Experience with Semi-Open Graded Asphalt Surfacings in South Africa

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Executive Summary

This paper describes the authors' experience with Semi-Open graded Bitumen-Rubber Asphalt (BRASO) wearing courses on heavily trafficked pavements where superior long-term structural and functional performances were required. The benefits in using these mixes on heavily trafficked roads are their superior fatigue, plastic deformation and binder ageing resistance that result in wearing courses that outperform more conventional asphalt mixes.

Bitumen Rubber Asphalt (BRA) has been used successfully in South Africa since the mid 1980's.

This paper describes the materials, the mixing process, mix characteristics, practical matters relating to the design, construction and post-construction performance of BRA wearing courses used in four projects in Gauteng Province, South Africa. The wet method was used on two of the projects with the dry process on the other two, for the production of the BRASO. Stricter quality control procedures on BRASO mixes, although initially considered to be cumbersome, proved to be essential to ensure consistent and acceptable mixes. Stringent monitoring of binder viscosity, digestion period and mixing temperatures, as well as the storage and binder content itself, proved to be crucial for the successful construction of BRASO wearing courses.

The differences in approach by following the wet and dry methods with respect to mix design, construction and quality control of BRASO mixes are described in the following paper.

The paper concludes with the identification of areas where improvements are still required.

1.0 Introduction

Bitumen-rubber technology has been used in South Africa since the mid 1980's in an attempt to improve the performance of hot mix asphalt to achieve:

- Increased binder softening point and higher binder viscosity resulting in increased binder film thicknesses and reduced drain-down of binder especially in open-graded mixes;
- Increased durability and long-term performance of the wearing course mixes due to the presence of carbon black in the rubber tyres which improves ultra violet resistance;
- Improved flexibility of the binder due to the presence of the elastomeric polymer in the crumb rubber. This allows the BRA to tolerate higher deflections and offer greater resistance to reflective cracking;
- Increased resilience and toughness of the binder which renders the mix more resistant to deformation;
- Reduced temperature susceptibility; and
- Improved fatigue resistance.

Many authors over the years have reported the superior performance of BRA surfacings over conventional mixes. Potgieter **[1]** reported that the somewhat higher initial cost of the BRA is more than off-set by the extended service life and the reduced thickness requirements.

The performance of BRA mixes in South Africa has been outstanding, especially on highly trafficked roads and pavements incorporating cement stabilised layers (prone to cracking or having already cracked). This success was highlighted in a 1998 report on the 12-year service life of BRA on an interchange near Johannesburg in South Africa (the Buccleuch Interchange) **[2]**.

This paper reports on the use of BRA mixes and experiences on four pavement rehabilitation projects in Gauteng Province, South Africa, by applying two different production processes— "dry" and "wet" methods.

2.0 Bitumen Rubber Asphalt Production Processes

2.1 Dry Method

BRA has been used successfully in South Africa since its introduction in the early 1980's **[3]**

The dry method is ideally suited for batch mix plants with insulated storage bins. The aggregates are pre-heated at 200–210ºC. The rubber crumbs were added to each batch and mixed with the aggregate for 15- 20 seconds. The bitumen binder was heated to 150–170ºC and introduced into the pugmill. Mixing took place within a few seconds and the uniform mix was then transferred to the insulated storage bins where the mix was stored for the required storage time. The storage time depends on the reaction time (at a given reaction temperature) and the time required for transporting the mix to site. For two of the projects describer below, the transport time was approximately one hour, so the storage time had to be approximately one hour. The reaction time for the BRASO—dry method mixes made at a particular plant was approximately two hours at 195°C. No earlier than two hours and no later than four hours after mixing, the mix was discharged into the paver at approximately 185°C.

Rolling with the three-point steel wheeled roller started when the temperatures were in the order of 165°C, followed by the pneumatic roller.

A typical BRA—dry method mix composition for the dry mixes comprises: **[3]**

- 60/70 penetration bitumen: 6%
- Rubber crumbs: 2%
- Aggregates: 91%
- Filler (hydrated lime): 1%

In the dry method the granulated rubber from tyres is introduced into the pre-heated aggregate prior to the introduction of the bitumen binder. **Figure 1** below illustrates the "dry' method for manufacturing BRA.

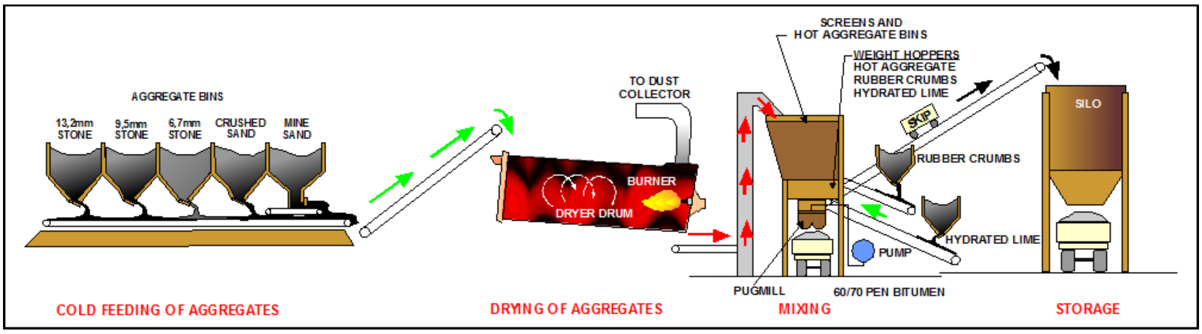

Figure 1 **BRASO (Dry method) Mixing Process**

Results from viscosity test conducted on bitumen-rubber binder extracted from asphalt mixes are included in **Table 1** below. Note the extremely high viscosity of the binder at different ages after mixing. The viscosity of the bitumen-rubber binder (up to 15000 cP) was approximately 75 times more viscous than a conventional 60/70 penetration bitumen (C320 in Australia) which is approximately 200 cP.

Table 1 **Rubber Crumb & SAPREF 60/70 pen Bitumen Blend – Digestion Period at temperature of 195°C**

Time in minutes	Viscosity (cP)	Softening Point (°C)
60	9000	72,3
120	15000	79,7
150	15000	74,9

Time in minutes	Viscosity (cP)	Softening Point (^{o}C)
180	14000	73,6
240	14000	72,5
300	10000	70,5
360	8000	65,2

2.2 Wet Method

Bitumen rubber “wet” method has been used in South Africa in 1983 **[4].** The wet method technology was introduced in South Africa from Arizona in the United States under the brand name of Arm-R-Shield. In the wet method, the rubber crumbs are pre-blended with the base bitumen before mixing with the heated aggregates. This has become the preferred practice for manufacturing BRA in South Africa.

