be different compositions which provide improved performance. For different ageing and traffic loads, the model will predict a different ravelling performance.

Another important part is the probabilistic model which relates ravelling to the distribution of material constituents, production conditions (e.g. binder content, roller load, etc.) and service life conditions (those that the contractor cannot control, e.g. climate traffic load, etc.), based on a numerical analysis of an empirical database. The input to the model is information on some or all of the process conditions in the database relating to the surface in question. The model calculates the effect on lifetime of changes in these distributions or conditions.

The objective of the LOT is to stimulate the optimization of TPA without the need for long and expensive trial periods. It is intended that surfacing contractors will be able to use the LOT to assess their surface concepts in order to develop a TPA surface with a structural lifetime (in terms of the upper layer) that it is at least two years longer than that of the TPA currently in use on the Dutch highway network.

Information from a range of projects has been used in the development of the LOT including studies on the ageing of porous asphalt, microscopic analysis of core samples using CTscanning and plane sections, and studies into the characteristics of failed pavements, i.e. those at the end of their structural lifetime.

The Acoustic Optimisation Tool

In addition to the Lifetime Optimisation Tool described above, an Acoustic Optimisation Tool (AOT) has been developed for the general investigation and optimisation of the acoustic performance of low-noise surfaces (Kuijpers et al, 2007). However, the AOT is not specifically focused on two-layer porous asphalt, but on both current state-of-the-art on low-noise surfaces and concepts that are still in development such as poro-elastic (rubber) road surfaces.

The AOT has been developed based on an existing software model and is supported by an integral database of measurement data that has been collected not only from the test sections laid on public roads in the IPG but also on an extensive database of measurements taken on the purpose-built IPG test track facility at Kloosterzande,

which by the end of the IPG included test sections for 40 different surfaces, including dense surfaces, single- and two-layer porous asphalt, thin surfaces and elastic surfaces.

The user specifies a range of input parameters for the AOT model, based on the following acoustic parameters:

- 3-D surface texture profiles;
- Flow resistance of the road surface;
- Acoustic absorption spectrum for normal incidence;
- General tyre/traffic characteristics.

This input data can either be taken directly from the AOT database or entered by the user based on external measurement data or results from other prediction models. The outputs from the AOT are noise levels and spectra corresponding to the microphone positions used for statistical pass-by (SPB) and close-proximity (CPX) noise measurements.

The objective of the AOT is for surface contractors to be able to produce optimised surfaces by modification of characteristics such as surface texture, acoustic absorption (for porous surfaces) based on layer thickness and void content, and mechanical impedance, and for highway authorities to potentially use it to develop appropriate functional specifications (IPG, 2008).

Additional Initiatives

In conjunction with all the projects developed in Europe, some bilateral projects aimed at providing guidance and advice on transport noise reduction. For instance, DEUFRAKO project "*P2RN*" (Prediction and Propagation of Rolling Noise), was a Franco-German effort (2005–2008) aimed at developing optimized noise reducing road surface. This was a project in which BASt, Müller-BBM on the German side and the Laboratoire Central des Ponts et Chaussées (LCPC), INRETS, ENPC, Colas, and Eiffage-TP on the French side developed and validated models for the prediction of tyre-road noise emission, used several noise propagation models to predict the acoustical effect of low noise pavements in the far field of roads, and developed an original prototype of an optimised dense road surface.

PREDIT was a national research and innovation program conducted in France. This effort was supported by the ministries in charge of research, transports, industries, and environment, the Ademe and the Anvar. The objectives of this program included the following:

- to ensure the sustainable mobility of people and goods,
- to increase the security of transport systems, and

- to improve the environment and contribute to the objectives to reduce greenhouse effect gases.

QUIET TRAFFIC in Germany started in 1999 and is still active. The total project costs have reached more than EUR 35 million. The latest component of the program was called Leiser Strassenverkehr 2 - LeiStra2 and a third program is underway. Five subject areas were established under this project and included the following [Sandberg 2009]:

- effects on humans,
- low-noise road traffic (tyre-road interaction, noise at expansion joints),
- low-noise trains and tracks,
- low-noise transport aircraft, and
- common technologies and methodologies.

