THE LONG-TERM BEHAVIOUR OF BITUMEN STABILISED MATERIALS (BSMs)

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Abstract

Bitumen stabilised materials (BSMs) behave differently from all other materials used to construct road pavements. Unlike asphalt where a continuum of bitumen binds all the aggregate particles together, the bitumen in a BSM is dispersed selectively amongst only the finer particles, regardless of whether bitumen emulsion or foamed bitumen is used as the stabilising agent. When compacted, the isolated bitumen-rich fines are mechanically forced against their neighbouring aggregate particles, regardless of size, resulting in localised bonds which are not continuous (i.e. not joined to each other).

A comparison of the shear properties of a granular material before and after stabilising with bitumen shows that the cohesion value increases significantly (due to the dispersed bitumen) whilst the angle of internal friction reduces a few degrees only (the coarser particles are not coated with bitumen). Such an increase in cohesion allows a pavement layer constructed from BSM to tolerate higher stresses imposed by heavy vehicle loads whilst retaining stability due to the largely unchanged friction angle. Pavement layers constructed from such non-continuously bound materials behave very differently to those constructed from continuously-bound materials (asphalt or cement treated material).

In spite of this non-continuous binding phenomenon being explained in the Technical Guideline published in 2009 by the Asphalt Academy (TG2 Second Edition), there is still confusion concerning the behaviour of BSMs. The mode of failure of these materials is permanent deformation, similar to granular materials. However, some engineers continue to argue that, similar to cemented materials and thick asphalt layers, BSMs fail in fatigue, supporting this stance by means of repeated-load laboratory tests carried out on beam specimens.

The principles of fracture mechanics are employed in this paper to demonstrate that, when confined within a pavement structure, stress concentrations in a BSM that exceed the elastic limit cause localised shear failure, causing permanent deformation. For a crack to propagate through a layer, the individual material particles must be bonded to each other for stresses to be able to concentrate at the crack head. The material must therefore be continuously bound, as is the case with asphalt. Turning from theory to practice, the performance of three heavy-duty pavements, each constructed at least five years ago with a base layer of BSM-1 class material, is then reviewed. All three pavements were properly designed and (more importantly) properly constructed. Deflection measurements taken at regular intervals show none of the symptoms that would indicate deterioration due to fatigue. To the contrary, these measurements suggest that the pavements are gradually improving with age.

1. INTRODUCTION

Over the past 15 years, bitumen stabilised materials (BSMs) have been used worldwide to construct the base layer for many thousands of kilometres of road pavements, mainly on rehabilitation projects by recycling the material in the existing pavement. In spite of the majority of these pavements performing well, there remains a general lack of understanding of BSMs, particularly concerning the nature of the material and its failure mechanism.

BSMs are non-continuously bound materials that fall in a class of their own. They are granular materials treated with small amounts of bitumen emulsion or foamed bitumen (usually < 3% residual bitumen, by mass) and active filler (<1% cement or lime, by mass) that significantly increases the cohesion of the material whilst having little effect on the angle of internal friction. BSMs are produced at ambient temperatures, typically in the range of 10°C to 40°C.

When used to construct a pavement layer, a BSM behaves more like an unbound granular material than one that is continuously bound, as would be achieved had cement been used as the stabilising agent. As a result, the failure mechanism for a BSM is more similar to that for granular materials than for a cement stabilised material (or hot mix asphalt that is also a continuously bound material). Consequently, the failure condition used for modelling is permanent deformation, not fatigue cracking. However, it should be noted that with the addition of excessive amounts of bitumen and/or cement, or at higher aggregate mixing temperatures, continuous binding can be introduced, thereby making the material prone to fatigue cracking. Such materials do not comply with the BSM definition.

The applicable failure condition (permanent deformation) does not imply that BSMs cannot crack. Like granular materials, they are prone to shearing when the material is overstressed. Such overstressing can manifest as a shear crack in a BSM, similar to granular material. These conditions, however, have no relationship with the fatigue cracking phenomenon that affects bound materials. Such fatigue cracks develop as a consequence of repeated loads that cause relative low levels of tensile strain in the material.

This paper aims to eliminate confusion concerning BSMs and their behaviour when used to construct a pavement layer. The development of BSM technology is summarised in the first "Background" section with a brief description of current practice. This is followed by a section on Response Modelling that explains the failure mechanism of BSMs using the concepts of fracture mechanics. Also included is a discussion on effective stiffness levels applicable to BSMs. The next section is concerned with Damage Modelling that explains the failure condition of cumulative deformation and the pavement design procedures that are relevant for these materials. Finally, the conclusion is drawn that BSM usage would gain a broader acceptance in the industry if they were better understood, rather than assumed to be a "poor asphalt".

