The Development in the use of Porous Asphalts in Europe

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Synopsis

Since their first applications, porous asphalts soon showed their great potential as concerns safety and environment issues.

Thanks to their water drainage ability, in wet conditions they perform better than traditional hot mix asphalts as regards safety and comfort. Moreover, the high porosity gives them excellent acoustical properties. These factors determined their great success, especially in Europe, and justified the great efforts of research in order to give a solution to the problems arisen in the early applications.

In these pages, at first a general short description of the advantages/disadvantages and the history of these asphalts is presented. Afterwards, the main issues related to the durability and effectiveness of these pavements is given as arose since 20 years of use. Various solutions are given based on the European experiences. Finally, the main actual research lines to optimise and to improve the reliability of porous asphalts are outlined.

THE DEVELOPMENT IN THE USE OF POROUS ASPHALTS IN EUROPE*

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In the last 20 years porous asphalts have become largely diffused in Europe because of their ability of draining surface waters and reducing tire/road noise. Figure 1 represents the current diffusion of porous asphalt friction courses in some European countries.

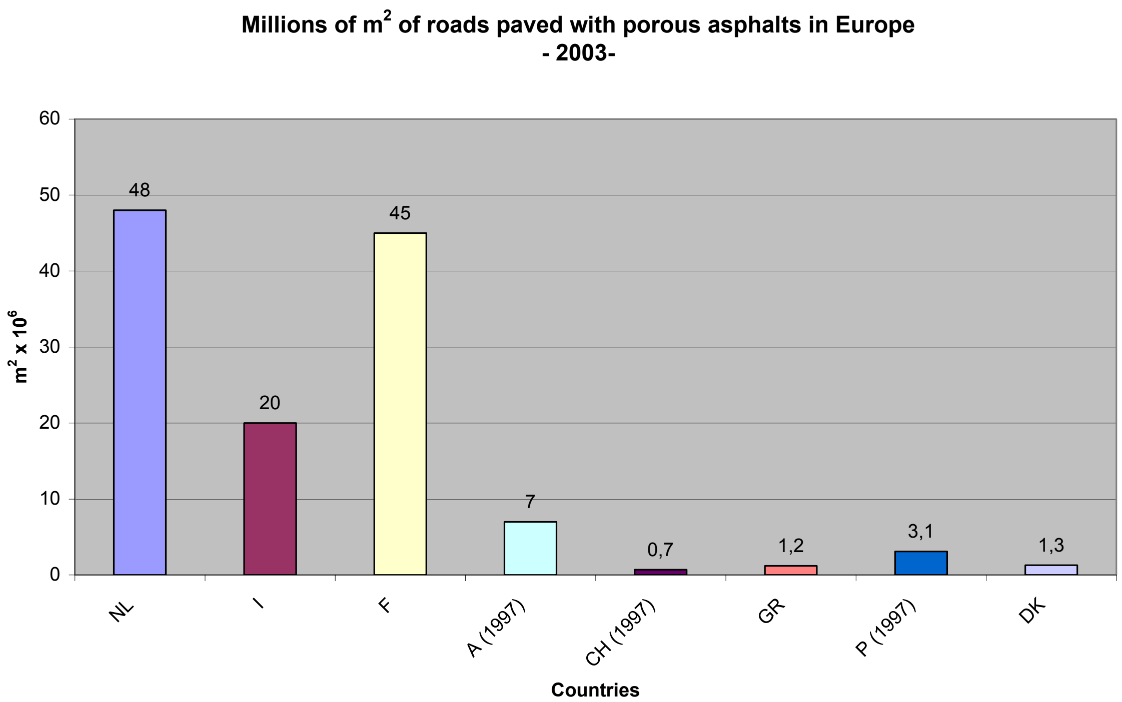

Figure 1: Diffusion of porous asphalts in some European countries

The large diffusion of these materials is due to the numerous advantages that they offer over the traditional bituminous concretes, against disadvantages which are basically economic ones and that, with the practice, are increasingly being resolved.

ADVANTAGES AND DISAVANTAGES

The advantages observed in 20 years of practice are here briefly summarized (More details on this subject can be found in (*Lefebvre, 1993*):

- Aquaplaning: porous pavements reduce and can completely eliminate surface runoff dramatically preventing the occurrence of this phenomenon;
- Splash & spray: the absence of surface runoff has the further consequence of eliminating spray which is normally thrown up on the side and behind tires when driving along traditional wet wear courses;
- Adherence: even when not in limit conditions of aquaplaning, the presence of water on the pavement reduces the adherence coefficient. In porous pavements, at high speeds, this reduction is less marked than traditional bituminous concretes. The same cannot be said as regards the low

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speeds for which their behaviour can, however, be compared;

- Reflection of light: porous pavements reflect light in a diffused manner unlike traditional surfaces which can however behave like mirrors reflecting light directly and more intensely;
- Comfort of driving: the improved driving conditions compared to traditional courses mainly come from both the absence of spray (which "warns" the driver) and the reduction of noise inside the vehicle;
- Increase in mean speeds: in the presence of wet pavements drivers tend to slow down; the "dry" aspect of porous pavements reduces this phenomenon contributing to increase the capacity of the road, thus reducing traffic congestion;
- Rutting: the strong discontinuity characterising the aggregate gradation of porous asphalts makes them particularly resistant to rutting;
- Noise reduction: the noise absorption ability of porous pavements is now well known; because of their high void content they can soften both moving and mechanical noises of the vehicle (which otherwise are reflected by traditional pavements) (*Delanne, 1989, Descornet and Luminari, 2000*).

