MATERIALS RECYCLED USING FOAMED BITUMEN STABILISATION: WHAT IS THEIR LONG TERM LOAD SPREADING CAPACITY

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Abstract

Bitumen stabilised materials (BSMs), whether incorporating emulsified bitumen or foamed bitumen, have been shown to behave differently to Hot Mix Asphalt HMA, even though they incorporate the same primary ingredients i.e. aggregates, bitumen and in some cases active filler. Previous research has attributed the differences to the cold (ambient) temperature of the aggregate during production of BSMs, resulting in the selective dispersion of the bitumen and "non-continuously bound" mixes. HMA on the other hand has bitumen in the continuous phase, resulting in dominance of the visco-elastic nature of the bituminous binder.

Although the nature of the binder dispersion is self-evident in the mix, through microscopic observations, the selection of applicable response and performance properties of BSMs, remains an area of dispute. Are the constitutive models and damage models of granular, cemented or asphaltic materials applicable?

This paper supplements previous research into Long-term Pavement Performance LTPP of BSM base layers in-service, with a recent test section constructed in South Africa, which include variables of base type (granular, cemented and BSM), mix compositions, layer thickness and time or traffic. The road was monitored with the use of FWD testing over time, supplemented by laboratory testing of lab specimens and field cores. The back-analysed layer moduli of the base layer provide insight into the evolution of stiffness over time, with clear influences of rainfall, cement content, bitumen stabilisation and other construction practices.

1. INTRODUCTION

Bitumen stabilised materials (BSMs) incorporating bitumen emulsion or foamed bitumen, have been used globally over the previous two decades to provide base layers for many thousands of kilometres of road pavements. Although the BSM technology is primarily applied on rehabilitation projects using recycled materials in the existing pavement, it can also be used for new projects. In spite of the majority of these pavements performing well, there remains a general lack of understanding of BSMs, particularly concerning the response models and failure mechanisms.

The quest for development of a behavioural and performance model for foamed bitumen stabilised materials is complicated by the diversity of materials that need to be incorporated in the model. Factors such as inclusion versus exclusion of cement or other active filler, low versus high bitumen content and cold versus warm aggregate, significantly influence the foamed mix properties (Jenkins, 2000) and hence the need for a range of performance functions. These combinations will influence the BSM response or resilient modulus i.e. the load spreading capacity of this material.

As an example, the Highveld region of Gauteng, South Africa has an abundance of pavement structures with good quality gravels and graded crushed stone, due to its natural resources. The initial tendency was to minimize stabilizer contents (both viscous and hydraulic) in such cases and produce mixes that resemble weakly bound granular materials. The coastal region of KwaZulu Natal, however, has higher rainfall and rock-weathering indices resulting in poorer quality materials; consequently, the region initially followed the higher stabilizer content philosophy with appurtenant strongly bound and more asphaltic mixes. In general, foamed bitumen contents commonly less than 2,5% were used on the Highveld and greater than 3,5% are commonly used on the coast. Higher bitumen contents result in greater flexibility of mixes but lower resistance to permanent deformation.

In 2002, the first edition of Technical Guideline TG2 was published. It initiated an equal footing for emulsion and foamed bitumen in BSM mix design and performance evaluation. This guideline highlights that the conditions for production of BSMs, result in non-continuous dispersion of bitumen in these materials. The second edition of the Asphalt Academy's TG2 (2009) moved to standardise bitumen and active filler contents in BSMs, In spite of this non-continuous binding phenomenon being explained in TG2 (2009), there is still confusion amongst practitioners concerning the behaviour of BSMs. This paper aims to provide insight into in-service response of different compositions of BSMs under traffic, and in terms of curing time, on the basis of FWD measurements and other field and laboratory evaluation tools.

2. BACKGROUND

The dichotomy of approaches to the mix design of BSMs is captured by current best practice in the Tri-Nation countries i.e. Australian, New Zealand and South Africa. Figure 1 shows how range of "best practice" binder application i.e. bitumen and active filler, differ between the three nations. These divergent approaches, into which the majority (but not all) of mix designs fall, can be summarised in terms of the objective performance functions of each nation:

- *Australia:* High binder contents (both bitumen and lime) for durability and high bitumen content for flexibility and flexural stiffness, load spreading and early strength. [Asphaltic approach to BSM]
- *New Zealand:* Moderate to high bitumen content for durability in a wet climate, above average cement content (early strength and durability). [Durability and strength objective, for a semi-bound BSM]
- *South Africa:* Relatively low binder contents (bitumen and cement or lime), sufficient for durability, without oversaturating the filler with bitumen, without creating a high

modular ratio for base:sub-base and economical. [“Granular material on steroids” approach to BSM]

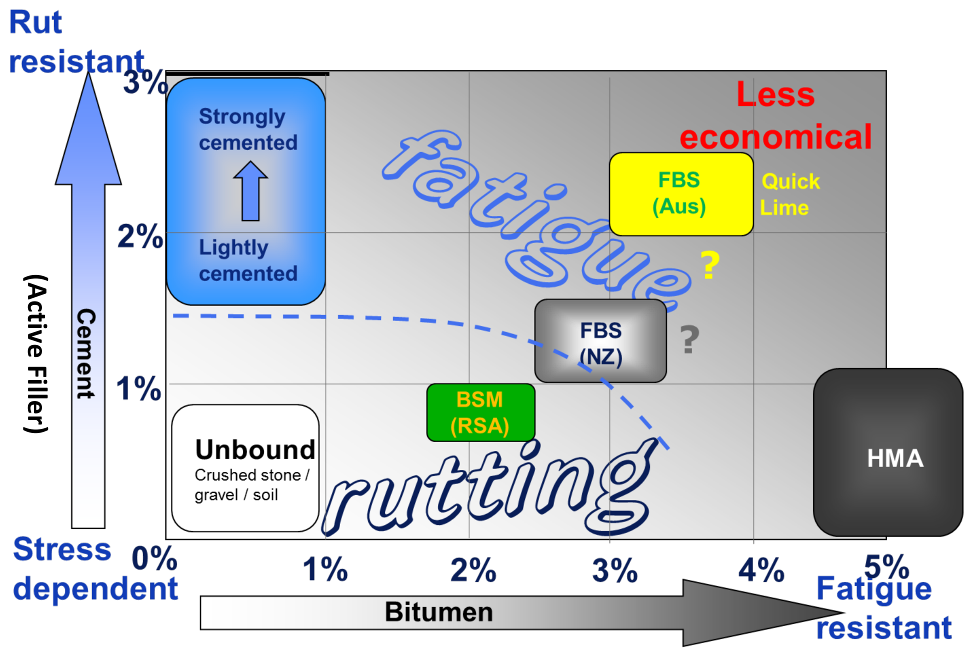

Figure 1. Typical Best Practice range of Binders Application Rates for BSMs in the Tri-Nations

This dichotomy raises the question: “Which of these approaches provides the ideal BSM mix”? This paper aims to explore some of the fundamental principles regarding the behaviour and performance of BSMs, using LTPP and experimental sections, with the objective of attempting to shed some light on the key factors that contribute to the composition of an “ideal BSM”.