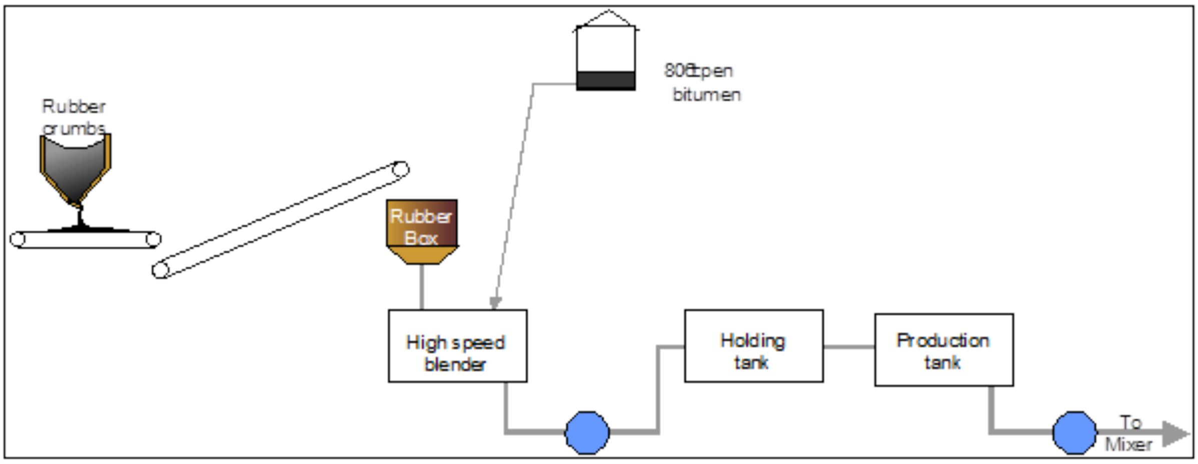

Figure 2 BRASO “Wet” Method – Bitumen and Rubber Crumbs Blending Process

The bitumen-rubber blends in the “wet” method were prepared in a patented blender. An 80±6 penetration bitumen was blended with rubber crumbs (20% of the blend in weight) at the asphalt mixing plants used for the respective projects.

The rubber crumbs from ground scrap tyres were obtained from specialist suppliers. Rubber crumbs had to comply with the latest standard technical specifications available at the time.

The optimum mixing and digestion temperatures and times were determined by evaluating the relationships of the viscosity, ring and ball softening point, compression recovery and flow versus temperature and time of the ARM-R-Shield bitumen-rubber blend. **Figure 3** depicts the viscosity-time relationships for the blend at different temperatures. The blending temperature was kept at 185^{o}C and reaction time ranged, at that temperature, between 45 minutes and one hour.

The viscosity of the bitumen-rubber blend generally varied between 2,000 and 3,000 cP during the reaction time compared to the approximately 200 cP of conventional binders. Therefore, it is crucial to lower the viscosity of the bitumen-rubber blend as far as possible to enable the pumping of the bitumen-rubber blend into the mixer.

The bitumen rubber blend produced by means of the wet method consisted of:

- 78% of 80 ± 6 penetration bitumen
- 20% of rubber crumbs (bulk density: 280-350 kg/m^3, max fibre length: 5 mm)
- 2% of extender oils

Typical viscosity/ time relationships of the rubber crumbs and the bitumen are depicted in **Figure 3**

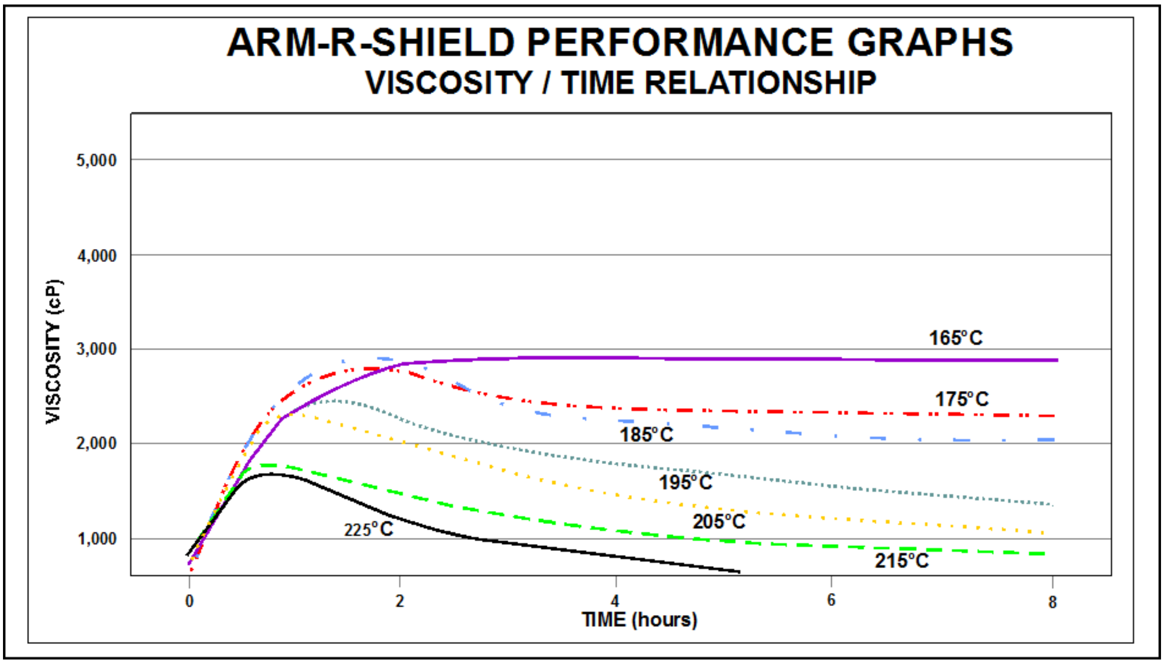

Figure 3 Arm-R-Shield Performance Graph – Viscosity versus Time

- The mixing process is depicted in **Figure 4.** Aggregates from the cold feed unit were fed by volume into the counter flow dryer (inner drum). In the double-barrel mixer, the dryer is equipped with flights around it, due to the mixing taking place between the dryer and the outer drum or coater. The binder and the filler were added to the aggregate in the coater, far enough from the burner to avoid binder burning. The bitumen-rubber blend was pumped into the outer drum by a vacuum pump. The final mix composition for the BRASO overlays was as follows:
    - Bitumen-rubber blend : 7.5% to 8%
    - Aggregates : 91% to 91.5%
    - Active filler (hydrated lime) : 1%

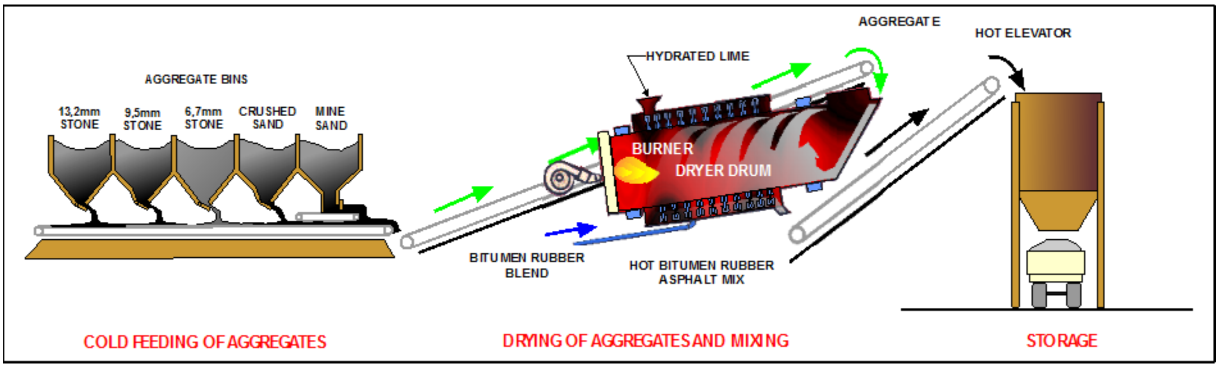

Figure 4 BRASO (Wet method) Mixing Process

The complete process for the preparation of the mix, starting from the blending of the rubber crumbs and the bitumen and ending at the paving site is summarised in **Figure 5** where temperatures and times are also shown.

