Improving durability and functionality retention of porous asphalt by using high performing bituminous binders

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ABSTRACT

Porous asphalt is a popular type of asphalt pavement in Europe and other parts of the world. Its well-known functional benefits are water drainage and reduction of splash and spray, which increases safety on the road. Moreover, the use of porous asphalt can significantly reduce traffic noise.

However, porous asphalt has a shorter life-time compared to more dense asphalt mixes, due to the higher ageing rate, especially when the initial pavement quality is poor or under severe weather conditions. In Japan, the quality of porous asphalt has been successfully improved by the use of binders modified with high concentrations of SBS (8% or higher). Although this approach to prevent raveling and clogging is successful, it has not been widely adopted outside Japan.

In the literature, the use of (SBS) modified binders for porous asphalt has been investigated, but these investigations are often focused on the damage profile, while the functional attributes (e.g. hydraulic conductivity or water drain capacity) are not always taken into account, which can lead to a distorted view.

In this paper, we discuss lab and field data of the use of (highly) SBS modified bitumen compared with unmodified bitumen for porous asphalt applications. These data make clear that in porous asphalt research both the durability and the functionality of the asphalt should be evaluated. Furthermore, we show the benefits of using highly SBS modified bituminous binders, especially during winter, which was investigated using the Lifetime Optimisation Tool (LOT), developed by the Delft University of Technology.

Keywords: Durability, Modified Binders, Permeability, Porous asphalt, Ravelling

1. INTRODUCTION

Porous asphalt is a popular type of asphalt pavement in Europe and other parts of the world. Its well-known functional benefits are water drainage and reduction of splash and spray, which increases safety on the road. Moreover, the use of porous asphalt can significantly reduce traffic noise.
However, porous asphalt has a shorter life-time compared to more dense asphalt mixes, due to the higher aging rate, especially when the initial pavement quality is poor or under severe weather conditions. The main type of damage of porous asphalt is raveling; the loss of aggregate from the asphalt pavement surface (Figure 1), which leads to wind shield damage and loss of noise reduction.

Figure 1: A highway section showing severe raveling

There are a few potential causes for early aggregate loss in porous asphalt. One option is that the binder ages much faster due to the open structure. Due to this aging, the binder is not tough enough anymore and has lower breaking strength in the brittle state. Furthermore, the healing capacity will be lower due to aging and traffic induced cracks do not get repaired anymore. Another option could be that aggregate is lost due to sagging of the binder in service. The third option could be loss of adhesion due to weathering, so for example UV radiation and water ingress between binder and stone. The third option is less likely, because then there should be more practical evidence in the form of clean aggregate, which is not the case.

To improve the resistance to raveling, a few possibilities can be considered. The first option is to use softer base bitumen and thereby reducing the vulnerability and/or applying thicker binder layers. However, with softer bitumen and thicker binder layers, the potential to clog up early increases and so does the tendency of the binder to sag. Another option could be to use special soft bitumen with a high penetration index. This type of bitumen is said to be less temperature susceptible. However, to our knowledge, this type of bitumen ages fast. The last option is to improve the binder's toughness and breaking strength. This last option can only be done by polymer modification.
A highly suitable polymer for this purpose is SBS. First of all, SBS forms an extended network in the bitumen at service temperature. The polystyrene blocks on the polymers form strong domains, while the polybutadiene blocks in between form flexible and elastic connections between the strong domains. At process temperature, the SBS is present as single molecules and therefore the processing is easy. Secondly, only a minimum amount of SBS is needed to form a continuous polymer rich phase. Figure 2 shows a schematic representation of the addition of SBS to bitumen and the resulting phase morphologies. When SBS is dissolved in bitumen, it absorbs the oily components of the bitumen up to 10 times its own volume. Therefore, only a minimum of 4-6% of SBS is needed to form the polymer continuous extended network.

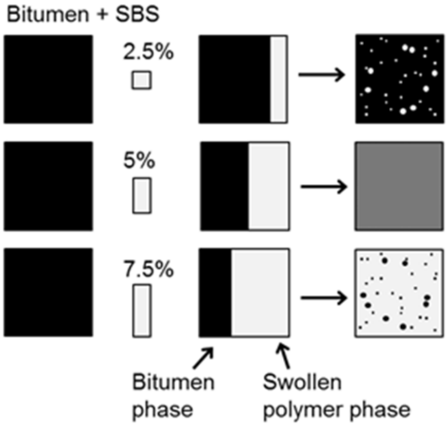

Figure 2: Schematic representation of phase morphologies of bituminous binder at different SBS concentrations

The SBS continuous extended network brings:

- (very) high viscosity at service temperatures
- (very) high toughness and breaking strength at service temperatures
- reduced stiffness at low temperatures
- increased stiffness at high temperatures
- the potential to use softer base bitumen

And these enable to improve the raveling resistance of porous asphalt using SBS modification.

