Laboratory Performance of Foamed Bitumen Stabilised Materials under Simulated Field Conditions

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1 Abstract

Foamed bitumen stabilised (FBS) pavements have gained increasing interest in Queensland, with the Queensland Department of Transport and Main Roads (TMR) having the largest volume of FBS pavements in Australia. Since 1997, TMR has rehabilitated over 1,000 km of existing roads using foam bitumen. Furthermore, in recent years, foamed bitumen has found application in the construction of new pavements and the rehabilitation of council roads and airports nationwide. FBS pavements exhibit increased strength and reduced permeability and moisture susceptibility. This can bring long-term benefits and help face the challenges of increasing freight tasks and more frequent extreme weather and flooding events.

Despite the widespread adoption of FBS pavements, the structural design of these materials relies on an empirical process based on the asphalt fatigue performance relationship originally developed for asphalt. It is recognised, however, that the fatigue behaviour of FBS material is unique and distinct from that of asphalt as demonstrated by recent Austroads research.

To better understand the fatigue behaviour of FBS materials and how flexural fatigue performance could translate into field performance this research investigates the effect of loading conditions and material confinement based on two laboratory testing configurations.

Flexural modulus and flexural fatigue performance is assessed based on beam fatigue testing under 4-point bending. In addition, extra-large wheel tracker testing is used to evaluate the fatigue resistance of FBS materials under simulated field conditions (i.e. rolling wheel loading, laterally confined and supported bending). The beams and slabs were manufactured from the same material and prepared using similar curing conditions. Two crushed rock aggregates sourced from Queensland quarries were used and prepared with the same binder content.

In addition to deflection measurements, fibre optic sensors are employed to monitor the evolution of the strain during slab testing that complemented the visual crack assessment during testing. The number of load repetitions until visible cracking was observed during the slab testing exceeded the estimated fatigue life from flexural fatigue test results.

The findings from this research contribute to a better understanding of FBS pavement degradation mechanism and assist the development of design guidelines and performance-based specifications for FBS pavements.

Keywords: Foamed bitumen stabilised (FBS) pavements, Flexural modulus, Flexural fatigue, Extra-large wheel tracker, Fibre optic sensors

1. Introduction

The fatigue performance of foamed bitumen stabilised (FBS) FBS materials holds significant importance in pavement design. FBS materials have increased strength, performance and resilience compared with typical unbound granular materials due to the distribution of dispersed bitumen through the aggregate mix. The bituminous binder is a viscoelastic material, therefore in FBS materials the loading speed and temperature can impact the stiffness and fatigue life.

Queensland Department of Transport and Main Roads (TMR) acknowledges fatigue cracking as the primary form of distress. While a higher bitumen content can enhance fatigue resistance, it may compromise rut resistance. In contrast, South Africa and New Zealand regard the bound fines matrix as non-continuous, suggesting lower susceptibility to fatigue cracking [1]. FBS materials are also considered to function as high modulus, rut-resistant, unbound granular material [1].

Field trials conducted in Australia have highlighted fatigue cracking as the primary distress mode, with rutting being less dominant [1]. Austroads' project TT2046, aimed at enhancing the cost effectiveness of FBS pavements, assessed the field performance of in situ FBS materials under full-scale accelerated loading. Results from the study indicated limited pavement deformation under accelerated loading conditions for the FBS trial pavement [2].

Laboratory testing is typically carried out at standard conditions, despite a range of subsurface temperatures expected including daily and seasonal oscillations and varying conditions around Queensland and Australia. The Austroads project APT6157 involved extensive laboratory testing of flexural beams to establish a fatigue relationship for individual FBS mixes. It resulted in determining an average strain damage exponent of 7.8 [3]. However, this laboratory-derived fatigue relationship did not consider the influence of temperature susceptibility on FBS mixes.

Pitawala [4] delved into the flexural fatigue behaviour of FBS materials to devise an analytical model for predicting the flexural fatigue of FBS pavements. The research explored the effects of temperature, density, bitumen content, moisture content, and hydraulic binder on the flexural modulus and fatigue life of FBS beams. Experimental findings revealed that flexural fatigue life increased with rising density and bitumen content but decreased with increasing temperature and moisture content. The correlation with temperature was attributed to variations in binder viscosity with temperature.

This paper discusses the research a part of an ongoing project (P132) undertaken by the National Transport Research Organisation (NTRO) and TMR as part of the National Asset Centre of Excellence (NACoE) partnership. The results presented in this paper aims at improving the temperature characterisation of FBS materials and its effects on the flexural performance of FBS materials and developing a laboratory fatigue relationship to predict the performance of FBS materials for Queensland, providing an accurate design model for various temperature conditions.

Two FBS materials representatives of TMR practice were selected and prepared in the laboratory to undertake testing to quantify the effect of temperature on the flexural modulus and flexural fatigue performance. Flexural testing also investigated the loading speed effect on the FBS materials modulus.

