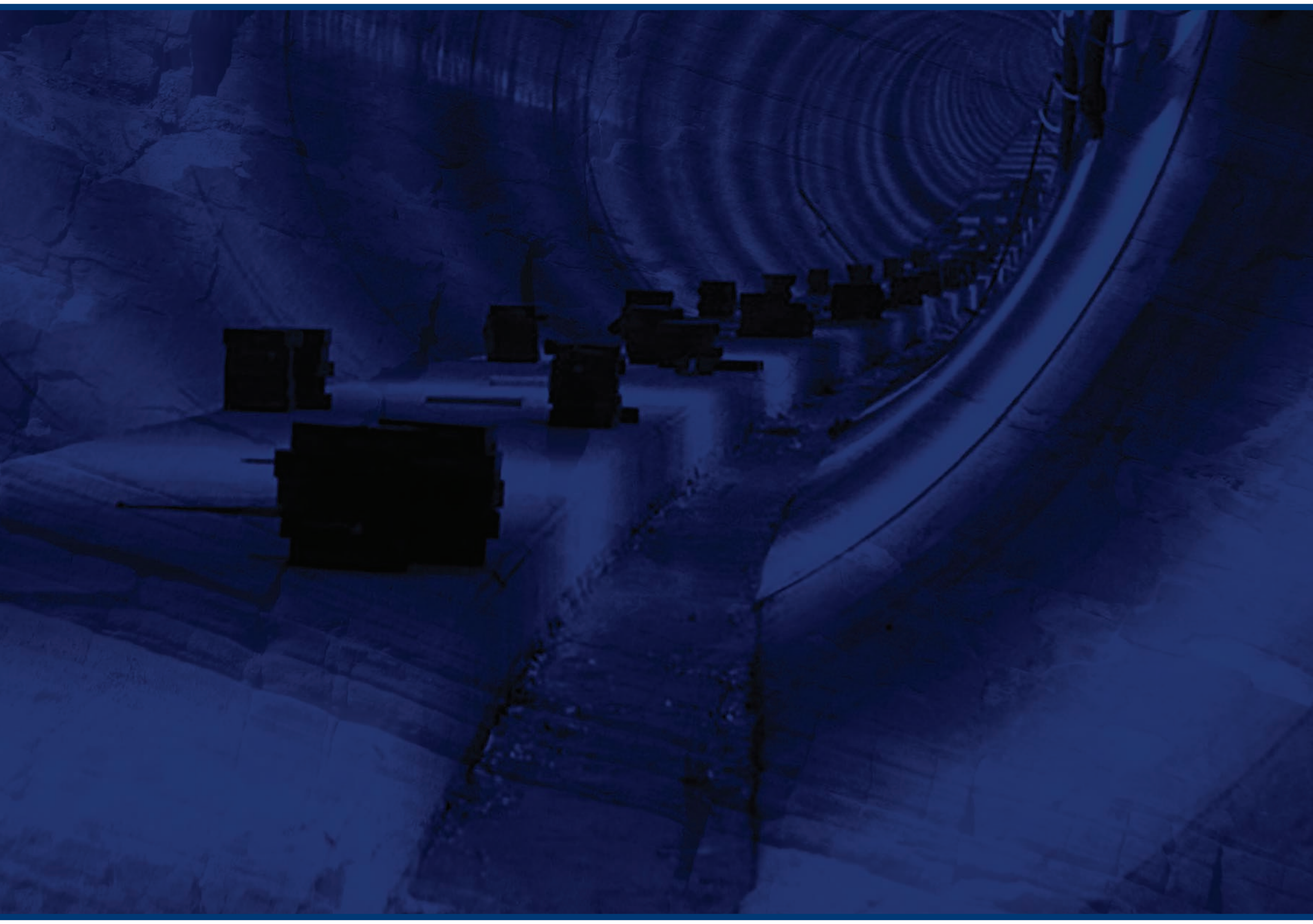
PROCEEDINGS

2018 AUSTRALIAN GEOMECHANICS SOCIETY VICTORIAN SYMPOSIUM

Geotechnics and transport infrastructure

Wednesday, 24 October 2018, 8:00am – 6:00pm
Rydges Hotel, 186 Exhibition Street, Melbourne



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PREFACE

The Victorian chapter of the Australian Geomechanics Society invited academics and practitioners in the field of geotechnical and ground engineering to attend the 2018 Australian Geomechanics Society Victorian Symposium on ‘Geotechnics and transport infrastructure’ held on 24 October 2018.

