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Cyclic loading responses of cement-stabilised base materials: An investigation on moduli for pavement design

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ABSTRACT

In the general Mechanistic-Empirical pavement design guideline, the design parameter normally used in representing the response of stabilised pavement material is the elastic modulus measured from a statically-monotonic compression test. Nevertheless, this elastic modulus may not respond to actual behaviour of real pavement which is subjected to cyclic loading from moving vehicles. Using the elastic modulus in pavement analysis could lead to an inaccurate estimation of the stress-strain relationship which is relevant to a pavement response prediction under traffic loading conditions. In this research, the dynamic modulus of cement-stabilised material measured from Asphalt Mixture Performance Tester was examined to be used as a pavement design parameter with consideration of cyclic (traffic) loading conditions. The laboratory results from this research reveal that the cyclic response of cement-stabilised material in term of the dynamic modulus is not much affected by a variation on temperatures and loading frequencies. However, the dynamic modulus is greatly influenced by cement contents and curing periods. Moreover, the elastic moduli measured based on different strain rates was also examined. In order to compare the effects of modulus to the pavement response, finite element analysis was performed in this research by altering the modulus of base course layer. Flexural modulus of cement-stabilised base material determined by Chummuneerat et al. (2013) was also included in the finite element analysis. The results of the finite element analysis show that a tensile strain at a critical location can be reduced by 20% if the elastic modulus of a base course layer were replaced by the dynamic modulus and the flexural modulus. In addition, stress induced by the traffic load can be evenly transferred to the subgrade layer by applying the dynamic modulus and the flexural modulus in the analysis.

Keywords: Cyclic Response, Dynamic Modulus, Finite Element Method, Cement-Stabilised Base

1 INTRODUCTION

The cement-stabilised materials are commonly used in a high traffic road pavement due to its relatively high stiffness, and its capability to evenly distribute the traffic load to an existing ground (subgrade) layer. This cement stabilisation technique is also applied to road construction using poorly-graded materials (i.e., sub-standard materials) in a pavement base layer, due to well-graded materials being very expensive or unavailable (Berthelot et al. 2010). To date, the road pavement containing cement-stabilised base material can be designed using various approaches; however, mechanistic design approach is becoming more preferable (Huang 2004). In mechanistic pavement design, pavement response in terms of stresses and strains induced by the moving wheels and axle load is significant. The reason is suitable pavement materials and proper thicknesses are fundamentally designed based on the pavement response. Moreover, estimated tensile strain is very important to the fatigue performance of cement-stabilised base material. This can be distinguished from the commonly used fatigue-life empirical formula adopted in Australia (Austroads 2010) as shown in (1).

$$N_f = RF[((113,000/E)^{0.84}+191)/\mu\varepsilon]^m \qquad (1)$$

which RF is reliability factor for cement-stabilised materials, N_f is allowable number of standard load repetitions, E is material modulus, $\mu\varepsilon$ is horizontal micro-tensile strain at the bottom of the base, and m is the damage exponent. The value of m recommended by Austroads (2010) is 12. According to the guideline, the application of (1) is limited by the modulus of cement-stabilised material. The equation is only suitable for cement-stabilised material with the value of elastic modulus ranges from 2,000 to

10,000 MPa (Austroads 2010). The fatigue-life formula shows that slightly change in predicted tensile strain value may leads to a significant difference in predicted fatigue life. This is because of the relatively high exponent of fatigue-life equation. Accordingly, an appropriate modulus input is necessary for mechanistic pavement design. It means that design modulus should satisfactory represents material response under the traffic loads.