2. BACKGROUND

2.1 The Early Days of BSMs

Adrian Bergh is credited as being the first "BSM pioneer" in South Africa. In the 1970s he used bitumen emulsion to address premature failures on the infamous S12 highway. Almost 40 years later, some of those sections are still performing well on the renamed N12. As a consequence of those early successes, numerous pavement rehabilitation projects were carried out using bitumen emulsion, normally added in small quantities (± 2%) in conjunction with a small amount of cement (< 2%). Initially, the bitumen emulsion was considered to be acting as both a compaction aid and a means of countering the inevitable shrinkage cracks emanating from the cement. However, as the technology gained popularity, design procedures were developed that used the results of unconfined compressive strength (UCS) tests as the yardstick for determining appropriate application rates. These, coupled with the results of Heavy Vehicle Simulator (HVS) trials, were published by SABITA in their GEMS and ETB manuals (Manual 14, 1993 and Manual 21, 1999 respectively).

Bitumen emulsion was also used to stabilise in situ aeolian dune sand on low volume roads in the Makhatini Flats region of Northern kwaZulu-Natal. Early successes resulted in several roads for the then Natal Parks Board (now KZN Wildlife) being upgraded. Although the benefits of this type of treatment were clearly demonstrated, several application problems relating to the use of bitumen emulsion were encountered. This encouraged those involved to look for an alternative means of introducing the bitumen and in 1994 a specialised mixing plant that could treat material with foamed bitumen was imported and used to stabilise aeolian dune sand for the construction of a new 150mm thick base layer on the 14km section of road between the town of Mbazwana and Sodwana Bay. Numerous challenges faced during this project were overcome (Collings, 2009) and, after 17 years of service, this road is still providing the only access to Sodwana Bay in spite of minimal maintenance to the thin slurry seal surfacing.

2.2 Technology Development

Subsequently, this mixing plant was used to construct several other roads for the kwaZulu-Natal Provincial road authorities, including MR504 that was the subject of a paper presented at CAPSA 2004 (Collings *et al*, 2004). However, on-going functioning problems saw the mixing plant replaced in 1996 by a properly engineered system developed in Germany and mounted on a large recycler. After a series of trials in South Africa, several of these machines were purchased by forward-thinking contractors who identified the economic advantages to be gained by substituting foamed bitumen for bitumen emulsion in tenders calling for the construction of an emulsion treated base (ETB). As a result, several contracts were awarded in favour of foamed bitumen.

Since there were no definitive guidelines specific to foamed bitumen, deciding on whether or not to accept such an alternative was considered a risk. Consequently, the then Gauteng Province Department of Transport (Gautrans) allocated their HVS to test a section of P243 near Vereeniging where foamed bitumen had been substituted for bitumen emulsion. (G6 quality existing base / subbase material was recycled in situ with < 2% bitumen (one section with 1.2%, another with 1.8% bitumen) and 2% cement.

The then CSIR Transportek, working in partnership with Gautrans, analysed the results from these trials and produced a report. The results showed that the recycled / foamed bitumen treated layer exhibited similar behaviour patterns as one treated with cement. This could be expected since the application rate of cement exceeded that of foamed bitumen. Shortly thereafter, the Asphalt Academy received sponsorship from SABITA and Gautrans to compile the first edition of the interim technical guideline document entitled "TG2, The Design and Use of Foamed Bitumen Treated Materials". This document relied heavily on the results of the one HVS trial and a parallel laboratory testing programme carried out by the CSIR.

TG2 was published early in 2002. Concerns expressed that the design procedures did not accurately portray the performance of bitumen stabilised materials were addressed by including "interim" in the title along with promises of an update as soon as additional information became available. However, this publication proved to be a serious setback for those who had invested in foamed bitumen technology since, by following the guidelines, the results invariably showed that stabilising with cement only would achieve the same end-product and be more cost effective than adding foamed bitumen to the mix (Jenkins *et al*, 2008).

Glaring difference between TG2 and the GEMS / ETB manuals resulted in confusion. Following the guidelines from the latter gave answers that were totally different from TG2 for an identical (residual) application rate of bitumen. This tended to lead practitioners into one of two "bitumen treatment camps":

- those with ETB experience who based their designs on UCS test results, often achieving the desired strength with a bitumen emulsion application rate of 2% (i.e. 1.2% residual bitumen) together with 2% (or more) cement; and
- proponents of bitumen stabilisation who advocated the application of more bitumen than cement, basing their designs on the results of ITS tests. The addition of cement was seen primarily as a catalyst for bitumen dispersion in the case of foamed bitumen and to control the "break time" with bitumen emulsion.

Since both camps used a bituminous product, such confusion was identified by SABITA as a being untenable and provided support for an early update of TG2 that encompassed both bitumen emulsion and foamed bitumen treatment.

