COMPARISON OF BITUMEN-RUBBER USE IN EXTREME CONDITIONS IN RUSSIA AND SOUTH AFRICA

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ABSTRACT. *The development of the use of crumb rubber from used tyres in asphalt started in the USSR during the 1960s independently and in parallel with the research in the USA and Western World during the 1970s. The result is that different processes were developed for making bitumen-rubber asphalt. The objective of the paper is to present and compare the bitumen-rubber specifications and asphalt experience in Russia and in South Africa (which was derived from the USA approach). The focus is on the wet process even though more recently the dry method has been used. Firstly, the properties of the constituent components are presented and discussed, where after the properties and manufacture of bitumen-rubber are compared. Finally, the properties of bitumen-rubber asphalt are compared and the experience and performance is presented. It was found that although the initial approach from the two schools differed, there are currently major similarities, even though the temperature ranges of use are vastly different. Bitumen-rubber has been shown to cater effectively for a wide range of environmental conditions and is superior to unmodified bitumen.*

KEYWORDS: *Bitumen-rubber, high temperature range, performance*

1. Introduction and background

Bitumen-rubber (BR) has been widely used internationally and it is of interest to draw parallels and compare the use in two relatively extreme climates, namely in Russia and in South Africa. This paper discusses the wet method as both countries originally used this method, although more recently novel application of the dry method has gained ground. Russia has extreme cold climates whereas in South Africa the temperatures are relatively warm. Furthermore, the development of the use of crumb rubber from used tyres started in the USSR during the 1960s (Duhovny et al, 2014) independently and in parallel with the research in the USA and Western World during the 1970s. The result is that different processes were developed but with the same positive results, with the target crumb rubber content of about 20% of the binder in both cases. The rationale for the use of crumb rubber from used car and truck tyres was the rapid growth in vehicle ownership and the concomitant growth of the piles of old tyres, as was found in many other countries. In most countries, including Russia and South Africa, the use of crumb rubber is voluntary and is dictated by technical and economic benefits, but it is likely that in future the use will become mandatory as was instituted in California in February 2015.

The objective of the paper is to present and compare the bitumen-rubber specifications and experience in Russia and in South Africa (which was derived from the USA approach). Firstly the properties of the constituent components are presented and discussed, where after the properties and manufacture of bitumen-rubber are compared. Finally the properties of bitumen-rubber asphalt are compared and the experience and performance is presented. It was found that although the initial approach from the two schools differed, there are currently major similarities, even though the temperature ranges of use are vastly different. Note that the GOST references are the Russian standard specifications, the SANS references are the South African National Standards and ASTM refers to the American Society for Testing Materials.

2. Comparison of bitumen-rubber constituent properties

2.1 Properties of crumb rubber

The wet method of preparing bitumen-rubber is used in both countries. This is to ensure better control and mixing, but in Russia (Duhovny et al, 2014) it was also found that emissions of carbon monoxide (CO) are 80% higher when the dry crumbs are added to the bitumen and aggregate in the pugmill rather than in the wet method. This has a major benefit for environmental concerns.

In Russia the average size of the rubber crumbs must be between 0.05 and 0.50 mm, and not more than 20% of the crumbs (by mass) must be greater than 0.63

mm. There are no requirements for the ratio of car and truck tyres in the crumbs, but there may be no cord impurities (Duhovny et al, 2014).

In South Africa (Jooste and Visser, 2012) it was found that the source of peelings and buffings is important since the ratio of natural and synthetic rubber determines the degree and rate of reaction between the rubber crumbs and the hot bitumen. The relative reactivity of the various types of rubber differ, being higher in natural than in synthetic and neoprene rubber. Rubber crumb that is high in natural rubber content has a greater degree of reaction between the rubber and the bitumen at high temperature. The natural rubber also provides better elasticity and adhesion than synthetic rubber. For this reason a minimum of 25% by mass of rubber component of the blend must be natural rubber, as determined by means of thermo-gravimetric analyses.

