Development of tensile fatigue criteria for bound materials

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Abbreviations and acronyms

ARRB:	Australian Road Research Board (now known officially as ARRB Group Ltd)
ASTM:	American Society for Testing and Materials (now known officially as ASTM International)
CAPTIF:	Canterbury Accelerated Pavement Testing Indoor Facility
CBR:	California Bearing Ratio
ESA:	equivalent standard axles
IDT:	indirect tensile
ITS:	indirect tensile strength
LVDT:	linear variable displacement transducers
MDD:	maximum dry density
RLT:	repeated load triaxial
TNZ:	Transit New Zealand
UCS:	unconfined compressive strength

Contents

Chapter 3 (cont.)

Executive summary

The purpose of this research, undertaken in 2008–2011, is to develop a methodology from laboratory beam fatigue tests to obtain the tensile fatigue design criteria of aggregates bound by stabilising agents for use in pavement design to guard against cracking and/or a return to an unbound condition within the design life. Several stabilised aggregate mixes were compacted in rectangular moulds (530mm long by 150mm square), and the resultant beams were tested for strength and fatigue lives (see figure XS1below).

Figure XS1 Test setup for measuring flexural beam properties

The testing found that stabilised aggregate beams can be successfully compacted in a rectangular mould with a vibrating hammer resulting in similar strengths (maximum tensile stress) to sawn cut beams at the NZ Transport Agency's test track (Canterbury Accelerated Pavement Testing Indoor Facility) CAPTIF and Australia's Accelerated Loading Facility.

Two repeat flexural beam breakage tests were conducted for all the material mixes tested, but for one material mix (CAPTIF's graded all passing alluvial gravel aggregate with 4% cement), a total of four repeat tests were conducted. Further testing is needed to determine the repeatability of the testing, although with these limited tests, the maximum difference between maximum tensile stress was up to 10%, while the difference between Young's modulus and maximum tensile strain could be as high as 80%. Because maximum tensile stress is a more repeatable measure, it was recommended that a stress-based approach which is readily converted into a tensile strain criterion (because strain = stress/modulus) be considered in any proposed bound design fatigue criteria.

Further research is needed to determine and validate a method of flexural beam testing and design using the results from the beam fatigue tests. As a starting point, the following design approach is proposed.

The results of the beam fatigue testing are varied: the results show that the fatigue life is greater than 1 million cycles if the applied stress is less than 0.4 of the maximum tensile stress. This is a conservative approach, as 1 million cycles were also readily achieved at applied stress levels of 0.5 of the maximum tensile stress, being the same prediction given in the new Austroads pavement design guide. This result could be one point of the design fatigue relationship. Assuming the same power exponent (12) as used by Austroads, the constant *k* in the fatigue relationship (equation XS1) can be determined.

$$N = \left(\frac{k}{\mu strain_{tensile}}\right)^{12} \qquad \text{(Equation XS1)}$$

A sample pavement design was undertaken using this method to determine the constant *k* for the fatigue relationship and it was found that the fatigue lives calculated were higher than those for the assumed relationships given by Austroads.

Fatigue lives for the CAPTIF pavements calculated using the method proposed were found to be less than 100 wheelpasses for the 1% and 2% cement-stabilised sections, and just below 100,000 for the 4% cement-stabilised section. The CAPTIF tests did not crack, but the strain and deflection measurements increased to a typical level for a fully unbound pavement after about 500,000 wheelpasses for the 4% cemented section that was not pre-cracked. CAPTIF supports the results of the beam tests, where a longer fatigue life was obtained for the 4% cemented material, but further field data is needed if any future shift factors are determined to relate beam fatigue life to actual fatigue life in the field.

Several key aspects touched on in this research project need more research, namely:

- repeatability of the beam test
- a methodology for lab curing and associated air-drying to induce or not induce microcracks if deemed appropriate
- further field data to validate and refine the proposed fatigue criteria derived from 40% of the maximum tensile stress and beam modulus.

A stress-based approach which is converted to a tensile strain criterion is recommended because of the large variation in modulus in the tests, particularly the 10-fold differences in beam modulus between the Australian Road Research Board and Pavespec tests, even though the maximum tensile stress varied by only 10%. Designers are encouraged to trial the proposed beam test and associated fatigue criteria, and record any feedback on its use.

Abstract

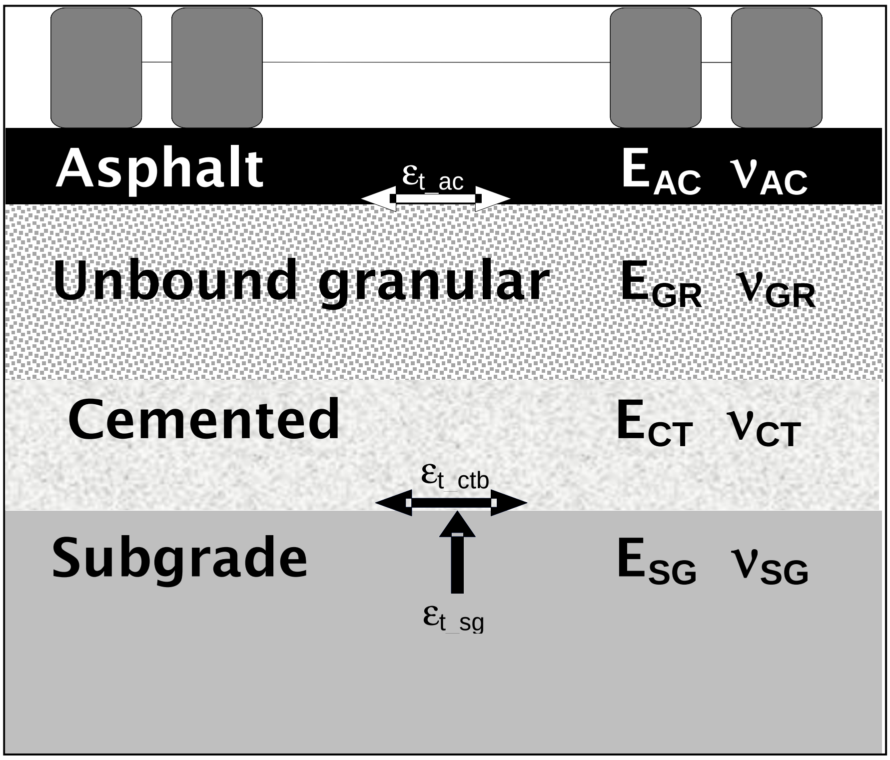
Flexural beam breakage and fatigue tests were conducted in 2008–2011 to determine their relationships with pavement fatigue life and tensile strain for a range of New Zealand materials for use in pavement design of stabilised aggregates. The results showed that the tensile fatigue relationships from several fatigue tests under repetitive loading could be approximated by single flexural beam breakage tests. These relationships resulted in significantly longer pavement lives than the Austraods pavement design criteria but still predicted shorter fatigue lives than what actually occurred at the Canterbury Accelerated Pavement Testing Indoor Facility test track, indicating some conservatism in the approach. Further research is required to validate the tensile fatigue design procedure against actual field data.

1 Introduction

1.1 Background

The Austroads pavement design guide (Austroads 2004) determines the life of cemented layers using a tensile fatigue criterion that relates the number of allowable equivalent standard axles (ESA) to the tensile strain (ε_{t_ctb}; figure 1.1) at the base of the cemented layer. Austroads (2004) suggests a relationship between tensile strain and ESA, but this has never been tested or validated in New Zealand for New Zealand materials.

Figure 1.1 Inputs required for mechanistic pavement design



Potential methods that can be used for determining the modulus of cemented materials include the flexural test, direct tension test, indirect tensile test, longitudinal vibration test and the direct compression test (Austroads 2004); however, the last two tests (the longitudinal vibration test and the direct compression test) are not suitable for determining the fatigue properties of cemented materials (Austroads 2008). The indirect tensile (IDT) test and the flexural beam test have been used in various studies (Otte 1978; Litwinowicz and Brandon 1994; Bullen 1994; Andrews et al 1998).

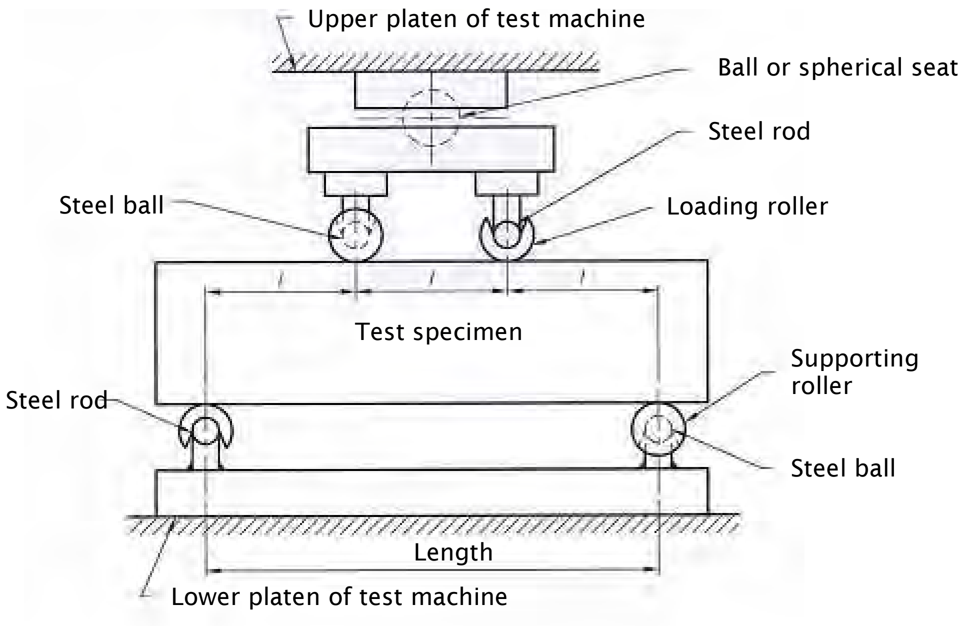
From a review by Yeo et al (2002) of potential methods for routine testing of cemented materials for strength, modulus and fatigue, and the method recommended in Austroads (2004), 'it was noted that both the indirect tensile test and the flexural beam test were suitable for estimation of the strength, modulus and fatigue life of cemented materials' (Austroads 2008).

Because of the lack of established test protocols in Australia to determine the modulus and fatigue properties of cemented materials, Austroads commissioned a significant development project (Austroads 2008).

While beam fatigue tests can be used, currently, no test is suitable for measuring the tensile fatigue characteristics of the aggregates bound by stabilising agents that are typically used in New Zealand. This is because the current standard tensile fatigue test requires 25mm^2 long beams, usually for asphalt materials. These very small beams cannot be manufactured from stabilised aggregates as the small beam will not stay together because of the low cement (or stabilising agent) content typically used in New Zealand. An alternative is indirect tensile testing with a circular cylinder tested on its side and repetitive loading to split the sample, but the literature and Austroads researchers at the Australian Road Research Board (ARRB) Ltd report that this method is inaccurate (because of the very small lateral measurements) and does not reflect the beam bending behaviour that occurs in real pavements. This project will aim to use beams of compacted stabilised aggregates (150mm × 150mm × 550mm long) placed under four-point loading (figure 1.2). The test configuration is the same as is currently used by ARRB for an Austroads project studying the fatigue characteristics of Australian cemented aggregates.

A fatigue test is needed for stabilised aggregates used in New Zealand to ensure that designers consider cracking as a mode of failure in their design approach, which is currently being ignored because of the conservative nature of the Austroads criteria. The test needs to allow for ease of manufacture so that it can be readily conducted as routine testing in design, as such a rectangular foot on a mounted vibrating hammer being used to compact the beam samples in moulds to the required density.

Figure 1.2 Four-point beam testing apparatus



1.2 Research objectives

The objectives of the research project are to:

- trial a method of manufacturing beams for laboratory fatigue testing of bound New Zealand roading aggregates
- validate the repeated load method of testing beams of bound aggregates as a method of establishing fatigue criteria
- develop fatigue criteria for use in mechanistic pavement design in New Zealand using fatigue tests on beams made in the laboratory and saw-cut from Canterbury Accelerated Pavement Indoor Facility (CAPTIF) pavements, and comprising bound New Zealand and Australian roading aggregates
- correlate a simple laboratory test for bound aggregates to indicate the fatigue criteria of each aggregate.

2 Literature review: indirect tension testing of cemented materials

2.1 Introduction

Tensile fatigue testing is generally conducted either with cylinders on their side (IDT testing) or with simply supported beams (flexural beam testing).

IDT testing applies a diametrical vertical load on the side of the cylinder while recording lateral displacement (figures 2.1 and 2.2).

Figure 2.1 IDT testing equipment (photo courtesy of Austroads 2008)

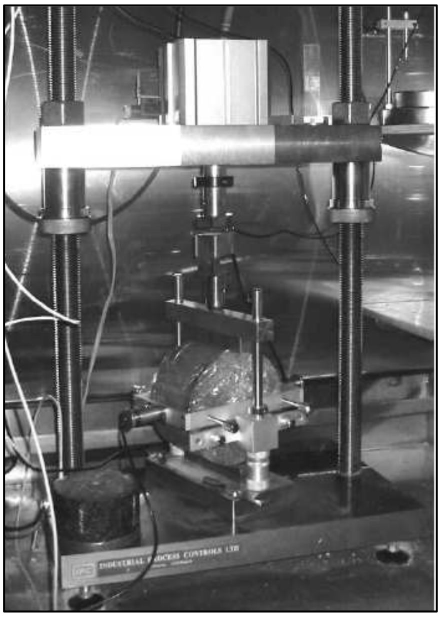


Figure 2.2 IDT equipment: detail (photo courtesy of Austroads (2008)

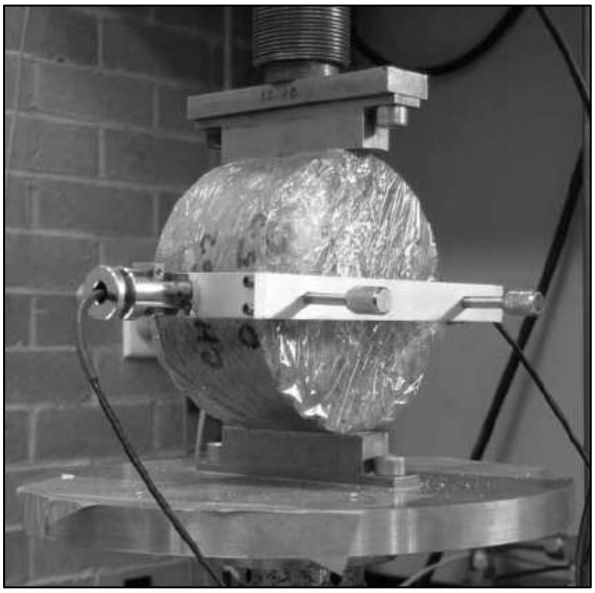
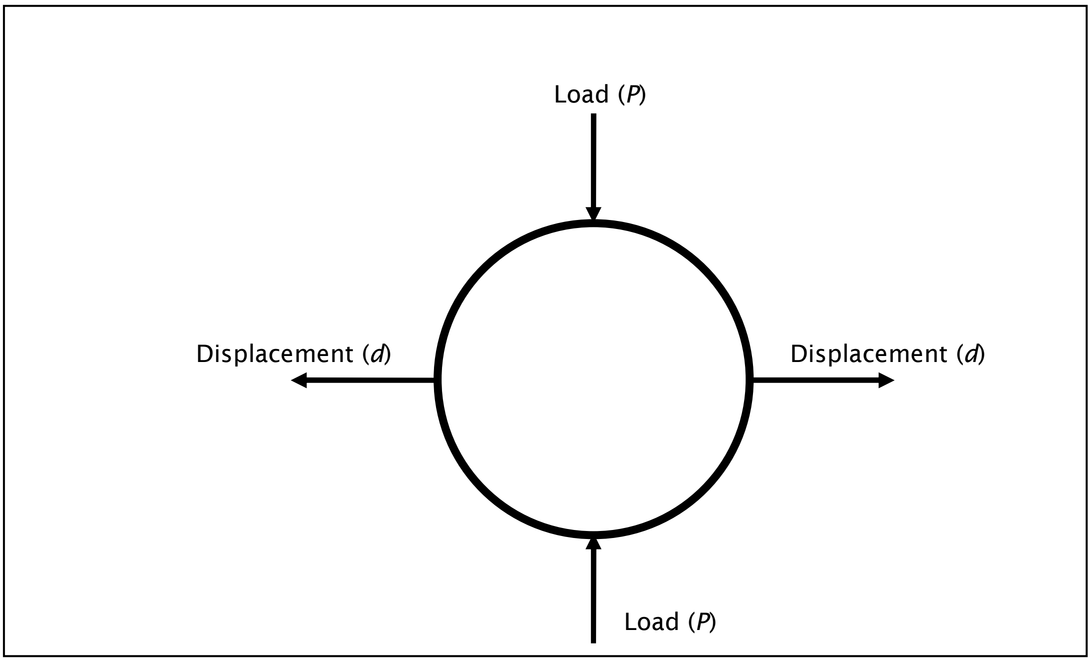


Figure 2.3 Diagram of forces involved in IDT



Prior to fatigue testing, strength tests are initially undertaken by applying a constant increasing load (*P*; figure 2.3) until the sample breaks or no further load can be sustained. The indirect tensile strength (ITS) of the specimen can then be calculated as shown in equation 2.1:

$$T = \frac{2000}{\pi \times D}\frac{P}{t} \qquad \text{(Equation 2.1)}$$

Where:

- T = ITS in megapascals
- P = maximum applied force indicated by the testing machine in kilonewtons
- t = sample thickness in millimetres
- D = diameter in millimetres.

Applying a repetitive load, usually for 100 cycles, allows the resilient modulus to be calculated. The resilient modulus is calculated using equation 2.2:

$$E = P\frac{(\nu + 0.27)}{H \times h_c} \qquad \text{(Equation 2.2)}$$

Where:

- E = the resilient modulus in megapascals
- P = peak load in newtons
- ν = Poisson ratio (assumed to be 0.2 for this calculation)
- H = recovered horizontal deformation of the specimen after application of the load in millimetres

- h_c = height of specimen in millimetres.

The fatigue life is the number of repetitive load cycles required until the modulus is half the initial modulus. However, for cemented materials, the sample ruptures before the modulus is halved (Yeo et al 2008).

2.2 Sample preparation

2.2.1 Significance

Material and sample preparation has a significant effect on the properties and behaviour of cemented materials. Similarly, for specimens prepared for laboratory testing, the material parameters to be measured by the laboratory test will be influenced by the sample's preparation (White 2002). The most appropriate sample preparation procedure would be one that produces laboratory prepared samples which represent the field conditions as closely as possible. White (2007) lists the variables in sample preparation as including the method of compaction, curing conditions and the curing period.

2.2.2 Specimen type

IDT tests are normally performed on specimens obtained from one of the following methods:

- field cores
- laboratory mixed and laboratory compacted samples
- field mixed and laboratory compacted samples.

2.2.3 Specimen dimensions

IDT test specimens are cylindrical in shape. The dimensions of laboratory compacted samples depend on the maximum particle size present. Austroads (2008) specifies nominal specimen dimensions of 150mm diameter and 85mm height for particle sizes up to 40mm. For particle sizes <20mm, specimens 100mm in diameter and 60mm high can be used.

2.2.4 Specimen compaction

In recent times, Australian practice has moved towards the use of gyratory compaction for the preparation of IDT test samples (White 2007). Reasons for this trend include common availability of test apparatus, its ability to produce samples with flat and uniform ends, as well as consistent dimensions and density (Yeo et al 2002).

The Austroads protocols (2008) call for gyratory compaction of samples that have been prepared by first adding the binder to the dry aggregate, followed by 30 minutes' delay between mixing of the ingredients (aggregate, binder and water) and beginning compaction.

Alderson (1999) reported that the compaction method did not have a statistically significant effect on the IDT modulus. This finding must, however, be not be interpreted in isolation because the different compaction methods used in this research did result in significantly different densities, and it was found elsewhere that the modulus was significantly dependent upon density: the modulus increased with increased density (Transport South Australia 1998; White and Gnanendran 2005).

White and Gnanendran (2005) investigated the influence of compaction method and density on the strength and modulus of two host materials, one a reclaimed base material from an existing road and the other a quarried rock, both stabilised with 7% slag-lime binder. They compared gyratory compaction with standard Proctor compaction, and concluded that although modulus increased with increasing density, the compaction method did not have a significant influence on either the unconfined compressive strength or on the modulus, provided the same density was achieved.

2.2.5 Curing of specimens

Curing is the strength gain in stabilised material that occurs after addition of the water as the cement hydrates. Curing method, temperature and duration are all factors having an impact on the strength and the rate of strength gain. Higher temperatures produce more accelerated curing of cementitious materials (White and Gnanendran 2005). Test methods that employ elevated curing temperatures normally do so in order to accelerate aging and are supposedly able to test the material's mature characteristics at an earlier age. In such cases, it is important to understand all the effects accelerated curing will have on the variables under investigation.

Austroads (2008) specifies moist curing of samples, wrapped in wet paper or cloth and doubled sealed in bags, initially for four hours in the compaction mould and then for a total of 7 or 28 days at 23±2°C.

Morkel (unpublished report) investigated the effects of accelerated curing temperature on the strength of concrete cylinders. He compared the crushing strength of cylinders cured for in water for 28 days at temperatures of 4°C, 22°C and 42°C. Using the 22°C samples as the basis, the strength was 12% lower at 4°C, and 12% higher at 42°C.

Angelone and Martinez (1996) investigated the dynamic characteristics of a soil-lime mixture, and reported that the results obtained were similar for samples cured at 50°C for 48 hours and at 20°C for 28 days.

Caution is required when considering very high curing temperatures. Bullen (1994) reported that curing in a very hot environment (100°C) can result in microcracking of the stabilised material, which significantly reduces the modulus. This microcracking, however, is thought to also occur in the field, either deliberately induced pre-cracking during construction or under sustained traffic loads, and a case can therefore be presented for careful controlled temperature-induced cracking in laboratory samples to reflect field performance better (White 2007).

Accelerated curing methods for concrete specimens are described in the American Society for Testing and Materials (ASTM) test method C918/C918M (ASTM International 2007), where the temperature of the curing concrete is monitored until the specimens are tested for strength at 24 hours old. The temperature history of the specimens is used to compute the maturity index at the time of testing. In this procedure, a series of compressive strength values and corresponding maturity indices are used to project the strengths at later ages based on early-age strengths.

2.2.6 Effect of age on IDT strength

Table 2.1 shows the relationship between the seven-day and 28-day IDT strength derived from several literature sources.

The overall trend was increasing strength with age, with the seven-day strength ranging from 57% to 76% of the 28-day strength. Well-established criteria for concrete practice (NZMP3100; Standards New Zealand 1999) put this figure in the range of 65–70%.

Table 2.1 Comparison of seven-day and 28-day IDT strength

Material		7-day IDT strength (MPa)	28-day IDT strength (MPa)	7-day strength as % of 28-day
Description (cement content)	**Source**			
Hornfels (3%)	Austroads 2008	0.51	0.71	73%
Siltstone (4%)	Austroads 2008	0.53	0.81	65%
Red sand (3%)	Hugo et al 2007	0.20	0.29	69%
Red sand (5%)	Hugo et al 2007	0.31	0.54	57%
Red sand (7%)	Hugo et al 2007	0.35	0.55	64%
Reclaimed crushed rock base (4%)	White 2007	0.16	0.27	59%
Reclaimed crushed rock base (7%)	White 2007	0.39	0.51	76%

Horpibulsuk et al (2006) investigated strength development in cement-stabilised low plasticity coarse-grained soils and concluded that the rate of strength development over time is identical for all soils since the strength is influenced predominantly by the hydration process. Using the 28-day strength as a reference, linear regression analysis gave the relationship shown in equation 2.3.

$$\frac{q_D}{q_{28}} = 0.270 + 0.219 \ln D \qquad \text{(Equation 2.3)}$$

Where:

- q_D is the strength after D days of curing
- q_{28} is the 28-day strength ($R^2 = 0.969$).

2.3 Strength tests

The IDT strength test measures the vertical diametric load at failure as well as the horizontal diametric change in diameter. This is converted to an indirect strength by means of the formula given in equation 2.1. A continuously increasing loading rate of 20 ± 2kN/minute is specified by Austroads (2008).

2.4 Resilient modulus tests

2.4.1 Modulus calculation

Modulus is obtained from a stress/strain relationship and, for a given material, depends upon the test configuration (Alderson 1999). The IDT modulus can be determined under the following different test configurations:

- monotonic (static) loading or cyclic (dynamic) loading
- controlled stress or controlled strain conditions.

2.4.2 Static v dynamic loading

The monotonic (static) test typically produces a stress/strain relationship which enables the modulus to be calculated. Depending on the definition of the rupture point on the stress/strain graph, different moduli can be calculated ie the secant modulus or tangent modulus. The modulus obtained from the slope of the initial straight line portion of the graph is normally defined as the tangent (or resilient) modulus (Alderson 1999). The secant modulus is obtained by using the stress and strain values associated with a specified point on the stress/strain curve.

Under cyclic (dynamic) testing, a repeated load is applied of specified stress or strain, and the modulus is calculated from the stress/strain relationship obtained for one or more of these cycles after a specified number of load applications.

2.4.3 Stress v strain control

Dynamic IDT testing can be conducted either as a stress-controlled or strain-controlled procedure. In a strain-controlled test, the applied stress magnitude is adjusted throughout the test so that the resulting strain remains constant. This requires that the stress magnitude typically has to be reduced as the material damage increases. In the stress-controlled mode, the specimen is subjected to a chosen stress regime (function) and the corresponding response of the specimen is measured, either in terms of displacement or strain.

Gnanendran and Piratheepan (2008) investigated the IDT characteristics of lightly stabilised granular materials both under monotonic and dynamic loading conditions. For the monotonic test, they opted for strain control, while for the dynamic loading, they used stress control because of the need to ensure that the material remained within its elastic limit. Austroads (2008) recommends a stress-controlled test, as this is considered the most appropriate simulation of normal repetitive wheel loads, particularly if results are to be correlated with field trials that are conducted at a given axle load.

2.4.4 Load application

Under a repeated load testing regime, decisions have to be taken regarding the type, magnitude and rate of load application. The load magnitude selected is some proportion of the failure load determined during the flexural strength test (refer to section 2.3). Normally, this is not more than 50% of the ultimate failure load. This relatively low value is chosen with the aim of testing for a modulus within the elastic range of the material such that no fatigue damage is induced. Austroads (2008) specifies an upper limit of 40% of the failure load for modulus determination; however, for weakly stabilised materials, a suitable upper limit has been found to be in the order of 30%.

Bullen (1994) found that load rise time did not significantly affect the modulus values returned.

NZS3112 (part 2) (Standards New Zealand 1986) specifies the loading rate for IDT and flexural beam testing of concrete specimens in terms of the rate of stress increase in the most extreme fibres, in the range of 1–2MPa/min.

2.4.5 Strain measurement

The IDT test contains no direct measurement of strain. The formula used to calculate the IDT modulus (equation 2.2) requires measurement of the recovered horizontal deformation (in mm) of the specimen after load removal. This is normally done by means of a linear variable differential transformer (LVDT).

2.4.6 Typical values

Table 2.2 shows typical IDT modulus values obtained from several literature sources. The IDT modulus typically ranges between 14,000 and 24,000MPa, influenced by factors including material type, cement content, curing conditions and age, and sampling method (refer to table 2.2).

Table 2.2 Typical values of the IDT modulus

Source	Material type	% cement	Curing conditions	Curing age (days)	Lab (L) or field (F) sample	IDT modulus (MPa)
Austroads 2008	Hornfels	3%		30	L	23,370
Austroads 2008	Hornfels	3%		57	L	24,260
Austroads 2008	Hornfels	3%		67	F	18,270
Austroads 2008	Hornfels	3%		101	F	16,030
Austroads 2008	Siltstone	4%		29	L	17,580
Austroads 2008	Siltstone	4%		58	L	17,730
Austroads 2008	Siltstone	4%		91	L	21,760
Austroads 2008	Siltstone	4%		28	F	13,870
Austroads 2008	Siltstone	4%		56	F	16,950
Austroads 2008	Siltstone	4%		102	F	14,330
Angelone and Martinez 1996	Cohesive soil-lime	3.5% lime	Moist	7	L	1285
Angelone and Martinez 1996	Cohesive soil-lime	3.5% lime	Moist	28	L	1750

Austroads (2008) notes that samples cured for seven days tend to be brittle, as the cementitious bonds are still forming, and consequently recommend that the curing period for IDT modulus testing be at least 28 days. This recommendation presumably refers to specimens cured in accordance with the specified conditions (moist curing at 23°C).

2.4.7 Relationship between IDT strength and IDT modulus

Gnanendran and Piratheepan (2008) investigated the use of monotonic and cyclic load IDT testing to determine the stiffness characteristics of lightly stabilised granular materials. The specimens were gyratory compacted (95% standard Proctor maximum dry density (MDD) at an optimum moisture content (OMC) ± 1%) and stabilised with slag-lime ranging from 3% to 5%. Curing lasted 28 days.

It was found that the dynamic stiffness modulus (DSM) increases in approximately linear proportion to dry density, IDT strength and the static stiffness modulus. They also determined a relationship between the applied submaximal cyclic load against the maximum horizontal tensile deformation during cyclical load IDT testing. This led them to conclude that cementitiously stabilised materials display an initial rigid behaviour when tested and that this rigidity increased with increasing binder content. They subsequently proposed a new equation for estimating the DSM of lightly stabilised materials and concluded that cyclic load IDT testing could be used reliably to determine the DSM of lightly stabilised materials.

2.5 Tensile fatigue tests

2.5.1 Principles of fatigue testing

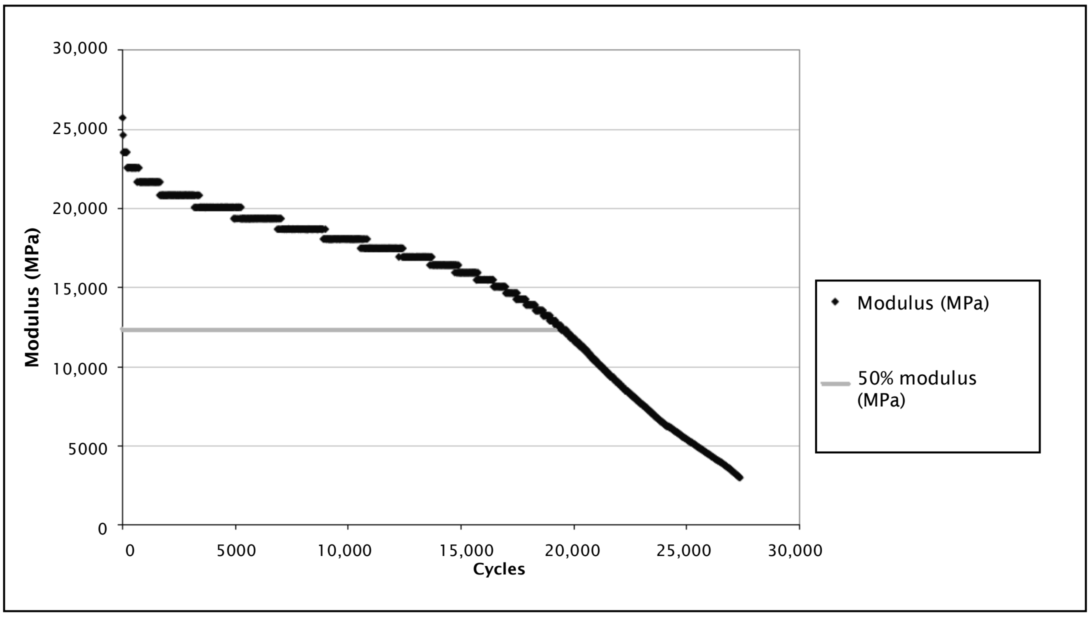
The principle behind cyclic fatigue testing is to apply a repeated load of specific stress or strain to the sample and count the number of load applications required to 'degrade' the material to a pre-determined failure condition (White and Gnanendran 2002)

Factors to be considered during laboratory testing of the fatigue performance of cemented materials include the test method used (eg the IDT or flexural beam test), the degree of load (and hence strain) applied, the frequency of load repetitions, the wave form of load application, methods of measuring stress and strain, the failure criterion applied and the material characteristics (White 2007).

In the field, fatigue failure is characterised by some failure criterion such as the initiation and propagation of tensile cracks on the tension surface of the layer. Eventually, cracks develop to form a continuous fracture surface and the material becomes substantially weakened (Alderson 1999). In the laboratory, an appropriate failure state may be defined in terms of a specified observable behaviour, such as sample collapse; alternatively, it may be defined indirectly in terms of a measurable parameter such as when the material reaches a nominal stiffness or modulus value (eg 500MPa as per Austroads 2008) or when the modulus reaches a certain proportion of a reference modulus (eg 50% of the 'initial' modulus).

During fatigue testing, the modulus of a cemented material decreases with an increasing number of load cycles. A typical result for an IDT fatigue test on a cemented material is shown in figure 2.4 (Austroads 2008; Angelone and Martinez 1996). Using the alternative fatigue state, the fatigue life is generally accepted as having been reached when the sample's modulus equals 50% of the initial sample modulus (White 2007). Therefore Austroads defines the initial modulus as the mean modulus for the first 50 cycles of the fatigue test. Using this 'mean' value helps to counter the effects of test initialisation issues (Austroads 2008). It was found that the load cycles to half the initial modulus were very close to the cycles of failure of the samples for the flexural beam test (Austroads 2008). Austroads also permits the use of a fixed terminal modulus of 500MPa to represent fatigue life.

Figure 2.4 IDT fatigue test determination (adapted from Austroads 2008)



2.5.2 Degree of stress or strain applied

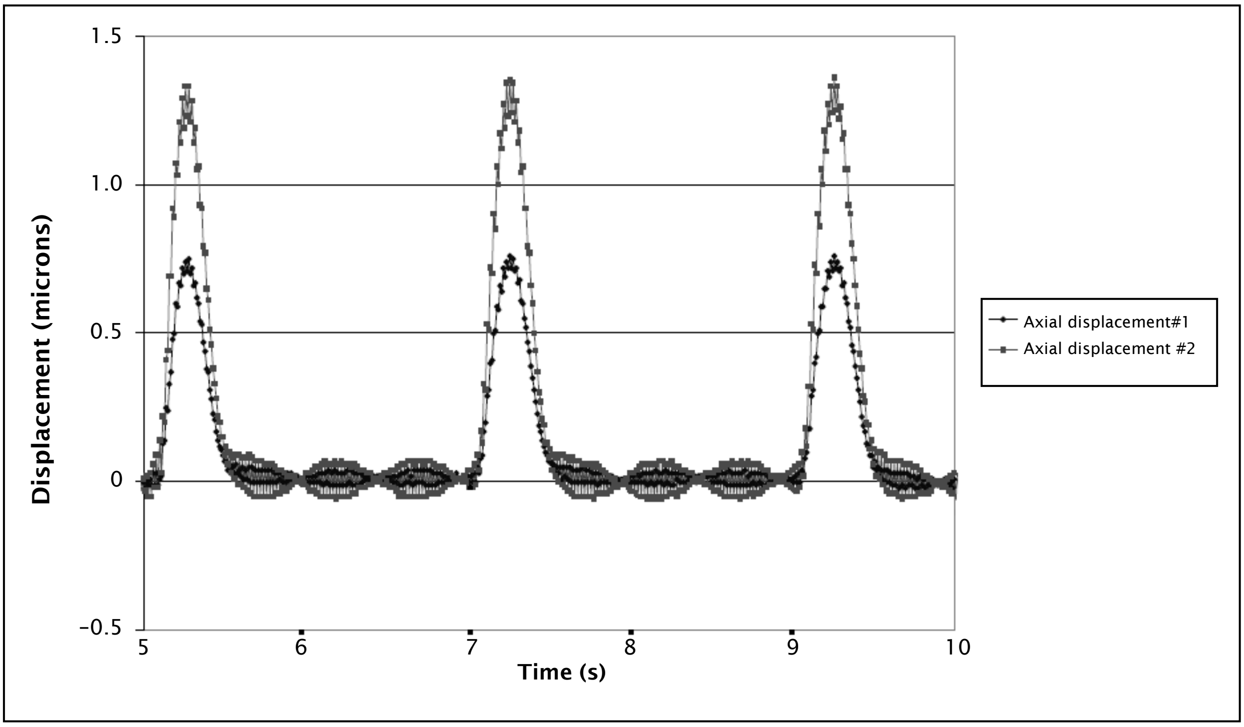
The IDT fatigue test is normally conducted in conjunction with the IDT modulus test, using the same samples that have been used for the latter. The applied load for the fatigue test is typically in the range of 60–90% of the failure load. The load magnitude selected within this range will influence the number of load repetitions required to cause failure of the specimen. At the higher end of the load range (90%), the applied strains are higher and, consequently, the number of load repetitions before failure may be very low, while at the lower end (60%), the strains are low and may require an excessive number of load cycles to bring the sample to failure – it may not reach failure at all if the strain levels are within the elastic limit of the material. It may be required to conduct preliminary tests to establish the appropriate stress/strain parameters to be used for the material in question.

2.5.3 Wave form of load applied and frequency of load repetitions

In all the literature surveyed, the wave form adopted for modulus and fatigue testing was an approximate haversine load pulse. Although the proposed Austroads test protocol (2008) specifies a haversine pulse repetition period of 2 seconds (ie 0.5Hz), the test programme used to develop these protocols used a load frequency of 1Hz initially, but later changed it to 2Hz to reduce fatigue testing time, stating that 'the fatigue response of cemented materials was not considered to be time dependent within the 1Hz to 2Hz cyclic loading frequency' (Austroads 2008).

One issue with the IDT testing of cemented materials under a dynamic loading regime is the signal to noise ratio of the LVDTs used to measure the sample response to loading. The signal to noise ratio is the ratio of the measurement value and the error caused by electrical noise in the readings. It is desirable that the signal to noise ratio not exceed 10. This aspect has more impact as the material stiffness increases and the measured responses decrease in magnitude. In this regard, the flexural beam test typically shows much better signal to noise ratios than the IDT test because of the much larger displacements that occur in flexural beam testing (refer to figure 2.5).

Figure 2.5 Pulse shape and noise from typical IDT and flexural beam testing (adapted from Austroads 2008)



2.6 Discussion of IDT testing

The most appropriate laboratory test to determine the modulus and fatigue characteristics of a material would be one that provides the most reliable and repeatable method, and which can be conducted in a timely and cost-effective manner while yielding a good correlation with field performance. The test method chosen will inevitably be a compromise between these contradictory criteria. Replicating the field boundary conditions, such as moisture content and curing, is also important and perhaps more difficult, as they vary greatly in the field (White and Gnandendran 2002).

Yeo et al (2002) reviewed potential methods for the routine testing of cemented materials and noted the following advantages which favour the use of the IDT test:

- The test equipment suitable for this test is widely available (it is a common test used for asphalt.
- Because the samples used in this test are cylindrical, they are relatively easy to prepare, be it in the laboratory using gyratory compaction or *in situ* by taking field cores.

Bullen (1994) investigated how to determine the resilient modulus of cemented materials using IDT testing and concluded that resilient IDT modulus determination was successful (White 2007).

White and Gnanendran (2002) note that the actual flexural stress state of the material is modelled only approximately in the IDT test.

3 Literature review: flexural beam testing of cemented materials

3.1 Introduction

Flexural beam testing loads simply support beams while recording central deflection on top of the beam (figure 3.1).