In this paper, we discuss laboratory and field data of the use of (highly) SBS modified bitumen compared with unmodified bitumen for porous asphalt applications. Furthermore, we show the benefits of using highly SBS modified bituminous binders, especially during winter.

2. DURABILITY OF POROUS ASPHALT: LABORATORY AND PRACTICE

In this section we discuss some literature examples of research on the durability of porous asphalt with SBS and other additives. The first example shows how the quality of porous asphalt wearing courses can be improved by using SBS polymers [1]. Plug et al. describe Cantabro tests applied at a lower temperature on laboratory aged asphalt samples to assess the effect of the SBS concentration in the binder on the raveling resistance. The results showed that the loss of mass was mainly dependent on the SBS concentration (2-7%); the higher the concentration, the lower the mass loss.

The positive effect of the use of SBS on the quality of porous asphalt was also proven by Chen et al. The authors performed both a laboratory study and field trials using a conventional binder and an SBS modified binder (the SBS concentration was not reported, but is likely rather low: softening point: 63 °C) [2]. In the laboratory they found reduced abrasion loss and enhanced durability for the SBS modified compared to the unmodified asphalt. The field tests confirmed the results: reduced rutting and raveling for the SBS modified section. Interestingly, the authors also investigated the permeability of the porous asphalt. This functional property is essential for porous asphalt to have the advantages of water drainage during rain and noise reduction, but is often not taken into account in research on porous asphalt (see for example reference [3]). Chen et al. monitored the permeability of the asphalt during 2.5 years and found that it was significantly better for the SBS modified asphalt than for the unmodified asphalt [2]. The authors explain this observation by a larger densification of the unmodified asphalt by the heavy traffic, but they also mention clogging of the voids of the unmodified asphalt.

A very extensive study on porous asphalt was performed by TRL, UK's Transport Research Laboratory [4,5]. In this study, fifteen road sections on the A38 in the UK with different modifications (fibers, polymers, etc.) were tested during several years on durability, but also on permeability to water, spray intensity, texture depth, skid resistance and voids retention. The researchers concluded that three of the sections performed better than average: an epoxy asphalt and two sections with asphalt based on binders with soft bitumen and SBS. Based on the overall performance of all test sections the conclusion was the following: "…it can be seen that improved durability resulting from increased binder contents, is generally obtained at the expense of hydraulic conductivity..." In other words: with higher binder content, the durability might improve, but the permeability to water has decreased! This is an important observation, as of course not only the durability of porous asphalt is important, but also the functionality retention.

3. LABORATORY EXPERIMENTS AND COMPARISON WITH PRACTICE

3.1 SBS modification and binder aging

In the laboratory the influence of SBS modification on binder aging was investigated. The selected test method is the penetration test. The reasoning behind this is the fact that the brittleness of the binder will eventually lead to raveling of the porous asphalt. Moreover, the penetration data of the artificially aged laboratory samples can be compared with the data generated in the A38 field trial [4,5].

Porous asphalt cores were prepared and these were aged in an oven at 50 °C for more than 30 weeks. These conditions were chosen to subject the porous asphalt for a prolonged period of time to the maximum road temperature. Other aging methods are less suitable here; e.g. RTFOT represents the ageing that takes place during asphalt mix production, while the PAV is run at temperatures that are well above the service temperatures on the road. The thin binder films in the asphalt mix should secure a sufficiently rapid ageing process. Compared to outdoor ageing at least the fact that it is aged in an asphalt mix at maximum service temperature conditions is an advantage, the non-exposure to rain, UV and debris is a disadvantage, but is also not used in other ageing tests.

After the aging period, the penetration value of the binder was measured at 25 and 40 °C as indication for the effect of aging. The binder samples were two pure bitumen grades: 80/100 and 100 pen laboratory bitumen (PX100) and three PMBs which are modified with Kraton D1101 at 3, 5 and 7 %.

Overall, a decrease of the penetration values is observed for all binders, with a faster decrease for the unmodified bitumen based samples (Figures 3 and 4).