2 Foamed bitumen materials and preparation method

2.1 Host material

Two type 2.1 crushed rock materials (CR1 and CR2) were sourced from QLD quarries to undertake the research. Figure 1 shows their particle size distribution and additional characterisation results are summarised in Table 1. They both complied with the MRTS05: Type 2.1 requirements. It was noted that Mix 1 was non plastic.

Figure 1: Particle Size Distribution

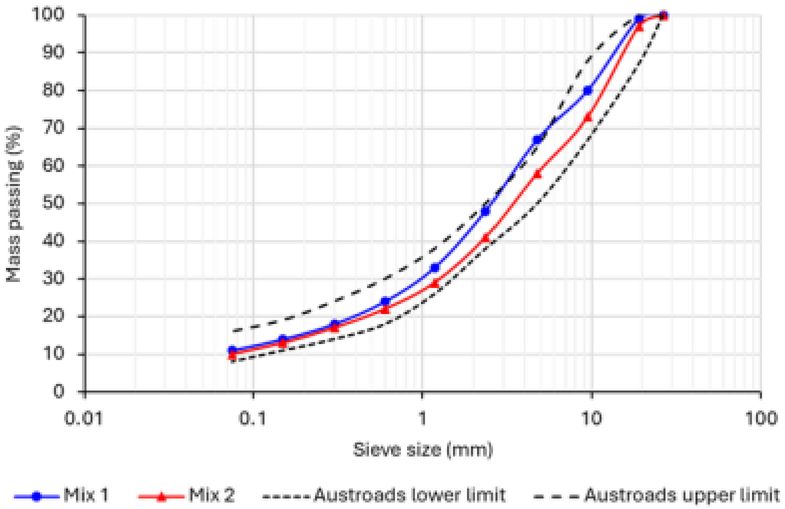


Table 1: Characterisation of Host Material

Property	Method	CR 1	CR2
Fine Content (% passing 75µm sieve)	AS 1289.3.6.1:2009	11	10
OMC std (%)	AS 1289.5.1.1:2017	7.5	8.0
MDD std (t/m^3)		2.30	2.22
Liquid Limit (%)	AS 1289.3.1.1:2009	na	16
Plastic Limit (%)	AS 1289.3.2.1:2009	na	13
Plasticity Index (%)	AS 1289.3.3.1:2009	Non-plastic	3.0
Linear Shrinkage (%)	AS 1289.3.4.1:2008	0.0	1.0

2.2 Foamed bitumen stabilised mixtures

The two FBS mixtures Mix 1 and Mix 2 were prepared respectively from CR1 and CR2 and stabilised using the typical binder combination currently used on TMR projects with a bitumen content of 3.5% and 1.5% of secondary additive (50/50 blend of hydrated lime and fly ash). Binder class C170 and Interfoam foaming agent IC 4952 at 0.5% by mass of bitumen were used in this study.

A Wirtgen WLB 10 S laboratory equipment was used for FBS material production following the TMR Q138A [5] method. The FBS materials were rifle-split into subsamples for specimen compaction. Marshall compacted specimens were prepared for indirect tensile (IT) modulus testing under 3-day accelerated curing conditions according to TMR Q139 [5] and shown the results summarised in Table 2.

Table 2: 3-day cured IT modulus

Material	**Bulk density (t/m3)**	**Bulk density (t/m3) (Q147b)**	**IT modulus dry (MPa)**	**IT modulus soaked (MPa)**	**Ratio soaked/dry modulus**
Mix 1	2.30	2.31	9570	6360	0.66
Mix 2	2.26	2.29	4605	325	0.71

The 3 day cured IT modulus results met the requirements for use under an average daily traffic greater than ESA in design year of opening [6].

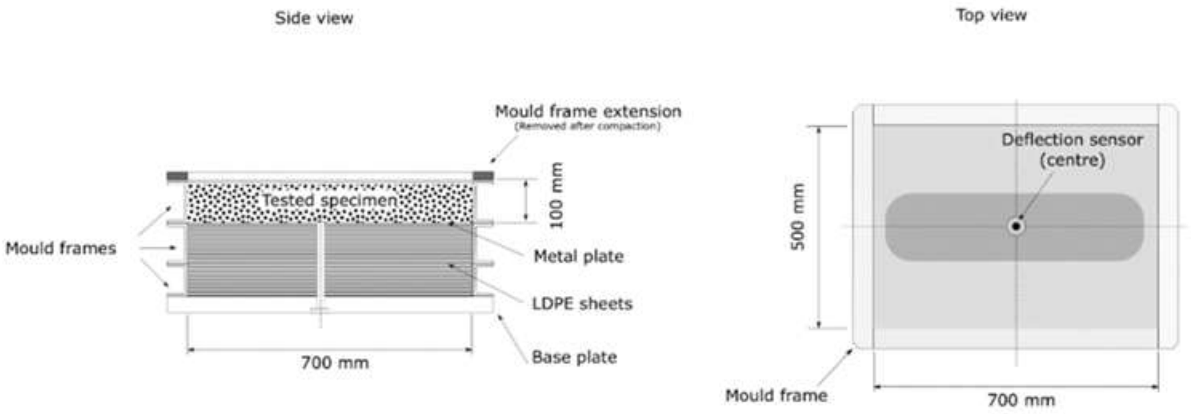
For performance testing, the Mix 1 and Mix2 specimens were compacted to a target bulk density of 2.29 t/m^3 and 2.28 t/m^3, respectively.

