Bitumen performance in pavements under extreme climatic conditions

Paper prepared for:

2\textsuperscript{nd} Symposium of Bitumen and Asphalt of Iran
22 – 24 November 2004
Tehran, Iran
Bitumen performance in pavements under extreme climatic conditions

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ABSTRACT

Quality and properties of bitumen for asphalt pavements depend largely on chemical composition and structure, which are mainly controlled by the origin of the crude oil(s) and the processes used during manufacture. Bitumen composition and structure change during storage at high temperature and during production, transport and laying of asphalt mixtures. This so-called oxidative ageing can change the properties of bitumen dramatically. Ageing continues, although at a much slower rate, also in the asphalt pavement. Bitumen performance can be improved (modified) by incorporating additives (e.g. polymers or crumb rubber) in the bitumen. The level of improvement depends largely on type and amount of additives that are used and the modification process that is applied. These aspects are all briefly discussed in this paper. Special attention is given to the performance of (modified) bitumen under extreme climatic conditions (like prevailing in most parts of the Middle-East and Asia).

KEYWORDS: bitumen composition, bitumen structure, ageing, low/high temperature performance, mechanical characterisation and bitumen improvement.

INTRODUCTION

Quality and properties of bitumen for asphalt pavements depend largely on chemical composition and structure. Oxidative ageing can change the properties of bitumen dramatically. Bitumen performance can be improved by incorporating additives (e.g. polymers or crumb rubber) in the bitumen. These aspects are all briefly discussed. Special attention is given to the performance of (improved) bitumen under extreme climatic conditions.

BITUMEN COMPOSITION AND STRUCTURE

Bitumen is a complex combination of molecules of predominantly hydrocarbon nature. The composition depends on the origin of the crude oil and the processes used during bitumen manufacture. Because the chemical composition of bitumen is extremely complex with the number of molecules with different chemical structures being very large, it is not feasible to attempt a complete analysis of bitumen. Besides, the elemental composition provides little information on the performance in a pavement.

In general, bitumen can be divided into two broad chemical groups: asphaltenes and maltenes. The maltenes can be further subdivided into saturates, aromatics and resins (SARA fractions). Although these groups are not completely defined and have some overlap, they enable to compare bitumen properties with broad chemical composition.

Bitumen is traditionally regarded as a colloidal system consisting of high molecular weight asphaltene micelles dispersed or dissolved in a lower molecular weight oily medium (maltenes). The micelles are considered to be asphaltenes together with a sheath of adsorbed high molecular weight aromatic resins, which act as a stabilising solvating layer and peptise the asphaltenes within the solvent maltenic phase. Away from the centre of the micelle, there is a gradual transition to less polar aromatic resins and, finally, to a less aromatic oily dispersion medium. The degree to which asphaltenes are peptised will considerably influence the viscosity of the bitumen. The viscosity of the saturates, aromatics and resins depend on their molecular weight distributions. The higher the molecular weight the higher the viscosity. The viscosity of the maltenes imparts an inherent viscosity to the bitumen, which is increased by the presence of the dispersed asphaltenes. Saturates decrease the ability of the maltenes to solvate the asphaltenes.
Most bitumen is produced by fractional distillation of crude oil. Usually, distillation is done in two steps. The residue from the second step is called short residue and is the feedstock for the manufacture of bitumen. Bitumen manufactured from the short residue is called straight run bitumen. The differences in properties between hard and soft bitumen (low and high Penetration Grade) are mainly caused by different amounts of molecule structures with strong interactions. Low Penetration Grade bitumen contains more of these molecule structures. This is the main reason why they are stiffer and more viscous at high temperature and more brittle at low temperature than high Penetration Grade bitumen. The fact that they contain less low viscosity products is of less significance.

One way to make bitumen harder is to blow air through it. This process is called blowing. The chemical reactions result in bitumen with a different mixture of molecular structures. Blown bitumen has more and stronger molecular interactions than the original bitumen and is therefore more cohesive. Blowing reduces the temperature susceptibility of bitumen. The effectiveness of blowing depends largely on the original bitumen (i.e. the original mixture of molecular structures). When bitumen is strongly blown, it becomes so cohesive that the adhesive properties will be so poor that it is not suited for asphalt mixture applications anymore. Therefore, only semi-blown bitumen is suited for asphalt mixture applications. Semi-blown bitumen can have both improved cohesion and improved adhesion.

Visbreaking is a way to break heavy products (e.g. the residue from crude oil distillation or even very heavy crude oils) into lighter products. Bitumen produced from VB products age fast. This is because these products contain very reactive constituents (oleofins). Even blends of straight run bitumen with bitumen from VB products have the same ageing problems. This makes them unsuitable for most asphalt mixture applications. The properties may be somewhat improved by blowing.

