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Pavement analysis and design for Hydrated Cement Treated Crushed Rock Base (HCTCRB) pavements

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ABSTRACT

Hydrated Cement Treated Crushed Rock Base (HCTCRB) is a cement modified basecourse material which the mixture of a standard crushed rock base and cement is disturbed after hydration. The unique production process for HCTCRB is different from that of a common cement-treated base to prevent cementitious bonding in order to maintain the unbound material characteristics with an improvement in material engineering properties. This paper presents the mechanistic-empirical pavement analysis and design for flexible pavements containing HCTCRB basecourse. The resilient modulus presenting the stress dependency behaviour of HCTCRB derived from the repeated load triaxial tests were used as one of the input for the analysis and design. Pavement analyses in this study covered various states of materials i.e., linearity or non-linearity, and isotropy or anisotropy of pavement materials. A three - dimensional finite element analysis of pavement structure was also carried out. The conventional pavement analysis in Australia by Circly software, using the anisotropic and quasi-non-linearity technique, is still deemed reliable in comparison with the various approaches examined in this study. However, there remains a concern regarding the reliability of the single input value of the resilient modulus derived from the resilient modulus tests. The average resilient modulus from the test results appeared to be too high for an effective analysis to be undertaken. Based on the stress-dependent analyses conducted and concerned with the thickness range of the basecourse layer, a typical value for the resilient modulus of HCTCRB was determined.

Keywords: HCTCRB, basecourse, resilient modulus, pavements

1 INTRODUCTION

Hydrated Cement Treated Crushed Rock Base (HCTCRB) is a cement modified basecourse material which the mixture of a standard crushed rock base (CRB) and cement is disturbed after hydration. The unique production process for HCTCRB is different from that of a common cement-treated base to prevent cementitious bonding in order to maintain the unbound material characteristics with an improvement in material engineering properties. In the mechanistic-empirical pavement analysis and design, pavement materials are characterised in term of resilient modulus (M_R) which is the ratio of the applied deviator stress to the recovery strain of test material under the cyclic loading. The resilient modulus of any unbound granular and modified materials are regularly determined through the repeated load triaxial tests under various applied stress conditions of different deviator and confining stresses, in order to simulate sophisticated traffic loadings. The resilient modulus of such material is generally non-linear and usually expressed as the stress dependent model in terms of the applied stresses e.g. the bulk stress model (Hicks and Monismith 1971) and the universal model (Witczak and Uzan 1988).

In Australia, Circly software (Mincad Systems 2009) is commonly used for the pavement analysis and design. It requires single value of M_R as one of the input parameters. However, there has been concern regarding to an appropriate input value of M_R. Saleh et al. (2009) conducted the resilient modulus test for unbound granular materials and used the average values from the tests as inputs into Circly. They found that the responses from anisotropic and quasi-non-linear cases produced by Circly were much lower than those from the non-linear isotropic analysis produced by Everstress for a particular pavement. This may be due to the average M_R being higher than it should have been. Thus this paper aims to achieve a typical M_R value of HCTCRB for effective use in the pavement analysis and design. Firstly, the resilient modulus and stress dependency of HCTCRB was analysed based on the repeated load triaxial test results. Consequently, the analyses of typical flexible pavement containing HCTCRB were performed which covered various conditions of materials i.e., linearity or non-linearity, and isotropy or anisotropy of pavement materials. A three - dimensional finite element analysis of pavement structure was also carried out.

2 MATERIALS

The HCTCRB in this research was made by blending standard CRB with 2% GP cement (by mass of dry CRB); the typical cement content used in the general manufacturing process in WA. The amount of water used was in accordance with MRWA specifications (Main Roads Western Australia 2012);that is the minimum moisture content of the mix at 90% optimum moisture content (OMC) of CRB. Accordingly, the fresh mixture was stored in closed containers, and cured in a temperature-controlled room (25 °C) to maintain constant curing conditions for specified hydration periods. Once the desired hydration time was completed, the hydrated mixture was returned to the mixer (without additional water) to break the cementitious bonds generated during the hydration reaction. This procedure, called a re-treating process, aimed to produce a cement-modified material whilst maintaining unbound basecourse characteristics in order to provide effective material engineering properties. Eventually, HCTCRB was obtained; its appearance is similar to CRB coated with cement.