The abovementioned IPG in the Netherlands was a program titled "*Noise Innovation Programme for Road and Rail Traffic*" (Innovatie Programma Geluid - IPG) The Innovatieprogramma Geluid (IPG; Noise innovation programme), was established to help meet Dutch national targets for noise reduction from transport noise in a cost-effective way by delivering ready-to implement, affordable noise reduction measures, as well as undertaking work on noise reduction concepts that would require further work beyond the end of the IPG prior to implementation. (IPG Research Report Innovative mitigation measures for road traffic noise DVS-2008-18, Delft The Netherlands). The program ran from January 2002 until December 2007 (some parts extending into 2008). In the program other countries (Germany, Denmark) participated. The budget for the research part of the IPG programme had a total of EUR 54 million until its end in 2007/2008 and the overall budget for the IPG programme was about EUR 110 million. Additionally, there was a budget for implementation of the IPG findings. A forerunner to IPG was WnT, "*Roads to the future*", which developed and tested innovative solutions to quiet pavements; a few of them brought further into the IPG project.

The objectives of the IPG road traffic noise programme were defined in terms of short-term and long-term goals, as follows:

- **short-term goal**: To deliver noise mitigation measures which were cost-effective compared to existing measures and which could be implemented to reduce noise from the Dutch main traffic infrastructure at the end of the IPG.
- **long-term goal**: To demonstrate noise mitigation measures which would provide superior levels of noise reduction and which would be ready to be implement on the Dutch main traffic infrastructure a few years after the end of the IPG.

In order to achieve these goals, work has focussed mainly on the investigation and implementation of source-oriented mitigation measures such as low-noise pavements. However the use of innovative, cost-effective noise barriers has also addressed within the short-term goals of the programme. The work in these areas has been managed by Rijkswaterstaat Dienst Verkeer en Scheepvaart (Centre for Transport and Navigation, formerly known as Rijkswaterstaat Dienst Weg- en Waterbouwkunde (Road and Hydraulic Engineering Division). The activities within the IPG associated with these noise mitigation measures can be broadly categorised as follows:

- testing of measures in-situ at actual sites on the main Dutch traffic infrastructure;
- the improvement of existing products and technologies;
- applied scientific research to support and/or stimulate the implementation of these measures, products and technologies.

IPG focused on the improvement of two-layer porous asphalt to provide both better durability and better noise reduction. It also tested several new proprietary pavements of the so-called "*thin layer*" type. As a result of the IPG, the national policy in the Netherlands now includes a widespread application of two-layer porous asphalt on the national highway and motorway system. Such pavements are also sometimes used on local (urban) roads and streets, although the thin layers are more commonly applied in such areas. Besides technical developments enormous steps forward have been made in a better understanding of the failure degradation mechanisms of porous asphalt have been made. The modeling of the failure mechanism and the use of FEM techniques and advances test methods provided a better understanding of those mechanism. This will lead to new design concepts and criteria for a more durable porous asphalt. (Huurman M., "*Lifetime Optimisation Tool, LOT, Main Report*", Report 7-07-170-1, Delft University of Technology, the Netherlands, 2008).

The knowledge dissemination has been achieved through the preparation of formal guidelines and recommendations that have been adopted as part of national legislation and through the programme website which has addressed both the road traffic and railway elements of the IPG (www.innovatieprogrammageluid.nl).

In the United Kingdom, there are two active research projects, sponsored by the Highways Agency, that are investigating the acoustic properties of low noise surfaces. The objectives of the first project are to investigate noise, skid resistance, durability, whole life costs, resource use, laying times, and water runoff of multiple pavement types. The second project is looking at the acoustic performance of thin surfaces over time. It will run from October 2007 until January 2010 and will cover both new (<1 year old) and old (>5 years old) surfaces. Additionally, this project will trial the SILVIA classification methodology on several of the test sections [Sandberg 2009].

In Norway, a large project ran from 2004 to 2008 with the title "*Environmentally Friendly Road Surfaces*". The objective was to obtain a reduction in noise exposure along Norwegian roads and streets and to obtain a better air quality in urban areas [Sandberg 2009]. This was part of an attempt to reach a goal decided by the Government which was to reduce noise annoyance by 25% before the year 2010. The total budget for the project was about EUR 2.3 million including the pavement costs, which included the construction of 25 test surfaces and measurements on another 43 surfaces; the latter of which are conventional Norwegian road surfaces [Sandberg 2009].

In Finland, the HILJA was a project that ran from 2001 to 2004. It was coordinated by the Laboratory of Highway Engineering at Helsinki University of Technology (HUT), where most of the research work was done. The Automotive Laboratory of HUT, Suomen Akustiikkakeskus (Acoustic Centre of Finland) and the VTT Technical Research Centre of Finland were also working partners for that project. The objective was to encourage asphalt companies to develop silent asphalt products which would also offer good durability at a reasonable cost.