2.3 Specimen preparation and curing for performance testing

Following the methodology developed by NTRO for Austroads [7] the 100 mm x 100 mm x 400 mm beams for flexural testing were compacted and initially sealed in the mould for 3-day accelerated curing at 40 °C. After the initial curing period, the beams were demoulded and wrapped in cling film and cured in controlled room with a temperature 20 ± 5 °C to be cured for a total of 90 days from compaction.

For wheel-tracking testing, the slabs were prepared using the methodology developed for lightly bound materials and laboratory fatigue of slabs [8] as illustrated in Figure 2. The specimens are wrapped and sealed in cling film and subsequently cured. The compacted specimens are sealed in cling film and initially cured at 40 ±2°C in a humidity chamber for 69 ±0.5 hours at 100% relative humidity. Following the accelerated curing period post compaction, the specimens are stored at 20°C at 35% relative humidity before testing at 90 days.

Figure 2: Schematic View of the Mould



Source: Grenfell et al. [9]

3 Flexural testing

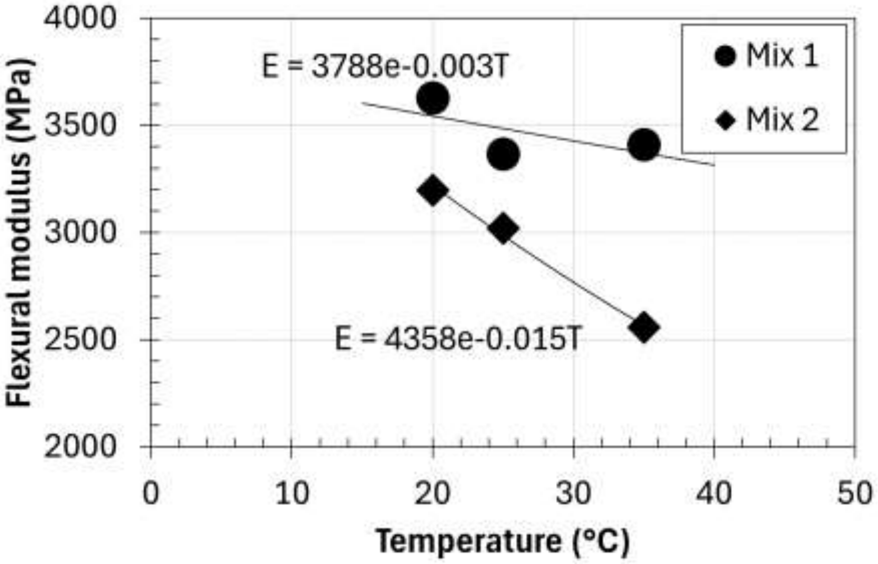
Flexural testing included the evaluation of FBS material modulus the sensivity to change in environmental condition (i.e. temperature) and loading speed induced by the viscoelastic bituminous binder.

3.1 Effect testing temperature and loading speed on flexural modulus

Flexural modulus is performed under sinusoidal loading at different temperatures and loading frequencies maintaining the specimen under low strain conditions (i.e. <50 µm/m). FBS materials will have temperature and time-dependent behavior, however expected lesser than asphalt materials with their lower bitumen contents. However, the flexural modulus is expected to decrease with increasing temperatures and increase with increasing loading speed.