Figure 3.1 Flexural beam testing equipment (photo courtesy of Austroads (2008))

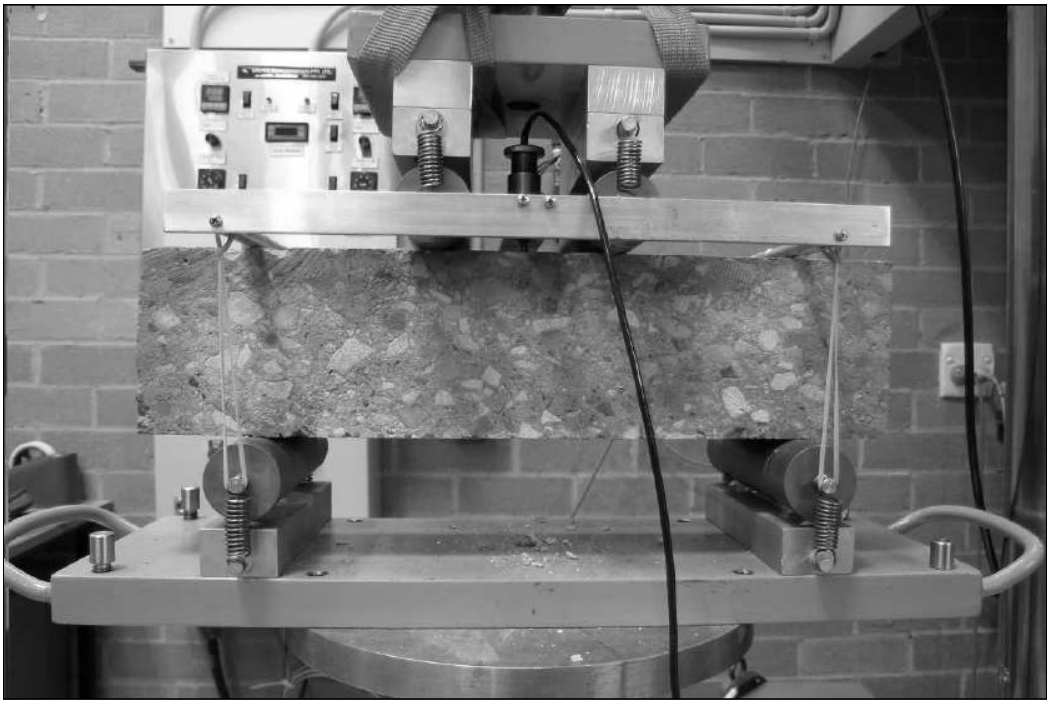
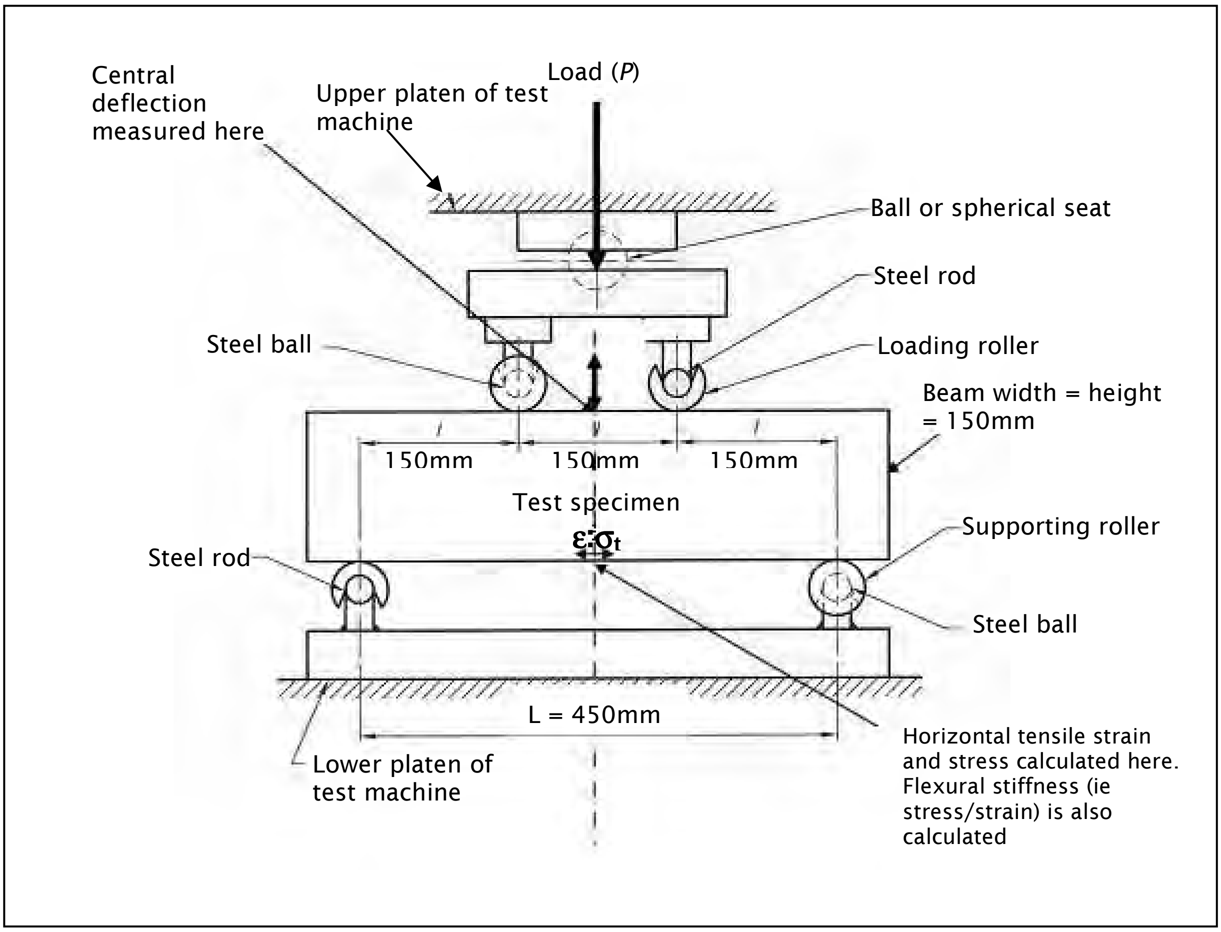


Figure 3.2 Diagram of flexural beam test (note dimensions are examples only; for example, the span can also be 300mm for 100mm x 100mm beams)



Prior to fatigue testing, strength tests are undertaken initially by applying a constant load rate *P* (figure 3.2) until the sample breaks or no further load can be sustained. The strength of the specimen is simply the maximum load *P*.

Applying a repetitive load, usually for 100 cycles, allows the flexural modulus/stiffness to be calculated. The fatigue life is the number of repetitive load cycles required until the modulus is half the initial modulus. Flexural stiffness is calculated using equation 3.1:

$$S_{max} = \frac{23PL^3}{108wh^3\delta} \qquad \text{(Equation 3.1)}$$

Where:

- S_{max} = flexural stiffness in Pascals
- P = peak force in Newtons
- L = beam span
- w = specimen width in metres
- h = specimen height in metres
- δ = peak mid-span displacement in metres.

Following the modulus test, the same specimen is further loaded to determine the fatigue life.

3.2 Sample preparation

3.2.1 Dimensions

The minimum dimensions of lab-compacted beams are dictated by the maximum particle size present. For 20mm maximum aggregate sizes Austroads (2008) uses beams with cross-sectional dimensions of 100mm × 100mm. A minimum span-to-depth ratio of 3 is typically used.

Majumder et al (1999) used beam specimens with cross-sectional dimensions of 102mm × 102mm with a span-to-depth ratio of 5.

3.2.2 Sample types

Beams for the flexural beam test can be produced by laboratory compaction or extracted from the field. Field samples require a procedure which produces undamaged and intact samples. Austroads (2008) describes a fairly successful procedure to saw-cut beam samples from a cement-stabilised pavement layer.

3.2.3 Compaction

The compaction method used for beam preparation influences the mechanical properties of the material in so far as it determines the orientation and distribution of the aggregate particles, and the degree of anisotropy. Little reference could be found in the literature to the comparison of various compaction techniques. Alderson (1999) refers to research work that was done on asphalt and unbound granular materials; both cases revealed a significant difference in the stress/strain properties resulting from applying different compaction techniques. Alderson suggests it is likely this will also be the case for stabilised materials.

The potential for segregation and the edge effects from compaction in a rectangular mould need to be addressed in specimen compaction. For laboratory compacted beams, Austroads (2008) compacts a slab of dimensions such that two test beams can be saw-cut from one slab. Considerable attention is devoted to the mixing and compaction process, with the aim of ensuring uniformity of material distribution and density.

3.2.4 Curing

Austroads (2008) specifies the following curing regime for laboratory compacted samples:

1 following compaction, moist curing for at least 48 hours in the compaction mould (which is sealed to prevent moisture loss)

2 moist curing at 23°C for the entire curing period of either seven or 28 days

3 immediately prior to testing, placing specimens in a moist curing environment (such as a fog room) for a minimum of 48 hours to ensure consistent specimen conditions.

Majumder et al (1999) kept beams and cubes inside airtight polyethylene bags for accelerated curing at a temperature of 50°C.

3.3 Strength tests

3.3.1 Load application

Loads applied for the flexural strength test normally start with an initial seating force (eg 50N) applied for a few seconds, after which a continuously increasing load is applied until the beam fails under flexure.

3.3.2 Effect of age on flexural beam strength

Sources surveyed report an overall trend of increasing strength with age. Where results contradicted this general trend, it was put down to variations in material properties. Table 3.1 shows typical flexural strength results.

Table 3.1 Flexural strength of cement-stabilised materials (source: Austroads 2008)

Material type	% cement	Curing age (days)	Lab (L) or field (F) sample	Flexural strength (MPa)	IDT strength (MPa)
Hornfels	3%	7	L	0.72	0.51
Hornfels	3%	28	L	1.01	0.71
Hornfels	3%	576	L	1.26	n.t.*
Hornfels	3%	29	F	0.97	n.t.
Hornfels	3%	71	F	0.77	n.t.
Hornfels	3%	95	F	0.64	n.t.
Siltstone	4%	7	L	0.73	0.53
Siltstone	4%	32	L	1.13	0.81
Siltstone	4%	616	L	1.06	n.t.
Siltstone	4%	34	F	1.32	n.t.
Siltstone	4%	56	F	1.52	n.t.
Siltstone	4%	97	F	1.40	n.t.

*n.t. = not tested

3.3.3 Relationship between IDT strength and flexural beam strength

For comparison purposes, the IDT strength values are also included in table 3.1. This shows that the flexural strength was consistently higher than the IDT strength, in this instance by a factor of 1.4. NZMP3100 (Standard New Zealand 1999) states that, for a given concrete, the flexure test gives a considerably higher value of tensile strength than the IDT test, and that no direct relationship between them exists. Lim and Zollinger (2004) refer to studies done on the relationship between the compressive strength and tensile strength of cement-treated materials that concluded that the flexural strength of these materials is in the range of 20–25% of the unconfined compressive strength (UCS) and the IDT strength was in the range of 10–15% of the UCS.

3.4 Flexural stiffness tests

3.4.1 Test conditions

Similar to the IDT test, the flexural beam test can be conducted under static or dynamic loading. Austroads (2008) uses a dynamic test and determines the flexural modulus as the average peak stress divided by the average rebound strain obtained during the last 50 pulses of a 100-pulse test. The pulse period is 1Hz (including a 750ms rest period between load pulses) and the magnitude of the load is about 40% of the breaking load determined from the strength test. This load intensity is selected to ensure the beam is not damaged, but is high enough to produce sufficient displacement for accurate estimation of the tensile strain – another factor that this has in common with the IDT test.

3.4.2 Stress level

Considerable variation is found in the literature regarding the threshold level of stress below which it is unlikely that fatigue failure would occur in cemented materials. Scott (1974) found that at stress levels below 60% of the flexural strength, fatigue did not occur within 1 million cycles, although it is possible that fatigue might have occurred if the tests proceeded beyond 1 million cycles. Otte (1978) suggests that although microcracks could start at levels as low as 35%, the material would still be able to withstand about 1 million load repetitions even if the load is increased to 50%. De Beer (1992) later revised Otte's crack initiation criteria to 22%. Shen and Mitchell (1966) examined the properties of both stabilised sand (7% cement) and clay (15% cement), and reported that neither material exhibited fatigue distress at stress levels up to 50% after 1×10^5 load cycles.

3.4.3 Stress v strain control

Alderson (1999) points out that controlled strain tests take considerably longer than controlled stress tests. This is consistent with experimental observations that complete failure or rupture of specimens is less likely to occur in controlled strain tests compared with controlled stress tests, and controlled strain tests require more loading cycles than controlled stress tests to cause the same level of damage when both tests begin at the same stress level (Masad et al 2008). It is important to adopt a consistent test methodology. Alderson (1999) analysed the results of flexural beam tests on three different aggregate types (basalt, rhyodacite and granite) at cement contents ranging from 1.5% to 4%, and established that the modulus obtained under controlled stress conditions was always greater than the controlled strain modulus by an average factor of 1.1. This relationship will, of course, be influenced by the respective damage criteria adopted for the two test conditions.

3.4.4 Measurement of stress and strain

Modulus calculation requires a measure of applied stress and the corresponding strain. It is customary in the flexural test to measure both these parameters indirectly. The stress is calculated by converting the load applied vertically to the beam to a horizontal tensile stress at the bottom using elastic beam theory. Elastic beam theory assumes a linear distribution of stress and strain across the beam's cross-section, reaching maximum values at the extremities of the section. This linearity is not true as the beam approaches rupture (Alderson 1999).

Bofinger (1965) examined the effects of mode of loading (compression, tension or flexure) on the determination of a fatigue limit for a cement-stabilised clay, and found that a better correlation between tensile test results and flexural test results are obtained if the calculated flexural stress is based on a sinusoidal rather than triangular stress distribution. The extreme fibre stress for the sinusoidal distribution is only 75% of that calculated for the triangular distribution.

Scott (1974) evaluated the application of flexural testing to the design of stabilised layers and fatigue performance. One of Scott's findings was that the flexural tensile modulus based upon measured strain was less than the flexural modulus based upon elastic beam theory using the deflection at the centre of the beam.

Typical values sourced for flexural beam test moduli are shown in table 3.2. Considerable variation can be seen in modulus values, ranging from 3000MPa to as high as 19,000MPa. An anomaly appears in the modulus variation as a function with age. The authors (Austroads 2008) attribute this variation to sample location and variations in material properties.

Table 3.2 Typical flexural beam test moduli (source: Austroads 2008)

Material type	% cement	Curing age (days)	Lab (L) or field (F) sample	Flexural modulus (MPa)
Hornfels	3%	28	L	16,560
	3%	579	L	12,490
	3%	30	F	14,740
	3%	71	F	3060
	3%	98	F	3760
Siltstone	4%	32	L	11,030
	4%	71	L	13,350
	4%	616	L	6760
	4%	34	F	9220
	4%	56	F	12,740
	4%	97	F	9530
Basalt	1.5%	N/A	L	9500
	3%	N/A	L	11,600
Granite	1.5	N/A	L	8600
	3	N/A	L	9500
	4	N/A	L	19,000

3.5 Tensile fatigue tests

Areas of cyclic testing that require consideration during laboratory testing include (White and Gnanendran 2002):

- type of test (eg flexural beam, IDT)
- stress versus strain control
- pulse frequency
- wave form

- the cycle of load repetition to adopt as the initial modulus to allow preconditioning
- definition of the point of 'fatigue failure'.

As for the IDT test, fatigue testing of beams is often done in conjunction with flexural modulus tests using the same beams (if undamaged), again using loads in the range of 60–90% of the flexural strength. Austroads (2008) recommends a load intensity of 80% of the flexural strength.

For laboratory tested beams, it is necessary to define a suitable 'end of fatigue life' (failure) parameter. In the absence of an established protocol, Austroads (2008) adopted the end of fatigue life as 'load cycles to reach half initial modulus', which was found to be very close to the cycles of load to ultimate failure. Initial modulus is defined as the average modulus determined from the first 50 load pulses applied to the specimen during the fatigue test.

For modulus and fatigue testing Austroads (2008) specifies a haversine pulse width of 250ms in duration with a 250ms rest between pulses, making a 500ms (0.5 second) pulse period.

The Austroads (2008) project reports a wide of fatigue results at a curing age of up to 28 days. It was found that greater consistency in fatigue results was achieved at higher curing ages. Consequently, Austroads recommends a curing age of more than six months for fatigue testing of cemented materials, citing comparison with the French practice of up to 365 days prior to fatigue testing (Laboratory Central des Ponts et Chaussees 1997). Austroads suggests this practice will also give a more realistic reflection of actual field performance.

Fatigue life modelling is critical to the characterisation of materials in mechanistic design. The aim of the fatigue tests discussed here is to establish a reliable fatigue life model for cementitiously bound materials. The current model adopted by Austroads relates applied strain (*S*) to the number (*N*) of load repetitions leading to fatigue failure in the form of the performance relationship given in equation 3.2.

$$N = \left(\frac{K}{strain}\right)^{LDE}$$

(Equation 3.2)

Where:

- N = number of load repetitions to failure
- K = material constant
- strain = horizontal tensile strain at the bottom
- LDE = load damage exponent.

The factor *K* is dependent upon the modulus of the material, for which a presumptive value is often adopted when more reliable material specific data is lacking. The 1992 version of the Austroads pavement design guide specified a value of 18 for the load damage exponent (LDE). This was reduced to 12 in the 2004 version. Many researches and practitioners have concluded that these values are too conservative when compared to field observations (White and Gnanendran 2002).

3.6 Discussion of flexural beam testing

Austroads (2004) acknowledges that several tests may be used to measure the modulus and fatigue properties of a cemented material but it favours the flexural test because 'it is considered to simulate field stress/strain gradients.' While this is considered to be a reasonable approach for materials with a high modulus (>2500MPa), at lower moduli, the material often does not have enough inherent strength to sustain significant loads in the end-support mode (White and Gnanendran 2002). It is noted that lightly bound cemented materials tend to act somewhat stress-dependently (not fully bound) (White and Gnanendran 2002), a fact that has been supported by repeated load triaxial (RLT) testing of low binder content cemented materials (Symons et al 1996).

The current Austroads fatigue life model (see section 3.5) for cemented materials has been critically examined and its validity questioned, with research continuing to refine the model and further knowledge in this regard (Foley et al 2001; Austroads 2008). Table 3.3 shows typical results reported for the load damage exponent in the sources surveyed.

Table 3.3 Load damage exponent values given for different materials and curing times by various authorities

Source	**Material (cement content)**	**Cure duration data included in results (days)**	**Load Damage Exponent**
Austroads (1992)	–	–	18
Austroads (2004)	–		12
Austroads (2008)	Hornfels (3%)	28–580	7.85
Austroads (2008)	Siltstone (4%)	34–616	6.29
Jameson et al (1992)	–	–	8
De Beer et al (1997)	–	–	6

White and Gnanendran (2002) point out that one significant drawback for flexural beam testing is that the failure can occur in the area of contact between the sample and the test apparatus, which, of course, is affected by local stress concentrations. This highlights the difficulty of simulating actual field support conditions in a laboratory environment. To overcome this problem, trapezoidal beams were used by the Queensland Department of Transport; however, the placement of material and achieving uniform compaction in sample moulds of this shape proved difficult, leading to highly variable results.

4 Literature review: other lab tests to estimate flexural modulus and tensile fatigue

Whether one measures modulus and fatigue behaviour by IDT, by flexure or by other methods, the values determined will vary depending on which of the many test methods is used (White and Gnanendran 2002). The characteristics determined by flexural bending currently seem to be the preferred approach from the perspective of replicating the strain and stress conditions occurring under traffic loads in the field. Because of the greater expense and relative difficulty of the flexural beam test, the modulus is often estimated by means of indirect tests that are easier and less expensive. The UCS is often used for this purpose. This requires a suitable relationship between strength and modulus to be applied, normally of an empirical nature. Published relationships between UCS strength and modulus are known to be unreliable across a large range of binder-host combinations and binder contents (Foley et al 2001). Table 4.1 lists a range of published relationships.

Table 4.1 Other relationships between strength and modulus encountered in literature

Source	Description	Relationship
Austroads AP-T16 (Transport South Australia 1998)	Type GB (blended) cement at 28 days	$E = 1245(UCS) + 300$
Austroads (1992)	Highly cemented crushed rock	$E(\text{MPa}) = 1814(UCS)^{0.88} + 3500$ (UCS in MPa after 28 days)
	Highly cemented natural gravel	$E(\text{MPa}) = 2240(UCS)^{0.88} + 1100$ (UCS in MPa after 28 days)
Austroads (2004)		$E_{\text{FLEX}} = k(UCS)$ k = 1000 to 1250* (UCS in MPa after 28 days)
White and Gnanendran (2005)	Quarried rock with 7% slag-lime	$E(\text{MPa}) = 7300(\text{dry density in t/m}^3) - 11{,}200$
Lim and Zollinger (2004)	Crushed rock 4-8% cement	$E(t) = 4.38w^{1.5}F_c^{0.75}$ $E(t)$ = Modulus of elasticity at time t (psi) W = mixture density (pcf**) F_c = compressive strength at time t (psi)

* Vorobieff (2004) points out that the lower k of 1000 must be used with caution as many binders are slow setting and these binders continue to gain strength after 28 days, making the value of 1000 overly conservative.

** pounds per cubic foot

The RLT test is used for the determination of the ‘resilient’ modulus for various material categories, including asphalt and unbound materials. Referring to work done in other research, White and Gnanendran (2002) noted that when applied to cemented materials, the RLT test produced very highly variable moduli values, and has limited use in the characterisation of cement-treated materials. Symons et al (1996) investigated the properties of stabilised soils using a wide range of soil types and binder types, all stabilised with 4% binder and moist-cured at 23 °C. Their results showed stress-dependent behaviour for this material, with RLT modulus values ranging between 600MPa and 5400MPa at 7 days, and as high as 8200MPa at 28 days.

Smith and Hansen (2003) investigated the effects of a range of blended cement mixtures with a range of host materials. In each case, the binder application rate was 4%. RLT resilient modulus values measured ranged from 7000MPa to 39,000MPa, depending on the host material, the binder blend and the curing age. They investigated the effect of curing age (8, 28 and 91 days) on the modulus, but could not establish a consistent trend. All materials showed an increase in modulus from 8 to 28 days, but, depending on the binder blend and the host material, some mixtures showed increasing modulus with age, but others a decreasing trend between the 28-day and 91-day results.

5 New Zealand flexural beam test development

5.1 Introduction

Flexural beam tests on cemented aggregates are rare – a one-off research project addresses this topic. One of the reasons is because a suitable standard is lacking and manufacturing the beams is difficult. Fatigue testing is also costly and time-consuming because of the need to test at a range of loads, with a new specimen required for each load. Austroads has, however, recently completed a research project on beam fatigue testing (Austroads 2008) on Australian cemented aggregates. The Austroads research prompted the methodology chosen for this project to gather data on New Zealand cemented aggregates. A significant difference between New Zealand and Australia is the size of the aggregates. In New Zealand, the maximum size aggregate is 40mm; in Australia, it is 20mm. Therefore, most tests in Australia are designed for the smaller aggregate with smaller specimen sizes. The beam test used by the Austroads researchers (2008) is no exception, with their beams being 350mm long by 100mm wide and 100mm high. It is recommended that the height and width (or diameter) be at least three times the maximum particle size for compaction and edge effects. Hence, a larger beam is required to test the New Zealand cemented aggregates.

5.2 New Zealand beam manufacture

The draft Austroads test method for flexural beam testing reported in *Austroads technical report AP-T101/08* (2008) allows for two different beam sizes. The larger beam was chosen for testing 40mm cemented New Zealand aggregates, as shown in figure 5.1. Austroads recommends saw-cutting the beams to the required dimensions after slab compaction, although compaction in a mould with a rectangular foot is mentioned as being acceptable, provided the edges remain intact. As a slab conpactor large enough to compact the 530mm long by 150mm square beam is available in New Zealand, it was decided to compact the beams in a mould.

Pavespec Ltd's compaction frame with a rectangular foot (figure 5.2) was used to enable accurate control of the finished compacted height and thus the density (as the dry weight of material is controlled). Cemented aggregate was compacted into a 530mm long by 150mm square beam mould with removable sides and base plates as detailed in figure 5.1.

Figure 5.1 Beam mould used for the 530mm × 150mm × 150mm beams

Figure 5.2 Compaction frame with vibrating hammer and foot for beam manufacture

A 4% cement-stabilised aggregate mixture as used at CAPTIF was used to trial the beam manufacturing process using a mould and a vibrating hammer with a rectangular foot. The method of compaction was considered a success, provided some care was taken over the compaction of the final surface layer and that the mould was lined with plastic film. Figure 5.3 shows the final compacted beam after curing for five days in the mould and sealed in a plastic bag in the 21°C concrete curing room.

Figure 5.3 Compacted and cured beam ready for testing

The initial compacted beam was placed in the Stevenson's concrete beam breaking machine (figures 5.4 and 5.5) as, at this stage, Pavespec's machine with electronic control and measurement was not available. This breaking test simply recorded the maximum load at breaking point with the rate of loading not being well controlled. A maximum vertical load of 10.38kN or a flexural tensile strength at breaking of 1384kPa was recorded for this test, which, on discussion with the Austroads researchers, was considered a typical result. This confirms that the method of manufacture produced sound and strong beams. As part of this study, repeat testing will determine the repeatability of beams compacted in a mould.

Figure 5.4 Initial beam breakage test, with the beam before breaking

Figure 5.5 Initial beam breakage test, with the beam at breaking point

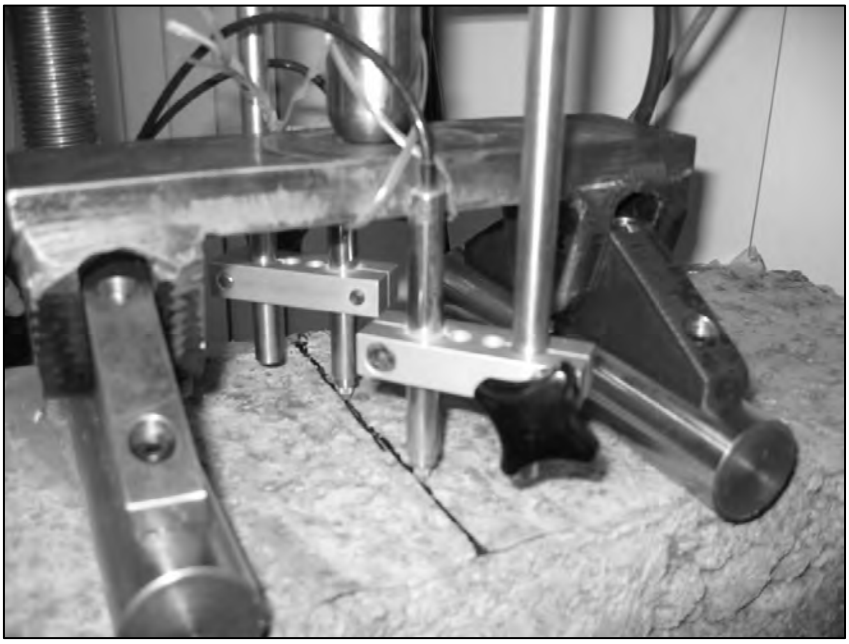
5.3 Beam test development

Pavespec Ltd's testing frame and the measuring and recording equipment for RLT testing were modified and adapted for testing the flexural beam properties (flexural modulus, tensile strength and tensile fatigue) for this research. A support and loading frame of the correct dimensions (figure 5.1) was built by Stevenson's Engineering. The LVDTs for measuring deflection were supported on the loading frame, with the complete setup shown in figures 5.6 and 5.7. Software is used to run the test, which is very versatile, allowing the user to specify the type of loading (repetitive or continuously increasing), loading speed, load magnitude and number of load cycles. The breakage test requires the user to specify whether to control stress or strain, and the loading rate (eg 3.3kN per minute or 1mm per minute). For the flexural modulus, the loading speed, magnitude and number of load cycles (100) are specified. Fatigue testing is the same as the modulus test but the number of load cycles is set to at least 1 million or until the sample breaks.

The beam test procedure is detailed in appendix A (an Austroads test method originally reported in Austroads (2008)). However, initial testing of the New Zealand materials has discovered that some changes in the guidance notes are required.

Figure 5.6 Test setup for measuring flexural beam properties

Figure 5.7 Measuring deflection during the flexural beam test using LVDTs



6 Materials

Most of the materials used in this study were the same as those used in the accelerated pavement test at CAPTIF. This material was a graded all passing (GAP) 40 from an alluvial gravel source from Isaac Construction in Christchurch mixed with either 1%, 2% or 4% by mass of cement (ie three different cement contents with the same source aggregate). Two materials used in the Australian research were tested to compare the two different methods of sample preparation (ie slab compaction and saw-cut to 100mm × 100mm × 350mm in Australia versus vibratory compaction in a 550mm × 150mm × 150mm mould in New Zealand). An additional two New Zealand materials used as cement-treated basecourse were selected for flexural beam testing as part of this study. Therefore, a total of six different pavement materials were tested as part of this study. Initial tests to estimate variability in the test method and refine the test method and equipment were done on the CAPTIF Isaacs GAP40 + 4% cement material.

Materials used in this study, along with target density and moisture contents are summarised in table 6.1.

Table 6.1 Materials, moisture content and density used in the flexural beam tests

Sample #	Material	MDD	OMC	Target density*	Target moisture content*
A	CAPTIF Isaacs GAP40 + 1% cement	2.4	4.0	2.18	3.0
B	CAPTIF Isaacs GAP40 + 2% cement	2.46	4.2	2.22	3.4
C	CAPTIF Isaacs GAP40 + 4% cement	2.41	4.5	2.19	3.3
D	Basalt (Mt Gambia, Australia) & 3% Blue Circle cement as used in Austroads study (2008)	2.14	12.0	2.09	10.42
E	Calcrete limestone (Renmark, Australia) and 3% Blue Circle cement as used in the Austroads study (2008)	1.95	13.0	1.88	12.81
F	Flat-top + 3% cement?	2.02	14.0	1.919	12.5
G	Whitford GAP40 + 3% foam bitumen + 1.3% cement	2.2	4.6	2.134	4.6

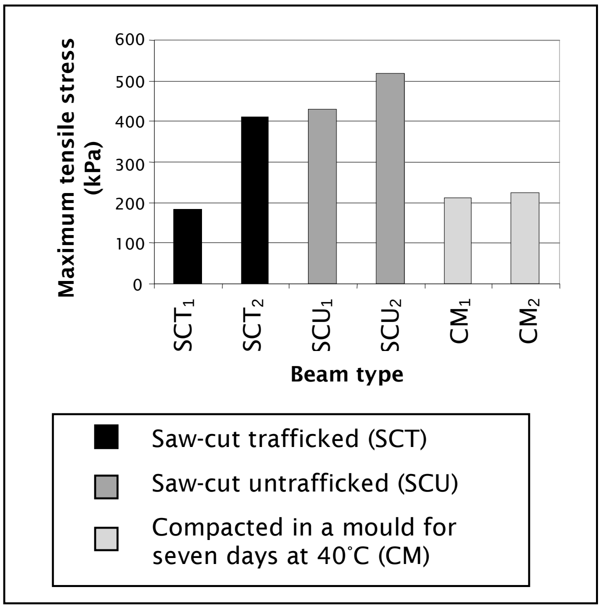
* Same as measured *in situ* at CAPTIF or on the road; if this is not available, the target is 95% MDD, being the minimum in TNZ B/2 (Transit 2005).

7 Flexural beam breakage test results

7.1 Overview[1]

The full set of flexural beam results are shown in appendices B and C. The tests in appendix B show a significant amount of results, with some repeat tests (on CAPTIF aggregate plus 4% cement) being presented in appendix C. Beams were also cut from the CAPTIF pavement (unpublished data by Transit New Zealand) and tested for strength and fatigue (figures 7.1–7.6; see section 7.3 for more details). For comparison, UCS and ITS tests were conducted on the same materials and are compared to the flexural beam breakage results as shown in figures 7.7 and 7.8. Figure 7.9 and table 7.1 show typical flexural beam breakage tests for cemented and foam bitumen stabilised aggregates used in this study. As can be seen from figure 7.9, every stabilised material is different but the results are, as would be expected, with the highest maximum tensile stress value occurring in the beam with the highest cement content (4%). In fact, the maximum tensile stress values can be ranked in order of cement content (4%, 3%, 2%, 1.3% and 1%). The foam-stabilised sample does show greater ductility than the other beams, although the 1% cement beam also shows some ductility but at a reduced strength.

Figure 7.1 Comparison of the maximum tensile strength of CAPTIF 1% cement saw-cut beams and of lab-manufactured beams



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[1] This project, entitled *The design of stabilised pavements in New Zealand,* is currently listed as an 'active project' that is still in process and has not been published at the time of writing.

Figure 7.2 Comparison of the Young's modulus of CAPTIF 1% cement saw-cut beams and of lab-manufactured beams

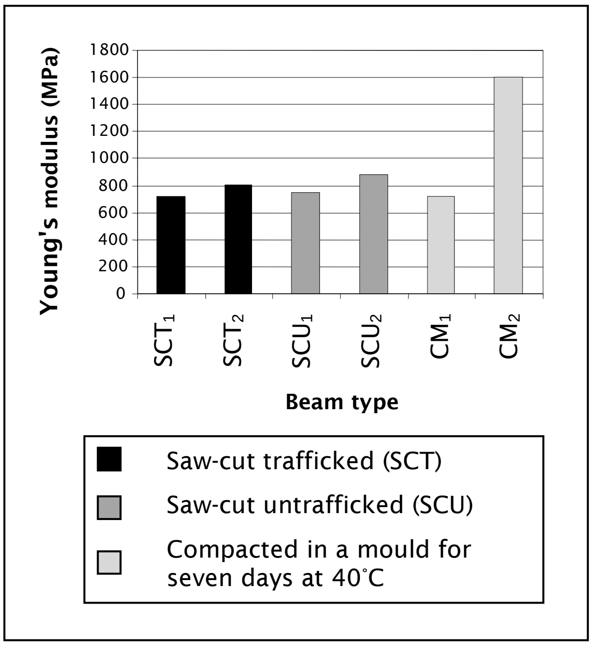


Figure 7.3 Comparison of the maximum tensile strain of CAPTIF 1% cement saw-cut beams and of lab-manufactured beams

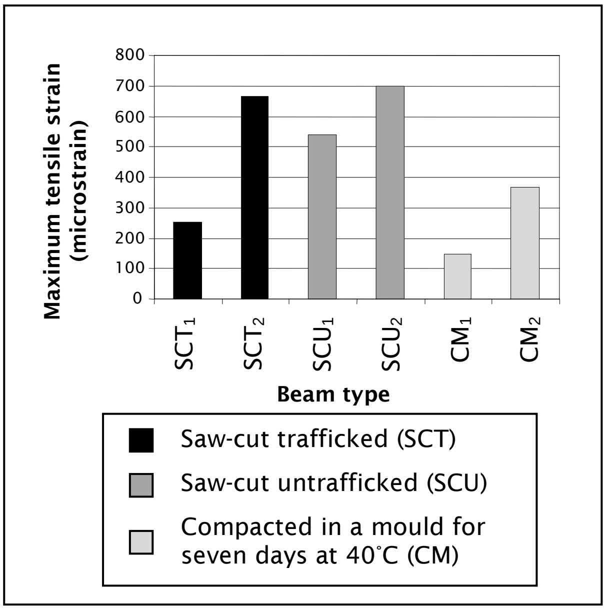


Figure 7.4 Maximum tensile stress comparison of CAPTIF 4% cement saw-cut beams with lab-manufactured beams

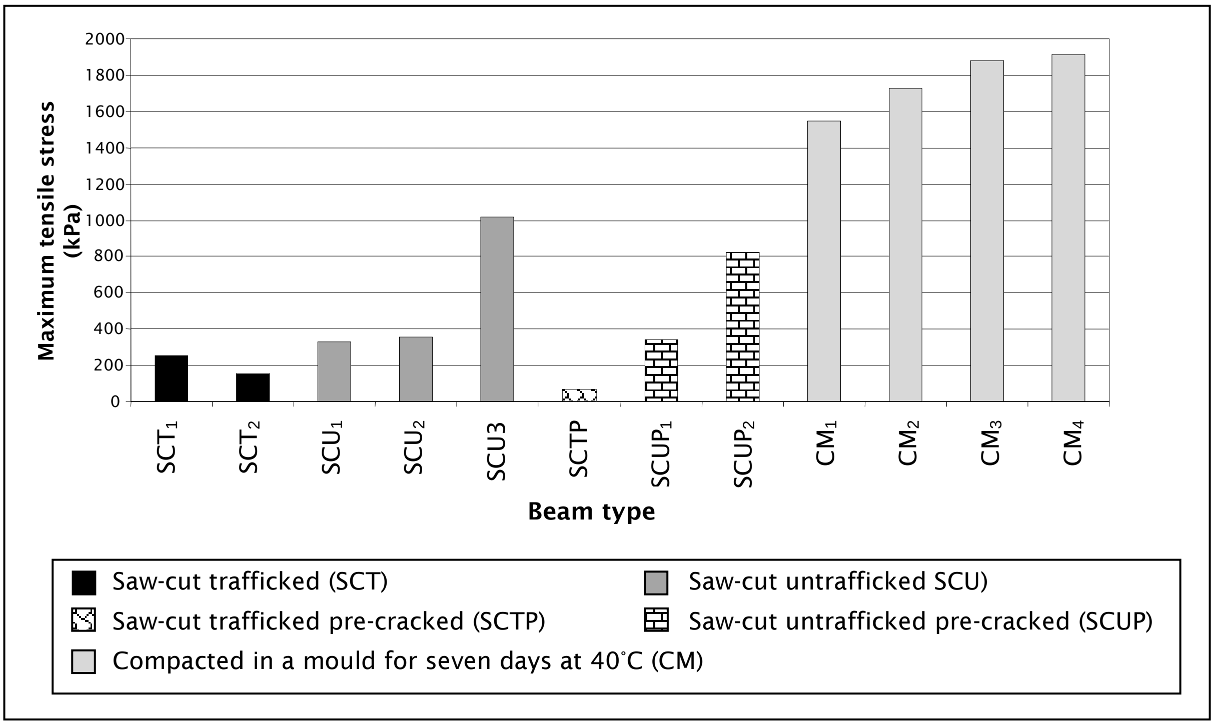


Figure 7.5 Young's modulus comparison of CAPTIF 4% cement saw-cut beams with lab-manufactured beams

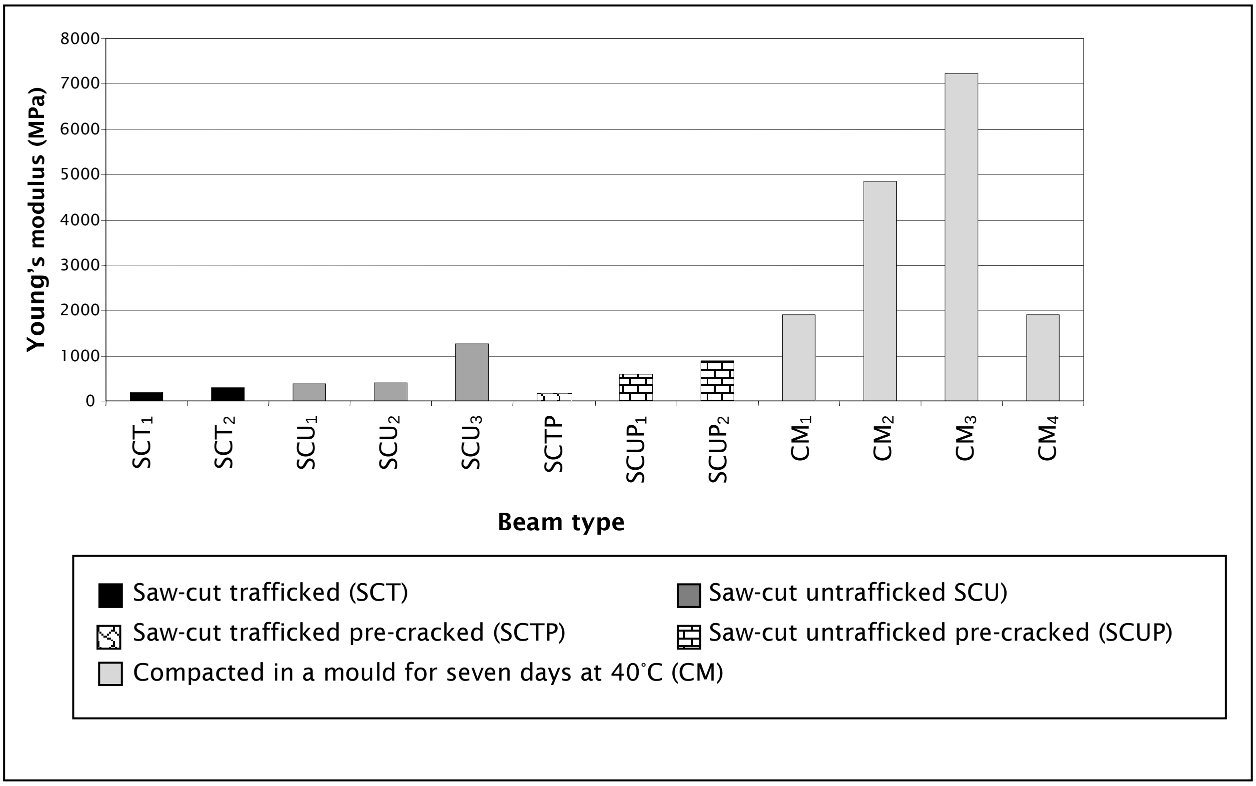


Figure 7.6 Maximum tensile strain comparison of CAPTIF 4% cement saw-cut beams with lab-manufactured beams