Against these advantages, the disadvantages can be summarised as follows:

- High costs: this refers to the cost of both preparing and laying as well as managing; the good success of a porous bituminous concrete is connected to the use of aggregates with excellent wear resistance; moreover, the preservation of its functionality largely depends on frequent maintenance operations; thus, these bituminous concretes have 50% higher overall costs (up to 400% depending on the availability on site of responding materials).
- Excessive speed: it has been said that, during rain precipitations, the "dry" look of porous pavements gives to drivers a sense of safety inducing them to keep up a high speed; on the one hand, this increases the capacity of the road, but on the other hand it increases the risk of accidents: in wet conditions the available adherence coefficient is much less than it appears to drivers.
- clogging: the main characteristic of porous asphalts is the high percentage of voids. Over the time the void content dramatically falls down. The rate of clogging depends on the traffic and on the environmental conditions. Clogging causes the reduction of both the hydraulic conductivity and noise absorbing abilities. In order to remain effective, porous pavements require constant cleaning, generally carried out with special self-propelled equipment (*Lefebvre, 1989 - Pariat, 1992 – Weiringer, 1993*).
- Winter use: if compared to the traditional dense graded friction courses, porous asphalts require greater quantities of salt and increased maintenance operations. Moreover they show high rate of consumption in presence of car chains and snow tires.
- Ravelling: main damage affecting porous asphalts is ravelling, which occurs because of the discontinuous grading of the mix.
- Initial skid resistance: new porous asphalts have low skid resistance. During emergency braking (locked wheels) the braking distance is the 20-40% longer than on traditional mixes. This is due to the thick asphalt film that covers surface aggregates reducing their microtexiture. Thanks to the polishing effect of traffic, this phenomenon disappears after a period varying from 3-6 months (when pure bitumen are used) up to 18 months (when modified bitumen are used).

The solution to these problems has coincided with a greater dissemination of the porous asphalts.

SOME HISTORY

First tentative application of porous asphalt was in UK in 1967 (*Bowskill and Colwill, 1997*). The mix was done with a 20 mm max size aggregate and 4.5 % bitumen modified with natural rubber. Even if its porosity soon decreased, it remained in service for about 15 years and at that time its noise absorption properties were already observed. After that date other trial sections (1970, 1975 and 1983) were laid in order to optimise combinations of aggregate gradations and binders. The first trials on large scale took place starting from 1984 on Burton by-pass where 22 sections (1984/1987) were laid in order to evaluate the effects of different binders and binder contents. Other trials were made in 1991 (7 sections) using different aggregate gradations chosen among those usually used in some European countries (UK, Belgium, The Netherlands and Sweden). The results of all these trials were further collected and used to draw some practical advice on design (*Nicholls, 1997*). In spite of these great research efforts, in UK porous asphalts never become really popular since the use of Hot Rolled Asphalt is preferred.

But UK was not the only country that experimented porous asphalts at the end of seventies - early eighties. Similar trials were made also in France (1976), Switzerland (1979), Belgium (1979), The Netherlands (1979), Germany (1978), Spain (1980) and Italy (1984). In that period in these countries (and in many others) were carried out studies in order to evaluate the effectiveness of these “new” pavements and to optimise the mixes.
As a consequence of these early trials, in many countries the use of porous asphalts become widespread. It is the case of France, Belgium, Italy and Holland that soon started to largely use these friction courses. In The Netherlands since 1990 it was decided that all the national motorway network should be paved with porous asphalts within 2010. In other countries, such as in Germany, Switzerland, UK and Austria, after an initial interest, the use of these pavements never took off and their use is now basically limited to those cases where their noise-reduction properties are needed. The poor diffusion of porous asphalts in these countries is due principally to their environmental conditions (principally problems in winter maintenance) and to the presence of other competing surfacing asphalt concretes (e.g. Splitmastix asphalt and Hot rolled asphalt) in their tradition.

By the way, since their introduction, many research efforts were done in order to solve the problems listed above.
Mainly they are linked to clogging, winter maintenance, ravelling and early low skid resistance. The solution to these problems is almost difficult, because the remedy for one of them often causes the worsening of another one.
Classic is the case of clogging. It is commonly accepted that the greater is the maximum particle size, the larger are the pores and thus the less is the tendency to clogging. But, on the other hand, the enlargement of pores causes the drop of acoustical properties, more difficulties in winter maintenance, less resistance to ravelling and, if modified binder are used to enhance mechanical resistances, longer low values of early skid resistance.
It is therefore evident that the solution to many of porous asphalt’s problems is in the optimisation of mixes in order to achieve a compromise giving “the less evil” with regard to the particular environmental conditions in which the porous asphalt should be laid.

The different environmental conditions are one of the reasons because there is no unity among European countries in this research field. The other, and most important, is the different “road culture” that each country developed since first asphalt concrete applications.

The upcoming European Standard prEN 13108-7 “Bituminous Mixtures – Material Specification – Part 7: Porous Asphalts (PA)” reflects this situation; it is very little restrictive as it should satisfy as much as possible the needs of all the European Union countries.

Nevertheless, since their first applications, porous pavements technique in Europe has greatly developed and porous asphalts of second and third generation are widespread in most of European countries; they are much more effective than those of early applications especially with regard to noise-reduction properties. The recent research efforts in this direction took place with the growing in the European Union of the sensitisation towards environmental problems. Porous asphalts, with their acoustic properties, were soon identified as a potential solution for the abatement of the level of noise coming from roads.

