3rd ISAP APE SYMPOSIUM

TITLE: Mix Design of Bitumen Stabilised Materials (BSMs) – A South African Perspective

Authors: Kim Jenkins – Stellenbosch University (kjenkins@sun.ac.za)
Dave Collings – UCD Technology / Loudon International (davecol@ifarica.com)

Background and Motivation for Triaxial Testing

The global growth in cold recycling technology as a pavement rehabilitation solution has necessitated the development and refinement of reliable materials performance models and design functions. The increased use of bitumen treated materials is evident from the number of recyclers with the capability to stabilise with either foamed bitumen or bitumen emulsion. In total, in excess of 50% of a global population of more than 2000 rubber-tyre recyclers are able to apply foamed bitumen or bitumen emulsion as a stabilising agent.

There are many parameters that influence the performance of BSMs and these include aggregate origin, aggregate properties, volumetric composition, climate, type of bitumen, bitumen content, bitumen dispersion, inclusion of active filler, relative density, moisture content, etc. The complexities of the multi-factorial performance function needed to design BSMs has led to differences of opinions in the distress mechanisms, especially fatigue versus permanent deformation (Ebels *et al*., 2006), (Twagira *et al*., 2006), (Collings et al. 2011).

Stellenbosch University has a history of researching the material properties of BSMs in an effort to develop more accurate performance models. Part of this programme has been an extensive triaxial test investigation. Similar to the methodology followed by Jenkins (2000), this tri-axial investigation to determine the shear properties of the BSM has provided a reliable performance function and uses three procedures:

- monotonic tests to determine cohesion (C) and friction angle (φ);
- short duration dynamic tests to determine resilient modulus (M_r);
- long duration dynamic tests to determine permanent deformation (ε_p).

The past 15 years has seen implementation of triaxial testing for characterisation of asphalt e.g. AMPT (Asphalt Material Performance Test) in the USA, as well as triaxial testing to determine the shear properties of BSMs, initially in South Africa. Figure 1 shows the global distribution of the implementation of this laboratory procedure in project level mix designs.

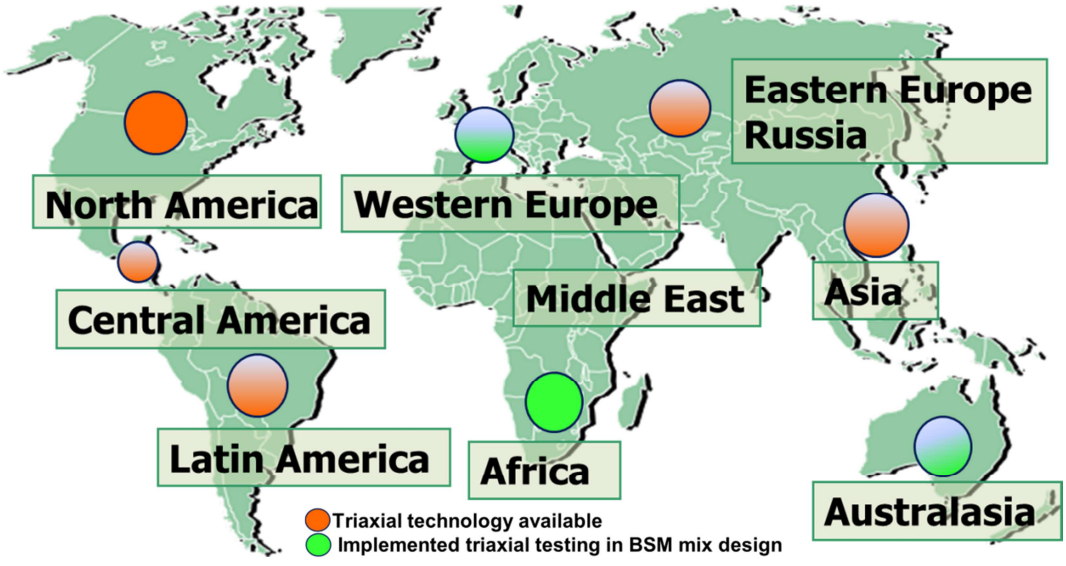

Figure 1. Global triaxial testing capacity and implementation for BSMs, full or partial

Ebels and Jenkins (2007) showed the importance of the Deviator Stress Ratio ($\sigma_{d,applied}$ / $\sigma_{d,failure}$) as a key parameter for determining the rate of permanent deformation accumulation . This research used long duration tests (up to one million load repetitions or 4% permanent axial strain) to verify a template of permanent deformation rates linked to the Deviator Stress Ratio. Figure 2 shows the conceptual implementation of this mix design approach in the structural pavement design.