In recent years Victoria has seen significant investment in transport infrastructure as part of a plan to manage the demands of a growing population and expanding urban fringe. The construction of Melbourne Metro, a second crossing of the Yarra River, rail and freeway upgrades as well as numerous level crossing removal projects are just some of the major transport projects currently underway in Melbourne and regional Victoria. Many of these projects carry numerous complex geotechnical challenges.

The 2018 Australian Geomechanics Society Victorian Symposium covers a variety of geotechnical challenges associated with transport geotechnics and present overviews of current infrastructure challenges, state of the-art practices, innovation, new research results and case studies demonstrating applications of advanced techniques and cost effective solutions in the construction and design of local transport infrastructure. The Symposium brought together professional engineers, researchers, specialist contractors, regulators, educators and students to share and discuss their experiences on the topic of transport infrastructure and associated geotechnical challenges and applications.

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An improved approach for characterisation and design of chemically stabilised pavement bases

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ABSTRACT

This paper aims to develop measures to minimise the initial fatigue damage of prematurely opened cement treated bases (CTBs) due to repeated application of heavy traffic loads. A laboratory investigation was undertaken to characterize the early-age flexural fatigue performance of cement-stabilised pavement materials (CSPMs) under repetitive loading. The flexural fatigue test results evinced the existence of an endurance limit in CSPMs, even at seven days curing age. A stress-based flexural fatigue performance model was developed for predicting the early-age flexural fatigue performance of CSPMs in service. In parallel with the laboratory tests, mechanistic analyses were performed using the CIRCLY program to assess the early-age response of CTBs to heavy traffic loading. The computed critical pavement responses and the flexural fatigue performance model developed in this study were then used to estimate the early-age fatigue damage of CTBs in terms of seven days curing. It was found that the asphalt cover over CTB required to prevent the occurrence of initial fatigue damage to CTB decreases with increasing modulus and thickness of CTB and subgrade strength.

Keywords: Early-age fatigue damage, road pavement design, fatigue endurance limit, cement-treated bases, prematurely opened highways, flexural fatigue performance

1 INTRODUCTION

Chemical stabilisation with cementitious materials is an effective technique to enhance the strength and stiffness properties of marginal road pavement materials, such as sandstone, for carrying heavy traffic loads applied on the road surface. The pavement base built using cement-stabilised pavement materials, hereafter referred to as CTB, usually undergoes bending in service to resist heavy traffic loading. The main deterioration mechanism of CTBs is fatigue cracking caused by repeated application of traffic-induced stresses at the bottom of the CTB (bottom-up cracking). A greater understanding of the performance of CSPMs under repetitive heavy traffic loading is vital for pavement engineers to avoid the premature failure of CTBs in the field.

