Fatigue cracking behaviours on Cement Treated Crushed Rock

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ABSTRACT

Fatigue cracking is considered to be one of the most important types of distress affecting the performance of flexible pavements on major highways. This report analyses the results of a laboratory study of the static and fatigue response of a typical Western Australia cement treated base (CTB) to evaluates its mechanical parameters i.e. flexural strength, flexural stiffness and tensile strains. Five different series of cement content were evaluated in the mix of 1%, 2%, 3%, 4% and 5%. Two major types of testing were conducted for the purpose of this study, i.e. Flexural Fatigue Tests (dynamic loading) and Flexural Beam Tests (static loading). The flexural fatigue tests were carried out with strain control mode. From the tests, the flexural stiffness for each specimen was calculated. The flexural stiffness was obtained from maximum tensile strains on the bottom of the specimens. The outcomes of the paper are as summarised as follow:

First, 1% to 3% CTB was found out to be classified as modified material while 4% and 5% CTB are categorized as stabilised materials. Second, fatigue cracking phenomenon can be seen in stabilised materials (4% and 5% CTB) while other types of distress may affect the behaviour of modified materials (1 to 3% CTB). Third, 4% cemented material is observed to be the most suitable material to perform under fatigue loading conditions. Fourth, a series of recommendations are presented for further research i.e. the Flexural Fatigue Test be conducted at a suitable (lower) strain value instead of the 400 με magnitude used in this research.

Keywords: Fatigue cracking behaviours, cement treated crushed rock.

1 INTRODUCTION

Fatigue cracking is considered to be one of the most important types of distress limiting the performance of flexible pavements on major highways. Stabilising materials with cement is an attractive option for improving the strength and durability of aggregates to be used as base course. The problem with this material is that they are very brittle in nature and sensitive to overloading. Since overloading always occurs, one has to take this into account when designing pavements with cement treated materials. Well performing pavements can only be designed when appropriate transfer functions such as fatigue relationships are available. Unfortunately the knowledge in fatigue behaviour of cement treated materials is not widely known at the moment. The overall purpose of this paper was to describe the fatigue behaviour (fatigue cracking and fatigue life) for cement treated materials to be used as a base course.

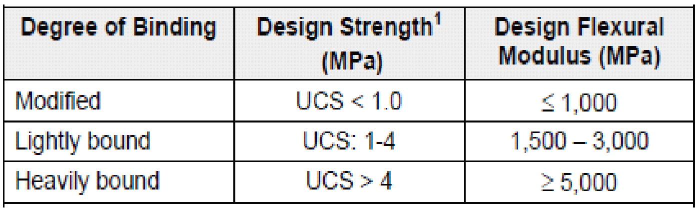
2 BACKGROUND

The base course is the main focus in this paper. From a structural perspective, the base course is the most important layer for it distributes the applied surface loads to ensure that the bearing capacity of the sub-grade is not exceeded. Increased traffic loadings exert pressure on pavements which leads to a shorter service life. Therefore understanding the primary failure criterion of flexible pavement, the fatigue cracking behaviour, is very important.

The treatment method used to improve the base course of the flexible pavement in this study was cement stabilisation, which the end product is widely known as cement treated base (CTB) materials (see Figure 1). It is composed of crushed rocks, cement and water which are compacted under controlled conditions of moisture content, cement content and grading conditions. Subsequently, they were cured for 28 days prior to testing.

According to Austroads [3], CTB materials can behave as a bound or unbound granular material. The level of binding is determined by the amount of binder added to the mix, thus it is essential to find out the correct proportion of cement to be blended with crushed rock materials to achieve the required purpose of a pavement. Bound material is typically formed from the treatment of larger amounts of binder to the base course layer. This level of binding is also termed as "stabilised" and the materials can be classified as "lightly bound" or "heavily bound" as shown in Table 1. When smaller amounts of cement are added into a CTB mix, it may still behave as an unbound granular material with insignificant development of tensile strength and fairly low of flexural modulus values (refer to Table 1). This form of treated material is classified as a "modified material". The range of flexural modulus or stiffness of modified and stabilised cemented materials can be seen in Table 1.