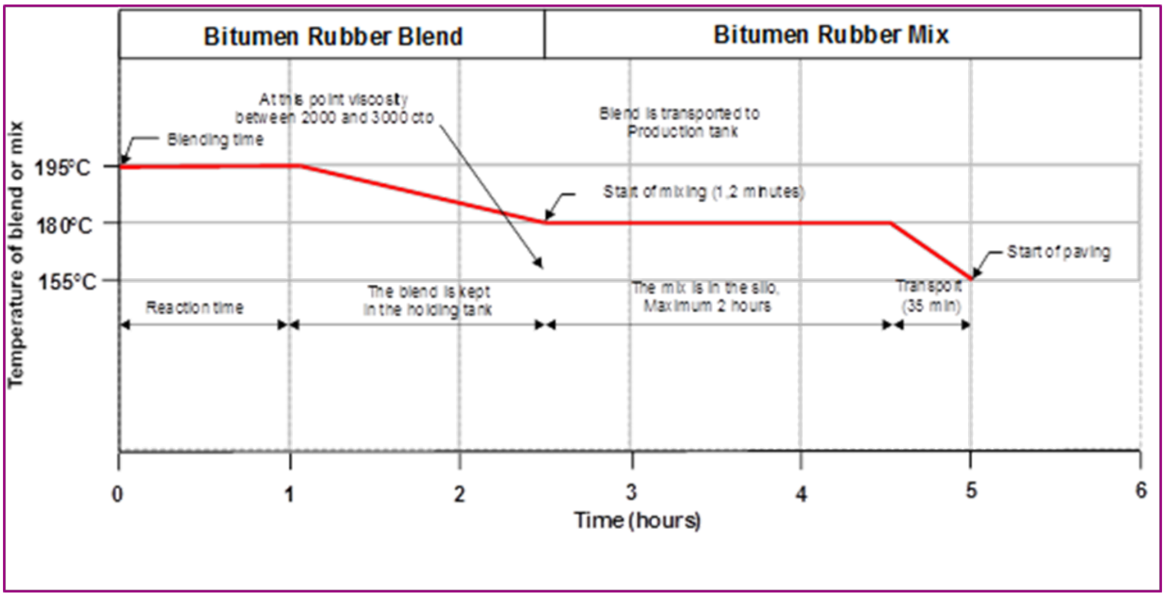

Figure 5 Time and Temperatures for blending, mixing and paving

The bitumen-rubber binder was mixed with the aggregates at the double-barrel drum. The mixing of the binder and the aggregates occurred immediately before the hydrated lime filler was added.

3.0 The four Projects

3.1 Brief Description

3.1.1 N3-12 National Highway, Johannesburg, South Africa

N3/12 (the section from Modderfontein Interchange (I/C) to Buccleuch I/C) is part of the ring road around Johannesburg. The road carried 121,000 vehicles per day in 1998, of which 10% were heavy vehicles.

The road was widened and rehabilitated in 1986/ 1987 with the existing asphalt and cement treated crushed rock base in the slow lane being recycled with bitumen emulsion into a new 100mm thick base. The entire road was then overlaid with a 100mm emulsion treated base and a 40mm asphalt surfacing.

In 1999, repairs were undertaken on distressed pavement areas and a BRASO—wet method overlay applied over the existing semi-gap graded asphalt surfacing or on a new dense graded asphalt course where repairs were undertaken. The existing pavement over which BRASO was applied included 40mm of semi-gap graded asphalt, 100mm emulsion treated base and 200- 300mm cement stabilised sub-base layers. The rehabilitation included the milling-out and replacement of distressed pavement layers with dense graded asphalt (AC20).

A section of the N1-20 highway at Buccleuch I/C was also part of the project scope. This section was resurfaced in 1986 / 1987 with a BRASO overlay which was found to be in excellent condition in 1999. No repairs were needed at that time.

3.1.2 Provincial Roads P88/1 and P24/1, City, South Africa

The BRA—dry method production technology was adopted for two heavily trafficked Gautrans roads, P88/1 and P24/1:: **Road P88/1—**the pavement rehabilitation that took place in 1999 included localised repairs, a single/ single seal and a 40mm BRASO—dry method overlay. The existing configuration of the pavements of divided four-lane carriageway of Road P88/1 included a 40mm semi-gap graded asphalt mix over a heavily stabilised base layer and two cement stabilised sub-base layers. At the time of the BRASO overlay application in 1999, the heavily stabilised base already exhibited fatigue cracking as well as shrinkage cracking in places. The AADT was 21,600 vpd with 15% being heavy vehicles. The rehabilitation of the P88/1 pavements included repairs consisting of milling-out distressed pavement areas and backfilling with dense graded asphalts, and th application of a single/ single seal and a 35mm BRASO—dry method overlay.

Road P24/1—consisted of a divided carriageway with two lanes in each direction. Road P24/1 pavement configuration consisted of a double/ double seal over two cement stabilised layers. The average annual daily traffic (AADT) on the project section of Road P24/1 was 5,300 vpd with 15% being heavy vehicles. Distress types observed on this pavement included fatigue cracking in the wheel paths, stabilisation cracks and potholing. The rehabilitation of the P24/1 pavements included the in-situ recycling of base and surfacing at locations into a new foamed bitumen modified base, the application of a single/ single seal and a 35mm BRASO—dry method.

3.1.3 N1/21 National Highway, South Africa

BRASO—wet method overlay was provided as overlay on National Route 1 Section 21: Brakfontein I/C (km 14 to km 24 just north of the R21 I/C). This is a section of the national route between Pretoria and Johannesburg. . The AADT of the six-lane divided carriageway was 123,000 vpd. with 4.9% being heavy vehicles.

This section of the N1 highway was upgraded and rehabilitated 10 years earlier when a Stone mastic asphalt (SM14) surfacing was provided. In 2008 the pavement condition was fair but had signs of aggregate stripping from the binder within the SM14 wearing course and cracking due to base fatigue of asphalt layers deeper in the pavement.

The pavement rehabilitation undertaken in 2008/ 2009 consisted of the following:

- Mill-out existing SM14 surfacing, so existing surface levels could be retained
- Base repairs by milling out existing distressed pavement materials and replacing them with asphalt base
- Application of a 10mm polymer modified (PMB) single/ single seal
- Re-surfacing with 40mm BRASO—wet method.