2.3 TG2 Second Edition

Gautrans with joint funding from the Western Cape Provincial Department of Transport undertook a second HVS trial on a section of the N7 freeway near Cape Town. The existing graded crushed stone base material had been recycled with foamed bitumen in accordance with a proper mix design undertaken at the Stellenbosch University (application rates were 2.5% foamed bitumen and 1% cement). The results were very different from the first HVS trial and were largely responsible for precipitating the extensive research programme that took almost five years to complete. This involved both laboratory work (Stellenbosch University) and LTPP analyses of 23 pavements (all older than 7 years) with either bitumen emulsion or foamed bitumen treated base layers (Fritz Jooste and Fenella Long). Funding was provided by SABITA and Gautrans with the new Technical Guidelines eventually being published in May 2009, entitled "TG2 Second Edition, Bitumen Stabilised Materials, A Guideline for the Design and Construction of Bitumen Emulsion and Foamed Bitumen Stabilised Materials".

This new publication removed much of the misunderstanding (and cause of confusion) surrounding bitumen stabilisation by including both bitumen emulsion and foamed bitumen under the same design philosophy. TG2 Second Edition replaced SABITA's GEMS and ETB Manuals (Nos. 14 and 21) as well as the original TG2. Material stabilised with either bitumen emulsion (BSM-emulsion) or foamed bitumen (BSM-foam) follow the same mix design for classifying into one of three BSM classes, taking no account of which stabilising agent was used in the mix. The shear properties of the material are of primary importance and the failure condition embodied in the new "Pavement Number" pavement design method (empirically based) is cumulative permanent deformation, similar to granular materials.

2.4 Current Practice

Since being launched in May 2009, TG2 Second Edition has been well received by industry and the relevant guidelines applied on numerous projects, both in South Africa and worldwide. Projects that have been designed and constructed in accordance with the new guidelines include major urban arterials (Ethekwini Metro) and sections of the primary National Road Network (the N2 south of Durban and the N3 between the towns of Warden and Villiers, amongst others). A specialist laboratory, BSM Laboratories (Pty) Ltd, was established in 2010 with participation from existing commercial laboratories to cater for the new mix design procedures required by these new guidelines (especially triaxial testing) and training programmes undertaken to explain the intricacies of bitumen stabilisation.

In spite of these advances, misunderstanding of the nature of BSMs is often encountered in the industry. Some practitioners still regard foamed bitumen treated materials as poor asphalt whilst others persist with the legacies of ETBs, insisting that BSM-emulsion designs should be based on simplistic UCS test results. In addition, premature failures that have occurred on some projects are often cited as the reason for avoiding this technology, even if the cause for such failures can be shown to be the result of an inappropriate design and/or poor construction, especially where foamed bitumen was involved.

In an endeavour to address these misunderstandings, the following sections describe the behaviour of a properly constructed layer of BSM in a pavement subjected to repeated traffic loads. The principles of fracture mechanics are employed to show that the primary failure mode of BSM is permanent deformation, not fatigue cracking. This is highlighted using deflection measurements taken over extended periods on different pavements that show conclusively that BSMs do not deteriorate with time and the cumulative effect of traffic loads. In simple terms, this means that BSMs do not suffer from the fatigue cracking phenomenon that affects other continuously bound materials (provided always that the layer was properly constructed).

3. RESPONSE MODELLING

The ability to manufacture beam specimens from a material used to construct pavement layers and subject them to various tests to measure the strain-at-break and fatigue characteristics does not imply that such properties are the dominant ones that determine the material's behaviour within a pavement layer. For example, under specific moisture and density conditions, it is possible to determine such properties for beams constructed from G1 material. However, no one would suggest that a G1 layer fails in fatigue; when confined within a pavement layer, such materials exhibit stress dependent behaviour and, when subjected to stresses that exceed their shear strength, localised deformation occurs as a consequence of individual particle movement (reorientation and/or displacement) within the body of the material. Cracking is only seen in such unbound materials when high-strain shear failure is continuous along a horizontal plane, normally due to deformation in the underlying support, or when the moisture content reduces to such an extent that the resulting pore fluid suction pressure is excessive (normally only encountered in arid regions).

3.1 Bitumen Dispersion in a BSM

Figure 1 has been used in many publications to explain the nature of a BSM. This picture shows a compacted slice of aeolian dune sand treated with 4% foamed bitumen, magnified 40 times. (The original picture was taken in 1994 using a slice prepared by KZN University's Geology Department). Since the dune sand is white and bitumen black, this picture clearly shows the bitumen is dispersed throughout the matrix of the dune sand as tiny splinters. The coarser particles (maximum size is 0.425mm) are not coated with bitumen. When such a material is compacted, the individual bitumen splinters are mechanically forced against their neighbouring particles and, being sticky in nature, the bitumen splinter adheres to its neighbour, setting up an isolated bond. With the bitumen dispersed as millions of such splinters, the result is millions of localised bonds that are isolated; hence the term "non-continuously bound" material.