In Australia, the flexural modulus is recommended by Austroads (2010) as a design modulus input due to its potential to represent the tension failure of pavement behaviour in the field. Theoretically, the flexural modulus is the modulus of a rectangular beam specimen subjected to a cyclic or monotonic bending force. It should be noted that the calculation procedure for the stress-strain relationship in pavement structure was developed based on the theory of elasticity. However, an accurate method for determining the elastic modulus from a beam under bending forces is not yet available (Iyer 2005). Moreover, parameters measured from flexural tests are largely influenced by sample preparation, handling, curing, and sample quality. This explicitly produces a significant degree of test result uncertainties (Walker and Bloem 1957). On the other hand, the National Cooperative Highway Research Program (2004) suggests the elastic modulus as a design input for mechanistic-empirical pavement design of cement-stabilised base course. In order to determine the elastic modulus, the stress-strain response obtained from the Unconfined Compressive Strength (UCS) test is required. This test can be performed according to ASTM C469 (2010). Alternatively, the elastic modulus of the cement-stabilised base material can be estimated from the empirical formula. However, pavement structure in the field is subjected to cyclic compressive loads from moving vehicles, which is totally different from the UCS test condition. In addition, it had recently been proved by many works that dynamic moduli of cement-stabilised base material are considerably greater than their elastic moduli measured from monotonic loading test (Mindess and Young 1981; Neville 1998; Lee, Kwan, and Zheng 2013; Kolias and Williams 1980). It should be noted that the dynamic moduli considered in previous literatures were measured from either ultrasonic pulse velocity or vibration resonance methods. Apart from the effects of loading condition, Bischoff and Perry (1991) characterised the behaviours of concrete under the fast compressive-monotonic loading. Based on their study, the material strength and modulus were also influenced by the strain rate of loading. The strain rates of monotonic loading fall between $5x10^{-5}$ per second and $5x10^{-4}$ per second were considered as static loading range, whereas the strain rates fall between 10^{-3} per second and 10^{-2} per second were corresponded to the earthquake (dynamic) loading range. Xiao, Li and Lin (2008) likewise performed a monotonic loading test on concrete specimens using different values of strain rate. From their tests, the initial elastic modulus was increased from $1.23x10^{4}$ MPa to $1.60x10^{4}$ MPa when the tested strain rate was changed from 10^{-5} per second to 10^{-1} per second.

From literature reviews, it can be noted that the modulus input for mechanistic pavement design recommended by various guidelines still contains some limitations. A reliable modulus input is necessary in order to capture the cyclic response of a pavement structure under repetitive loading conditions. In this study, an alternative method for modulus measurement was introduced. The testing machine, namely Asphalt Mixture Performance Tester (AMPT), which has been extensively used for characterising the dynamic response of asphalt concrete material, was used to determine the dynamic moduli of cement-stabilised materials in this study. By using AMPT, the cyclic load can be directly applied to the test specimens. Therefore, same testing scheme as asphalt concrete was adapted and applied to the study materials. In addition, compressive loading rate and test temperature can be controlled during the dynamic modulus measurement by AMPT. Accordingly, effects of loading rate, temperature, curing time and cement content were also examined in this research. At the final stage of this research, the finite element analysis was performed in order to investigate the effects of modulus types to the pavement response.

2 MODULUS OF CEMENT-STABILISED BASE MATERIAL

In this research, elastic moduli interpreted from UCS test using different test strain rates was characterized. Two sets of UCS test were conducted based on different strain rates. The first set of UCS test was subjected to strain rate recommended by the test standard (AS 5101.2.2 2008), that is 0.0087 per minute ($1.45x10^{-4}$ per second). An additional strain rate of 0.0667 per minute ($1.11x10^{-3}$ per second) was selected for the second set of UCS test as it is coincided with earthquake (dynamic) loading range (Bischoff and Perry 1991). After that, the dynamic moduli were determined by considering the effects of cement content, curing time, temperature and loading frequency. Moreover, flexural modulus and relevant information from previous literature (Chummuneerat et al. 2013) were summarised and compared with the test results from this research.

2.1 Elastic modulus of CTB

Korakod et al. (2014) determined the Optimum Moisture Content (OMC) and other index properties of cement-stabilised crushed rock base material. The percentage of cement by aggregate weight greater than 3% was selected since their research focuses on characterising the behaviours of stabilised material. According to Austroads (2008), at least 3% of cement content is required to achieve the structural characteristics of stabilised or bound pavement. Therefore, the specimens with cement content equal to 4%, 5% and 6% were tested in their research. After the OMC values were determined from the compaction test, the UCS specimens were prepared based on AS 5101.2.2 (2008). Table 1 summarises the values of OMC, MDD, UCS and elastic moduli at different curing duration.