Table 1: Modulus for Cemented Materials (Vorobieff(4))



Degree of Binding	**Design Strength[1] (MPa)**	**Design Flexural Modulus (MPa)**
Modified	UCS < 1.0	≤ 1,000
Lightly bound	UCS: 1-4	1,500 – 3,000
Heavily bound	UCS > 4	≥ 5,000

Figure 1: CTB Specimens

NDT Resource Centre [5] stated that ultimate fatigue failure takes place in three stages, crack initiation; stable crack growth; and rapid fracture. First, crack initiation occurs after large numbers of cyclic loadings that lead to disruption near surface stress concentrations. Second, stable crack growth takes place when tiny (initial) cracks start to join and form a bigger crack. As the repetitive loadings continue, the cracks will continue until at some point, the whole structure cannot support the load resulting in the third stage, a rapid fracture.

The overall purpose of this study is to describe the development of fatigue cracking for cement treated bases (CTB) used for road construction. The problem with cement treated materials is that they are susceptible to fatigue failure, a phenomenon not well understood. There is a lack of information and knowledge of the fatigue performance of cement treated base results in low performing roads. The objectives of this project are to:

- establish the delineation point between modified and stabilised materials of different CTB with varying cement content based on the fatigue cracking behaviour;

- analyse the fatigue behaviour of (CTB) with different cement contents;
- determine a best fit for purpose CTB mix design to be used in base course construction in flexible pavement to achieve higher fatigue life;
- study the relationship between the mechanical parameters of CTB (flexural strength, flexural strength, tensile strain, etc);

3 LABORATORY RESULTS AND DISCUSSION

Two major types of testing were conducted in the study, Flexural Beam Tests (static loading condition) and Flexural Fatigue Tests (dynamic loading condition). First of all, samples preparations were conducted to create 30 specimens of CTB materials ranging from 1% to 5% cement. After a 28 days curing period, 15 CTB specimens (1 to 5% cement content) were tested by using Flexural Beam Test machine and 5 CTB specimens (1 to 5% cement content) were tested by using Flexural Fatigue Test machine.

3.1 Analysis of the flexural beam test results – static loading condition

This test was conducted at loading rate of 1 mm/minute and carried out in accordance with AS 1012.11-2000. Its objective was to evaluate the relationships between the mechanical parameters of CTB (flexural strength, flexural modulus and tensile strain) under static loading - the relationship was observed through the R-squared value. The results from the test are summarised in Table 2.

Table 2: Summary of the Correlations of CTB's Mechanical Parameters

No	**Variable 1**	**Variable 2**	**R square relationship**	
			R-square	**Relationship**
1	Tensile strain	Percentage of cement content	0.1817	None
2	Flexural strength	Percentage of cement content	0.9692	Strong
3	Flexural strength	Tensile strain	0.1309	None
4	Flexural strength	Flexural modulus	0.8746	Strong
5	Flexural modulus	Percentage of cement content	0.9051	Strong
6	Flexural modulus	Tensile Strain	0.0014	None
7	Flexural modulus	Applied load	0.8718	Strong

From Table 2 the following observations are derived:

1. There is no relationship between tensile strains with an increase of cement content ($R^2 < 0.25$). From this particular study, it can be concluded that the data is inconclusive to support any apparent optimal cement content to maximize strain at break (low R-square value). This is a subject of considerable interest for research at a future date.

2. A strong linear correlation exists between the flexural strength with the increase of cement content ($R^2 > 0.75$). The results show that there is a significant increase in flexural strength with increasing cement content.

3. There is no linear relationship between flexural strength and tensile strain ($R^2 < 0.25$). It is a matter of interest to examine the relationship between these parameters to try to find an opportunity to develop new fatigue relationships. From this study, it can be concluded that flexural strength may not be strongly related to tensile strain.

4. A strong linear relationship exists between the flexural strength and the flexural modulus, with a highly significant R-squared value ($R^2 > 0.75$). From this study, the flexural strength appears to be significantly dependent on the flexural modulus. It is recommended that further investigation be conducted to investigate the implications of this finding.

5. There is a strong linear relationship between the flexural modulus and cement content ($R^2 > 0.75$). To determine whether the flexural modulus of cemented materials is influenced by binder content, CTB were tested by using Flexural Beam Test with varying cement content using a total of 15 specimens. These indicate that the flexural modulus of these materials is highly influenced by variations of binder content. The results for these cemented materials show a significant increase in flexural modulus when the cement content is increased from 1% to 5%. The magnitude of flexural modulus increase ranged from 23% to 60%.