SPECIFICATIONS AND COMPOSITION – MIX DESIGN

Specifications and Composition

The high void content of these asphalt concretes mainly depends on the adoption of largely discontinuous aggregate grading, characterised by percentages of coarse aggregate usually ranging between 80% and 90%. This fact gives to the mix stability problems. In dense graded mixtures most of the mechanical resistance is due to the aggregate skeleton: the more continuous is the gradation, the more are the contact points among particles and the less is the contact pressure. In porous asphalts, because of their particular aggregate gradation, the points of contact among particles are dramatically reduced and, thus, the load transfer acts on a smaller surface; it means that each grain is loaded with increased pressures. Mechanical resistance of such mix is therefore reduced.
This is one of the reasons why aggregate should have good mechanic characteristics (the other, regarding skid resistance, will be discussed further in the paper). As for this matter standards of

various countries typically ask for crushed coarse aggregate with low flakiness and elongation index (typically less than 0.15 ÷ 0.25), Polished Stone Values more or equal to 0.50 ÷ 0.55 and Los Angeles Index less or equal to 0.15 (e.g. France, Switzerland, Portugal, Germany, Netherlands and Belgium). In other countries, because of the unavailability of good materials, standards are less severe. It is the case of Italy where Autostrade (the major motorway concessionary) in its standards asks for PSV not less than 0.40 and Los Angeles Index no more than 0.25 (limestone cases).
As for binders and fillers, there is not a particular trend. Each country has its own specifications according to their experiences and to the availability of materials.
Table 1. reports typical mix compositions of several countries, while in table 2 typical aggregate gradations used by the Italian Autostrade are represented.

Table 1: Some typical mix composition of some European countries

FRANCE	Coarse aggregate 6/10	85-90%
	Sand	8-12%
	Filler	1-4%
	Pure bitumen*	4.4 ÷ 4.8%
	Modified bitumen*	4.7-5.2%
	Rubber modified bitumen*	5.7 – 6.1%
	Fabric modified bitumen*	5.1 - 5.5%
BELGIUM	Coarse aggregate 7/14	83%
	Sand	12%
	Filler	5%
	Bitumen 80/100	4.0 - 5.0%
	Rubber modified bitumen	5.5 - 6.5%
GERMANY	Corse aggregate 5/11	75-88%
	Fine aggregate 2/5	2 -15%
	Filler	4-6%
	Bitumen	5.3-6.8%
THE NETHERLANDS	Coarse aggregate 6/16	85%
	Sand	10.5%
	Filler	4.5%
	Bitumen 80/100	4.5%
UK	Coarse aggregate 3/10	82-88%
	Sand	6-15%
	Filler (minimum 2% of hydrated lime)	3-6%
	Modified Bitumen (100/200 pen)	3-5%
AUSTRIA	Coarse aggregate 8/11	80-85%
	Sand	10-16%
	Filler	4-8%
	Modified bitumen	≥ 5.2%

* referred to an aggregate density of 2.65 g/cm^3.

Table 2: Autostrade mix composition for typical porous asphalt friction courses.

Sieve mm	Limestone PA (% passing)	Micro PA (% passing)
20	100	-
15	80 – 100	-
10	15 – 35	100
5	5 – 20	80 – 95
2	4 – 10	4-18
0.4	4 – 8	4– 10
0.18	4 – 8	4 – 8
0.075	4 – 8	4 – 6
Bitumen	5.0-6.0%	5.0-6.0%

Mix compositions are typically 0/11-16 mm with discontinuity ranging between 2 and 7 mm. Maximum particle size varies considerably, going from the 10/11 mm typical for France, Germany, UK and Austria and the 15/16 mm of Italy, Netherlands and Belgium. This reflects the different philosophy adopted in these countries in the use of porous asphalts. The greater is the maximum particle size the more is the durability of the pavement in terms of clogging. On the other side, the smallest is the maximum particle size, the highest are acoustical, friction and mechanical performances.
As regards void contents, specifications never ask for less than the 20%. In the upcoming European Standard void contents ranging from 14% to 30% are considered. In some countries such as Switzerland (*Dumont, 1997*) and France, it is also required a minimum percentage of connected voids in order to ensure a good water drainage. Typically the connected void content is the 80-90% of total void content (*Ganga et al, 1997*).
As regards the draining requirements, they vary considerably depending on the referring aggregate gradation. The European Standard provides for a range between $0.1\text{x}10^{-3}$ to $4.0\text{x}10^{-3}$ m/s, both for horizontal and vertical permeability.
Finally the thickness of layers typically are 3-5 cm.

Mix design

Porous asphalt mix design is based on the control of void content, mechanical resistance and, in some cases, of binder drainage.
In France it is based on the use of gyratory compactor to verify that void meets the requirements of the specification and the use of Duriez test to verify the resistance to the effects of water. No other mechanical tests are provided, even if some companies perform also the Cantabro test in order to evaluate the resistance to ravelling. No tests are standardised as regard the optimisation of binder content.
On the contrary, in Belgium the exact binder content is calculated using Cantabro test (*Centre de Recherches Routieres, 1997*). The method consists in representing the wear, measured in terms of loss of percentage weight, as a function of the percentage of bitumen. Thus, a curve with an approximately hyperbolic trend is obtained (see fig. 2): as the percentage of bitumen increases, the loss in weight falls, less and less rapidly until it reaches a percentage of asphalt above which there are no significant variations in weight loss; this value is usually made corresponding to the optimal percentage of bitumen as long as good cohesion of the bituminous concrete is ensured.

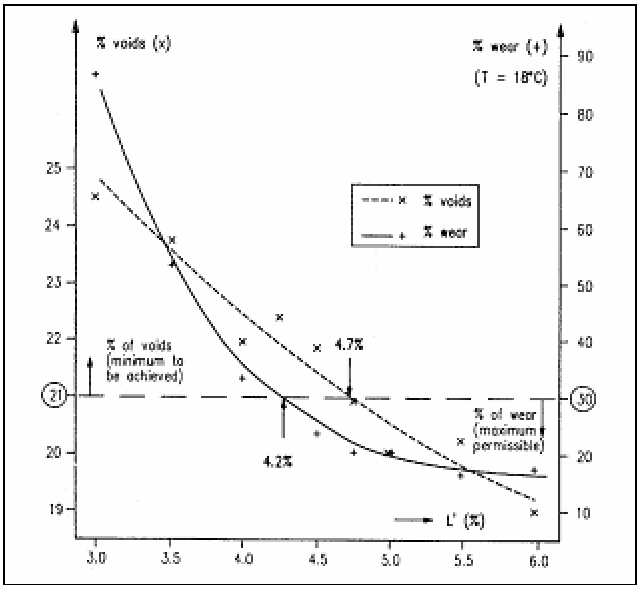

Figure 2: Example of porous asphalt mix design using Cantabro test.