Mechanistic-empirical analysis provides the major and minor principal stresses in the BSM base layer. These values are analysed together with the shear parameters (Cohesion C and Friction Angle ϕ), to calculate the Deviator Stress Ratio which, in turn, determines the rate of permanent deformation.

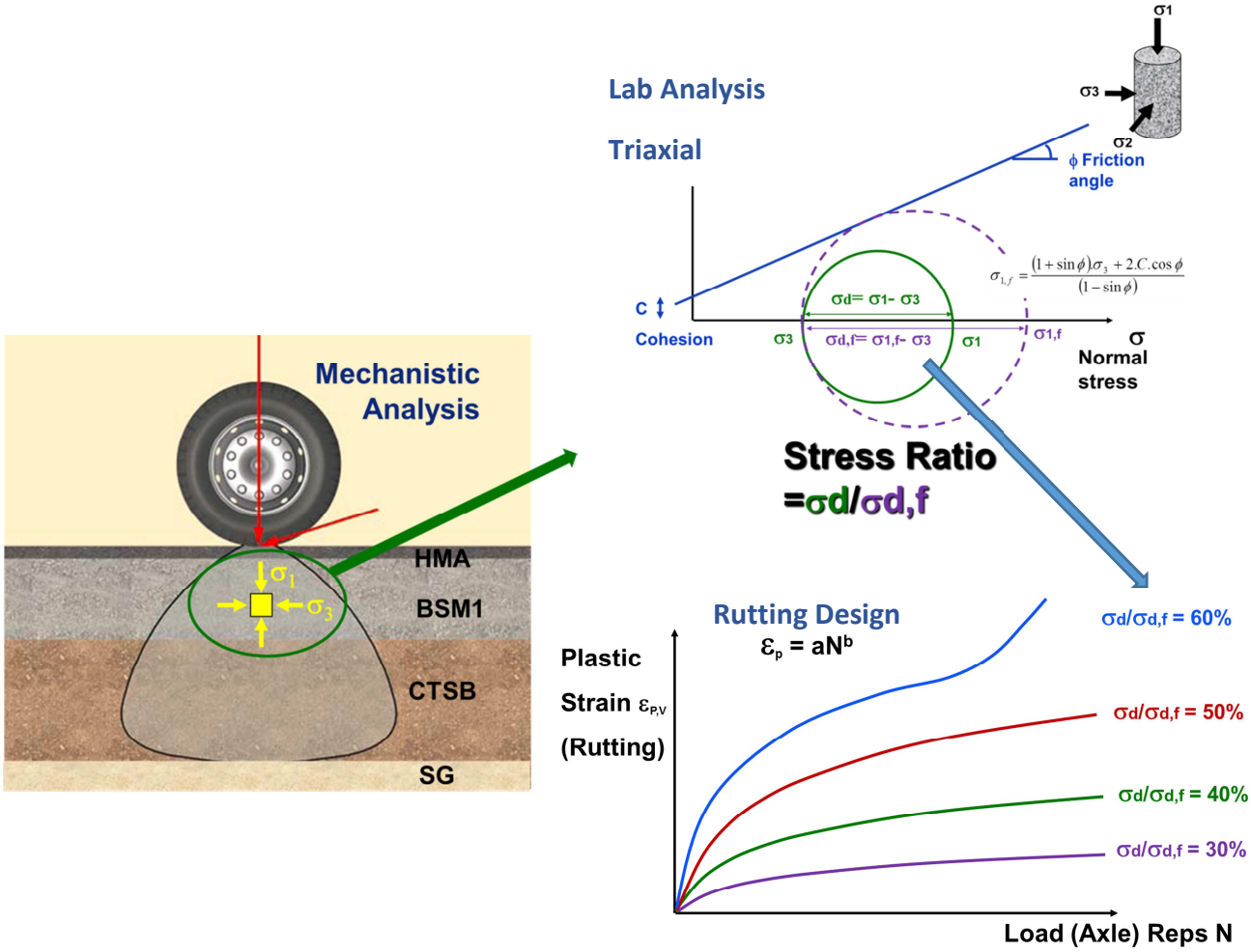

Figure 2. Conceptual BSM Pavement Design based on Triaxial Testing and Deviator Stress Ratio

As highlighted in Figure 2, the shear parameters (cohesion, C and friction angle, ϕ) for a BSM play a critical role in the pavement design process. The mix design approach that has evolved in South Africa has therefore focused on determining these parameters. The current mix design procedure includes four sequential steps. These are introduced in the next section. Although this approach might appear to be straightforward, the section that follows explains some of the challenges that were encountered and how they were addressed.