6. There is no linear relationship between the flexural modulus and the tensile strain, as shown with the low R-squared value ($R^2 < 0.25$). Some fatigue equations are based on strain while others are based on stress. It is a matter of interest to examine the relationship between those parameters to try to find an opportunity to develop new fatigue relationships. In the process of evaluating the relationships of those parameters, the CTB specimens were analysed based on tensile strain (taken at 95% load) against flexural modulus. From this particular study, tensile strain was found not strongly related to the modulus.

7. A strong linear relationship exists between the flexural modulus and the applied load, as shown with a high R-squared value ($R^2 > 0.75$). From this particular study, it appears that the flexural modulus is significantly related to the applied loads as it increases linearly with the increase of applied loads.

3.2 Analysis of the flexural fatigue test results – dynamic loading condition

This laboratory testing involved the Flexural Fatigue Tests machine to analyse the fatigue cracking behaviour of CTB specimens with different cement content (1% to 5%), to determine the material classification (modified or stabilised) and the best proportion of cement content to be added into the mix design.

A hydraulic testing machine applied repetitive loads to the beam samples and measured the resulting deflection using Linear Variable Displacement Transformers (LVDT). It applied a repetitive Haversine loading at 10 Hz frequency. This fatigue testing was conducted in a controlled strain mode where the strain was maintained at 400 microstrains and the stress was allowed to vary. This test was a derivation from the asphalt bending test; AG:PT/T233.

Alderson(6) highlighted that specimens reached failure (end of its fatigue life) when their flexural stiffness was reduced to half its initial flexural stiffness (E_i) or the number of load repetitions equals to 1 million cycles of loading.

3.2.1 Evaluation of fatigue performance - 1 to 5% CTB

Figure 3 illustrates the fatigue performance in terms of the relationship between the flexural stiffness and loading cycles for 1 to 5% CTB in a log-log scale. From this figure, it can be seen that CTB with a cement content of 1% to 3% has a low flexural stiffness values (less than 1,000 MPa) and is classified as a modified material (as discussed in Section 2). It can also be seen that stiffness values of 1 to 3% CTB seem fairly constant under repetitive loadings throughout the test, i.e. the reduction in stiffness throughout its fatigue life is low.

It is, however, noted that 1% CTB showed traces of fatigue susceptibility (significant reduction in stiffness from the pre-cracked stable crack growth phase – see Table 3). This might have happened due to the very small cement content which caused the specimen to behave purely as an unbound material thus being too fragile for the test. The material possibly cracked even before the testing commenced reflecting real life situations where 1% cemented materials behave generally as unbound materials during construction. From the study, it can be concluded that 1 to 3% CTB are classified as modified materials (see Table 3) and fatigue cracking is not their limiting distress mode.

From Figure 3, it can be seen that there is a huge increase in flexural stiffness value from 3% to 4 % CTB. It shows that 4% and 5% have high flexural stiffness values, thus they should be classified as stabilised materials (see Table 3). 4 and 5% CTB (stabilised materials) show a significant reduction in flexural stiffness from the crack initiation phase to the stable crack growth phase, as well as demonstrating a phenomenon exhibited distinctively by fatigue susceptible materials. From this particular study, it can be concluded that fatigue cracking phenomenon only occurs in stabilised materials (4 and 5% CTB).

The flexural stiffness of a 5% cemented material shows the most significant drop during the crack initiation phase. It contains the highest cement content of the specimens prepared leading to a greater potential to undergo cracking. A stiffer layer generates larger tensile strains at its bottom layer which leads to increased cracking. The specimen is thought to have suffered severe cracks during initial loadings when the flexural stiffness started to drop drastically. A summary of the flexural stiffness values during the 3 stage fatigue failure of 1 to 5% CTB can be seen in Table 3.

Figure 3 shows only two stages of the fatigue failure; the crack initiation and the stable crack growth phases. A longer test duration is required to observe the behaviour of CTB at the rapid fracture phases, otherwise, extrapolation of data can be carried out to predict the flexural stiffness of CTB specimens at this phase. This method was employed by substituting 1 million loading cycles (the number of load repetitions to failure) into the fatigue relationship equation derived (as discussed in Section 4.2). Refer to Table 3 for a summary of all the stages of fatigue failure of 1 to 5% CTB obtained from this study.