3 EXPERIMENTAL WORKS

3.1 Specimen Preparation

HCTCRB samples were used in resilient modulus tests bound by particular conditions. These included: hydration periods (7, 14, 28 and 45 days), amount of added water during compaction (no added water, OMC of CRB-cement and OMC of HCTCRB) and degree of moisture content after dryback (60% OMC, 80% OMC and no dryback). The test specimens were produced in a standard 100 mm diameter, 200 mm high mould using a modified compaction method. After compaction, the specimens were cured in wrapped moulds for 28 days to prevent moisture loss, and then removed from the moulds. The specimens were set up successively upon the RLT apparatus.

3.2 Repeated Load Triaxial (RLT) Test

The resilient moduli of HCTCRB samples were evaluated using a repeated load triaxial (RLT) test in accordance with Austroads standard test method AG:PT/T053 (Austroads 2007). The tests were conducted under drained conditions, samples were not saturated and suction measurement was not performed. The repeated vertical force, lasting for a period of 3 s, comprises a load pulse width of 1 s with rise and fall times of up to 0.3 s. The resilient modulus tests were performed under applied stress conditions in 66 stress stages (stage no's. 0 – 65) with different deviator and confining stresses. The stress ratio between the deviator stress and the confining stress varied from 2 at the first stage to 25 at the final stage. The deviator stresses varied from 100 kPa to 600 kPa, while the confining stresses ranged from 20 kPa to 50 kPa. One thousand loading cycles of pre-conditioning was carried out prior to the tests. The aim of the process was to allow the end caps to bed-in to the specimen and to ensure that the applied stresses and resilient strains became stable under the imposed stress conditions. Subsequently, 66 stresses were applied to each specimen in stages to conduct the resilient modulus test. At each stress stage, a minimum of fifty loading cycles was applied to the specimen. Each stage terminated when the standard deviations of the last six values of the resilient moduli were less than 5%, or until two hundred loading cycles were reached. The stages then continued in order until all given stress stages were completed.

4 RESILIENT MODULUS (M_R) TEST RESULTS

The test results for all samples are shown in Figure 1a. The scatter pattern of the test data is visible due to the different test sample conditions which produced differing HCTCRB resilient moduli. This data provided a relatively low degree of determination (R^2) of about 40%, when evaluated with the bulk stress model (1). To normalise the critical conditions appropriate to the resilient moduli of HCTCRB, the moisture and density conditions of HCTCRB were integrated with the bulk stress model and the universal model to improve the R^2, as expressed in (2). The moisture content ratio (WCR) is the ratio of moisture content in any sample to the average optimum moisture content of HCTCRB. The dry density ratio (DDR) is the ratio of the dry density of any sample to the average maximum dry density of HCTCRB. The experimental results were then evaluated once more and yielded (3), and improved R^2 values to approximately 70% (see Figure 1b). The values of the DDR being 0.98 and the WCR being 0.70, which were in keeping with the requirements of Main Roads Western Australia (2012), were substituted into (3) and eventually resulted in (4). This equation was then used in the resilient modulus models of HCTCRB in the pavement analysis.