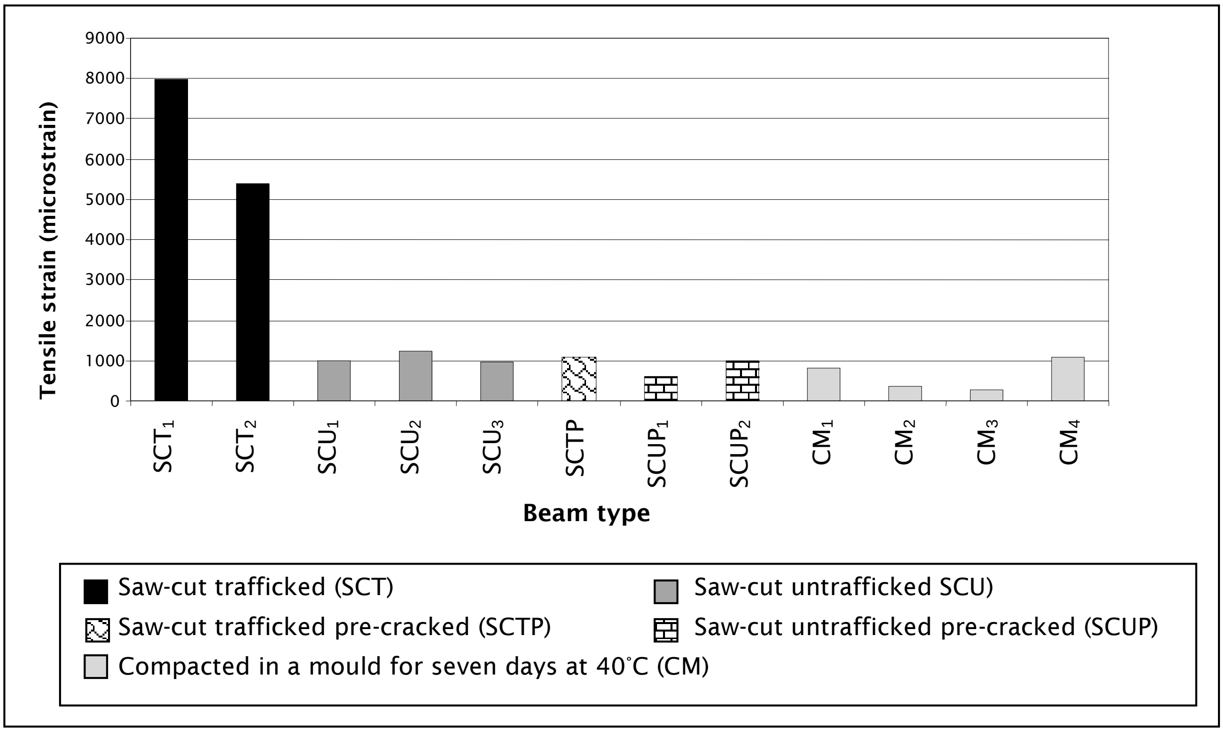


Figure 7.7 Relationship found between ITS and beam tensile strength

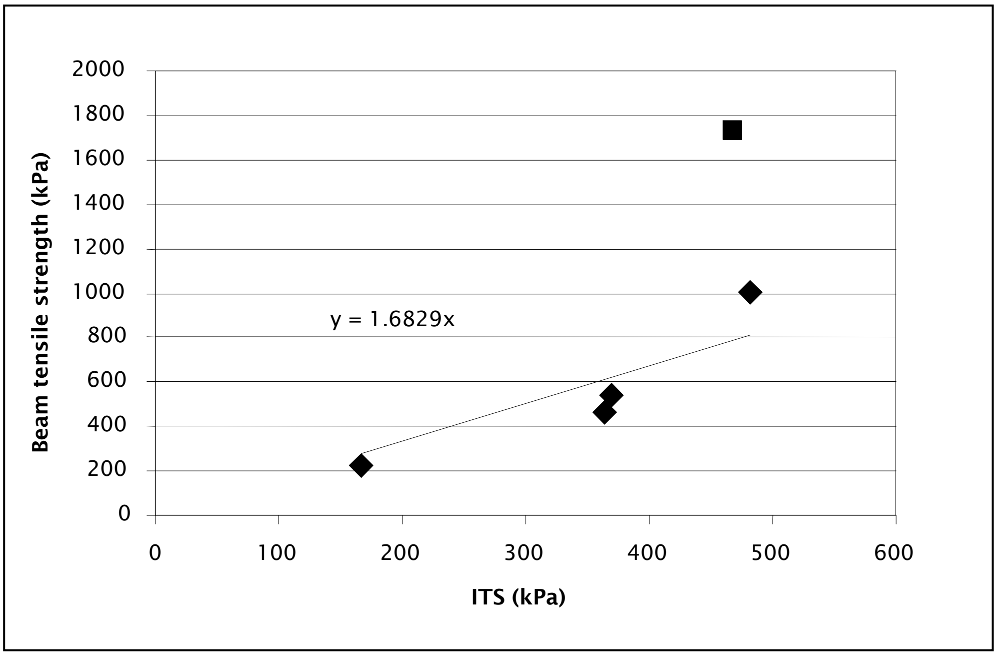
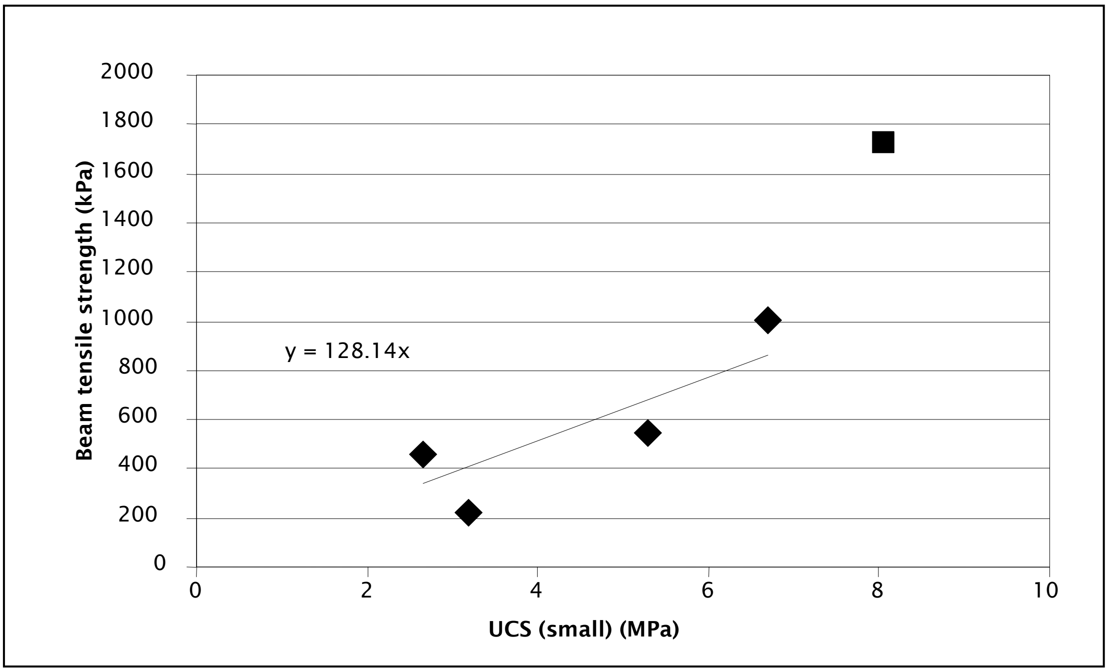
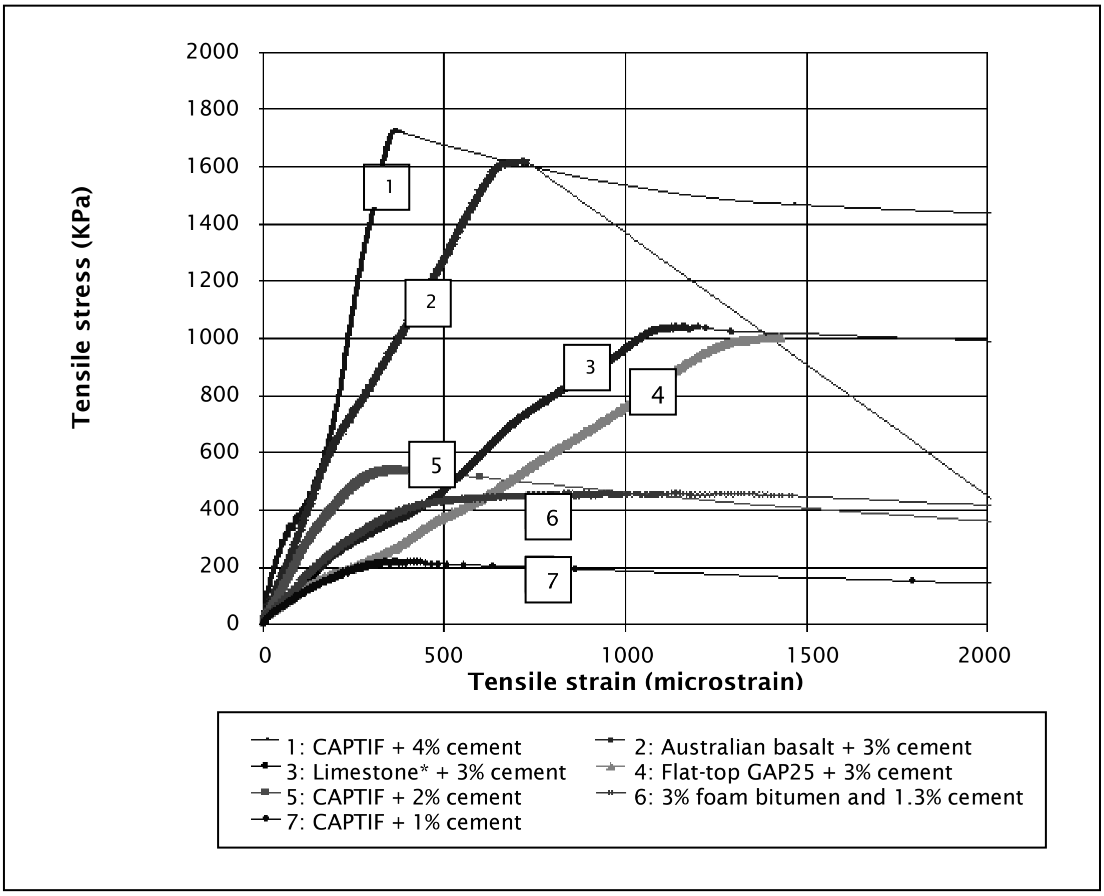


Figure 7.8 Relationship found between UCS (small)* and beam tensile strength



* Small UCS = sample size 152mm diameter by 126mm tall

Figure 7.9 Selected flexural beam breakage plots for a range of cement beams



*Australian origin

Table 7.1 Flexural beam test results for the selected tests shown in figure 7.9

Sample #	Material	UCS (small)[a] (MPa)	UCS (large)[b] (MPa)	ITS (kPa)	Flexural beam breakage test results		
					Young's modulus (MPa)	Maximum tensile stress (MPa)	Maximum tensile strain (microstrain)
C	CAPTIF + 4% cement	8.06 (11, 19.0)[c]	5.5	468 (951, 1263)[c]	4851	1727	360
D	Australian basalt + 3% cement	-	-	-	2424	1620	716
E	Australian limestone + 3% cement	-	-	-	1062	924	939
F	Flat-top GAP25 + 3% cement	6.7	5.5	482	775	1004	1426
B	CAPTIF + 2% cement	5.3 (8, 11.8)[c]	2.2	369 (413, 761)[c]	1815	544	372
G	Whitford GAP40 + 3% bitumen + 1.3% cement	2.65	-	364	1038	461	1326
A	CAPTIF + 1% cement	3.18 (4.0, 7.17)[c]	1.4	167 (202, 423)[c]	721	225	366

Notes to table 7.1:

a UCS (small) = sample size was 152mm diameter by 126mm tall.

b UCS (large) = sample size was 150mm diameter by 300mm tall.

c Values are taken from CAPTIF research (unpublished research by Transit New Zealand) where they are high (96% MDD, 98% MDD) because the density was significantly higher than the values shown.

7.2 Error in flexural beam breakage test

The flexural beam breakage tests appear to provide reasonable data on the properties of stabilised materials and give results as expected for the various cement contents (table 7.1 and figure 7.9). However, some scatter appeared in the results of the beam breakage tests. This scatter was possibly caused by the curing conditions, any drying that occurs and sample manufacture (mixing and moisture content). As the research project progressed, a more consistent approach that reduced the variation was adopted. Repeat ITS tests are often undertaken because of the variability expected with the result. Table 7.2 shows all the flexural beam breakage test results, including the repeat tests. The actual repeatability of the test is unknown as, generally, only two tests were conducted. Nevertheless, reviewing the results in terms of the difference between maximum and minimum as a percentage of the mean (figures 7.10–7.12) shows that the maximum tensile stress shows the least variation, with an error of 10% compared with up to 80% for the Young's modulus and tensile strain.

Table 7.2 All flexural beam test results

Sample #	Material	Flexural beam breakage test results		
		Young's modulus (MPa)	**Maximum tensile stress (MPa)**	**Maximum tensile strain (microstrain)**
C	CAPTIF + 4% cement	4851	1727	360
		1887	1916	1077
		7218	1878	265
		1891	1548	819
D (28d*)	Australian basalt + 3% cement	2424	1620	716
		2436	1570	677
D (7d)**	Australian basalt + 3% cement	1455	1304	956
		1425	1335	962
E (28d)*	Australian limestone + 3% cement	1062	924	939
		955	1040	1160
E (7d)**	Australian limestone + 3% cement	1376	649	575
		1169	733	645
F	Flat-top GAP25 + 3% cement	775	1004	1426
		1398	1100	861
B	CAPTIF + 2% cement	1815	544	372
		1188	622	563
G	Whitford GAP40 + 3% bitumen + 1.3% cement	1038	461	1326
		877	519	1139
A	CAPTIF + 1% cement	721	225	366
		1599	213	147

* 28 days' curing

** 7 days' curing

Figure 7.10 Maximum variation in percentage from mean for Young's modulus obtained from the flexural beam breakage test

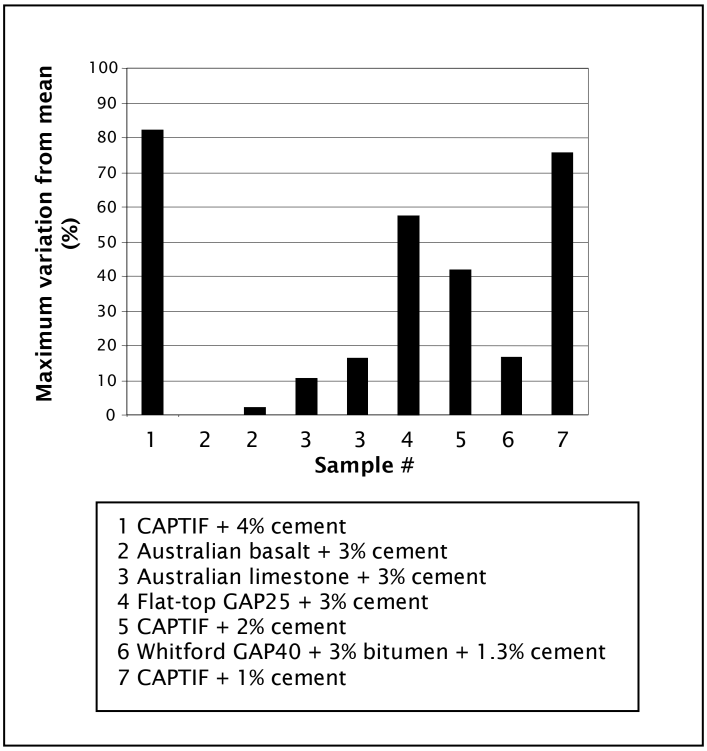


Figure 7.11 Maximum variation in percentage from mean for maximum tensile strain obtained from the flexural beam breakage test

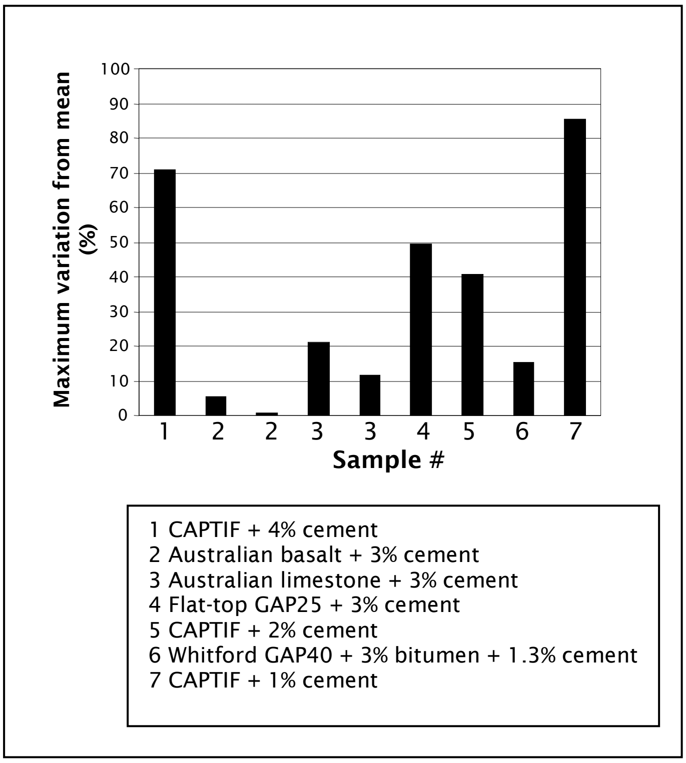
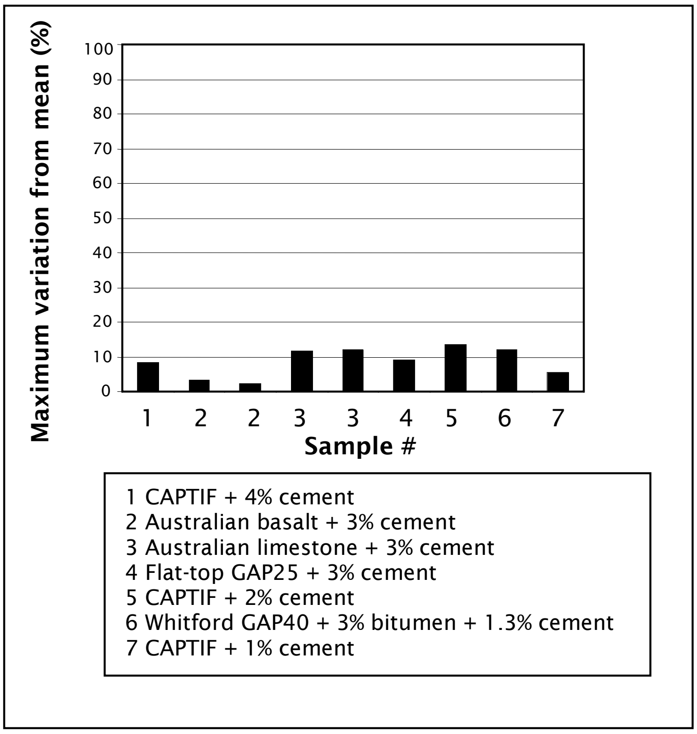


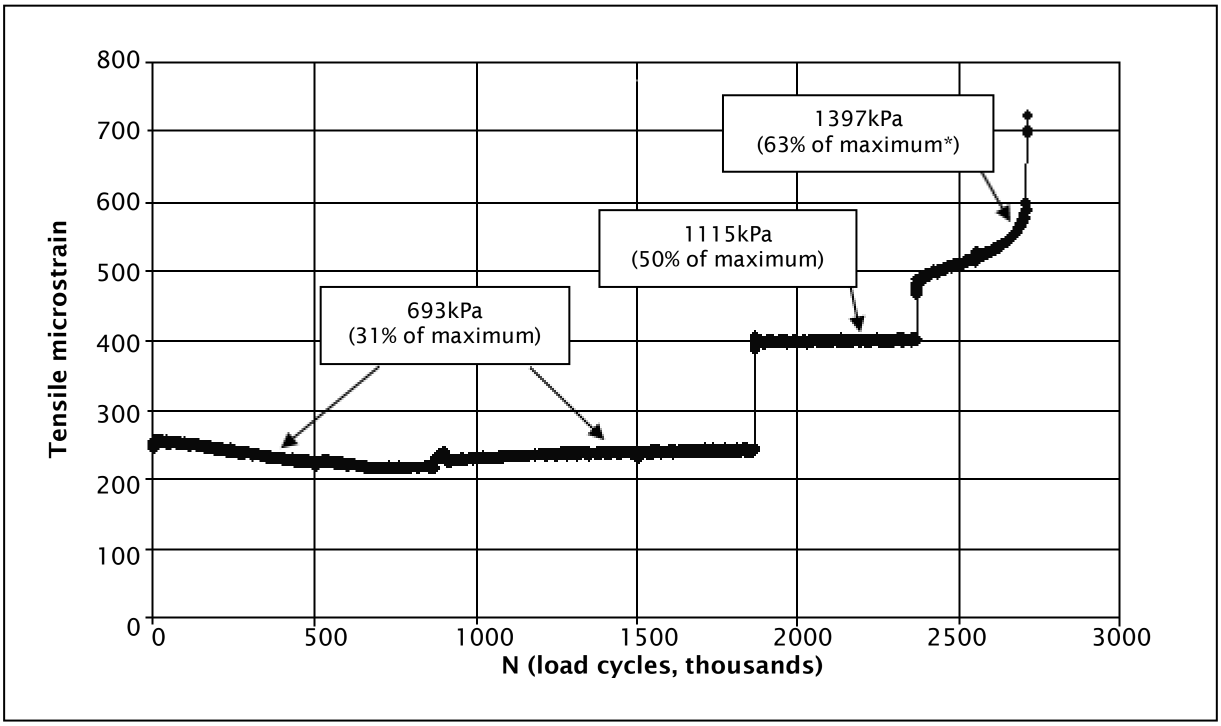
Figure 7.12 Maximum variation in percentage from the mean for maximum tensile stress obtained from the flexural beam breakage test



7.3 Comparison of CAPTIF saw-cut beams to lab-manufactured beams

Beams were cut from the CAPTIF test track in and outside the wheelpaths, and were tested for flexural strength. Results show that the saw-cut beams had a higher strength than the lab-manufactured beams for those with only 1% cement (figure 7.1). However, the lab-manufactured 4% cemented beams had a significant higher strength (approx. 1700kPa) than the saw-cut beams (approx. 400kPa). Although, as discussed in chapter 8, the CAPTIF 4% cement beams manufactured in the lab and tested for fatigue were very low in strength, being an estimated 500kPa, which is comparable to the strength of the saw-cut beams. It is postulated that the 4% cement lab-manufactured beams, when tested for breakage, were tested immediately after removal from the mould and sealed plastic bag. Therefore, the microcracks caused by drying outside of the mould and plastic that can weaken the beam had not occurred. This was confirmed by undertaking a repeat beam fatigue test for the CAPTIF 4% cement mix, where it was shown that the beam could sustain a tensile stress of 1115kPa (61% of a breakage stress of 1700kPa) for 500,000 load cycles (figure 7.13; further details of this repeat test are presented in appendix C).

Figure 7.13 Beam fatigue test result on CAPTIF 4% cement mix (beam 110902)



* Maximum tensile stress at break was estimated at 2234kPa.

7.4 Comparison of flexural beam strength with Austroads/ARRB research

Aggregate and cement was shipped from ARRB in Melbourne to replicate beam tests conducted in an Austroads project (Austroads 2008). The Austroads research manufactured beams using a slab compactor and used a concrete saw to cut the beams to 350mm long by 100mm square in size. This New Zealand research developed the approach to compact beams in a mould to achieve a larger beam size of 550mm long by 150mm square in order to cater for the larger aggregate sizes used in New Zealand. These different sized beams and methods of manufacture were compared in the flexural beam test on different equipment (ARRB equipment for Austroads small beam tests and Pavespec Ltd's equipment for large beam tests). Results for both the Australian basalt and limestone with 3% cement (tables 7.3 and 7.4, figures 7.14–7.16) all show similar maximum tensile strengths. However, the modulus values measured by ARRB/Austroads are up to 10 times higher than those measured with the larger beams. Therefore, the tensile strains measured by ARRB/Austroads are 10 times lower, which has implications in any design criteria that Austroads develops as a result of their research. However, if a stress-based approached is used for developing design strain criteria, as suggested earlier, where a maximum tensile strain is calculated from the measured maximum tensile stress in the beam test from an assumed modulus, then the resulting design criteria would be the same from the Austroads and Pavespec test results on the same material.

Table 7.3 Flexural beam test results for Australian basalt + 3% cement

Method	Beam size	Curing time	Tensile stress (kPa)	Young's modulus (MPa)	Maximum tensile strain (microstrain)
ARRB/Austroads	small	6 months	1240	14670	85
Lab mould	large	7 days	1304	1455	956
Lab mould	large	7 days	1335	1425	962
Lab mould	large	28 days	1570	2436	677
Lab mould	large	28 days	1620	2424	716

Table 7.4 Flexural beam test results: Australian limestone + 3% cement

Method	Beam size	Curing time	Tensile stress (kPa)	Young's modulus (MPa)	Maximum tensile strain (microstrain)
ARRB/Austroads	Small	6 months	1010	11,244	90
Lab mould	Large	7 days	649	1376	575
Lab mould	Large	7 days	733	1169	645
Lab mould	Large	28 days	1040	955	1160
Lab mould	Large	28 days	924	1062	939

Figure 7.14 Flexural beam test results for maximum tensile stress for Australian basalt plus 3% cement

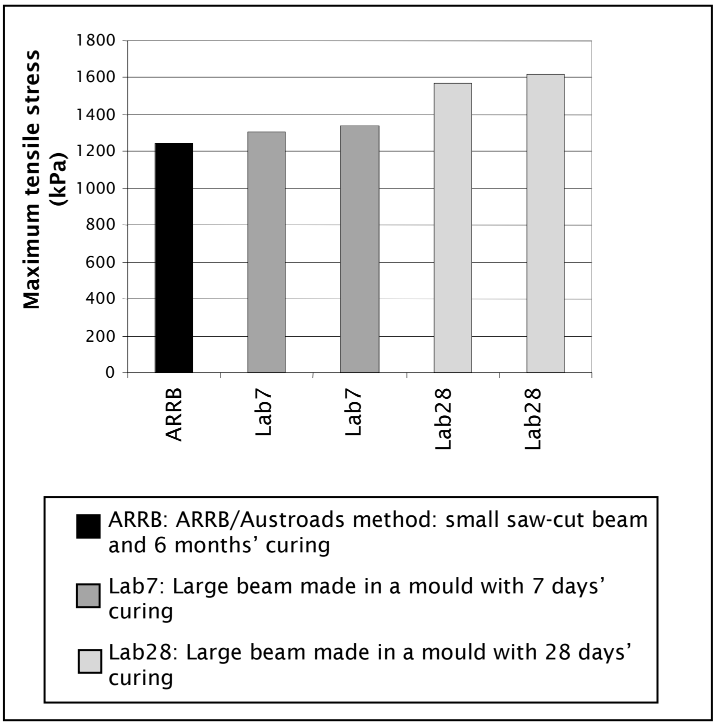


Figure 7.15 Flexural beam test results for Young's modulus for Australian basalt plus 3% cement

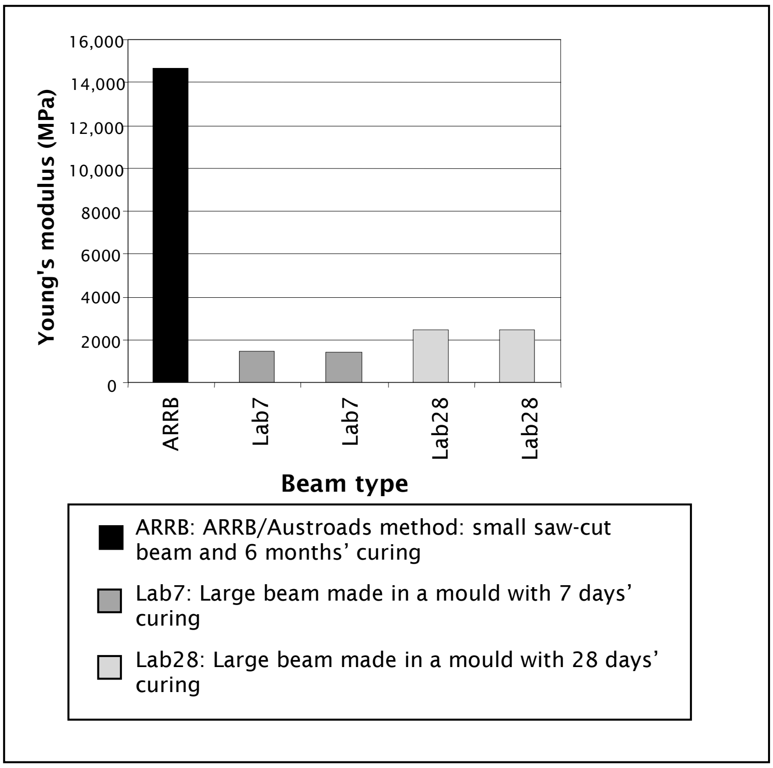
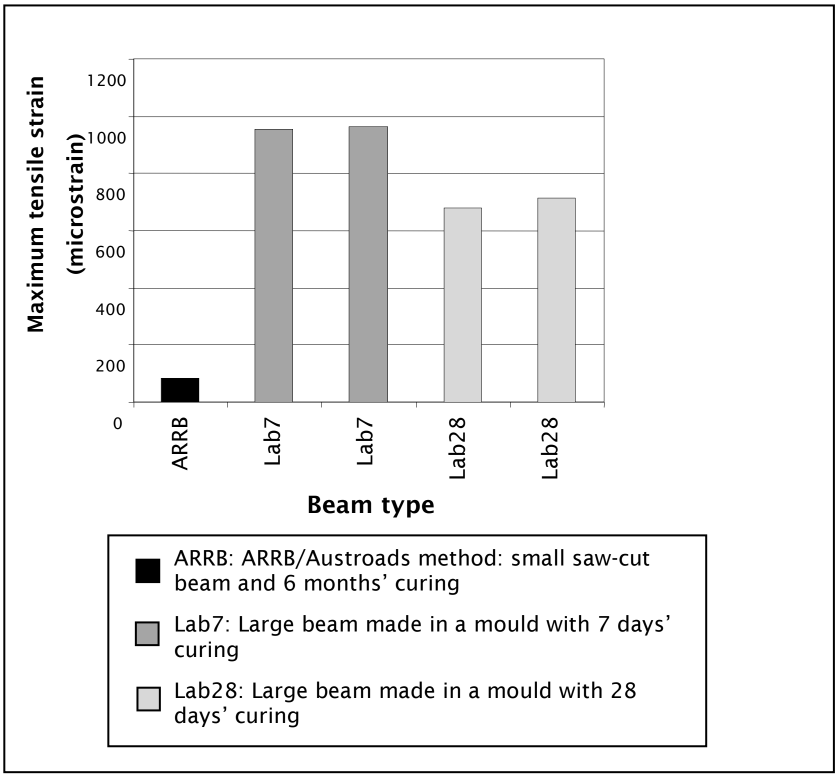


Figure 7.16 Flexural beam test results for maximum tensile strain for Australian basalt plus 3% cement



7.5 Discussion of flexural beam breakage tests

Testing has shown that flexural beams can be successful made in a rectangular mould compacted under a vibrating hammer. The finished beams are strong, their edges are intact and all surfaces are smooth. The maximum flexural beam tensile stress is less variable (10%) than the other measures of modulus and strain (up to 80%). Maximum tensile stress correlates with cement content and ITS, and for the Australian materials, the values are close to those obtained in the Austroads research with smaller saw-cut beams.

Comparing the maximum tensile strength obtained from beam tests to UCS and ITS (figures 7.7 and 7.8) test more or less agrees with the findings from Thompson (1986), who reviewed the work of a number of researchers and came to the following generalised conclusions:

- tensile strength = ITS
- ITS = 0.5 × flexural beam strength
- ITS = 0.1 × UCS
- flexural beam strength = 0.2 × UCS.

The beam tests did not show any single relationship between the strength and modulus. Williams (1986) also found this to be the case and concluded that fine-grained stabilised materials would have a low modulus/strength ratio, whereas clean crushed aggregate would have a high modulus/strength ratio. The results showed large variations in modulus, while the tensile strength was more consistent.

The number of repeat tests and how a final tensile strength and modulus value is determined (average, minimum, removal of outliers, etc) will require further tests and then discussion/agreement with industry groups. The initial results indicate that the maximum tensile strength is more repeatable and should be considered in design. As modulus is equal to stress divided by strain (or strain is equal to stress divided by modulus) then, for a given maximum tensile stress (a repeatable measured result in the lab test), a range a maximum tensile strains can be calculated for a range of modulus values. This idea of using the maximum tensile stress as the first input for fatigue design will be recommended in the design section of this report.

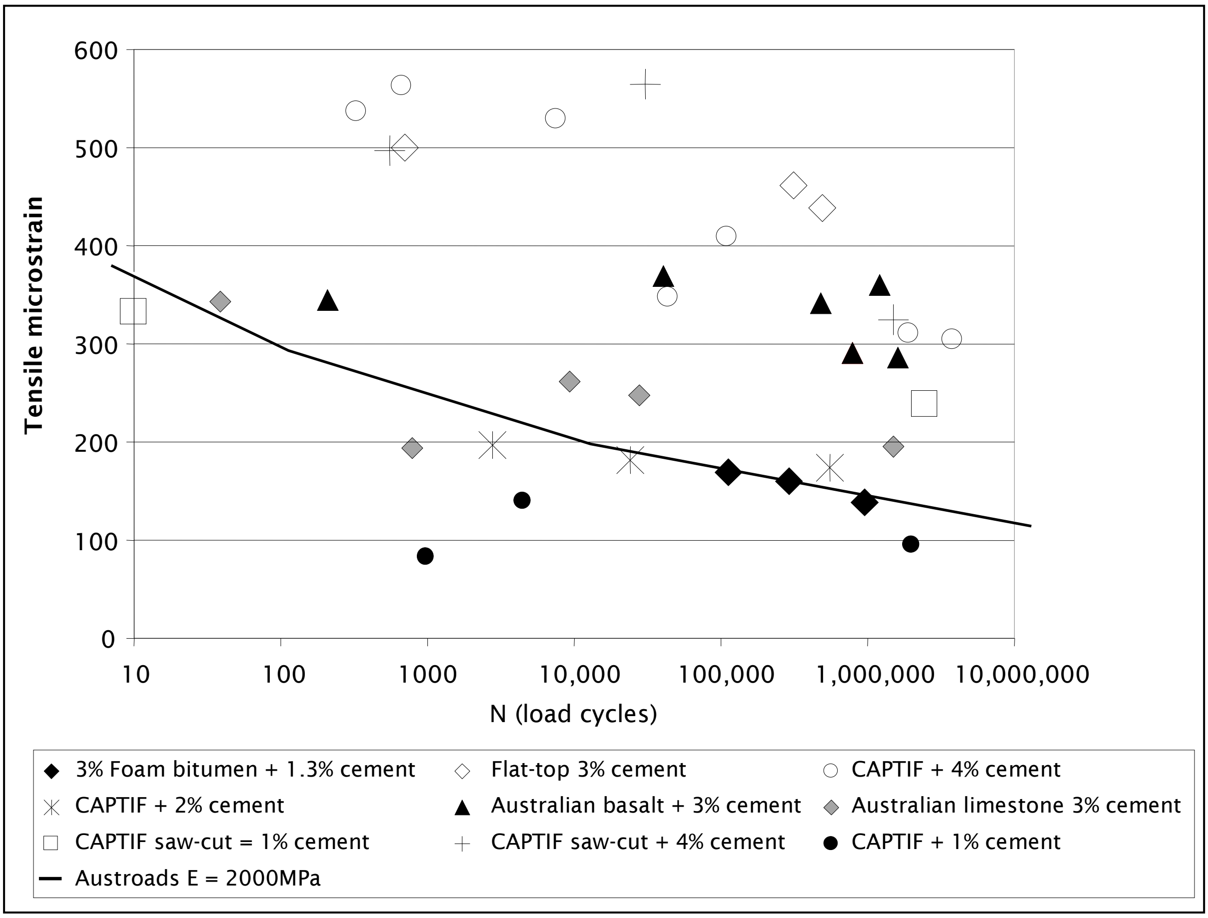
The smaller beam tests conducted by ARRB in Australia resulted in up to 10 times the modulus than those determined using larger beams by Pavespec. However, the maximum tensile stress calculated is the same, which suggests the beams are comparable. Reasons for the difference in modulus are unknown but the difference does reinforce the idea of a stress-based design.

8 Flexural beam fatigue test results

8.1 Fatigue relationships

In addition to flexural beam breakage tests, at least three duplicate beams were manufactured and repetitive loading was applied. For each beam fatigue test, a different loading was applied to enable the determination of a fatigue relationship relating the number of load cycles to failure (when the beam breaks, brittle failure is observed or the modulus does not reduce with increasing load cycles) and tensile strain. The full results are given in appendix B, while the fatigue relationships are plotted in figure 8.1. The plots of fatigue relationships are not directly comparable, as they depend on the pavement design in question, which includes an assumed modulus that affects the tensile strain.