3. RESPONSE OF BSM

Within the divergent objectives and approaches to BSMs, there are too many variables contributing to the behaviour of these materials to cover them all. For this reason, this paper will focus solely on BSM-foam and the response parameters rather than the damage models of the material. It should however be borne in mind that the evolution of stiffness, a response parameter, over time can have damage built in implicitly.

It has been published elsewhere by Jenkins *et al* (2011) and Malubila (2005) that the response parameters e.g. Resilient Modulus, measured in the laboratory cannot be considered to be representative of the in-service properties, unless curing time, traffic, moisture fluctuations and other factors are taken account of. Nevertheless, laboratory analyses can highlight characteristics such as stress dependency and visco-elasticity in BSMs, as shown in Figures 2 and 3 respectively, that need to be considered when conducting field evaluations. These characteristics draw attention to influences that load magnitude, loading rate and temperature could have on BSM response. However, they provide a “snap shot” of the response in the overall time frame of the BSM’s existence in the pavement structure.

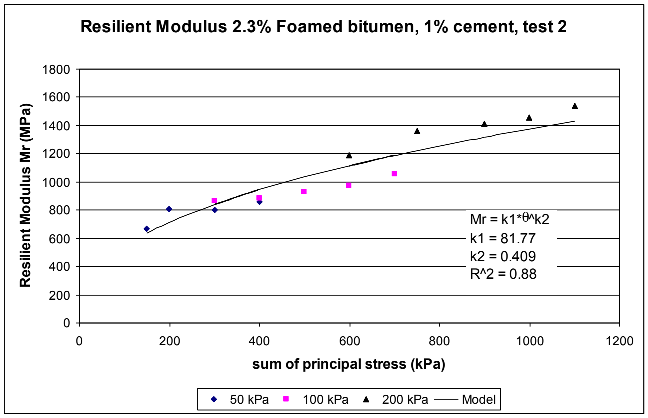

Figure 2. Dynamic triaxial tests on BSM-foam (Jenkins *et al*, 2002)

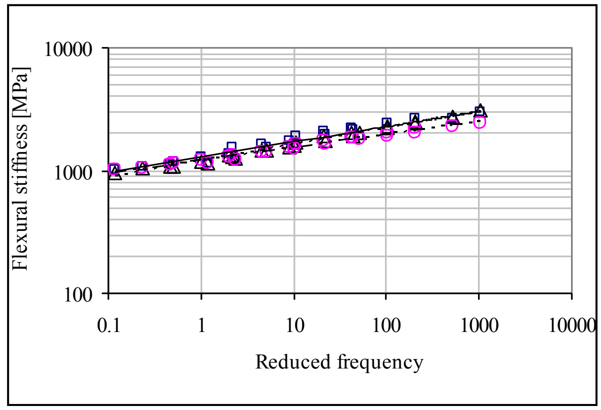

Figure 3. Master curves of BSM-emulsion and BSM-foam (Mathaniya *et al*, 2006)

3. LONG TERM BEHAVIOUR: PREVIOUS RESEARCH

The evolution of stiffness over time is a key to the understanding of the performance of BSM layers under traffic, as it evaluates the changes in load spreading by the base layer over the life of a pavement. In order to determine definitively what the long term behaviour of BSM layers is, Collings and Jenkins (2011) investigated three heavy-duty pavements, each with less than 3% residual binder and less than 1.2% cement, which is representative of the South African BSM philosophy and the majority of BSMs currently being applied globally, as "state of the art". (BSM layers incorporating higher application rates of either bitumen or cement may yield different findings.)

3.1 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 4 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 provide a reciprocal relationship of the long term stiffness. During the period of the deflection measurements, which was almost 4 years (Collings and Jenkins, 2011), 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 gained stiffness and then stabilised.

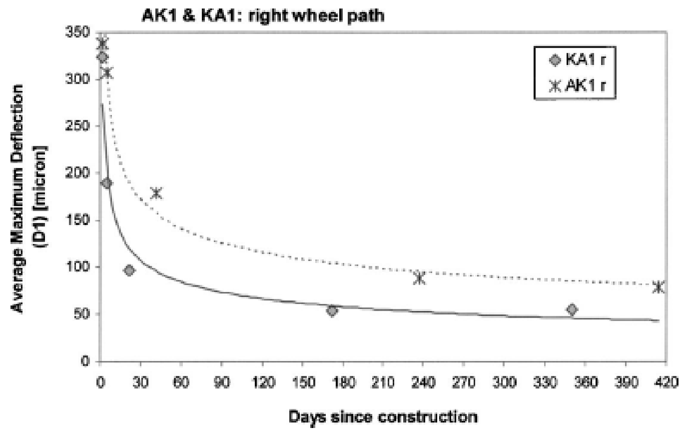

Figure 4. Change in FWD Maximum Deflection with time (Loizos *et al*., 2007)

3.2 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 4 and 5 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).

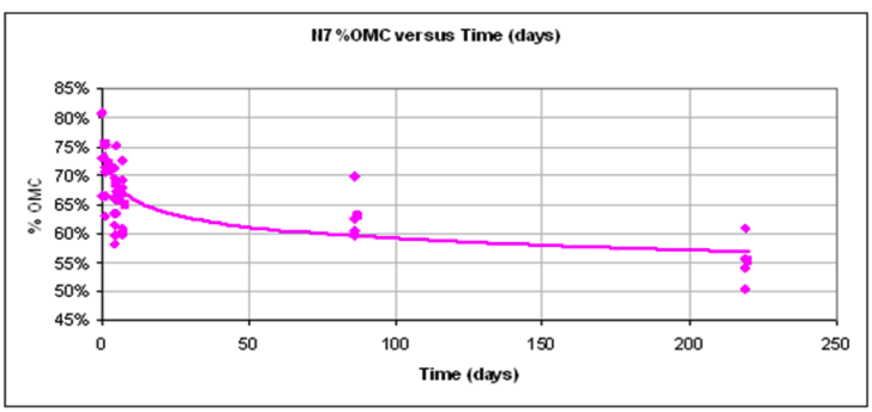

Figure 4. Moisture content in BSM-emulsion base from oven drying (Malubila, 2005)