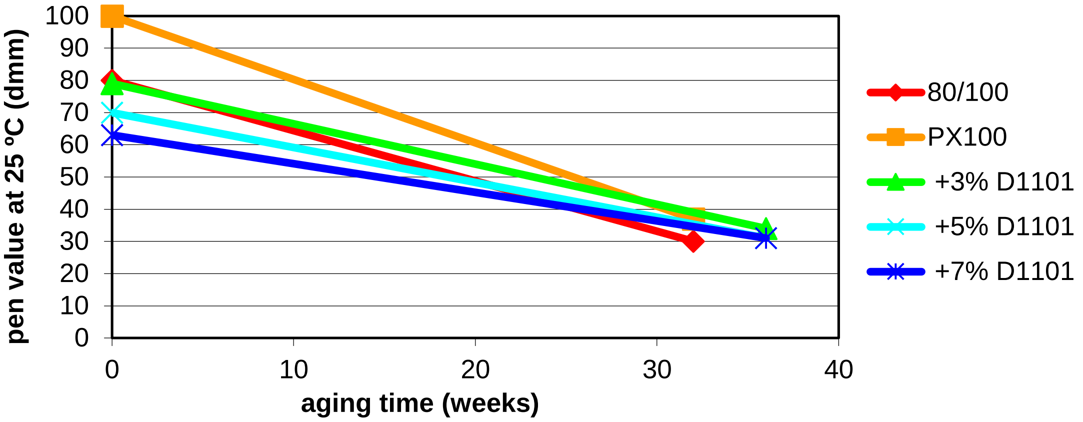

Figure 3: Penetration values at 25 °C of laboratory aged porous asphalt cores

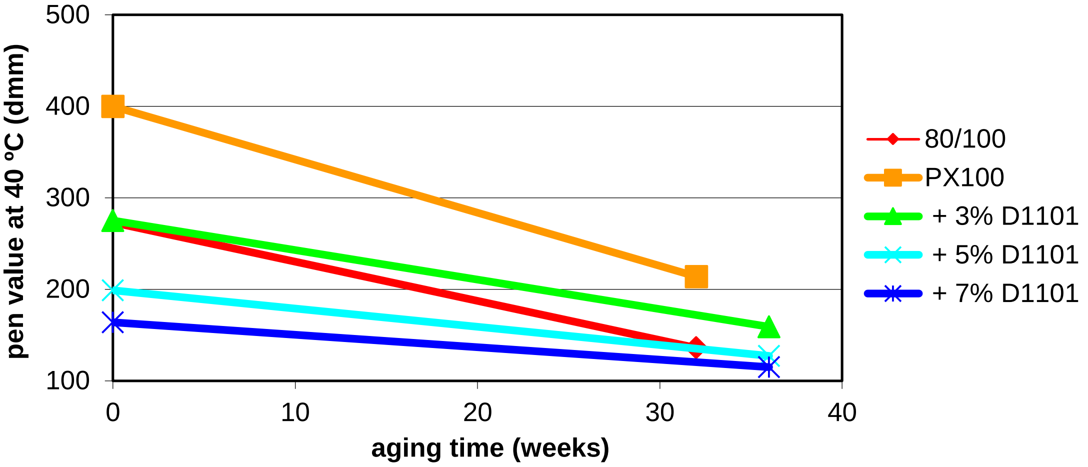

Figure 4: Penetration values at 40 °C of laboratory aged porous asphalt cores

The equations for the trend lines of the graphs in Figures 3 and 4 are listed in Table 1. Comparison of the slope of each line confirms the slower aging of the modified binders compared to the pure bitumen. A clear trend is observed: the higher the modification level, the slower the decrease of the penetration value, which indicates that SBS modification, has a positive effect on the aging resistance.

Table 1: Pen value aging slopes for different modification levels

Binder	at 25 °C	at 40 °C
PX100	y = -2.0x + 103	y = -5.8x + 396
80/100	y = -1.6x + 81	y = -4.3x + 273
PX100 + 3%	y = -1.2x + 79	y = -3.2x + 275
PX100 + 5%	y = -1.1x + 70	y = -2.0x + 199
PX100 + 7%	y = -0.9x + 63	y = -1.4x + 164

3.2 Comparison with practice

For the comparison with field experience, the A38 trial data are used [4,5]. Figure 5 shows a comparison of the best performing sections; the best draining sections and the most durable sections. Clearly, the most durable sections do not show sufficient permeability to water. Furthermore, the sections that score the best on permeability show an average durability.