Over the past few decades, researchers have given increased attention to both laboratory and field characterisation of the flexural fatigue behaviour of CSPMs. Many laboratory-based studies (Litwinowicz and Brandon 1994, Bhogal et al. 1995, Sobhan and Das 2007, Austroads 2010, Yeo 2012, Gnanendran and Paul 2016, Mandal et al. 2017) and large-scale experimental studies (Jameson et al. 1992, Moffat et al. 1998, Hugo and Martin 2004, Austroads 2008, Cai and Wang 2013) have been undertaken on the fatigue performance of CSPMs in flexure (bottom-up fatigue cracking), and several fatigue models have been developed to predict the in-service fatigue life of CSPMs (e.g. Eq. 1). In the aforementioned studies, a range of curing ages between 28 days and 400 days was adopted to assess the fatigue performance of CSPMs. For instance, the fatigue model given in Eq. 1 was developed on the basis of the fatigue performance of CSPMs at curing ages of 150 days and 270 days (Austroads 2014). Moreover, this fatigue model (Eq. 1) is currently used in Australia for the structural design of CTBs (Austroads 2017). Aside from fatigue assessment studies, the revised Australian pavement guide (Austroads 2017) recommends a curing period of 90 days to determine the dynamic flexural modulus and flexural fatigue performance of CSPMs for pavement design purposes.

$$N_{allowable} = RF\left[\frac{k_{fc} \times SF}{\mu\varepsilon}\right]^{M} \tag{1}$$

where, $N_{allowable}$ is the allowable number of load repetitions; k_{fc} is the laboratory fatigue constant; SF is the laboratory-to-field strain shift factor (a presumptive value of 1.8 is suggested for CSPMs); $\mu\varepsilon$ is the load-induced tensile strain at the base of the CSPM (microstrain); M is the load damage exponent (12.0 for CSPMs); and RF is the reliability factor for CSPM fatigue, which takes into account the uncertainty associated with material input data.

Notwithstanding the abovementioned guidelines and fatigue assessment practices, in current pavement management practice, newly-constructed highways using CTB are generally opened to traffic a mere seven days after construction (Young 2007, Austroads 2012, CDT 2014). Trafficking of a CTB before it gains sufficient fatigue resistance and strength can lead to impairment of the pavement structure. Table 1 summarises the traffic measured at some highway locations in Australia in 2010. For most of the highways shown in Table 1, the estimated standard axle repetitions for CSPM fatigue exceed one million within a month.

Although extensive research has been conducted on CSPM performance, particularly under fatigue loading, there is a significant lack of research on the flexural fatigue performance of prematurely opened CTBs under repeated heavy traffic loading. Moreover, appropriate measures have not yet been developed to prevent the occurrence of initial fatigue damage to prematurely opened CTBs. This paper primarily focuses on the evaluation of early-age fatigue damage in prematurely opened CTBs under repetitive heavy traffic loading to develop appropriate measures to minimise the early-age fatigue damage of prematurely opened CTBs.

2 EXPERIMENTAL PROGRAM

2.1 Pavement Beam Samples Preparation

Two pavement materials, Holcim road base (sourced from Holcim Gosnells quarry, Western Australia) and quartzite (sourced from Boral Para Hills quarry, South Australia), were employed in this experimental investigation. The properties of these materials are reported by Sounthararajah et al. (2016). Rectangular steel moulds measuring 200 mm (length) × 50 mm (width) × 50 mm (height) were used to manufacture the beam specimens for flexural tests. The pavement material was first preconditioned (defined as the addition of water to the pavement material 24 hours prior to compaction, and the amount of water to be added was estimated on the basis of the average water absorption of that material concerned), and then mixed with 3% (percentage by mass of dry pavement material) general purpose cement and water at the optimum moisture content of the mixture (i.e. cement-aggregate-water). A predetermined amount of the mixture was then placed in the rectangular steel moulds and manually compacted in a single layer with modified compaction effort, in accordance with AS 1289.5.2.1 (AS 2003). Following the compaction process, the prepared samples were covered to prevent moisture loss and left to cure in the steel moulds for 2 days at ambient room temperature (23°C) until they gained sufficient strength to be removed from the mould. Subsequently, the manufactured beam samples were demoulded and placed in a temperature controlled fog room for further moist curing.