In Italy, studies were done already in 1990 that included the development of a pavement wearing course based on an expanded clay aggregate, either entirely or in smaller proportions. Continued work on this pavement type was conducted by Professor Canestrari at the Institute of Hydraulics and Transportation Infrastructures of the Università Politecnica delle Marche in Ancona [Sandberg 2009]. Italians consider that expanded clay surfaces not only reduce noise but also provide a surface with good strength in curves and at road intersections. Thus, they should be of interest in urban areas, although they presently seem to use them primarily for highway use. Several projects were developed over the years. Another project was started in 2010 (PRIN Project, Porous asphalt from porous asphalt) and is still active. One of the main intended results deals with assessing a better knowledge on surface properties of the recycled porous asphalt [PRIN 2008; Praticò et al, 2011]. The following main key-issues were addressed: mitigating the drawback of clogging and its related consequences (decay of acoustic and drainagebility performance over the time); preserving traditional (bearing properties, skid resistance) and premium (silentness, drainagebility) performance; recycling high percentages of RAP-from-PEM (where RAP stands for reclaimed asphalt pavement and PEM for porous European mix).

4.3 UNITED STATES OVERVIEW

In the United States, activities related to quiet pavements have been funded by three main sources: nationally via the Federal Highway Administration (FHWA) and the National Cooperative Highway Research Program (NCHRP), State Highway Agencies (SHAs), and the pavement industry (Sandberg et al, 2009). An overview of the activities performed by each group is provided in this section.

4.3.1 FHWA and NCHRP

The FHWA and NCHRP have conducted great efforts to study and implement quiet pavement technology in the United States. The FHWA Office of Pavement Technology has funded highway research programs to identify materials that can provide quiet pavements. Some other programs developed by the FHWA that relate to pavement technology include the Pavement Surface Characteristics and the Concrete Pavement Technology Program. Both programs have, at some extent, interacted with quiet pavement technologies.

The NCHRP has sponsored various research projects that relate to quiet pavements. Among these studies, NCHRP 1-44 focused on measuring tyre pavement noise at the source. New pavements were evaluated along with theirs noise mitigating characteristics. Study NCHRP 10-67 recommended appropriate methods for texturing concrete pavements for specific applications and ranges of climatic, site, and traffic conditions. Project NCHRP 10-76 is a currently active program scheduled to end in the summer of 2010 that evaluates pavement strategies and barriers for noise mitigation.

4.3.2 State Highway Agencies

A number of SHAs in the United States are conducting studies to promote the use of quiet pavements. In some cases, these studies have been formalized into either Quiet Pavement Pilot Programs (QPPP) or Quiet Pavement Research following the guidelines established by FHWA [Shrouds 2005]. Some of the activities conducted by these SHAs are summarized in this section.

California Department of Transportation

The California Department of Transportation (Caltrans) began formal quiet pavement research in 1998 with the application of a 1 inch-thick open-graded asphalt course (OGAC) overlay that was compared to the performance of an existing older dense-graded asphalt course (DGAC) surface. A 5.6-mile stretch of pavement was built along a high volume, multi-lane section of Interstate 80 near the city of Davis, in the State of California. From 1998 through 2009, time averaged noise levels have been measured three times per year on either side of the roadway at a reference distance 65-feet from the center of the outside lane of travel. Beginning in 2002, on-board sound intensity (OBSI) tyre/pavement noise measurements were added to the data acquisition program. The results through 2008 have been published in the Noise Control Engineering Journal [Lodico and Reyff 2009].

In 2002, Caltrans began another quiet pavement research project that monitored the initial and subsequent performance of five asphalt concrete overlays on State

Route LA 138. These sections have been monitored using a variety of methods including statistical passby (SPB) measurements [Rochat and Read 2009] and controlled passby (CPB) and OBSI measurements [Donavan 2009]. Other properties of these pavements including durability, permeability, and friction performance have also been documented [Ongel 2008].

In 2003, Caltrans began additional research on quieter PCC pavement textures on a newly constructed highway bypassing the town of Mojave in the State of California. Eight varieties of additional texturing were applied to three different initial textures of the test sections. The performance of these sections has been monitored through 2008 using primarily OBSI [Donavan 2009].