**AGEING**

The (rheological) properties of bitumen change with time (i.e. bitumen becomes harder and more vulnerable to cracking). This phenomenon is called ageing. Oxidation is considered to be the main cause of bitumen ageing. Like many organic substances, bitumen slowly oxidises when in contact with air. Polar groups are formed which tend to associate into micelles of higher molecular weight. The increased and stronger interactions make the bitumen more viscous. Results from studies show that not all bitumens harden (age) to the same extent. This may be explained by differences in bitumen structure.

Oxidation causes the fractional chemical composition of bitumen to change. The asphaltene content increases continuously due to oxidation of polar resins. A part of the aromatics changes in such a way that in the composition analysis it gets included within the resins. Since these ‘new resins’ do not have the natural properties of resins, an evaluation of the properties of aged bitumen on basis of the SARA fractions can be misleading.

Irrespective of the ageing resistance of the bitumen, the degree and rate of oxidation depend on temperature, time, exposure to oxygen, bitumen film thickness and the nature of the other asphalt mixture constituents. With respect to temperature the most severe conditions are to be found during bitumen storage, mixing with aggregate and transport. When bitumen is stored at high temperature, normally (when procedures are followed up 100 %) very little oxidation occurs. This is because the surface of the bitumen exposed to oxygen is very small in relation to the volume. However, care should be taken during heating up. When the temperature difference between the bitumen and the heating oil is large (more than 30°C), reactive constituents (oleofins) are formed, which have a detrimental influence on bitumen. During mixing with aggregate at high temperature, the molecular mixture of the bitumen and the viscosity change significantly.

Some aggregates and fillers act as catalyst for the oxidation reactions, while others have inhibitive effects. Ultraviolet attack from the sun act also as catalyst. This is especially relevant for areas high above sea level, for areas with a lot of sunshine and for asphalt wearing courses with high void contents. Even elements present in the bitumen can act as catalyst. An example is Vanadylporphyrin. During the service life of the pavement, oxidation depends, apart from climatic conditions and the ageing resistance of the bitumen, mainly on the bitumen film thickness and the amount of air voids in the asphalt mixture (determines the exposure to oxygen and UV radiation). To minimise oxidative hardening, thick bitumen films and low void contents are required.
BITUMEN IMPROVEMENT

The response of bitumen to stress depends on temperature and loading time. At low temperatures and/or short loading times bitumen behaves predominantly elastic. At high temperature and/or long loading times bitumen behaves like a liquid (viscous behaviour). For typical pavement temperatures and load conditions bitumen generally exhibits both viscous and elastic behaviour. The behaviour of bitumen can be improved (modified) by adding additives to the bitumen. Bitumen modification usually aims at increasing the stiffness and/or the elasticity of the bitumen at high (pavement) temperatures and reducing the stiffness and/or elasticity of the bitumen at low (pavement) temperatures. The most world-wide commonly used additives for bitumen improvement are crumb rubber and two types of polymer (plastomers and elastomers).

Plastomers increase the stiffness and viscosity of the bitumen. The effect diminishes above their crystallisation temperature (50 to 80°C). Since they are often prone to phase separation, continuous mixing during storage is required. Examples of plastomers are EVA (Ethylene-Vinyl-Acetate) and PE (Polyethylene).

Elastomers increase the elasticity of the bitumen at high temperatures and reduce the stiffness at low temperatures. Styrene-Butadiene-Styrene copolymer (SBS) is the most used elastomer. Both linear and radial SBS copolymers are used. In bitumen, SBS forms a highly elastic network. The network disappears above 100°C but reforms on cooling. It is found that SBS also improves the resistance against oxidative ageing (1). It is important to note that the quality of SBS modified bitumen depends to a large extent on the production process. This is especially so for radial SBS, which requires a special modification process. Properly produced radial SBS modified bitumen usually has better performance than linear SBS modified bitumen.

The effect of crumb rubber is comparable to that of elastomers. Usually very high amounts of crumb rubber are added to bitumen (typically 15 – 20%). Most crumb rubber modified bitumen are not stable during storage and therefore need to be used directly after manufacture.

The effect of polymer modification not only depends on the type of polymer but also on the amount of polymer. In bitumen, polymers swell to maximum nine times their original volume. Up to about 4% of polymer (by mass), the bitumen remains the continuous phase. The properties of these polymer modified bitumen (PMBs) are dominated by the properties of the base bitumen. However, the polymer can already have a significant effect. Above 5%, the polymer usually forms the continuous phase. For these PMBs the polymer dominates the properties. Both PMBs with a continuous bitumen phase and PMBs with a continuous polymer phase are used.