An additional UCS test on 6 specimens was conducted in this research. The same specimen preparation and test procedures as performed by Korakod et al. (2014) were employed, except the strain rate was changed. Three specimens with 5% cement content and three specimens with 6% cement content were cured at 7 days mark and tested at strain rate equal to 0.0667 per minute. Comparison between the stress-strain curves from the tests with different strain rate are shown in Figure 1.

Table 1: Summary of UCS test results and compaction test (by Korakod et al. 2014)

Cement content	OMC[a]	MDD[b]	7 Days				28 Days	
			UCS[c] (MPa)		E[d] (MPa)		UCS[c] (MPa)	E[d] (MPa)
(%)	(%)	(g/cm^3)	0.0087/min	0.0677/min	0.0087/min	0.0677/min	0.0087/min	
5	2.30	6.10	8.0	8.5	455	1,060	10.4	1,770
6	2.33	6.40	9.6	10.6	680	1,200	12.5	2,350

[a] Optimum moisture content.
[b] Maximum dry density.
[c] Unconfined compressive strength averaged from three UCS specimens.
[d] Secant elastic modulus averaged from three UCS specimens.

Figure 1 shows the similar finding by Xiao, Li and Lin (2008). UCS and the elastic moduli from monotonic compression tests increase with respect to the test strain rates. Average elastic moduli of 5% cement content specimen increased from 455 to 1,060 MPa when test strain rates were changed from 0.0087 per minute to 0.0667 per minute. Same observation was found from the specimen with 6% cement content that is average elastic moduli rose up almost two times if the test strain rate was increased. It should be noted that, the calculation method for elastic modulus in this research is based on the procedure recommended by ASTM C469 (2010).

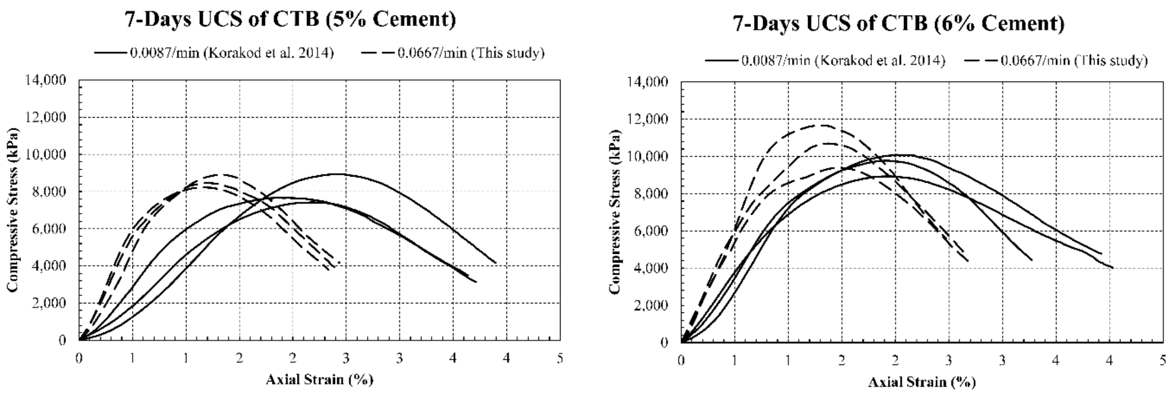


Figure 1. Strain rate effect to the stress-strain curve of CTB with 5% and 6% cement content

It can be seen from the test results that, for monotonic compression test, elastic modulus of the cement-stabilised base is influenced by the strain rate. This finding is important because of strain rate in the field caused by traffic loads may not equal to the test value; in fact, loading condition in the field is usually complex, hence in-situ strain rate would vary greatly. Accordingly, the elastic modulus of cement-stabilised base material is influenced by the strain rate, which may result in imprecise estimation of stress-strain response by the mechanistic pavement design.