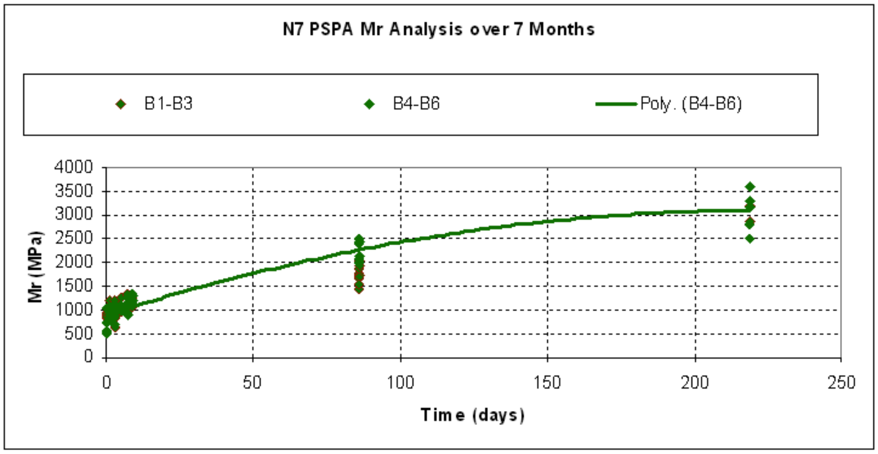

Figure 5. Modulus of BSM-emulsion base measured with PSPA (Malubila, 2005)

4. LONG TERM BEHAVIOUR: NEW RESEARCH

4.1 R35 Experimental Section, Mpumalanga, South Africa

As part of the revision of the South African Mechanistic Design Method, the South African National Roads Agency (SANRAL) constructed a 4.5 km long experimental section to investigate the long term performance of both purely cement and bitumen stabilised materials (BSM). The foamed bitumen stabilised materials constructed are reported on in this paper.

The experimental section was constructed on the R35, north of Bethal, Mpumalanga, South Africa during 2012. According to the modified Thornwaite Moisture Index (Leyland & Paige-Green, 2010) the experimental section falls within a region with a modified Thornwaite Index of 0 – 20, classifying the locality as having a moist sub-humid climate.

4.2 Experimental Section Layout, Design and Construction

The experimental section consists of 25 sub-sections, each approximately 350m in length, in the northbound and southbound lanes of the R35 between road chainages km 5.5 and km 10.0. Sub-sections, in both the northbound and southbound direction, were constructed, by cold in-place recycling (CIPR) with a varying pavement structure and stabiliser content design.

Eight of the 25 experimental sections were constructed by CIPR with foamed bitumen. The construction of the BSM foam experimental sub-sections was implemented by the CIPR of an existing cement stabilised dolerite gravel base and sub-base on-top of a varying combination of stabilised and non-stabilised dolerite gravel layers, as identified by test-pits excavated as part of the main R35 rehabilitation project.

From the experimental section design investigation (Theyse, 2013), the existing sub-base was found to have very low back-calculated stiffnesses. It was proposed that this indicated the sub-base layer was in a poor condition. This observation was corroborated by cores taken in the existing pavement structure where the existing base was found to continuously bound while the existing sub-base had broken down into lumps of continuously bound material. The CIPR of the existing base on top of this broken down, low effective stiffness layer, was used to create an accelerated pavement deterioration setup where the poor support beneath the CIPR base would induce excessive strain within the CIPR layer. The design layer thicknesses and stabiliser contents for the BSM foam sub-sections are tabulated below.

Table 1: BSM foam sub-sections experimental design - northbound and southbound

Sub-section Identifier	Layer Thickness (mm)	Cement Content (% by mass)	Residual Bitumen Content (% by volume)
175 BSM Foam (1%c, 2.4%b)	175	1	2.4
200 BSM Foam (1%c, 2.4%b)	200	1	2.4
175 BSM Foam (2%c, 2.4%b)	175	2	2.4
200 BSM Foam (2%c, 2.4%b)	200	2	2.4

4.2 FWD deflection measurements and back-calculation

FWD deflection measurements were carried out at five metre intervals at various temporal intervals over the 360 day period since the construction of each BSM foam sub-section. The FWD setup is depicted in Figure 6. The target peak stress beneath the 300mm diameter FWD load plate was 566 kPa.

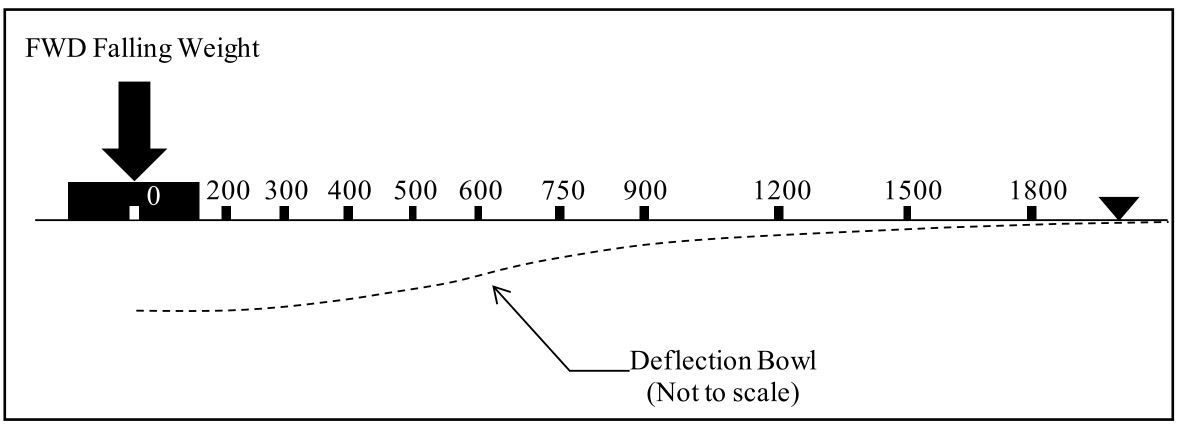

Figure 6: FWD geophone setup and distance from load plate (mm)

The number of days since the construction of each sub-section, on which FWD deflection measurements were taken varied but typically occurred on 0, 3, 7, 14, 28, 90, 180 and 360 days after the foamed bitumen stabilised base layer construction.

The back-calculation of the measured deflections bowls was carried out utilising back-GAMES. Back-GAMES is an automatic, pavement surface deflection bowl, back-calculation software package developed by the CSIR, South Africa. It utilises the General Analysis of Multi-layered Elastic Systems (GAMES) modelling engine (Maina & Matsui, 2004).

At the time of the back-calculation of the measured deflection bowls, limited reliable information relating to the as-built CIPR base layer thickness was known therefore the base layer design thickness, remaining existing stabilised sub-base layer thickness and a combined effective semi-infinite subgrade was utilised within back-GAMES to represent the actual experimental pavement structure constructed. The back-calculation process estimated the effective layer stiffnesses of the modelled pavement structure, from the FWD measured deflection bowls in both the northbound and southbound lanes of the experimental section. The pavement models utilised in the back-calculation process are depicted in Figure 7. After FWD testing at 90 days, each experimental sub-section pavement structure was paved with a bituminous surfacing, half the sub-section length surfaced with a 45mm asphalt layer and the remainder with a Cape seal.