3.2 The Mix Design Processes

The mix design processes followed for all four projects included:

- Selection of the mix type to achieve design objectives (structural and functional properties). For all four projects, the selection of the BRASO mixes was dictated by the need for wearing courses with high resistance to fatigue cracking, high resistance to plastic deformation, high resistance to crack propagation from lower cement stabilised layers and a durable wearing course with adequate functional properties.
- Selection of mix type and gradation.
- Evaluation of mix components: aggregates, bitumen, rubber crumbs, bitumen-rubber blend.
- Volumetric evaluation: selection of target gradation and analysis of volumetric parameters: VMA, VIM, binder film thickness.
- Performance related tests: permanent deformation, fatigue, durability, moisture sensitivity.
- Selection of target grading and binder content.
- Trial sections.

As an example of the volumetric analysis and selection of target grading and binder content, the process followed for the BRASO placed on N1/21 can be summarised as follows:

- Theoretical and laboratory sieve analyses trials were performed to obtain gradings that could be expected to produce the required volumetric properties.
- With 7.5% bitumen-rubber, the VFB was expected to be between 71% and 74% and the air voids (VIM) approximately 6%.
- The passing 2.36mm fraction was 17% and it was decided not go finer due to risk that the VFB might close up (i.e. become >80%).

- Considering the gyratory voids, the best suited combined grading would be used as the target with additions of between 7% and 8% binder.
- Initial indications were that the gyratory voids and air voids (7.5%) were too high with 7.5% binder.
- The intention was to aim for a VFB between 71% and 75% and air voids of between 5.5% and 6%, with a film thickness of sub 27 micron.
- It was also decided that the Bulk Relative Density (BRD) determinations be undertaken after two hours when the resilience of the particular bitumen-rubber product achieved an 'optimum'.

3.3 The mix components

3.3.1 Bitumen

The bitumen had to comply with the requirements of the relevant South African National Standard (SABS 307) for penetration bitumens.

3.3.2 Rubber

Rubber was obtained by processing and recycling rubber tyres. The pulverised rubber had to comply with requirements that limited or prohibited the presence of certain contaminants such as fabric, steel cords, calcium carbonate or talc. Calcium carbonate or talc is sometimes added to prevent rubber particles from sticking together. The rubber also had to comply with strict grading requirements (100% passing 1.18mm sieve and 0-5% passing sieve 0.075mm sieve) and rubber intrinsic properties such as fibre length (mm) and poly-isoprene content.

3.3.3 Highly Aromatic Extender Oils (wet method)

The wet method also required the introduction of highly aromatic extender oils to reduce the binder viscosity and to extend the shell life of the bitumen-rubber blend. These extender oils had to be added in proportions less than 3% by mass of blend.

3.3.4 Bitumen-rubber Blend (wet method)

The bitumen-rubber blend in the wet method had to comply with certain requirements. The latest available requirements for bitumen-rubber blends are summarised in the Sabita Manual 19 **[5]** which are practically the same requirements that existed at the time the reported projects took place, are include:

- Bitumen penetration grade: 80/100
- Rubber by mass of the total blend: 20%–24%
- Extender oil by mass of the total blend: 3% maximum
- Blending reaction temperature: 170^{o}C- 210^{o}C
- Reaction time: 45 minutes minimum. The reaction time commences when all the rubber crumbs have been added to the blend and the blend temperature reaches the asphalt mixing temperature.
- Typical shelf life at mixing temperature: 6 hours
- Compression recovery: 5 minutes: > 80%, 1 hour: > 70%
- Ring & Ball Softening Point: 55 – 65^{o}C
- Resilience @ 25ºC: 10–50(%)
- Viscosity: 20-50 dPa.s

3.3.5 Bitumen Rubber Properties (dry method)

The same bitumen penetration grade requirements as well as its percentage by mass of the total bitumen-rubber blend that apply to the wet method also apply to the dry method although the dry method is more forgiving in regard to the binder penetration grade.

3.3.6 Aggregates

Aggregates had to comply with resistance to crushing, shape, polishing, adhesion and absorption requirements.

It is also important to limit fine dust or clay like materials in the fine aggregate fraction. Therefore a sand equivalent of at least 50 is generally required.

3.3.7 Grading

The various mixes produced for the four sites via the dry or the wet methods had aggregate size distributions falling inside the BRASO envelope shown in **Figure 6. Figure 6** also illustrates the differences between the grading of BRASO mixes and those of typical Queensland Transport & Main Roads TMR dense graded and open graded asphalt mixes.

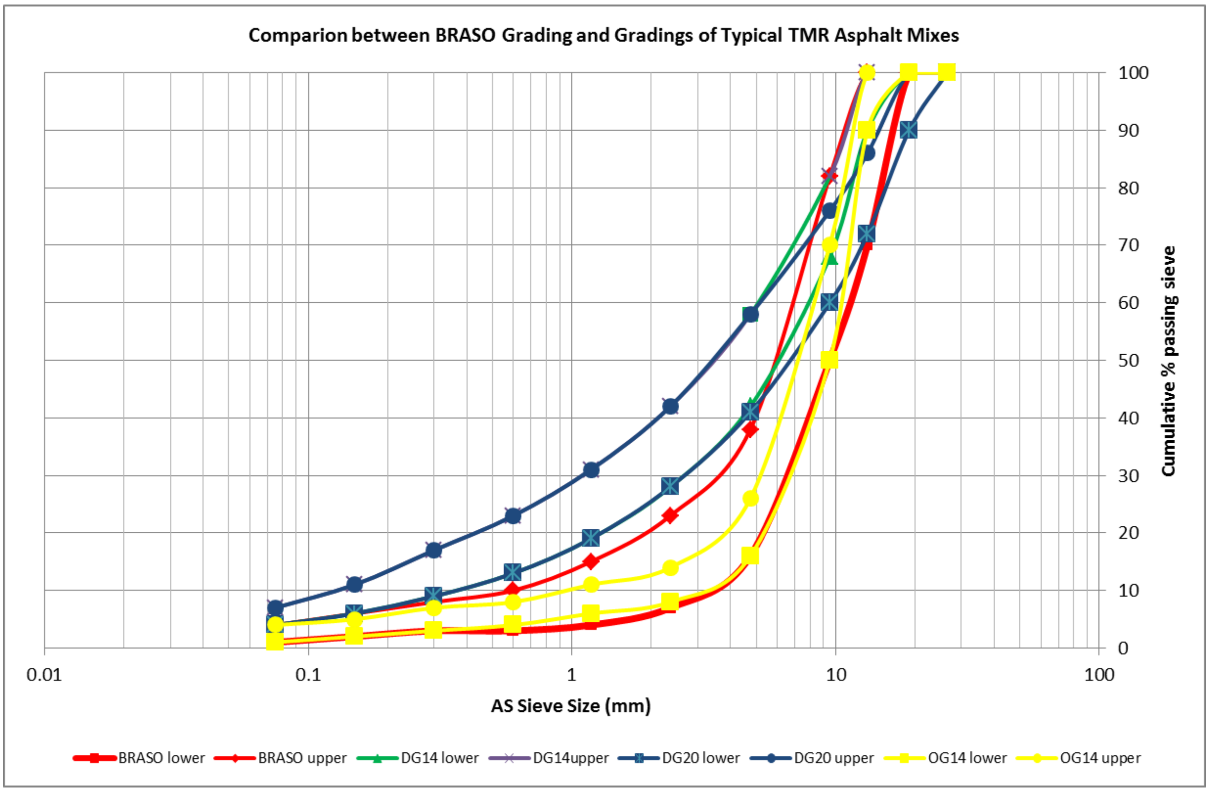

Figure 6 Comparison between BRASO grading envelope and TMR typical asphalt grading envelopes

For each of the four projects, Contractors were requested to provide a number of candidate mixes and construct a number of trial sections before the preferred mix was adopted.