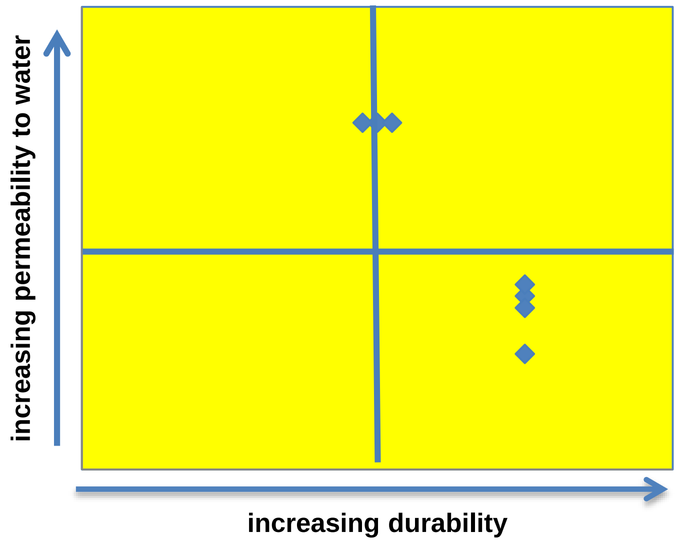

Figure 5: Schematic comparison of three best draining and four most durable sections of the A38 trials

If we take a closer look at these sections regarding aging, the graph in Figure 6 can be drawn. The unmodified bitumen based binders show a slower decrease of the penetration value than the modified binders. In other words; these results show that unmodified binders age slower in practice than SBS modified binders. Interestingly, if we look at the permeability rating of these materials, we see that the SBS modified sections score above average and better than the unmodified sections (Table 2).

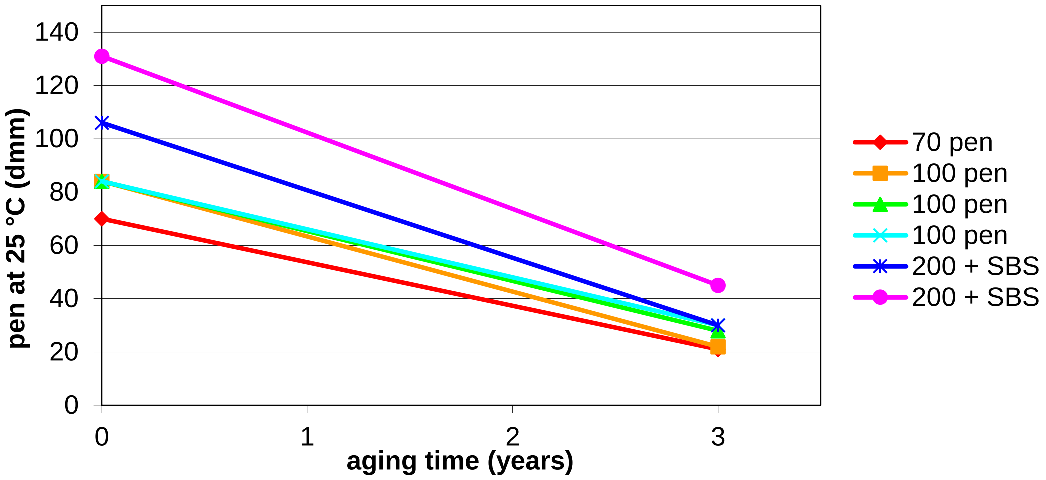

Figure 6: Penetration values at 25 °C of A38 trial materials

Table 2: Pen value aging slopes and permeability rating for selected A38 sections

Binder	at 25 °C	permeability to water
70 pen	y = -16.3x + 70	**
100 pen	y = -20.7x + 84	**
100 pen	y = -18.7x + 84	**
100 pen	y = -18.0x + 84	**
200 pen + SBS	y = -25.3x + 106	***
200 pen + SBS	y = -28.7x + 131	***

Summarizing these observations; the aging behavior in the laboratory compared to practice is different. The SBS modified porous asphalt samples age slower in the laboratory, but faster in practice. The A38 trial results have shown that the use of SBS modification retains the permeability to water. Furthermore, the A38 sections which had a reduced permeability to water (the sections which have clogged voids), are more durable.

In the next section we attempt to answer why some systems would clog up earlier than others while the mix design and aggregate quality is the same.

3.3 Porous asphalt clogging mechanism

Field experience with surface dressing binders showed that some of these binders absorb more dirt than others. At that time, a clear relation was found between dirt absorption by the binder and the viscosity of these binders. This mechanism could also be valid in the case of the porous asphalt. Normally, dirt will disappear from the pores by the pumping action of the traffic. However, what is referred to here is the residual dirt absorbed by the binder, which will be reflected in lower water drainage capacity of the porous asphalt. SBS modified binders have (very) high viscosities when the polymer rich phase is the continuous phase, while unmodified binders have a much lower viscosity. Less absorption of dirt by a binder with higher viscosity will lead to less clogged voids because the dirt can still be removed by the pumping action of the traffic. The A38 trials indeed showed that the high viscosity binders sections kept their drainage capacity significantly longer than the low viscosity binders sections [4,5]. Hence, we postulate that permanent clogging is (partly) related to dirt absorption by the binder and to demonstrate the difference in rate of dirt absorption we performed the following experiments. Samples of 40 g of binder (pure bitumen and the same bitumen with 4 and 8% of SBS) in glass beakers were prepared. On top of the binder surface 5 g of crushed stone fines were dropped using a small funnel. The beakers were stored in an oven at 40 °C for up to 24h for the pure bitumen and 48 and 120h for the PMB samples. After certain times photos were taken of the binder surface of each sample (Figures 7-9).