2.2 Flexural Beam Testing

The experimental procedures for determining the flexural strength, dynamic flexural modulus, and flexural fatigue performance of CSPMs employed in the present study were identical to those detailed in Sounthararajah et al. (2018). The four-point bending test was employed to examine the flexural fatigue behaviour of CSPMs. Fig. 1 shows a picture of the flexural fatigue failure of a cement-stabilised Holcim road base (CSHRB) beam specimen subjected to cyclic flexural loading at a high flexural stress level. The configuration for measuring the midspan deflection of the beam specimens in four-point bending tests is also illustrated in this figure. At least eight beam specimens of each type of material were tested for flexural fatigue performance at curing ages of seven days and 28 days, respectively, but for the purpose of this paper, only the seven-day flexural fatigue test results are reported herein.

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 Fatigue Life Prediction Model of CSPMs

Based on the flexural fatigue results obtained in this study, a stress-based fatigue model for determining the flexural fatigue life of a CSPM was established, as shown in Eq. 2. Fig. 2a shows the fitting of this fatigue model respectively for CSHRB beam samples and cement-stabilised quartzite (CSQRT) beam samples tested for flexural fatigue performance at a curing age of seven days. The empirical coefficients of the model (i.e. *m* and *n*) were determined from the statistical analysis shown in Fig. 2a. The model was found to be a reasonable fit to

Table 1: Measured road traffic at selected locations in Australia and standard axle repetitions for CSPM fatigue (Austroads 2012)

State	Road	Location	Lane Average Daily Traffic*	Heavy Vehicle Axle Groups/Day	Standard Axle Repetitions for 30 days
NSW	Newell Highway	Forbes	1,890	1,600	325,540
NSW	F6 Freeway	Wollongong	8,725	3,235	704,860
QLD	Pacific Motorway	Tugun	16,530	5,565	**1,294,640**
QLD	Mackay-Slade Point Rd	Harbour Road	4,070	1,510	447,160
VIC	Calder Highway	Macedon Ranges	7,825	1,595	327,935
VIC	Hume Freeway	Mitchell	7,975	6,270	**1,540,000**
VIC	Monash Freeway	Greater Dandenong	22,950	5,185	**1,424,960**
WA	Kwinana Freeway	Mandurah	10,665	2,940	944,660
WA	Reid Highway	Middle Swan	7,030	2,035	429,210
SA	South East Freeway	Monarto	4,480	2,570	**1,351,640**
SA	Port River Expressway	Wingfield	7,830	3,660	**1,452,400**

*traffic measured in 2010.

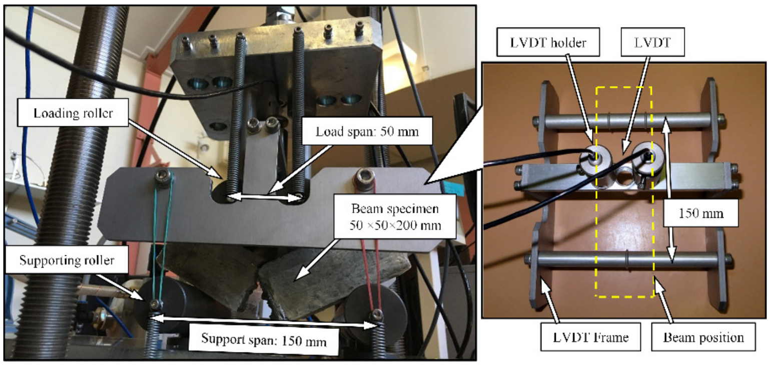

Figure 1. Flexural fatigue fracture of CSHRB specimen under cyclic four-point loadin

the data in calculating the flexural fatigue life of both the CSPMs at seven days curing.

$$\ln N = m\left\{1 - n\left(\frac{\sigma_{max}}{\sigma_0}\right)\left[1 + \left(\frac{\sigma_{max}}{E_{flex,25\%}}\right)\right]\right\} \qquad (2)$$

where, N is the flexural fatigue life of the CSPM; σ_{max} is the maximum applied tensile stress (kPa); σ_0 is the flexural strength or modulus of rupture of the CSPM at the selected curing period (kPa); $E_{flex,25\%}$ is the average dynamic flexural modulus of the second fifty consecutive load cycles at the 25% stress level (MPa); m is an empirical coefficient (25.1 for CSHRB and 23.4 for CSQRT); and n is am empirical coefficient (0.781 for CSHRB and 0.725 for CSQRT).