Developments in South African Mix design of BSMs

In general, the need for developing new mix design tests for BSMs have been driven by several factors. The main ones were:

- *Testing of a representative composition of recycled material*: in particular, maximum aggregate size, incorporation of RA (Reclaimed Asphalt), specimen geometry (max. particle size: specimen diameter ratio),

- *Compaction*: improved representation of field compaction by laboratory specimens i.e. simulation of vibratory rollers; also, the ability to prepare large specimens for triaxial testing,
- *Analysis of primary distress mechanism*: permanent deformation of BSMs determines the layer life, whilst judicious selection of ELTS Equivalent Long Term Stiffness takes account of stiffness adjustments during the service life,
- *Evaluation of critical material properties linked to performance*: shear parameters as determined from triaxial specimens enables aggregate angularity, packing, moisture, bitumen content and the influence of active filler to be determined.

The development of key components in the mix design that address these requirements, are explained in this section of the paper.

Compaction

During construction the primary compaction of BSMs is carried out using either single-drum vibrating rollers fitted with either a padfoot or smooth drum. Laboratory compaction should aim to simulate this as accurately and efficiently as possible. Currently there is a plethora of compaction methods, e.g. Marshall and gyratory compaction for asphalt, Modified Proctor, Modified AASHTO and vibratory hammers for granular layers. Based on the postgraduate research of Kelfkens (2008), Chilukwa (2013) and dal Ben (2014) at Stellenbosch University, as well as trials at BSM Laboratories (Pty) Ltd, some of the challenges associated with compaction of BSMs have been identified, including:

- *Granular behaviour of BSM*: this negates kneading action of gyratory or impact energy of Marshall, that are applicable to asphalt
- *Interlayer debonding and poor packing*: both Modified Proctor and Modified AASHTO do not provide homogeneous specimens and show stratified failure in ITS tests, with poor packing shown in CT scans (Chilukwa, 2013)
- *Lack of specifications for vibratory hammer compaction*: variations in power of the motor, deadweight, surcharge, point energy, tamping foot weight, frame for hammer mounting, etc. all contribute to variability in dry density achieved and homogeneity of the specimen. (Figure 3 highlights the effect of changing the weight of the tamping foot.) Some countries are using more than five different hammer types and as many frames.
- *Influence of material type*: Vibratory hammers are eminently suited to the compaction of graded crushed rock, achieving densities in excess of 100% Modified AASHTO density in less than 20 seconds. However, material with significant PI requires impact energy above 25 Joule to achieve equivalent density.

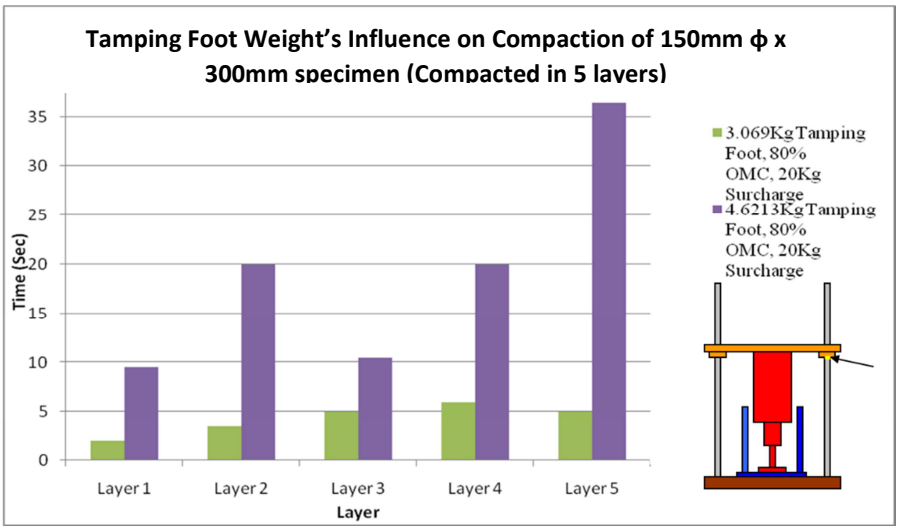

Figure 3. Time required to achieve 100% Mod AASHTO density for G2 (Bosch GSH 11E hammer)

The example of the influence of the weight of the tamping foot, as shown in Figure 3, has led to a specification of a maximum weight of 3 000 grams for this component being adopted.