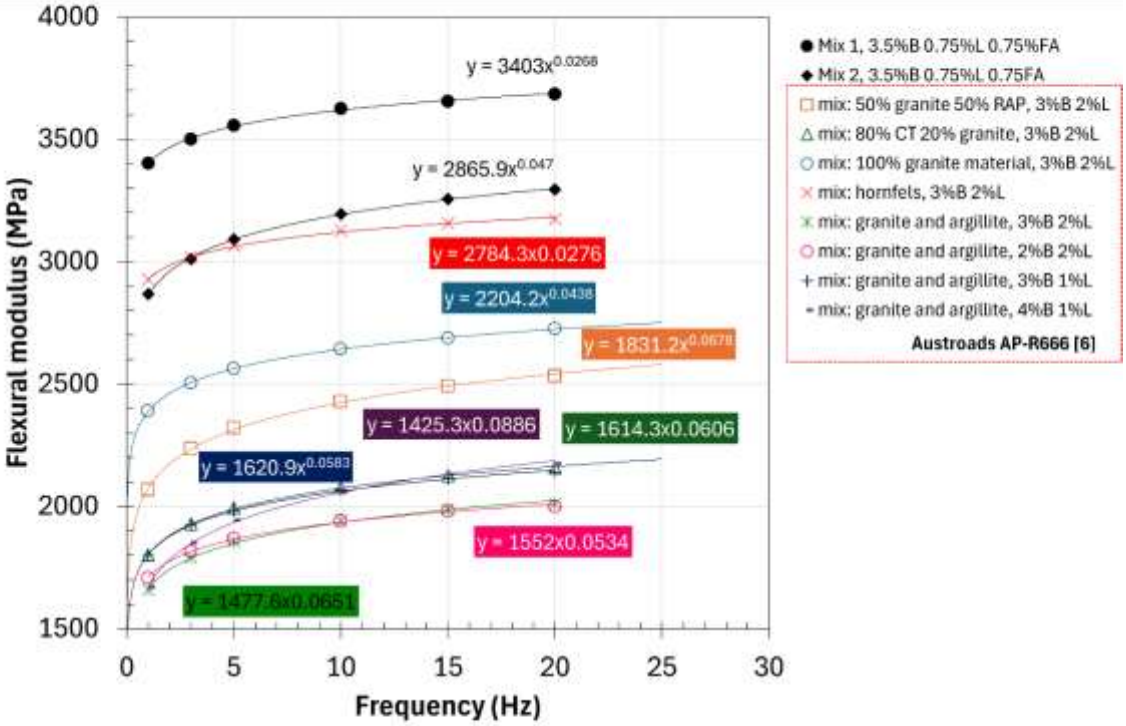
The flexural modulus data at 10 Hz against temperature is presented in Figure 3. In this graph the temperature dependency is interpolated by an exponential equation. The temperature dependency parameters are 0.003 and -0.015 for Mix 1 and Mix 2 respectively. In comparison the current Austroads temperature relationship for FBS material parameter is -0.025 [3], which is greater than the exponent determined from Mix 1 and Mix 2 material determined from the testing in this research. These results from this study suggest a lower temperature dependency compared to what is assumed in current practice.

Figure 3: Effect of temperature flexural modulus at 10 Hz



The flexural modulus results at 20 °C measured at different loading frequencies are plotted in Figure 4 and compared with previous Austroads [3] research investigation presented. Based on the linear frequency speed relationship used for asphalt materials [10] the modulus of FBS materials can be represented by a power law equation with an exponent of 0.027 and 0.047 for Mix 1 and Mix 2 respectively. When compared with testing reported in AP-R666 [3] the exponent was found to range from 0.027 to 0.068. These results show a lesser sensitivity to loading speed than the relationship currently used in rehabilitation design [11].

Figure 4: Flexural modulus at 20 °C with load frequency



Overall, the temperature and loading speed of the tested FBS material appeared less pronounced compared with what has been derived from previous results and form the basis of the current procedures. The temperature and loading speed dependency was formerly examined based on IT modulus testing as opposed to flexural testing. Comparative testing under indirect tensile conditions is on its way, as part of the continuing research to further investigate this aspect.

3.2 Effect of temperature on fatigue performance

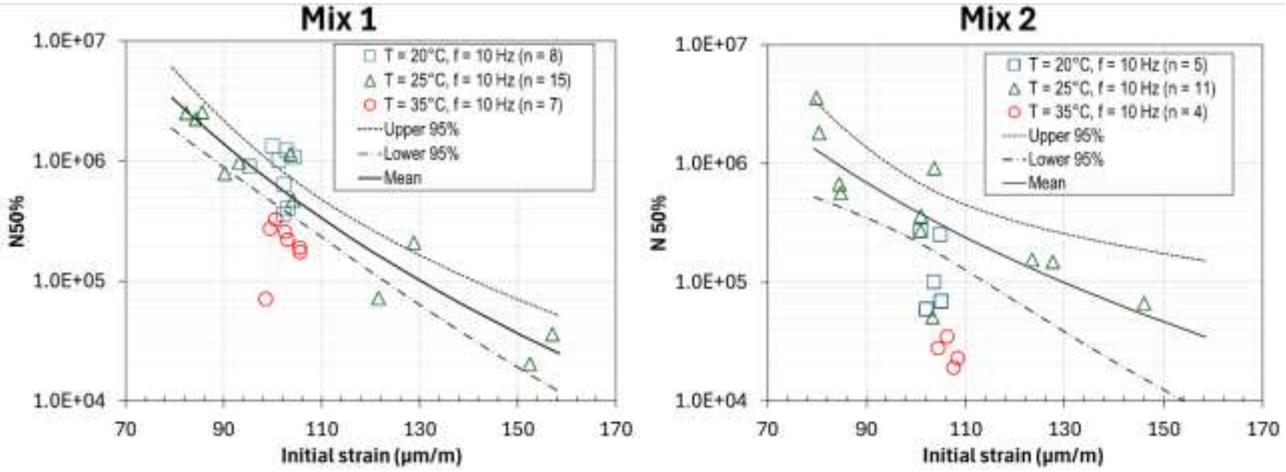
Limited data is available regarding the effect of temperature on the flexural fatigue performance of FBS material. The most research was undertaken by Pitawala [4] who used a specimen preparation derived from the NTRO method and relatively consistent fatigue testing protocols. This previous research determined a very significant effect of temperature with the fatigue live measured at 33ºC being more than tenfold lesser than at 22ºC. This trend is not considered consistent with field observations in QLD where weighted mean pavement temperatures are typically between 30 ºC and 40 ºC.