An attempt was made to develop a strain-based fatigue model using the initial peak resilient flexural tensile strain of each individual CSPM beam specimen tested under flexural fatigue loading. The model had a better fit (R^2 = 0.77) to only the CSHRB beam specimens, as shown in Fig. 2b. The variability between beam samples for CSQRT is anticipated to result in dispersion of the flexural fatigue life (N) at the same applied strain level. The other plausible reason for the strain-based fatigue model not being a good fit for CSQRT beam specimens is that the peak resilient flexural tensile strain for high stress levels was widespread in the first fifty load cycles. The beam specimens tested at lower flexural tensile stress levels (~60% of the flexural strength) survived the fatigue loading and the testing (see Fig. 2) was terminated after 1 million load repetitions (more than 4 days testing for each specimen). The flexural moduli of these beam specimens were reduced by only around 20% of their initial value. The beam specimens were also closely inspected for fatigue damage after 1 million load repetitions and there were no fatigue cracks at the bottom of the both CSPM beams. Therefore, it is apparent that the flexural tensile stress level of 60% of the flexural strength can be considered as the fatigue endurance limit for both CSPMs at seven days curing. The fatigue endurance limit is a tensile stress level or a tensile strain level below which no or very little fatigue damage occurs at the bottom of the pavement base. Nonetheless, very little information was found in the literature regarding the existence of the fatigue endurance limit in CSPMs.

3.2 Analysis of Laboratory Fatigue Test Data

An analysis of laboratory fatigue data using the available CSPM fatigue models was also performed. The Australian fatigue model (Austroads 2012) and the U.S. fatigue model (NCHRP 2004) were used to analyse the seven-day fatigue test data obtained from the present study. The data analysis procedure for these fatigue models is described in Sounthararajah et al. (2018). Table 2 presents the coefficient of determination (denoted by R^2), between the flexural fatigue life from the

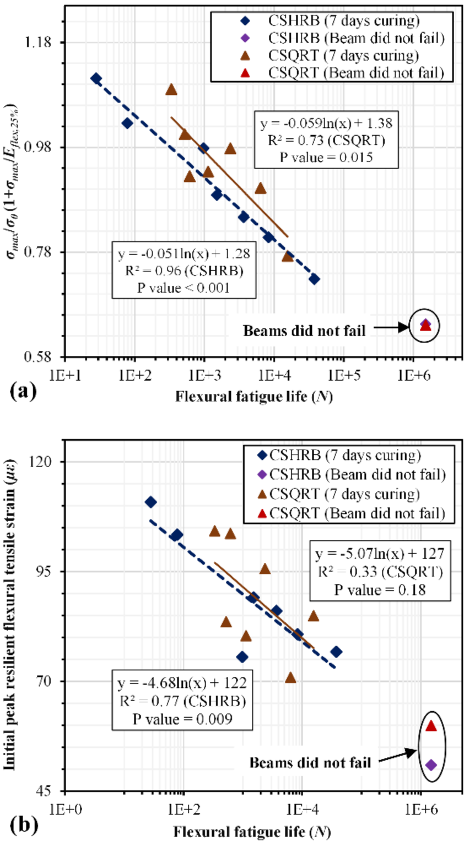

Figure 2. Fatigue relationship for CSPMs: (a) stress-based fatigue model; (b) strain-based fatigue model

Table 2: Seven-day fatigue test data analysis using CSPM fatigue models [adapted from Sounthararajah et al. (2018)]