Research into the most appropriate vibratory (demolition) hammer was guided by comparisons between the different options. It is apparent from Table 1 that, in order to compact a triaxial specimen 300mm high x 150mm diameter in 5 layers, for a range of recycling materials, there are only two options of hammers. Of these, the Hilti hammer has been selected as the benchmark for the standard.

Table 1. Comparative specifications for demolition hammers, vibratory tables, and roller compactors

Compaction Unit	**Rated power** [W]	**Point energy** [J]	**Impact rate** [min^{-1}]	**Frequency** [Hz]	**Amplitude** [mm]	**Deadweight mass** [kg]	**Number of layers for 300mm high specimen**
Demolition hammers							
Kango 637®	750	27	2750	45.83		7.5	9
Bosch GSH 11E®	1500	16.8	900-1890	15 – 31.5		10.1	9
Bosch GSH 11VC®	1700	23	900-1700	15– 31.5		11.4	5
Hilti TE 1000.2 AVR®	1750	26	1770-1950	35		12.5	5
Vibratory tables							
Stellenbosch Uni	1200		3000	50	0.1 – 0.4	50	>6
CSIR	1100		1800	12- 60 (30)	0.5 – 4	50	>6
Field rollers							
Asphalt (tandem)		31 kg/cm	3000 -4250	50 – 70	0.4 – 0.8	>10 000	
Granular (single)		56 kg/cm	3000	27 – 30	1.9 – 2	>16 000	

Triaxial Apparatus

The link between mix design testing and in-service material performance is an important ingredient for accurate and economical pavement designs, as motivated above. Up until 2008, triaxial testing of granular materials (outside of the realm of research) was only carried out in limited applications. The Texas Triaxial was applied in southern USA and, to a limited extent, in Southern Rhodesia, now Zimbabwe. In order to bring monotonic triaxial testing into the realm of commercial laboratories, where shear parameters can be determined efficiently and accurately, a research project was undertaken at Stellenbosch University by Mulusa (2009).

Based on principles of Texas Triaxial, but scaling up the specimen size to 150mm diameter x 300mm high, Mulusa developed a torus shaped tube (latex bladder) within a solid cylinder that can be inflated to the required confinement pressure for testing. As shown in Figure 4, a split confining cylinder was later developed by BSM Laboratories to prevent damaging the latex bladder whilst assembling the unit.