2.2 Dynamic modulus of CTB

The dynamic modulus of cement-stabilised base material measured from AMPT was also analysed in this research. The configuration and component of AMPT are illustrated in Figure 2. AMPT was developed by the National Cooperative Highway Research Program (NCHRP) to characterise the asphalt concrete performances under cyclic loading condition (Bonaquist, Christensen, and Stump 2008). To determine the critical strain of asphalt concrete material for mechanistic-empirical design, the dynamic modulus was recommended to be the design parameter. Basically, dynamic modulus is the modulus of a visco-elastic material under sinusoidal loading conditions. In general, dynamic modulus can be measured from laboratory testing or calculated from the predictive models (Robbins 2009). Mathematical definition of dynamic modulus is the absolute value of a complex modulus; therefore it can be calculated by (2).

$$|E^*| = |\sigma^*/\varepsilon^*| = |(\sigma_0/\varepsilon_0)e^{i\phi}| = \sigma_0/\varepsilon_0 \quad (2)$$

which σ_0 is stress amplitude, ε_0 is strain amplitude, ω is angular frequency, and ϕ is the phase angle. For elastic material, the phase angle is equal to 0°, while it becomes 90° for viscous materials. Figure 3 shows the sinusoidal stress (σ^*) and sinusoidal strain (ε^*) plotted against time (t) with the phase lag of ϕ degree.

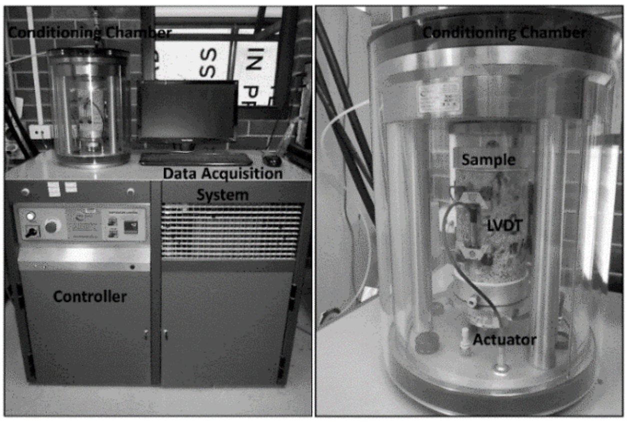


Figure 2. Asphalt Mixture Performance Tester (AMPT)

The same standard practice as used in asphalt concrete testing (AASHTO PP 61 2009) was employed to guide the dynamic modulus measurement of cement-stabilised base material in this research. According to the standard of test, the dimensions of the test specimen are a height of 150 mm and a diameter of 100 mm. At least two specimens are required for each test, therefore six specimens represent different cement content and curing duration were prepared (see Table 2). Besides its potential to characterise the cyclic response of a material, the AMPT also has a capability to control and vary test temperatures and loading frequencies. Accordingly, the cement-stabilised base specimens were tested at 4 °C, 20 °C and 40 °C. At each test temperature, the test frequencies were 10 Hz, 1 Hz, 0.1 Hz, plus an additional 0.01 Hz for the test at 40 °C. The test dynamic strain ranges from 45 to 85 microstrains were employed during the test. More detail on specimen preparation and test procedure can be found from Korakod et al. (2014). The average dynamic moduli (from 2 samples per set) determined from AMPT are summarised in Table 2.

Table 2 indicates that, temperatures and loading frequencies slightly affect the dynamic moduli of the cement-stabilised base material. However, the dynamic modulus notably relies on the cement content and curing duration of the specimen. Moreover, the value of dynamic modulus is much higher than the elastic modulus measured from monotonic compression test (see Figure 4). It should be highlighted that, elastic modulus from monotonic compression test with the strain rate falls within earthquake loading range (strain rate = 0.0667 per minute) is considerably smaller than the dynamic modulus measured by AMPT.

Table 2: Dynamic moduli of cement-stabilised base specimens

Cement content (%)	Curing (Days)	Dynamic Modulus (MPa)									
		4 °C			20 °C			40 °C			
		10 Hz	1 Hz	0.1 Hz	10 Hz	1 Hz	0.1 Hz	10 Hz	1 Hz	0.1 Hz	0.01 Hz
5	**28**	19,689	18,719	18,112	18,269	17,678	17,321	17,582	16,855	16,411	16,301
6	**7**	19,192	18,820	18,496	18,432	18,043	17,678	17,840	17,356	17,106	17,165
6	**28**	24,545	24,134	23,612	23,515	22,933	22,451	22,776	22,085	21,533	21,327