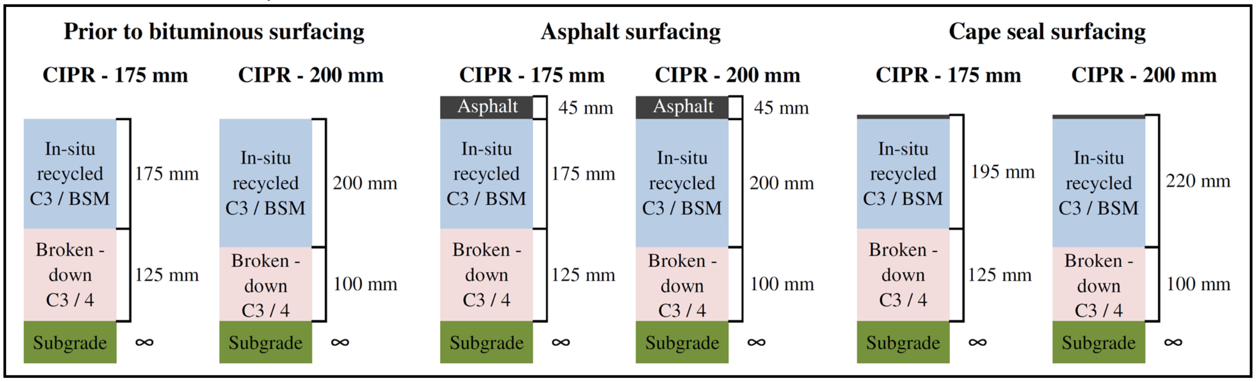

Figure 7: Back-calculation pavement structure models

4.3 Trends in average back-calculated stiffness of BSM foam layers

Figure 8 depicts the trend in back-calculated stiffness for the BSM foam layer in southbound lane of the experimental section. The spread of stiffness values at each temporal location indicates the variability of stiffness values determined for each 350m sub-section.

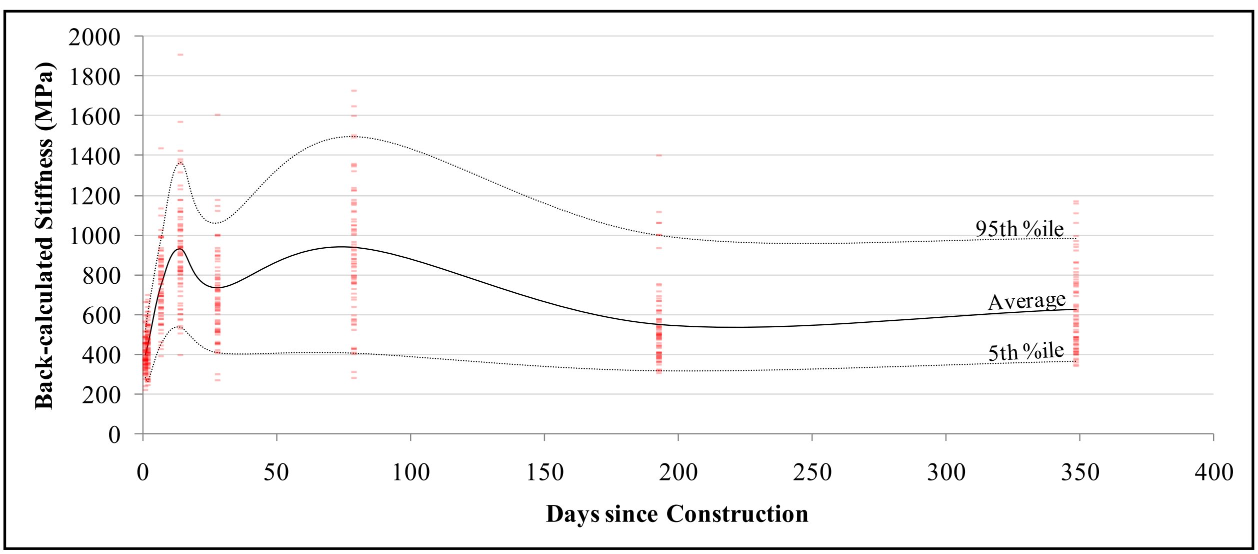

Figure 8: Average back-calculated stiffness trend – 175mm BSM-foam 1% cement

For the purpose of observing trends in the stiffness of the BSM foam layers with varying stabiliser content and layer thickness, the average of stiffnesses back-calculated at 5m intervals along each sub-section are depicted at each temporal interval, along with significant events occurring during the 360 day monitoring period which may have influenced the BSM foam layer stiffness. The variability of the back-calculated stiffness per sub-section will be discussed in Section 4.3.5.

4.3.1 BSM Foam with 1% cement active filler

(i) Southbound

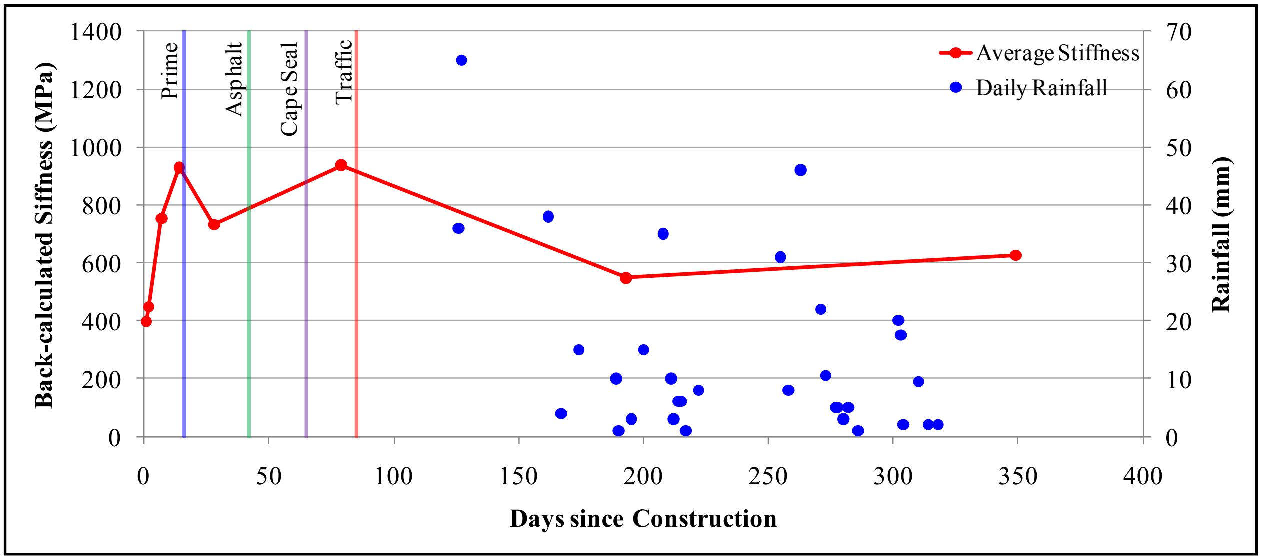

Figure 9: Average back-calculated stiffness trend - 175mm BSM-foam 1% cement, Southbound

Figure 9 exhibits the trend in average stiffness of the 175mm thick BSM foam layer with 1% cement / active filler added. Events identified which may have induced reductions in stiffness include the application of an MC-30 cut-back bitumen prime between day 14 and day 28 FWD testing. The stiffness of the layer seems to recover as indicated by stiffness values determined from day 90 FWD testing.