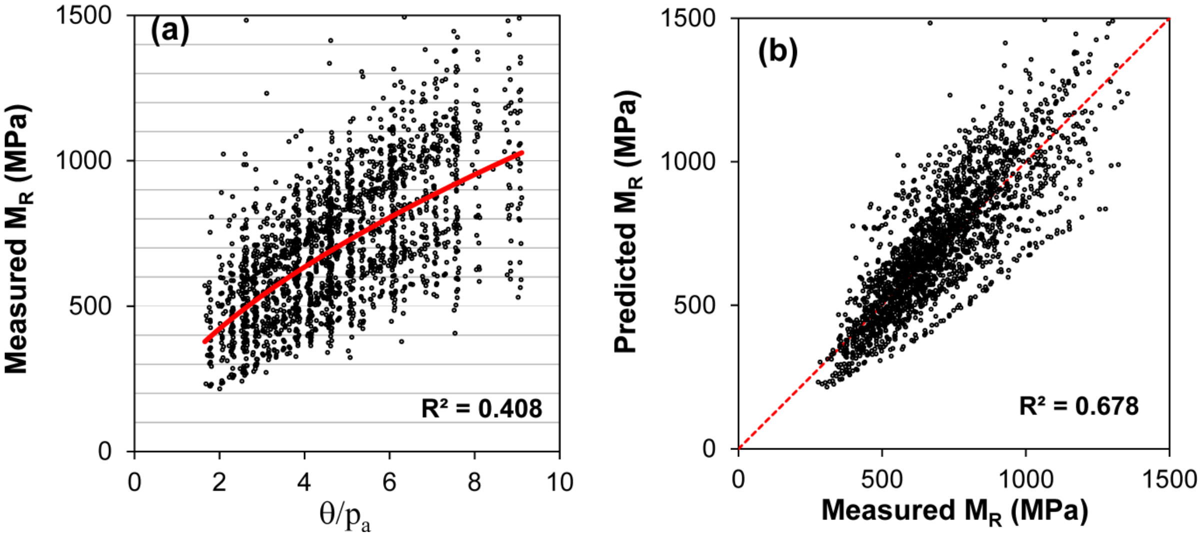


Figure 1. Resilient modulus test results for all HCTCRB samples

$$M_R = k_1 \left(\frac{\theta}{p_a} \right)^{k_2} \tag{1}$$

$$M_R = k_1 * DDR^{a} * WCR^{b} \left(\frac{\theta}{p_a} \right)^{k_2} \tag{2}$$

$$M_R = 206 * DDR^{1.187} * WCR^{-0.932} \left(\frac{\theta}{p_a} \right)^{0.588} \tag{3}$$

$$M_R = 280 \left(\frac{\theta}{p_a} \right)^{0.588} \tag{4}$$

where M_R = resilient modulus; pa = atmospheric pressure (100 kPa); □□= bulk stress; $□_{oct}$ = octahedral shear stress; DDR = dry density ratio; WCR = moisture content ratio; and a, b, k_1, k_2 and k_3= regression constant

5 PAVEMENT STRUCTURAL ANALYSIS

Pavement analyses in this study covered various states of materials i.e., linearity or non-linearity, and isotropy or anisotropy of pavement materials, using three types of available software. The analyses that accounted for the anisotropy and quasi-non-linearity of materials were performed using Circly 5.0 (Mincad Systems 2009),this being a popular and commonly used software for pavement analysis and design in Australia. Everstress 5.0 (Washington State Department of Transportation (WSDOT) 2005) was used for the analysis of linearity and non-linearity of isotropic materials. A three- dimensional finite element analysis (3D FEA) of pavement structure was also carried out using Abaqus 6.10 (Dassault Systèmes 2010). The analysis of the pavement structure provided the responses of pavement materials in terms of stress and strain behaviour. Based on Austroads (2010) criteria, the allowable

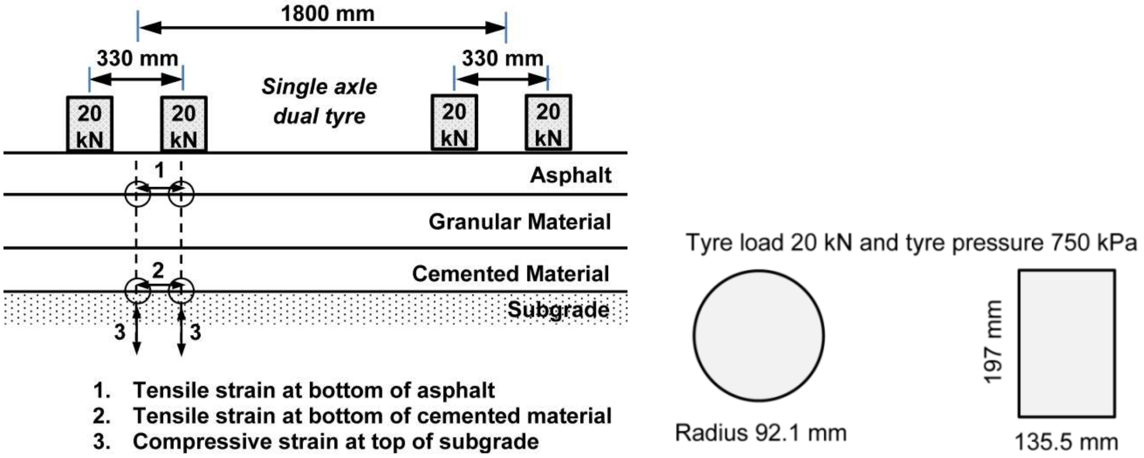
ESA of a certain pavement is usually converted from the strain values occurring in pavement layers (such as asphalt and subgrade) by applying transfer functions as shown in (5) and (6) respectively. Finally, allowable ESAs or SARs for specific pavement configurations were obtained and then evaluated as to whether such pavement would be capable of carrying the designed ESA (DESA) or designed SAR (DSAR).