Fatigue model	General equation	Parameter	Material	
			CSHRB	CSQRT
Australian fatigue criterion (Austroads 2012) In pavement design, a load damage exponent (M) of 12.0 is adopted for all CSPMs	$N = \left[\dfrac{\dfrac{113{,}000}{E_{flex,design}^{0.804}} + 191}{\mu\varepsilon}\right]^M$	M	8.75	6.80
		R^2	0.51	0.74
U.S. fatigue criterion (NCHRP 2004) A presumptive value of 1.00 is adopted for field calibration factors β_{c1} and β_{c2}.	$logN = \left[\dfrac{0.972\beta_{c1} - \left(\dfrac{\sigma_t}{\sigma_o}\right)}{0.0825\beta_{c2}}\right]$	β_{c1}	1.10	1.19
		β_{c2}	1.00	1.00
		R^2	0.99	0.39

Note: N = allowable number of load repetitions; $E_{flex,design}$ = design flexural modulus of CSPM (MPa); $\mu\varepsilon$ = load-induced tensile strain at base of CSPM (microstrain); M = load damage exponent; σ_t = maximum traffic-induced tensile stress at bottom of CTB (kPa); σ_0 = flexural strength of CSPM at the selected curing period (kPa); β_{c1} and β_{c2} = field calibration factors.

laboratory data and the flexural fatigue life calculated using these fatigue models, including the load damage exponent *M* (Australian fatigue model) and the field calibration factors β_{c1} and β_{c2} (U.S. fatigue model). The laboratory fatigue data showed a moderate fit for both the Australian and U.S. fatigue models. The load damage exponents of CSHRB and CSQRT at seven days curing were determined to be 8.75 (R^2 = 0.51) and 6.80 (R^2 = 0.74), respectively. These values are appreciably lower than the value currently used in the Australian fatigue model for all CSPMs (i.e. 12) to determine the flexural fatigue life (*N*) of CTB layers after *28 days* curing in the field.

4 FLEXURAL FATIGUE LIFE OF CTBS IN SERVICE

Based on the seven-day dynamic flexural modulus of CSPMs, the seven-day design flexural moduli of CSQRT and CSHRB were chosen to be 5,000 MPa and 10,000 MPa, respectively, for modelling purposes. The dynamic flexural modulus test results for both the CSPMs can be found in Southararajah et al. (2018). The ratio (R_{ms}) between the average initial dynamic flexural modulus of the CSPM beam specimens in the flexural fatigue test ($E_{i,avg}$) and the average flexural strength of the CSPM (σ_0) was evaluated using the laboratory test data. The R_{ms} values of CSHRB for seven days curing and 28 days curing were determined to be 10,265 and 11,645, respectively. The average R_{ms} value of the CSPM in the laboratory (10,952 for CSQRT and 10,954 for CSHRB) was assumed in the field to estimate the seven-day design flexural strength of that material ($\sigma_{0,design}$). Table 3 presents the estimated flexural properties of the CSPMs in the field, including the average R_{ms} values and seven-day design endurance limits, for pavement design.

The maximum horizontal tensile stresses (σ_{yy}) at the bottom of the CTB under a standard axle determined using the CIRCLY program (MS 2012), the estimated seven-day design flexural strength of the CSPM ($\sigma_{0,design}$ – Table 3) and the generalised fatigue model given in Eq. 2 were used to estimate the in-service fatigue life of CTBs. Table 4 summarises the allowable number of standard axle load repetitions of the CTB ($N_{allow,standard}$) calculated for various pavement profiles. The pavement structure consisting of a 325 mm thick CTB layer with a design flexural modulus of 10,000 MPa (CSHRB) is able to theoretically sustain an infinite number of standard axle load repetitions, as the peak horizontal tensile stresses at the bottom of the CTB under a standard axle are lower than the estimated seven-day design endurance limit of the CSHRB. Conversely, the 150 mm thick CSQRT pavement base ($E_{flex,design}$ = 5,000 MPa) appears to be unsuitable for arterial highway construction, since its structural capacity is not sufficient to carry the highway design traffic.