3.4 Theoretical Determination of BRASO Volumetrics

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To control the grading of the mixes theoretically calculated, based on the available aggregate fractions, a grading control was undertaken in the laboratory. Samples were prepared in the laboratory to check whether the specified mix requirements were met.

Test briquettes were manufactured in accordance with the procedure described in TMH1, method C2 **[6]** and tested to Marshall stability and flow as well as % voids in the mix in accordance with the procedure described in TMH1, methods C1 to C3. The briquettes were compacted by applying 50 blows on each of the faces of the specimen (for conventional mixes 75 blows per face are usually applied). In terms of the volumetrics of the mixes, the specification requirements as well as the results obtained from production mixes are shown in **Table 2** below.

For the Roads P88/1 and P24/1, a mix grading similar to the one chosen for the Route N3/12 was adopted and subjected to the same testing as the mix for Route N3/12.

3.5 Properties of BRASO mixes

3.5.1 Design Criteria and Test Results

Table 2 summarises the test results for candidate mixes for all four projects and well as the end product specification for the BRASO. Asphalt briquettes were made of production mixes compacted with 50 blows per face of the briquette. Binder contents were calculated with the conversion factor.

Table 2 BRASO End Product Specification and Summary of Test Results from Volumetric Evaluation of Candidate Mixes

Test	BRASO Specifications	Range of results obtained BRASO at the 4 project sites		
		N3-12	**P88/1 & P24/1**	**N1-21**
Bitumen – rubber content (%)	7 - 8	6.9 – 8.2 Adopted: 7.5	7.4 – 8.6	7.0 – 8.0 Adopted: 7.5
Marshall Stability (kN)	min. 6	3.2 – 6.9	5.3 – 5.9	7.1 – 9.0
Marshall Flow (mm)	2 – 5	1.7 – 6.3	4.2 – 7.9	2.1 – 2.2
VMA (%)				20 - 22
VFB (%)				71 - 74
Voids in Mix (%)	3 – 6	4.5 – 8.4	6.2 – 9.1	4.0 – 8.7 Adopted: 7.0
Indirect Tensile Strength (kPa)	min. 600	199-999		565 - 649
Immersion Index (%)	min. 75	73–86	69,6–84,4	80.1 – 92.1
Static Creep Modulus (MPa.s)	min. 80	57.,8 – 156.4 (average = 114.5)	63.9 – 98.4 (average = 81,15)	
Dynamic Creep	min. 15	4,4-17,2 (average: 11,1)	10,8 – 15,2 (average = 13.5)	
Film Thickness	min. 18	20 - 23	21- 25	28 – 31
Air Voids @ 300 Gyratory Compactor gyrations	min. 3			6.02 – 5.06
Modified Lotman	Min. 75	Cores = 85.8	Cores = 81.3	> 80
Cantabro Abrasion	-----	2.1 – 2.7	0.83 – 1.93	4.8 – 3.3
Wheel Tracking Test – Soillab (mm)	----	1.8 – 2.3	1.0 – 1.4	----
Transportek Wheel Trucking Test (WTT) (mm / wheel passes)		7 mm after 4000 wheel passes	----	----

3.5.2 Discussions of Results

3.5.2.1 Marshal Stability and Flow

The applicability of the Marshall stability and flow tests is debatable since these tests should be conducted until the maximum load (point at which the briquette collapses) is attained. BRASO briquettes never collapsed but continued deforming. The Marshall stability measured was the maximum load attained.

The Marshall stabilities measured on BRASO—wet method mixes were lower than those measured on BRAS—dry method mixes for similar binder contents.

3.5.2.2 Film Thickness

The film thickness on these mixes were significantly higher than those of conventional mixes (between 20 and 31 microns).

3.5.2.3 Indirect Tensile Strain

The Indirect Tensile Strain Test (ITS) was performed by loading a cylindrical specimen with a single compressive load which acts parallel to and along the vertical diameter plane. This test was performed at 25^{o}C at a rate of 50mm/min. This loading configuration theoretically develops a relatively uniform tensile stress perpendicular to the direction of the applied load and along the vertical diametrical plane. With the exception of isolated results, the specifications were never met by any of the mixes. Damage to the briquettes after testing seldom occurs.

ITS tests were considered to have limitations for these mixes as the briquettes deformed or squeezed without breaking in most cases. **Figure 7** illustrates the condition of a BRA—wet method briquette and a conventional continuously graded asphalt briquette. Note how the BRA briquette deformed without cracking. The continuously graded asphalt briquette did not deform but cracked.

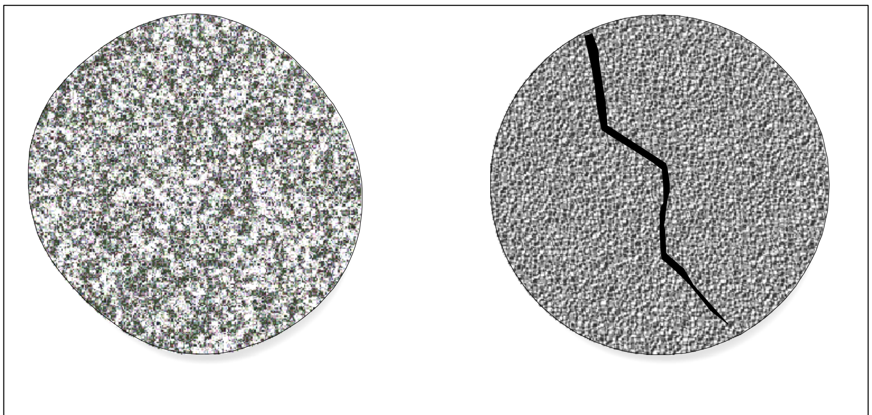

Figure 7 BRASO and dense graded asphalt briquettes after ITS testing

3.5.2.4 Static Creep

Low static creep test results were generally obtained. These test results did not reflect the rut resistance of the mixes.

3.5.2.5 Dynamic Creep

Creep is high temperature progressive deformation at constant stress. The creep test involves a tensile specimen under a constant load maintained at constant temperature. Dynamic creep tests were conducted on Marshall briquettes placed between circular plates by applying a load of 100 kPa (800 N) as a square wave for one second and by removing it for one second for 3600 cycles, 120 minutes at a temperature of 40^{o}C. The strain of the sample was measured after initial conditioning of 30 load cycles until the sample had been subjected to 3600 load repetitions. The creep modulus was calculated as the reciprocal of the creep compliance, which was calculated by dividing the total strain observed (function of time) by the applied stress. Initially, two briquettes were tested by Bitutek laboratory. One briquette failed and for the second, a tensile strength of 4 MPa was calculated from measured the total strain by the applied stress. Such poor results could have been caused by over-compaction of the briquettes before testing, as 75 instead of 50 blows were applied on each face of the briquettes. A number of tests were conducted at a later stage by the Council for Scientific and Industrial Research CSIR on briquettes made with production mixes. High variability was observed and the results hardly ever satisfied the specification requirements (15 kPa minimum).