$$\mathrm{N} = RF\left(\frac{6918(0.856V_b+1.08)}{S^{0.36}\mu\varepsilon}\right)^5 \qquad (5)$$

$$\mathrm{N} = \left(\frac{9300}{\mu\varepsilon}\right)^7 \qquad (6)$$

where N = the allowable number of standard axle repetitions; □□□= critical microstrain in the considered material; RF = reliability factor for asphalt fatigue; V_b = % of binder volume; S = elastic modulus of asphalt in MPa

5.1 Loading and Pavement Configuration



(a) (b)

Figure 2. (a) standard axle load and critical strains (b) loading shape used for the analysis

Austroads (2010) established applied loading and critical responses for flexible pavement analysis and design, as shown in Figure 2a. Standard loading is represented by a single axle with dual tyres with a total load of 80 kN. The total load is allocated equally; 20 kN to each tyre, and distributed uniformly with a tyre pressure of 750 kPa over a circular area (radius of 92.1 mm) on the contact surface. Circular loading is normally applied with regard to analysis by Circly and Everstress. For 3D FEA, loading contact is transformed from a circle into a rectangle of equivalent area (Huang 2004). The shapes and dimensions of the load contact used for analysis are shown in Figure 2b.

A typical pavement structure used in the analysis throughout this study comprised four layers of asphalt surface overlying HCTCRB basecourse, and a crushed limestone subbase on a subgrade of Perth sand, as detailed in Table 1. From Figure 1a, the average M_R for all HCTCRB samples was 700 MPa. At the average applied bulk stress of 470 kPa from the standard tests, the M_R of HCTCRB varied from 300 MPa to 1,000 MPa. Thus, analyses were conducted over this range of M_R.

Table 1: A typical pavement configuration

Layer	Material	Thickness (mm)	Vertical modulus (MPa)	Poisson's ratio
Surface	Asphalt	50	2,500	0.40
Basecourse	HCTCRB	200	varied	0.35
Subbase	Crushed limestone	200	300	0.35
Subgrade	Perth sand (CBR 10)	infinite	100	0.35

5.2 Pavement Analysis by Circly

Circly has program features which comply with the approach to mechanistic empirical pavement analysis and design. Asphalt is assumed to be homogeneous, elastic and isotropic. Unbound granular materials and subgrade are assumed to be anisotropic and from this the ratio of vertical modulus to horizontal modulus is assigned, in this case being 2. However, Poisson's ratio for both directions is equal. Unbound granular layers (such as basecourse and subbase) are divided into 5 equal sub-layers. The modulus for each layer is then reduced by a reduction factor (R), as stated in (7). This reduction demonstrates the quasi-non-linearity of the materials (Saleh et al. 2009) as the modulus decreases with depth. However, each sub-layer still acts as a linear elastic material with a constant modulus throughout the depth of each sub-layer. There is also another condition for the modulus of the overlying layer, as shown in (8), which depends on its thickness and the modulus of the adjacent underlying layer. The two conditions for modulus calculation indicate that the modulus of the overlying layer is also greatly dependent on the proximity of the underlying layer, rather than solely on itself.

$$R = \left(\frac{E_{v1}}{E_{v2}}\right)^{\left(\frac{1}{5}\right)} \tag{7}$$

$$E_{v1} = E_{v2} * 2^{\left(\frac{t_1}{125}\right)} \tag{8}$$

where R = the reduction factor for the modulus of the overlying layer; E_{v1} = modulus of the overlying layer; E_{v2} = modulus of the adjacent underlying layer; t_1 = thickness of the overlying layer.