For prematurely opened newly constructed highways, the early-age fatigue damage to CTB caused by repeated heavy traffic loading could be considerably minimised by keeping the traffic-induced stresses at the bottom of the CTB below the endurance limit of the CSPM during its initial curing period (generally 28 days).

The thickness of the asphalt layer required above a CTB layer to keep the vehicle-induced stresses at the bottom of the CTB below the fatigue endurance limit of the CSPM relies on many factors, including the properties of the CTB parent material, amount and type of binder used, age of curing, the initial stage of the compacted material, subgrade strength, the properties of asphalt, construction practices and the climate. Fig. 3 presents the minimum asphalt layer thickness (*E* = 3,000 MPa) necessary over CTB to maintain the peak tensile stresses at the bottom of the CTB below the estimated seven-day design endurance limit of the CSPM during its initial curing phase. For thicknesses of asphalt layer less than those shown in Fig. 3, an appropriate curing age should be chosen for newly-constructed highways with

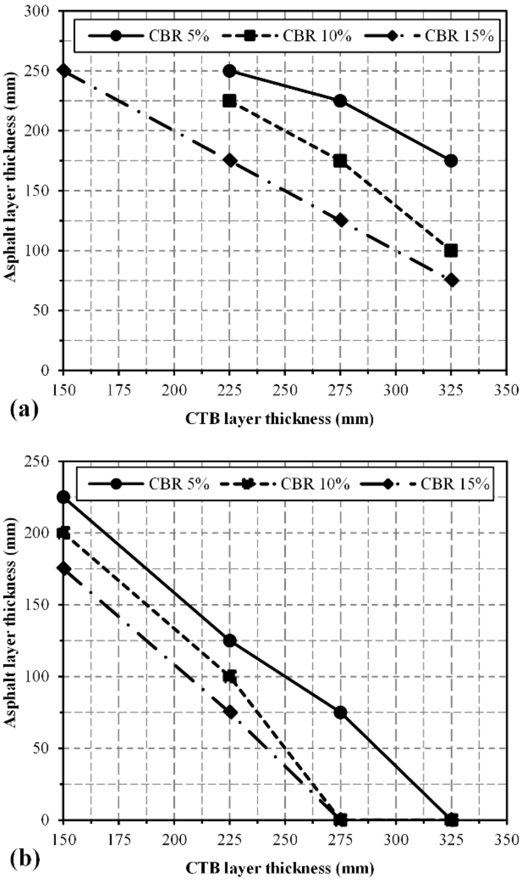

Figure 3. Minimum asphalt cover (E = 3,000 MPa) over CTB to avoid initial fatigue damage to CTB: (a) CSQRT; (b) CSHRB [adapted from Southararajah et al. (2018)]

Table 3: Estimated flexural properties of CSPMs for pavement design (Southararajah et al. 2018)

Material	Curing age (Days)	Design flexural modulus (MPa)	Average value of R_{ms}* ($\times 10^3$)	Design flexural strength ($\sigma_{0,design}$) (kPa)	Design endurance limit (kPa)
CSQRT	7	5,000	10.95	457	275
CSHRB	7	10,000	10.95	912	547

*ratio between average initial dynamic flexural modulus of CSPM beam specimens in flexural fatigue test ($E_{i,avg}$) and average flexural strength of CSPM (σ_0) in the laboratory.