2h 6h 24h

Figure 7: Surface of bitumen with crushed stones after 2-24h at 40 °C

2h 6h 48h

Figure 8: Surface of PMB with 4% of SBS with crushed stones after 2-48h at 40 °C

2h 6h 120h

Figure 9: Surface of PMB with 8% of SBS with crushed stones after 2-120h at 40 °C

The photos clearly show the difference in speed of absorption of the crushed stone fines by the different binders; the pure bitumen has absorbed significant amounts of fines after two hours (binder is visible near the glass) and after 24h all fines have been absorbed by this binder. The absorption of fines can be significantly limited by modification with 4% of SBS (Figure 8). However, because the polymer phase in the binder is not yet continuous, most of the fines have been absorbed after 48h. Figure 9 clearly shows the benefit of the polymer continuous phase in this binder; after 120h at 40 °C, only a very small part of the binder surface has become visible, which means that the fines absorption of this highly modified binder is negligible compared to the pure bitumen sample.

Schematically the relation between the viscosity at service temperature, the clogging up rate and relative aging can be depicted as shown in Figure 10. Pure bitumen has a relatively low viscosity at service temperatures and therefore absorbs dirt relatively easy, which leads to fast clogging of the voids and therefore slower aging. Highly modified binders, on the other hand, have high viscosities at service temperatures and therefore the dirt absorption will be limited, which means slow clogging of the voids in the asphalt, but as a consequence faster aging.

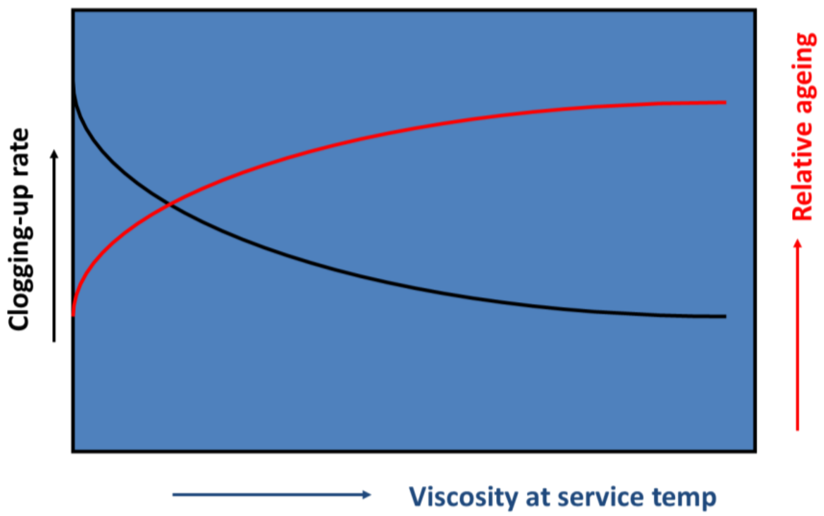

Figure 10: Schematic representation of relation between viscosity at service temperature, clogging up rate and relative aging

To retain the functionality of the porous asphalt during its life-time, it is necessary to prevent clogging of the voids. With the open voids a higher ageing rate needs to be compensated. Adding SBS will help to increase the viscosity and hence reduce the clogging rate, but its positive effect on compensating for the increased ageing may be insufficient. Therefore higher SBS contents may be required (possibly in combination with softer base bitumen). The principle of this mechanism is shown in Figure 11.