5.3 Pavement Analysis by Everstress

Although Everstress is unable to make a determination regarding the anisotropic case, it is able to account for the linearity and non-linearity of the unbound granular materials. For non-linear analysis cases, Everstress uses the bulk stress model for coarse-grained unbound granular materials and the deviator stress model for fine-grained subgrade. However, this study only accounted for the non-linearity of the HCTCRB basecourse using the resilient modulus model in (4). Everstress also requires the initial modulus as the input, together with the bulk stress model parameters (k_1 and k_2). It then uses an iterative procedure to adjust the modulus according to the induced stress throughout the layer depth. The resilient modulus values of HCTCRB, which varied with its thickness, are illustrated in Figure 3. An average M_R of 700 MPa for HCTCRB obtained from the tests seems too high as an input for Circly and linear cases. Figure 3 shows that the M_R of HCTCRB over a typical range of its thickness would not be as high as 700 MPa. Based on the average values from Figure 3, the M_R for HCTCRB should be 400 MPa for Circly and linear analysis.

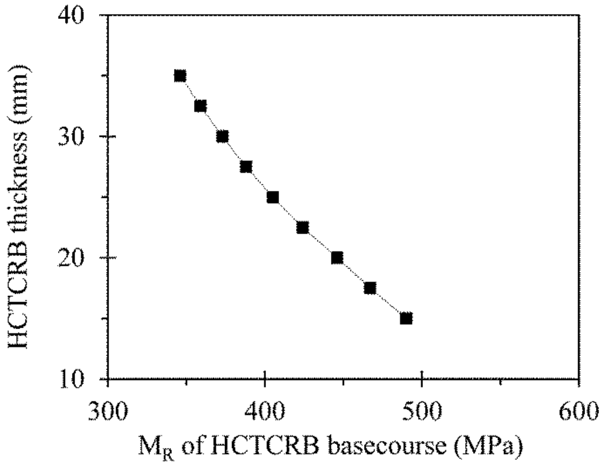


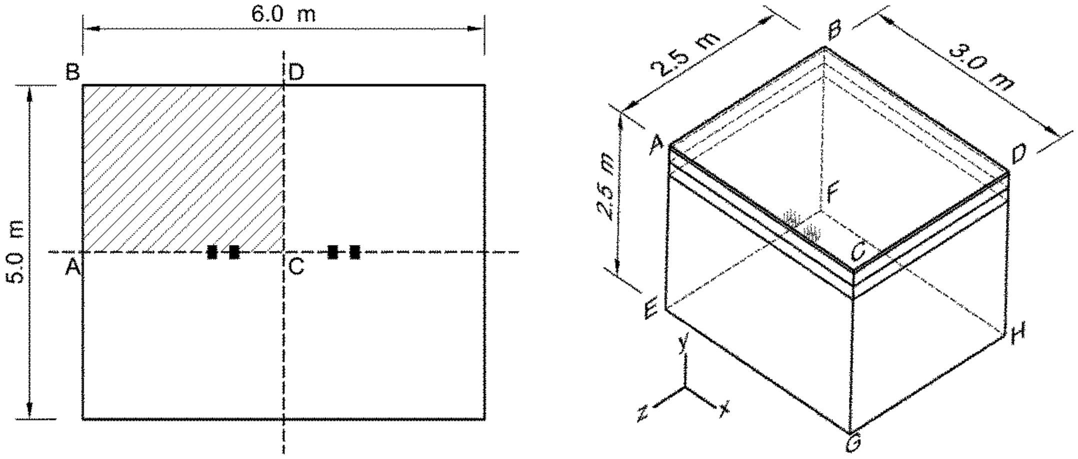
Figure 3. Variation of M_R with thickness for HCTCRB from non-linear analysis

5.4 Finite Element Modelling for Pavement Analysis

This study employed Abaqus software for the three dimensional finite element model (3D-FEM) of pavement materials. A sub-layering technique was also used for the basecourse and subbase layers in addition to the isotropic analyses. A pavement model size of 5 m long (in the direction of the traffic) by 6 m in a transverse direction and 2.5 m in depth was used for modelling. This was subjected to a load of four rectangular tyres of 20 kN and 750 kPa each (see Figure 4). Due to the two symmetrical planes (as shown in Figure 4a), only a quarter portion was necessary for the carrying out of the analysis as shown in Figure 4b. The pavement was modelled with C3D20R (Continuum 3-Dimensional 20-node element with reduced integration) brick elements. The boundary conditions of the model consisted of:

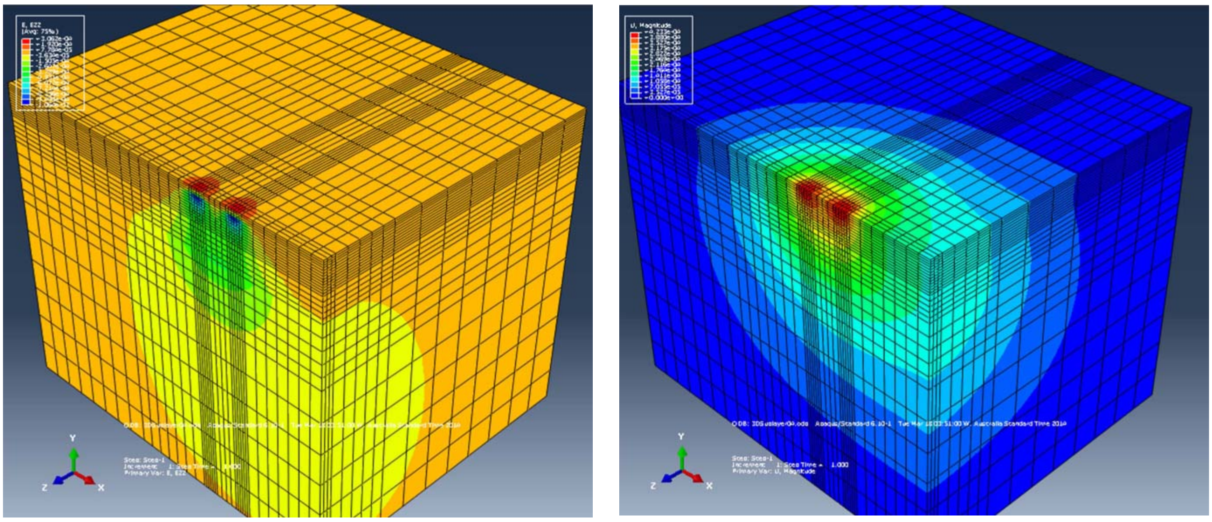
- symmetry along the z-axis on the EACG plane;
- symmetry along the x-axis on the GCDH plane;
- restraint of horizontal movement along the z-axis on plane HDBF;
- restraint of horizontal movement along the x-axis on plane EABF; and
- restraint of movement along the x, y and z-axes on bottom plane EFHG.

Examples of the analysis results, chosen from the isotropic and linear cases for the M_R of HCTCRB 400 MPa, are demonstrated in Figure 5.



(a) (b)

Figure 4. 3D-FEM model for a typical pavement (a) top view (b) one quarter model used for analysis

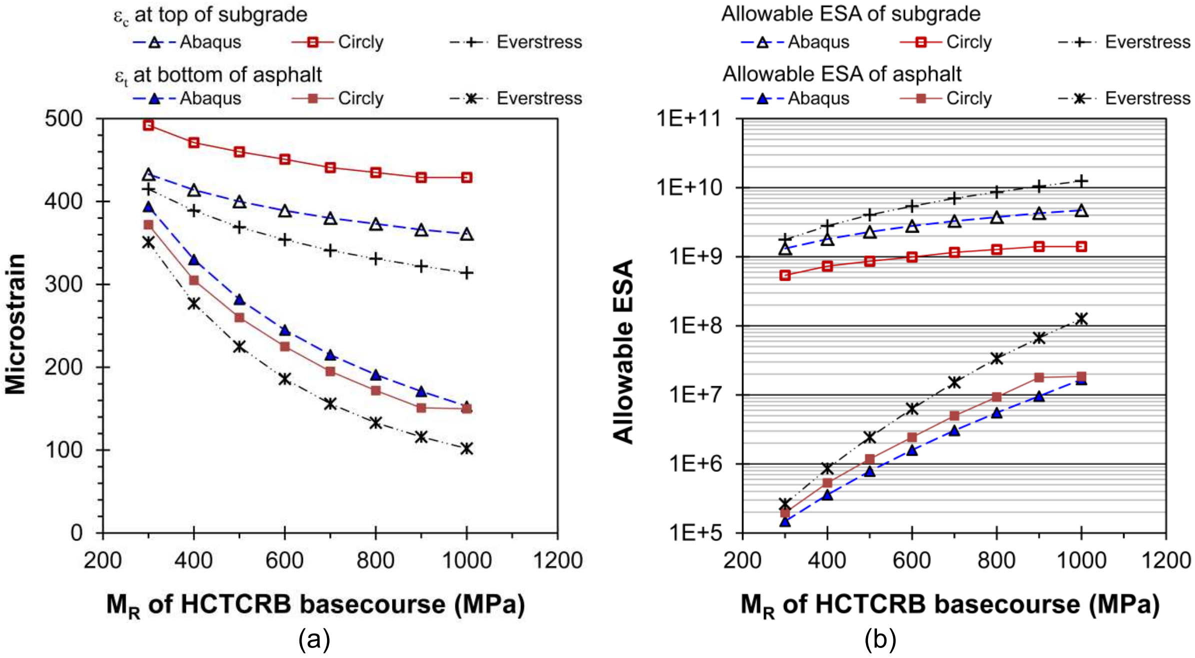


(a) (b)