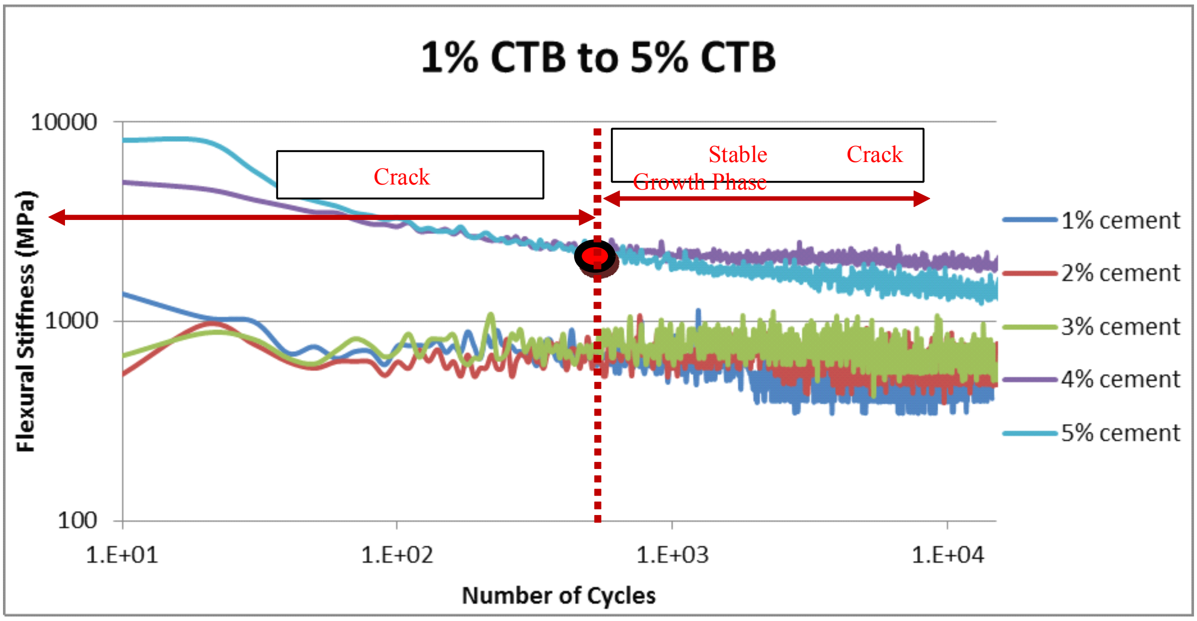


Figure 3: The Fatigue Performance of 1 to 5% CTB

Table 3: Summary of the Fatigue Phases Failure of 1 to 5% CTB

Materials	**Flexural Stiffness (MPa)**			**Material Types Classification**
	Crack Initiation Phase	**Stable Crack Growth Phase**	**Rapid Fracture Phase**	
CTB (1% cement)	650	550	286	Modified
CTB (2% cement)	583	575	571	Modified
CTB (3% cement)	657	550	523	Modified
CTB (4% cement)	2,640	1,800	1,433	Stabilised
CTB (5% cement)	2,684	1,500	1,300	Stabilised

3.2.2 The Fatigue Life of CTB Samples

This section provides a prediction of fatigue life of CTB based on the fatigue relationship equation derived from the loading cycles vs. flexural stiffness graph (N-S graph) from the Flexural Fatigue Test. As discussed in Section 4.2, the failure of a pavement is defined when the flexural stiffness of the specimen is reduced to half the initial flexural stiffness. Thus, the prediction of fatigue life of the material can be calculated by substituting half of the initial stiffness (FS) into the fatigue relationship equation available in Table 4. It should be noted that the values of initial stiffness were obtained from Table 3, in the values during the “pre-cracked phase”.

Table 4: Fatigue Life of 1 to 5% CTB

Material	**Half of the initial Flexural Stiffness (FS) (MPa)**	**Fatigue Relationship**	**Predicted Fatigue Life (N)**
1% CTB	325	$N = 5E + 10\ FS^{-2.618}$	13,270
2% CTB	291.5	$N = 2E + 10\ FS^{-2.153}$	98,779
3% CTB	328.5	$N = 2E + 23\ FS^{-6.708}$	2,630,939
4% CTB	1,320	$N = 7E + 47\ FS^{-13.52}$	1,901,312
5% CTB	1,342	$N = 2E + 23\ FS^{-6.115}$	11,213

As discussed in Section 4.2.1, 1 to 3% CTB are classified as modified materials while 4 and 5% CTB are classified as stabilised materials. From this part of the study, it can be observed that 3% CTB has the best fatigue life (2,630,939 loading cycles) for modified materials. This suggests that fatigue is not the dominant distress mechanism for modified materials (1 – 3% CTB) and that they will perform as an unbound granular material in service.