HIGH TEMPERATURE PERFORMANCE

The type of asphalt pavement failure associated with high temperatures is normally permanent deformation (rutting). From cyclic compression tests the so-called asphalt mixture viscosity can be derived, which gives an indication of the rutting resistance of a specific asphalt mixture. It has been found that the zero-shear viscosity of bitumen correlates well with the asphalt mixture viscosity (2,10). Resistance against permanent deformation is improved when bitumen is used with a higher zero-shear viscosity. This property can be calculated from bitumen creep tests using a Dynamic Shear Rheometer (DSR), carried out at constant (low) shear stress. It can be seen in table 1 that at 40°C the zero shear viscosity of SBS, EVA and crumb rubber modified bitumen is significantly higher than that of standard bitumen. At 60°C the zero shear viscosity of the (radial) SBS modified bitumen remains very high, whereas the effect of EVA has diminished. This is typical for plastomer modified bitumen. Also, the zero shear viscosity of the crumb rubber modified bitumen has dropped significantly. It should be mentioned that, because of the size of the rubber crumbs (0-2 mm) used in this case, the crumb rubber modified bitumen was tested under slightly different conditions (bigger gap between the plates of the DSR). However, it is unlikely that this has influenced the performance significantly. Consequently, at very high (pavement) temperatures, rutting can be best prevented by proper elastomer (SBS) modified bitumen.

Most bitumen specifications are based on Penetration at 25°C or viscosity at 60°C. Generally, for standard bitumen low Penetration and high viscosity give best performance with respect to resistance against permanent deformation. For modified bitumen traditional specifications are not sufficient.
In the nineties of the 20th century, in the USA a more performance orientated bitumen specification (Superpave Asphalt Binder Specification) has been developed (3). Bitumen performance at high temperature is addressed by the rutting parameter \((G^*/\sin \delta)\) of both fresh and short-term aged bitumen. This parameter is measured with a DSR at a specified frequency. The (highest) test temperature at which both fresh and short-term aged bitumen just meet the specified minimum values for the rutting parameter determines the so-called ‘high temperature Performance Grade’ (high temp PG) of the bitumen. Ideally, the rutting parameter should be known for a range of loading times. However, in the Superpave Asphalt Binder Specification the minimum values for the rutting parameter are for one frequency only. To allow for longer loading times higher Performance Grades are specified. Therefore, the required high temp PG depends on maximum pavement design temperature and traffic loading (number and speed).

The high temp PG of commonly used standard straight run bitumen (Pen 60/70) is normally 64. Based on climatic factors only, e.g. many parts of India require bitumen with a higher high temp PG. For example for areas with summer temperatures of 45°C or more, like parts of central and southern India and the Great Indian Dessert in the north-west, the minimum required high temp PG is 70. Modification can improve the high temp PG significantly. For example, the SBS modified bitumen\(^1\) for the new wearing course of Cairo International Airport complied with the requirements for Superpave high temp PG of 76. The bitumen that was modified was a local Pen 60/70 bitumen with a high temp PG of 64 (4).

Overall, the best high temperature performance indicator for bitumen in general, and for modified bitumen in particular, appears to be the zero shear viscosity at high temperature. This value has in general to be as high as possible (for relevant pavement temperatures!). However, it should not be too high, because then the asphalt mixture becomes too stiff. The latter has caused severe cracking failures with some plastomer modified bitumen types in practice, even at (air) temperatures of 40°C and higher.

**LOW TEMPERATURE PERFORMANCE**

For areas with very low temperatures and/or large daily (pavement surface) temperature variations, the asphaltic layers should be resistant to low temperature cracking. Large and quick temperature drops result in development of stresses in the bitumen(films) between the aggregates. When the bitumen can not withstand these stresses it will break, which eventually will lead to (surface) cracking. Low stiffness and high ductility of the bitumen at long loading times (11) and good relaxation behaviour minimise the generated stresses. Oxidative ageing has a negative influence on the low temperature performance of bitumen.