The effect of temperature on the fatigue performance of Mix 1 and Mix 2 was performed using the fatigue line determined for 20ºC as a base case according to report APR-666 [3] and for the intermediate loading level (lives between 2E5 and 5E5) two sets of specimens were tested at 25 and 35 ºC and determine the relative mean fatigue life.

The fatigue performance results at the different tested temperature are shown in Figure 5 with the 95% confidence limits for the 25 °C testing. The degree of scatter present in the results is likely attributed to the variability of laboratory sample preparation. The tested stress aiming at $7x10^5$ of Mix 1 and Mix 2 specimens are 96 kPa and 90 kPa, respectively at 25 °C equivalent to an average initial testing strain around $100x10^{-6}$. At 25 °C, Mix 1 and 2 showed strain damage of 7.1 and 5.8 respectively, although Austroads [3] reported a mean damage exponent of 7.8. Despite the difference damage exponent, the results are within the expected level of uncertainty observed on FBS materials when considering the 95% confidence limits.

Generally, as temperature increased from 25 °C to 35 °C the fatigue life decreased. There is a greater variance in the fatigue life of Mix 2 materials when compared to Mix 1. For both Mix 1 and Mix 2 specimens, there is a statistically significant difference in fatigue life from specimens at 20 °C and 35 °C. Based on the intermediate fatigue loading conditions, the relative mean fatigue life between 20 °C and 35 °C is relatively consistent for both mixtures and between four to five times lower for the 15 °C temperature increase.

Figure 5: Fatigue performance for different temperatures for Mix 1 and 2



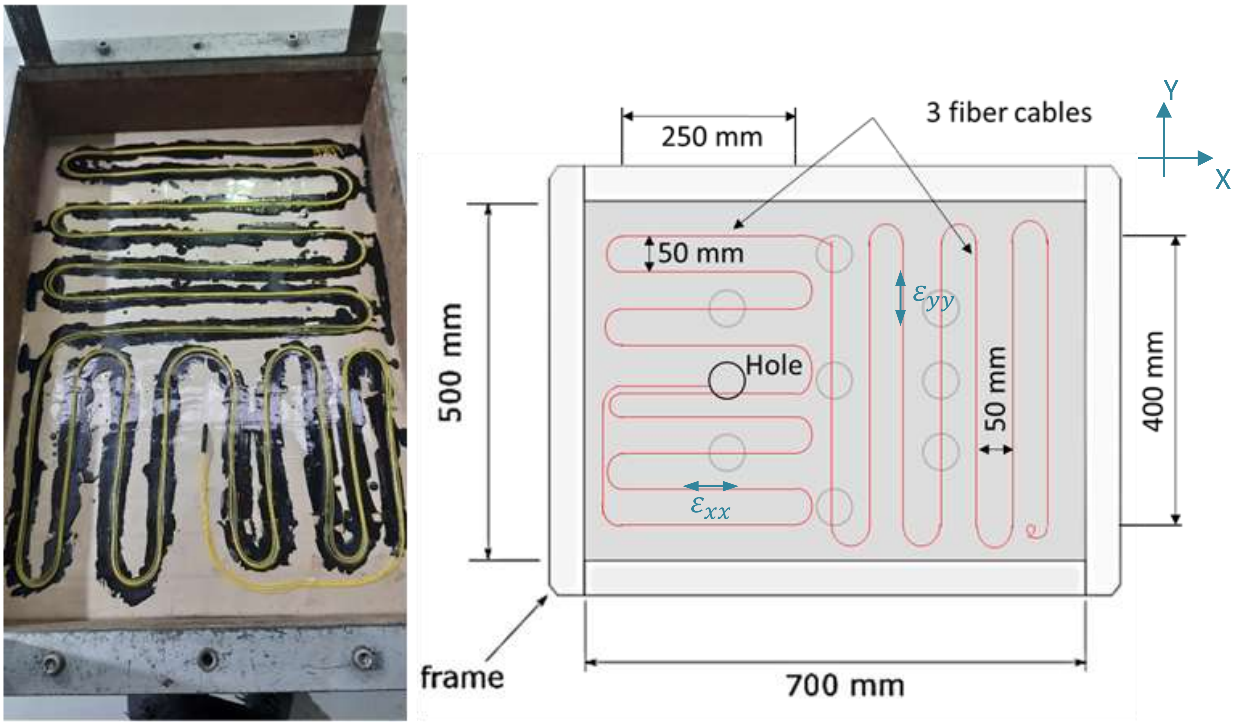
4 Fatigue testing of slabs under laboratory wheel-tracking conditions

4.1 Testing configuration and Strain monitoring

In the XL-WT and as illustrated in Figure 2, the flexural testing of the slab specimens under the rolling wheel load is achieved by using a supportive layer (around 190 mm thick) of low-density polyethylene (LDPE) sheets. The nominal modulus of the LDPE is between 200 and 400 MPa depending on the grade. This artificial subgrade allows full-depth slabs to be instrumented with deflection sensors to measure the deflection of the specimen during testing. For each material (mix 1 and mix 2), one 700 mm long x 500 mm wide x 100 mm thick slab is manufactured.