The surface area of material, and therefore the grading (Table 1), also greatly affects the degree of chemical reaction. The larger particles remain functionally undissolved rubber floating in the bitumen with a small proportion of gel on the surface. The small particles form a large amount of gel so that the compound is a matrix of gel, bitumen and resilient rubber which defies separation.

Morphology of the rubber particles is the most important factor affecting elastic recovery and hence performance of the bitumen-rubber binder and is a function of the method of manufacture. Buffings mainly have smooth-faced particles with an elastic recovery of 21%. Ambiently-ground crumb (the South African method) has a particle surface covered with porous nodules with an elastic recovery of 35%. Cryogenically-produced crumb (general method used in the USA) consists of smooth-faced angular cracked particles which have elastic recovery of only 6%. The preferred method is obviously the ambiently-ground one with its much higher elastic recovery (TG1, 2007).

Crumbed (granulated) rubber also contains approximately 40% of carbon black, a natural antioxidant, which will considerably prevent the aging of the bitumen-rubber binder on the road.

These results show that the crumb rubber is more highly specified in South Africa, resulting in a more uniform and controlled product. The crumb rubber is also slightly coarser than in Russia, which provides a more elastic product.

Table 1. *Typical grading of the rubber crumb (COLTO, 1998, TG1, 2007).*

Passing screen (mm)	Percentage by mass
1,180	100
0,600	40 – 70
0,075	0 – 5

2.2 Properties of the extender oil / cutter used in bitumen-rubber

Extender oils and cutters are used in varying quantities depending on the source of bitumen, the topographical area and the season, but is typically 2% in South Africa. Work by Potgieter and Van Zyl (1992) has shown that the highly-aromatic high flash-point extender oil dissolves the fine rubber fraction particles and causes the coarse fraction rubber crumb to swell substantially, thereby increasing the viscosity of the material. This produces a product with improved flexibility, elasticity and adhesion while reducing temperature susceptibility. Because such a small quantity of extender oil is added to the bitumen-rubber blend, it has an almost negligible effect on the chemical constitution of the bitumen and also does not interfere with the stability and durability of the chemical components of the bitumen (Jooste et al, 2008, Jooste and van Zyl, 2010). In some countries extender oils are no longer permitted for environmental reasons, but since the quantities are so small there are no restrictions in South Africa.

The use of extender oils in the production of the modified binders is limited in Russia. Bitumen-rubber production technology does not require significant additional equipment at the asphalt mixing plant. This simplicity of production may be compared with the more complicated process to produce a polymer bitumen binder. A two-step technology of mixing polymer with the binder in the colloid mill is currently applied. Evidently, this way of producing polymer bitumen binder leads to the fracture of the polymer threads that significantly affects the high- and low-temperature characteristics of the binder without increasing but, actually, shifting the interval of the reliable temperature use. This is a further benefit of bitumen-rubber.

2.3 Properties of the base bitumen

The source and grade of base bitumen is important since the chemical properties of bitumen vary in accordance with the type of crude oil being processed, as well as the refining process. Penetration grade bitumen with a penetration of 80-100 has been extensively used throughout South Africa for bitumen-rubber seal type and asphalt applications. The base bitumen complied with the national standard requirements of the South African National Standards - SANS 307 specification for penetration grade bitumen. Recently the refineries started producing mainly 70-100 pen bitumen according to the revised bitumen specification, which is now contained in the national standard SANS 4001 BT1:2012. Although not specified in SANS 4002, bitumen in South Africa is air blown as is the case in Russia. However, in Russia as well as in South Africa the properties of the bitumen-rubber are specified as the system performance is important, not the individual characteristics.

3. Comparison of bitumen-rubber properties

There are no Russian requirements for the properties of bitumen-rubber. Standard binder test protocols such as needle penetration and flash point are used. In Table 2 the requirements for 40 pen grade polymer modified binders (PMAB) (one of 6 types) and results for a typical bitumen-rubber binder (RBV) are shown. It is evident that the RBV exceeds the PMAB requirements.

