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Dynamic Effects on Fatigue Life of Cement Treated Crushed Rock

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Synopsis: Fatigue life prediction of cement treated crushed rock is not a well understood concept in pavement engineering. The complexity to understand fatigue response of pavement lies not only in the structural model or the defining criteria for measurement, but also includes the testing regime to be adopted. Despite the well established testing methodologies for asphalt, minimal literature and standardised laboratory regimes exists for cemented basecourse. Fatigue testing of these materials is complicated by a multitude of variables that has to be considered in order to provide meaningful and representative data for design. Recent studies have been undertaken in Australia recently to characterise the fatigue phenomenon using a four point bending test setup by Austroad. Nevertheless, the loading frequency on fatigue life has not been addressed explicitly. A laboratory investigation to assess the loading frequency during pavement testing is undertaken. The paper presents the challenges and results achieved from test.

Keywords: fatigue, dynamic loads, flexural beam test, cemented materials.

1. Introduction

Fatigue was first discovered after World War 2 and is a phenomenon that is not well understood in the engineering world. Even so, the study of fatigue predominantly revolves around homogenous materials such as steel and other metals. Regardless, fatigue damage is the predominant failure mechanism of stiff pavement layers, e.g. asphaltic concrete seals and cemented basecourse layers. These structures are made up of composite materials which add considerable complexity if a mechanistic explanation is sought to characterise their structural behaviour.

Austroads mechanistic design guidelines idealises the structural analysis of pavements using a multi-layered model [1]. Within the model, cemented base courses are characterised as bound materials having developed tensile strength from the formation of interlocking cement matrices between aggregates. The critical response of this layer is designed as the tensile strains at the base of the layer [1], where distress is manifested as a bottom-up fracture. The model further assumes the pavement layer to be homogeneous, elastic and isotropic. These assumptions allow the simplification of the pavement structure for elastic analysis as part of the Mechanistic-Empirical design adopted in Australia [2]. The M-E approach is selected as a compromise between the two idealisations since at either end of the spectrum the analysis will either be overly complex or unrepresentative [2].

With the advent of supercomputers available at men’s fingertips, academia now seeks to produce a -paradigm shift in fatigue life prediction of cemented layers using mechanistic models. Significant works have been done for asphaltic material due to the financial incentives of improving the material. However, limited understanding has been developed for fatigue life prediction of cemented basecourse, especially in Western Australia.

The fatigue mechanism of cemented material is characterised as a reduction in stiffness [3] caused by an accumulation of damage at locations of inhomogeneities [4] rather than a distinct transverse rupture normally seen from ultimate loadings. The accumulation of damage by the pavement structure averaged across the volume of material affected from repeated traffic loads ultimately reaches a distress limit whereby the localised cement matrices disintegrates, consequently resulting in block cracking or aggregates returning to its original unbound mechanical state, a service stage known as equivalent granular phase [1].

A recent study by Austroads [3] have shown that the four point bending test have shown a substantial correlation between the testing regime adopted and fatigue induced deflection of pavements loaded by the Accelerate Loading Facility. The testing regime adopts havershine pulses of 2 Hz which includes a 250ms rest period between pulses as shown. The selection of the loading frequency was dictated primarily by the time consuming nature of fatigue testing. However the impact of loading frequency, or the dynamic effect of loads, to the test was not discussed.

2. Dynamic Effects of Load on Pavements

The assessment of dynamic response for pavements is critical in anticipating road damage properties particularly with cement treated materials the dominant failure mechanism is fatigue [5]. Beskou and Theodorakopoulos [5] have provided a thorough and comprehensive literature review on the effects of dynamic loads on pavements, where various numerical models developed to date have been presented.

Under constant velocity, the deflected shape of pavements under a specific traffic load is similar at any given time, i.e. the deflected shape travels with the load [6]. Conversely, at constant amplitudes, when velocity increases, more pronounced fluctuations occur and the maximum displacement and the effected region of the traffic load increases in the direction of the traffic movement while in the lateral direction only maximum deflection increases [6] as shown in Figure 1 below.