Figure 2 reports a diagram of this design method (*Lefebvre, 1993*): the continue curve refers to the loss of weight due to wear while the dotted curve represents the percentage of voids, both expressed as a function of the percentage of binder. The content of binder is determined within the values that simultaneously verify the requested minimum void content and maximum loss in weight due to abrasion. The Belgian standard also provides for the Schellenberger test to make sure that the best quantity of bitumen so determined does not cause the flow-back of the binder during the storage and transport phases. In some cases the Cantabro test is also performed in wet conditions in order to evaluate the resistance to water of the mixes.

The design method based on Cantabro test is largely diffusing in Europe because of its simplicity of execution and the soundness of the results. About the latter point some doubt arose in France, where some researchers stated that "the result of these tests are considerably improved by the use of polymer-modified or fibre-modified bitumen, whereas our 8 years of experience has not indicated that porous asphalt which contains unmodified binders is more susceptible to this type of damage (ravelling) than that containing modified binders" (*Bonnot, 1997*). This is a point that needs further investigations since in other experiments, such as in Burton by-pass trials discussed above, seem to give different results. As concerning this matter the results of a recent Dutch research on the effects of the bituminous binders to the resistance to ravelling are interesting. The researchers found that polymer modification has beneficial effects on the resistance to short term ravelling when this damage occurs at low and high temperatures. At the temperatures ranging between 4°C and 20 °C it does not seem that there are differences if a modified bitumen is used (whether elastomer or plastomer) (*Molenaar and Molenaar, 2000*).

By the way, Cantabro test is largely used in nearly all the European countries, especially in Spain, where the test was set up in early eighties.

As for in France, in Italy Autostrade (*Centro Studi e Ricerche, 2001*) prescribes a mix design based on the use of gyratory compactor in order to achieve the required void contents, while the Indirect Tension Test is preferred in order to verify the mechanical characteristics of the mix. The design values of void contents required by Autostrade are in table 3.

Table 3: Design values of void content required by Autostrade

Gyrations	**Limestone PA (minimum void content)**	**Micro PA (minimum void content)**
10	≥ 28	≥ 30
50	≥ 23 (design value)	≥ 25 (design value)
130	≥ 20	≥ 22

FUNCTIONAL PROPERTIES

Water drainage

Permeability is an important characteristic of porous asphalts. The idea of discharging rain water within the friction course was the main aim when porous asphalts were introduced in road practice. But soon after first trials, it was evident that satisfying levels of hydraulic conductivity were hard to maintain over time. In fact, soon after the laid of a porous friction course, debris and dusts start to settle into the pores and hydraulic conductivity begins to drop. In many cases the rate of clogging is so fast that after one year, hydraulic conductivity is halved. Clogging is therefore a great problem for porous asphalts.

Aggregate gradation plays a fundamental role in hydraulic conductivity of porous pavements and on its preservation over time. Greater particle size, gap grading and low sand contents favourite a good initial permeability as well as a good resistance to clogging.

Other expedients to favourite a good drainage over time can be summarised as follow:

- To lay porous asphalts at least 4/5 cm thick.
- To ensure an adequate velocity to discharging water in order to limit dusts settlement. It can be obtained:
    - by ensuring an initial void content at least of 20%;
    - by giving an adequate cross slope to the pavement (about 2.5%). If this is not possible, it could be useful to dispose subdrains in order to enhance drainage capacity (see fig. 3) ;
    - by disposing transverse subdrains in presence of more than two lanes carriageways. In this matter interesting is the Portuguese experience. They use to execute 8 mm groves, 6/8 m spaced, prior to laying the mix (*Luis, 1997*).
    - by maintaining free flow at road edges. Road edges should have well studied shapes and they should be always clean. Figure 4 shows some typical edge arrangements.
- Traffic (especially when it is fast) helps the prevention of clogging because of the pumping effect of tires. Thus porous asphalts should not be laid on untrafficked roads.
- Avoid the placement of such an asphalt in places subjected to soling: neither the environment nor the traffic should contribute large amount of extraneous materials.

Because of these two last issues currently there is the tendency to avoid the use of porous asphalts on rural roads and urban areas.

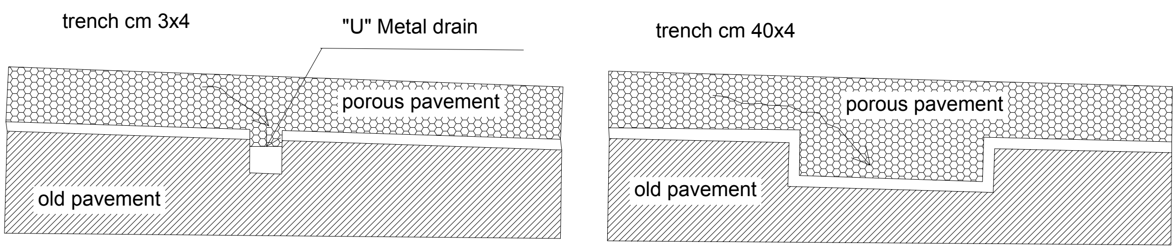

Figure 3: Example of transverse subdrains.