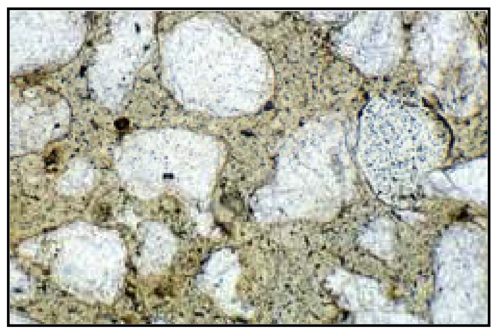

Figure 1. Dispersed bitumen splinters

The addition of a similar amount of residual bitumen by means of bitumen emulsion will produce a similar result with a slightly different dispersion mechanism. The charged bitumen droplets in an emulsion are initially attracted to the finest particles with the highest surface area, progressively coating larger particles as more emulsion is added until, ultimately, a cold-mix asphalt is achieved. Thus, by limiting the amount of emulsion added, a non-continuously bound material is produced.

Unlike bitumen emulsion, foamed bitumen cannot be used to make cold mix asphalt. The dispersion mechanism results in the bitumen splinters encapsulating only the finest aggregate particles at ambient temperatures (i.e. at 20°C, only the fraction < 0.075mm is coated). Adding more bitumen will not result in coarser particles being coated unless the temperature of the material is increased; the bitumen splinters will tend to stick to each other, forming sticky lumps (sometimes referred to as “stringers”).

Non-continuously bound materials are different from all others and therefore fall into a class of their own. Since the coarse particles remain uncoated with bitumen, they retain their friction properties, thereby explaining why the angle of internal friction is largely unaffected when a material is stabilised with bitumen. The millions of local isolated bitumen bonds, however, have a significant influence on cohesion of the material, increasing the value by up to ten times (i.e. from 30kPa to 300kPa). This explains why these materials exhibit stress dependent behaviour when confined within a pavement layer and the reason for regarding them as “super-performing” granular materials.

Hot mix asphalt and cement stabilised materials behave very differently. Being continuously bound with each particle linked to its neighbour, individual particles play an insignificant role; it is the continuum of bound particles that are important. Layers of such material behave in the same manner as a slab when loads are applied, with compressive stresses developing in the upper portion of the layer and tensile stresses in the lower part under the centre of load. It is these tensile stresses that lead to crack development and propagation, as explained below.

3.2 Fracture Mechanics

Fracture mechanics has proven to be a very useful tool for modelling materials that suffer fatigue cracking under repeated loading conditions. The principles of facture mechanics have been successfully applied in pavement engineering to the design of asphalt overlays where reflective cracking requires analysis. Paris’ Law shown in Equation 1, is used to describe crack growth in a material.

$$\frac{dc}{dN} = A.K^n \qquad \text{Equation 1}$$

where,

$\frac{dc}{dN}$	=	increase in crack length per load cycle
K	=	stress intensity factor at the tip of the crack, due to bending or shear
A,n	=	material constants

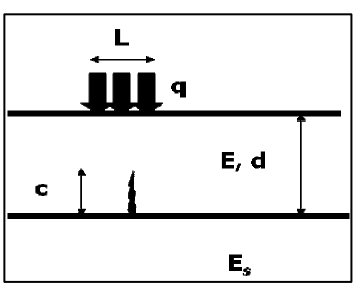

Figure 2. Beam approach to crack-growth analysis

It is understandable that Paris’ Law can be applied to asphalt, which incorporates bitumen that is distributed in a continuum and the asphalt layer can be treated as a beam since it is a continuously bound material. Besides other factors, the crack intensity factor is dependent on the ratio of crack length to beam thickness, c/d shown in Figure 2.

In addition, methods are available to determine each of the Paris Law parameters (Lytton, 1989) and asphalt is sufficiently homogeneous to enable such analyses to be undertaken.

Unlike asphalt, BSMs do not have a continuum of bitumen and are seldom homogeneous, especially when recycled material is stabilised. This is shown conceptually in Figure 3. Discrete distribution of bitumen splinters in BSM-foam does not allow classical fatigue and fracture mechanics to apply. If shear deformation between individual particles ruptures a “spot weld” of bitumen, there is no continuity of bound material that will allow a crack to develop, so c/d becomes meaningless. Stated differently, there is neither opportunity for a crack “head” nor stress intensity at the tip to develop. A broken spot weld will result in particles re-orientating (micro-shearing), resulting in permanent deformation, as with granular material. Rupturing of spot welds can influence the effective stiffness of the layer, as discussed later.

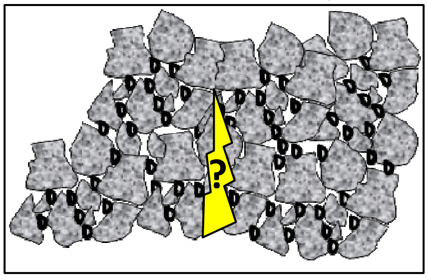

Figure 3. Non-continuous bound BSM-foam

In addition, the relatively low effective stiffness of BSM’s need to be taken into consideration (often less than 50% of HMA stiffness, depending on temperature and loading time). The horizontal strains experienced by a BSM are commonly in the order of 10 to 70 $\mu\varepsilon$ and very seldom exceed 90 $\mu\varepsilon$. By comparison, strain-at-break (ε_b) tests from monotonic flexural beam tests on BSMs yielded results of 1000 to 3000 $\mu\varepsilon$ and four-point beam fatigue results can yield between one and several million load repetitions at 200 $\mu\varepsilon$ □constant strain loading (Mathaniya *et al*., 2006). The non-continuously bound nature of BSMs, coupled with their relatively low effective stiffness regime, does therefore not create conditions conducive to fatigue failure.