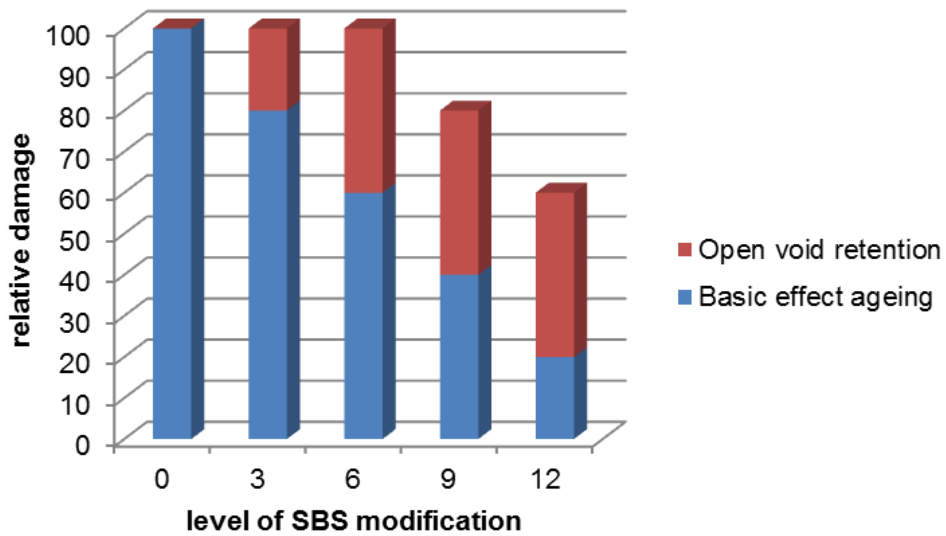

Figure 11: Possible relation between relative damage and level of SBS modification

The effects of modification on the overall porous asphalt quality are shown in Figure 12. Positive effects can be noted at lower levels of SBS modification, but the ultimate durability will not improve. By using high SBS concentrations (> 6%) and soft bitumen, the highest performance can be achieved, both on durability of the material and the positive attributes of porous asphalt by keeping the porosity. Proof of this concept stems from Japan, in which country high modified porous asphalt binders are actually being used.

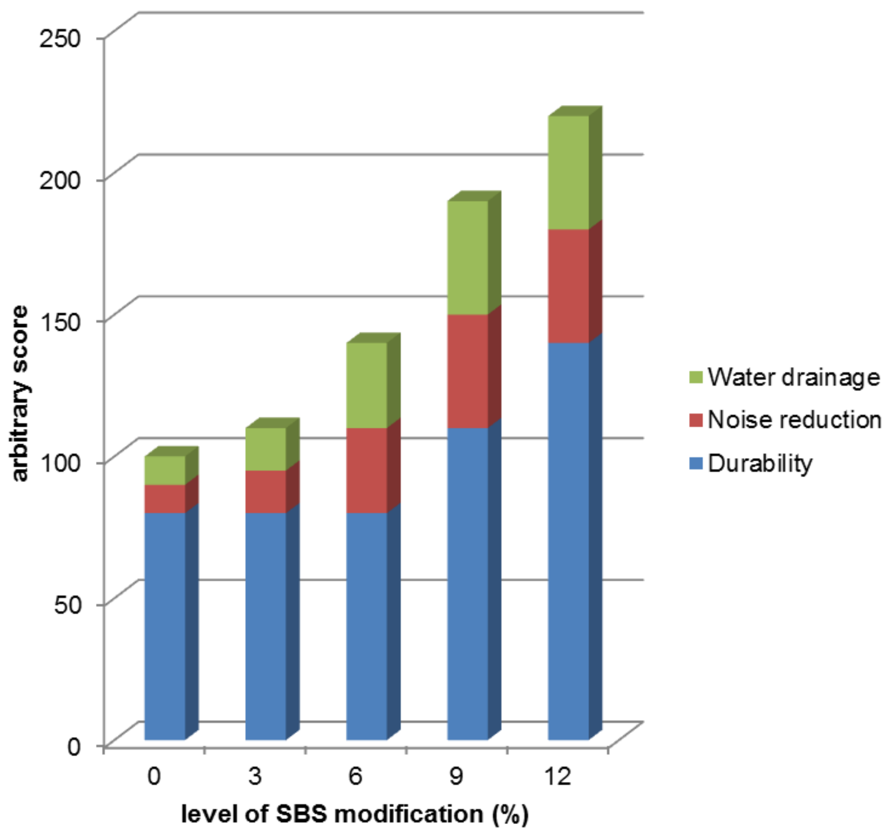

Figure 12: Benefits of SBS modification for porous asphalt quality

3.4 Japanese experience with porous asphalt

The use of highly SBS modified binders to prepare high quality porous asphalt is not new; this type of binders for porous asphalt has been widely applied in Japan for more than 20 years. In Japan, these binders have been developed because high drainage capacity and low-noise performance was being demanded of this type of pavement. The use of unmodified or low modified binders resulted in: raveling of aggregate and clogging of voids under service conditions, which led to decreased durability and functional capability.