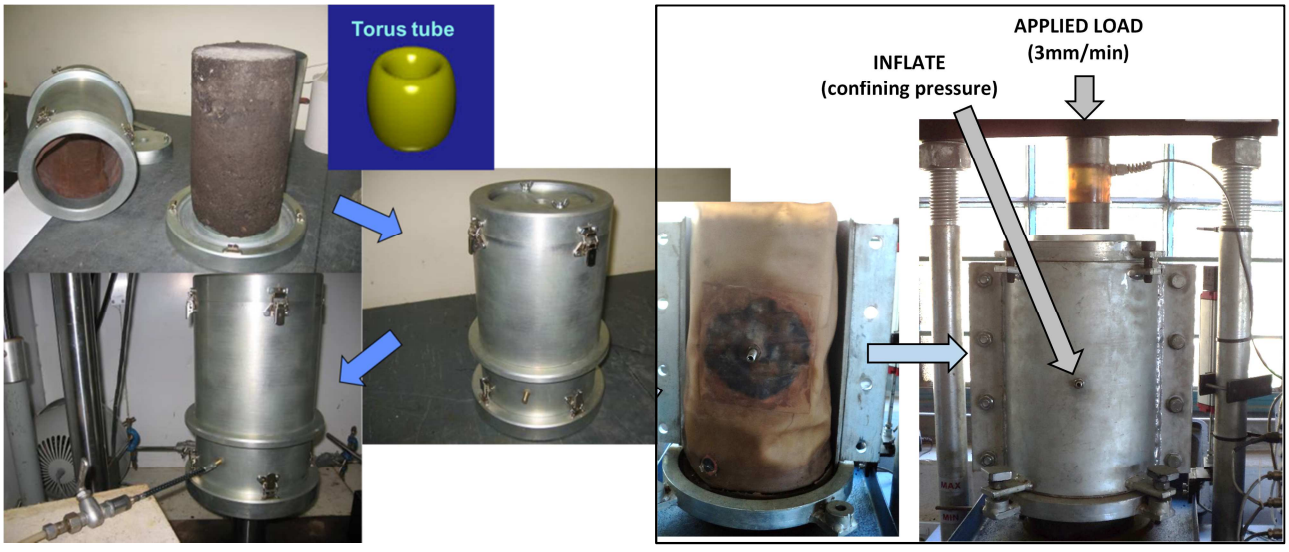

Figure 4. Setting up the simple apparatus for triaxial testing left (Mulusa, 2009), right BSM Laboratories

In order to validate its reliability, the Simple Triaxial Test (STT) apparatus was tested against the Research Triaxial Test (RTT) apparatus for monotonic testing. Figure 5 shows a significant correlation between STT and RTT test results, confirming that the STT can be used to provide reliable shear parameters in a simple procedure.

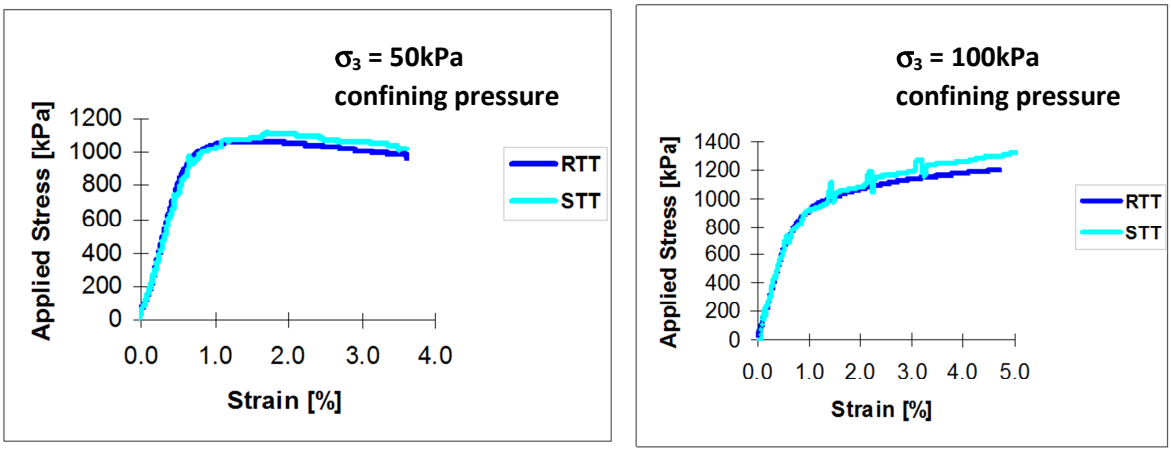

Figure 5. Comparison between the STT and RTT apparatus for G2 (Hornfel material) treated with 3.3% bitumen emulsion at different confining pressures (Mulusa, 2009)

Current South African Mix Design Procedure

Following the launch of Asphalt Academy's TG2 2nd Edition in 2009, those closely involved in the development of BSM technology recognised that a specialist laboratory was required to provide a services for which mainstream commercial laboratories were not equipped, especially triaxial testing. This led to the establishment of BSM Laboratories (Pty) Ltd in late 2009, based in Durban KZN where the technology had been successfully used for several years on numerous road rehabilitation projects.

Working closely with the researchers at Stellenbosch University, BSM Laboratories took the proposed test protocols for vibratory hammer compaction and triaxial testing from a research background to commercial routine production. Some of the challenges faced are described in the next section.

The original mix design procedure described in TG2 called for three "levels" of testing:

- Level 1. Adequate for low volume roads with a structural capacity < 3 million ESALs. Design based on ITS tests on 100mm ϕ x 63mm high Marshall briquettes, cured dry.
- Level 2. Adequate where the structural capacity < 6 million ESALs. Design based on ITS tests on 150mm ϕ x 127mm high specimens cured at equivalent moisture content.
- Level 3. Required where the structural capacity > 6million ESALs. Design base on the shear properties determined by triaxial tests carried out on 150mm ϕ x 300mm high specimens cured at equivalent moisture content.