Table 2. *Bitumen-rubber requirements in Russia (Duhovny et al, 2014)*

Test	GOST P52056 PMAB 40	RBV	Testing Method
Penetration at 25°C (dmm) Penetration at 0°C (dmm)	40 – 60 25 min	41 29	GOST 32154-2013
Ring and ball softening point, °C	56 min	67	GOST 11506-73
Ductility at 25°C, cm Ductility at 0°C, cm	15 min 8 min	15 10	GOST 32056-2013
Fraass brittle temperature, °C	-15 max	Not used	GOST EN 12593-2013
Flash point, °C	230 min	230	GOST R 53317-2009
Adhesion	Sample 2	Sample 2	GOST EN 13614-2013

These requirements are in contrast to that used in South Africa where the test protocol was specifically focussed on a non-homogeneous binder. The test protocol was originally published in (SABITA, 1992) which were interim requirements, but more recently (SABITA, 2014) the definitive protocol was published (the interim method is shown in brackets as many projects were built according to this protocol):

- Method BR1 T: Sampling, storing and preparation of samples of bitumen-rubber for testing. The hot sample is taken from the tank through a sampling valve. The sample is allowed to cool, and is stored at below 30^{o}C. When needed for testing, the sample is heated to 140 ± 5^{o}C and poured into the moulds. The sample may not be kept at the preparation temperature for longer than one hour, and this sample may not be reheated.

  Method MB10 (BR2 T): Ball penetration and resilience of bitumen-rubber blends. The penetration of a standard ball into non-aged and oven-aged bitumen-rubber is determined together with the rebound recovery after the ball penetration tool has been pushed a further 10 mm into the material. This test is related to the ASTM tests D3407 and D3408.

- Method MB11 (BR3 T): Determination of the compression recovery of bitumen-rubber blends. The elastic recovery of a 25.4 mm bitumen-rubber cylinder is measured after it has been compressed to half its original height at a temperature of 25°C.
- Method MB12 (BR4 T): Flow test for bitumen-rubber blends. This test measures the flow in mm at 60°C by placing the sample in an oven on a tray inclined at 35°.
- Method MB13 (BR5 T): Determination of the dynamic viscosity of bitumen-rubber blends using a rotary viscometer. The dynamic viscosity in Pa.s at the spraying temperature can be determined in the field as well as in the laboratory by means of the handheld rotary viscometer.

Requirements for bitumen-rubber used for spray applications are given in Table 3 as published by the Southern African Bitumen Association (1992, 2014). Initially these interim requirements in brackets were used, and their application has been valuable in ensuring a quality product. These interim requirements were modified as more experience was gained (SABITA, 2014). It is interesting to note that the usual penetration test is not used, but a ball penetration test which is not affected by individual rubber crumbs.

Table 3. *Requirements of bitumen-rubber for asphalt and spray applications in South Africa (SABITA, 1992, SABITA, 2014)*

Property	Requirements	Test method
Compression recovery	After 5 min 80% min (70%) After 1 hour 70% min (After 4 days: 25-45%)	MB11 (BR3 T)
Hot flow, mm	10 – 50 (20-80)	MB12 (BR4 T)
Ball penetration and resilience at 25 °C, %	13 - 40 (No spec.)	MB10 (BR2 T)
Softening point, °C	55 – 65 (52 – 57)	MB17 (ASTM D36)
Dynamic viscosity at 190°C dPa.s	20 – 50	MB13

It is interesting that the requirements have changed as further experience in South Africa was gained, as evidenced by the changes of the limits for some of the tests. The increase in the softening point is not surprising as the high temperature requirement makes the binder more stable at high road temperatures. The requirement for 70/100 pen bitumen is 42 - 51 ^{o}C, and shows the benefit of using BR in hot climates. The Russian RBV in Table 2 even exceeds the current South African requirement. As discussed, an empirical characterisation of crumb rubber modified (CRM) bituminous binders has historically been the only means of predicting their performance in a pavement. Mturi et al (2014) presented results of an improved characterisation of South African CRM by means of rheological analysis using a dynamic shear rheometer (DSR).