A significant drop in stiffness is observed between the day 90 and day 180 average stiffness values. As indicate by the blue markers, heavy rainfall occurred between day 90 and day 180 average stiffness values. Also noted is that the experimental section was opened to traffic subsequent to day 90 FWD testing. A similar trend was observed for the 200mm thick BSM foam with 1% cement / active filler content. No significant change in average back-calculated stiffness is observed between day 180 and day 360 determinations.

(ii) Northbound

The northbound BSM foam layers with 1% active filler content were constructed approximately three months after the southbound experimental sub-sections. Figure 10 shows the trend in average stiffness of the 200mm thick BSM foam layer with 1% active filler added. In this case significant rainfall occurred between day 5 and day 14 stiffness values and a brief reduction in stiffness is observed up until day 28 where an increase in average stiffness is observed, which continues until the day 360 stiffness determination. The trend in average stiffness values observed is suggested to be due to seasonal moisture variation within the pavement layers. A similar trend in average back-calculated stiffness was observed for the 175mm BSM foam with 1% active filler content. It should also be noted that no reduction in stiffness was observed with the opening of the experimental section to traffic after the day 90 FWD testing.

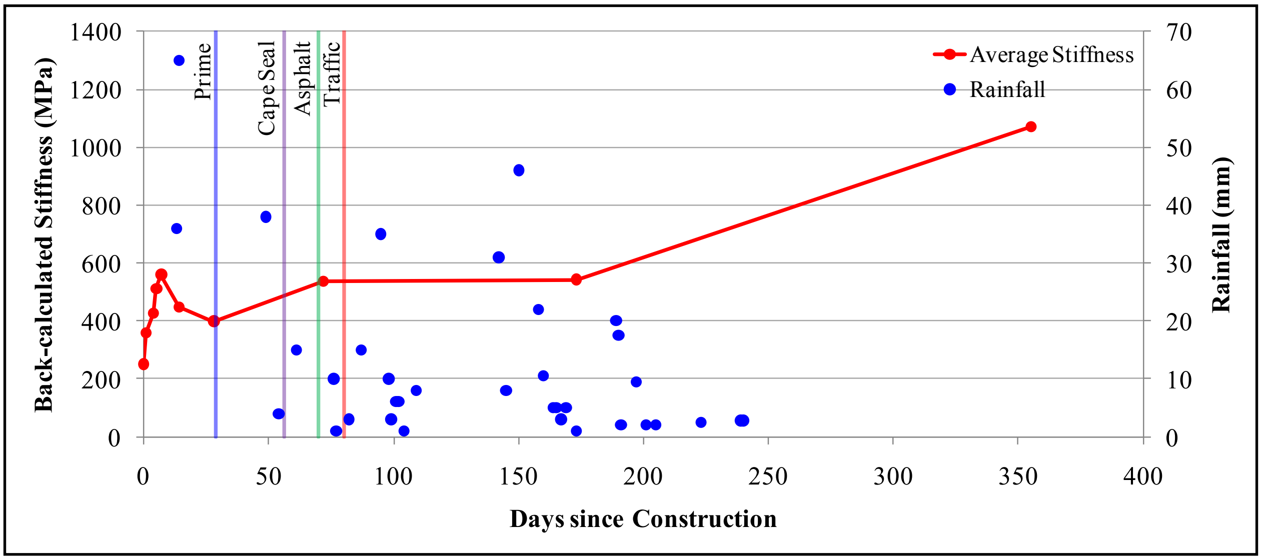

Figure 10: Average back-calculated stiffness trend - 200mm BSM foam 1% cement, Northbound

4.3.2 BSM Foam with 2% cement active filler

(i) Southbound

Figure 11 below provides the trend in average back-calculated stiffness for the 175mm BSM foam with 2% active filler content. A slight drop in stiffness is observed between day 14 and day 28 stiffness values. A prime application was applied to the base layer during this period and is identified as a possible cause of the temporary stiffness reduction.

A more significant reduction in stiffness is noted between day 90 and day 180 average back-calculated stiffness values. During the period between these two FWD test days significant rainfall was recorded. Also it is noted that the opening of the experimental section to traffic occurred during the intervening period. The average back-calculated stiffness remains stable between day 180 and day 360 determinations.

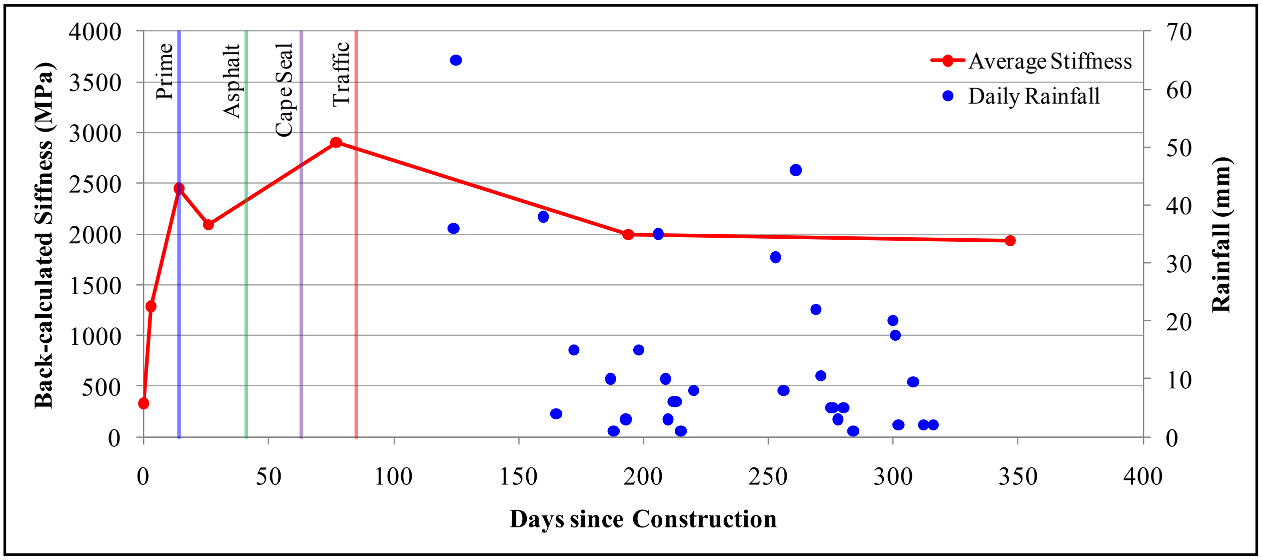

Figure 11: Average back-calculated stiffness trend – 175mm BSM foam 2% cement, Southbound

(ii) Northbound

The trend in average back-calculated stiffness for the 200mm BSM foam layer with 2% active filler content, in the northbound lane shows a continued increase in stiffness over the 360 day observation period, see Figure 12. The heavy rains which occurred over the initial 90 days since construction of this BSM foam layer seem to have had no effect on the back-calculated stiffness of the layer. Also no effects of opening the experimental section to traffic loads on the back-calculated stiffness of the BSM foam layer are apparent.