Between 2009 and mid-2015, BSM Laboratories carried out in excess of 200 BSM-foam and BSM-emulsion mix designs for industry with almost half including triaxial tests. In the process, numerous shortcomings in the initial procedures were encountered. A primary concern was the number of tests required and the duplication of tests between Level 1 and Level 2. In addition, ITS tests carried out on the smaller 100mm ϕ specimens gave erratic results, especially with coarser material. Modifications were made piecemeal and these have resulted in the following mix design procedures being developed and adopted. This procedure will, in time, be included in the revision to the TG2 guidelines that are currently in progress.

Step 1. Sampling

The mix design procedure starts with obtaining a bulk sample of representative material. (The size of the bulk sample required to carry out a full BSM mix design is approximately 600kg.) Where the project concerns in situ recycling, separate samples from test pits are taken from each layer encountered in the upper pavement structure. These are later combined in proportion to the depth of the recycling horizon. Where the project calls for mixing material from stockpile(s), bulk samples are taken from each stockpile following normal sampling methods. The following procedures are followed in preparing the sample for testing:

- The material is air-dried and the hygroscopic moisture content determined;
- A sieve analysis is undertaken to determine the grading of the bulk sample;
- The material is then separated into 4 fractions using the 19mm, 12.5mm and 4.75mm sieves;
- The material retained on the 19mm sieve is then broken down to pass through the 19mm sieve and be retained on the 12.5mm sieve; and
- The resulting 3 bulk (sized) samples are then placed in sealed containers and later reconstitutes in their respective proportions for the various tests.

Step 2. Preliminary Tests

The following tests are carried out using the standard TMH / SANS test methods:

- Sieve analysis following the wet (washed) procedure;
- Determination of the Atterberg Limits; and
- Determination of the moisture / density relationship (mod AASHTO).

In addition, a series of tests are carried out on the bitumen stabilising agent to be applied in order to determine the basic characteristics:

- Bitumen emulsion: the charge (anionic or cationic) and the stability
- Foamed bitumen: the Pen grade and foaming characteristics

The results obtained indicate the suitability of the material and the bitumen agent for effective stabilisation.

Step 3. The effect of active filler

Three samples of approximately 15kg each are then prepared at the correct moisture content and all treated with the same application rate of bitumen stabilising agent. The amount of bitumen is applied (the nominal application rate) is determined from published guidelines, based on the material type and the grading (the fractions passing the 4.75mm and 0.075mm sieves).

1% (by mass) of cement is added to the first sample, 1% lime to the second whilst the third sample has no active filler added. Six 150mm ϕ x 75mm high specimens are manufactured from each mix using vibrating hammer compaction to achieve 100% of the mod AASHTO density. All specimens are then placed in a forced-draught oven at 40°C and cured to constant mass (normally 72 hours). After curing, the bulk density of each specimen is determined and, in the unlikely event of a specimen deviating from the average by more than 5%, it is discarded. Three specimens from each mix are then submerged in a water bath at 25°C and soaked for 24 hours. The remaining specimens are placed in a room where the temperature is controlled at 25°C.

All specimens are then tested to determine their respective indirect tensile strength (ITS) values. The average ITS of the unsoaked specimens is then calculated and reported as the ITS_{DRY} value and the ITS_{WET} value determined in a similar way using the results from tests on the soaked specimens. The tensile strength retained (TSR) value is then determined and, together with the relevant ITS_{WET} value, used as primary indicators for active filler preference. A nominal 1% of such active filler is then applied in all further mixes.

Step 4. Determination of the optimum bitumen application rate

Three samples of approximately 15kg each are then prepared at the correct moisture content, each with 1% of the preferred active filler. A different application rate of bitumen stabilising agent is then added to each mix:

- 0.5% less than the nominal application rate
- 0.025% less than the nominal application rate
- 0.25% more than the nominal application rate

(Note. Tests on the mix with the nominal application rate was previously undertaken in Step 3.)

The same procedure described in Step 3 is then followed to determine the ITS_{DRY}, ITS_{WET} and the TSR for each mix. The amount of added bitumen that provides both adequate strength and maximum reduction in moisture susceptibility is then selected as the optimum bitumen application rate.

Additional sensitivity tests
Additional ITS tests are sometimes carried out using the procedure described above to determine the effect of reducing the application rate of active filler (typically 0.5% and 0.75%).

Step 5. Determining the Shear Properties
Five 30kg samples are mixed, all at the optimum bitumen application rate and with 1% of the preferred active filler. These are then combined in a large container, thoroughly mixed together and sealed to retain moisture. Ten large triaxial specimens are then manufactured in 5 equal layers in split moulds using vibrating hammer compaction. To ensure continuity across the joint between layers, the surface of the lower (compacted) layer is prepared using an inter-layer roughening device. Once complete, the specimen is left in the mould for 4 hours before being removed from the mould and placed in a forced-draught oven at 40°C.