The dynamic creep test was found to be of dubious applicability to BRASO mixes as a result of the lack of confinement of the briquettes during testing, unlike the condition on the road. Due to the lack of confinement of the samples during testing, low creep module values were obtained in most cases.

3.5.2.6 CSIR Transportek Third Point Loading Fatigue (TPLF) Test – Fatigue Resistance

This test can be conducted on beam specimens cut from slabs prepared in the laboratory from mixes manufactured in the laboratory or a production mix and compacted using the Transportek Rolling Wheel Compactor (TRWC), and on beams cut from the road. For the determination of the fatigue resistance of the N3/12 and the Vereeniging BRA mixes, the tests were conducted on beams manufactured in the laboratory using production mixes. Repeated sinusoidal loads were applied at the third points of a beam specimen. The load rate was 10 cycles per second (10 Hz) at 5^{o}C. The tests were conducted at fixed strain levels and the number of cycles was measured until crack initiation occurred. Crack initiation was that specified in the Strategic Highway Research Program 2 SHRP2 study, that is, when the initial stress had reduced to 50% of its initial value. Two or three points (two or three strain levels) were determined. The test proved to be of significantly long duration if it was conducted at relatively low strain levels. Plots of fatigue data using constant strain mode of loading for both BRA types are shown in **Figure 8**.

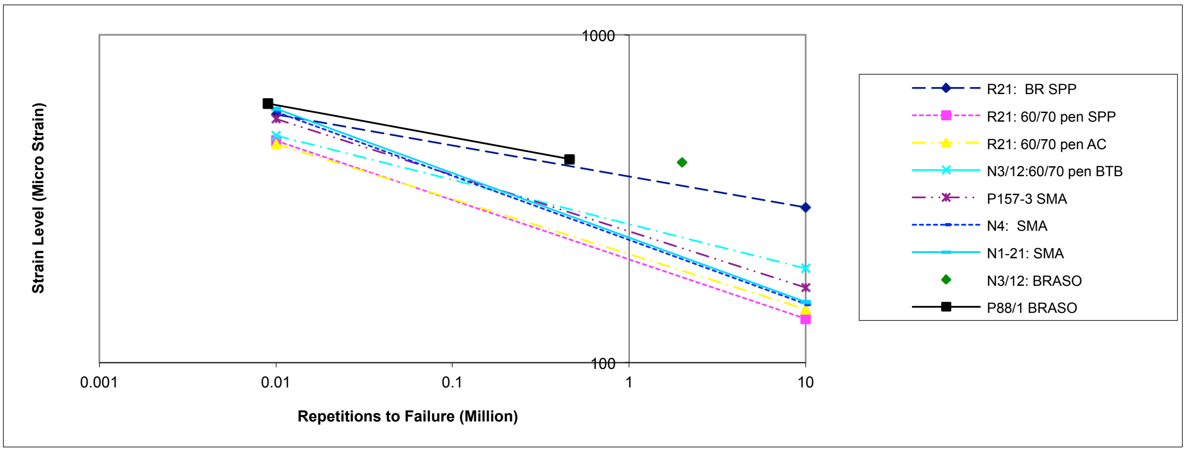

Figure 8 Third Point Loading Fatigue Test Results

The TPLF test results on both BRA types demonstrated that the resistances to fatigue of these mixes were outstanding, as expected. No other mix tested showed the performance of the bitumen-rubber mixes from these projects. It was found that this test should be performed on beams cut from the road rather than specimens compacted in the laboratory.

3.5.2.7 Wheel tracking test (WTT) Test Results

BRASO mixes were tested by means of the Hamburg Wheel Tracking Test which measures the combined effect of rutting and moisture damage by rolling a steel wheel across the surface was used to evaluate the rut resistance of the mixes. The apparatus consists of a 205mm diameter loaded wheel running on a linear wheel track along the upper side of the specimen which is installed in a sealed container and is encased in gypsum in a smaller steel container. The large container was sealed at the top with a flexible neoprene membrane. The test was carried out on soaked specimens under water at 40^{o}C. The specimens were 220mm long and 75mm wide, while the width of the wheel was 47mm. The total load per wheel was 17.755kg with a contact stress of approximately 2.2 MPa. The measurements were taken after 5000 cycles.

For this project, the specimens were compacted to 95% and 100% of the Marshall densities of briquettes manufactured with the same production mix and compacted with 50 blows per face. Usually, the test is only conducted on samples compacted to 95% of the Marshall density. The criteria to assess the rutting resistance of mixes depend primarily on the thickness of the layer, operating temperature and traffic loads and speeds.

A number of tests were carried out to assess the performance of the preferred bitumen-rubber mixes. Even though deformations ranging between 1mm and 2mm were expected based on previous testing on conventional mixes, the test results on both bitumen rubber mixes ranged between 1.7mm and 2.5mm. However, the results obtained on a Superpave bitumen-rubber mix laid on Road P157 (R21) in 1997 ranged between 2mm (5.5% binder content) and 4mm (6.5% binder content). It was suspected, however, that bitumen-rubber specimens may have rebounded from the static compaction and that the testing had achieved re-compaction rather than rutting.

Test results on BRASO—dry method mixes were significantly better than those from BRASO—wet method mixes.

3.5.2.8 CSIR Transportek Rut Tester (TRT) Test Results

BRA slabs (with dimensions length: 655mm, width: 345mm and thickness: 60mm) were compacted in the laboratory using the Transportek rut tester which was fitted onto a 60mm thick base made out of polyurethane with a stiffness of approximately 20 MPa that was chosen to facilitate the development of higher strains in the asphalt while using relatively low loading conditions. Twenty two passes per minute of a 390mm diameter, 600kg stationary smooth tired solid rubber wheel (width: 100 mm) were applied to the moving asphalt slab (reproducing the conditions created by a moving wheel onto an stationary asphalt slab). Strains on the asphalt slab were measured by strain gauges attached to the bottom of the BRA slabs.

The TRT seemed to be an adequate way of measuring the rut resistance of the mixes. However, it became apparent that little data existed against which to assess the test results. To make matters worse, the test method was modified (the stroke was lengthened) since its development stage resulting in a smaller historical data-base available as a reference.

The rate of deformation of the bitumen-rubber—wet method mix placed on the N3/12 was similar, after an initial densification, to that of the SMA mix placed on the N1/21 in 1999 between Rigel Interchange and Brakfontein.

3.5.2.9 Cantabro Abrasion test

The test consisted of measuring the loss in weight of a specimen before and after it was subjected to the abrasion effect of 300 revolutions at a speed of 30 rpm of the Los Angeles Machine without any steel spheres at a temperature of 25^{o}C. This test was developed to evaluate open graded mixes although it was thought that some indication of the cohesion of the semi-open graded mixes could be obtained when comparing the candidate mixes in both projects.