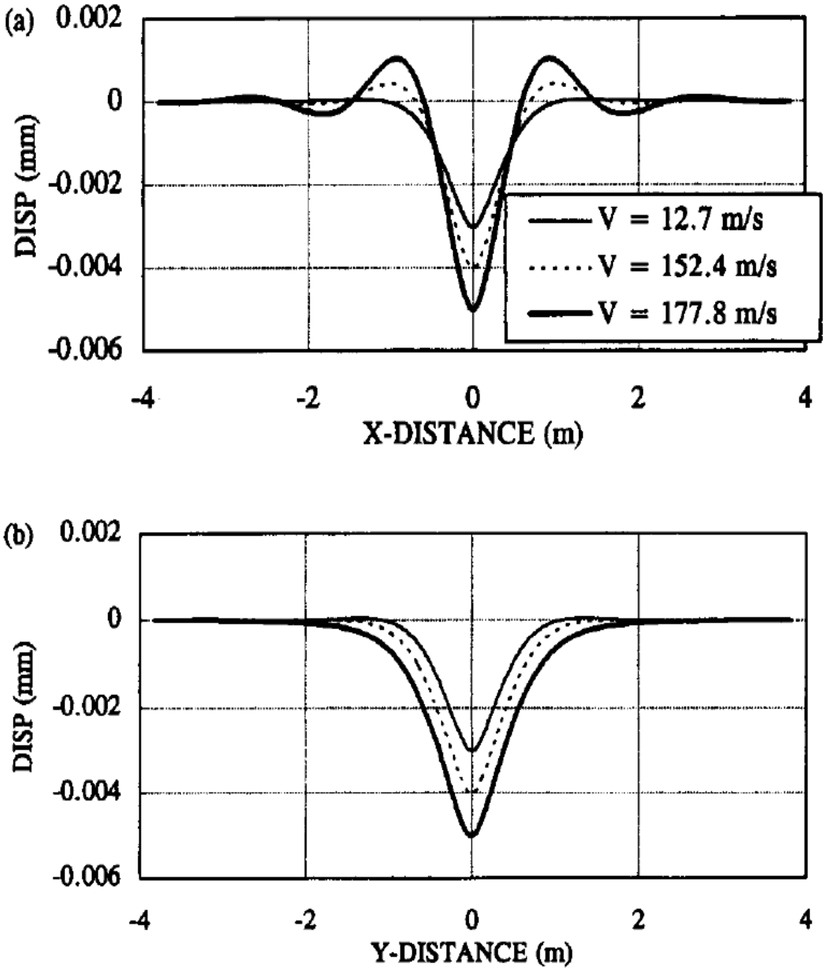

Figure 1. Effects of velocity on deflected shape along: (a) x-axis (moving direction); (b) y-axis (lateral direction) [6]

Nevertheless, due to the effect of damping, the deflection increases as the velocity increases to a critical resonant velocity, where deflection then begins to decrease. On this note, when pavements undergo moving harmonic loads for velocities before reaching critical velocity and after reaching velocity shows varying results as shown in Figure 2 below.

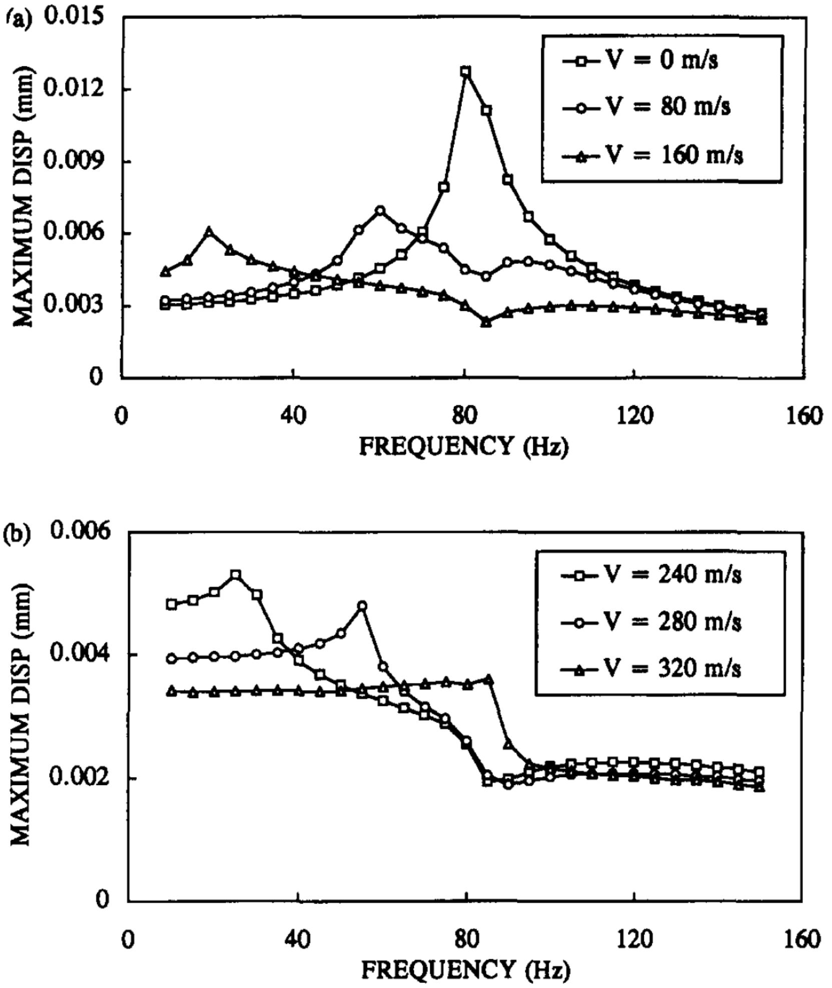

Figure 2. Relationship between maximum deflection, velocity and load frequency when (a) velocity are smaller than V_{cr}; (b) velocity are higher than V_{cr} (where V_{cr} = 195m/s) [6]

Based on the data above, it is observed that the dynamic effects as a function of loading frequency do affect the deflection behaviour of pavements.