Figure 5. Examples of the responses in a pavement model (a) vertical strain (b) deflection

5.5 Comparison of the Analysis Methods

The comparison of routine analyses using each of the three types of software (i.e., fully elastic and isotropic analyses by Everstress, isotropic with sub-layering by Abaqus, and anisotropic with sub-layering by Circly) is shown in Figure 6. The critical tensile strain at the bottom of asphalt resulted from Circly were approximately 5% lower than that of Abaqus analysis. However, the critical compressive strains on the subgrade determined by Circly were significantly higher than those from Abaqus (approximately 25%). This does not affect the allowable ESAs for thick asphalt pavement design which is governed by the tensile strain of asphalt. Nevertheless, for thin asphalt pavements (less than 40 mm) or unbound granular pavements, Circly provides the more conservative allowable ESAs due to the higher strain on the subgrade. Thus, with pavement analysed by Circly, the anisotropic and sub-layering techniques are still reliable for use in pavement analysis and design. However, care are must be taken with the M_R inputs derived from the resilient modulus tests. Based on this study, and that of Saleh et al. (2009), the average M_R from the test results seemed too high for use as an input into the linear and quasi-non-linear analyses. An appropriate M_R input must be carefully determined through the induced stress conditions over the range of typical pavement configurations.



(a) (b)

Figure 6. Comparison of the results from three analysis methods (a) strain (b) allowable ESA

Pavement responses from structural analyses can be further validated and compared to the real pavement responses such as full scale pavement sections subjected real heavy vehicle or moving wheel load e.g. accelerated pavement facility and heavy vehicle simulator. Field measured responses i.e. stress, strain and deflection at any particular position in pavements can be monitored through the installation of pressure cells, strain gauges and deflectometers, respectively buried at the desired depth and position of the pavement section. For surface deflections, the analysis results can be compared to the field measurements by the falling weight deflectometer (FWD) which provide the deflected surface under the given load.

The calculated results from this study agreed with those of Christopher et al. (2006) that tensile strain at bottom of asphalt and compressive strain at top of subgrade are getting lower with an increasing in M_R for base course material and subgrade. Sævarsdóttir (2014) monitored the pavement responses resulted from instrumentation in the accelerated pavement tests (APT) to study the effect of increased moisture content (i.e. decreased resilient stiffness) in unbound granular base, subbase and subgrade layers of the flexible pavements. These measured results were compared with calculated responses of the pavement model using multilayer elastic theory and 3D FEM. It was found that all the unbound layers resulted in higher vertical strain and lower vertical stress with an increase in moisture content. The measured deflections obtained from FWD were also closed to results from 3D FEM.

6 CONCLUSION

This study achieved the resilient modulus models representing the stress dependency of HCTCRB at specific moisture and density conditions based on the bulk stress model. Then the resilient modulus test results were implemented into the pavement analysis and design. A typical pavement structure was set up and analysed in different degrees of material isotropy and linearity. Changes in the tensile strain in the asphalt with the modulus of the basecourse material are more pronounced than those in the subgrade compressive strain. However, the compressive strain at the top of the subgrade is more sensitive to analysis methods. The Circly pavement analysis, using the anisotropic and sub-layering technique, is still deemed reliable in comparison with the other two approaches examined in this study. However, there remains a concern regarding the reliability of the value of the M_R input derived from the resilient modulus tests. The average resilient modulus from all experimental data was quite high for linear and quasi-non-linear analyses, which produced an overestimation of the allowable amount of traffic loading. Based on the stress-dependent analyses conducted and concerned with the thickness range of the basecourse layer, a typical value for the M_R of HCTCRB may be determined as being approximately 400 MPa.

7 ACKNOWLEDGEMENT

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