In other research test sections, Caltrans has used and documented the performance of quieter pavements used for reducing noise at neighbouring residents. This has included application of rubberized asphalt overlays [Donavan 2005, Pommerenck and Donavan 2009] and grinding of PCC surfaces [Donavan 2005]. Caltrans also sponsors research into the more complete performance of AC surfaces with the investigation of noise, acoustical absorption, durability, permeability, and friction performance on a statewide basis [Ongel 2008, Ongel 2007].

Arizona Department of Transportation

The Arizona Department of Transportation (ADOT) has been conducting research on the noise performance of pavements since the early 2000s prior to initial stages of their quiet pavements pilot program (QPPP) in 2003. The initial work investigated the performance of an asphalt rubber friction course (ARFC) relative to other "*off-the-self*" AC pavement designs for both noise and other pavement properties. Once selecting ARFC, ADOT investigated the acoustic longevity of this pavement type by measuring a large number of ARFC pavements in the state that have been applied as overlays in different years using on-board measuring techniques [Donavan and Scofield 2004]. ADOT also investigated three types of PCC texturing to determine the noise reducing potential of these options [Donavan and Scofield 2003]. Based on this information, ADOT commenced the Arizona QPPP with FHWA in which approximately 115-miles of PCC freeway were overlaid with ARFC with the agreement to monitor the acoustic performance of the overlay over its life cycle. This is being done on an ongoing basis using wayside, time-average traffic noise measurements and on-board tyre/pavement noise measurements [Reyff 2007], [Reyff and Donavan 2005].

Washington Department of Transportation

In 2006, the Washington State Department of Transportation (WSDOT) began research on the use of open graded friction courses (OGFC), asphalt-rubber asphalt concrete friction courses (AR-ACFC), and ACFC modified with Styrene Butadiene Styrene (SBS) relative to the WSDOT standard dense-graded hot mix asphalt (HMA) [Pierce 2009]. The investigations are being made at three locations

with the construction of the first sections in 2006, followed 2007, and lastly those to be constructed in 2009. The primary measurement method has been the use OBSI. The durability of quieter pavements is compared to the HMA pavements. In addition to the AC pavements, WSDOT is also investigating PCC with different textures at various locations throughout the state since 2004 [WSDOT website].

Colorado Department of Transportation

The State of Colorado in the United States conducted a study that looked at tyre-pavement noise levels generated by different pavement types. Results of testing were obtained to define the noise levels of selected highway sections within the state. A total of 18 concrete and asphalt pavements were tested and recommendations were made based on the results obtained.

The study found that the quietest hot mix asphalt (HMA) pavement was an open-graded friction course (OGFC) surface. It was also found that the age of the HMA has a great effect on the noise level of the pavement. For Portland cement concrete pavement (PCCP) it was observed that the noisiest pavement texture was an eleven year-old transversely tined pavement. Other PCCP textures tested included longitudinally tined concrete, ground concrete, and drag textures [Hanson and James 2004, Rasmussen 2008, Rasmussen 2009].

Colorado's DOT recommended that an implementation stage should consider the construction of test sections that would evaluate the effect of thickness and gradation on the noise characteristics of an OGFC wearing course.

Texas Department of Transportation

The State of Texas in the United States has been active in the research of quiet pavements. The initial research looked at tyre-pavement noise levels in selected pavements. A research study measured noise levels in fifteen different pavement types used in Texas. The study became with a test procedure that used a standard microphone to record noise levels at roadside and onboard the test vehicle within a few centimetres of the tyre of a towed trailer. This test procedure was designed to develop comparisons of pavements while keeping other variables constant [McNerney 2000].

Another project in Texas evaluated available technology for measuring pavement noise and recommended equipment, protocols and test sections to be evaluated in the state. Efforts were conducted by the University of Texas at Austin and the Texas Department of Transportation (TxDOT) to compare measuring equipments and to define testing needs [Trevino and Dossey 2006].

Minnesota Department of Transportation

The State of Minnesota in the United States has been studying quiet pavements since 1979. Then, in 1987 and 1995, subsequent studies were conducted in the

area. In all three projects one of the main focuses was a comparison between noise levels of hot mix asphalt (HMA) and PCCP. In the first project, OGFC was found to be quieter than conventional HMA, this was later confirmed by other studies conducted elsewhere.

Additionally, the Minnesota Department of Transportation (MnDOT) has participated in pooled fund and partner projects directed at solving local problems for the state and local agencies through research sponsored by the Local Road Research Board (LRRB). Among some initiatives conducted in Minnesota are the Investigation of High Performance (60 Year Design) Concrete Pavement, Unbonded Concrete Overlay, Permeable (HMA) Pavement Performance in Cold Regions, Pervious Concrete Pavement Study, PCC Surface Characteristics – Construction, and Concrete Pavement Optimization.