Another expedient (not mentioned above) is to seal the untrafficked lanes (especially shoulders) for a depth of 1 cm from the top. In this way the top of the pavement is impermeable to dirt intrusions while at the same time a 3-4 cm thick porous layer is left free for the filtration of water coming from the other lanes. This technique has been successfully used in some countries as Belgium, France and The Netherlands (*Brosseaud, 1997 – Colwill, 1997*).

In order to fight against clogging, special cleaning equipment was developed. It is a self propelled machine that, while going forward, injects water into the pores at the front and sucks it on the rear (see figure 5a, b). But after some years of use of these machines, some doubt arose on their effectiveness.

At first it must be stated that their use should be a preventive measure and not a curative one, since clogged porous asphalts are quite impossible to be cleaned. Thus, shoulders and untrafficked lanes should be cleaned at least once a year. Moreover, the cleaning procedure requires more than one pass (typically 2 or 3) to be really effective. It means that costs are high both in terms of money and time.

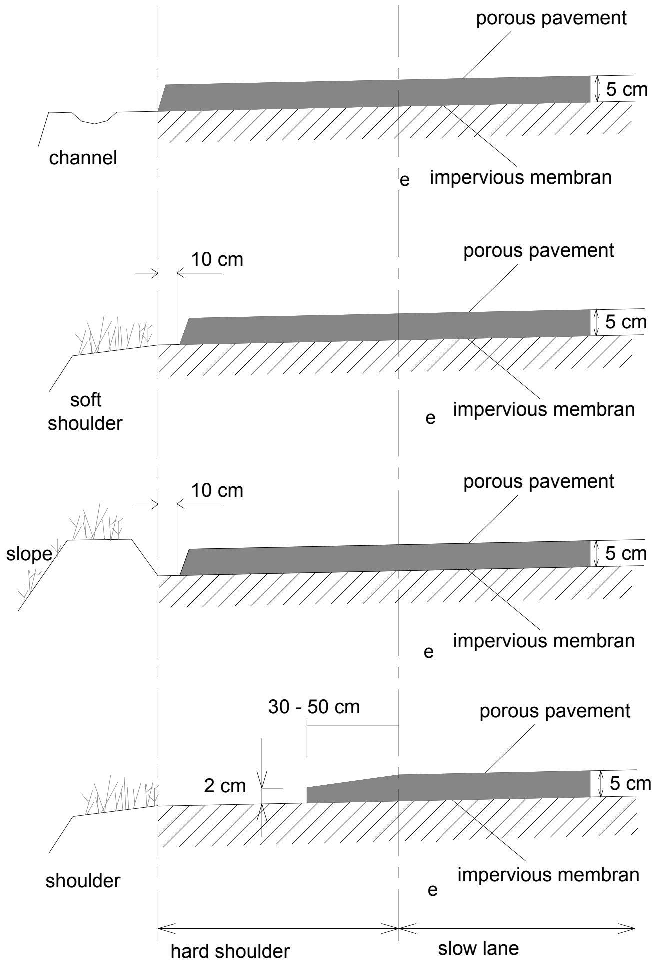

Figure 4: Typical examples of porous pavement edge arrangements.

Figure 5a, b: View of a cleaning machine (a) with a detail of the cleaning device (b) (Sakai, 2004).

Moreover, it was also stated that the cleaning effect of this procedure is effective only for the upper 1-2 cm of the porous layer. Its lower part is not interested by the cleaning. Nor the increasing of the water jet pressure represents a solution as it would compact more and more the intruded particles into the

pavement. The best solution should be to sprinkle the pavement, leave water acting for some time and then sucking the "juice". But this procedure requires too much time.
For all these reasons some Agencies prefer to make periodical resurfacing of the pavements instead of cleaning them.
As for the thickness of the pavement, it was said above that in European practice it is typically of 4-5 cm. Nevertheless this value is due to experience and not to a specific design criterion. Recently such a criterion was developed in Italy (*Ranieri, 2002*). It is based on the use of the chart reported in figure 6. Given the design rainfall rate (I), the geometric characteristics of the carriageway (slope - i - and width - L -) and the Darcy's permeability k_D of the porous asphalt, the chart provides the minimum thickness (H_{max}) of the porous course so that rain water always flows within it.