The Russian developments investigated the properties of the bitumen-rubber binder in accordance with performance grade (PG) classification of the American Superpave system (Duhovny et al, 2014). Superpave requirements simulate the operating conditions of binders forming part of asphalt concrete, unlike the conditional indicators of applicable GOSTs. The requirements are based on binder tests of three critical stages throughout the service life of the binder. Tests of the original binder present the first phase of its transportation and storage. The second phase corresponds to the aging of the binder in the preparation of asphalt-concrete mixtures and construction of asphalt-concrete pavement. The third stage simulates aging of the binder during its life. The territory of the Russian Federation is divided into road-climate zones. Zones with the highest interval of the summer-winter temperatures conform to the American PG 64-28 bitumen specification. The surface temperature in the Northern part of the Russian Federation may be lower than -40^{o}C. A comparison of actual RBV results is presented in Table 4. Consequently, as shown in Table 4, the use of the rubber bitumen in the asphalt concrete is possible for the interval from +64 ^{o}C to -43 ^{o}C, which assures the reliable operation of the asphalt in the territory of the Russian Federation. According to ASTM standards, only modified bitumen should be used when a binder with a temperature range of more than 90 °C is required. Note that the bending beam rheometer (BBR) was used to determine the low temperature cracking.

The results of RBV show that:

- the bitumen-rubber binder is slightly affected by asphalt production aging, and its long-term aging index is much less than the requirements. This can be explained by the fact that the rubber in highly oriented state significantly affects the diffusion of oxygen from the environment and inhibits oxidative processes;

- the RBV has a wide temperature range of reliable operation from -43^{O}C to +65^{O}C, which is 16^{O}C higher than requirements.

In South Africa the implementation of the PG classification is being investigated. A typical Fraass brittle temperature of BR in South Africa is about -12^{O}C, but low temperatures are not as low as in Russia. An SBS modified binder Fraass brittle temperature measured in South Africa is about -11^{O}C. These properties are highly dependent on the quality of the source bitumen.

Nevertheless the BR is shown to have superior performance properties, and the Russian binder is of a higher quality than in South Africa, possibly because of a choice of the source bitumen. Airey et al (2004) demonstrate the importance of sufficient light fractions in the bitumen. In South Africa the viscosity during mixing of the bitumen and rubber is monitored and if the viscosity drops rapidly after reaching the peak value, additional extender oil is added to compensate for the deficiency in the bitumen.

Table 4. *Bitumen-rubber in Russia compared with the PG classification (Duhovny et al, 2014)*

Test method	Requirements for PG 64-28 binder	Rubber-bitumen binder (RBV)
DSR (temperature of binder performance in hot periods without rutting), ^oC	>= 64	65
DSR (after RTFO, simulating asphalt production aging of binder), ^oC	>= 64	64
DSR (after PAV, simulating aging during 8 - 10 years of use), ^oC	<= 22	11
BBR (crack resistance at low temperatures), ^oC	<= -28	-43
Temperature operating range, ^oC	92	108

4. Comparison of bitumen-rubber asphalt properties

Table 5 shows the asphalt property requirements of an SMA-15 (SMA grading with 15 mm maximum stone size) of three mixes with a regular 40/60 pen bitumen (BND), a polymer modified bitumen (PMAB) and a bitumen-rubber (RBV). The binder content was 5.7% although GOST 31015-2002 requires that for SMA-15 binder content should be 6-7%.

Also given in the Table are the standard mix requirements according to GOST 31015-2002. Due to the formation of the thick bitumen films in the production of the SMA, the measure of the drainage that reflects the stability of the mix against segregation during the transportation and loading–unloading processes is specified in Russia. The drainage test is performed in accordance to GOST 31015-2002 (Application B). From these results it is evident that the bitumen-rubber mix has superior qualities for all the test results compared with the regular bitumen and the polymer modified bitumen.

Typical mix gradings used in South Africa are given in Table 6. Note that the semi-open graded mix is also known as a SMA. Active fillers, such as hydrated lime or Portland cement can be used to improve adhesion, but not more than 2% is permitted. The selection of the binder content was performed according to the Marshall design method as given in Table 7 (a new asphalt mix design procedure is being introduced). The benefit of using bitumen-rubber is that a higher binder content can be used which gives a longer life, and by ensuring that sufficient voids are present the higher binder content will not result in bleeding (excess binder on the surface).