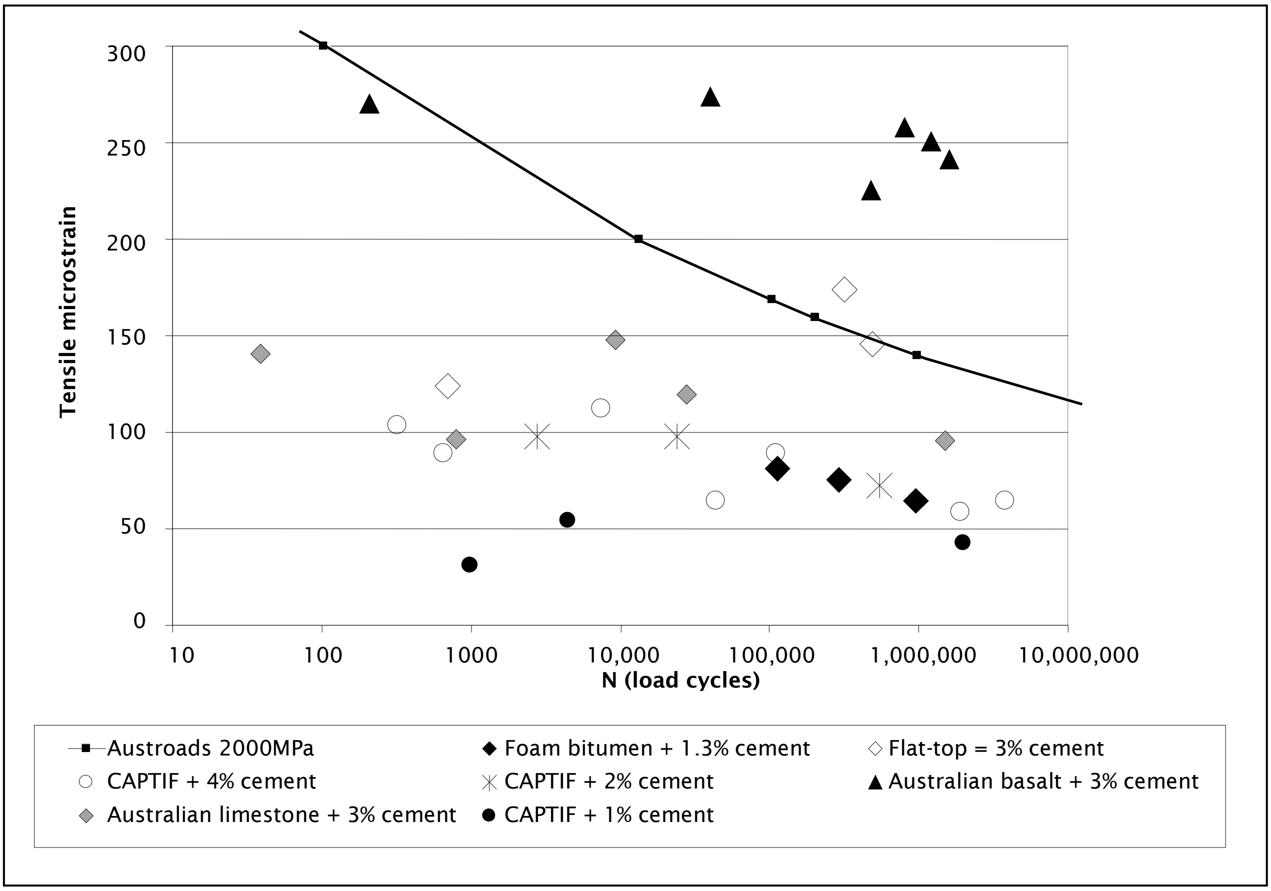
Figure 8.1 Beam tensile fatigue test results: tensile strain v load cycles for selected beams (full results in appendix B)



As discussed earlier, the modulus of the beams varies, while the maximum tensile stress in the flexural beam tests is a more consistent value. Therefore, the beam fatigue results were reanalysed by keeping the applied tensile stress the same but calculating the associated tensile strain for an assumed modulus of 2000MPa for all tests. This method gives a direct comparison for fatigue performance for the different materials at a design modulus of 2000MPa as shown in figure 8.2. Apart from the

Australian basalt with 3% cement and the flat-top with 3% cement, all other materials showed very poor fatigue performance.

Figure 8.2 Beam tensile fatigue test results: tensile microstrain versus load cycles for selected beams assuming a constant beam modulus of 2000MPa (full results in appendix B)



Another way of looking at the fatigue data is tensile stress, both actual values and as a fraction of average maximum tensile stress (table 8.1), versus number of load cycles (figures 8.3 and 8.4). As discussed earlier, maximum tensile stress is a more repeatable measure and is thus recommended when taking a stress-based approach in design. Results show that in general, provided the stress is below 0.4 of the maximum tensile stress at breaking point, then good fatigue life is likely (although fatigue testing in the lab for each new stabilised material recipe is still recommended). However, results of the CAPTIF 4% cement lab-manufactured beams fatigue tests undertaken early in the research project could not sustain repetitive loads greater than 280kPa being only 16% of the maximum tensile stress at breakage (the maximum found was 1700kPa). This result was unusual and highlighted the effect of reduced strength occurring because of the sample microcracking when left on the bench to dry out. In June 2011, beam fatigue tests were repeated on a CAPTIF + 4% cement mix where the beams were kept moist with wet rags, with a result showing that high repetitive loading stresses up to 63% of the maximum stress at break (figure 7.13) could be sustained (appendix C presents the results of these repeat tests in more detail).

Table 8.1 Average maximum tensile stress from the beam tests

Material	Maximum tensile stress (kPa)
1: CAPTIF + 4% cement	1767
2: Australian basalt + 3% cement (28 days' curing)	1595
2: Australian basalt + 3% cement (7 days' curing)	1320
3: Australian limestone + 3% cement (28 days' curing)	982
3: Australian limestone + 3% cement (7 days' curing)	691
4: Flat-top GAP25 + 3% cement	1052
5: CAPTIF + 2% cement	583
6: Whitford GAP40 + 3% bitumen + 1.3% cement	490
7: CAPTIF + 1% cement	219

Figure 8.3 Beam tensile fatigue test results: load cycles v applied tensile strength for selected beams (full results in appendix B)

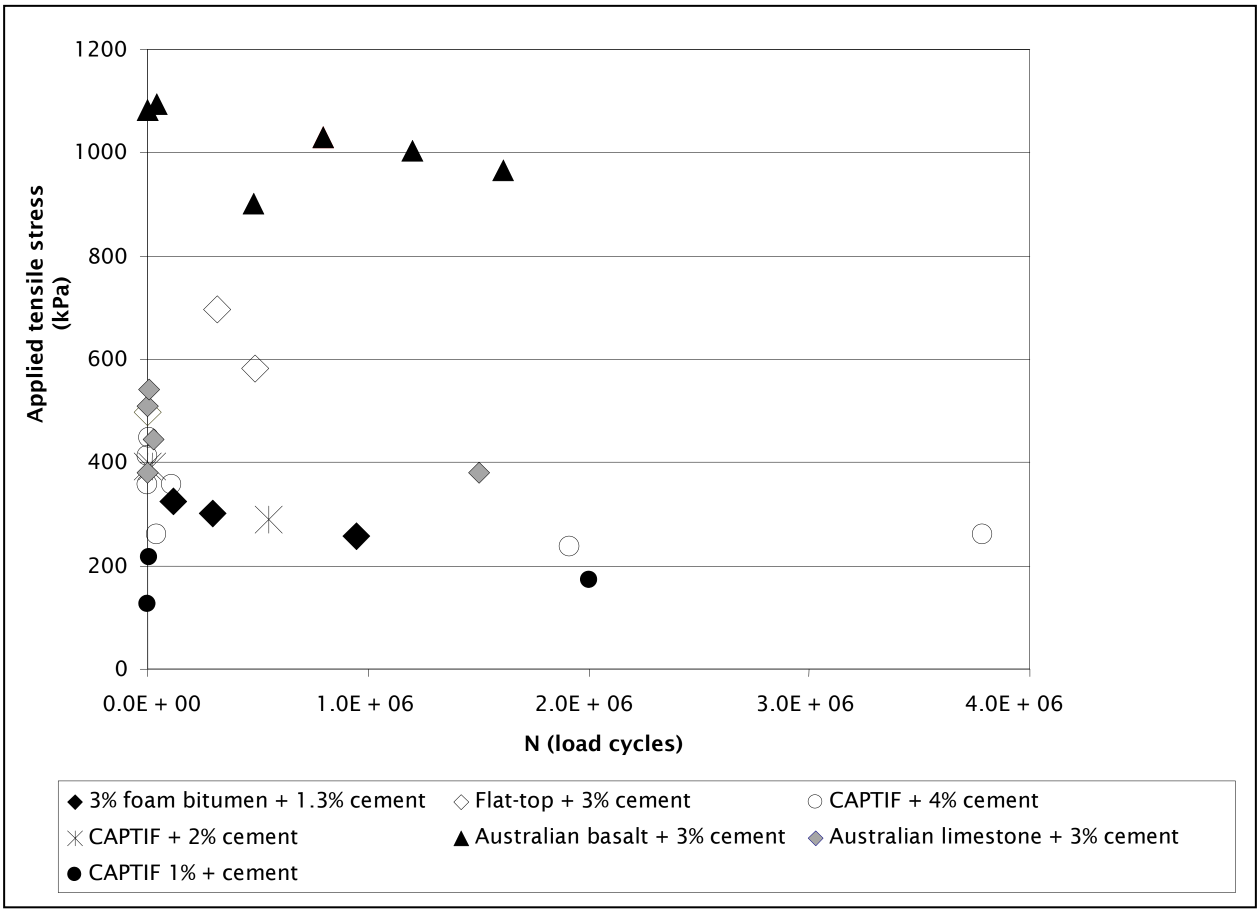
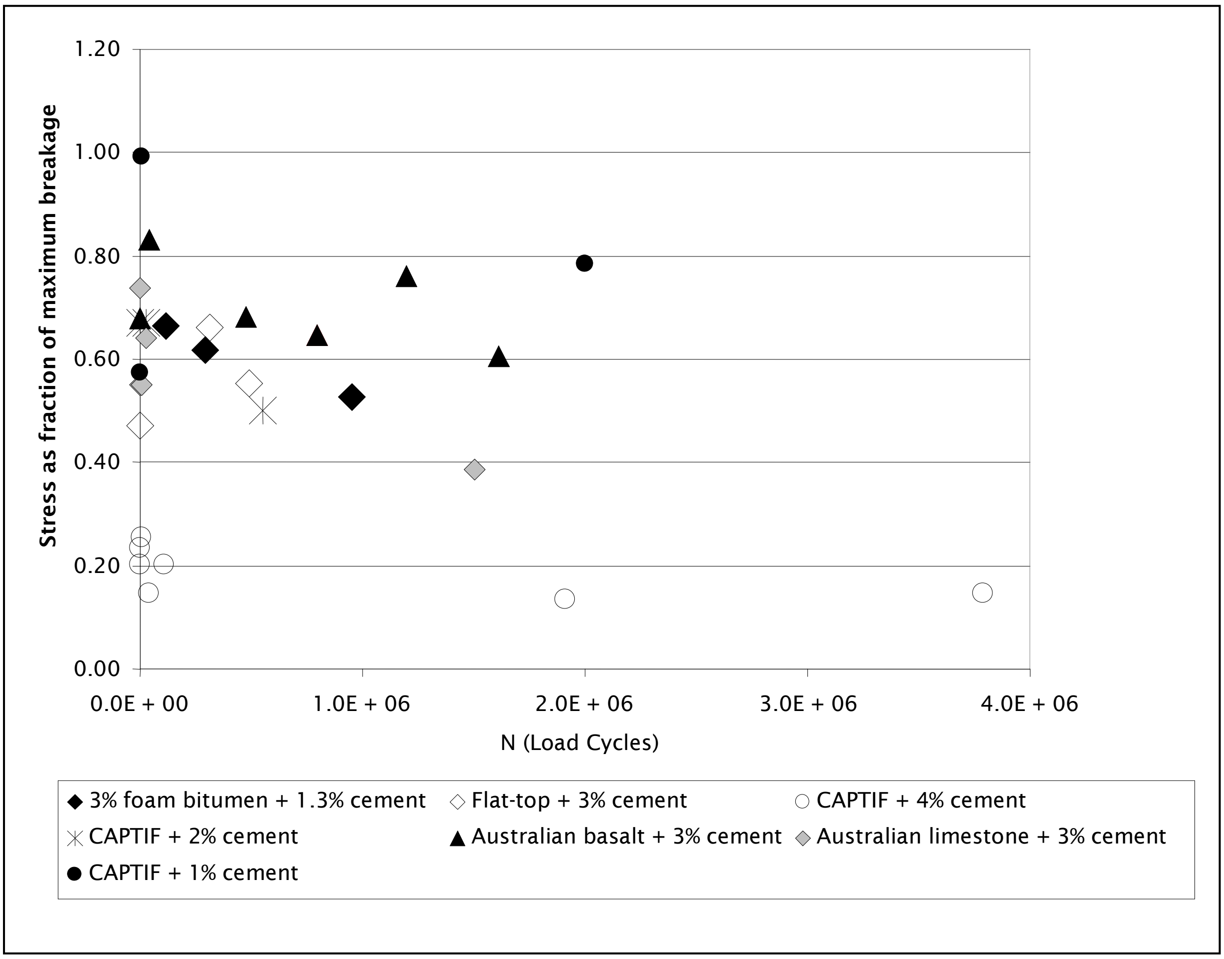


Figure 8.4 Beam tensile fatigue test results for selected beams: applied tensile stress as a fraction of maximum tensile stress versus load cycles (full results in appendix B)



8.2 Pavement design using a tensile fatigue criterion from beam tests

Further research is needed to determine a method of design using the results from the beam fatigue tests but as a starting point, the following design approach is proposed. The results of the beam fatigue testing are varied, ignoring the poor results for the early CAPTIF 4% cement beam tests (recent repeat testing on CAPTIF 4% cement found the results can be used to confirm the design approach), and they show that the fatigue life will probably be greater than 1 million cycles if the applied stress is less than 0.4 of the maximum tensile stress (figure 8.4), although further research and tests on the material to be stabilised are needed to confirm this. This result can be one point of the design fatigue relationship (equation 8.1). If one assumes the same power exponent (12) as Austroads (2004), the constant *k* (equation 8.1) can be determined using equation 8.2.

$$N = (k/microstrain)^{12} \qquad \text{(Equation 8.1)}$$

Where:

- N = fatigue life in ESA

- k = constant (calculated using equation 8.2)
- microstrain = tensile strain at the bottom of the beam or stabilised pavement layer in microns.

$$k = \frac{0.4 \times TS_{max} \times N^{\frac{1}{12}}}{modulus \times 10^6} \qquad \text{(Equation 8.2)}$$

Where:

- k= constant in microstrain used in equation 8.1
- *modulus* = modulus assumed for the bound layer in pavement design
- TS_{max} = maximum tensile stress found in the flexural beam breakage test (MPa) (table 8.1)
- N = 1 million, as this is the expected minimum fatigue life when the applied stress is 0.4 × TS_{max} (alternatively, this number could be determined from fatigue testing at 0.4 × TS_{max} but limited to a maximum of 1 million).

Equation 8.2 yields a range of fatigue constants (*k*, equation 8.1) for different assumed moduli as shown in table 8.2.

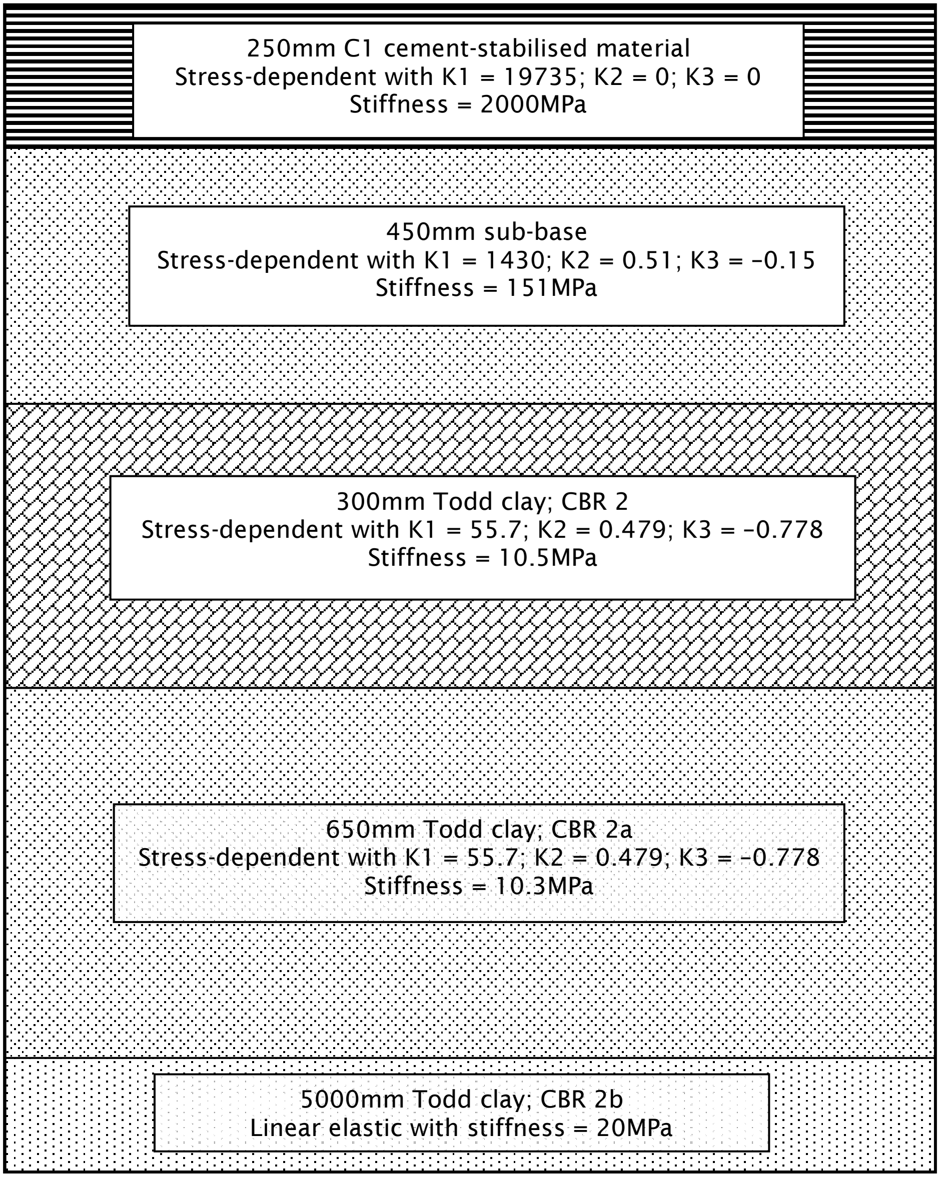
Table 8.2 Tensile fatigue constants calculated from maximum tensile stress (equation 8.2)

Material	Max tensile stress (kPa)	0.4 × maximum tensile stress (kPa)	Values of *k**			
			Modulus			
			1000	2000	3000	4000
1: CAPTIF + 4% cement	1767	707	2235	1118	745	559
2: Australian basalt + 3% cement (28 days' curing)	1595	638	2018	1009	673	504
2: Australian basalt + 3% cement (7 days' curing)	1320	528	1670	835	557	417
3: Australian limestone + 3% cement (28 days' curing)	982	392.8	1242	621	414	311
3: Australian limestone + 3% cement (7 days' curing)	691	276.4	874	437	291	219
4: Flat-top GAP25 + 3% cement	1052	420.8	1331	665	444	333
5: CAPTIF + 2% cement	583	233.2	737	369	246	184
6: Whitford GAP40 + 3% bitumen + 1.3% cement	490	196	620	310	207	155
7: CAPTIF + 1% cement	219	87.6	277	139	92	69

* calculated using equation 8.2

The fatigue equation constants shown in table 8.2 were used to determine the cracking fatigue life for a thin-surfaced 250mm stabilised basecourse layer overlying 450mm of an unmodified aggregate sub-base on a soil with a California bearing ratio (CBR) of 2% (figure 8.5). Fatigue lives for the different assumed moduli were compared with the life calculated using the Austroads equations (2004) and are summarised in table 8.3, and figures 8.6 and 8.7. The calculated fatigue lives are higher than those calculated with the Austroads equation. However, the relationship between laboratory beam fatigue and performance in the field has not been established. Should this approach be considered, at least one fatigue test at 0.4 times the maximum tensile stress for 1 million load cycles is recommended to confirm this fatigue life assumed in design.

Figure 8.5 Pavement structure with cement-stabilised basecourse (example shows a basecourse modulus of 2000MPa)



Notes to figure 8.5:

Maximum vertical displacement = 690 microns

Load setup: 40kN load; 550kPa contact pressure

Table 8.3 Cracking fatigue life for a range of assumed stabilised basecourse modulus values

Stabilised basecourse layer	Unit	Modulus (MPa)			
		1000	2000	3000	4000
Depth	mm	250	250	250	250
Tensile stress	kPa	324	482	575	644
Tensile strain	microstrain	237	163	127	106
K (Austroads)	-	520	440	375	344
Life Austroads	*N (ESA)	1.23E + 04	1.50E + 05	4.41E + 05	1.38E + 06
CAPTIF + 4% cement	*N (ESA)	4.95E + 11	1.08E + 10	1.66E + 09	4.60E + 08
Australian basalt + 3% cement (28 days' curing)	*N (ESA)	1.45E + 11	3.16E + 09	4.86E + 08	1.35E + 08
Australian basalt + 3% cement (7 days' curing)	*N (ESA)	1.49E + 10	3.26E + 08	5.02E + 07	1.39E + 07
Australian limestone + 3% cement (28 days' curing)	*N (ESA)	4.30E + 08	9.36E + 06	1.44E + 06	4.00E + 05
Australian limestone + 3% cement (7 days' curing)	*N (ESA)	6.33E + 06	1.38E + 05	2.12E + 04	5.89E + 03
Flat-top GAP25 + 3% cement	*N (ESA)	9.82E + 08	2.14E + 07	3.29E + 06	9.13E + 05
CAPTIF + 2% cement	*N (ESA)	8.24E + 05	1.80E + 04	2.76E + 03	7.66E + 02
Whitford GAP40 + 3% bitumen + 1.3% cement	*N (ESA)	1.02E + 05	2.23E + 03	3.44E + 02	9.52E + 01
CAPTIF + 1% cement	*N (ESA)	7	0	0	0

Figure 8.6 Estimated fatigue lives where the modulus of the bound layer is assumed to be 2000MPa

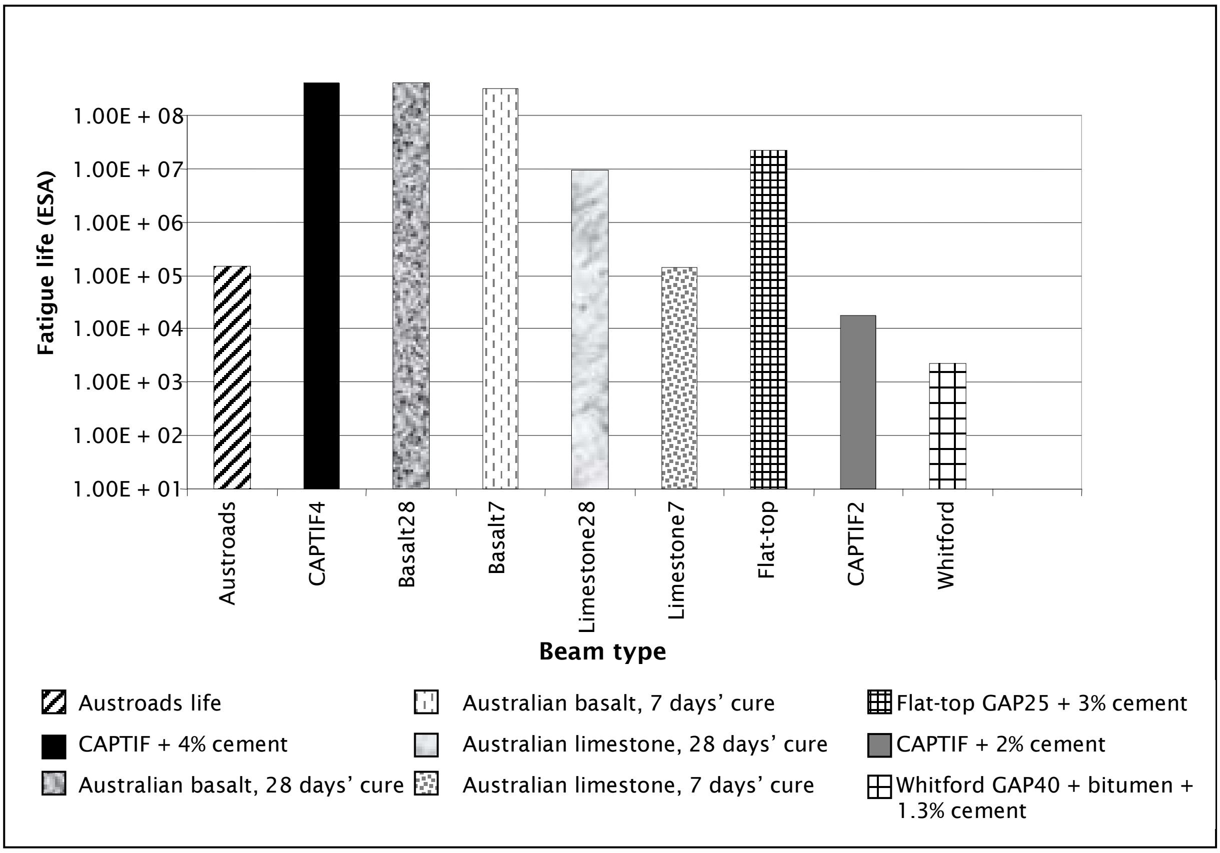
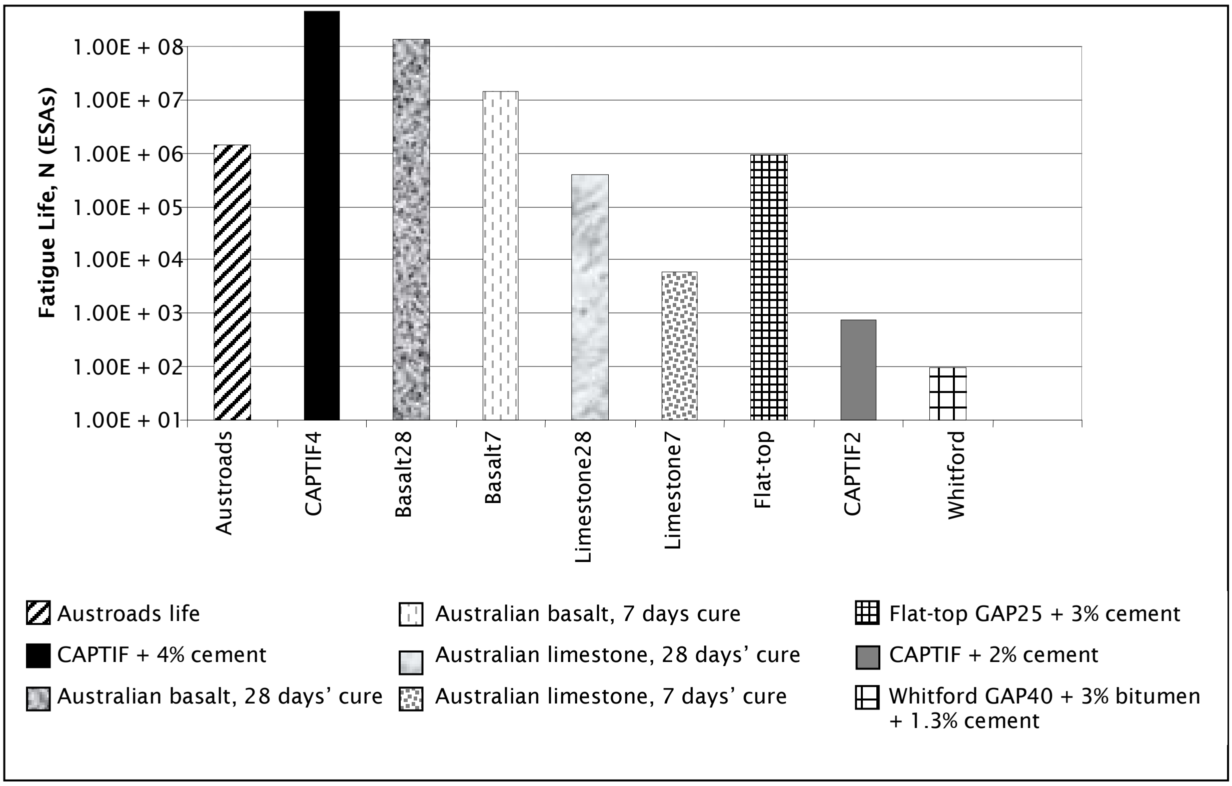


Figure 8.7 Estimated fatigue lives where the modulus of the bound layer is assumed to be 4000MPa



8.3 CAPTIF saw-cut beams

Beams were also cut from the CAPTIF pavement and tested under repetitive loading to determine their fatigue lives. These beams were over one year old and only a few of the untrafficked 1% and 4% cemented beams could be tested. The predicted fatigue lives of these 'stronger' beams saw-cut from the CAPTIF test pavement compared well with beams compacted in a mould (figure 8.8). Results in terms of tensile stress versus life (figure 8.9) show that the saw-cut beams for the 1% cement CAPTIF sections are stronger than those compacted in the laboratory, while the saw-cut and lab beams for the 4% cement are similar.

Figure 8.8 Flexural beam tensile fatigue results (strain v life) comparing saw-cut beams with those compacted in moulds in the laboratory

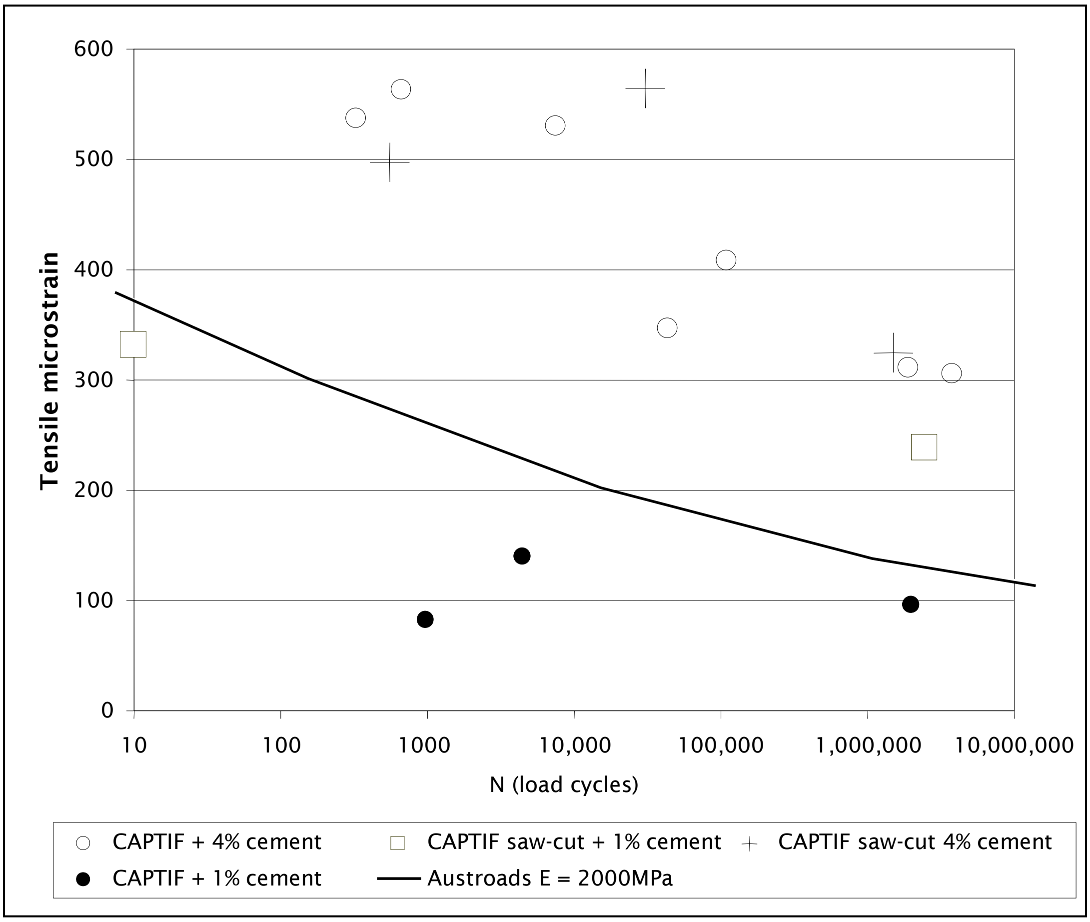
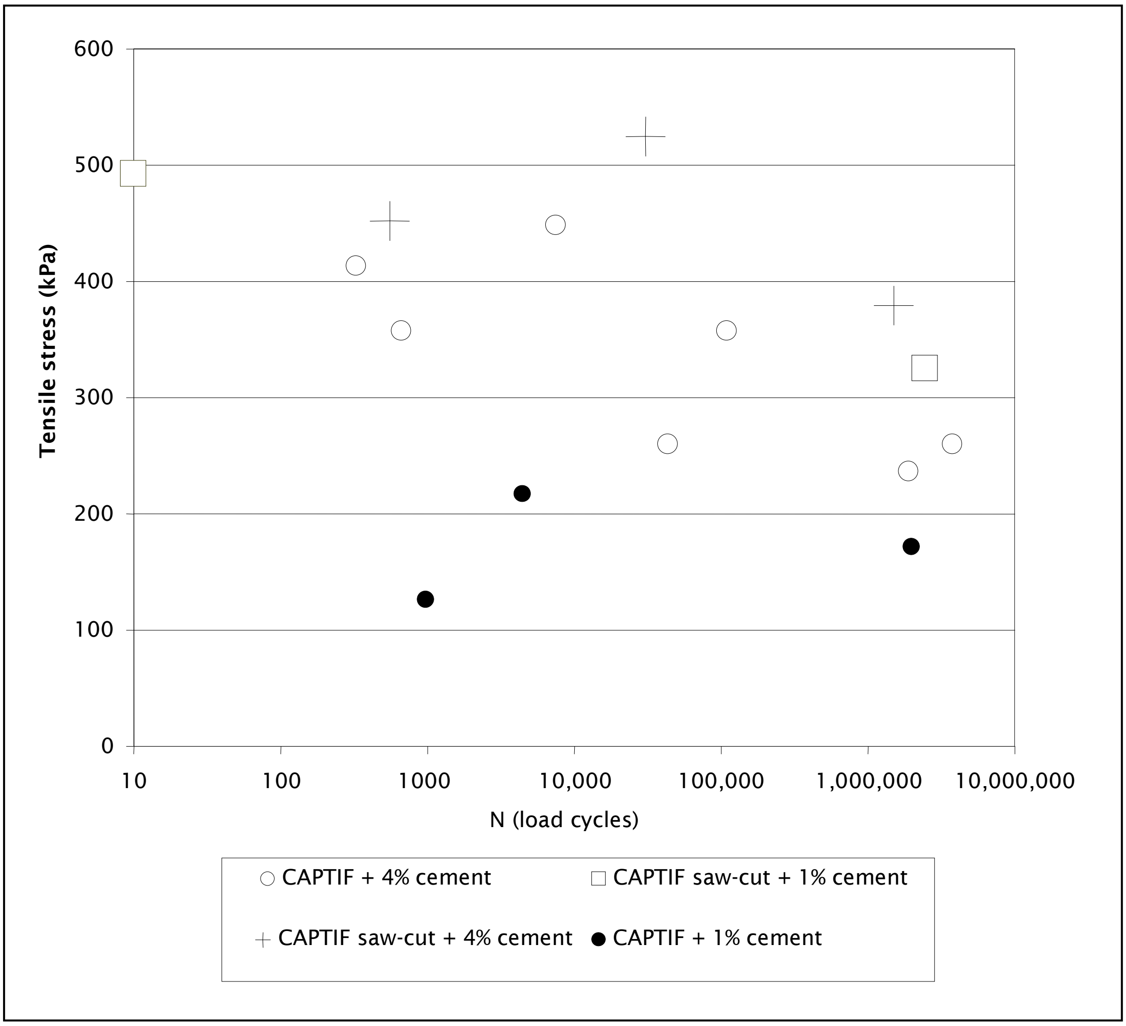


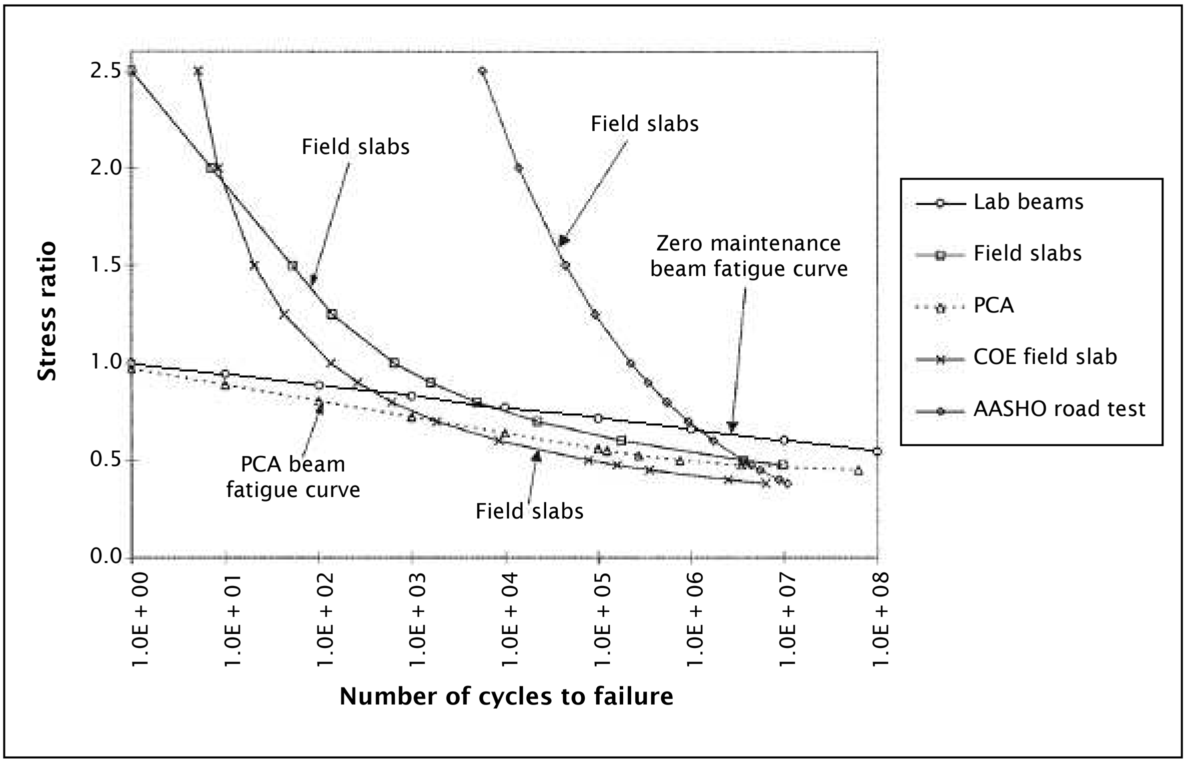
Figure 8.9 Flexural beam tensile fatigue results (stress v life) comparing saw-cut beams with those compacted in moulds in the laboratory



8.4 Discussion of flexural beam fatigue tests

Fatigue testing showed that if the repetitive load was kept below 40% of the maximum load at breaking (found from the flexural beam breakage test) then the fatigue life was at least 1 million load cycles. This long life when the stress is below half the maximum stress at breaking is common with concrete beams and slabs (figure 8.10; Jeffery et al 1999)

Figure 8.10 Comparison of fatigue curve relationships for concrete beams and slabs (adapted from Jeffery et al 1999)



Scott (1974) also attempted to discover a threshold level of stress below which it was unlikely that fatigue failure would develop. He found that when the applied stress was less than 60% of the flexural strength (modulus of rupture), fatigue did not occur within 1 million cycles. However, Scott suggested that fatigue might have taken place with ratios less than 60% had the tests proceeded past 1 million cycles.

Otte (1978) believed that microcracks were initiated when the applied stress level exceeded 35% of the flexural strength (modulus of rupture). This was determined from examining data derived from testing statically-loaded flexural beams prepared from crushed rock stabilised with Portland cement. At stress levels below this threshold, the material would be able to withstand an infinite number of load repetitions. If the stress level was increased to 50% of the flexural strength, the material should be able to withstand about 1 million load repetitions. The crack initiation criteria determined by Otte (1978) have since been revised for South Africa to 22% (de Beer 1992).

This research and findings by other researchers provides evidence to support the development of a design fatigue criterion from beam breakage tests so that the working stress or strain in the pavement is at least below 40% of the strain and/or stress at breakage.

Other interesting findings were that the fatigue life for the more highly cemented beams (3% and 4% cement) and the beams stabilised with foam bitumen were higher than the fatigue lives predicted by Austroads (2004). The 1% and 2% cement-stabilised CAPTIF beams had low fatigue lives that were similar to the Austroads predictions.