The low temperature performance of asphalt mixtures can be assessed by so-called thermal stress restrained cooling tests. During these tests, rectangular asphalt specimens are kept at constant length while decreasing the temperature at a rate of 10°C per hour. This will result in the development of tensile stresses in the specimen. The specimen breaks when these stresses reach the tensile strength of the asphalt mixture. The temperature at which the specimen breaks (the so-called fracture temperature) is a good indicator of the low temperature performance of the asphalt mixture. Results from a series of cooling tests carried out by the Technical University of Braunschweig in Germany with different standard and modified bitumen are shown in table 2 (5,6). The fracture temperature of the tested asphalt mixture with standard Pen 60/70 bitumen is about -27°C. As may be expected the fracture temperature is lower when softer standard bitumen (Pen 160/220) is used (± 5°C lower). However, the high temperature performance of this type of bitumen is for most areas not sufficient. The three high polymer content SBS modified bitumen resulted in a fracture temperature which was respectively 6 to 10°C lower than for the standard Pen 60/70 bitumen and 1 to 5°C lower than for the soft bitumen. This clearly demonstrates the improvement in low temperature performance that can be achieved by SBS modification. However, it must be noted that the low polymer content SBS modified bitumen (PmB 45A) resulted in a fracture temperature that was only one degree lower than for the standard Pen 60/70 bitumen.

\(^1\) Sealoflex\textsuperscript{®} SFB 5-50 (JR)
In the Superpave Asphalt Binder Specification, stiffness, relaxation and failure strain of long-term aged bitumen address bitumen performance at low temperature. Stiffness and relaxation are measured with a Bending Beam Rheometer (BBR). Failure strain is measured with a direct tension testing machine. The (lowest) test temperature at which the bitumen just meets both the specified minimum value for the relaxation and the maximum value for the stiffness or (in some cases) the minimum value for failure strain, determines the so-called 'low temperature Performance Grade' (low temp PG) of the bitumen. The required low temp PG depends on the minimum pavement design temperature.

In figure 1 the asphalt mixture fracture temperature (data from table 2) is shown against the average low temp PG of the used bitumen. The correlation is relatively poor ($R^2 = 0.53$). It appears that the low temp PG based on stiffness and relaxation measured with the BBR, underestimates the performance of the SBS modified bitumen (especially for the high polymer content bitumen). This has also been recognised in the USA. Consequently, improved procedures to assess (the effect of) the low temperature performance of bitumen are under development (7,8). These procedures include an estimation of the thermal stress build-up in the pavement and determination of the tensile strength, failure strain and glass-transition temperature of the bitumen.

CONCLUSIONS

From this paper the following conclusions can be drawn:

- The performance of road bitumen largely depends on chemical composition and structure, which in turn are influenced by factors like crude oil, manufacture processes and ageing.
- Bitumen performance can be improved by incorporating additives (e.g. polymers or crumb rubber) in the bitumen. The level of improvement depends largely on amount and type of additive used and the modification process that is applied. Some additives (e.g. plastomers) improve only the high temperature performance while others (e.g. elastomers) can improve both high and low temperature performance.
- A good high temperature performance indicator for (modified) bitumen is its zero shear viscosity.
- The Superpave low temperature Performance Grade seems to underestimate the low temperature performance of SBS modified bitumen.

REFERENCES

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5. W. Arand, “Comparative study into the low temperature performance of an asphalt mixture with five different types of bitumen” (in German), Braunschweig, Germany, 1998.
TABLES

Table 1: Zero shear viscosity values for standard and modified bitumen

<table>
<thead>
<tr>
<th>Penetration at 25°C [dmm]</th>
<th>Zero Shear Viscosity [Pa·s]</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>At 40°C</td>
</tr>
<tr>
<td>Pen 40/60 bitumen</td>
<td>55</td>
</tr>
<tr>
<td>5% EVA modified bitumen</td>
<td>56</td>
</tr>
<tr>
<td>Sealoflex® 5-50 (HS)1</td>
<td>60</td>
</tr>
<tr>
<td>20% crumb rubber modified bitumen2</td>
<td>61</td>
</tr>
</tbody>
</table>

1 High polymer content SBS modified bitumen
2 Standard production process

Table 2: Fracture temperatures of an asphalt mixture with different types of bitumen (6 %)

<table>
<thead>
<tr>
<th>Penetration at 25°C [dmm]</th>
<th>Fracture temperature [°C]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pen 60/70 bitumen</td>
<td>60 – 70</td>
</tr>
<tr>
<td>Pen 160/220 bitumen</td>
<td>160 – 220</td>
</tr>
<tr>
<td>PmB 45A</td>
<td>20 – 60</td>
</tr>
<tr>
<td>Sealoflex® 5-50 (HS)1</td>
<td>40 – 70</td>
</tr>
<tr>
<td>Sealoflex® 5-50 (JR)2</td>
<td>50 – 80</td>
</tr>
<tr>
<td>Sealoflex® 5-902</td>
<td>80 – 120</td>
</tr>
</tbody>
</table>

1 Low polymer content elastomer modified bitumen meeting German specifications
2 High polymer content SBS modified bitumen

FIGURES

Figure 1: Fracture temperature asphalt mixture against low temperature Performance Grade