Table 5. *Physical SMA-15 asphalt properties in Russia (Duhovny et al, 2014)*

Test	SMA-15 BND	SMA-15 PMAB	SMA-15 RBV	GOST 31015 -2002
Compressive strength, MPa				
at 20^{o}C	3.17	3.85	4.53	2.2 min
at 50^{o}C	1.10	1.28	1.44	0.65 min
Shear resistance				
Internal friction, MPa	0.94	0.97	0.97	0.93 min
Shear adhesion at 50^{o}C, MPa	0.19	0.25	0.36	0.18 min
Crack resistance (MPa)				
Ultimate tensile strength at 0^{o}C	3.22	3.01	2.87	2.5 – 6.0
Drainage	0.14	0.12	0.10	0.20 max
Retained tensile strength at 0^{o}C after 15 days soaking	0.86	0.89	0.93	0.85 min

Table 6. *Typical mix gradings used in South Africa (SABITA, 2014)*

Sieve (mm)	Percentage passing by mass			
	Continuously graded		Semi-open graded	Open-graded
	Medium	Coarse		
20		100	100	100
14	100	85 - 100	84 - 100	100
10	80 - 100	70 - 85	68 - 83	55 - 75
5	50 - 75	45 - 65	29 - 43	20 - 30
2	30 - 45	25 - 45	12 - 20	5 - 15
1	-	17 - 30	-	-
0,600	13 - 25	13 - 25	-	-
0,300	8 - 18	10 - 18	-	3 - 8
0,150	-	6 - 13	-	-
0,075	4 - 8	4 - 10	1 - 4	2 - 5

Of interest is that the mix design procedures in Russia and South Africa are completely different as is shown in Tables 7, 8 and 9. The environmental conditions in Russia are extreme and nevertheless the retained tensile strength is obtained after 15 days soaking, whereas the retained tensile strength in South Africa is determined by the Modified Lottman test, which encompasses soaking and freezing cycles and the retained value must exceed 0.8.

Table 7. *Asphalt mix design procedures in South Africa (SABITA, 2014)*

PROCEDURES	REFERENCE
Preparation of asphalt specimens for Marshall testing and voids analysis **Variations:** Mixing and compaction temperatures **Marshall compaction:** Continuously-graded and semi-open graded mixes - 75 blows Open-graded mixes - 50 blows	SANS 3001-AS1: *Making of asphalt briquettes for Marshall tests and other specialised tests*
Determination of bulk density of a compacted mixture and calculation of void content	SANS 3001-AS10: *Determination of bulk density and void content of compacted asphalt*
Determination of maximum theoretical density and bitumen absorption	SANS 3001-AS11: *Determination of the maximum void-less density of asphalt mixes and the quantity of binder absorbed by the aggregate*
Determination of durability (TSR) Modified Lottmann Test	ASTM D4867 M
Determination of dynamic creep	CSIR RMT 004
Determination of indirect tensile strength	ASTM D4123
Fatigue/tensile strength - Semi-circular bending test (SCB)	ASTM D7313-07

Table 8. *Bitumen-rubber asphalt mix requirements in South Africa (COLTO, 1998)*

Property	Requirement
Voids in mix (%)	3 - 6
Voids in mineral aggregate (%)	17 minimum
Indirect tensile strength at 25^{o}C (kPa)	550
Dynamic creep at 40^{o}C for laboratory briquettes (MPa)	10 minimum