9 Full-scale pavement trials at CAPTIF

The CAPTIF 4%, 2% and 1% cement-stabilised aggregates were constructed at the NZTA's test track (CAPTIF) and trafficked for 1.5 million passes of a 60kN dual-tyred half axle with 700kPa tyre pressure (unpublished report by David Alabaster). Interestingly, cracking of the pavement test sections were not observed at the surface, but the top layer modulus for all sections dropped to well below half the initial modulus when measured using the falling weight deflectometer after 667,000 laps of a 60kN dual-tyred wheel. Therefore, the fatigue life is less than 667,000 laps of a 60kN dual-tyred wheel. Beams saw-cut from the pavement test sections in the wheeltracks were weaker than those cut in a untrafficked region of the pavement (figures 9.1 and 9.2). Figures 9.1 and 9.2 are selective results from the saw-cut beams, as many were significantly weaker possibly, because of the difficulties associated with obtaining intact beams for testing. Rutting of around 6mm was observed in the CAPTIF test pavements for the 1% and 2% cement contents, while rutting in the 4% cement content was only 3mm after 1.5 million passes of the 60kN dual-tyred wheel. This result indicates that the 1% and 2% cement sections were behaving more like modified unbound materials, while the 4% cement section was behaving more as a bound material.

Figure 9.1 Comparison of beam strength (maximum tensile strength at breaking) for saw-cut beams from the CAPTIF test track

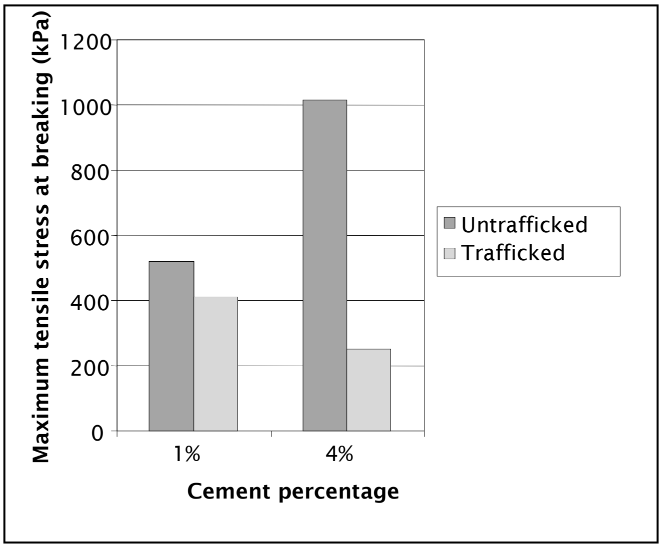
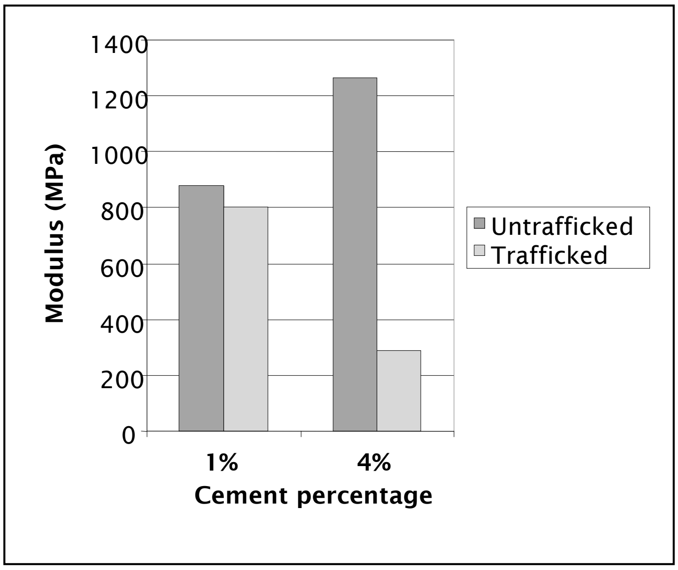


Figure 9.2 Comparison of beam strength (modulus) for saw-cut beams from the CAPTIF test track

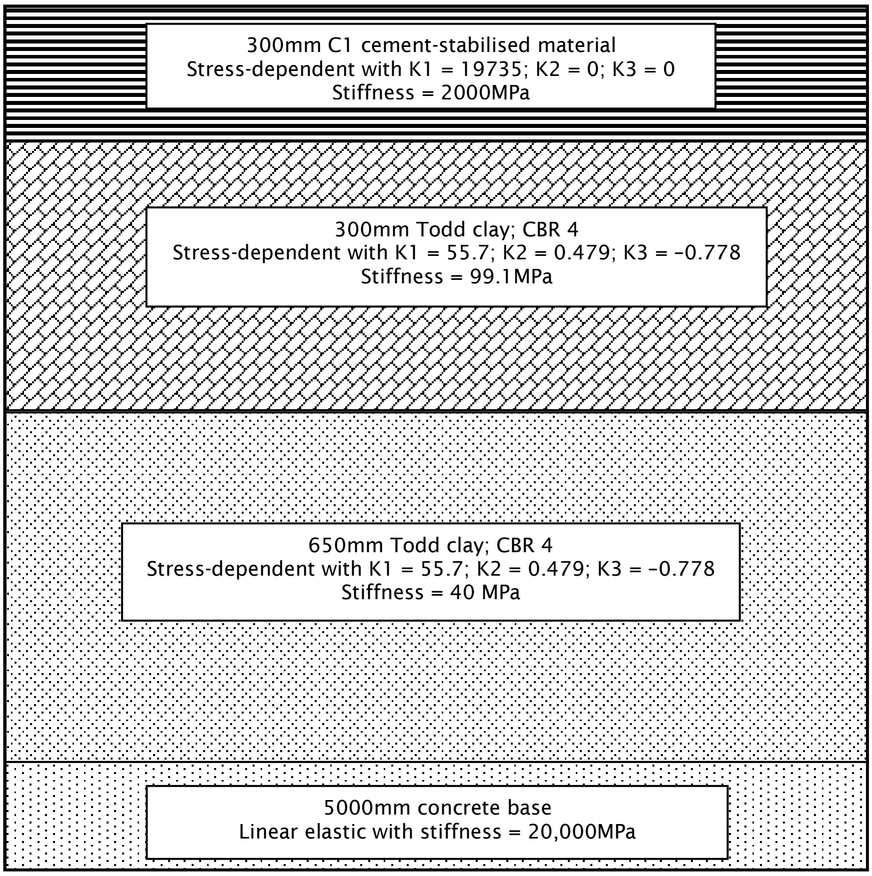


The CAPTIF pavements (200mm stabilised basecourse over a subgrade CBR of 4%; figure 9.3) were analysed to determine the tensile strain and stress at the bottom of the stabilised layer, which were then used to determine pavement fatigue lives using the fatigue constants found in table 8.2 for the CAPTIF materials. Results showing the calculated tensile strain and stress at the base of the stabilised layer, along with the resulting fatigue lives, are shown in table 9.1 and figures 9.4–9.7.

Table 9.1 Pavement tensile strain and stress in the base of the stabilised layer at CAPTIF for a range of assumed stabilised basecourse modulus values

Stabilised basecourse layer	Modulus (MPa)			
	1000	2000	3000	4000
Stabilised depth over subgrade CBR 4% (mm)	200	200	200	200
Tensile stress (kPa)	1017	1240	1351	1426
Tensile strain (microstrain)	694	411	295	234

Figure 9.3 Typical pavement cross-section at CAPTIF



Notes to figure 9.3:

Maximum vertical displacement = 701 microns

Load setup: 60kN load, 700kPa contact pressure

Figure 9.4 Pavement fatigue lives predicted for the CAPTIF pavements for an assumed modulus of 1000MPa

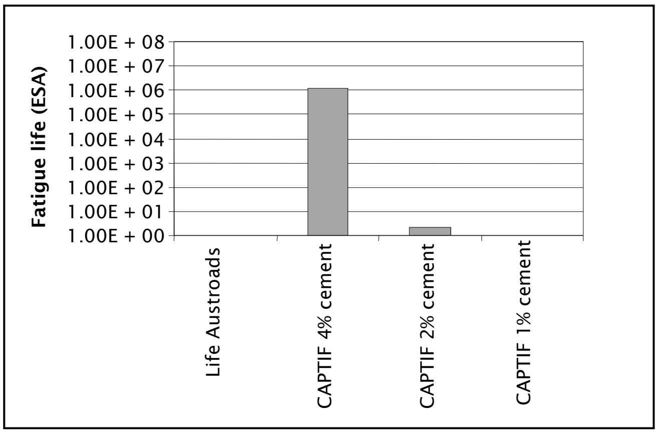


Figure 9.5 Pavement fatigue lives predicted for the CAPTIF pavements for an assumed modulus of 2000MPa

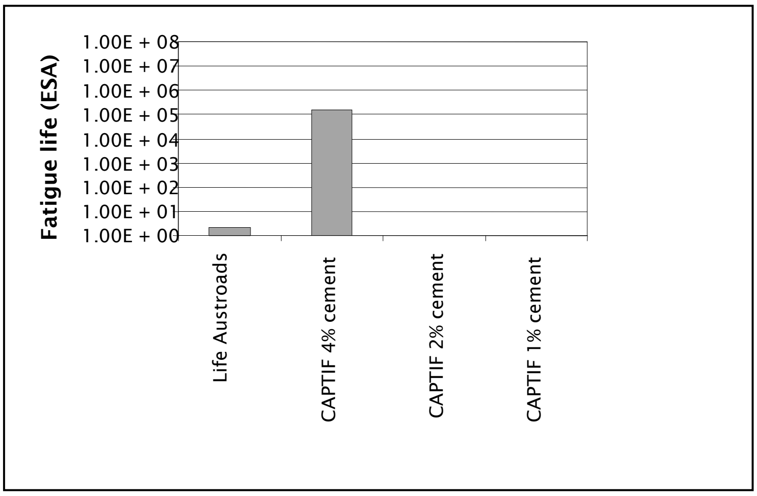


Figure 9.6 Pavement fatigue lives predicted for the CAPTIF pavements for an assumed modulus of 3000MPa

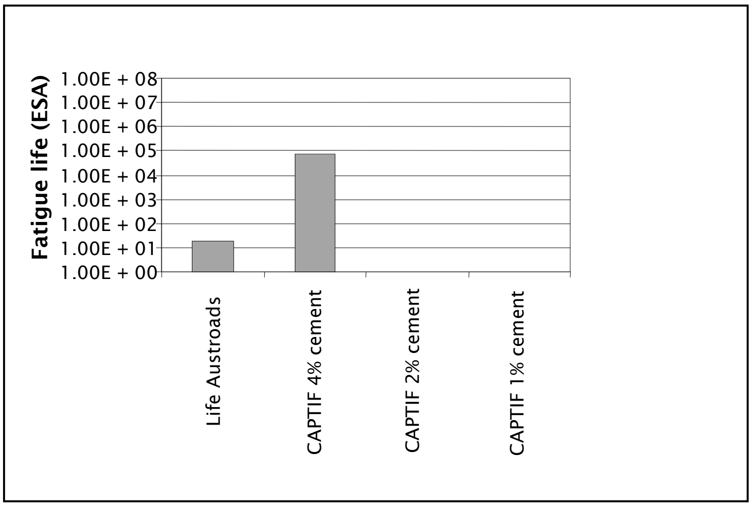
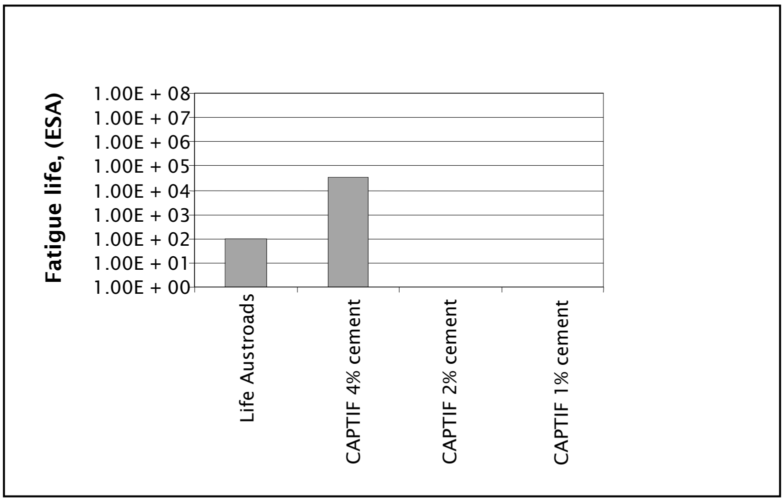


Figure 9.7 Pavement fatigue lives predicted for the CAPTIF pavements for an assumed modulus of 4000MPa



Fatigue predictions show that the fatigue lives would be virtually nil (figure 8.2) for all sections. The exception to this was the CAPTIF 4% cement section, which showed a fatigue life of just less than 100,000 cycles for an assumed modulus of 3000 and 4000MPa. Additional validation with field data is needed before a conclusion can be reached in terms of the ability of the flexural beam tests to predict fatigue life within the pavement. Many saw-cut beams, especially in the wheeltracks, were either too weak to test or had low strengths, with flexural beam moduli around 200MPa, which suggests that the CAPTIF pavement test sections became fatigued within the testing and thus the low predictions of fatigue lives are were considered a 'safe' conservative estimate of fatigue life.

10 Discussion

This research project is a starting point for further research in developing design guidelines for bound materials. Beam testing does result in sometimes variable results, while the maximum tensile stress is less variable. A suggested design approach for design is based on the maximum tensile stress by limiting the applied tensile strength to 40% of the maximum tensile stress. This approach requires further validation with actual pavements in the field. Materials tested in this research may have not been fully bound and future research should investigate higher cement contents. The 1% and 2% cement-stabilised aggregates did result in solid and 'bound' looking beams. However, when tested, they were low in tensile strength and the numbers generated for design tensile fatigue criteria resulted in short fatigue lives for typical pavement designs. Therefore, the 1% and 2% cement-stabilised aggregates in this study would always be considered as unbound, as their phase 1 bound behaviour is very short. Thus, a boundary in terms of tensile strength or cement content is not needed to define when a material is unbound, modified and bound because the tensile strength measured in the lab, combined with use in design, will quickly determine if any phase 1 fatigue life is possible. This will be something for future consideration by the national pavements committee.

Another concerning and interesting finding of this project was the large mismatch between the flexural beam breakage and fatigue tests for the CAPTIF aggregate stabilised with 4% (by mass) of cement. The flexural beam breakage tests show the highest maximum tensile stress of all the material mixtures in this research was approximately 1700kPa, while the fatigue tests showed that the repeated stress applied had to be below 400kPa or else failure would occur within a few hundred load cycles. The beam modulus in the breakage test was in excess of 4000MPa; in the fatigue test, the modulus was around 800MPa. This mismatch in strength between the breakage and fatigue tests only occurred for the CAPTIF + 4% cement mixtures. One reason could be that the slight difference in curing had an effect on this mixture only (CAPTIF plus 4% cement). The breakage tests were completed quickly on beams only just removed from the steel mould and plastic bag (with wet rags on top of the exposed top surface of the beam, which were removed just before testing). These beams were moist to touch and close to OMC, and exhibited high strengths when tested in the breakage test. For the fatigue tests, the beams were taken out of the moulds sometimes a few days before testing (oven curing had finished, but the machine was busy fatigue testing another material and the mould was needed to compact another sample). Wet rags were placed on top of the beam fatigue samples but some drying did occur. It is postulated that this time sitting on the bench caused microcracking from shrinkage and drying, thus weakening the CAPTIF 4% cement beams. If this reduction in strength occurs readily in the lab through microcracking then it probably occurs in the field with wetting and drying cycles. This microcracking is thought to also occur in the field, either as deliberately induced pre-cracking during construction or under sustained traffic loads. A case can therefore be presented for careful controlled temperature-induced cracking in laboratory samples to reflect field performance better (White 2007).

A recently completed fatigue test on the CAPTIF 4% mix that was kept moist was able to sustain high loadings and supported the fact that a repeated load of 693kPa (40% of a breakage load of 1700kPa) can be sustained for 2 million load cycles (figure 7.13). Therefore, beam manufacture, curing and keeping moist is important to ensure that the appropriate results for the design are obtained.

Any future testing standard should consider a period of keeping a sample on the bench without a mould in order to expose any weaknesses in the stabilised material that may occur in the field. Further, the effects of leaving a beam sample to dry on the bench before testing to induce microcracking should be investigated.

Unfortunately, very little field data is available for validating any design approach developed for bound stabilised aggregates. The CAPTIF tests used stabilised aggregates at a depth of only 200mm on a very springy subgrade (a low modulus of around 40MPa but a CBR of around 10%) and were loaded with an equivalent of a 120kN dual-tyred axle (12 tonnes). This pavement configuration at CAPTIF resulted in very high tensile stresses and strains in the stabilised aggregate layer, where the proposed design procedure from the beam testing predicted almost a nil fatigue life for 1% and 2% cemented sections, and 100,000 cycles for the 4% cemented sections . These fatigue predictions were less than what actually occurred at CAPTIF, thus ensuring the design approach is conservative

Despite some variations in results and a lack of field data to validate a method of using beam testing data for designing bound behaviour, this research did yield some useful results and a starting point for design for future research and validation.

11 Pavement design using stabilised aggregates

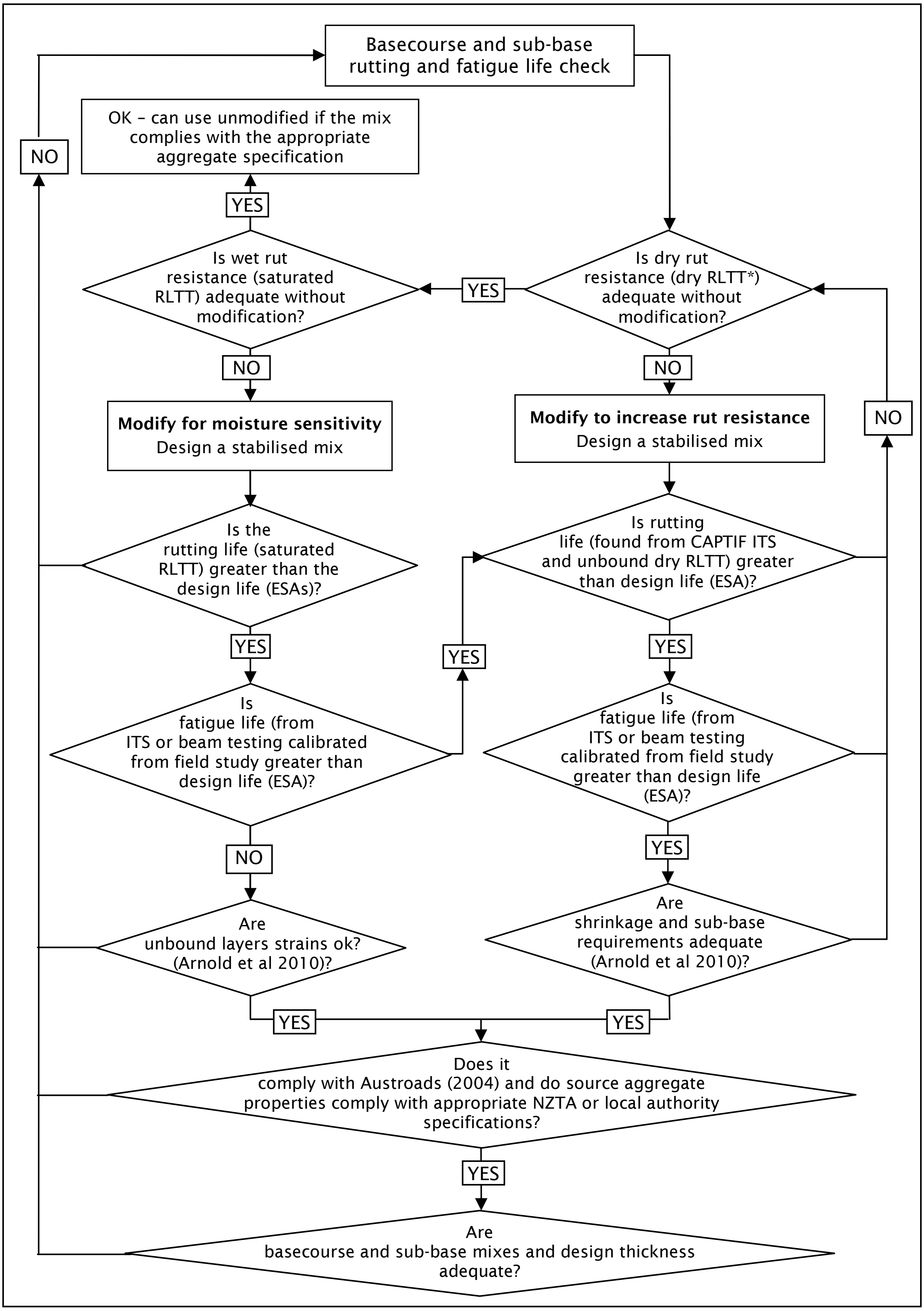
Three large NZTA research projects have recently been completed on stabilised aggregates. These being this study on flexural beam testing, CAPTIF tests and a field study, the latter two of which are listed as 'active projects' by the NZTA. The key researchers met recently to discuss how the outputs of their research can be used in a pavement design process. A flow chart was developed that captured all aspects of a design check for rutting and cracking. The rutting check is based on earlier research using the RLT test (Arnold and Werkemeister 2010; Arnold et al 2010), while checking the fatigue life is based on the recent three research projects on stabilised aggregates. Fatigue life is the number of load cycles when the stabilised aggregate returns to an unbound aggregate. The flow chart detailing a current 'draft' design process is shown in figure 11.1. This design process will be finalised in the next edition of the New Zealand supplement to the Austroads pavement design guide.

It was generally agreed that a design check when using stabilised aggregates is to ensure the actual tensile stress at the base of the stabilised layer using CIRCLY software is less than 50% of the maximum stress/strength recorded in the flexural beam test. This approach is supported by the new Austroads tech series (Austroads 2010):

> ***6.4.5 Means of Determining the Fatigue Characteristics of Cemented Materials***
>
> *Alternative methods*
>
> *Fatigue characteristics of cemented materials may be determined through laboratory testing, preferably in conjunction with field trials, or by adopting relationships contained in the literature.*
>
> *Laboratory fatigue measurement*
>
> *As already discussed, laboratory fatigue testing of cemented materials can be carried out using flexure testing or, to a lesser degree, direct tension testing and indirect tensile testing. The flexure test, in particular, is favoured, as it is considered to simulate field stress/strain gradients. However, the test procedure is still under development.*
>
> *Correlations*
>
> *Static testing may be used to obtain an approximate estimate of fatigue life. Research work has indicated that, for common material types and binder contents, approximately 50% of the strain at break corresponds to a fatigue life of some one million load repetitions. In the absence of more accurate data, this relationship may be used to estimate the fatigue life by determining strain at break from a static stress and linearly interpolating the fatigue life for strain levels greater than 50% of the breaking strain. The fatigue life thus obtained should be considered as indicative only.* (Austroads 201, s6.4.5)

This approach is also broadly supported by Gray's falling weight deflectometer field data (Gray et al 2011), which found the best performing sites were those that had the lowest tensile stresses below 50% of the tensile stress at break.

Figure 11.1 Pavement design process to prevent rutting and cracking within the design life



*RLTT = repeated load triaxial testing

12 Conclusions

12.1 Summary

This research explored a new method of testing stabilised aggregates by undertaking flexural beam tests on a range of materials. The aim was to develop a proposed design method utilising the flexural beam test results. A design method was proposed, but further research and tests are required to develop the approach and refine the lab testing method.

12.2 Background and literature review

From a review by Yeo et al (2002) of potential methods for routine testing of cemented materials for strength, modulus and fatigue, and the method recommended in Austroads (2004), 'it was noted that both the indirect tensile test and the flexural beam test were suitable for estimation of the strength, modulus and fatigue life of cemented materials' (Austroads 2008).

IDT testing uses a circular cylinder tested on its side and repetitive loading to split the sample. However, the literature and Austroad researchers at ARRB report that this method is inaccurate (because of the very small lateral measurements) and does not reflect the beam bending behaviour that occurs in real pavements

A fatigue test is needed for the stabilised aggregates used in New Zealand to ensure that designers consider cracking as a mode of failure in their design approach, which is currently being ignored because of the conservative nature of the Austroads criteria. This proposed test needs to allow for ease of manufacture such that it can be readily conducted as routine testing in design, such as a rectangular foot on a mounted vibrating hammer to compact the beam samples in moulds (150mm square by 550mm long) to the required density, as used in this research.

The flexural beam test chosen for this research is the same as used by ARRB in Austroads research, and a draft standard test method has been developed (appendix A). The main difference is the beam size and the method of manufacture (this research used a mould and vibrating hammer to compact large 150mm square by 550mm long specimens, while ARRB research cut smaller beams from a compacted slab).

Scott (1974) found that at stress levels below 60% of the flexural strength, fatigue did not occur within 1 million cycles. Otte (1978) suggested that although microcracks could start at levels as low as 35%, the material would still be able to withstand about 1 million load repetitions even if the load is increased to 50%. De Beer (1992) later revised Otte's crack initiation criteria to 22%. Shen and Mitchell (1966) examined the properties of both stabilised sand (7% cement) and clay (15% cement), and reported that neither material exhibited fatigue distress at stress levels up to 50% after 1×10^5 load cycles.

Austroads research found considerable variation in modulus values from beam tests, ranging from 3000MPa to as high as 19,000MPa. An anomaly appears in the modulus variation as a function with age. This variation was attributed by the Austroads researchers to the sample location and variations in material properties.

Published relationships between UCS strength and modulus are known to be unreliable across a large range of binder–host combinations and binder contents (Foley et al 2001).

12.3 New Zealand flexural beam testing

The draft Austroads test method for flexural beam testing reported by Austroads (2008) allows for two different beam sizes. The larger beam size (150mm square by 530mm long) was chosen for testing New Zealand 40mm cemented aggregates (table 12.1).

As a slab compactor large enough to compact the 530mm long by 150mm square beam was not available in New Zealand, the stabilised aggregate was compacted in three layers in rectangular mould using a vibrating hammer with a rectangular foot mounted on a frame to control layer height and surface level. Beams compacted in this way were successful and intact, with high tensile strengths obtained (maximum tensile stress just before the beam breaks) that were close to those measured with saw-cut smaller beams from the Austroads/ARRB research project (table 7.3).

Table 12.1 Density and moisture content of the materials used in flexural beam tests

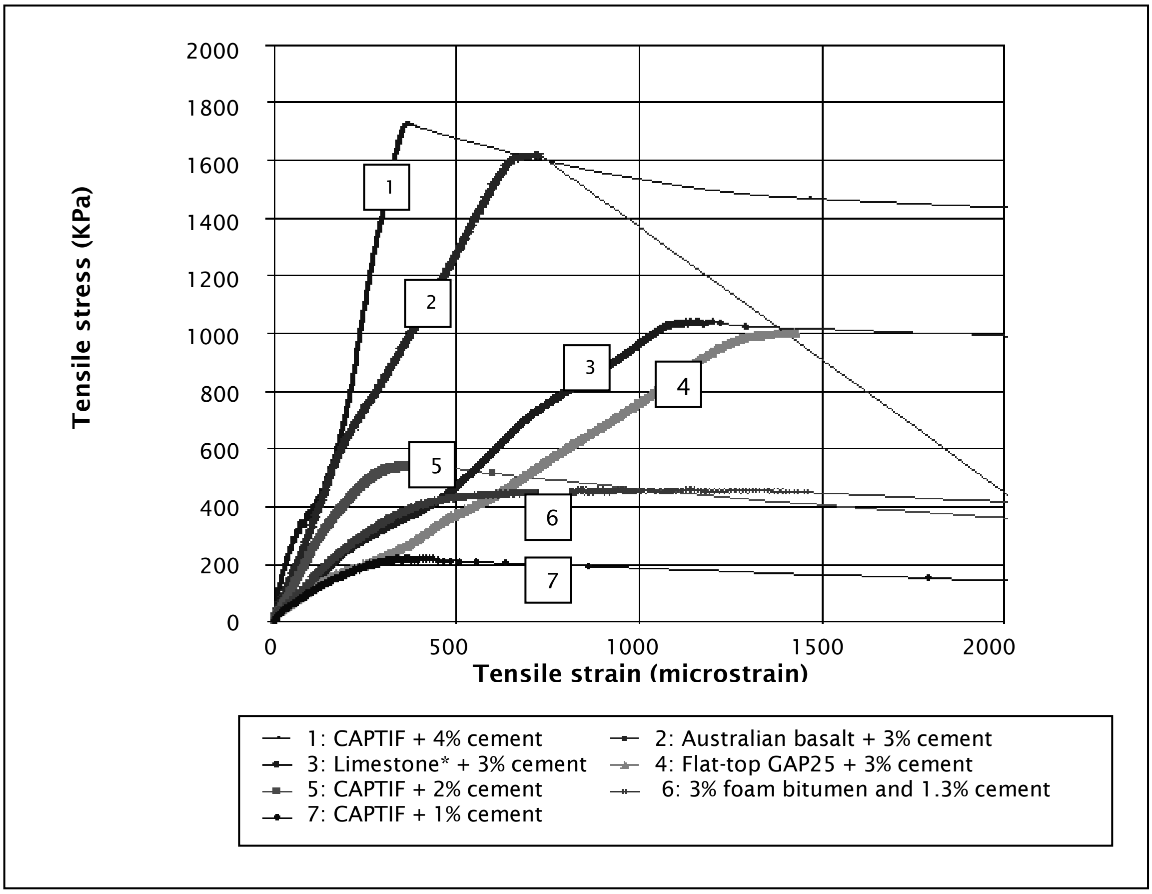
#	Material	MDD	OMC	Target density*	Target moisture content*
A	CAPTIF Isaacs GAP40 + 1% cement	2.4	4.0	2.18	3.0
B	CAPTIF Isaacs GAP40 + 2% cement	2.46	4.2	2.22	3.4
C	CAPTIF Isaacs GAP40 + 4% cement	2.41	4.5	2.19	3.3
D	Basalt (Mt Gambia, Australia) + 3% Blue Circle cement, as used in Austroads study (2008)	2.14	12.0	2.09	10.42
E	Calcrete limestone (Renmark, Australia) + 3% Blue Circle cement as used in Austroads study (2008)	1.95	13.0	1.88	12.81
F	Flat-top +3% cement	2.02	14.0	1.919	12.5
G	Whitford GAP40 + 3% foam bitumen + 1.3% cement	2.2	4.6	2.134	4.6

* The target is the same as was measured *in situ* at CAPTIF; if tested targets were not available, the target was 95% of MDD, which is the minimum according to the B/2 standard (TNZ 2005).

12.4 Flexural beam breakage tests

The maximum tensile stress values can be ranked in order of cement content (4%, 3%, 2%, 1.3% with 3% bitumen, and 1%). The foam-stabilised sample shows greater ductility than the other beams and has almost double the tensile strength of the 1% cement beam (figure 12.1).

Figure 12.1 Flexural beam breakage plots for selected materials



Four tests revealed a reasonably good relationship between ITS and flexural beam maximum tensile stress, where flexural beam maximum tensile stress equals 1.7 times ITS. A similar relationship has been found by other researchers.

A weaker relationship between UCS (2 to 1 ratio) and flexural beam maximum tensile stress was found, where flexural beam maximum tensile stress equals 0.13 times UCS. A similar relationship has been found by other researchers (but with a greater scatter in the results than ITS).

Two repeat flexural beam breakage tests were conducted for all the material mixes, while a total of four repeat tests were conducted for one material mix (CAPTIF with 4% cement). Further testing is needed to determine the repeatability of the testing, although these limited tests found that the maximum difference between maximum tensile stress was up to 10%, while the difference between Young' s modulus and maximum tensile strain could be as high as 80%.

Because maximum tensile stress is a more repeatable measure, it was recommended that a stress-based approach be considered in any proposed bound design fatigue criteria.

The 1% cement CAPTIF beams manufactured in the lab were half the tensile strength (200kPa v 400kPa) of the untrafficked saw-cut beams from the test track, possibly because of the shorter curing periods in the lab, although one of the two lab beams had a modulus of 700MPa, which was close to the four saw-cut beams (700–900MPa) both inside and outside the wheelpath.

One out of five saw-cut beams from the 4% cement CAPTIF pavement in the untrafficked wheelpath had a tensile strength of 1000kPa, while the other beams in and outside the wheelpath had a tensile strength of 180–370kPa. One pre-cracked 4% cement saw-cut beam from CAPTIF in the untrafficked area had a tensile strength of 800kPa. These results compared poorly with the lab-manufactured beams, which had a tensile strength of around 1700kPa. However, the lab beams used in the fatigue test reduced in strength to around 500kPa because of microcracking caused by some air-drying. Large variations appeared in modulus and tensile strain, and were thus not comparable. Moduli for the saw-cut beams were below 500MPa, while the lab beams had moduli of 2000–7000MPa.

Results for both the Australian basalt and limestone with 3% cement (tables 7.3 and 7.4, and figures 7.13 and 7.15) tested by ARRB (using a slab compactor and saw-cut smaller beams of 100mm square by 330mm long) and in this research project (vibrating compaction in a 150mm square by 530mm long mould) all show similar maximum tensile strengths (within 15%). However, the modulus values measured by ARRB/Austroads are up to 10 times higher (approx. 15,000MPa v 1500MPa) than those measured with the larger beams. Therefore, the tensile strains measured by ARRB/Austroads are 10 times lower, which has implications for any design criteria that Austroads develops as a result of their research.

If a stress-based approached is used for developing design strain criteria, as suggested earlier (where a maximum (or limiting) tensile strain is calculated from the measured maximum tensile stress (or, say, 40% of the maximum) in the beam test from an assumed modulus) then the resulting design tensile strain criteria would be the same as those revealed by the Austroads and Pavespec test results on the same material (because the maximum tensile stress measured in the flexural beam breakage test is the same).

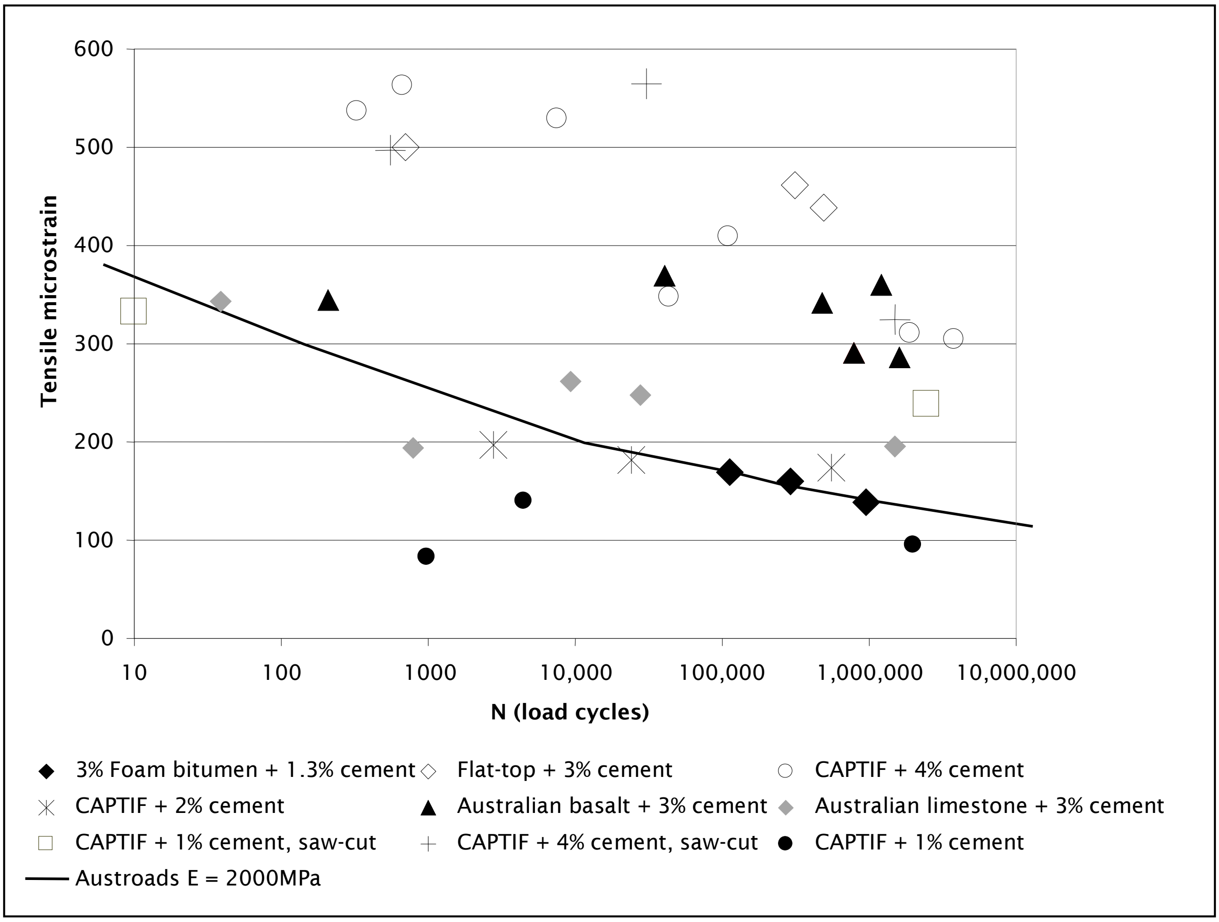
The beam tests showed no single relationship between the strength and modulus, which is supported in other research (Williams 1986).

12.5 Flexural beam fatigue test results

In addition to flexural beam breakage tests, at least three duplicate beams were manufactured and repetitive loading was applied. For each beam fatigue test, a different loading was applied to determine a fatigue relationship relating the number of load cycles to failure (when the beam breaks, brittle failure is observed and the modulus does not reduce with increasing load cycles) and tensile strain.