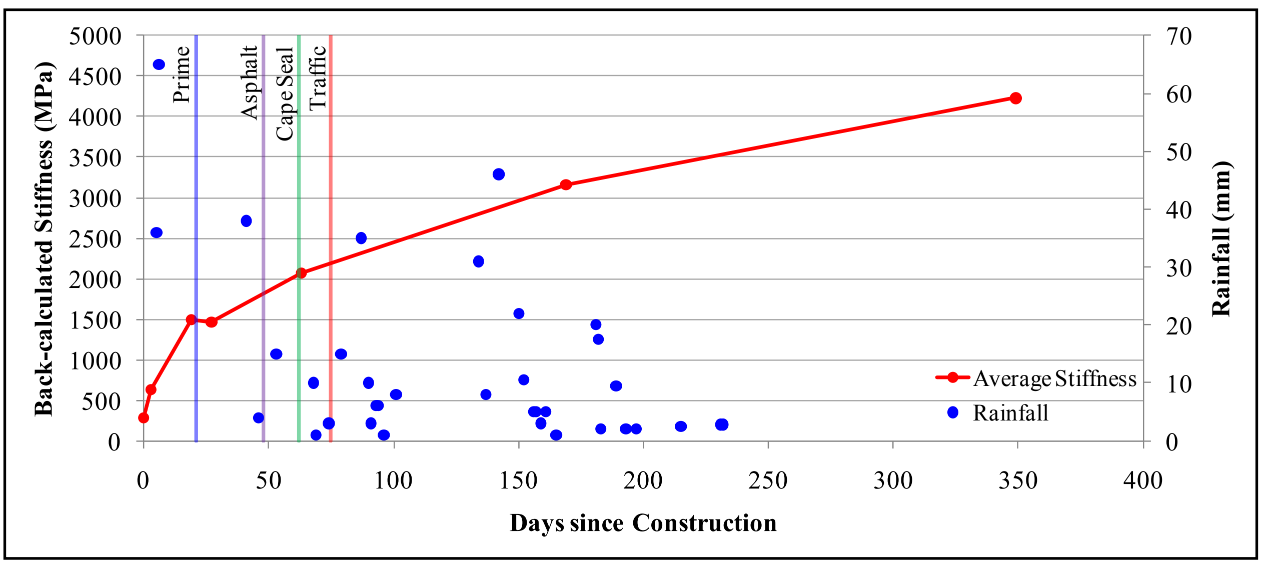

Figure 12: Average back-calculated stiffness trend – 175mm BSM foam 2% cement, Northbound

4.3.3 Back-calculated Stiffness and Chord Modulus (Field Cores) at 28 days since construction

The chord moduli of cores sampled from each BSM-foam sub-section were determined by dynamic tri-axial testing. Figure 13 depicts the comparison between the average back-calculated stiffness and chord moduli determined from field cores for corresponding BSM-foam sub-sections. A reasonable linear correlation exists between the back-calculated stiffness values and those determined through dynamic tri-axial tests.

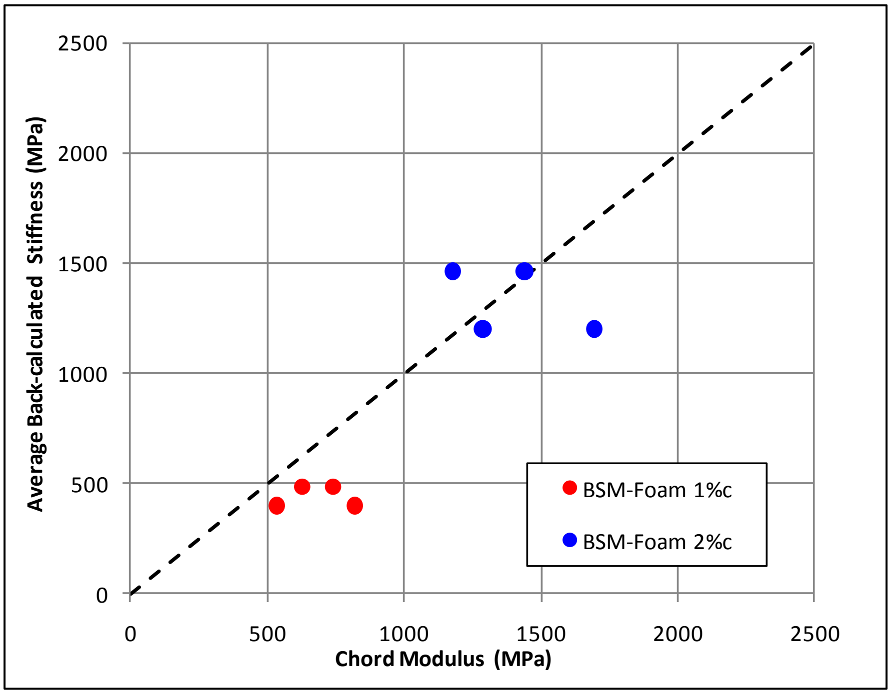

Figure 13: Resilient modulus comparison – Back-calc vs. Dynamic Triaxial

4.3.4 Comparison with cement and lime stabilised pavement layers

Experimental sub-sections, in-situ recycled to a depth of 200mm and stabilised with cement and lime at 2% and 1% contents by mass respectively, were also constructed. Figures 14 and 15 depict the trends in average back-calculated base layer stiffness of the cemented C3 layers. Neither C3 layers show significant changes in average stiffness over the 360 day observation period. A slight reduction in stiffness may be observed in northbound C3 layer. These plots in comparison to those depicted previously for BSM foam materials show significant differences in stiffness behaviour.

The cause of significant average stiffness reduction between 28 and 90 day stiffness values has not been identified beyond all doubt, however it is suspected to be due to bituminous surfacing layer construction activities and the damaging effects of construction traffic on the brittle continuously bound material on a low stiffness supporting sub-base.