The results from the tests conducted on the BRASO mixes show that the mixes were neither water susceptible nor prone to abrasion by traffic. Output data from Cantabro tests were conducted on cores drilled from the BRASO overlay paved in 1987 on Route N3/12 at Buccleuch I/C (results ranged from 7,8 to 42,9, average: 30,4) clearly indicate that the newly paved mixes are abrasion resistant. Cantabro tests were also conducted during the mix design stage to evaluate candidate mixes.

3.5.2.10 Immersion Index

TMH1 Test method C5 consists of testing a set of six Marshall briquettes as follows: three Marshall briquettes after immersion in water at 60^{o}C for 30 minutes and the other three after immersion in water for 24 hours at the same temperature of 60^{o}C.

Immersion indices of briquettes and cores from the four projects under discussion were all higher than 75%.

3.5.2.11 Modified Lotmann's test

The test modified test method [7] was followed. The test consisted of conducting ITS testing on a set of six briquettes of a particular mix. The test was conducted on three of the briquettes in dry condition and on the other three after they were soaked in distilled water at 60^{o}C for 24 hours.

3.6 Functional Properties

3.6.1 Skid Resistance and Texture Depth

3.6.1.1 Grip Tester

The three wheeled trailer which measures friction by the braked smooth tread tyre wheel (fixed slip principle) made to ASTM specifications was used to measure the skid resistance of a number of asphalt surfaces throughout Gauteng. The BRA (dry and wet method) used in these projects were compared against other asphalt surfacings, some were recently constructed while others were in place for a number of years. The tests were conducted at two trailer speeds (50 and 80km/h) and two water film thicknesses (0.25 and 1mm). A summary of the test results is included in **Table 3**.

3.6.1.2 Gautrans Sand Patch Test

This test is a combination of two other tests: Method ST1 **[8]** widely applied in South Africa (especially before re-surfacing activities), and the Glass Beads Test which is normally applied on asphalt surfaces rather on seal surfaces. The test consists of spreading the sand in a circular fashion and that the surface voids are filled without leaving an excess of sand. The diameter of the circle is then measured and the surface texture depth is calculated and expressed in mm. Sand patch values are included in **Table 3** below.

3.6.1.3 Summary and discussion of results

Table **Table 1** summarises the skid resistance test results from a microtexture (Grip Tester) and macro-texture (Gautrans sand patch) viewpoints.

Table 3 Skid Resistance and Surface Texture Depth

Road / Asphalt	Asphalt Wearing Course	Year of Construction	Skid Resistance – Grip Tester (Avg. GN)		Surface Texture – Gautrans Sand Patch Test (mm)
			50km/h – 0.25mm water film	80 km/h – 1mm water film	
N3/12 – Modderfontein to Buccleuch	BRASO (wet method) – Mix 1B	1999	0,80	0.68	X
N3/12 – Modderfontein to Buccleuch	BRASO (wet method) – Mix 2B	1999	0.69	0.59	1.13
N3/12 – Modderfontein to Buccleuch	Asphalt semi-gap graded with rolled in chips	1986	0,73	0.63	1.21
N3/12 @ Buccleuch I/C	BRASO (wet method)	1986	0,71	X	1.33
P158 (R28, Ben Schoeman)) –	SMA	1998	0,72	X	X
P158 (R28, Ben Schoeman):	BRA-AC (wet method)	1998	0,71	X	X
N4 – Pretorius Street to Vermooten Str I/C	SMA	1998	0,62	0.56	0.98
P88/1 & P24/1 – Vereeniging	BRASO (dry method)	1999	0,59		0.93 / 0.86
R21 – Pretoria to Airport	BRA-AC Superpave (wet method)	1998	0,59	0.45	0.58
N1-21 – Rigel I/C to Brakfontein I/C	SMA	1999	0,58	0.60	0.90
N1-21: Rigel I/C to Brakfontein I/C	BRASO (wet method)	2009	X	X	> 1.0

From **Table 3** above, BRASO—wet method wearing course offered an adequate skid resistance as shown by the Grip Tester Measurements, comparable to skid resistance measured on SMA wearing courses on other roads. Surface texture depth measurements of approximately 1mm would minimise the risk of aquaplaning during wet weather.

Surprisingly, the Grip Tester measurements of both roads P88/1 and P24/1 were not as good as Route N3/12, probably as a result of a less sticky binder being used. In terms of macro-texture, the BRASO—dry method wearing course paved on Roads P88/1 and P24/1 resulted better than that of the BRASO—wet method wearing course of Route N3/12.

3.6.2 Water and air permeability

Water **[9]** and air permeability **[10]** tests were conducted on cores from BRASO surfacings. The wearing courses placed on N3/12, P88/1 and P24/1 were found to be permeable. Permeable BRASO wearing courses should be combined with waterproofing seals to prevent water ingress into lower layers, or, if the lower are impermeable, to minimise the risk of aggregate stripping from layer immediately below the BRASO wearing course.

Air permeability tests results ranged between 2.4 and 2.5 x $10^{-8}cm^2$ for the BRASO—wet method and between 2.9 and 7.9 x $10^{-8}cm^2$ for the BRASO—dry method. Water permeability test results ranged between 0.07 and 0.082 10^{-5}cm/s for the BRASO—wet method wearing course.

3.7 Construction Issues

The following construction issues were of notable mention.

3.7.1 Integrity of the bitumen-rubber blend

The integrity of the bitumen-rubber product should be monitored vigorously prior to mixing with the heated aggregates in the wet method. For the wet method, the degree of reaction between the bitumen and the rubber of the bitumen-rubber blend can be properly controlled by measuring viscosity, flow and compression recovery. Bitumen rubber degrades rapidly at temperatures in excess of 200°C. Therefore the blending of the bitumen and the rubber crumbs generally takes place in close proximity of the asphalt mixing plant. To have close control by means of viscosity – temperature – time charts as that shown in **Figure 3** is of utmost importance.

3.7.2 Determination of binder content of bitumen-rubber (wet method) mixes:

During the process of manufacturing bitumen rubber, the rubber crumb becomes digested by the bitumen. Binder content determinations during the manufacturing process will be subject to a correction factor as some of the undigested rubber is not accounted for during the extraction process. A correction factor is required to determine the actual binder content of a mixture (Cf = Actual Binder Content / Extracted Binder Content).

When determining the grading of the mixture, the fines get stuck in the binder and the extraction % as per test is up to 1.5% less than the actual %. It is recommended that the slush is added to aggregate to determine the BC.

In spite of the use of the factor to determine the "true" binder content, the authors experience is that high variability can still be expected.

3.7.3 Compaction control

92% and 93% of the Rice's maximum theoretical density were specified for the Route N3/12 and Roads P88/1 and P24/1 respectively. As mentioned above, only three-point steel-wheeled 15 ton rollers were used on the N3/12 while a combination of a three-point steel-wheeled roller and a pneumatic roller was used on Roads P88/1 and P24/1. Initially, in-situ densities achieved were lower than those specified. Thereafter, the in-situ densities increased as a result of better control.

The salient aspects with regard to the control during compaction were:

(i) Pneumatic rollers were not used with BRASO—wet method wearing courses due to material pick-up. Pneumatic rollers were used with BRASO—dry method only when asphalt temperatures were 130°C or lower.

(ii) Roller drums must be smooth without indentations to avoid pick-up and to start compaction earlier.