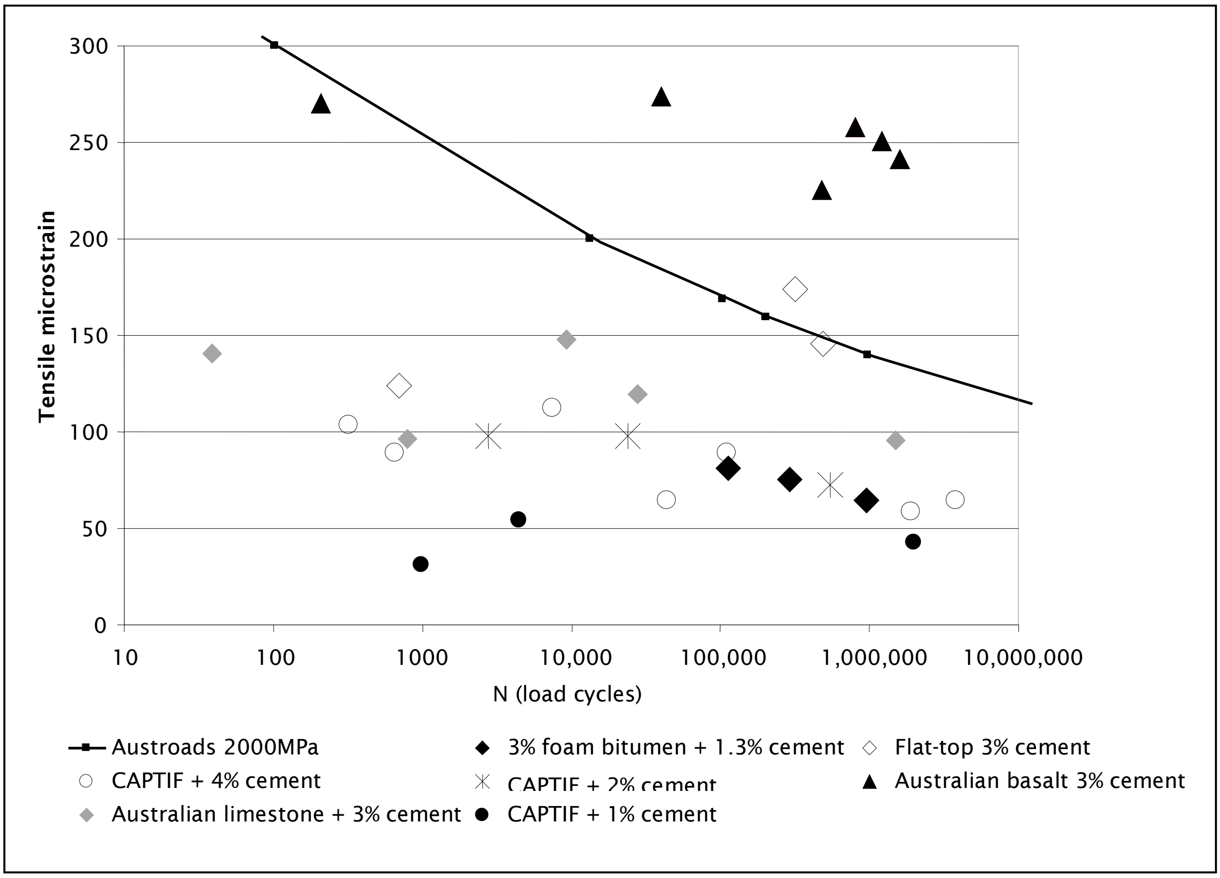
The raw results of the fatigue tests are shown in figure 12.2

Figure 12.2 Tensile fatigue test results for a range of tested materials



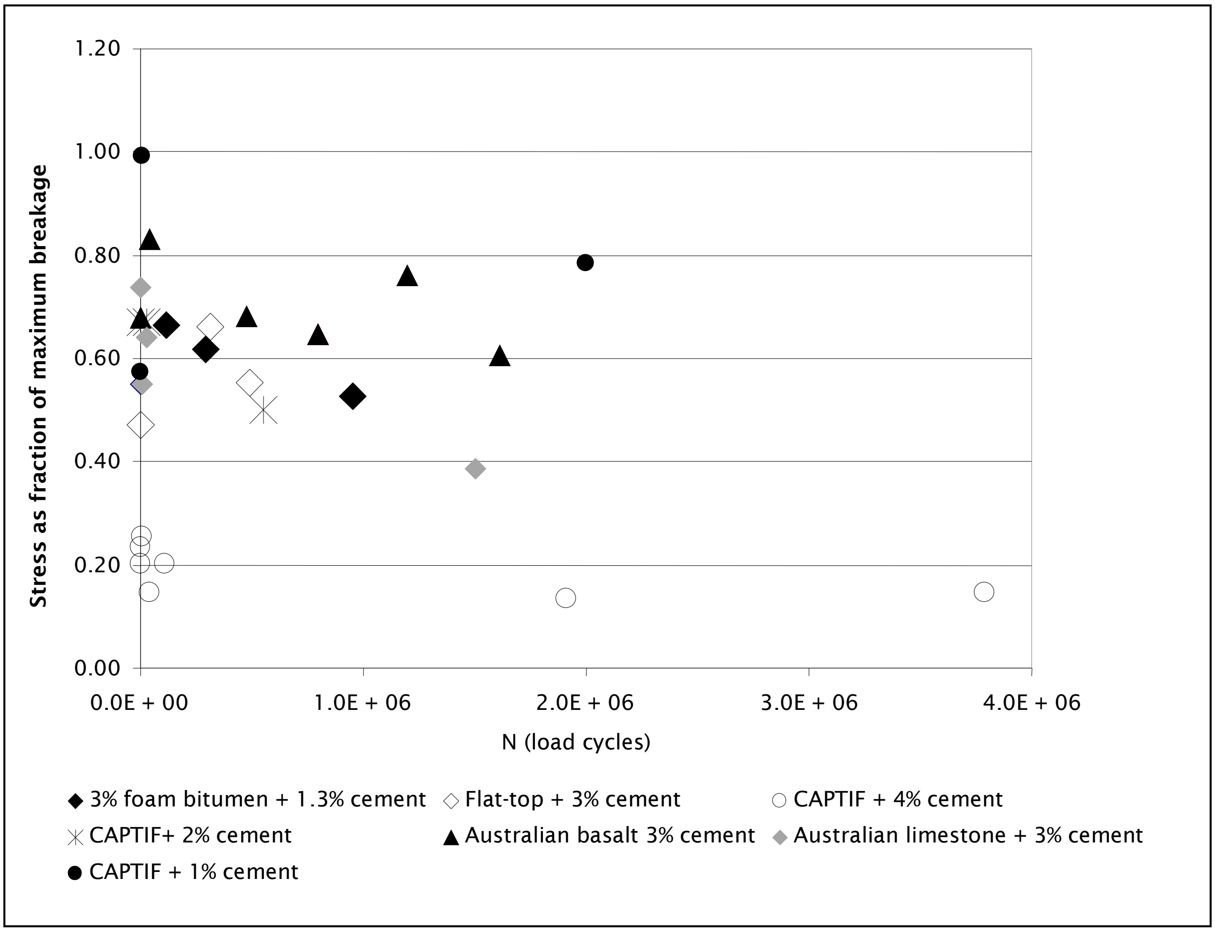
The beam fatigue results were reanalysed by keeping the applied tensile stress the same but calculating the associated tensile strain for an assumed modulus of 2000MPa for all tests. This method gives a direct comparison for fatigue performance for the different materials at a design modulus of 2000MPa, as shown in figure 12.3. Apart from the Australian basalt with 3% cement and the flat-top with 3% cement gave the best fatigue performance. However, in design, it is important that the actual measured beam modulus of the material is used, as a brittle material (high modulus, eg 5000MPa) will have a lower fatigue life than a more flexible material (low modulus, eg 2000MPa) that has the same tensile strength at breakage.

Figure 12.3 Tensile fatigue test results assuming a constant beam modulus (normalised strain) of 2000MPa



Several researchers analysed fatigue performance in relation to the applied tensile stress as a fraction of maximum tensile stress and found that if the applied tensile stress is below 50% of the maximum, then the fatigue life will be in excess of 1 million. A repeat fatigue test on the CAPTIF 4% cement beams supported this result. It has been suggested that a proposed design approach should be based on limiting the applied tensile stress to less than 40% of the maximum as, in general, fatigue lives in excess of 1 million cycles were obtained (figure 12.4).

Figure 12.4 Tensile fatigue test results in relation to applied tensile stress as a fraction of maximum tensile stress



Air-drying, which caused microcracking in the CAPTIF 4% cement beams, resulted in a reduction of tensile strength from around 1700kPa (found in the breakage test where the beams were not air dried) to 500kPa (estimated in the fatigue test). This did not occur for other beams tested. This microcracking is also thought to occur in the field, either deliberately induced pre-cracking during construction or cracking under sustained traffic loads. A case can therefore be presented for the carefully controlled temperature-induced cracking in laboratory samples to reflect field performance better (White 2007).

Any future testing standard should consider keeping a sample on the bench without a mould for a period of time in order to expose any weaknesses in the stabilised material that may occur in the field. The effects of leaving a beam sample to dry on the bench before testing to induce microcracking should be investigated.

Further research is needed to determine and validate a method of flexural beam testing and design using the results from the beam fatigue tests. As a starting point, the following design approach is proposed. The results show that the fatigue life will probably be greater than 1 million cycles if the applied stress is less than 0.4 of the maximum tensile stress. This result can be one point of the design fatigue relationship. Assuming the same power exponent (12) as Austroads (2004), the constant *k* in the fatigue relationship (equation 12.1) can be determined.

$$N = \left(\frac{k}{tensile\_microstrain} \right)^{12} \qquad \text{(Equation 12.1)}$$

An example of pavement design was undertaken using the method described above to determine the constant *k* for the fatigue relationship. The fatigue lives calculated were higher than those for the assumed relationships in the Austroads pavement design guide (2004).

Fatigue lives for the CAPTIF pavements calculated using the method proposed were found to be less than 100 wheelpasses for the 1% and 2% cement-stabilised sections and just below 100,000 for the 4% cement-stabilised section. The actual fatigue lives found in the CAPTIF test were higher than those predicted, which shows the current design method proposed is conservative.

13 Recommendations

Several key aspects touched on in this research project need more research, namely:

- repeatability of the beam test
- a methodology for lab curing and associated air-drying to induce microcracks if deemed appropriate
- further field data to validate and refine the proposed fatigue criteria derived from 40% of the maximum tensile stress.

A stress-based approach is recommended because of the large variation in modulus in the tests, particularly the 10-fold differences between the ARRB and Pavespec moduli and strain values, while the maximum tensile stress varied by only 10%. Designers are encouraged to trial the proposed beam test and associated fatigue criteria and record any feedback on their use.

The number of repeat tests and how a final tensile strength and modulus value is determined (average, minimum, removal of outliers, etc) will require further tests and then discussion/agreement with industry groups. Initial results would indicate that the maximum tensile strength is more repeatable and should be considered in design. As the modulus is equal to stress divided by strain (strain is equal to stress divided by modulus), for a given maximum tensile stress (a repeatable measured result in the lab test), a range of maximum tensile strains can be calculated for a range of modulus values. This idea of using the maximum tensile stress as the first input for fatigue design was recommended in the design section of this report (chapter 11).

Any future testing standard should consider a period for keeping a sample on the bench without a mould in order to expose any weaknesses in the stabilised material that may occur in the field. Further, the effects of leaving a beam sample to dry on the bench before testing to induce microcracking should be investigated.

Cross-sections from actual pavements with bound stabilised layers should be analysed using the proposed design methodology. Data on actual pavement life and the amount of cracking (either seen or inferred through changes in surface deflections) should be used to validate and/or refine the design approach proposed.

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Appendix A Flexural beam test (from Austroads 2008)[2]

A1 Scope

To set out the method for the laboratory determination of the modulus and fatigue life of stabilised materials using flexural modulus techniques.

A2 Referenced documents

The following documents are referred: AS 1012.11-2000: *Methods of testing concrete: method 11: determination of the modulus of rupture*, AS 1545-1976: *Methods for the calibration and grading of extensometers*, AS 2193: *Methods for the calibration and grading of force-measuring systems of testing machines*[3].

A3 Apparatus

The following apparatus is required:

- *Testing machine* – pneumatic or hydraulic testing machine that is capable of applying an approximately haversine load pulse with a rise time (defined as the time required for the load pulse to rise to 10% to 90% of the peak force) in the range of 0.03s to 0.1s with an accuracy of ±0.005s. The machine shall be capable of applying load pulses with peak load adjustable over the range as specified in clauses 6.1 and 6.2 with an accuracy of ±0.05kN dependent on the range of material stiffness to be tested. The pulse repetition period shall be adjustable over the range 0.5s to 2s ±0.005s. The machine shall be capable of applying this load pulse repeatedly until sample failure.
- *Measuring and recording apparatus* – measuring and recording apparatus consisting of
    - A load-measuring device of equal to or greater than the maximum capacity of the loading ram, meeting the requirements of [the] AS 2193 Grade B testing machine when calibrated statically.
    - A displacement measuring device meeting the requirements of an AS 1545 Grade B extensometer with a range of at least 100μm for measurement of vertical mid-span displacements of the beam for each pulse and capable of being in contact with the specimen during the complete test. The device shall be capable of being anchored to the specimen through a support frame resting over the lower specimen support rollers.

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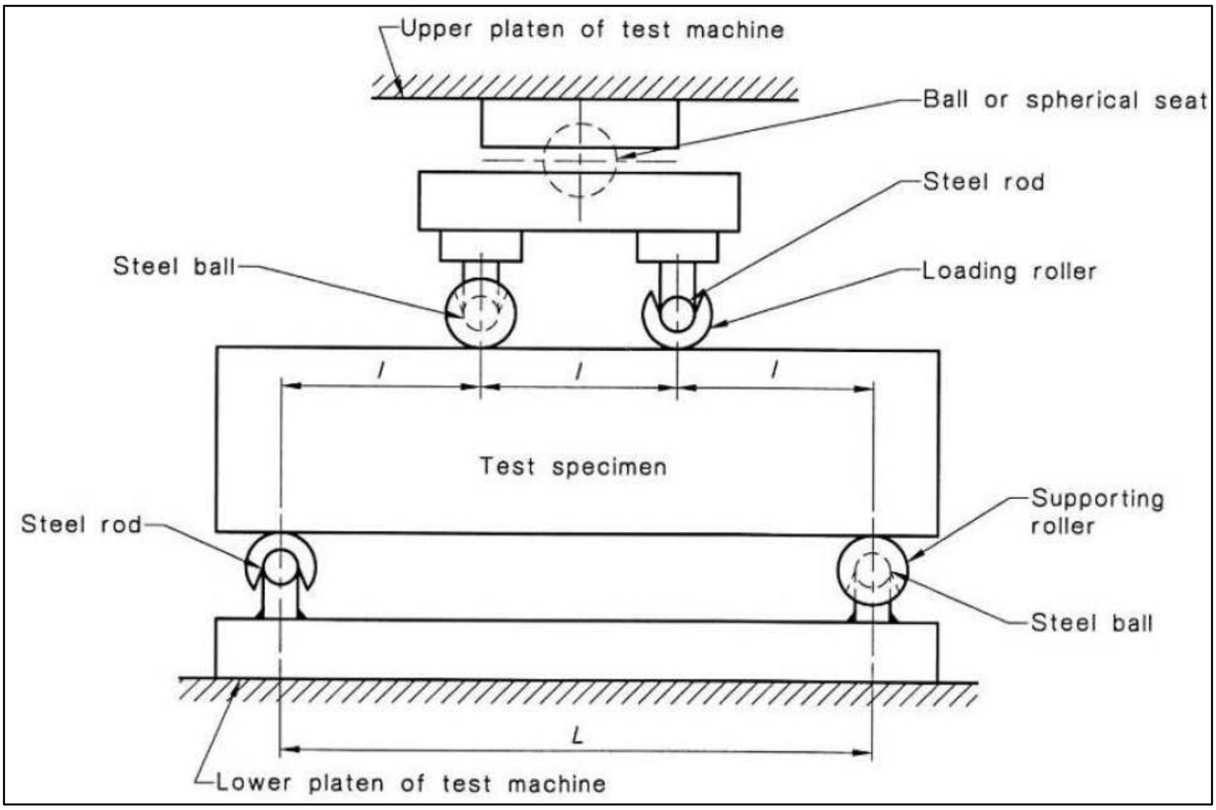
[2] This appendix was originally published as appendix D of *Austroads technical report – AP-T101/08* (Austroads 2008) and has been reproduced with the kind permission of Austroads. The headings have been renumbered and the text has been subjected to minor editing to make this appendix conform with NZTA house style.

[3] See Standards Australia (1976, 2000, 2005) in the references section of this report.

   - A recorder able to read and record the individual measurements of load and displacement.

- *Flexural beam roller supports and load rollers* – beam support apparatus as described in AS 1012.11-2000 as shown in figure A1 (sourced from Standards Australia 2000).
- *Vernier calliper* – or other suitable device capable of measuring the height and diameter of the *sample to the ne*arest 1mm.

Figure A1 Flexural beam roller supports and load roller equipment setup



A4 Test specimens

A4.1 Specimen dimensions

Specimens shall be rectangular with smooth, uniform parallel surfaces. The beam specimen dimensions may vary in cross-section from 80mm upwards with a typical cross-section dimension of 100mm (see note 1). The span to depth ratio for the beams should be 3 or greater. Example dimensions for typical samples are shown in table A1. The top and bottom faces of the specimens shall not depart from squareness to the axis by more than 2 degrees (about 3mm in 100mm).

Table A1 Typical specimen dimensions in millimetres

Span (L)	Width of specimen (w)	Height of specimen (h_c)
300	100 ± 5	100 ± 5
450	150 ± 5	150 ± 5

A4.2 Specimen preparation

Laboratory specimens should be prepared using the following general guidelines:

- Binder should be added to the dry aggregates. Thorough mixing is required for the whole mix initially with the dry ingredients then after the addition of the required moisture.
- Minimal (zero) delay shall apply between mixing the host material, binder and water, and commencement of compaction.

A means of compacting the beam specimens using either vibratory or compressive force in a suitable mould shall be used for compaction. The BP slab compactor has been shown to be suitable apparatus to manufacture slabs of cemented material. These slabs are cut down to the required specimen dimensions on a diamond tipped saw prior to testing. The potential for segregation and edge effects from compaction in a rectangular mould need to be addressed in specimen compaction.

Specimens shall be moist cured initially for at least 48 hours in the compaction mould (which must be sealed to prevent moisture loss) then for a total of 7 or 28 days at 23 ± 2°C (see note 2). Specimens shall be wrapped in wet newspaper or hessian and sealed in plastic bags for moist curing if they are removed from the mould.

Field specimens can be obtained from material placed and cured in the road bed. A portable large diameter circular diamond saw may be used to cut slabs of the cemented material.

These slabs can be carefully extracted and subsequently sawn to the required specimen size in the laboratory. Care must be taken to ensure the cemented material is not damaged in the sampling process.

Note that all specimens should be placed in a moist curing environment such as a fog room for a minimum of 48 hours prior to testing to ensure consistent moist specimen conditions for testing.

A5 Procedure

A5.1 Modulus testing

The procedure shall be as follows:

(a) Measure the dimensions of the specimen to the nearest 1mm; taking four measurements for each dimension. Calculate the averages of the four measures for length (L), width (w) and height (h).

(b) Note the span of the apparatus (L).

(c) Place the specimen in the loading apparatus, ensuring that the specimen is orientated with the ‘top of the specimen’ upwards.

(d) Determine an appropriate peak load to apply to the specimen such that the specimen remains within its elastic range. As a guide, loading for the fatigue test shall be up to 40% of the estimated ultimate breaking load of the specimen.

(e) Apply repeated haversine loading to the specimen for 100 load pulses. The haversine pulse width shall be 250ms in duration with a 750ms rest between pulses making a 1000ms pulse period. Record the maximum force applied to the specimen (P) as indicated by the testing machine, and the peak displacement (δh) for the haversine load pulses applied for each pulse.

A5.2 Fatigue testing

On completion of the modulus test, the same specimen may be used for the fatigue test provided no fatigue damage has occurred in the sample (hence the requirement for the modulus test to be conducted at 40% or less of the ultimate failure load of the specimen). If this is the case, continue with the steps below. Alternatively, if a new specimen is to be used for the fatigue test, follow steps (a) to (c) above, then continue below.

(d) Determine an appropriate peak force to apply to the specimen to induce fatigue. As a guide the force should be in the range of 60% to 90% of the ultimate failure load on the beam. The haversine pulse width shall be 250ms in duration with a 250ms rest between pulses making a 500ms pulse period. Record the maximum force applied to the specimen (P) as indicated by the testing machine, and the peak displacement (δh) for the haversine load pulses applied for each pulse (or a representative sample of the pulses which covers the full fatigue test).

Apply repetitive haversine loading pulses, continuing until the beam fails.

(e) At the conclusion of the test note the appearance of the sample, the location and type of fracture and note if the fracture is unusual.

A6 Calculations

A6.1 Resilient modulus

The resilient modulus of the specimen shall be calculated as the average of the last 50 load pulses of the 100 load pulses applied to the specimen as follows:

$$S_{\max} = \frac{\sigma_t}{\varepsilon_t} \times 10^3 = \frac{\dfrac{PL}{wh^2 \times 10^6}}{\dfrac{108\delta h}{23L^3 \times 10^6}} \times 10^3 = \frac{23PL^3}{108wh^2\delta h} \times 10^3$$

where:

- $S_{\max}$ = flexural stiffness, in megapascals
- P = peak force, in kilonewtons
- L = beam span
- w = specimen width, in millimetres
- h = specimen height, in millimetres
- δ = peak mid-span displacement, in millimetres.

A6.2 Fatigue

The initial modulus of the specimen is defined as the average modulus determined from the first 50 load pulses applied to the specimen during the fatigue test. The modulus is calculated as described in section 7.1 [of Austroads (2008)]. The fatigue life is then defined as the number of pulses applied to the specimen to reduce the specimen modulus to half of the initial modulus.

A7 Test report

The following information shall be recorded for each test specimen:

- stabilised material mixture, identification and relevant component details including nominal mix size, grading type, binder content and type
- for laboratory compacted specimens, report the method of the specimen preparation (for example, if a BP slab compactor is used, the number of cycles of the BP slab compactor and applied vertical stress would be reported)
- if a field specimen is tested, the date of trenching and location information relating to the specimen (for example the pavement chainage/offset and direction of traffic flow)
- date of specimen manufacture or date of placement of layer, if known, age of specimen at date of test and curing history
- date and time of test
- moisture condition of the specimen, where applicable
- any apparent defects of the specimen
- mean height of each specimen to the nearest 1mm
- mean width of each specimen to the nearest 1mm
- mean length of each specimen to the nearest 1mm
- peak force applied for each haversine load pulse (or a representative sample of pulses)
- peak mid-span deflection resulting from each load pulse (or a representative sample of pulses)
- other properties of stabilised material that may be considered to have influenced the results
- identification of the operator carrying out the test
- job site or laboratory where tested
- reference to this test method.

A8 Notes on test

1. Standard specimen dimensions are 100mm by 100mm square cross-section with a length suitable for a 300mm span. Larger specimens may be required dependent on the maximum aggregate size in the mix.
2. The test has been designed with the aim of sample fatigue within approximately 3 hours or about 10,000 load cycles. However, as fatigue life may vary considerably for different stabilised materials, it is recommended that the test equipment be designed to operate for in excess of 1,000,000 cycles for each test.
3. If the strength test on a specimen is to be used as an input to the modulus and/or fatigue test, the same specimen properties (material mix, cure period and sample size and preparation method) [as] that proposed for the modulus and/or fatigue test should be adopted. A cure period of 28 days or greater is recommended for the modulus and an extended period of greater than 3 months or more is recommended for the fatigue test.

Appendix B Flexural beam test results

B1 Comments

The numbering system for the saw-cut beams is the section letter (B = 1% cement, C = 2% cement, D = 2% lime, E = 4% cement and F = 4% cement and pre-cracked) followed by ‘U’ or ‘T’ for untrafficked or trafficked, respectively, then a sequential number in the direction of rig travel, except for section B, which was removed in the opposite direction. Lab-compacted beams for CAPTIF + 1% cement, CAPTIF + 2%, Australian basalt, Australian limestone, flat-top GAP25 and Whitford GAP40 stabilised with foam bitumen are numbered as shown in tables B1 to B3.

Table B1 Numbering of lab-compacted beams using CAPTIF aggregate (test number PS0839)

Material	#	Date
CAPTIF aggregate (Isaacs) + 4% cement	2	28/11/08
	3	14/01/09
	4	14/01/09
	5	14/01/09
	6	14/01/09
	7	14/01/09
	9	03/02/09
	10	10/02/09
	11	11/02/09
	13	11/02/09
	14	11/02/09
CAPTIF aggregate (Isaacs) + 2% cement	15	25/02/09
	16	25/02/09
	17	25/02/09
	18	25/02/09
	19	02/03/09
CAPTIF aggregate (Isaacs) + 1% cement	20	-
	21	-
	22	-
	23	-

Table B2 **Numbering of lab-compacted beams using Australian aggregate (test number PS0840)**

Material	#	Date
Australian basalt + 3% Blue Circle cement	1	22/10/09
	2	23/10/09
	3	23/10/09
	4	27/10/09
	5	28/10/09
	6	19/11/09
	7	19/11/09
	8	19/11/09
	9	26/11/09
	10	30/11/09
Australian limestone + 3% Blue Circle cement	11	3/11/09
	12	3/11/09
	13	3/11/09
	14	4/11/09
	15	4/11/09
	16	2/12/09
	17	2/12/09
	18	2/12/09
	19	3/12/09

Table B3 **Numbering of lab-compacted beams using Winstone flat-top aggregate (test number PS0839)**

Material	#	Date
Winstone flat-top GAP25 + 3% cement	1	17/06/09
	2	17/06/09
	3	17/06/09
	4	19/06/09
	5	19/06/09

An initial review of the flexural beam breakage tests for the saw-cut beams showed some unusual results, which may be explained by differences in construction and/or the water leaking on the pavement. Five days into the testing period, the untrafficked saw-cut CAPTIF + 4% beams had reached nearly 2 million load cycles at a tensile strain value of 400 microstrain and a tensile load of around 490kPa (the modulus was 1200MPa). This performance reflected the results found from the beams compacted in the moulds.

B2 Lab-compacted CAPTIF + 1% cement

The lab-compacted beams containing CAPTIF aggregate + 1% cement are compared with each other, and also against the saw-cut beam BU2 (CAPTIF + 1% cement, untrafficked). Beams #20, #21 and #22 were kept sealed in plastic in the mould with wet rags for seven days in an oven at 40°C.

Figure B1 **Flexural beam breakage test plot for lab-compacted CAPTIF + 1% cement beams**

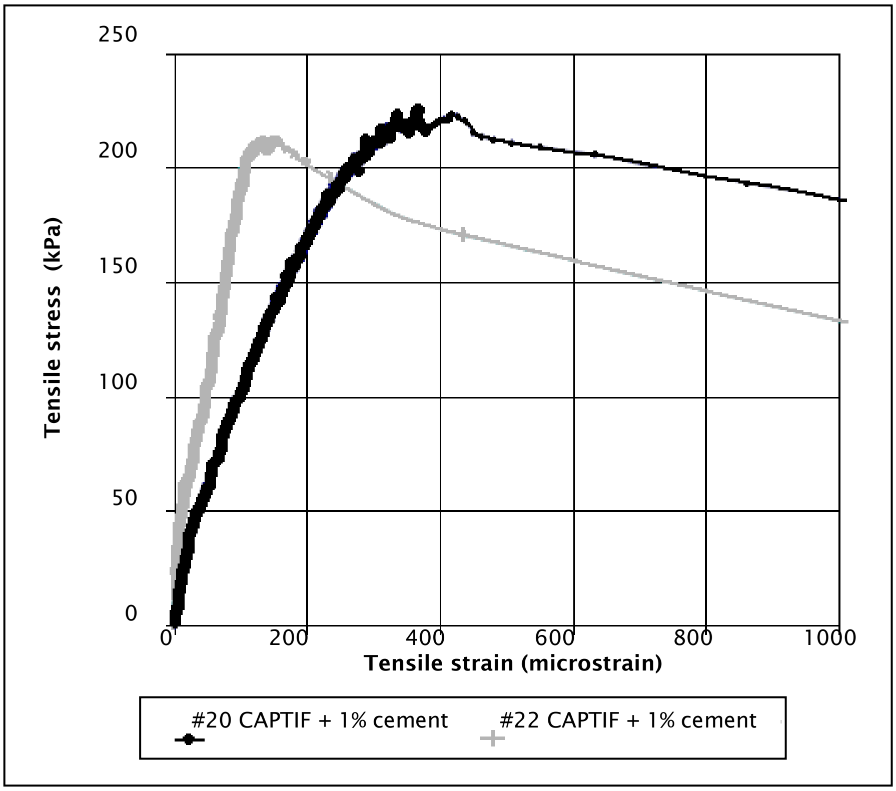


Table B4 **Flexural beam breakage test result for CAPTIF + 1% cement beams**

Test	Description	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)
20	Linear limit	207	288	721
22	Linear limit	211	132	1599
20	Low strain	104	100	1037
22	Low strain	197	100	1972
20	Maximum	225	366	615
22	Maximum	213	147	1445

Table B5 **Flexural beam modulus test results for CAPTIF + 1% cement**

Test	Load (kN)	Tensile strength (kPa)	Tensile strain (mm)	Flexural modulus (MPa)
20	0.61	81	41	1949
23	0.61	81	54	1505
BU2	1.57	164	147	1114

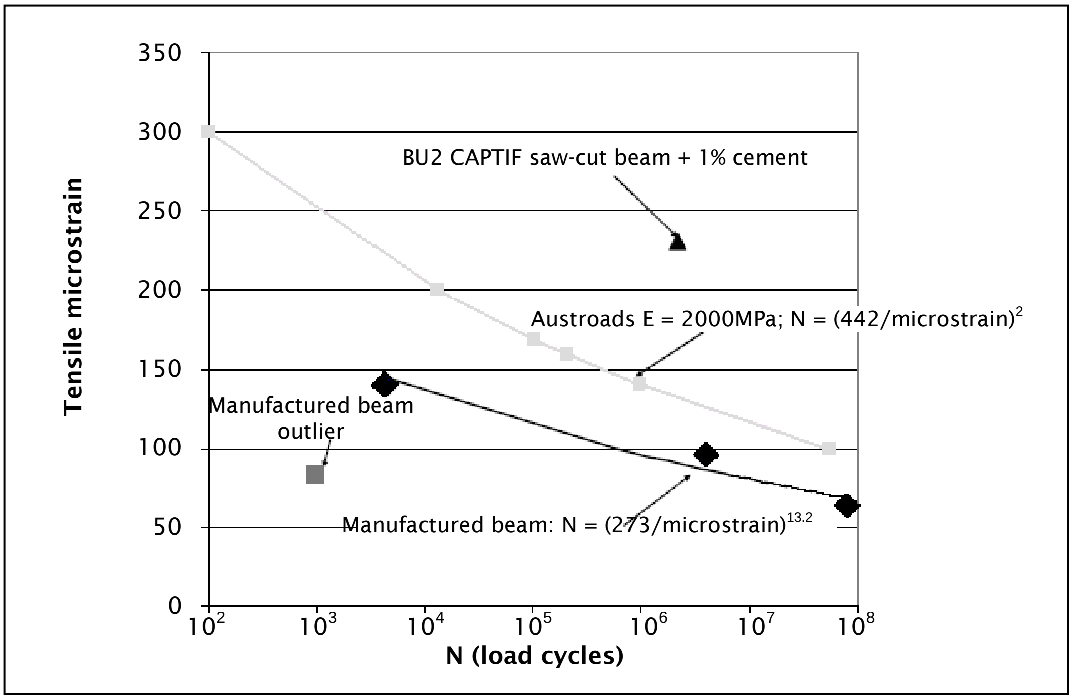
*Repeated loading for 100 cycles is haversine at 4Hz; values are maximum load.

Table B6 **Flexural beam fatigue test results for CAPTIF + 1% cement**

Test	Description	When	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)	Load cycles to failure
21i	Beam #21 restarted at different stress	Start	217	140	1549	4441
		End		177	1227	
21g	Beam #21 restarted at different stress	Start	172	96	1795	970,009 (test stopped); extrapolated data suggests 4 million cycles
		End		107	1642	
21b	Beam #21 restarted at different stress	Start	63	40	1602	1 million (test stopped); extrapolated data suggests the beam will not fatigue (>10 million)
		End		37	1725	
21c	Beam #21 restarted at different stress	Start	125	64	1966	1 million (test stopped); extrapolated data suggests the beam will not fatigue (>10 million)
		End		68	1925	
23b	New beam #23	Start	125	83	1518	977
		End		103	1222	
BU2	Saw-cut beam	Start	325	231	1405	2,154,810
		End		238	1367	

* Repeated loading is 4Hz haversine; values are maximum load.

Figure B2 **Flexural beam fatigue test results for CAPTIF + 1% cement beams**



*Repeated load is haversine at 4Hz; values are maximum load.

Figure B3 **Flexural beam tensile strain (fatigue testing): beam BU2 (saw-cut CAPTIF + 1% cement, untrafficked)**

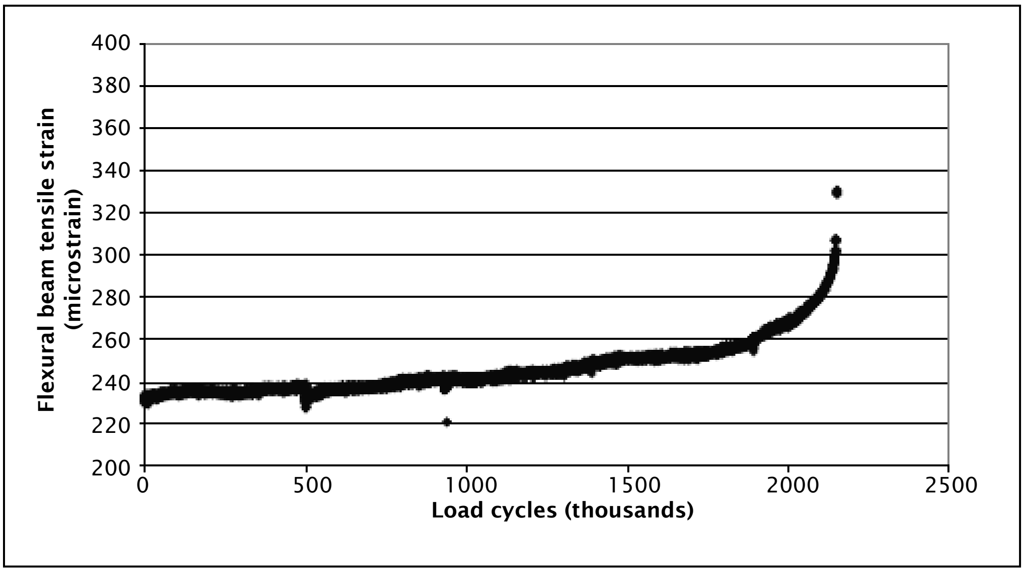
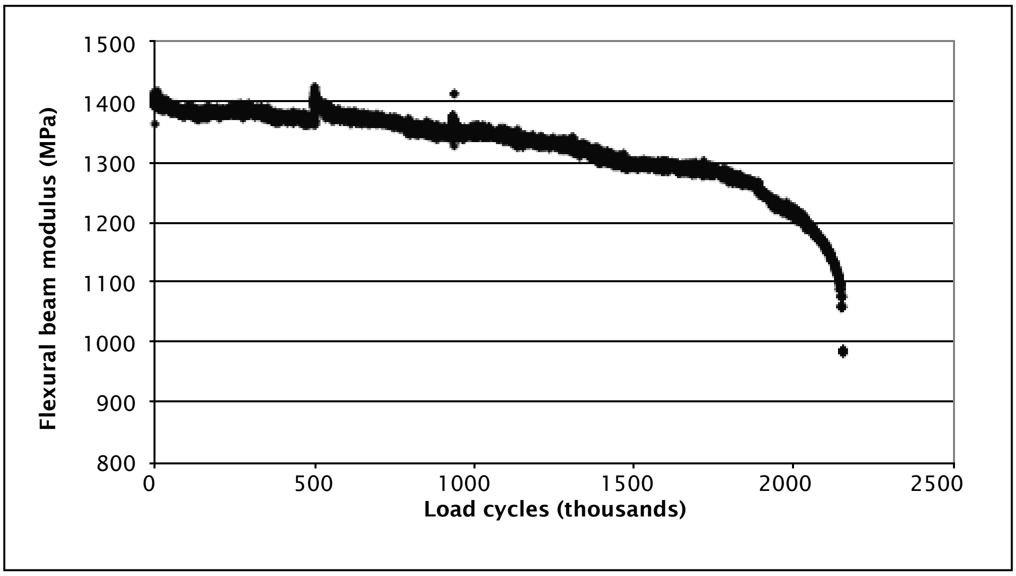


Figure B4 **Flexural beam modulus (fatigue testing): beam BU2 (saw-cut CAPTIF + 1% cement, untrafficked)**



B3 Lab-compacted CAPTIF 2% cement

Beams #15–#19 were used for these tests. Manufactured beams #15–#19 were kept sealed in plastic in the mould with wet rags for seven days in the oven at 40°C.

Figure B5 Flexural beam breakage test plot for CAPTIF + 2% cement

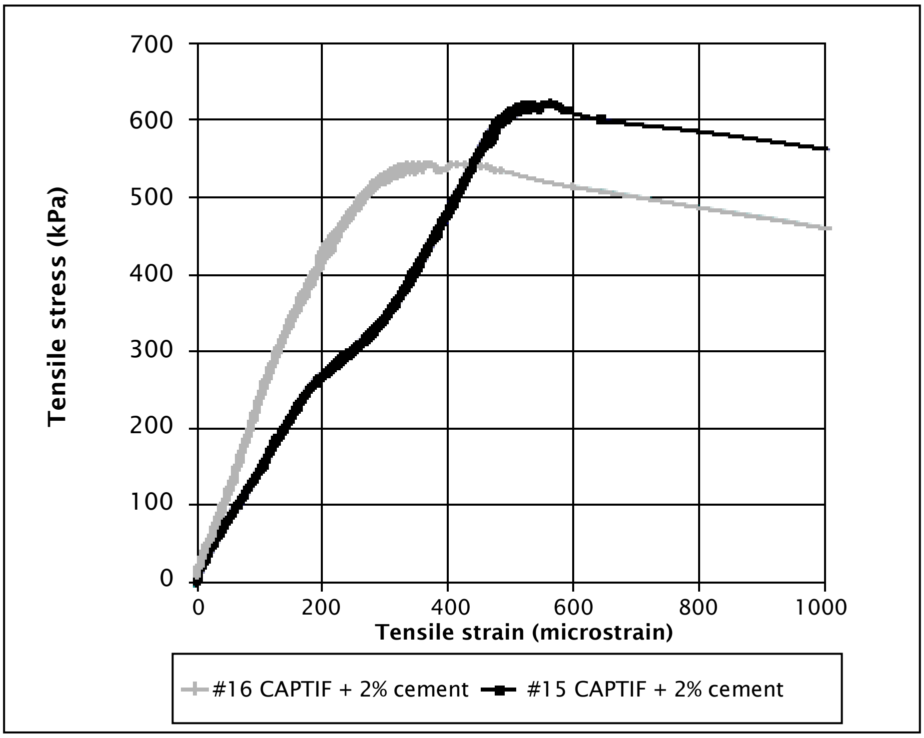


Table B7 Flexural beam breakage test results for CAPTIF + 2% cement

Test	Description	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)
16b	Linear limit	523	288	1815
15	Linear limit	613	516	1188
16b	Low strain	240	100	2398
15	Low strain	148	100	1482
16b	Maximum	544	372	1464
15	Maximum	622	563	1105

Table B8 Flexural beam modulus test results for CAPTIF + 2% cement

Test	Load (kN)	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)
17b	1.83	244	123	1982
16a	1.83	244	98	2498
18a	1.83	244	107	2288
19a	1.83	244	88	2769

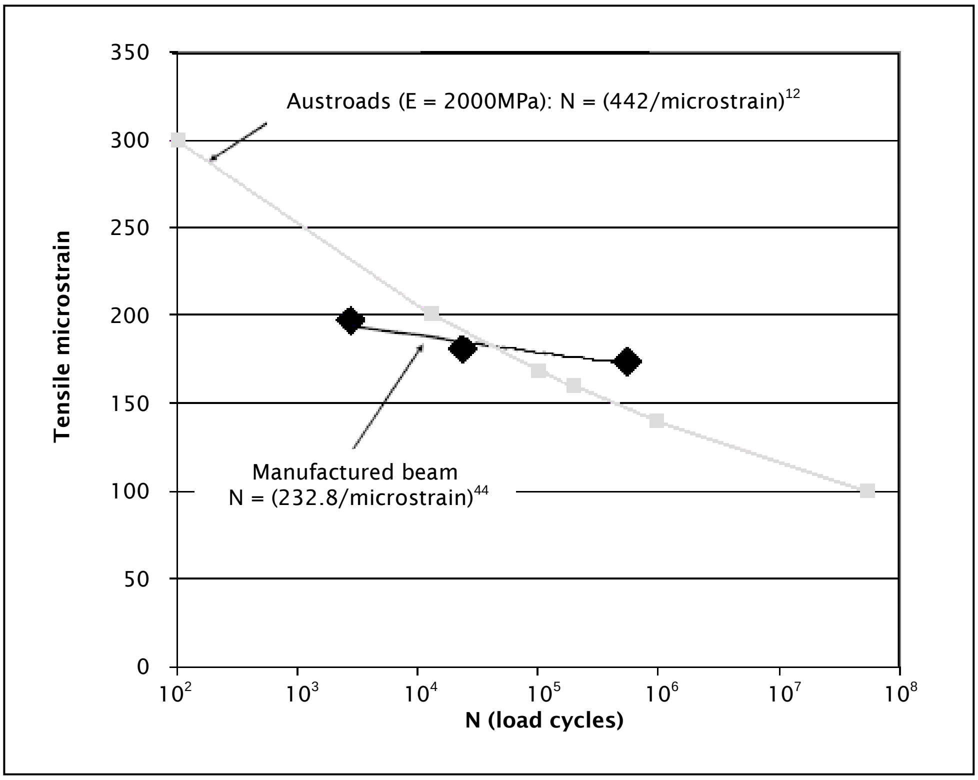
* Repeated loading for 100 cycles is haversine at 4Hz; values are maximum load.