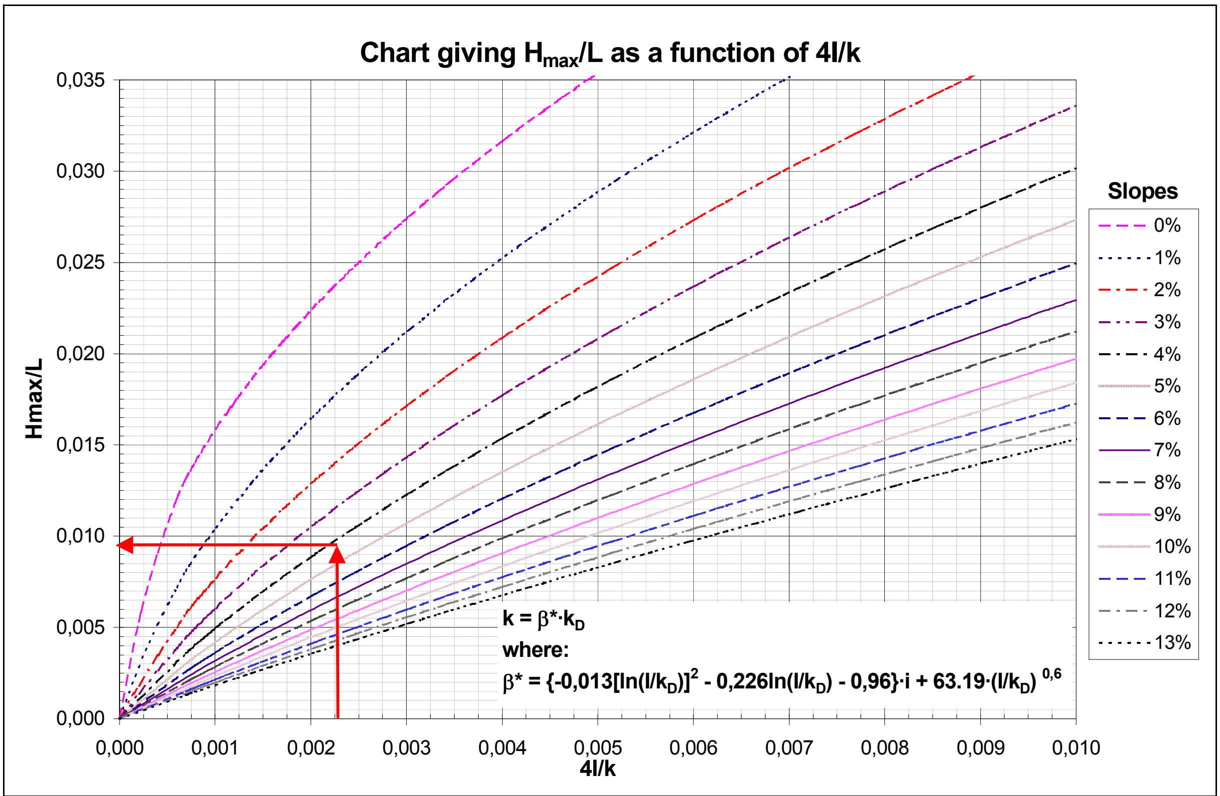

Figure 6: Example of use of the chart giving the values of Hmax/L as a function of the ratio 4·(I/k).

Durability

Porous asphalts have excellent resistance to rutting, even under very heavy traffic. Average increase in rut depth is typically less than 0.5 mm per year.
Their typical life is about 10 years. The most common damage that afflicts this type of asphalts is ravelling due to the rapid oxidation of binders.
From structural point of view, they are capable of less strengths if compared to traditional dense graded asphalts. As they are usually used as friction courses, this reduced strength is not really important for design purposes. However, to allow for this reduction, the Dutch use to express the strength of porous asphalts by the equivalence factor (*Swart, 1997*). It is defined as the ratio of the thickness of the course aggregate of dense and porous asphalt to be laid to give the same structural effect. In The Netherlands they use a factor 0.75.

Skid Resistance

Surface characteristics of the wearing courses are the main factors influencing road safety (apart from road configuration and related aspects) especially in adverse weather conditions. Porous asphalts have been primarily developed to improve road safety. Under bad weather conditions their high water-drainage capacity ensures a drastic reduction of water film thickness on the pavement (or its total

elimination) so that friction is enhanced and risks of aquaplaning are strongly reduced. Moreover, the absence of water on the pavement reduces splash and spray which means that driver's visibility is strongly improved.
No matter on these beneficial effects.

As for skid resistance in dry conditions, they also give high friction values. For medium and high speed values they perform better than traditional friction courses while at low speeds their skid performance are comparable to those of the other friction courses.
The main factors that influence skid resistance are:

- the aggregate Stone Polished Value (PSV): this is particularly important as the porous asphalts' microtexture largely depends on the aggregate microrugosity. This result is confirmed by French studies (*Bonnot, 1997*) in which a survey on skid resistance measured over time on several trial sections paved with aggregate with different PSV values (ranging between 0.50 and 0.60), showed that the lower is the PSV, the lower are the values over time of the Breaking Friction Coefficient (BFC – range values: 0.49 – 0.53).
- maximum particle size: for porous pavements skid resistance increases at all speeds the smaller is the maximum particle size of the aggregate.

One great problem that afflicts porous friction courses is their initial low skid resistance at all speeds. It is the result of the thick layer of binder which coats surface particles. As long as the traffic does not remove the binder from the particles, skid resistance remains low. This process can need a period ranging about from 3 months up to 18 months, during which the level of road safety is dramatically reduced. This time depends principally on traffic characteristics and on binder types. Higher traffic volumes reduce it. Modified bitumen extends it (typically 3-6 months for pure bitumen and 12-18 months for modified bitumen).
In order to solve this problem some trials were done by applying solvents to remove bitumen from the surface. But this policy is not powerful because of environmental and health reasons as well as the high costs. Another solution was tried by spreading and rolling some crushed sand (about $300g/m^2$) over the still warm porous friction course. French and Dutch experiences with this method showed contradictory results. However it is sure that the permeability of the pavement decreases of about the 20% after this treatment. Another method tested in The Netherlands consists in subjecting the pavement to a high pressure water jet so to polish surface particles. Also this method seems to be ineffective since it has strong negative effects on the operative life of the pavement.
Further researches are therefore needed on this matter. Currently the best safety feature to contrast the problem is to place road signals to warn drivers (*Van der Zwan, 1997*)!

Acoustical properties

Porous asphalts can reduce rolling noise levels drastically. This property is due to the concomitance of three effects (*Bonnot, 1997*):

1. during compaction, surface particles of porous asphalts are pressed flat. It means that low frequency noise generated by the impact between particles and tires is reduced.
2. As this material is porous, the emission of high frequency noise produced by the compression and decompression of the air retained between tire and pavement is drastically reduced.
3. The pavement porosity reduces the acoustic horn effect which amplifies noises in the rear and front part of the contact area tire/pavement.

In comparison with normal dense graded friction courses, traditional porous asphalts can reduce noise emissions of about 2-3 dB(A). But not all the types of porous pavement produce the same noise reduction. Noise levels depend on three main factors:

- maximum aggregate size, which acts on the wideness of pores: the larger they are the less is noise absorption;
- void content: low porosity means low noise absorption;
- layer thickness: traditional 4 cm thick porous layer act mostly on high frequency emissions. Getting the layer thicker, low frequencies are absorbed too. This is important because low frequencies (which are mostly produced by heavy vehicles) are those that propagate over great distances.