3. Testing Methodology – Four Point Bending Test

As discussed, the complexity of characterising fatigue life does not only lie on the numerical properties to be considered, but also includes the various testing methods available. In general, two predominant form of testing are most common, first, the indirect tensile configuration and second, the flexural beam configuration. Neither configuration provides a realistic representation to actual pavements however, recent work by Yeo [7], have shown a better correlation between flexural beam and in service pavements. This paper has therefore utilised the four point bending test.

Sufficient to say, the fatigue data of specimens are limited due to countless challenges of tests. Table 1 below therefore presents a discussion on each consideration applied to the test to isolate or control the assessment of dynamic effects:

Table 1. Testing Configuration for Beam Fatigue Test

Testing Configuration	Discussion
Duration of test	Austroads [3] have identified three stages of fatigue test, i.e. an initial stage, an effective fatigue life stage, and an equivalent granular stage. The longer the duration of the test, the higher the propensity to cause permanent deformation. Specimens used by the author for fatigue life characterisation has been used. Upon achieving a resilient state without undergoing fatigue damage, specimens are tested for an additional 1200 cycles to provide sufficient data to assess the dynamic effects
Loading Shape	Haversine load patterns are believed to be the most representative of traffic loading and have been adopted as seen in Figure 2 above.
Loading Type and Magnitude	The applied load may be a constant strain or constant stress. Realistically, load varies based on the thickness of the overlying pavement and the type of vehicles. Austroads [3] have identified a strong relationship between strain and fatigue life, the constant strain setting has been used. 75$\mu\varepsilon$ has been selected, representing typically 65% of the strain at break of cemented basecourse where appreciable damage is limited for 1200 cycles.
Rest Periods	Rest periods are the pause between successive loads and are important to the analysis of asphaltic materials as healing can potentially occur between applied loads. However, no literature has suggested that healing occurs in cemented material within the timeframe of the test, as the rehydration of broken bonds takes a much longer period and requires sufficient moisture to occur. No rest periods have been allowed with loads applied successively. This also assists in shortening the testing duration.
Size of Specimen	The size of quassi-brittle materials play an important role in the propagation of cracks, a mechanism closely related to fatigue development. With cement treated pavements typically built to 150 – 250mm thick and maximum aggregate sizes of the cement mix 35mm, the ideal specimen size would be at a minimum of 100mm x 100mm in cross section. Specimens measuring 390mm (L) x 63mm (W) x 50mm (D) are prepared for this test due to the limitations of the testing rig available.
Laboratory Compaction / Specimen Preparation	There is no current standard methodology to fabricate beams used for flexural beam tests. An in-house mould has been prepared and specimens are hand compacted with a modified Proctor compactor to MMDD of 2.35 t/m^3 at OMC.
Cement Content	Typical cement treatment for cement treated basecourse material ranges from 2% to 4% content by mass. Specimens with 2%, 3% and 4% cement content are produced and tested.

With the above testing configurations controlled, a laboratory test is undertaken to assess the effects of varying frequency. The loading frequency is varied for 4Hz, 10Hz and 100 Hz to provide a data range for assessment.

4. Equipment and Materials

The Four Point Bending Test Fixture for UTM fitted to the IPC Global Repeated Triaxial Load Test for asphalt materials available at the Curtin University Pavement Research Centre is used for the analysis as shown in Figure 3 below.

Figure 3: IPC four point Bending test rig

The test measures the flexural stiffness of a specimen when applied with a strain, where the flexural stiffness, S, is given as,

$$S = \frac{\sigma_f}{\varepsilon}$$

Crushed rocks sourced from Western Australia which meets Main Roads Western Australia (MRWA) Specifications 501 [8] for aggregates are used for this experiment. Cement Type General Purpose (GP) conforming to Australian Standards AS372 is used for stabilisation and are mixed dry to the specimen prior to the addition of water.

5. Results for Dynamic Test

A typical result for a specimen with 2% cement content by mass is shown in Figure 4 below. Figure 4 presents the relationship between flexural stiffness under the three different loading frequencies applied for up to 1200 cycles undertaken after completion of fatigue tests. It is noted that a significant amount of noise is experienced for lower frequency testing, which can be potentially attributed to the difficulty of the pneumatic system to maintain a constant pressure with high rest periods. Also, to better visualise the results, an accumulative average line is shown on the scatter to determine whether any appreciable damage is still being absorbed by the specimen and to quantify the impact of the varying frequency.