Table B9 **Flexural beam fatigue test results for CAPTIF + 2% cement**

Test	When	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)	Load cycles to failure
17c	Start	291	174	1675	548,830
	End		221	1318	
18c	Start	391	197	1980	2801
	End		258	1515	
19c	Start	391	181	2155	23,901
	End		221	1768	

* Repeated loading is haversine at 4Hz; values are maximum load.

Figure B6 **Flexural beam fatigue test results for CAPTIF + 2% cement**



Repeated loading is haversine at 4Hz; values are maximum load.

Figure B7 Fatigue test results: flexural beam tensile strain v load cycles for beam 17 (CAPTIF + 2% cement)

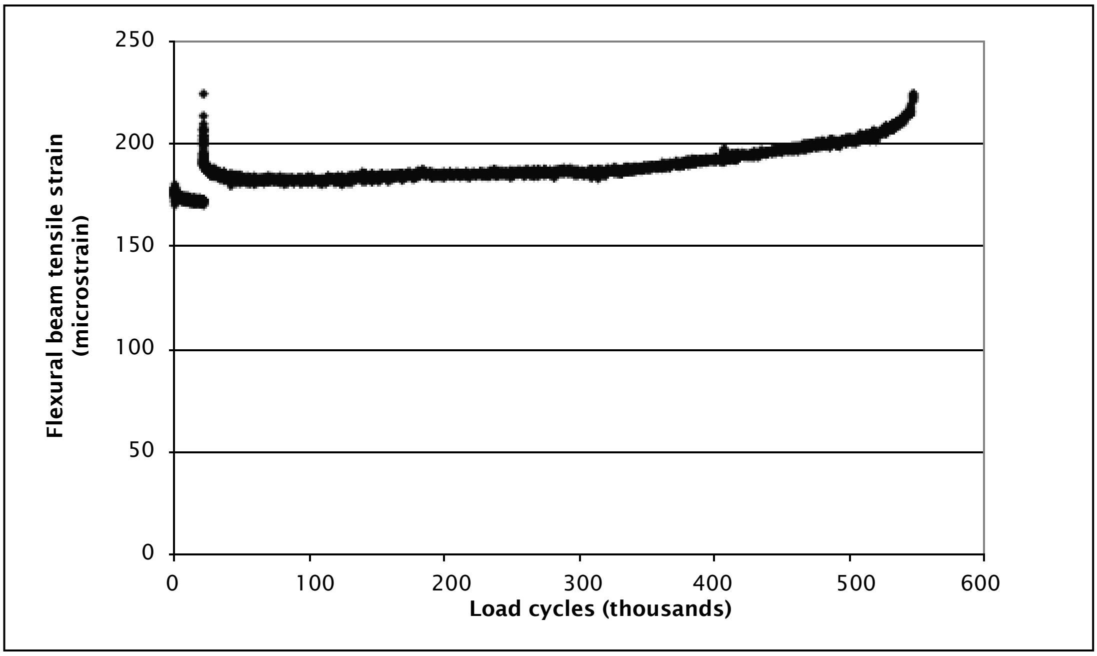
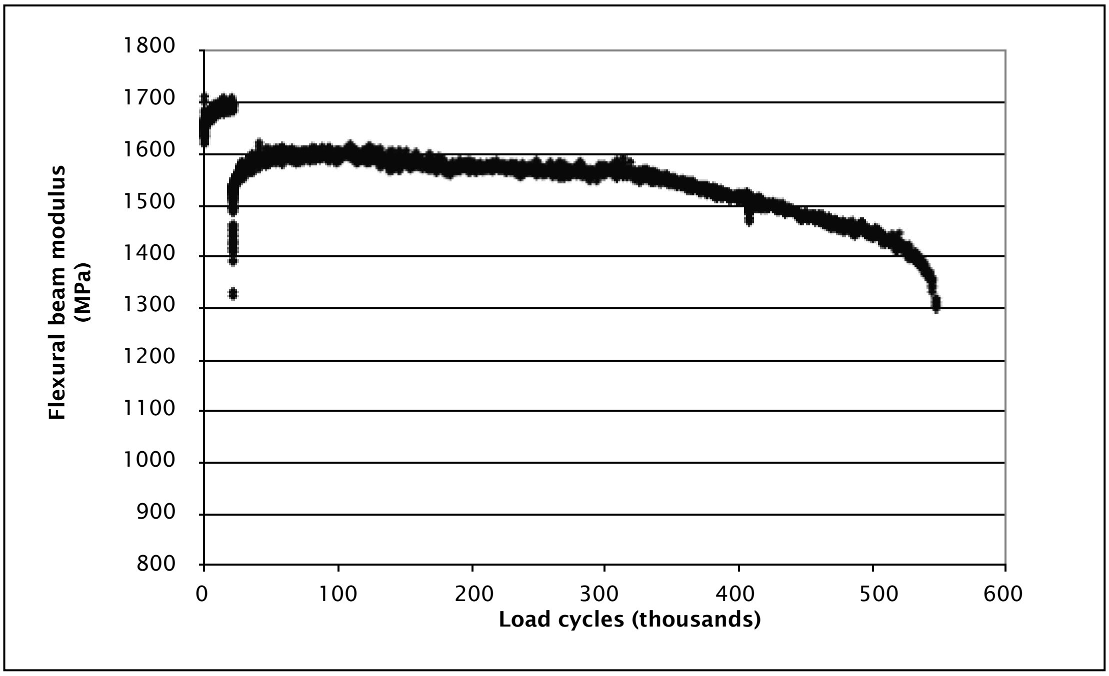


Figure B8 Fatigue test results: flexural beam modulus v load cycles for beam 17 (CAPTIF + 2% cement)



B4 Lab-compacted CAPTIF + 4% cement

The manufactured beams were kept sealed in plastic in the mould with wet rags for seven days in an oven at 40°C.

Figure B9 Flexural beam breakage test plot for lab-compacted CAPTIF + 4% cement beams

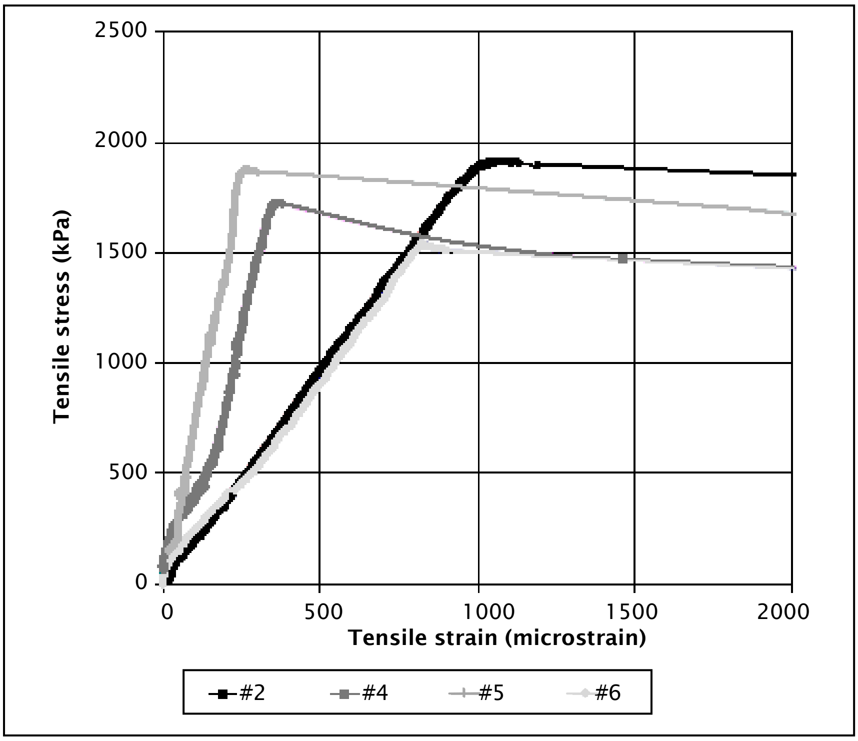


Table B10 Flexural beam breakage test results for CAPTIF + 4% cement beams

Test	Description	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)
2	Linear limit	1895	1004	1887
4	Linear limit	1722	355	4851
5	Linear limit	1874	260	7218
6	Linear limit	1531	810	1891
2	Low strain	378	200	1890
4	Low strain	777	200	3885
5	Low strain	1419	200	7097
6	Low strain	373	200	1867
2	Maximum	1916	1077	1779
4	Maximum	1727	360	4796
5	Maximum	1878	265	7096
6	Maximum	1548	819	1890

Table B11 Flexural beam modulus test results for CAPTIF + 4% cement

Test	Load (kN)	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)
3a	2.26	301	326	924
7a	2.26	301	405	744
9b	2.26	302	320	941
10a	2.26	301	270	1115
11a	2.26	302	315	957
13a	2.26	302	329	916
14a	2.26	302	295	1023

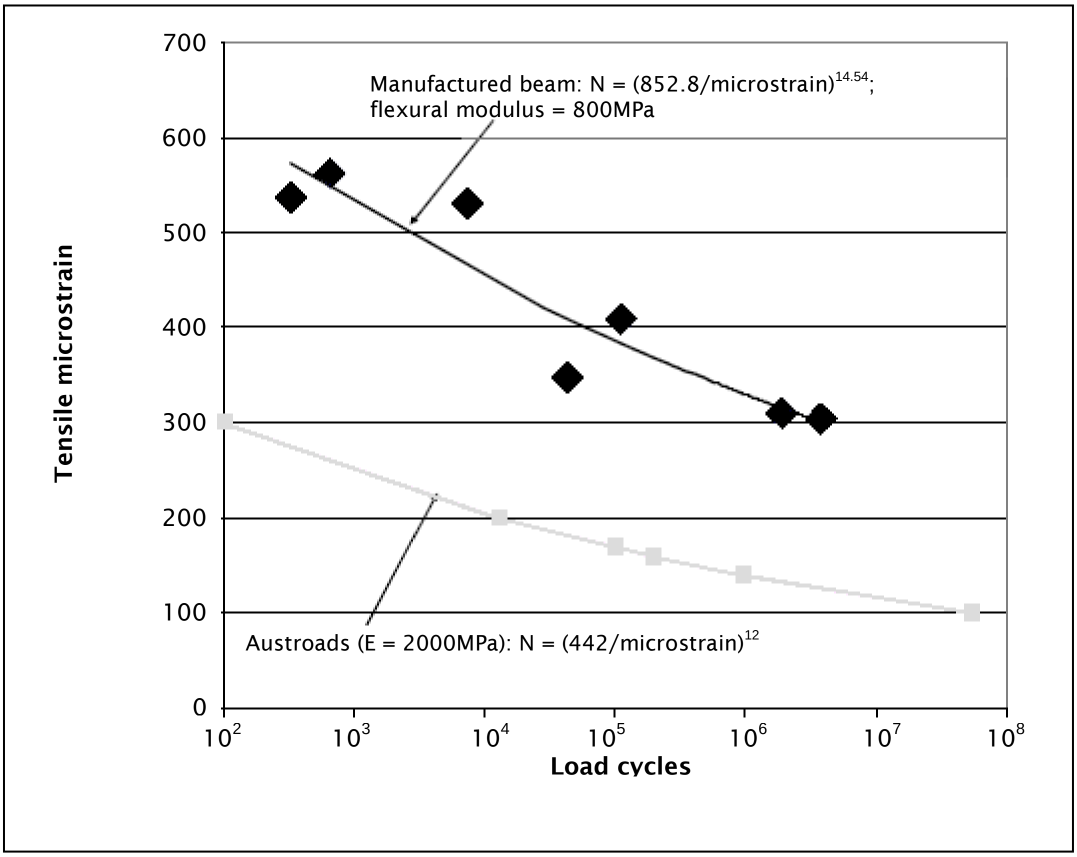
*Repeated loading for 100 cycles is haversine at 4Hz; values are maximum load.

Table B12 Flexural beam fatigue test results for CAPTIF + 4% cement

Test	When	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)	Load cycles to failure
3c	Start	448	530	846	7491
	End		586	767	
7b	Start	357	563	635	661
	End		599	598	
9b	Start	236	310	761	1,911,196
	End		305	775	
10c	Start	357	409	875	111,201
	End		426	840	
11c	Start	413	537	770	324
	End		607	688	
13b	Start	259	347	747	44,062
	End		396	655	
14b	Start	259	305	850	3,790,042
	End		496	734	

* Repeated loading is haversine at 4Hz; values are maximum load.

Figure B10 Flexural beam fatigue test results for lab-compacted CAPTIF + 4% beams



* Repeated loading is haversine at 4Hz; values are maximum load.

Figure B11 Fatigue test results: flexural beam tensile strain v load cycles for beam 14 (lab-compacted CAPTIF + 4% cement)

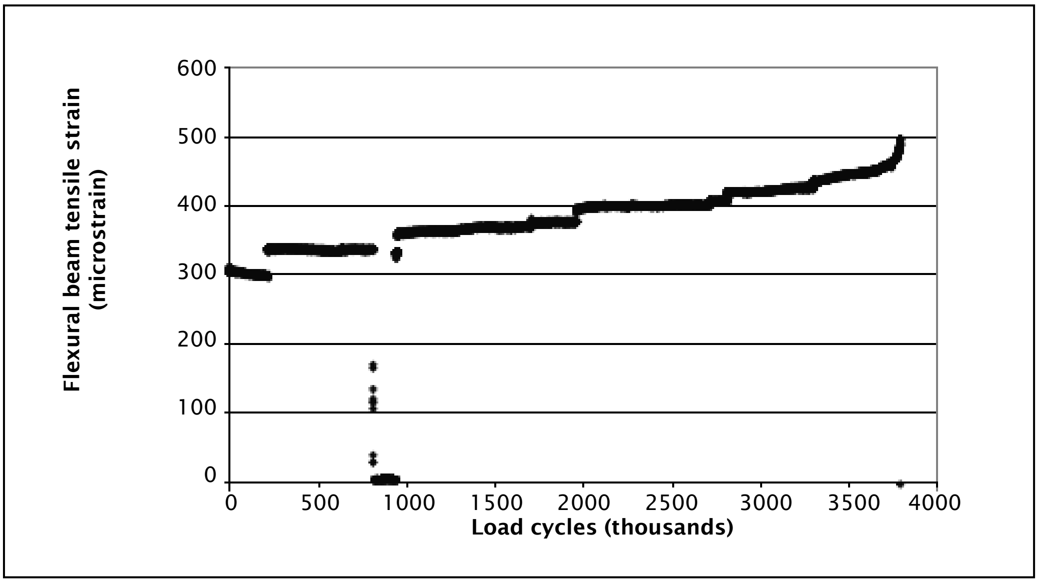
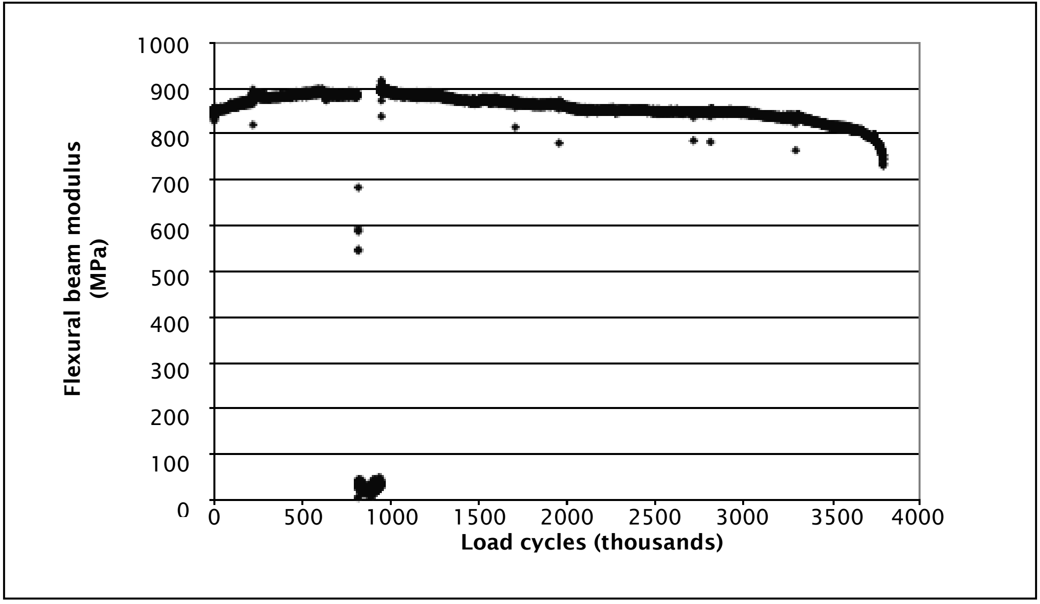


Figure B12 Fatigue test results: flexural beam modulus v load cycles for beam 14 (lab-compacted CAPTIF + 4% cement)



B5 Saw-cut CAPTIF + 1% cement (section B)

B5.1 Untrafficked samples

The beams for this test (BU3 and BU4) were sampled in April and May 2009. The repeated load flexural beam modulus for beam BU3 was 958MPa, with haversine loading at 4Hz, tensile load from 8kPa to 178kPa and tensile strain from 0 to 119 microstrain.

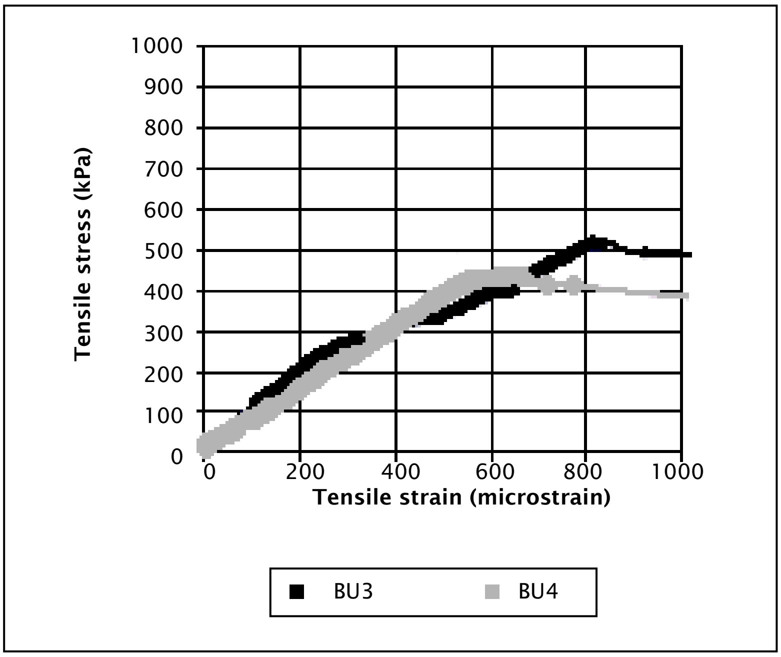
Figure B13 Beam BU3 (saw-cut CAPTIF + 1% cement) at breakage during the modulus test

Figure B14 Beam BU4 (saw-cut CAPTIF + 1% cement) at breakage during the modulus test

Table B13 Flexural beam breakage test results for saw-cut CAPTIF + 1% cement

Description	Beam	Tensile stress (kPa)	Tensile strain (µm/m)	Flexural modulus (MPa)
Maximum	BU3	515	801	642
	BU4	425	600	709
	Average	470	701	676
Low strain	BU3	208	200	1043
	BU4	161	200	801
	Average	185	200	927

Figure B15 Tensile strain v tensile stress for beams BU3 and BU4



B5.2 Trafficked samples

The beams used in this section (BT2 and BT3) were sampled in April and May 2009. The repeated load flexural beam modulus for beam BT3 was 573MPa with haversine loading at 4Hz, tensile load from 8kPa to 184kPa and tensile strain from 0 to 322 microstrain. Sample BT3 failed.

Figure B16 Beam BT2 (saw-cut CAPTIF + 1%) at breakage during the modulus test

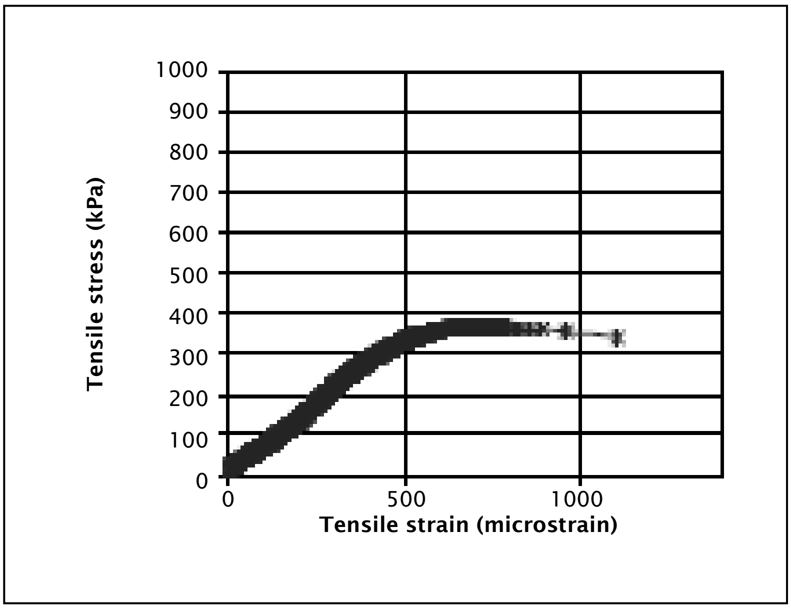
Figure B17 Beam BT3 (saw-cut CAPTIF + 1%) at breakage during the modulus test

Table B14 Flexural beam breakage test results for saw-cut trafficked CAPTIF + 1% cement

Description	Beam	Tensile stress (kPa)	Tensile strain (μm/m)	Flexural modulus (MPa)
Maximum	BT2	365	654	557
Maximum	BT3*	184	322	573
Low strain	BT2	138	200	690

* BT3 failed the modulus test, from which these numbers are inferred.

Figure B18 Tensile strain v tensile stress for BT2



B6 Saw-cut CAPTIF + 2% cement (section C)

B6.1 Untrafficked samples

The repeated load flexural beam modulus for beam CU3 was 322MPa with haversine loading at 4Hz, tensile load from 7kPa to 26kPa and tensile strain from 0 to 61microstrain. Samples were taken in April and May 2009.

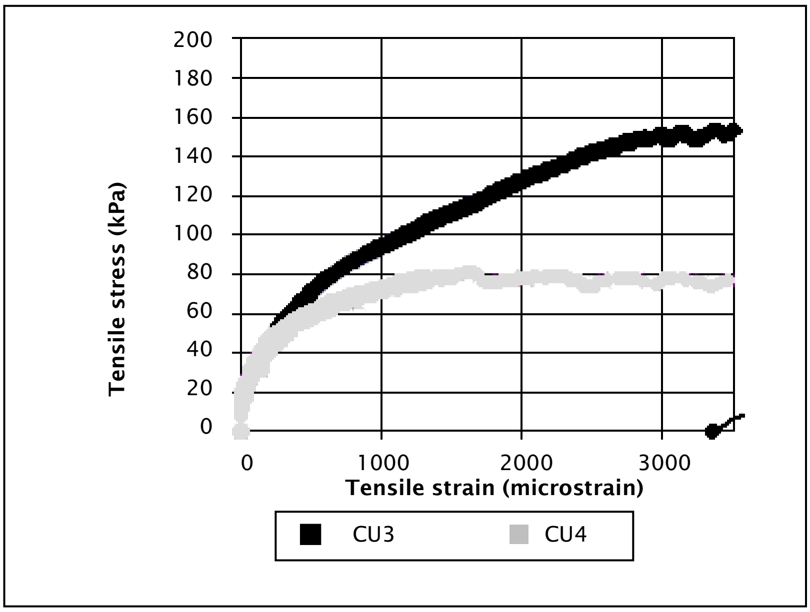
Figure B19 Beam CU3 (saw-cut CAPTIF + 2% cement) at breakage during the modulus test

Figure B20 Beam CU4 (saw-cut CAPTIF + 2% cement) at breakage during the modulus test

Table B15 Flexural beam breakage test results for saw-cut CAPTIF + 2% cement

Description	Beam	Tensile stress (kPa)	Tensile strain (μm/m)	Flexural modulus (MPa)
Maximum	CU3	151	2963	51
	CU4	82	1618	51
	Average	117	2291	51
Low strain	CU3	47	200	233
	CU4	44	200	220
	Average	46	200	227

Figure B21 Tensile strain v tensile stress for beams CU3 and CU4



B6.2 Trafficked samples

These samples (CT3, CT4 and CT5) were sampled during April and May 2009. They failed during handling and were not tested.

Figure B22 Beam CT3 (saw-cut CAPTIF + 2% cement) at breakage during handling

Figure B23 Beam CT4 (saw-cut CAPTIF + 2% cement) at breakage during handling

Figure B24 Beam CT5 (saw-cut CAPTIF + 2% cement) at breakage during handling

B7 Saw-cut CAPTIF + 4% cement (section E)

B7.1 Untrafficked samples

These samples (EU1, EU2, EU3, EU4 and EU4) were sampled during April and May 2009. The repeated load flexural beam modulus for EU2 was 728MPa, with haversine loading at 4Hz, tensile load from 8kPa to 144kPa and tensile strain from 0 to 187 microstrain.

Figure B25 Beam EU1 (saw-cut CAPTIF + 4% cement) at breakage during the modulus test

B26 Beam EU2 (saw-cut CAPTIF + 4% cement) at breakage during the modulus test

Figure B27 Tensile microstrain v load cycles for untrafficked saw-cut CAPTIF + 4% cement

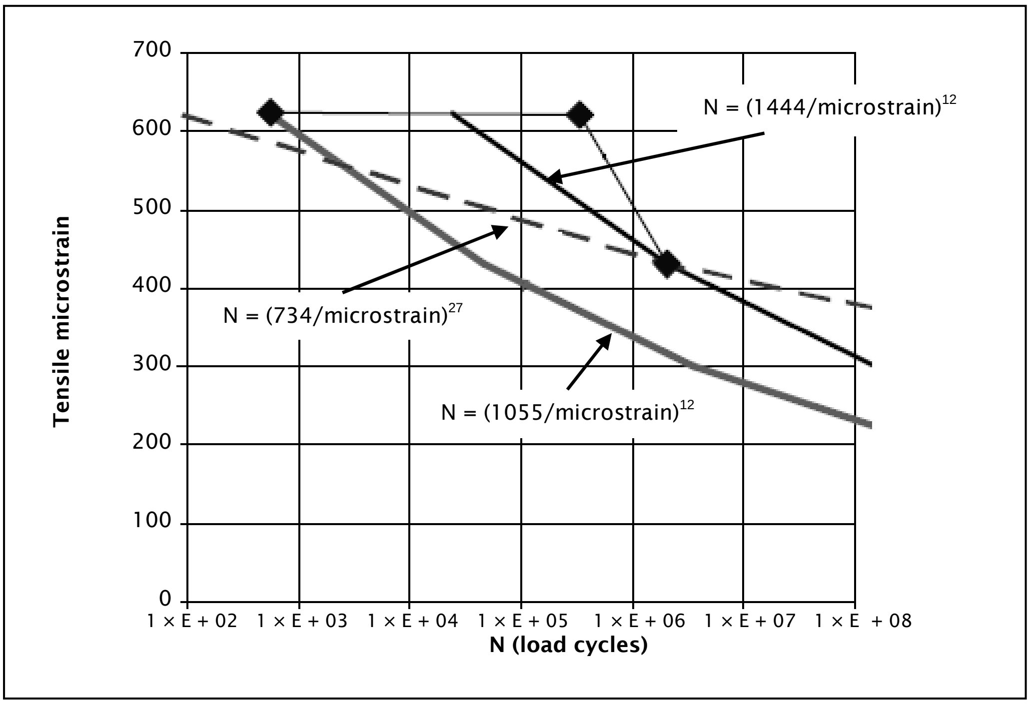


Table B16 Flexural beam breakage test results for untrafficked saw-cut CAPTIF + 4% cement

Description	Beam	Tensile stress (kPa)	Tensile strain (μm/m)	Flexural modulus (MPa)
Maximum	EU1	320	972	329
	EU2	346	1046	331
	Average	333	1009	330
Low strain	EU1	71	200	354
	EU2	53	200	267
	Average	62	200	311

Table B17 Flexural beam breakage test after 2 million load cycles* for untrafficked saw-cut CAPTIF + 4% cement

Description	Beam	Tensile stress (kPa)	Tensile strain (μm/m)	Flexural modulus (MPa)
Maximum	EU5	1011	1170	864
	EU2	346	1046	331
	EU1	320	972	329
Low strain	EU5	132	200	665
	EU2	53	200	267
	EU1	71	200	354

* The load cycles in this breakage test after 2 million cycles were applied as per the fatigue test, which did not break. Fatigue loading was at around 40% of breakage load. The result was as expected and the beam did not fatigue.

Table B18 **Flexural beam fatigue testing after 2 million cycles**

Beam	When*	Tensile stress (kPa)	Tensile strain (µm/m)	Flexural modulus (MPa)	Load cycles to failure
EU5	Modulus test	136	187	728	First 100
	Start	387	431	899	2 million (did not fail)
	End	387	435	890	
EU4	Modulus test	362	532	680	First 100
	Start	487	622	783	341,000
	End	487	636	766	
EU3	Modulus test	362	483	749	First 100
	Start	452	624	725	546
	End	452	624	725	

* Haversine loading at 4Hz; values are maximum

Figure B28 **Tensile strain v tensile stress for beams EU1 and EU2**

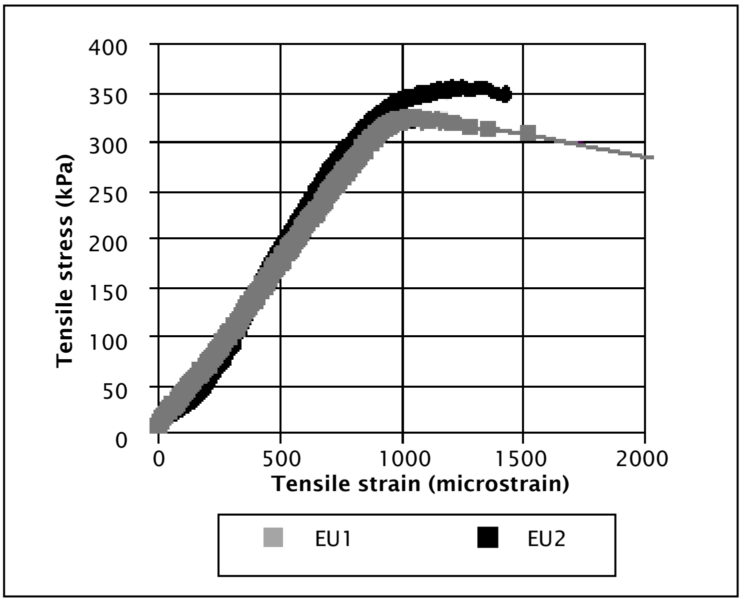


Figure B29 Tensile strain v tensile stress after 2 million load cycles for beams EU1, EU2 and EU5

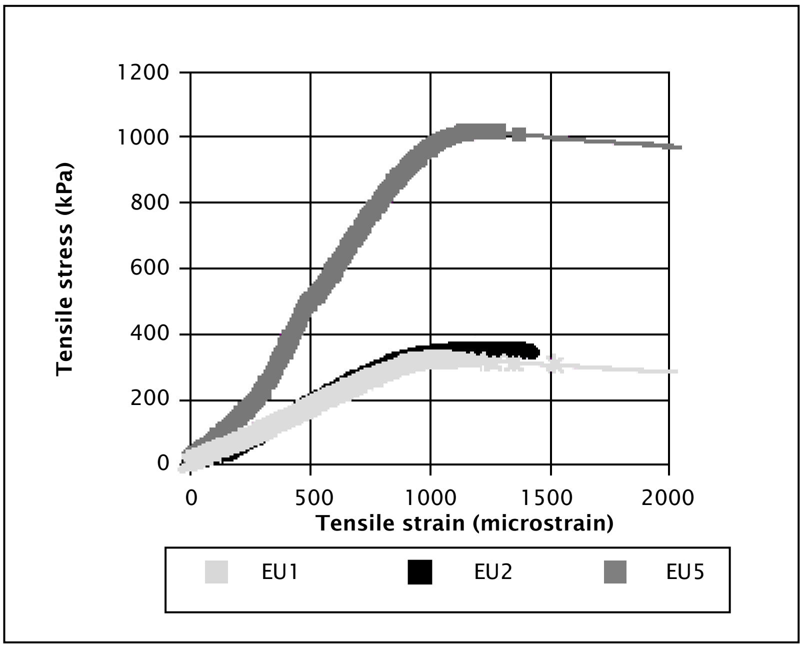


Figure B30 Beam EU1 (saw-cut CAPTIF + 4% cement) at breakage

Figure B31 Beam EU2 (saw-cut CAPTIF + 4% cement) at breakage

Figure B32 **Beam EU4 (saw-cut CAPTIF + 4% cement) at breakage**

Figure B33 **Fatigue crack in beam EU4**

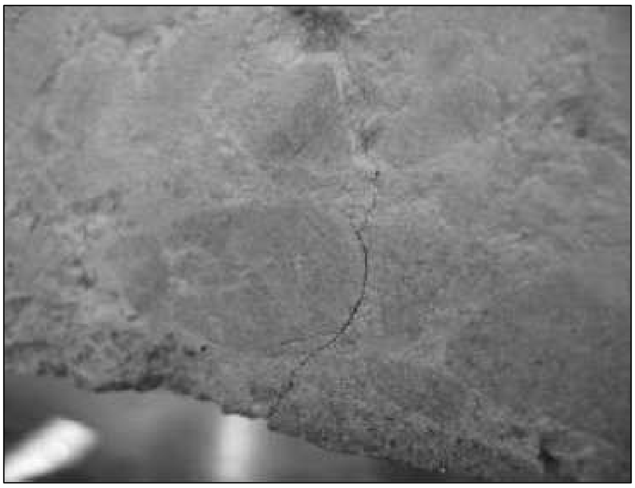
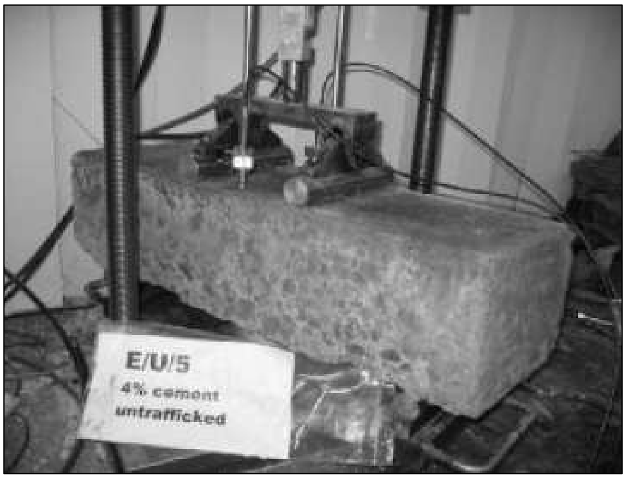


Figure B34 **Beam EU5 after two million cycles**



B7.2 Trafficked samples

These samples (ET4 and ET6) were taken during April and May 2009. The repeated load flexural beam modulus for beam ET6 is 326MPa, with haversine loading at 4Hz, tensile load from 7kPa to 98kPa and tensile strain from 0 to 277 microstrain.

Figure B35 Beam ET4 (saw-cut CAPTIF + 4% cement) at breakage during the flexural beam modulus test

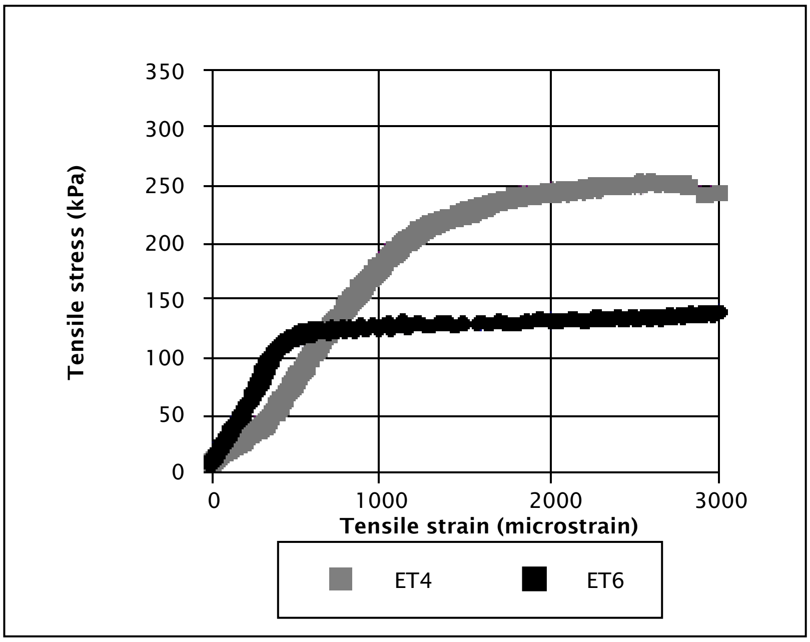
Figure B36 Beam ET6 (saw-cut CAPTIF + 4% cement) at breakage during the flexural beam modulus test

Table B19 Flexural beam breakage test results for trafficked saw-cut CAPTIF + 4% cement

Description	Beam	Tensile stress (kPa)	Tensile strain (µm/m)	Flexural modulus (MPa)
Maximum	ET4	215*	1299	165
	ET6	122	572	213
	Average	169	938	189
Low strain	ET4	30	200	148
	ET6	57	200	284
	Average	44	200	216

* linear limit

Figure B37 Tensile strain v tensile stress for beams ET4 and ET6



B8 Saw-cut CAPTIF + 4% cement, pre-cracked (section F)

B8.1 Untrafficked samples

These sections (FU4 and FU7) were sampled during April and May 2009. The repeated load flexural beam modulus for beam FU7 was 761MPa, with haversine loading at 4Hz, tensile load from 7kPa to 99kPa and tensile strain from 0 to 122 microstrain. Sample FU7 failed.

Figure B38 Beam FU4 (saw-cut CAPTIF + 4% concrete, pre-cracked) at breakage during flexural beam modulus testing

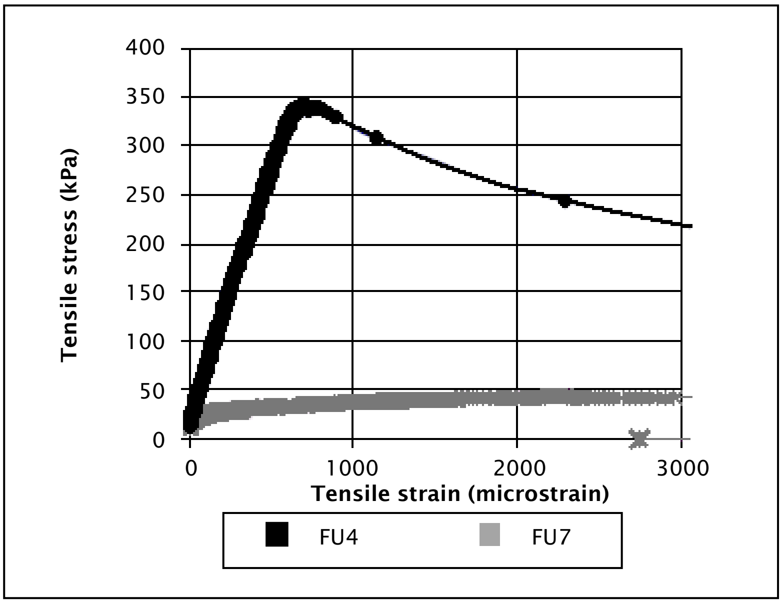
Figure B39 Beam FU7 (saw-cut CAPTIF + 4% concrete, pre-cracked) at breakage during flexural beam modulus testing

Table B20 Flexural beam breakage test results for saw-cut untrafficked CAPTIF + 4% concrete, pre-cracked

Description	Beam	Tensile stress (kPa)	Tensile strain (µm/m)	Flexural modulus (MPa)
Maximum	FU4	340	709	479
	FU7*	44	2270	19
Low strain	FU4	129	200	643
	FU7*	28	200	141

* Sample FU7 had low strength, possibly because of a crack occurring during the modulus test prior to this breakage test.