Florida Department of Transportation

In the early 2000s, the Florida Department of Transportation (FDOT) began quantifying the noise performance of pavements used in the state using close proximity (CPX) tyre/pavement noise measurements [Berrios 2004]. Additionally, data obtained by the University of Central Florida suggested that Florida's OGAC design was quieter than the average pavement used in the FHWA Transportation Noise Model (TNM) [Berrios 2006]. Based on this information, FDOT became interested in performing additional quiet pavement research to more fully document the performance of this pavement to consider applying for a QPPP. In 2006, FDOT began a three-phase project with this goal in mind. In the first phase, SPB measurements were made at 24 sites throughout the state along with OBSI measurements [Wayson 2008]. With the completion of these data in 2009, direction for remaining phases will be established and implemented subject to future funding availability.

Virginia Department of Transportation

Different studies have been conducted in the State of Virginia in the United States. Due to the high cost of noise barriers, two other alternatives have been used to reduce traffic noise levels. The first one is achieved by using certain vegetation on the roadside when possible. The other strategy is using quiet pavements, which with adequate selection can achieve considerable noise reductions caused by tyre-pavement interaction.

A current project titled "*A Functionally Optimized Hot-Mix Asphalt Wearing Course*" will look at the design, production and placement of a new-generation open-graded friction course. Noise measurements will be conducted and other properties like safety, ride quality, splash and spray, wet night, and pavement marker visibility will be evaluated [Lee 2008].

Pavement Industry

Another important force looking at quiet pavement technology is the pavement industry. Mainly, the American Concrete Pavement Association (ACPA) at the national and chapter levels and the National Center for Asphalt Technology (NCAT) at Auburn University have shown great interest on the benefits of quiet pavements.

American Concrete Pavement Association (ACPA)

The American Concrete Pavement Association (ACPA) has been very active promoting quiet concrete pavements. ACPA's role has been more in the form of newsletters, bulletins and research and technology updates that summarize research findings not only in the United States, but from around the world that relate to pavement noise improvements. The information issued by ACPA is very well accepted by all professionals and practitioners in the concrete pavement area.

National Center for Asphalt Technology (NCAT)

Studies have been conducted at the NCAT test track, where different pavement materials have been used in single and double layers for noise reduction purposes. Sound pressure and intensity was evaluated using the NCAT close proximity (CPX) acoustic trailer at speeds of 45 and 60 mph. Likewise, sound intensity testing of the low noise sections was also done using a triple trailer truck. According to the results obtained from the tests double layer structures with fine open-graded surfacing were the best performing of all tested [de Fortier Smit and Waller 2007].

CONCLUSIONS

Based on the analyses the following key conclusions can be drawn.

There is a number of national/international projects and research programs looking at reducing the physical impacts of environmental noise, developing innovative reduction measures and/or assessment schemes and/or reducing costs.

There is a strong focus on source-related mitigation measures and an increasing emphasis on cost-effectiveness. Low noise road surfaces are one of these cost-effective measures and authorities have been supporting their development for many years.

Many solutions exist on the market, adapted to high speed road or to urban conditions. Among them, many proprietary products have appeared on the market in the recent years.

There are several ongoing research projects aimed at developing noise optimised road surfaces and it seems that a significant step in noise reduction can still be expected in the future.

Fast acoustic ageing of low noise road surfaces can be a hindrance to their use and development. However, knowledge on ageing effects is still insufficient. Therefore, there is a need to better understand the process, the cause, and to optimise the maintenance techniques for durable low noise surfaces.

It still remains crucial that knowledge and experiences are shared in order to permit that innovations and products developed for use within specific member states may be equally beneficial/valid for use in a wider area.

There is an urgent need for the standardisation of assessment methods for road surface noise efficiency and acoustic labelling. This would facilitate the sharing of knowledge on low noise road surfaces, the comparison of products and this would help road owners to achieve the selection of the appropriate products.

Due to the evolution of traffic spectrum, it becomes more and more relevant to include truck tyre noise in mitigation research.

Infrastructure sustainability is growing in interest, in the sense of a development that meets the needs of the present without compromising the ability of future generations to meet their own needs. The fact could imply the opportunity of considering, in future projects, the combination of noise, air pollution and other environmental issues. In particular with what concerns road surface characteristics, the combined study of noise, rolling resistance and shear resistance properties would be of a great practical value.

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