Additional instrumentation was used to monitor the strain developed at the bottom of the slab under loading. Fibre optic sensors (length: 10 m and specification: SC APC Simplex OS2 Single Mode PVC (OFNR) 0.9mm Fiber Optic Pigtail) are installed at the bottom of the mould before placing the material (Figure 6). First the sensors are glued with three layers of bitumen emulsion to a paper sheet and further coated with 3 additional coats of bitumen emulsion to ensure bonding of the fibre with the FBS material after compaction.

Figure 6: Fibre Optic Sensor Installation at the Bottom of the Slab

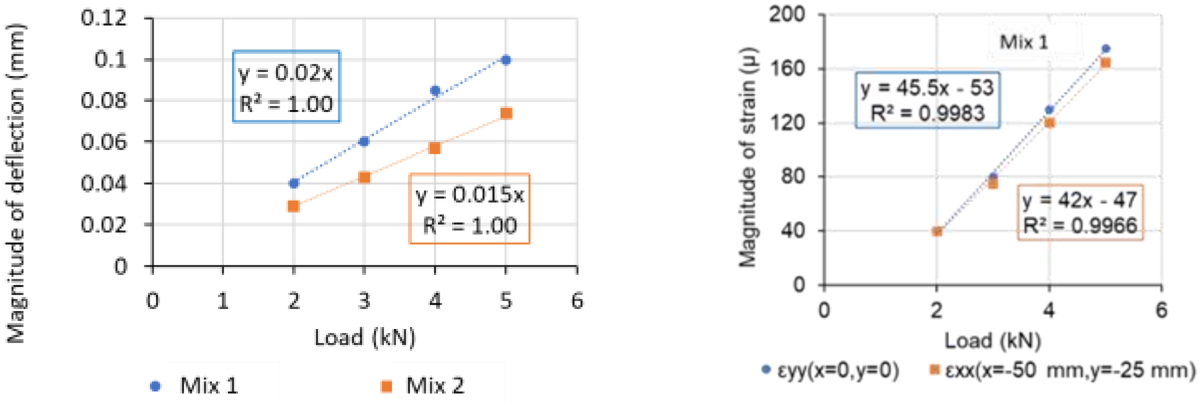


4.2 Response to load under short cyclic tests

Before starting the fatigue testing sequences, the slab was tested for a limited number of cycles (i.e. 100 cycles) increasing the load magnitude from 2 kN to 5 kN expecting to remain in relatively low strain conditions. The slab deflection at center and strain at the bottom of the slab are shown in Figure 7 (a) and (b) respectively. Strain in both longitudinal and transverse direction showed magnitudes in the same range, this is major difference compared to beam bending testing where the test geometry imposed a mostly uniaxial strain conditions along the beam cross-sections. Nevertheless, another major difference in the confinement of the slab in its mould during WT where the specimen is unconfined during the beam flexural testing.

Both deflection and strain exhibited a linear relationship with vertical wheel load between 2 to 5kN. The longitudinal strain ε_{xx} measured at 4.5 kN load is 142 and 144 x 10^{-6} for Mix 1 and Mix 2 respectively.

Figure 7: Slab centre deflection (a) and bottom strain for Mix 1 (b) with load


(a)

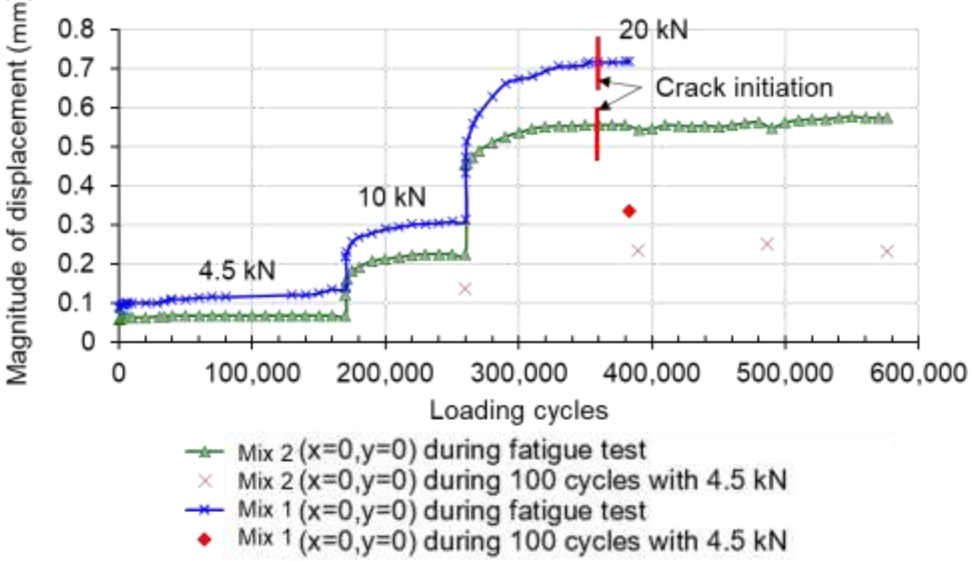
(b)