3.3 Material behaviour and Strain-at-break

Extensive investigations have been undertaken to find a relationship between strain-at-break (ε_b) and fatigue for BSMs or, at least, to provide a performance indicator (Twagira *et al*, 2006). Before such a link is investigated, however, it is important to understand the nature of the material behaviour. A BSM is elasto-plastic, as illustrated by its granular-type, stress-dependent behaviour shown in Figure 4. However, a BSM is also visco-elastic, as shown by its loading time and temperature dependency, due to the presence of bitumen in the mix, as shown in Figure 5. Combining these types of material behaviour yields visco-elasto-plastic material behaviour for BSMs. It is evident that even when BSMs incorporate 1% cement, they do not behave in a purely elastic manner.

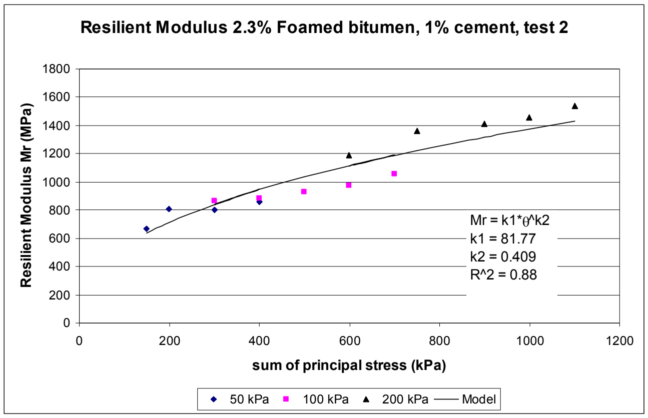

Figure 4. Dynamic triaxial tests on BSM-foam (Jenkins *et al*, 2002)

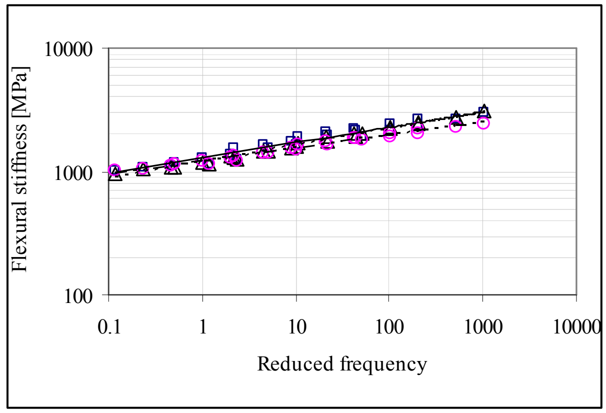

Figure 5. Master curves of BSM-emulsion and BSM-foam (Mathaniya *et al*, 2006)

This begs the question: what is the extent of the visco-plastic component's influence on the behaviour of BSMs? By combining the results of "high-cycle" versus "low-cycle" fatigue, the linearity of the fatigue relationship or conversely, the deviation from Basquin's Law, can be tested (Ashby and Jones, 1987). In the case of BSMs this can be tested by combining fatigue (dynamic) results and "strain-at-break" ε_b (monotonic) results from beam specimens prepared in the same manner and tested in a Beam Fatigue Apparatus. This research was carried out with meticulous attention to detail in compacting slabs of representative mixes, curing and sawing the slabs to provide beams for testing at Stellenbosch University. Prior to this point, attempts at carrying out fatigue testing of BSM-foam had been aborted due to premature collapsing of beams. The lightly bonded nature of the bitumen stabilisation makes fatigue testing difficult. Nevertheless, the research at Stellenbosch University on three different material compositions, has allowed for comparisons to be made between dynamic and monotonic tests, see Figures 6 to 8 (Mathaniya *et al*, 2006). The fatigue functions have been extrapolated to the measured strain-at-break values in order to test the linearity of the material behaviour.

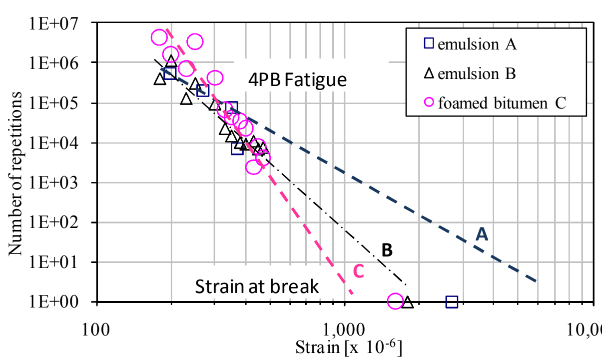

Figure 6. Fatigue versus Strain-at-break ε_b for BSMs with Crushed Aggregate including 25% RAP, three different bitumen stabilising agents and 0% Cement