Therefore, in Japan the typical modification level is 8% and in the coldest parts of the country 10% or higher concentrations of SBS are used. The use of high modification levels is considered to be a standard and cost-effective measure to obtain more durable porous pavements. The structural durability of porous pavements in Japan is generally the same as the durability of dense graded asphalt mixes [6].

4. POROUS ASPHALT UNDER WINTER CONDITIONS AND THE BENEFIT OF HIGHLY SBS MODIFIED BINDERS

In The Netherlands, porous asphalt is widely used in wearing courses on motorways. Often these asphalt layers are not modified or modified at a relatively low level. Some years ago, severe raveling damage was experienced after often only one winter, even on relatively new road sections. Only a few cold winter nights can cause years' worth of raveling damage to roads when stresses due to traffic loads and day to night temperature variations reach the binder's breaking point.

Delft University of Technology developed a finite element model, the Lifetime Optimisation Tool (LOT), to study this phenomenon by predicting asphalt mix response from asphalt mortar properties (Figure 13) [7,8]. Mortars of long-lasting porous asphalt roads were compared to those from early-failure roads.

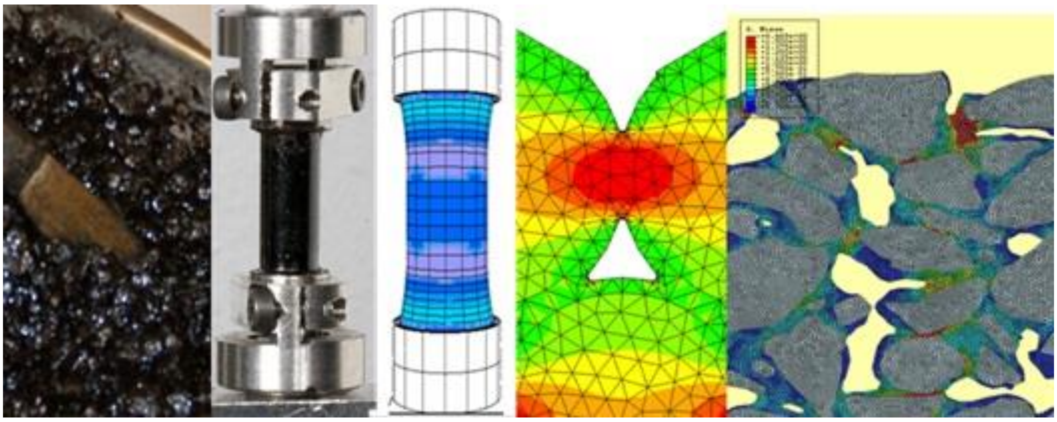

Figure 13: Steps in LOT research: mortar, DSR testing, modeling

The study concluded that two factors are critical to prevent winter damage:

- Limited binder stiffness at low temperature, particularly after aging
- Binder stress relaxation at these low temperatures.

In a search for improved binder performance, different highly SBS modified binders were produced in the laboratory. Master curves were developed on laboratory aged binders for viscoelastic properties and the mortar performance was evaluated at different temperatures and temperature fluctuations using the protocol of the LOT model. The results were compared with literature data of the existing road sections and showed a dramatic improvement in raveling resistance (Figure 14) [9].

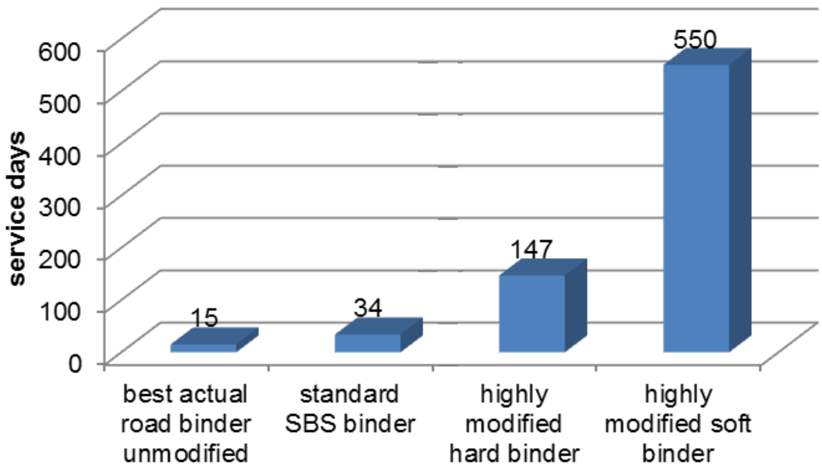

Figure 14: Computer modeling results of winter damage of extracted lab tested actual road binder and formulated aged binders at -10 °C (day and night variation of 6 °C)

The SBS polymer-modified binders demonstrated exceptional performance in the winter and at least an equally good performance under summer conditions (Figure 15).