The moisture content of the specimens is monitored by frequent weighing and, as soon as the level has reduced to 65% of the OMC, the specimens are placed in loose-fitting plastic bags and returned to the oven for a further 48 hours (curing), after which they are removed from the oven, left in their sealed bags, and placed in a temperature-controlled room for 24 hours at 25°C. Two of the specimens are removed from their bags and submerged in a water bath at 25°C for 24 hours.

The eight unsoaked specimens are then removed from their bags and subjected to triaxial testing, two specimens at each of four confining pressures: 0kPa, 50kPa, 100kPa and 200kPa. The maximum applied stress is then determined for each confining pressure and used to plot the Mohr-Coulomb circles from which the shear properties of Cohesion (C) and the Internal Angle of Friction (ϕ) are determined.

The 2 soaked specimens are then tested at a confining pressure of 100kPa and the resulting applied stress compared with that for the unsoaked specimen at the same confining pressure to determine the Retained Cohesion (RetC).

Challenges Encountered

Developing new equipment and test methods has proved to be both a challenging and expensive exercise.

Vibratory hammer compaction
Researchers at Stellenbosch University had identified the Bosch GSH 11E demolition hammer as being suitable for manufacturing 150mm ϕ specimens. Drawings for mounting the hammer on a frame were obtained from the University and a replica (aptly named “Prototype 1”) was manufactured by a local engineering workshop in Durban. Several problems were encountered:

- The frame had to be securely anchored to both the floor and a wall. In the absence of a suitable wall, the frame could not be used. This was overcome by developing a “four-poster” frame with a sheet metal base plate that was bolted to the floor.
- The frame had to be sufficiently strong to prevent any distortion that would prevent the hammer from sliding vertically. This was addressed by thickening the frame member and the sliding rods.
- The floor mounting had to be robust since the vibrating energy was transferred through the material into the base. This was achieved by mounting the frame on a large concrete plinth (1m x 1m x 300mm) that was cast on a section of rubber conveyor belt to prevent vibration damaging the building structure.

After several modifications, the frame shown in Figure 6 was developed and has proved successful in both the central laboratory and in temporary field laboratories (quality control testing). Several sets of this equipment are in use, both in South Africa and abroad.

Fig. 6. Vibratory hammer set-up

Triaxial confining cylinder and bladder

The confining cylinder developed by researchers at Stellenbosch University was a single unit with separate top and bottom end plates. The latex bladder that provides the confining pressure must first be installed into the cylinder and then the specimen carefully inserted into the bladder. The top and bottom plates then have to be positioned and clamped to the cylinder, ensuring that the bladder is properly positioned and not crimped in the process. This proved to be difficult and, within a few months of commencing with triaxial testing, numerous bladders were destroyed due to crimping.

The problem faced was that these bladders cannot be purchased, they have to be manufactured internally (attempts to have them manufactured by the rubber industry came to naught since volumes are too low). Such manufacture involves purchasing the required latex (fluid) that is poured into a shallow bath into which an electrically driven roller is slowly rotated, forming a skin. This process is repeated several times until a membrane with sufficient thickness has been achieved. This membrane is then removed from the rolled, glued to form a tube and a valve attached. This proved to be a time consuming and expensive process.

The life of the bladders was significantly extended by modifying the single unit confining cylinder to a two-part split unit, as shown in Figure 4. Such a modification allows the specimen to be inserted into the bladder before positioning it onto the base plate (whilst one half of the confining cylinder is already in place).

Determining moisture susceptibility

TG2 calls for the Moisture Induced Sensitivity Test (MIST) to be performed in order to determine the moisture susceptibility of triaxial specimens. This is not a routine test and therefore requires special equipment, equipment that is not locally available. Messrs IstroTek in the USA manufacture a unit for "HMA moisture sensitivity testing" which may, or may not be suitable, but at considerable cost. Since the research at Stellenbosch University was carried out with equipment that was put together in-house (and the amount of research undertaken was limited), it seemed prudent to delay pursuing this test until more research had shown it to be a reliable predictor of moisture susceptibility. (BSM Laboratories had already invested heavily in developing the vibrating hammer and triaxial equipment and were therefore loathe to go down this road.)