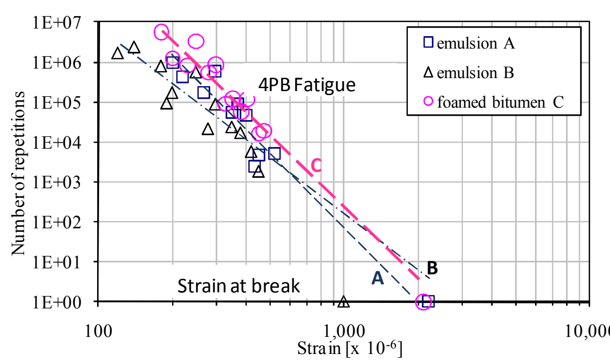

Figure 7. Fatigue versus Strain-at-break ε_b for BSMs with Crushed Aggregate including 25% RAP, three different bitumen stabilising agents and 1% Cement

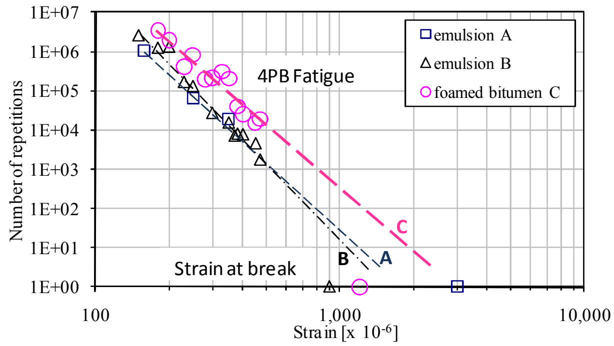

Figure 8. Fatigue versus Strain-at-break ε_b for BSMs with Crushed Aggregate including 75% RAP, three different bitumen stabilising agents and 0% Cement

Figures 6 to 8 make it abundantly clear that strain-at-break does not provide a reliable correlation with the fatigue relations that have been tested. Not only does the influence of the particular bitumen stabilising agent need to be considered, but also the non-linearity of the log strain versus log load repetitions relationship. Linear elastic behavioural modelling will not suffice due to plastic behavioural influences, and strain-at-break can therefore not provide a reliable performance indicator (which should be expected since BSMs are visco-elasto-plastic materials).

3.4 Long Term Behaviour of BSMs

To determine definitively whether or not BSM layers suffer from fatigue failure, the behaviour of three heavy-duty pavements were investigated, each with less than 3% residual binder and less than 1.2% cement, which is representative of the vast majority of BSMs currently being applied as "state of the art". (BSM layers incorporating higher application rates of either bitumen or cement may yield different findings.)

3.4.1 The Athens – Corinth Highway in Greece

A study of the relationship between BSM stiffness and time lapsed was carried out on a section of the major 6-lane highway between Athens and Corinth in Greece. This pavement was rehabilitated in 2002/2003 using in place recycling with 2.3% foamed bitumen and 1% cement. The National Technical University of Athens NTUA carried out FWD measurements on the pavement initially as part of the rehabilitation investigation and then subsequently at 1 month, 6 months and then at yearly intervals until 4 years after construction. The reduction in maximum deflection measured using the FWD is plotted in Figure 9 for the slow lane on both carriageways. The new layers in the pavement structure included only BSM-foam and HMA, so the stiffening of the pavement structure could only have emanated from the BSM layer. The FWD data was analysed further using deflection bowl back-analyses to determine the relationship in Figure 10 (Loizos et al, 2007). The absolute values of BSM-foam stiffness are high, which could be a product of

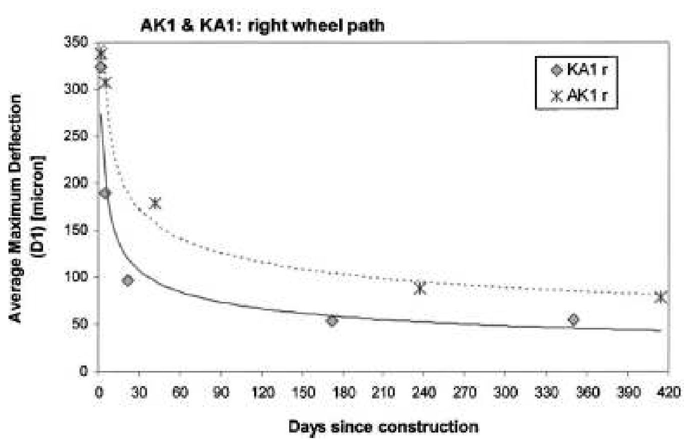

Figure 9. Change in FWD Maximum Deflection with time (Loizos *et al*., 2007)

the in situ materials, but the trends of increase in stiffness are undeniable. During the period of the deflection measurements, the pavement was exposed to some 60,000 vehicles per day (20% heavy vehicles with a legal axle load of 130 kN). The important feature of these analyses is the asymptotic relationship between the back-calculated modulus of the BSM-foam layer with time; the BSM-foam layer continued to gain stiffness.