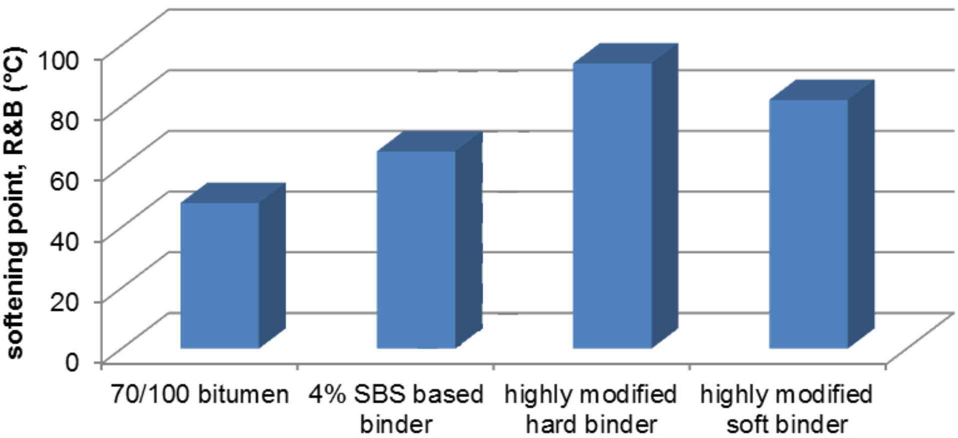

Figure 15: Softening points of used binders

5. COSTS AND HSE CONSIDERATIONS

Obviously, challenges to this approach are justified. Although 15-20% of the global paving market is now using PMBs, which is indicative for the economic (and performance) acceptance of this solution, there are still questions around cost effectiveness and HSE related aspects. In 2005, the Asphalt Institute issued a report that presented a comprehensive inventory of direct comparison of modified and unmodified asphalts in the US and their conclusion was unambiguous: Polymer Modified Asphalt increased the service life of pavements and reduced the maintenance costs, by which the Net Present Values or Life Cycle Costs became favorable [10]. This is related to PMAs with relatively low polymer content, but it has been demonstrated that such solutions do not necessarily work for porous asphalt.

It is also important to define what costs are involved. Shell published a paper as early as 1988, in which they presented model calculations on how much more a binder might cost in case a longer lifetime is achieved [11]. They were then looking at three levels: simply the asphalt costs only, the asphalt costs + delay in traffic costs and those latter two with the costs to society as result of accidents and casualties as result of road maintenance. Those data were impressively ranging from 20 to 45% of net saving.

Two examples of the potential cost saving by improving the quality of asphalt are the following. The European GNSS Supervisory Authority reported that when the average road repair cycle is increased from 10 to 11 years, this will result in a cost saving of 4.5 billion euros per year within Europe [12]. Besides these primary cost savings, they also mention reduction of traffic jams, reduction of resource consumption, reduction of air pollution and CO_2-emissions, increased safety and better riding comfort as benefits.
The second example deals with The Netherlands. Here, the average annual costs for major repairs amounts 180 million euros, but by extending the lifetime of standard porous asphalt concrete with 25% (from 12 to 15 years), the annual costs for major repairs can be reduced by 35-50 million euros. Less maintenance means less traffic jams costs, which would be for The Netherlands: 22 million euros. In short, this life-time extension of the porous asphalt concrete area in The Netherlands corresponds with a saving of in total approximately 65 million euros annually [13].

So if the highly modified porous asphalt solution offers the same performance as in Japan (same durability as dense asphalt structures [6]) and as is suggested by LOT analysis, it offers serious cost saving and HSE opportunities.

6. CONCLUSIONS

- The durability of porous asphalt needs to be judged on both functional performance and raveling resistance
- Evaluations focused on all performance aspects demonstrated correlations between:
  - More clogging up → less water drainage
  - More clogging up → less ageing, hence less raveling
  - Less clogging up → more water drainage
  - Less clogging up → more ageing, hence more raveling
- The resistance to clogging is related to the nature (viscosity) of the binder and it has been shown that the higher the modification level, the less dirt absorption takes place
- There is also a discrepancy in the ageing rate of binders between the road and the laboratory; obviously in the latter there is no clogging up
- The highest quality binders for porous asphalt are based on soft bitumen with high concentrations of SBS to retain the functionality of the asphalt and limit the effect of aging
- Highly modified porous asphalt has proven itself in Japan, where the SBS modification level is 8% or more
- LOT model by TU Delft predicted a significant durability improvement of highly modified porous asphalt after ageing (under winter conditions)

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