So, tire/pavement noise increase with the increasing of the maximum aggregate size. It is in oppositions with both permeability and clogging prevention needs since they call for larger pores and high void contents.

A solution to these problems seems to be the development of the new double layer porous asphalts which were introduced firstly in The Netherlands at the beginning of nineties. This kind of pavements will be discussed further in the paper.

WINTER MAINTENANCE

In winter time porous asphalts show more slipperiness than traditional asphalts. Because of their porosity they ask for some special requirements. Three are the main effects that can be observed:

- porous asphalts are about 1-2 °C colder then dense graded asphalts. Thus wet sections freeze quicker and defrosting takes longer. To prevent this kind of slipperiness preventive spreading of wet salt is needed. Because of their porosity, a grater quantity of salt is necessary.
- In presence of slush, porous asphalts perform worse than dense asphalts. This because slush is first pushed into the pores and then comes up again. It means that salt should be spread little by little in more passes to avoid freezing.
- Under certain conditions of humidity and temperature, moisture can freeze and precipitate into the pavement. This is extremely dangerous as the phenomenon is sudden and does not give any warning to the driver. Even in this case for porous asphalts more quantities of salt are needed.

In all the cases above, the solution of the problem could be the preventive spreading of salt (only salt because other materials, such as sand and grit, may clog the pores). But experience demonstrated that for porous pavements it is almost ineffective as salt falls into the pores. To enhance the effectiveness of preventive salting, large quantities of wet salt should be spread (Camomilla et al., 2003), preferably in several application with little quantities than in a single pass with large quantities.
Thus, winter maintenance of porous friction courses needs more attention than dense friction courses: frequent patrols, close monitoring of weather conditions and improved logistic organisation are strongly recommended in order to ensure a safe winter service.

Finally, it should be highlighted the destructive effects of car chains. As stated before, porous asphalts have a structural weakness to ravelling. The extensive use of chains lead to the rapid consumption of the pavement.

SAFETY

Safety improvement was the first aim for the introduction of porous asphalts in the practice.
Statistical data after 20 year of use, seem to say that this is not true. Even if some reduction of accidents have been observed in wet conditions, on the contrary in dry conditions some increasing of accidents were observed.
It may be due to the safe aspect that these friction courses have on drivers which are induced to increase their confidence with the road and to elevate the speed. This seems to be confirmed by some surveys that stated the general satisfaction of road users with this type of wearing courses. A further confirmation comes from other investigations that indicate a somewhat higher traffic capacity on porous wearing courses.

POROUS ASPHALTS AS RIGID PAVEMENTS OVERLAYS

As regards this matter, there are some contrasting experiences. According to the French experience reported by Y. Brosseaud (*Brosseaud, 1997*), the use of porous asphalts as overlays for rigid pavements should be avoided. It presents several problems concerning both reflective cracks in correspondence of joints and water infiltration into the pavement. On this matter in the UK in 1994, an experiment was done by overlaying a rigid pavement originally constructed with 5 m bays. The first years in service of this trial section showed that “reflective cracks only occurred in relatively limited locations in the first two years of trafficking and the cracks that have emerged in fours years of monitoring have not spread in service” (*Mercer and Nicholls, 1999*). Italian experience on this matter is essentially due to Autostrade that has laid on its motorways large quantities of porous asphalts as overlays of continuously reinforced rigid pavements. These constructions did not show particular problems over time. However, it must be highlighted that the rigid pavements we are speaking about, are continuously reinforced ones.

DEVELOPMENTS

Studies and researchers on porous asphalts are going on. Because of the problems mentioned above, many research efforts are being made toward the development of new porous pavements which can combine high performances in draining, noise absorption, skid and clogging resistances. On this matter, in France a new 0/6 graded, 4 cm thick, porous wearing course is in advanced stage of development. The aim of this mix is to achieve high void contents with a reduced maximum particle size. Another development is represented by the new double layer porous asphalts which were introduced in The Netherlands at the beginning of nineties and that, now, are largely diffusing especially in The Netherlands and in Italy.
Some other research projects are going on with the aim of developing pavements of innovative conception, capable of very low noise emissions. It is the case of the European Project SI.R.U.US. (SIlent Road for Urban and extra-urban USe – BRPR CT98 0659).

The French 0/6 porous asphalt

Since early nineties the French began to develop new porous asphalts with maximum grain size extremely reduced. The aim is to obtain wearing courses that perform very well under all the points of view: water percolation, noise emission, clogging and skid resistance. The result is a 0/6 mix, 2/4 gap grading, with 10/12% of sand (*Spillemaecker and Bauer, 2000*). Some trials sections were laid in 1995 giving very good results; thus, since 1997 it was introduced in French motorways.
The average thickness of these wearing courses is 3-4 cm. Performance measurements took soon after the laid on the A84 Motorway are here summarised:

- Hydraulic conductivity: 0.94 cm/s;
- Void content: 22.5 – 24.5%;
- Connected voids: 81-88%;
- BFC (40 km/h): 0.59;
- BFC (90 km/h): 0.43;
- BFC (120 km/h): 0.39;
- $L_{rev.}$ (light vehicle – 90 km/h): 70-71 dB(A);
- $L_{rev.}$ (light vehicle – 120 km/h): 75-76 dB(A);

Skid resistance and noise emissions are good, while percolation rates are quite lower than those typical of others new French porous wearing courses.
According to these results, this kind of wearing course seems to be a good (and economic) compromise solution for all porous asphalts' problems. By the way, long term performance measurements are not available.