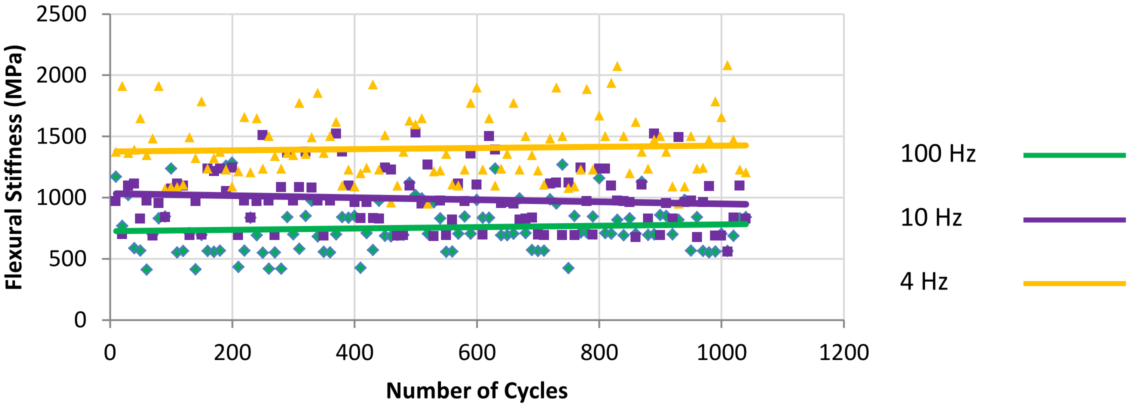

Figure 4: Typical specimen under 4Hz, 10Hz and 100Hz applied strain frequency

A distinct reduction in flexural stiffness, or stress required to achieve a constant strain, is observed from Figure 4 above. This observation is summarised along with specimens with 3% and 4% cement content by mass in Figure 5 below.

Figure 5 shows the results plotted on a logarithmic scale on the x-axis (frequency). It can be seen that a linear relationship exists between log-frequency and flexural stiffness, which suggests that a semi log relationship occurs between load frequency and flexural stiffness. Generally, the increase in frequency results in the reduction of flexural stiffness, indicating that the pavement is weaker and that a lesser load is required to induce a similar amount of strain. This in turn suggests that faster vehicular speed would induce more damage as discussed previously.

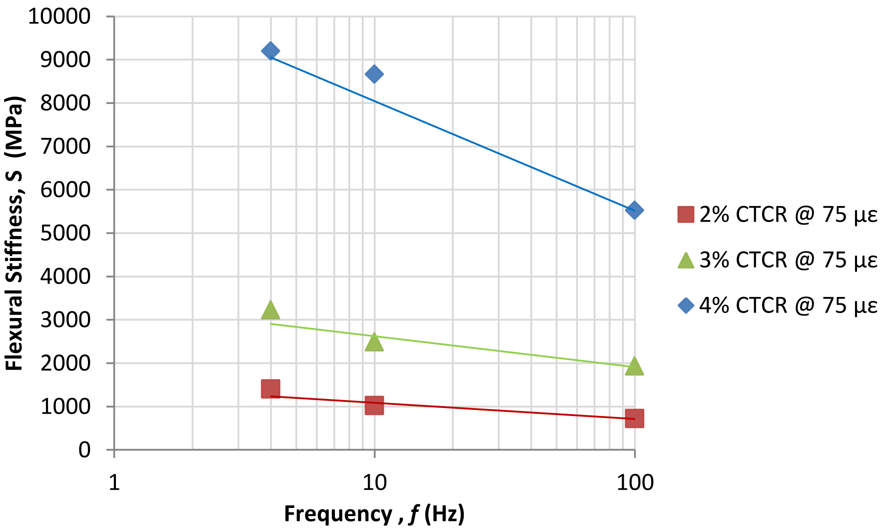

Figure 5: Flexural stiffness vs. frequency of applied strain

The data above also means that loading frequency affects the testing regime for fatigue and an assessment on what best represents traffic loading has not been addressed in this paper. This ambiguity also implies that the laboratory works may not yield reliable data for pavement testing. Future studies will be required in order to more confidently ascertain the implications of load frequency to pavements.

6. Conclusion

This paper has presented evidence to support that the increase in loading frequency will result in reduced stiffness, signifying the detrimental effects of vehicular frequency on pavements. The results are however indicative and the data do not provide a quantitative measure for pavement design.

Instead, the data provided in this laboratory investigation points out that ambiguity exists in the appropriate loading frequency to be used. Further studies are required in order to undertake laboratory investigations that are capable of providing meaningful results.

7. References

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