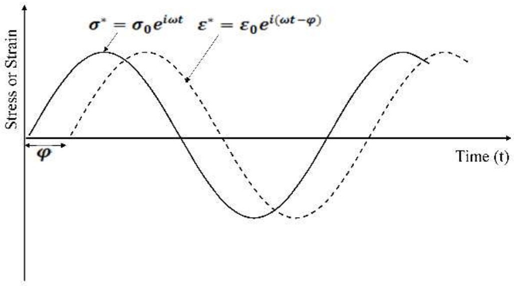


Figure 3. Sinusoidal stress, sinusoidal strain and phase angle

2.3 Flexural modulus of CTB

Chummuneerat et al. (2013) conducted the beam fatigue test on cement-stabilised base specimens with the cement content of 3% and 5%. The curing duration for every specimen was 28 days. The tests were conducted using various strain magnitude which fall within a range of 50 to 200 microstrains. Prior to the fatigue test, the flexural modulus was measured and assigned as the initial flexural modulus for every individual specimen. According to the test standard (AG:PT/T233 2006), the fatigue test is performed under a continuous haversine loading frequency of 10 Hz. The fatigue test is continued until the flexural modulus of the specimen is reduced to half of the initial value or the one million loading cycle is obtained. The test temperature was 25 °C for every test specimens. Figure 4 shows the initial flexural modulus of specimen with 5% cement content plotted against the elastic moduli and dynamic moduli determined in this research.

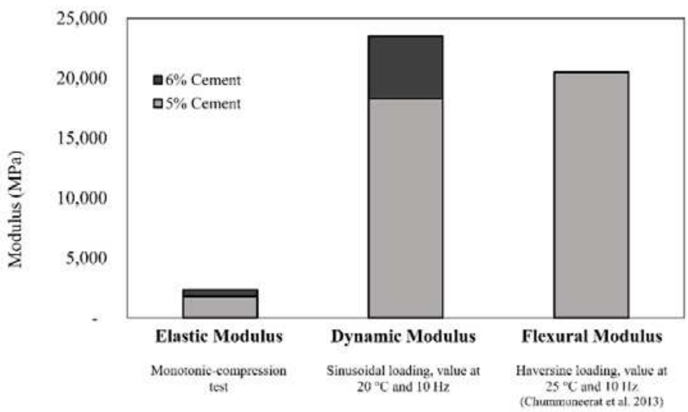


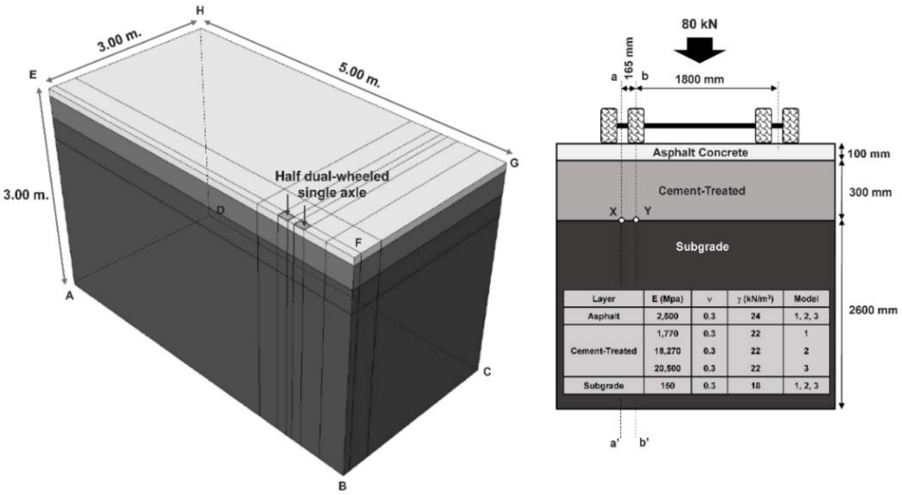
Figure 4. Elastic moduli, dynamic moduli, and initial flexural modulus of cement-stabilised base specimens with 5% cement content and cured at 28 days

Based on available information shown in Figure 4, the elastic modulus measured from monotonic-compression test is much lesser than those of the dynamic modulus and initial flexural modulus. Nevertheless, the initial flexural modulus of the specimen with 5% cement content approximately equals to the dynamic modulus determined by the AMPT. It should be noted that, this comparison was made by using the dynamic modulus and initial flexural modulus measured at 20 °C and 25 °C respectively. The applied dynamic strain by the AMPT was 45 to 85 microstrains, therefore the initial flexural modulus measured at 50 microstrain was chosen. However, the sinusoidal load of 10 Hz frequency was used by the AMPT, whereas haversine load of 10 Hz was employed during the beam fatigue test.