4.3 Fatigue Testing Under Wheel-tracking

Fatigue testing was performed at a constant temperature of 25 ºC using a staged approach where the load was increased gradually from 4.5 kN (aiming at strains of $100\text{x}10^{-6}$) to 10 kN and 20 kN. Under 4.5 kN, the expected initial strains are 142 and 144 x 10^{-6} for Mix 1 and 2, respectively. At these strain levels the lives predicted by the flexural beam fatigue relationship at 25 ºC (**Error! Reference source not found.**) are 41,000 and 61,000 cycles for Mix 1 and 2 respectively.

Figure 8 shows the increase in deflection magnitudes through testing (i.e. three testing stages). The increase in deflection for each sequence is attributed to micro-cracking in the material under cyclic loading which tends to reduce in rate for each sequence. Between each stage, the increase in deflection is also due to the increased loading conditions for each stage. For Mix 2, after each loading phase, the deflection was measured under the initial load of 4.5 kN as another way to quantify the loss of slab stiffness during testing.

Figure 8: Variation of the magnitude of centre deflection during fatigue test



For the comparison of the performance under XL-WT testing vs beam bending the following assumptions were considered. For the XL-WT test, the terminal condition of the slab (damage = 1) is when cracking becomes visible at the slab surface. For the bending test, the terminal condition was aligned with the standard fatigue testing analysis practice assuming that the damage = 1 when the beam stiffness has reached half of its initial value. Under these assumptions, the direct use of the laboratory relationship under the initial strain predicts a slab failure after 41,000 and 61,000 repetitions of the 4.5 kN load cycle for Mix 1 and 2 respectively. However, during testing the slab did not show significant changes or signs of damage after 170,000 cycles.

The first cracks observed at the specimen surface showed transversely on the side of the wheel-path and observed after similar loading conditions in both tests (i.e. 358,000 and 358,100 cycles for Mix and Mix 2 respectively). The first cracking occurred during the third loading stage after 170,000 cycles at 4.5 kN, 90,000 cycles at 10 kN and around 98,000 cycles at 20kN.

The number of cycles to crack initiation at the surface of the slab is significantly higher than would have been predicted for the laboratory flexural beam testing.

A theoretical analysis of the damage in the XL-WT is underway to better understand how a shift factor between the two modes of loading and failure can be derived.

5 Conclusion

The research presented in this paper investigated the significance of variations in field conditions and laboratory methods on the performance evaluation of FBS materials. This included evaluating the effect of temperature and loading speed based on laboratory flexural beam tests. To better understand the difference between beam flexural fatigue performance and field performance where the material is confined and a rolling wheel load impose a cyclic 3D stress state, XL-WT testing was undertaken as a proxy mimicking better the wheel-induced stresses and material confinement.

The host materials of the two mixes were sourced from two quarries in Queensland and stabilised with foamed bitumen at 3.5% bitumen content and 1.5% lime and fly ash blend. The FBS materials were tested for their flexural properties (modulus and fatigue) under the effects of temperature and loading speed.

Flexural modulus caried out on 90-day cured at three temperatures and frequencies between 1 Hz to 20 Hz (i.e. representative of traffic speed between 6 to 120 km/h) allowed assessing the sensitivity to temperature increase and sensitivity to loading speed. Test results shown a lesser sensitivity of the modulus to temperature and loading speed than currently assumed in practice. These results would be corroborated with IT modulus testing to replicate the testing conditions used to develop current factors.

The stress-controlled fatigue testing of beams performed at varying temperatures 20, 25, and 35ºC confirmed the general trend of decreasing fatigue life with temperature as previously determined through academic research. However, the two materials tested showed a decrease in fatigue life between 4 to 5 folds between 20 and 35ºC, whereas previous research showed a difference greater than 10 folds between 22 and 31 degrees. However, this difference remains significant and will be considered further as part of the development of a new in-service relationship for FBS materials.

For both mixes, the fatigue life in the XL-WT test exceeded the fatigue life predicted from the laboratory flexural fatigue relationship based on the measured initial strain in the slab. For flexural beam testing, the specimen is unsupported, and no confinement is provided to the material as opposed to the field or in the XL-WT where the slab in confined within a steel mould. Flexural beam testing provides a simplified and predominantly uniaxial stress states compared to the realistic physical model provided by the wheel tracker test. In the laboratory, the wheel tracker test leads to higher and likely more realistic fatigue life predictions when compared to beam testing for a set of environmental/loading conditions. As a research tool, it provides a material performance assessment closer to the real world in controlled laboratory conditions. For targeted purpose, the XL-WT offers a time and cost-effective approach compared with accelerated pavement testing. However, laboratory performance assessment method methods will always require calibration against the performance monitoring road sections in ranging traffic and environmental conditions.