Four percent CTB displays the best fatigue life (1,901,312 loading cycles) for stabilised materials, the best performing CTB mix design, as it has a higher flexural strength but lower reduction in stiffness. Five percent has a low fatigue life because it is very brittle (high flexural stiffness), and cannot sustain fatigue loading.

4 CONCLUSSIONS

In conclusion, reflections on the objectives set out in Section 3 of this report are discussed below.

(1) Under fatigue loadings, CTB with cement contents ranging from 1% to 3% are categorised as modified materials as their average flexural stiffness has a value of less than 1,000 MPa. Four percent and five percent cemented materials are categorised as lightly bound materials as their average flexural stiffness values ranged from 1,500 MPa to 3,000 MPa. There is a significant increase in flexural stiffness from the modified to stabilised materials.

(2) The flexural stiffness values of modified materials (1 to 3 % CTB) were considerably low (less than 1,000 MPa) and moderately constant throughout the test. The reduction in stiffness of these materials was not significant. From this particular study, it can be concluded that modified materials are not limited by fatigue loading, i.e. it is not the dominant distress mode. Other types of distress mode may limit the performance of modified materials (1 to 3% CTB), therefore further research is required.

Stabilised materials (4 and 5% CTB) have a high flexural stiffness from 1,500 MPa to 3,000 MPa, however, stiffness values decreased signficantly during itntial loadings thus the stabilised materials exhibit the behaviours of fatigue life development, i.e. the crack initiation phase. Thus the fatigue phenomenon (fatigue cracking) is obvious in these materials.

(3) Although cement is required to be added to base course layers to ensure durability and strength, an excessive amount will lead to a disastrous performance of the pavement (greater cracking). A definite amount of cement, therefore, has to be added to increase pavement performance in terms of fatigue life. From this particular study, 4% cemented materials give the best performance for stabilised materials in terms of fatigue life and flexural stiffness. It has a relatively high flexural stiffness value and its rate of reduction under fatigue loading is low. Therefore, 4% cement is the recommended amount to add in base course construction for a flexible pavement.

(4) There is a strong linear relationship between the flexural modulus with the increase of binder content, with a high R-squared value ($R^2 > 0.75$). Flexural modulus of the cemented materials was observed to significantly increase when cement content was increased from 1% to 5%. Based on the variability and range of the experimental data, there is a poor linear relationship between flexural modulus and tensile strain ($R^2 < 0.25$) but there is a strong linear relationship between flexural modulus and applied load ($R^2 > 0.75$). A strong linear relationship is shown between flexural strength with the increase of cement content, with a high R-squared value ($R^2 > 0.75$). Flexural strength of the cemented materials was observed to significantly increase when cement content was increased from 1% to 5%. The degree of flexural strength increased varied from 7% to 62%. Based on the variability and range of the experimental data, there is a poor linear relationship between flexural strength and tensile strain ($R^2 < 0.25$).

5 RECOMMENDATIONS

The following recommendations for future studies are based on the findings of this project.

1. For further study, it is recommended that the Flexural Fatigue Test be conducted at an amended strain value instead of the 400 $\mu\varepsilon$ magnitude used in this research. The controlling strain

should be selected to prevent the CTB specimens from early and severe cracking and to model more realistic traffic induced strains.

2. The duration of the Flexural Fatigue Test conducted in this study ranged from 15,000 to 800,000 cycles. The short fatigue life (15,000 cycles) could be attributed to the surface of the specimens – some of which were fairly rough. A rough surface will tend to disrupt accurate reading during tests and decrease material's fatigue life. For further studies, it is recommended that specimen surfaces be smoothed prior to testing; with an expectation to run the tests for longer periods and more cycles.

3. For the failure criteria of cemented materials, further investigation of fatigue cracking behaviour is required. It is recommended that Flexural Fatigue Tests be carried out for all specimens up to 1 million cyclic loadings or failure.

4. By comparing the performances of 1% to 5% CTB under fatigue loadings, it was observed that 4% cemented materials gave the best fatigue performance, i.e. it displayed the least reduction in flexural stiffness. It is recommended that further laboratory study be undertaken on other mix designs, e.g. 6%, 7% and 8% cemented materials to investigate their fatigue behaviour under cyclic loadings.

5. Further research is recommended to investigate the effects of clamps on the Flexural Fatigue Test machine. The restraint behaviour of in-service CTB layers should be investigated and related back to a testing procedure that will more realistically model in-service pavements.

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