In the next section, the stress-strain response of pavement structure with a cement-stabilised base layer was analysed by the Finite Element Method (FEM). The analysis was performed based on different moduli which were characterised in the previous section. Only the moduli of cement-stabilised base material of 5% cement content and 28 days curing point were used in the finite element calculation. It should be noted that, the purpose of finite element analysis is to identify the effects of modulus types to the pavement response and fatigue performance of the cement-stabilised base course.

3 FINITE ELEMENT ANALYSIS

Three dimensional (3D) finite element simulations for each modulus types were carried out using ABAQUS 6.12. The typical pavement structure and the finite element model employed in the simulation are illustrated in Figure 5. In order to compare the effects of modulus types, three models with different moduli of a cement-stabilised base layer were established. The element type for the pavement structure model was C3D20R (Continuum 3-Dimensional 20 node elements with reduced integration) brick element. A standard axle load recommended by Austroads (2010) was used in the calculation as the applied load. This means the pavement structure was subjected to a dual-wheeled single axle with the applied load of 80 kN. Figure 6 shows a rectangle and two semicircles shape of contact area between single tyre and pavement surface. Tyre pressure of 750 kPa is recommended by the guideline (Austroad 2010). To model the load contact area, Huang (2004) recommended to transform a rectangle and two semicircles shape to be only single rectangle shape as shown in Figure 6. Therefore, a rectangle with dimension of 0.196 m x 0.135 m was used in this research. However, half wheel load was considered in the calculation due to the symmetry (Figure 5). The boundary conditions of finite element model shown in Figure 5 are established as follow; (1) vertical displacements of the nodes on the plane ABCD are fixed, (2) orthogonal displacements to the plane AEHD and DHGC are fixed, and (3) orthogonal displacements to the planes of symmetry (BCGF and ABFE) are prevented.



Layer	E (Mpa)	v	γ (kN/m³)	Model
Asphalt	2,500	0.3	24	1, 2, 3
Cement-Treated	1,770	0.3	22	1
	18,270	0.3	22	2
	20,500	0.3	22	3
Subgrade	150	0.3	18	1, 2, 3

Figure 5. Finite element model, material properties and loading condition

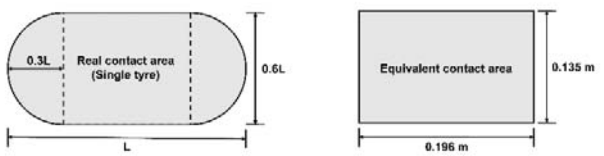


Figure 6. Contact area between single tyre and pavement surface (Left) and equivalent contact area (Right)

In the finite element calculation, Model 1 represents the pavement structure with cement-stabilised base course analysed based on elastic modulus, whereas the dynamic modulus and initial flexural modulus were used in the calculation of Model 2 and 3 respectively (Figure 5). The properties of asphalt concrete and subgrade were kept constant throughout the analysis of the three models. By applying the same traffic load to all the models, deformed mesh and horizontal stress generated by the traffic load only were presented in Figure 7. The figure clearly shows that induced horizontal stress can be evenly transferred to the subgrade layer by applying the stiffer material as a pavement base course (Model 2 and 3).