It is recommended that the temperature and loading speed effects be further consolidated as the effects are less pronounced than current or suggested. In addition, alternative fatigue testing through XL-WT testing could be explored but would require a more robust strain measuring method to withstand the heavy compaction and wheel-tracking loads without rupture.

6 Conflict of Interest

This paper presents independent research findings and does not raise conflicts of interest.

7 Acknowledgement

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8 Authors' Biography

Dr Didier Bodin is a Principal Technology Leader at NTRO. He joined NTRO in 2010 after working for 10 years as a researcher at the French National Transport Laboratory (LCPC). As part of the Pavement Research Team, his main activities are focused on several areas of pavement technology, including the laboratory material characterisation and field performance evaluation of unbound granular material resilience under varying moisture conditions. He managed and conducted a series of full-scale pavement testing trials using the Accelerated Loading Facility (ALF) to assess the performance of unbound and stabilised sealed granular pavements. His strong interest in sustainable practice is applied to viable, low whole-of-life cost technologies including recycled material solutions and in-situ recycling (re-use) of pavement materials.

Jaspreet is a Senior Professional Engineer at NTRO with more than 5 years of combined, research, teaching, and consulting experience. He has contributed to research solutions for road infrastructure projects and challenges across Australia. Before joining NTRO, Jaspreet worked as a geotechnical consultant, where he coordinated and delivered various geotechnical investigations and assessments for roads and railways, for both government and private sectors. He has gained extensive experience in pavement evaluation, construction, and earthworks. Jaspreet's PhD research focused on soil stabilization for unsealed roads and pavement response modeling to operational loads.

Dr Suthakaran Sivagnanasuntharam is a Professional Engineer at National Transportation Research Organisation (NTRO) with over five years of combined research and teaching experience. Prior to joining NTRO, Suthakaran completed his PhD at Smart Pavements Australia Research Collaboration (SPARC) Hub, Monash University, and then worked as a research officer at the same institution, where he conducted various laboratory and field experiments on pavement materials. His PhD research focused on advancing intelligent compaction technology for asphalt pavement layers.

David Firth is a Professional Laboratory Technician at NTRO. David has over 10 years of experience working in the NTRO Laboratory on various projects focusing on development of laboratory testing protocols relevant to field performance of road base materials. David has undertaken testing on various cement-stabilised and un-stabilised materials as well as bituminous products in line with Australian Standards. David’s other tasks include the calibration of equipment and internal auditing. He is the dangerous goods advisor on the OH&S committee. Prior to joining NTRO, David worked in the Mobil Technical Services Laboratory in both the used oil analysis team and the expert analysis team, where he was involved in the chemical analysis of used oils, and non-routine investigative analysis of greases and oils.

Damian Volker is a Principal Engineer in the Pavement Rehabilitation Section of the Queensland Department of Transport and Main Roads (TMR), with over 18 years of experience. He specializes in pavement materials testing, construction, and performance, with a focus on stabilization. Starting his career as a Cadet Materials Technologist, he gained extensive knowledge of material properties and failure mechanisms through detailed pavement investigations and work as an asphalt Roadworks Inspector. Known for his innovative and environmentally sustainable solutions, Damian contributes to all aspects of stabilization projects, including design, testing, construction, training, research, and the development of TMR specifications.

9 References

1. Austroads, “Design and performance of foamed bitumen stabilised pavements,” Austroads, Sydney, NSW, AP-T336-18, 2018.
2. Austroads, “Deformation Performance of Foamed Bitumen Stabilised Pavements Under Full-scale Accelerated Loading,” Austroads, Sydney, NSW, AP-T343-19, 2019.
3. Austroads, “Laboratory Fatigue Characterisation of Foamed Bitumen Stabilised Materials,” Austroads, Sydney, NSW, AP-R666-22, 2022.
4. Pitawala S., Sounthararajah A., Bodin D., and Kodikara J., “Advanced characterisation of flexural fatigue performance of foamed bitumen stabilised pavement materials,” Constr. Build. Mater., vol. 341, p. 127881, Jul. 2022, doi: 10.1016/j.conbuildmat.2022.127881.
5. Queensland Department of Transport and Main Roads 2024, Materials Testing Manual Edition 6, TMR, Brisbane, Qld
6. Queensland Department of Transport and Main Roads 2021, Supplement to ‘Part 2: Pavement Structural Design’ of the Austroads Guide to Pavement Technology, TMR, Brisbane, Qld
7. Austroads, “Flexural beam test methods for cemented materials,” Austroads, Sydney, NSW, AGPT-T600-18, 2018.
8. Austroads, “Development of design procedures for lightly bound cemented materials in flexible pavements,” Austroads, Sydney, NSW, AP-R640-20, 2020.
9. Grenfell J., Firth D., Berry D., and Bodin D., “Development of a wheel-tracking test for fatigue testing of lightly-bound granular materials,” Brisbane, 2018.
10. Austroads, “Guide to pavement technology: Part 2,” Austroads, Sydney, NSW, AGPT02, 2017.
11. Austroads, “Guide to pavement technology: Part 5,” Austroads, Sydney, NSW, AGPT05, 2019.