In the interim, a procedure for testing soaked specimens at one confining pressure (as described above) has been adopted and results obtained to date suggest that the Retained Cohesion determined in this manner are realistic since, invariably, the result is lower than the TSR obtained from ITS tests.

Conditioning (curing) the specimens

One of the primary reasons for abandoning the ITS test at equilibrium moisture content (ITS_{EQUIL}) was the difficulty experienced in achieving such a moisture content in the relatively small specimens. The original test method called for the specimens to be oven cured, unsealed, for a specific length of time before placing them in sealed bags. This proved to be impractical since different materials loose moisture at different rates (specimens of coarse material loose moisture at a faster rate than those made from finer material).

The moisture content of the larger triaxial specimens can, however, be controlled since there is significantly more moisture involved. This permits the specimens to be placed in the oven and weighed at regular intervals.

Conclusions

The mix design procedure described above has taken 5 years to evolve through a process of trial-and-improve, based on the developments at Stellenbosch University. BSM Laboratories has been the key to such development, if only due to the number of tests carried out in their facilities. This procedure will be incorporated in the revision of TG2 that is currently underway. It streamlines the previous procedure, making mix designs less costly whilst providing the key data (shear properties) for structural design.

References

Asphalt Academy, 2002. **Interim Technical Guideline: The Design and Use of Foamed Bitumen Treated Materials**, Asphalt Academy, Pretoria, South Africa (TG2 Interim Guideline).

Collings DC and Jenkins KJ. **The Long-Term Behaviour of Bitumen Stabilised Materials (BSMs).** Conference on Asphalt Pavements for Southern Africa, CAPSA '11, Drakensberg Sun, South Africa, August 2011

Jenkins KJ, Collings DC and Jooste FJ, 2008. **TG2: The Design and Use of Foamed Bitumen Treated Materials. Shortcomings and Imminent Revisions.** NZIHT Recycling and Stabilisation Symposium, Auckland, NZ

Jenkins KJ, Collings DC, and Long FM (main authors) with contributions from Jooste F, Grobler J, Hughes M, J and Thomson H. **Technical Guideline TG2: Bitumen Stabilised Materials: A Guideline for the Design and Construction of Bitumen Emulsion and Foamed Bitumen Stabilised Materials**. Second Edition. Published by Asphalt Academy. May 2009. ISBN 978-0-7988-5582-2

Wirtgen Cold Recycling Technology Manual. 1st Edition 2012.Windhagen, Germany

Jenkins K.J. van de Ven M.F.C., Molenaar A.A.A. and de Groot J.L.A, 2002. **Performance Prediction of Cold Foamed Bitumen Mixes.** Ninth International Conference on Asphalt Pavements, Copenhagen, Denmark. pp16

Jenkins K.J, Long F.M, and Ebels L.J., 2007. **Foamed Bitumen Mixes = Shear Performance?** IJPE International Journal of Pavement Engineering. Volume 8 Number 2. June 2007

Twagira EM, Jenkins KJ, and Ebels LJ. **Characterisation of Fatigue Performance of Selected Cold Bituminous Mixes**. International Conference on Asphalt Pavements ICAP, Quebec, Canada, August 2006

Ebels LJ, and Jenkins KJ. **Determination of Material Properties of Bitumen Stabilised Materials using Triaxial Testing.** International Conference on Asphalt Pavements ICAP, Quebec, Canada, August 2006

Jenkins, K. J., 2000. **Mix design considerations for cold and half-warm bituminous mixes with emphasis on foamed bitumen.** PhD dissertation University of Stellenbosch, South Africa

Ebels LJ, and Jenkins KJ. **Mix Design of Bitumen Stabilised Materials: Best Practice and Considerations for Classification.** Conference on Asphalt Pavements for Southern Africa CAPSA '07, Sun City, South Africa, September 2007

Kelfkens R.F.C. **Vibratory Hammer Compaction of Bitumen Stabilised Materials.** MScEng thesis. University of Stellenbosch 2008.

Mulusa W.K., **Development of a Simple Triaxial Test for Characterising Bitumen Stabilised Materials**. MScEng thesis. University of Stellenbosch, March 2009

Chilukwa, N. **Vibratory Hammer Compaction of Granular Materials**. MScEng thesis. University of Stellenbosch. March 2013

Dal Ben M**. Resilient Response and Performance of Bitumen Stabilized Materials with Foam Incorporating Reclaimed Asphalt** . PhD (Eng) dissertation. University of Stellenbosch. March 2014