Table 9. *Asphalt mix design procedures in Russia*

PROCEDURES	REFERENCE
Analysis of the future operating conditions for the designed asphalt concrete in the structure (vehicle loads, maximum gradient, geological and climatic conditions). The choice of the future asphalt concrete performance type.	GOST 9128 – 2009
Grading design in accordance with the gradation curves. The aim is to design a grading with minimum void content. The grading can be continuous or open-graded.	GOST 9128 – 2009
Practical determination of the optimum bitumen content: Asphalt specimens from the 3 test mixes (each with the different bitumen content) are prepared and tested for compressive strength (at 0, 20 and 50 ◦C)	GOST 12801-84 GOST 31015-2002
Preparation and testing of the control mix specimens: Determination of the physical and mechanical properties (Table 5) and comparison of the results with the GOST.	GOST 12801-84 GOST 31015-2002

Note that the project specifications based on prior experience or research may modify the requirements given in the Standard Specifications (COLTO, 1998). Interestingly in South Africa, the binder content is calculated as the percentage of bitumen, by mass, as a percentage of the total mix (aggregate plus binder). In Russia the binder content is expressed as the percentage of bitumen as a percentage of the aggregate. There are thus small differences in the absolute values of binder content.

5. Performance of bitumen-rubber asphalt

In the Russian Federation the position towards the asphalt concrete pavements modified with rubber crumbs is still a cautious one, despite more than a half-century of intermittent experience of developing such pavements and the modern experience in their use. There are experimental sites built with use of rubber crumbs or rubber bitumen binders that prove significant rutting resistance, crack resistance and aging resistance of such pavements. But the use of these pavements is limited by the absence of the valid regulatory base that would allow the desired performance and control of the quality of the built pavement. All the pavements in the Russian Federation that are built with crumb rubber rely on the regulatory documents developed by the manufacturers of the rubber modifiers. The problem is that these requirements vary greatly. Currently Russia is in a middle of the path that leads to the countrywide construction of the rubber asphalt concrete pavements as the most durable and economically effective solution in the field of road construction. Despite these limitations the good performance has encouraged widespread use. Many projects are located far from asphalt mixing plants, and it is not uncommon to find asphalt mix being transported over 8 hours or more. No detrimental effects have been found, and this confirms the findings of experience in South Africa and elsewhere.

A number of papers have been produced documenting the performance of chip seals constructed with bitumen-rubber in South Africa. However, not much has been documented on the performance of bitumen-rubber asphalt. Sadzik et al (1999) presented the performance of the first 5 years of an open-graded friction course constructed on a road carrying 100 000 vehicles per day on 6 lanes. On sections where the binder content was lower that specified there was initial ravelling (stone loss), whereas on the correctly constructed sections performance was good. Although not published, it is known that this surfacing was replaced after 15 years, with minimal maintenance of the ravelled sections (a slurry seal was placed as a holding action).

During the Gauteng Freeway Improvement Programme (GFIP) many of the freeways after rehabilitation and new construction in some sections, received a bitumen-rubber semi-open graded asphalt during the period 2009 to 2013. Many of the sections have now completed more than 5 years under substantially heavy freeway traffic providing good performance where the mix complied with specifications. In some sections, where the aggregate percentage passing the 0.075 and 0.425 mm sieves was too high bleeding occurred and the asphalt was replaced during the maintenance period.

The South African BR technology was also applied in China. The oldest sections are now 10 years old, and are still performing excellently (Visser et al 2015). This may be compared to typical surfacing lives of asphalt constructed with unmodified or polymer modified binders of 5 years in China.

6. Conclusions and recommendation

Bitumen-rubber asphalt has proven to provide excellent performance in Russia as well as in South Africa, and superior to unmodified binders. The specifications used to manufacture the asphalt in the two countries are substantially different both in terms of the constituent properties as well as the asphalt properties. This demonstrates that local knowledge and experience are important, and that there is no single test protocol that is universally applicable.

From the comparisons presented in the paper the quality of the bitumen-rubber in Russia is better than in South Africa, as good quality bitumen was selected for the Russian study. In South Africa the choice of binder is limited as the refineries are subject to the availability of crude oil compatible with the refining process. The refineries are only controlled by the national standards for the bitumen.

It is important that local experience be integrated into the local protocols and it is recommended that other proven protocols be used as a starting point, but adjusted based on local experience. It is therefore important to carefully document the construction and performance results of projects for a reliable adaptation of protocols.

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