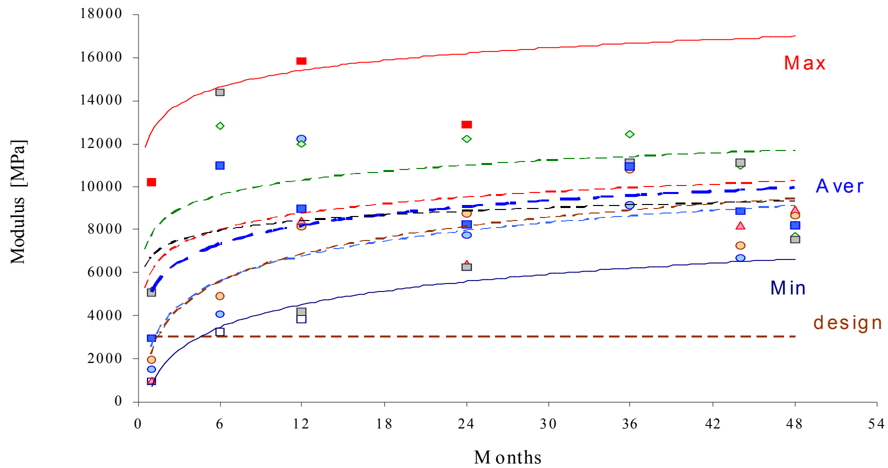

Figure 10. Change in effective modulus of BSM-foam with time (after Loizos *et al.*, 2007)

3.4.2 The Jingshen Highway in China

An analysis of pavement behaviour over time was carried out on the Jingshen Highway in China. This pavement was rehabilitated in 2005 by milling off 200mm existing asphalt and removing to temporary stockpile prior to recycling in situ 200mm of subbase comprised of cemented stabilised crushed stone material (addition of 2.3% foamed bitumen and 1% cement). A 150mm layer of pre-screened RA material treated in plant with 2% foamed bitumen and 1% cement was then paved as a new base layer, overlain with 50mm of MHA surfacing before opening to traffic. A Benkelman Beam was used by the Research Institute of Highways to measure the deflections up to one year after construction, as shown in Figure 11.

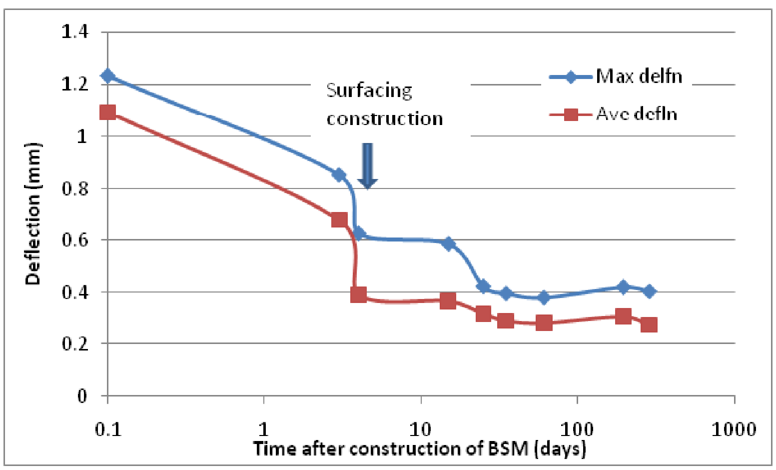

Figure 11. Jingshen Highway, Benkelman Beam deflections with time after construction

A significant reduction in the maximum and average deflections measured with the Benkelman Beam is apparent. The deflection reduction and hence increase in the Modulus of the BSM is almost asymptotic, showing the majority of the change occurring during the first month and reducing exponentially with time. Throughout the entire year the pavement was exposed to extreme traffic loading (this particular highway is well known for overloading with loads in excess of double the legal axle load limit of 10 tons recorded). In spite of such abuse, the BSM layer continued to increase in stiffness during the first year.

3.4.3 National Route 7 Section 1, Cape Town

This example concerns the behaviour of a section of the N7 highway near Cape Town, part of which was rehabilitated by recycling with BSM-foam (2.3% bitumen and 1% cement) on the Southbound Carriageway in 2002. The Northbound Carriageway was rehabilitated by recycling with BSM-emulsion in 2007 (2% residual bitumen and 1% cement). Both carriageways were recycled in situ and stabilised to a depth of 250mm. Physical moisture measurements of the BSM-emulsion base layer were tested in the laboratory, supplemented by moisture button monitoring in the layer (Moloto, 2010). In addition, Portable Seismic Pavement Analyser (PSPA) measurements were taken on the BSM base with time in order to evaluate the change in modulus of the base with time. Figures 12 and 13 show that the modulus is inversely proportional to the moisture content of the BSM-emulsion layer, a phenomenon known as "curing". For the seven months evaluation period, the rate of change in both moisture content and modulus is exponential as a function of time. The change in moisture content of the BSM-emulsion concurs with the trends found for BSM-foam curing rates (Malubila, 2005).