Double layer porous asphalts

Double layer porous asphalts were introduced for the first time in The Netherlands at the beginning of nineties. Main goals of these kinds of pavement are:

- increasing drainage performance;
- increasing clogging resistance;
- increasing skid resistance;
- increasing sound absorption;
- reduce costs.

The idea is to lay a porous friction course divided into 2 layers: an upper one, 1-2 cm thick, with fine aggregate gradation, having filter functions; a second one, in the bottom, 2-5 cm thick, with coarse aggregate gradation, with draining functions (see figure 7).

In this way almost all the goals above mentioned were achieved: as the upper layer is 1-2 cm thick, a less consumption of high quality aggregates is needed; the upper layer, with its small maximum particle size, represents a barrier to dust intrusion into the lower drainage layer; moreover, the upper layer is easier to clean since it has been stated that cleaning equipment are really effective only on the first 1-2 cm; the small particle size of the upper layer favourites skid resistance; the combination of the fine aggregate gradation of the upper layer and of the coarse aggregate gradation of the lower layer, improves greatly noise absorption; finally, the high void content of the lower layer ensures good percolation rates.

Figure 7: View of a typical composition of the double layer in a trial section laid in Italy (*La Torre et al, 2002*).

In The Netherlands these pavements were firstly laid with a 4/8 aggregate gradation for the top layer (1.5 cm thick) and a 11/16 aggregate gradation for the bottom layer (4.5 cm thick) (*Van Bochove, 1996*).
In further applications a reduced maximum aggregate size for the top layer (2/4 mm) was adopted (*Van Bochove, 2000*). In Italy the applications of these pavements begun in 1995. Table 4 reports the main characteristics of these double layers (*Battiato et al., 1996, 2000*).

Table 4: Characteristics of the mixes of an Italian porous double layer

Top layer (1.5 cm)	Coarse aggregate 4/6	84%
	Sand	8%
	Filler	8%
	Modified bitumen	5.0%
	Void content	25%
Bottom layer (3 cm)	Coarse aggregate 8/12	84%
	Sand	8%
	Filler	8%
	Modified bitumen	4.5%
	Void content	22%

In all the applications, the goals above mentioned seem to be achieved.
In particular sound absorption properties are strongly enhanced since these pavements show 4/6 dB(A) of noise reduction if compared to new dense graded wearing courses. As regards the noise reduction, further experiments are now going on with a research of the University of Florence in joint venture with Agip Petroli (*La Torre et al., 2002*).

The SI.R.U.US. Project

The SI.R.U.US. Project started in 1998 as a joint venture of some European companies coming from France, Belgium, Portugal and Italy. The main goal of the project is to develop new pavements capable of (*Luminari, 1998*):

- a noise reduction (in extra-urban environment) of at least 3dB(A) in comparison to a standardised traditional porous pavement;
- a noise reduction (in urban environment) of at least 5dB(A) in comparison to a standardised traditional dense graded pavement;
- a significant reduction of the ratio cost/benefit.

Two types of pavement have been developed: the “euphonic composite multilayer motorway pavement” for the extra-urban use and the “ecotechnic composite multilayer urban pavement” for the urban use. The first is a continuously reinforced rigid pavement which contains inside a resonant system. This is constituted by some horizontal metal pipes of several opportune diameters, properly

spaced, connected to the top by other vertical, smaller pipes. The friction course of this pavement is given by a double layer porous asphalt overlay.
The second is a bituminous pavement which contains in the base course a resonant system conceptually similar to that mentioned above. Also in this case the friction course is given by a double layer porous asphalt.

Several (different) prototypes of these pavements have been tested under controlled traffic conditions at the Autostrade's Anagni (I) test track (*Camomilla et al., 2003*). The results of these tests have been encouraging: noise reduction levels always resulted higher than those of the referring traditional porous pavement, especially at higher speeds (which are typical for motorways). Ranges of reduction were between 4 dB(A) and 10 dB(A).
Recently a restricted sample of these pavements was also tested under real traffic conditions on the A1 motorway (Italy). The results of these tests are still not available.

CONCLUSIONS

Since their first applications, porous asphalts soon showed their great potential as concerns safety and environment issues.
Thanks to their water drainage ability, in wet conditions they perform better than traditional hot mix asphalts as regards safety and comfort. Moreover, the high porosity gives them excellent acoustical properties. These factors determined their great success in Europe and justified the great efforts of research in order to give a solution to the problems arisen in the early applications.
Most of porous wearing courses that can be found on European roads have an aggregate gradation 0/10 – 0/16 with 2/8 discontinuity and sand content of about 10-12%. As regards binders, modified and unmodified bitumen are used, with preference for the modified ones. Friction courses thickness typically are 4 cm. Void content typically ranges between 20% and 25%.
Porous asphalts techniques are still under development in order to solve the issues highlighted in about 20 years of use and, most of all, to improve their acoustical properties. So, the improvements basically concern the enhancement of acoustical properties, of adherence, clogging prevention and mechanical durability. Giving a solution to these problems is quite difficult since the optimisation of one of them often implies the worsening of one or more of the others.
Currently three line of research can be recognized:
- the first involves the optimisation of mixes for the traditional porous friction courses (single layer, 3 ÷ 5 cm thick) so to obtain a good arrangement among the various issues above mentioned. The current trend in this matter goes toward the development of friction courses with smaller maximum particle size (e.g. 0/6 gap 2/4).
- the second involves a new concept of porous friction courses made by two different layers of porous asphalts each with a different functional specialization. Typically the upper layer has small maximum particle size in order to ensure good skid resistances and good high frequency noise reduction, while the bottom has larger maximum particle size to enhance permeability, clogging prevention and good low frequency noise reduction.
- the third involves the study of completely new pavements such as those studied in the SI.R.U.US project.

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