Table 4: Estimated in-service fatigue life of CTBs after seven days of curing

CTB modulus (MPa)	**CTB layer thickness (mm)**	**Allowable number of standard axle load repetitions ($N_{allow,standard}$)**							
		Asphalt layer thickness (mm)							
		40	**75**	**100**	**125**	**175**	**200**	**225**	**250**
Subgrade CBR 5%									
5,000	150	0	0	0	1	72	494	2,477	10,394
	225	1	24	206	1,229	19,943	61,990	169,512	392,712
	275	141	1,934	8,475	29,928	233,575	540,216	>10^6 repetitions[z]	
	325	6,365	41,382	118,097	309,044	>10^6 repetitions[z]			
10,000	150	0	5	84	863	31,610	129,484	>10^6 repetitions[z]	
	225	3,008	29,449	115,180	>10^6 repetitions[z]				
	275	179,629	>10^6 repetitions[z]						
	325	>10^6 repetitions[z]							
Subgrade CBR 10%									
5,000	150	0	0	3	40	1,934	9,196	33,798	108,971
	225	42	920	4,979	20,770	198,998	498,851	>10^6 repetitions[z]	
	275	3,736	31,166	104,674	285,300	>10^6 repetitions[z]			
	325	78,963	377,349	>10^6 repetitions[z]					
10,000	150	5	291	2,800	17,924	321,772	>10^6 repetitions[z]		
	225	51,849	337,104	>10^6 repetitions[z]					
	275	>10^6 repetitions[z]							
	325	>10^6 repetitions[z]							
Subgrade CBR 15%									
5,000	150	0	4	52	436	12,236	44,869	144,372	392,712
	225	474	6,631	28,739	100,546	>10^6 repetitions[z]			
	275	21,631	144,372	408,697	>10^6 repetitions[z]				
	325	321,643	>10^6 repetitions[z]						
10,000	150	88	2,800	19,243	93,278	>10^6 repetitions[z]			
	225	237,689	>10^6 repetitions[z]						
	275	>10^6 repetitions[z]							
	325	>10^6 repetitions[z]							

[z] peak tensile stress at bottom of CTB is lower than estimated seven-day design endurance limit of CSPM (Table 3).

CTB to avoid the occurrence of early-age fatigue damage, or the fatigue damage of CTBs during their initial curing period (usually 28 days) needs to be taken into consideration in evaluating the flexural fatigue life (N). The main limitation of this study is that only the pavement response to the standard axle loading was analysed to determine the minimum asphalt layer thicknesses, whereas pavement bases may undergo higher axle loads than the standard axle in service. Nonetheless, in pavement structural design, this could be addressed by assessing the candidate pavement response to the peak axle loads of each axle configuration considered in the traffic analysis (Sounthararajah et al. 2018).

5 CONCLUDING REMARKS

The aim of this study is to develop measures to minimise the early-age fatigue damage of prematurely opened CTBs due to repetitive heavy traffic loading. The four-point bending test was adopted in this study to characterise the early-age flexural fatigue performance of two different locally-sourced pavement materials stabilised with 3% of general purpose cement. All the flexural tests were executed in stress-controlled mode.

- The beam specimens subjected to stress-controlled cyclic loading at low stress levels evinced the existence of an endurance limit, even at seven days curing age. The flexural tensile stress level of 60% flexural strength was inferred as the seven-day fatigue endurance limit for both CSPMs.
- A stress-based fatigue model is proposed to estimate the in-service fatigue life of CSPMs, and the model matches well the seven-day fatigue test data obtained in this study.
- Moreover, the laboratory fatigue data (i.e. seven-day fatigue performance data) from this study were also examined by fitting the data to the Australian fatigue model and the U.S. fatigue model. These models show varying levels of suitability for describing the flexural fatigue behaviour of the CSPMs employed in this investigation.
- The results of the mechanistic analysis clearly demonstrate that the fatigue resistance of CTBs during their initial curing phase is very low, resulting in great reduction of their flexural fatigue life in service. It was also found that the asphalt cover over CTB required to minimise its early-age fatigue damage decreases with increasing modulus and thickness of CTB and subgrade strength.

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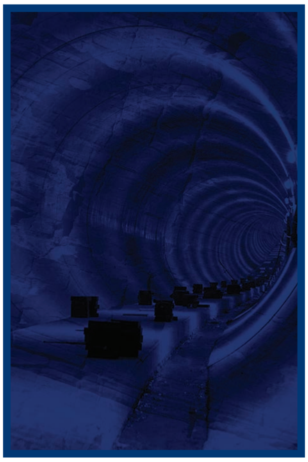

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