(iii) Compaction must be monitored with the aid of a calibrated nuclear density meter to determine the need for additional roller passes. Care had to be taken to not over-compact the mixes as densities of 96% could be achieved, which would lead to premature bleeding problems.

(iv) Temperature of compaction. The mix must not be allowed to cool down significantly. Compaction temperature was approximately 155°C for Route N3/12 and 165°C for Roads P88/1 and P24/1.

(v) Compact the briquettes as soon as possible at the plant, with spot checks of the BRD's of samples taken at the paver.

(vi) Coring after 48 hours with dry ice.

(vii) It is never certain whether the laboratories are performing the quality control testing in a similar manner. Agreement on sampling positions and binder content determination is required. A sampling and testing protocol for BRASO is required.

3.7.4 Bleeding of BRASO wearing courses

Localised bleeding has been observed in localised areas. Even though the bleeding spots on the N1/21 project were minor and with no relevance, other projects that run simultaneously with the N1/21 project in 2009 experienced the bleeding and flushing phenomena to areas less than 4% of the total area, as reported by Muller et al **[11].**

The potential causes of such defects on N1/21 are believed to be one or more of the following:

- Diesel spillage.
- Segregation in trucks.
- Lower binder viscosity due to prolonged storage time at high temperatures.
- The passing 4.75mm and 2.36mm sieve fractions are critical in terms of bleeding control.

3.8 Occupational Health, Safety and the Environment

BRA mixes are generally applied at higher temperatures than conventional binders to offset the increase in viscosity. Extender oils are also added to BRA mixes as a means to extend the shelf life of the mixes. As a consequence of the above, the following hazards were identified:

- Workers being exposed to additional fumes emanating from asphalt at temperatures higher than those of conventional asphalt mixes.
- Workers being exposed to potentially harmful polycyclic aromatic hydrocarbons (PAHs) present in some extender oils.
- Laboratory personnel being exposed to fumes from bitumen extraction tests where toluene is used.

The above two potentially negative implications on the workers' health and safety need to be addressed in the work methods and protection equipment. Sabita Manual 19 **[5]** recommends that the laboratory must be fitted with a fume extraction cupboard or the use of an alternative bitumen extraction method to that of the toluene method.

In terms of environmental impact, the use of use of tyres in the production of crumb rubber is a significant contribution to the elimination of reduction of scrap tyre piles and landfills. Even though it can be argued that the increased blending and mixing temperatures when dealing with crumb rubber asphalt may translate in an increased usage of fossil fuels, the superior performance and durability of these mixes will result in lesser number of re-surfacing interventions, thus reducing the consumption of fossil fuels.

3.9 Performance of BRASO Wearing Courses to date

The BRASO—wet method wearing course applied in 1999 has been reported to have performed well. That section of the N3 highway was upgraded as part of the planned freeway upgrade in the larger Gauteng area prior to the 2010 FIFA Soccer World Cup. The BRASO wearing course placed in 1999 required practically no repairs during the 2009 upgrade of that section of road N3.

No visual assessment was recently made on the sections of roads P88/1 and P24/1. However, pavement management system reports do not report unusual deterioration in ride quality. Long reported in 2005 **[12]** that the performance of the rehabilitated pavement of P24/1 was fair.

The BRASO surfacing applied on N1-21 in 2009 was reported to be in very good condition, four years after its placement.

4.0 Discussions / Conclusions

4.1 A comparison between the Dry and the Wet Method

There is still a great deal of debate among practitioners regarding the advantages and disadvantages of one method versus the other in terms of cost, quality control, consistency of and performance.

Lessons learnt from the four projects discussed in this paper, reveal the advantages and disadvantages of the BRASO wet and dry methods which are summarised in **Table 4** below.

Table 4 Advantages of BRASO mixes produced through the Dry and the Wet Methods

Criteria	Description	Preferred Method	
		Wet	Dry
Constructability	The dry method requires less handling on raw materials, thus reducing cost, reducing safety hazards		✓
	For the wet method, the binder that has to be pumped into the mixer is at least 10 times more viscous than conventional binders. This results in a reduction of the plant capacity, variability in the feeding of the blend into the mixer and possible pump blockages.		✓

	If the dry method is followed, the mix cannot be discharged from the pugmill into the trucks as a period for reaction between the rubber and the bitumen is still needed.	✓	
	The base bitumen has to have special viscosity. Penetration of the base bitumen should not be too low (80/100 pen) resulting in an unstable mix nor too high (60/70 pen) resulting in pump blockages. This leads to extra care thus increased costs.	✓	
Rubber Content	More rubber can be accommodated if the dry method is used, as the pumps will only pump conventional binder (lower viscosity). This will result in a more durable and rut resistant mix (within certain ranges). More viscous binders can be used, thus more binder can be accommodated in the mix, resulting in improved durability, flexural strength and fatigue and rut resistance.		✓
Binder quality control	The degree of reaction between the bitumen and the rubber of the bitumen-rubber blend can be properly controlled by measuring viscosity, flow and compression recovery if the wet method is used. If the dry method is used, quality control of the binder can only be controlled after extracting it from the premix.	✓	
Risk of bleeding	The dry method does not require the pre-blending of the bitumen and the rubber crumbs, thus reducing storage times, lowering the risk of bitumen rubber degradation due to excessive storage times.		✓
	Bleeding is less likely to occur if the dry method is followed since the viscosity of the binder, after reaction has taken place can be as high as 15000 cP against the 2000 or 3000 cP of the binder of the BRASO—wet method. This is only valid if mixes are produced and laid within the temperature time limits for bitumen rubber binders.	✓	
Material pick-up during compaction and hand work behind the paver	Material pick-up during rolling was found to be lower if the dry method was applied due to the higher viscosity of the bitumen-rubber binder. Better compaction can be achieved as rolling can start earlier. However pneumatic tyred rollers should only be used when temperatures reach 130^{o}C.		✓
	Handwork behind the paver or the rollers is more critical if the dry method is used. However, handwork for both asphalt types should be avoided.	✓	

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4.2 Issues Requiring Attention

There are still aspects related to bitumen rubber technology that require attention, so that these mixes may become more attractive to road authorities. The salient aspects include:

- Binder content control via extraction from production mixes at different times and temperatures after blending and mixing. The variability observed in the "true" binder content after the recorded binder content has been affected by the factor discussed in Section 3.7.2 may not always be that accurate.
- The relatively short shelf life of the bitumen rubber binder at elevated temperatures.
- The need for extender oils to extend the shell life and to reduce the binder viscosity negatively impact Occupational Health and Safety.
- Alternative bitumen extraction methods to that requiring the use of toluene.

4.3 New Developments

Research is currently underway to extend the shelf life and reduce the blending and mixing temperatures of BRA mixes **[13]**. The warm asphalt technology applied to BRA will certainly have positive implications in the shelf life of bitumen rubber binders, the reduction in fumes that may be harmful to workers, the elimination of extender oils from the bitumen rubber equation that will also reduce the risk to workers' health.

Even though the results from the investigation conducted by Alexandru and Distin **[13]** are promising for bitumen rubber binders for seal application, the technique appears to be equally suitable to BRA production.

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