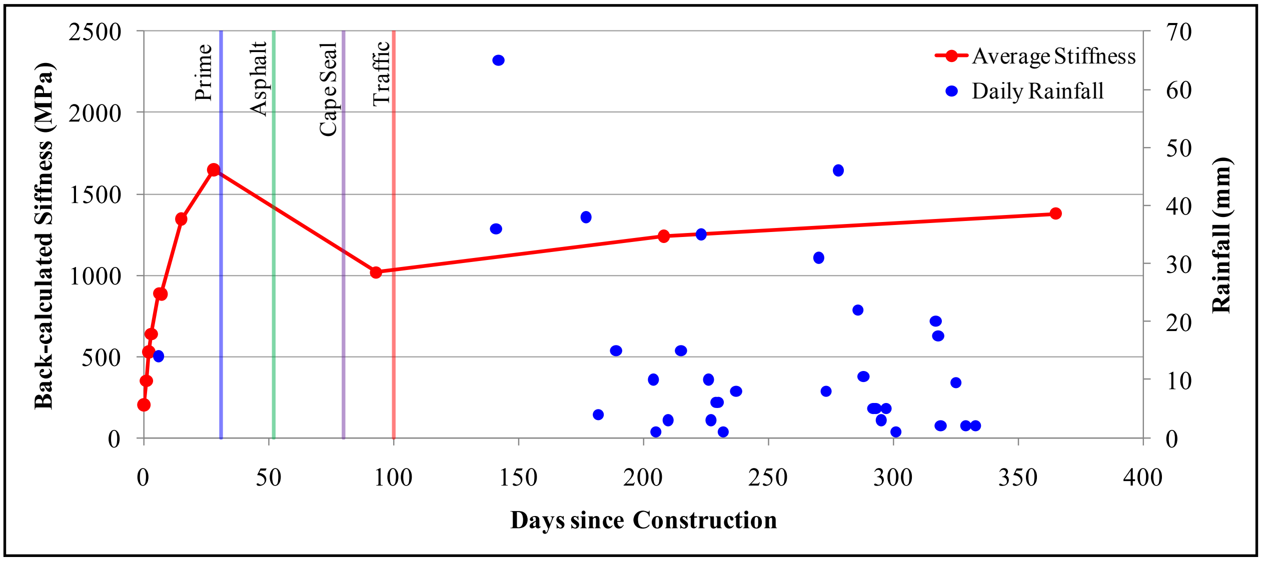

Figure 14: Average back-calculated stiffness trend – 200mm C3-1 2% cement, 1% lime SB

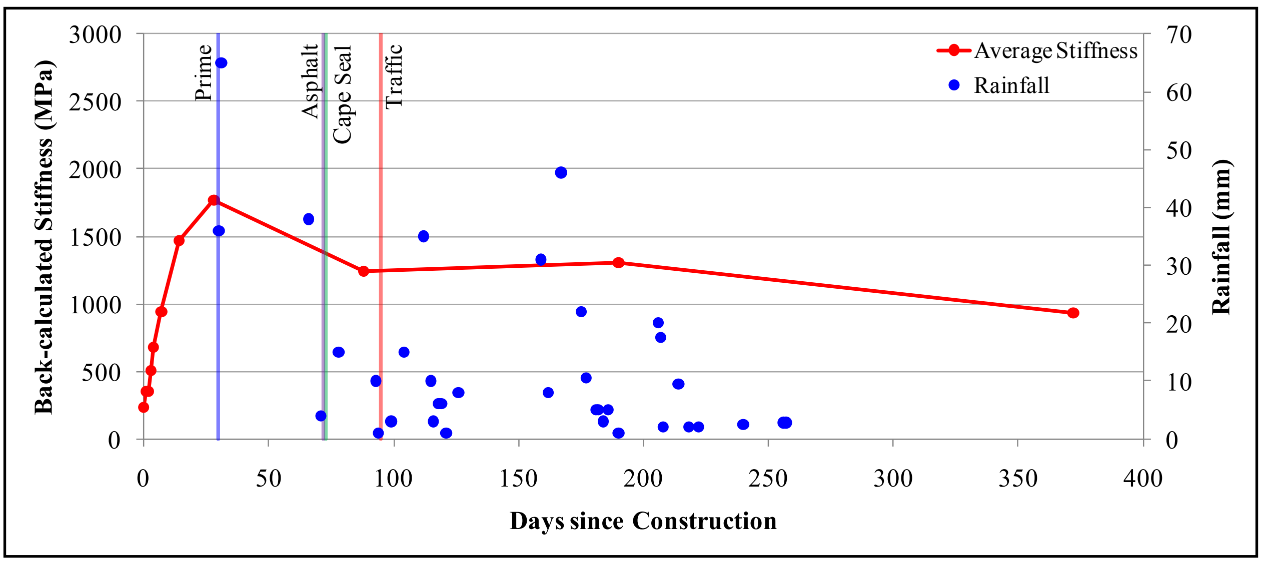

Figure 15: Average back-calculated stiffness trend – 200mm C3-1 2% cement, 1% lime NB

4.3.5 Back-calculated stiffness spatial variability per sub-section

The variability of back-calculated stiffness per sub-section for the 200mm BSM foam with 2% active filler content in the Southbound lane is depicted in Figure 17. The stiffness values back-calculated, determined at 5m intervals, are illustrated using colour coding as outlined in Figure 16. The spatial variability and the variability of the stiffness profile are clear. As the stiffness of the material increases the variability, as quantified by the coefficient of variation (COV), increases. The spatial stiffness profile can also be seen to change as the curing of the material proceeds and also when external influences such as rainfall or prime application induce changes in the average material stiffness. The events tabulated include Rainfall (R), Prime application (P) and Traffic (T). A similar, high variability in back-calculated stiffness per experimental sub-section was observed along each experimental sub-section.

Back-calculated Stiffness (Mpa)
0
500
1000
1500
2000
2500
3000
3500

Figure 16: Back-calculated stiffness colour code

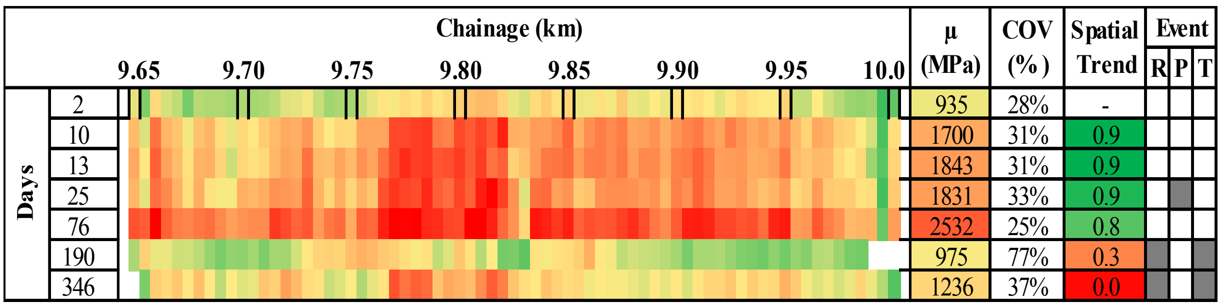

Figure 17: Spatial variability in back-calculated stiffness - 200mm BSM foam 2% cement SB

4.3.6 Summary of analyses

It is apparent from the plots shown in Section 4 that the application of a cut-back bitumen prime, MC-30, has a slight and temporary effect on the back-calculated stiffness of the BSM foam layers in general. The same prime coat did also have an influence on the cement base layer.