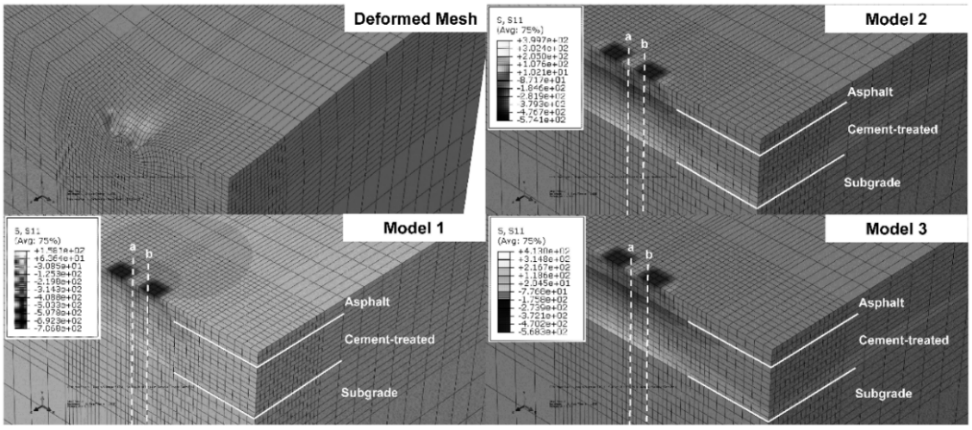


Figure 7. Deformed mesh and horizontal stress distribution induced by the wheel load

Figure 8 shows the horizontal strains induced by the traffic load along the axis a-a' and b-b' (see Figure 5). Positive value indicates tensile strains and vice versa. The critical tensile strain of cement-stabilised base layers at point X reduced from $1.26\text{x}10^{-4}$ to $0.98\text{x}10^{-4}$ and $0.99\text{x}10^{-4}$, when the elastic modulus was replaced by dynamic modulus and initial flexural modulus in the analysis, respectively. Similarly, critical tensile strain at point Y from the analysis using elastic modulus, dynamic modulus and initial flexural modulus are $1.08\text{x}10^{-4}$, $0.86\text{x}10^{-4}$ and $0.87\text{x}10^{-4}$ respectively. However, the critical tensile strains of Model 2 and 3 are almost identical because of the magnitudes of modulus used for both models are not much different. Assuming (1) is applicable to the cement-stabilised base material with elastic modulus greater than 10,000 MPa, the reduction in tensile strain approximately of 25 microstrain leads to an increasing in predicted N_f of $2\text{x}10^{11}$ cycles. This approximation was made based on *RF* = 1 (95% of desired project reliability) and *E* = 20,500 MPa.

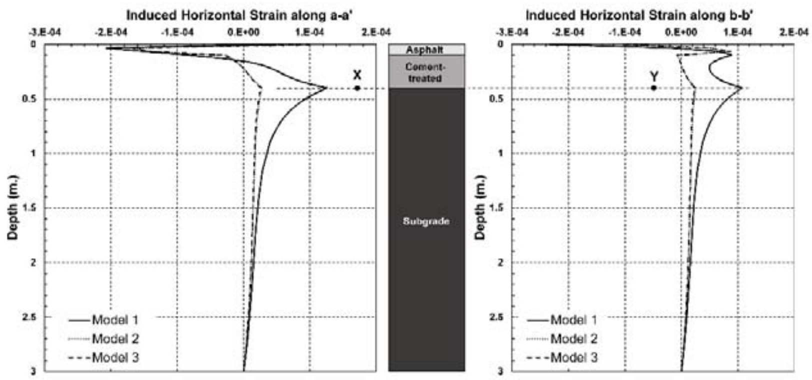


Figure 8. Induced horizontal strain along the section a-a' (Left) and b-b' (Right) of the three models

4 CONCLUSION

The modulus of the cement-stabilised material is important to an estimation of its fatigue performance in the new mechanistic pavement design and analysis. In this research, the elastic modulus and the dynamic modulus of a cement-stabilised base material were determined and characterised, whereas the flexural modulus obtained from Chummuneerat et al. (2013) is also examined. The finite element analysis of typical pavement section was also performed based on those three different modulus types of a cement-stabilised base course layer. Results from the finite element analysis show that analyses using the dynamic modulus and the flexural modulus produced lower values of a tensile strain at the critical location in pavement than that analysed using the elastic modulus. The reduction in a tensile strain value results in an increasing in fatigue life of the cement-stabilised pavement structure according to Austroads empirical formula (Austroads 2010). The magnitudes and performance trends of strains computed using the dynamic and the flexural modulus are almost identical. According to the test procedure, both types of modulus are determined based on the cyclic response of material. However, the cyclic response of cement-stabilised base material characterised by AMPT is the simplest in term of sample preparation, handling and testing.

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