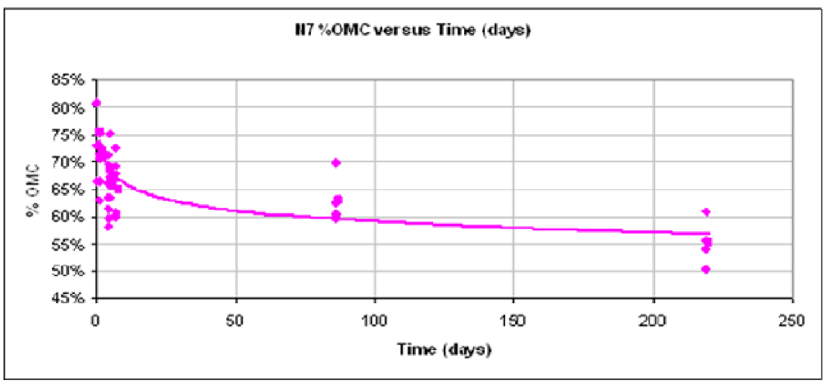

Figure 12. Moisture content in BSM-emulsion base from oven drying (Malubila, 2005)

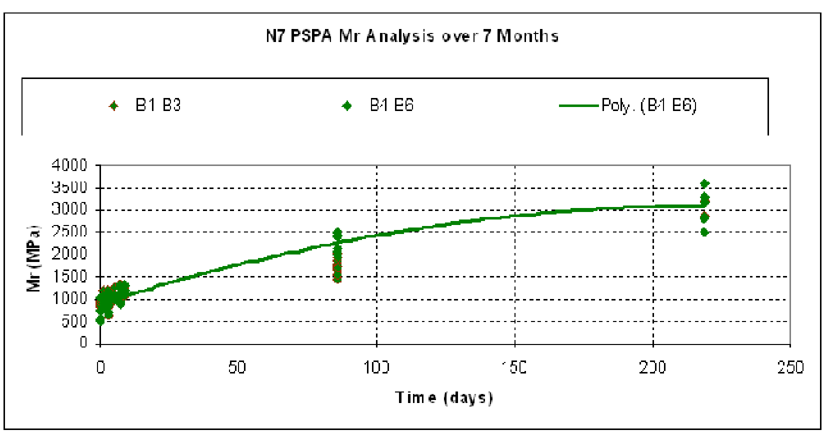

Figure 13. Modulus of BSM-emulsion base measured with PSPA (Malubila, 2005)

Focusing on the first year after construction, the above three examples of in situ measurements of BSM bases all show an increase in effective stiffness. This is consistent with the trends found in the laboratory during curing of BSMs. The following insights are obtained from these findings:

- the effects of curing and moisture reduction within BSMs that are exposed to traffic dominate the material behaviour for approximately one year after construction, ,
- it is probable that the effective stiffness of a BSM can stabilise (Loizos, 2007) and may even reduce to some extent after several years in-service. Any such reduction in effective stiffness is more likely to be attributed to rupturing of bitumen "spot welds" due to excessive shear stresses from heavy vehicles (or an elevated moisture content in the BSM) rather than fatigue failure resulting from trafficking.

4. CONCLUSIONS

Using the theory of fracture mechanics, the non-continuous nature of the bonds within a BSM render such materials immune to the formation and propagation of conventional fatigue cracks; tensile stress concentration at a crack-head can simply not develop within a material that is not continuously bound.

The response of three different pavement structures incorporating either BSM-foam or BSM-emulsion base layers, on three different continents, has been evaluated with respect to time. Two different deflection measurement techniques and one seismic measurement technique has been used to determine the response properties of the BSM layer in these pavements. The periods of evaluation of these pavements range between 7 months and 4 years. During these periods, all of the pavements were exposed to medium to heavy trafficking. The following conclusions can be drawn:

- The moisture in one of the BSM-emulsion layers was shown to reduce asymptotically with time due to curing. This concurs with findings with regard to curing effects on BSM-foam.
- All of the BSM base layers showed a non-linear increase in the stiffness of the layer versus time, tending towards a plateau after one year of service.
- A gradual increase in the stiffness of all BSM layers suggests that the effects of curing within a BSM overshadow the detrimental effects of trafficking for at least a year after construction.

All three examples show the effective stiffness of the BSM layer increasing with time (and accumulated traffic load) within at least the first year. These findings suggest that BSMs run counter to the trend for continuously bound materials that are prone to fatigue degradation (reduction in effective stiffness with time). Such a trend would appear to confirm the theoretical postulation that non-continuously bound BSMs are not prone to fatigue degradation. However, at this point in time, insufficient reliable data is available to analyse the trends of effective stiffness of BSMs beyond 4 years of service. Significantly more LTPP data is required for this purpose, incorporating the variables of traffic, pavement structure, subgrade support, BSM mix design and climate.

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