It is clear that the occurrence of rainfall and subsequent increase in pavement layer moisture content reduces the BSM foam layer stiffness. The effects seem more pronounced for BSM foam layers in the southbound lane than in the northbound lane. Rainfall occurs subsequent to the initial curing period for sub-sections in the southbound lane, while rainfall occurred during the initial 28-day curing period for sub-sections in the northbound lane, stunting the layers curing development. This difference can be seen in Figure 18 summarising the stiffnesses of all the BSM foam layers depicting the maximum average back-calculated stiffness achieved over the initial 90 day period since construction and the average back-calculated stiffness occurring between 90 and 360 day FWD tests. While rainfall and its subsequent pavement layer moisture effects are identified as possible influencing factors, the seasonal variation in air temperature follows a similar pattern to that of rainfall occurrence and hence may also be a contributing factor to the BSM foam pavement layer stiffness variability.

While the initial average stiffness values of the BSM foam layer are low, they can be seen to increase significantly at the FWD testing at 360 days, which occurred during the dry season. Day 360 FWD testing in the southbound lane occurred in the middle of the wet-season and the average stiffness values indicate lower values when compared to the northbound lane. The discrepancy between the day 360 back-calculated stiffness values can be seen in Figure 18.

The correlation of reduction in average back-calculated stiffness values due to traffic loading and subsequent BSM foam layer damage is not consistent. From average stiffness values observed in the southbound lane a correlation may exist between day 90 and day 180 stiffness determinations where a significant reduction is observed. However between day 180 and day 360 no stiffness reduction is observed where a heavier traffic load is applied due to the completion of the construction of the northbound experimental section and the removal of traffic accommodation. The northbound BSM foam layers show no correlation between average stiffness reduction and traffic loading over the 360 observation period.

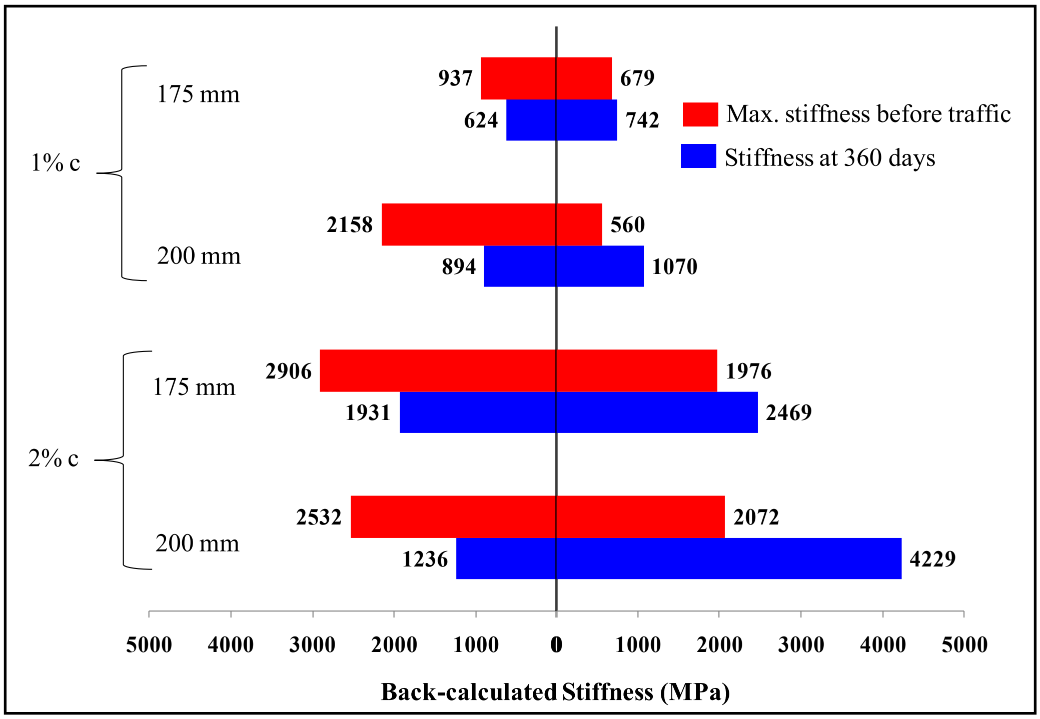

Figure 18: Summary of average back-calculated stiffness values over 360 day period

The average back-calculated stiffness values achieved by BSM foam materials with 2% cement added show significantly larger stiffness values than those for BSM foam layer with 1% active filler added. The trends in average back-calculated stiffness for BSM foam materials with design active filler contents of 2% seem to show a reduced susceptibility to stiffness fluctuation due to seasonal moisture and temperature variability, this is most evident from observations for sub-sections in the northbound lane. It should be noted that these measurements only reflect the response up to **one year of trafficking**. The experimental sections require monitoring further into the life of the BSM in order to verify whether the benefits of the higher cement content in the BSM endure for longer into the life of the road.

When comparing the trend in average stiffness values of BSM foam materials with that of purely cement and lime stabilised materials the fluctuation of the average back-calculated stiffness with seasonal moisture and temperature variations is not as apparent in the cemented material.

Subsequent to 90 day FWD testing average back-calculated stiffness values for purely cement stabilised materials remain constant or show slight average stiffness reduction.

Finally, the benefits of BSM-foam bitumen stabilisation are notable after a year construction with Mr values between 600 and 1000 MPa (with 1% cement) and > 2000 MPa (with 2% cement). The equivalent Mr values of the granular material are between 350 and 550 MPa.

5. CONCLUSION

From previous LTPP monitoring projects discussed in Section 3 and the initial outcomes of the recent research carried out on the R35 Experimental Section outlined in Section 4, the benefits of the addition of foamed bitumen to granular materials on the load spreading capability of the stabilised layer is apparent. The stiffness of the material is observed to increase with time, up to a year after construction.

The results of analysis from both previous LTPP studies on BSM-foam and the R35 Experimental Section show no evidence of stiffness reduction within the first year, due to the damaging effects of traffic loading during the respective observation periods.

The R35 Experimental Section results indicate significant fluctuations in the average back-calculated stiffness values for BSM-foam layers due seasonal moisture and/or temperature variability.

The variability of back-calculated stiffness values at each 5m spatial interval within a sub-section, from the R35 Experimental Section study, was observed to be significant and to increase with time. The effect of this variability on the design of pavement structures utilising CIPR of existing materials is significant. If the observed variability were incorporated within the pavement design of a CIPR project, to confidence levels typically utilised such as 80th, 90th and 95th percentiles, the majority of the pavement would be significantly over-designed.

The load spreading capability of BSM-foam layers, as indicated by layer stiffness, was observed to have been significantly greater than those of un-bound granular materials, thus providing greater protection to the under lying pavement layers and subgrade from the development of damaging stress/strain conditions within.

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