Figure B40 Tensile strain v tensile stress for beams FU4 and FU7



B8.2 Trafficked samples

The samples (FT4, FT5 and FT7) were taken during April and May 2009. They failed during modulus testing.

Figure B41 Beam FT4 (saw-cut CAPTIF + 4% cement, pre-cracked) at breakage during flexural beam modulus testing

Figure B42 Beam FT5 (saw-cut CAPTIF + 4% cement, pre-cracked) at breakage during flexural beam modulus testing

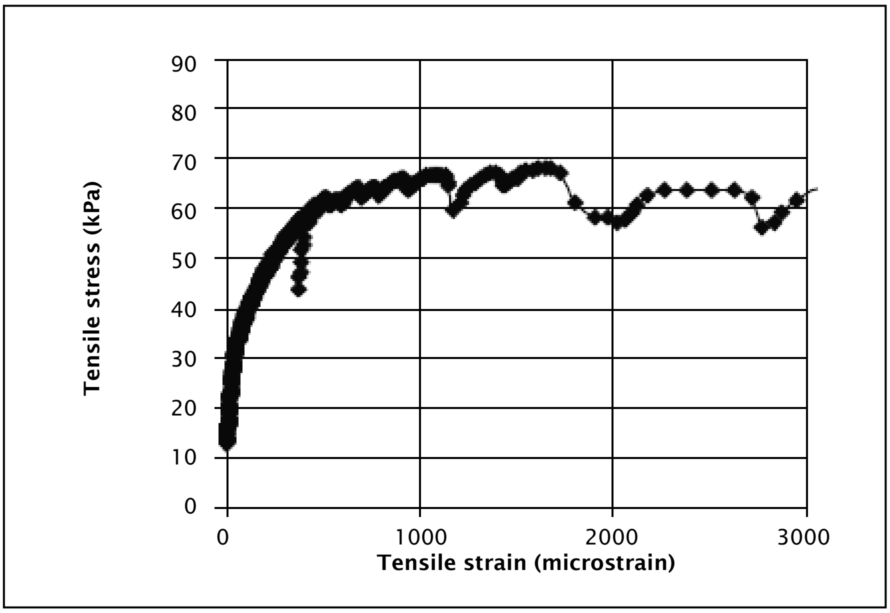
Figure B43 Beam FT7 (saw-cut CAPTIF + 4% cement, pre-cracked) at breakage during flexural beam modulus testing

Table B21 Flexural beam breakage test results for saw-cut CAPTIF + 4% cement, pre-cracked (beam FT4)*

Description	Tensile stress (kPa)	Tensile strain (µm/m)	Flexural modulus (MPa)
Maximum	67	1095	61
Low strain	48	200	237

* FT4 failed the modulus test, which these numbers are inferred from

Figure B44 Tensile strain v tensile stress for beam FT4



B9 Australian basalt + 3% Blue Circle cement

Beams #1–#5 were kept sealed in plastic in the mould with wet rags for seven days in the oven at 40°C degrees. The beams were then left in open bags with wet rags on the bench at room temperature for 24 hours. Beams #6–#9 were kept sealed in plastic in the mould with wet rags for seven days in an oven at 40°C, followed by 21 days in sealed bags at 21°C in the concrete curing room. The bags were then left open with wet rags on the bench at room temperature for 24 hours.

Figure B45 Flexural beam breakage test plot for Australian basalt + 3% cement

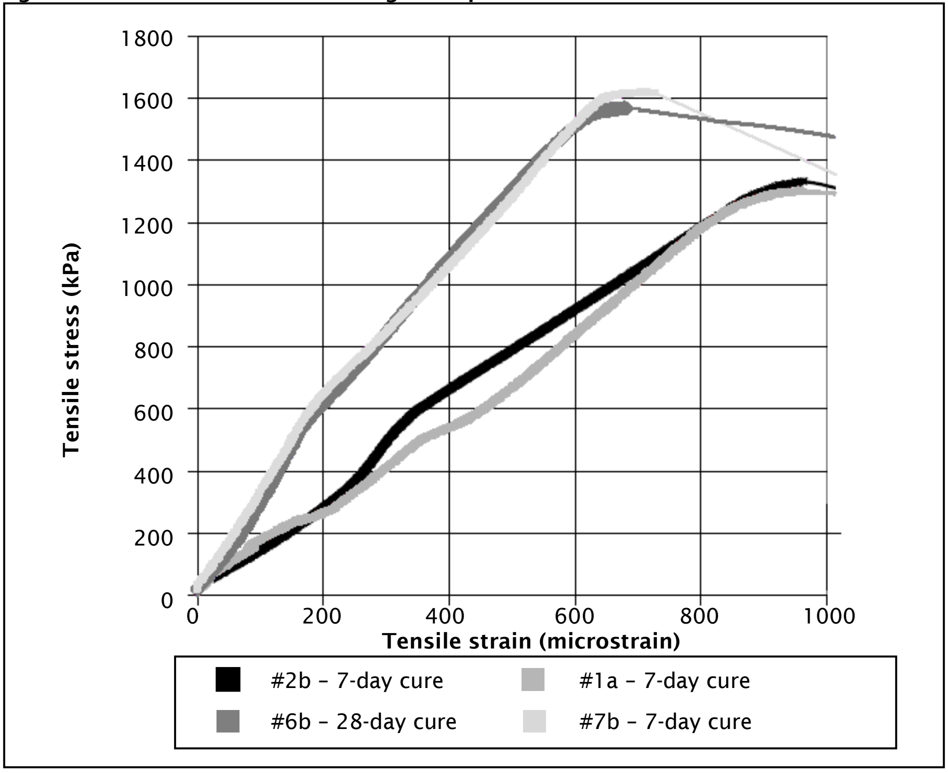


Table B22 Flexural beam breakage test results for Australian basalt + 3% cement

Curing period (days)	Test	Description	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)
7	1a	Linear limit	1265	869	1455
7	2b		1323	928	1425
28	6b		1559	640	2436
28	7b		1610	664	2424
7	1a	Low strain	268	200	1341
7	2b		282	200	1414
28	6b		622	200	3114
28	7b		645	956	3230
7	1a	Maximum	1304	962	1364
7	2b		1335	677	1388
28	6b		1570	716	2319
28	7b		1620	–	2262

Table B23 Flexural beam modulus test results for Australian basalt plus 3% cement

Curing period (days)	Test	Load (kN)	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)
7	2a	3.83	511	282	1811
	3a	3.83	511	257	1988
	4a	3.83	511	211	2118
	4b	7.24	965	344	2806
	4c	8.22	1096	376	2910
	5a	3.83	511	213	2396
28	6a	3.83	511	157	3254
	7a	3.83	511	147	3484
	8a	3.83	511	181	2825
	9a	3.83	511	195	2620
	9b	3.83	511	192	2663
	10a	3.83	511	160	3186

*Repeated loading for 100 cycles was haversine at 4Hz; values are maximum load.

Table B24 Flexural beam fatigue test results for Australian basalt + 3% cement

Curing period (days)	Test	When	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)	Load cycles to failure
7	3b	Start	901	341	2641	478,838
		End		414	2204	
	4b	Start	1096	370	2963	40,141
		End		364	3005	
	5c	Start	1004	360	2792	1,198,122
		End		451	2311	
28	8b	Start	965	286	3376	1,614,772
		End		329	2937	
	9c	Start	1082	344	3144	211
		End		393	2799	
	10b	Start	1032	291	3544	797,201
		End		344	3084	

* Repeated loading is haversine at 4Hz; values are maximum load.

Figure B46 Flexural beam fatigue test results for Australian basalt + 3% cement

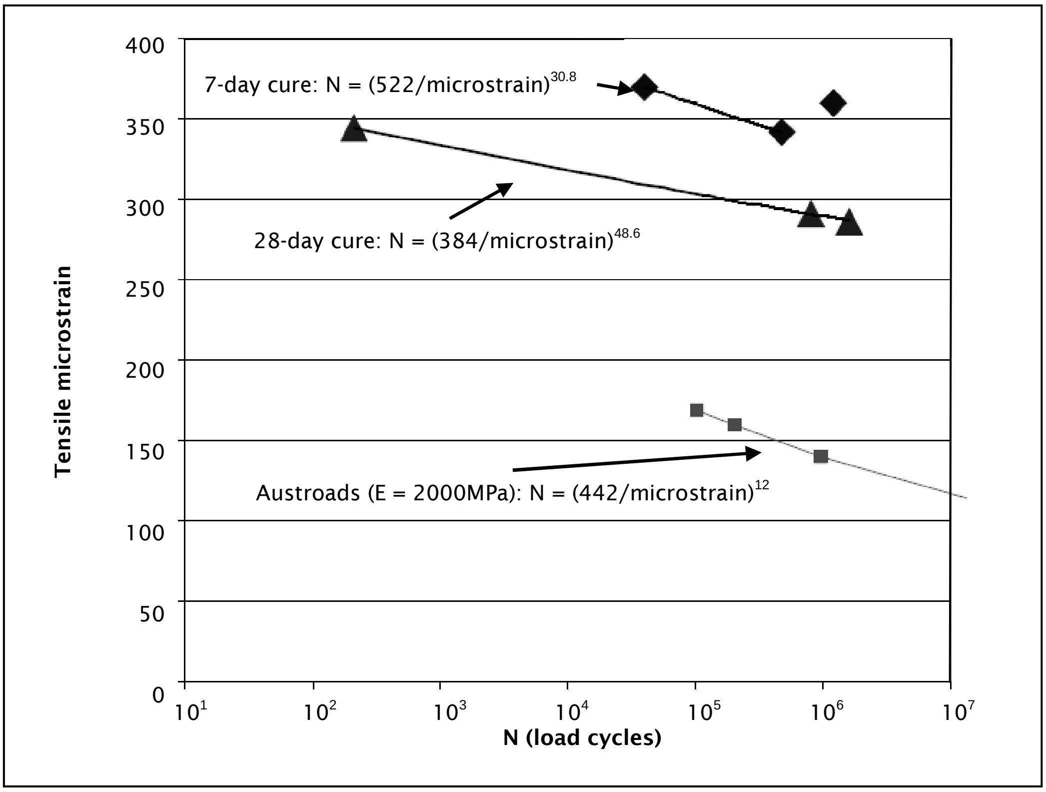
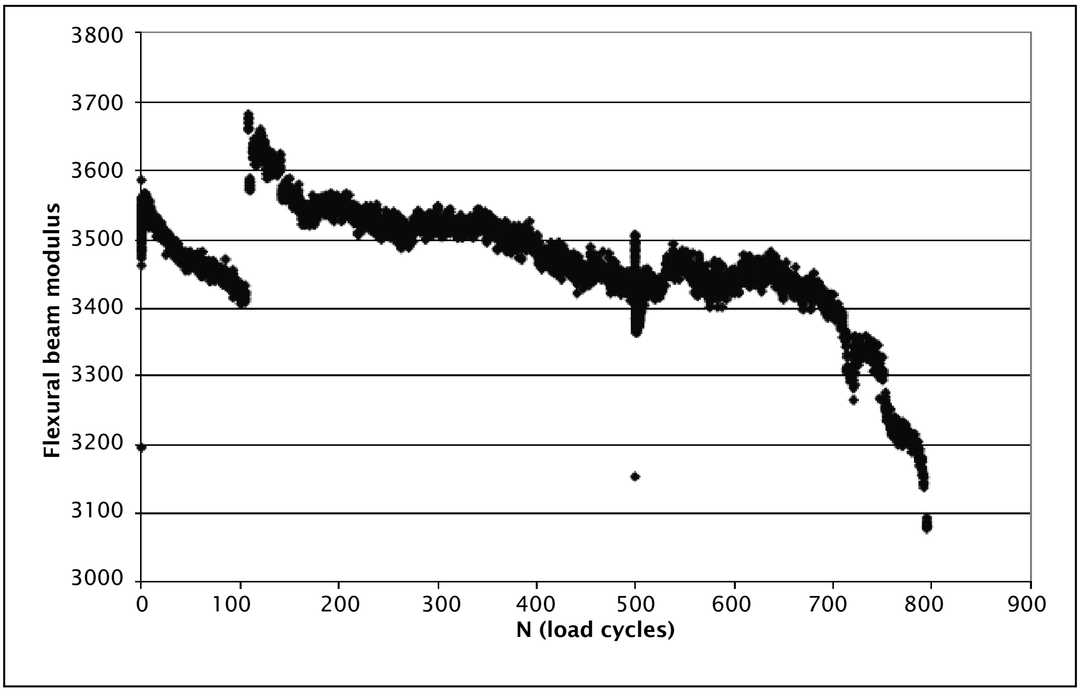


Figure B47 Flexural beam modulus v load cycles for beam 10b (Australian basalt + 3% cement, 28 days' curing)



B10 Australian limestone + 3% Blue Circle cement

This test (PS840) used beams #11–#19. Beams #11–#15 were kept sealed in plastic in the mould with wet rags for seven days in an oven at 40°C. The beams were then kept in open bags with wet rags on a bench at room temperature for 24 hours. Beams #16–#19 were kept sealed in plastic in the mould with wet rags for seven days in an oven at 40°C and then in sealed bags for 21 days at 21°C in a concrete curing room. The beams were then kept in open bags with wet rags on a bench at room temperature for 24 hours.

Figure B48 Flexural beam breakage test plot for Australian limestone + 3% cement

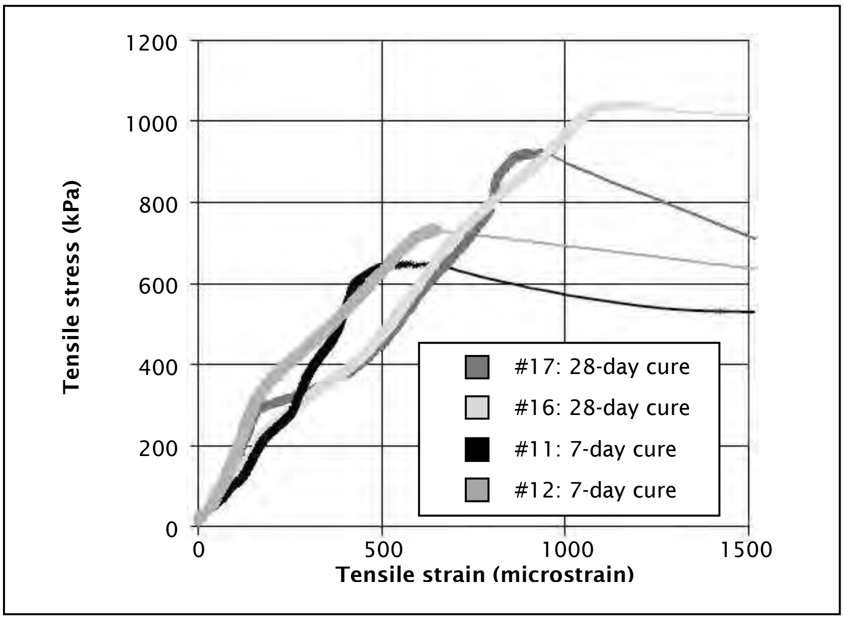


Table B25 Flexural beam breakage test results for Australian limestone + 3% cement

Curing period (days)	Test	Description	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)
7	11	Linear limit	607	441	1376
7	12		727	621	1169
28	16		1020	1068	955
28	17		882	831	1062
7	11	Low strain	236	200	1183
7	12		366	200	1833
28	16		247	200	1235
28	17		306	200	1530
7	11	Maximum	649	575	1129
7	12		733	645	1136
28	16		1040	1160	896
28	17		924	939	984

Table B26 Flexural beam modulus test results for Australian limestone + 3% cement

Curing period (days)	Test	Load (kN)	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)
7	12a	1.87	250	176	1423
	13a	1.87	250	132	1889
	14a	1.87	250	147	1702
	15a	1.87	250	130	1927
28	17a	1.87	250	137	1826
	18a	1.88	250	163	1538
	19a	1.88	250	131	1912

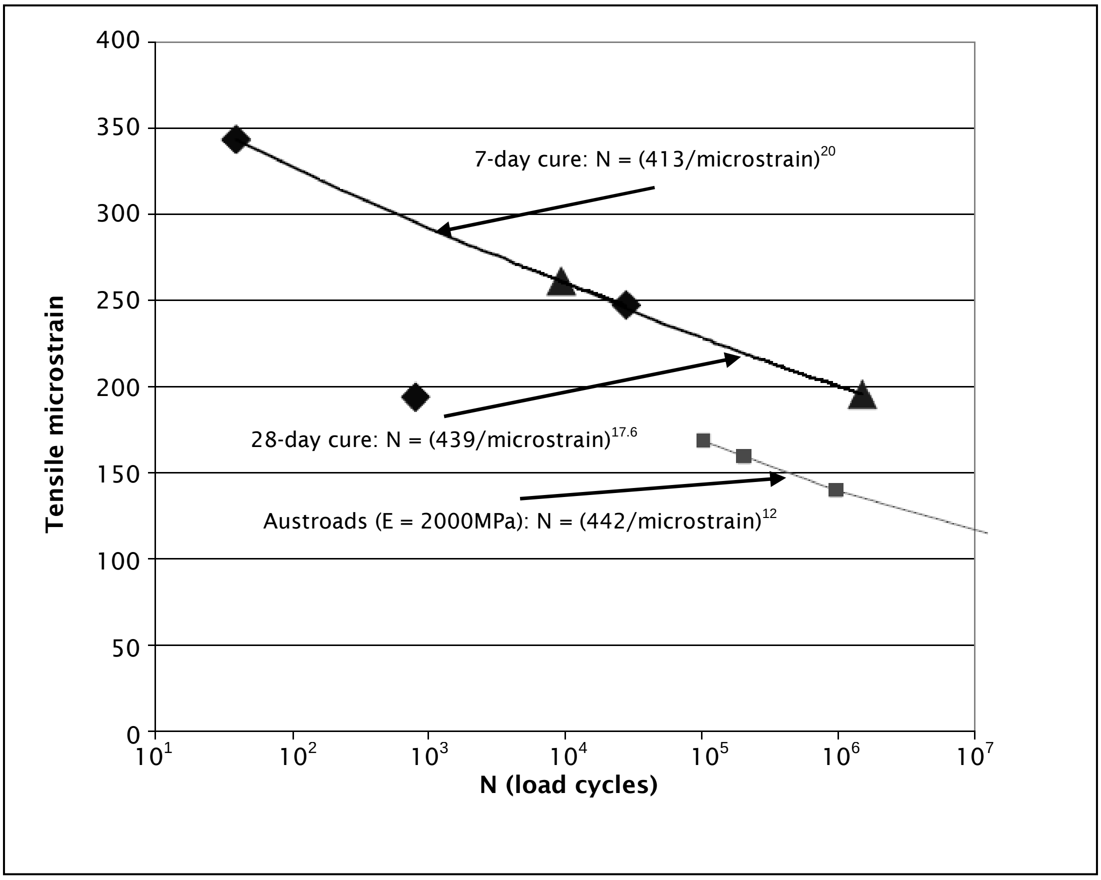
* Repeated loading for 100 cycles was haversine at 4Hz; values are maximum load.

Table B27 Flexural beam fatigue test results for Australian limestone + 3% cement

Curing period (days)	Test	When	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)	Load cycles to failure
7	13b	Start	509	343	1637	39
		End			1172	
	14b	Start	444	247	1933	27,581
		End			1707	
	15b	Start	380	194	1986	798
		End			1037	
28	18b	Start	541	261	2260	9262
		End			2005	
	19b	Start	380	196	1954	1,500,649
		End			1990	

* Repeated loading is haversine at 4Hz; values are maximum load.

Figure B49 Flexural beam fatigue test results for Australian limestone + 3% cement



B11 Winstone's flat-top GAP25 + 3% cement

The beams for this test were kept sealed in plastic in the mould with wet rags for seven days in an oven at 40°C. The beams were then kept in open bags with wet rags on a bench at room temperature for 24 hours. However, some of the beams used for the flexural beam modulus test (3d and 3e) had a 12-day curing period.

Figure B50 Flexural beam breakage test plot for flat-top GAP25 + 3% cement

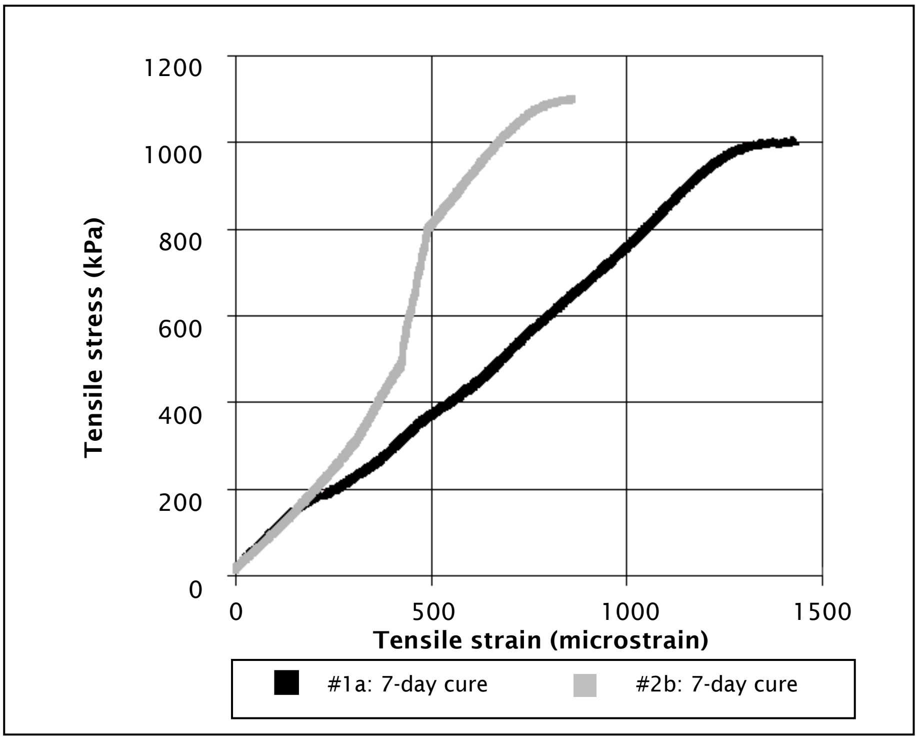


Table B28 Flexural beam breakage test results for flat-top GAP25 + 3% cement

Test	Description	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)
1	Maximum	1004	1426	704
1	Linear limit	964	1245	755
1	Low strain	182	199	914
2b	Maximum	1100	861	1277
2b	Linear limit	1071	766	1398
2b	Low strain	196	200	980

Table B29 Flexural beam modulus test results for flat-top GAP25 + 3% cement

Curing period (days)	Test	Load (kN)	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)
7	2a	2.91	389	353	1100
7	3a	2.91	388	285	1365
7	3b	4.83	643	430	1496
7	3c	5.13	684	499	1524
12	3d	5.30	707	309	2291
12	3e	6.99	932	446	2089
7	4a	2.91	388	322	1204
7	4b	4.82	642	577	1113
7	5a	2.91	387	300	1292
7	5b	3.48	394	300	1293

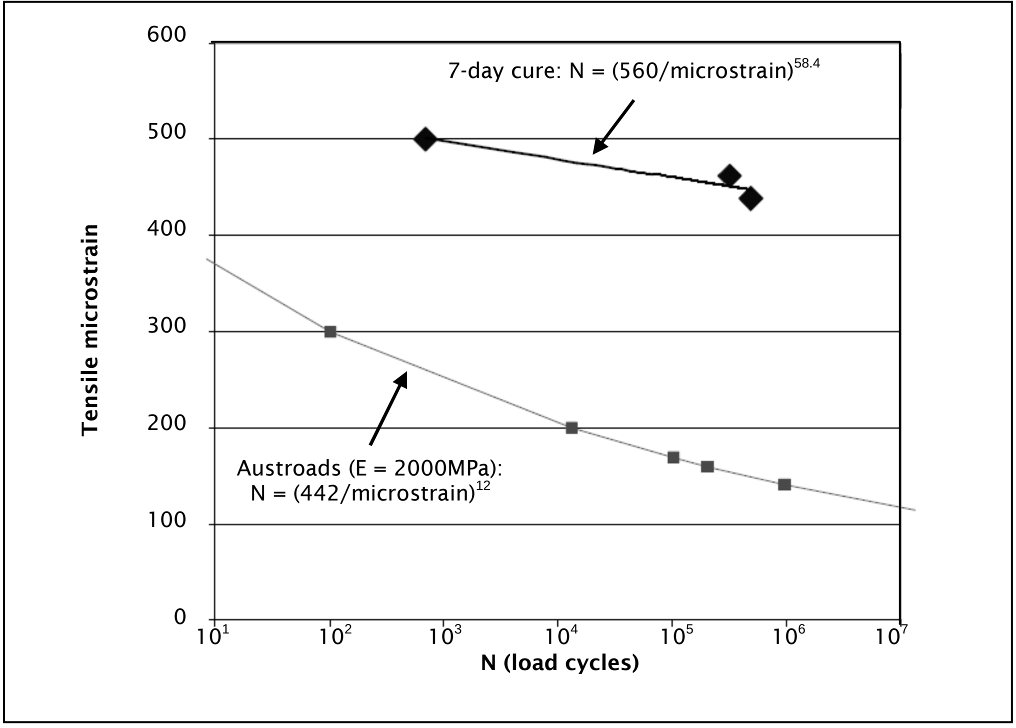
* Repeated loading for 100 cycles is haversine at 4Hz; values are maximum load.

Table B30 Flexural beam fatigue test results for flat-top GAP25 + 3% cement

Curing period (days)	Test	When	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)	Load cycles to failure
7	3	Start	697	462	1508	315,037
		End		478	1480	
	4	Start	496	501	991	700
		End		681	730	
	5	Start	583	439	1329	489,353
		End		507	1151	

* Repeated loading is haversine 4Hz; values are maximum load.

Figure B51 Flexural beam fatigue test results for flat-top GAP25 + 3% cement



B12 Whitford GAP40 stabilised with foam bitumen

For these tests, Whitford GAP40 aggregate was used. This aggregate was scalped (>25mm) with a dry density of 2.136 t/m^3 at a moisture content of 4.6% with:

- 1.3% cement only
- 2% foam bitumen + 1.3% cement
- 2.5% foam bitumen + 1.3% cement
- 3% foam bitumen + 1.3% cement
- 3.5% foam bitumen + 1.3 cement.

All beams, except for those used in the fatigue tests, were compacted at Opus Laboratories in Albany on 17 September 2009. These beams were kept sealed in plastic in the mould with wet rags for seven days in an oven at 40°C and then in the curing room (sealed in plastic with wet rags at 21°C) until 10 November 2009, when the plastic was removed for open-air curing with wet rags on top of the beam until testing. Testing was carried out between 16 December 2009 and 6 January 2010. The beams used for the fatigue tests had the same curing period and conditions but were compacted at CAPTIF.

Figure B52 Flexural beam breakage test plot for Whitford GAP40 + 1.3% stabilised with foam bitumen

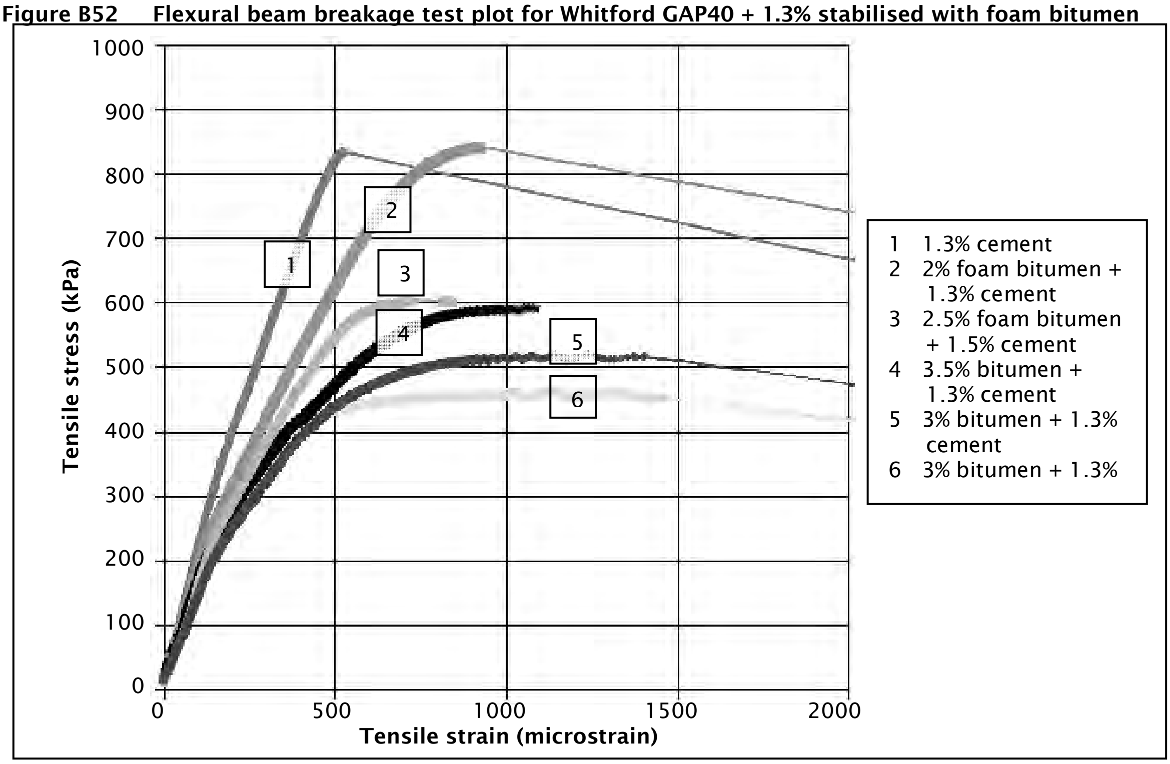


Table B31 Flexural beam breakage test results for Whitford GAP40 + 1.3% cement stabilised with foam bitumen

Test	Bitumen (%)	Description	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)
2b	0.0	Linear limit	817	500	1635
3b	2.0		791	715	1105
5b	2.5		580	568	1020
1b	3.0		438	500	877
10c	3.0		405	390	1038
4b	3.5		561	716	784
2b	0.0	Low strain	398	200	1991
3b	2.0		318	200	1593
5b	2.5		291	200	1458
1b	3.0		254	200	1271
10c	3.0		263	200	1318
4b	3.5		276	200	1383
2b	0.0	Maximum	834	520	1605
3b	2.0		842	909	926
5b	2.5		604	708	853
1b	3.0		519	1139	456
10c	3.0		461	1326	347
4b	3.5		594	1069	556

Table B32 Flexural beam modulus test results for Whitford GAP40 + 1.3% cement

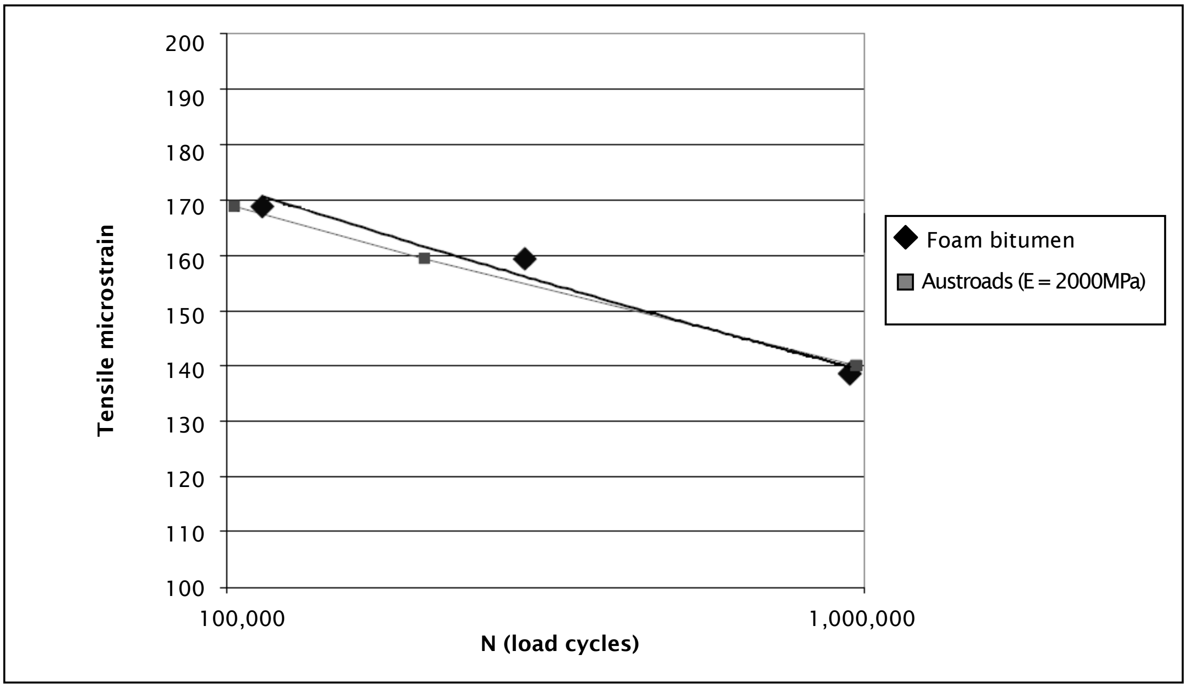
Test	Bitumen (%)	Load (kN)	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)
2a	0.0	1.27	169	89	1895
3a	2.0	1.27	169	85	1976
5a	2.5	1.27	169	106	1600
10a	3.0	1.27	169	114	1481
1a	3.0	1.27	169	111	1522
7a	3.0	1.27	169	95	1780
8b	3.0	1.27	169	93	1819
9a	3.0	1.27	169	89	1895
4a	3.5	1.27	169	98	1732

* Repeated loading for 100 cycles is haversine at 4Hz; values are maximum load.

Table B33 Flexural beam fatigue test results for Whitford GAP40 + 1.3% cement

Test	Bitumen (%)	When	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)	Load cycles to failure
7b	3.0	Start	302	159	1897	293,351
		End		181	1675	
8c	3.0	Start	258	139	1861	949,241
		End		168	1535	
9b	3.0	Start	325	169	1927	113,601
		End		189	1722	

Figure B53 Flexural beam test plot for Whitford GAP40 + 1.3% cement



Appendix C Additional flexural beam fatigue test results for CAPTIF + 4% beams

Further tests on lab-compacted CAPTIF aggregate + 4% cement beams were undertaken in May 2011. These beams were moist-cured for seven days at 40°C.

Table C1 Flexural beam breakage test results for lab-compacted CAPTIF + 4% cement

Test	Description	Tensile stress (kPa)	Tensile strain (mm)	Young's modulus (MPa)
110901	Maximum	1407	730	1927
110902		1864	586	3180
110903		1384	510	2713
110904		1119	371	3017
110905		2243	552	4065
110901	Low strain	479	200	2395
110902		520	200	2602
110903		472	200	2359
110904		916	200	4569
110905		949	200	4736
110901	Linear limit	1366	645	2118
110902		1862	586	3179
110903		1346	490	2747
110904		1091	297	3677
110905		2188	506	4327

Table C2 Flexural beam repeated load modulus for lab-compacted CAPTIF + 4% cement

Test #	Beam depth	Load (kN)*	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)
110901	150mm	1.27	169	56	3044
110902	150mm	1.27	169	66	2561
110904	100mm	0.67	200	33	6053
110905	100mm	1.27	380	45	8488
110906	150mm	5.20	693	232	2989
110907	150mm	5.20	693	247	2801

* Repeated loading for 200 cycles, haversine at 4Hz. Values are maximum load.

Table C3 Flexural beam breakage CIRCLY design criteria

Beam test #[a]	Beam thickness (mm)	Maximum tensile stress (kPa)	Breakage test modulus[b] (MPa)	Repeated load modulus (MPa)	Tensile fatigue criterion[c]
110901	150	1407	2118	3044	$N = (1,780,277/(E.\varepsilon))^{12}$
110902	150	1864	3179	2561	$N = (2,357,555/(E.\varepsilon))^{12}$
110903	100	1384	2747	-	$N = (1,750,459/(E.\varepsilon))^{12}$
110904	100	1119	3677	6053	$N = (1,415,899/(E.\varepsilon))^{12}$
110905	100	2243	4327	8488	$N = (2837446/(E.\varepsilon))^{12}$

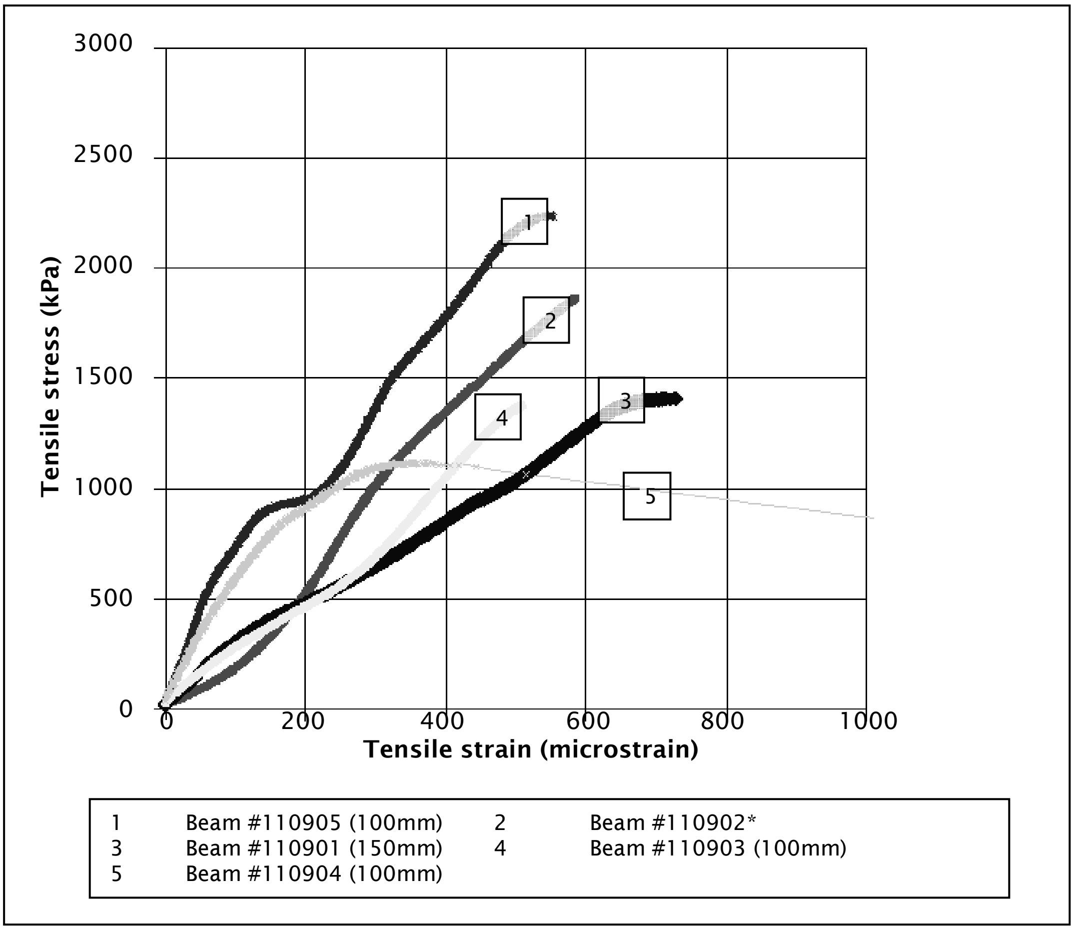
Notes to table C3:

a Tests were performed on 31 May 2011.

b Linear limit.

c E = modulus in MPa, N = ESA, ε = tensile microstrain.

Figure C1 Flexural beam breakage plots for lab-compacted CAPTIF + 4% cement beams



* This beam did not break.

The results in figures C2–C6 show three different stages of loading on the same beam as, initially, the beam did not break after nearly 2 million load cycles. Maximum tensile stress at breakage is estimated at 2234kPa.

Figure C2 Fatigue results (tensile microstrain) for beam 110902 (CAPTIF + 4% cement): first stage

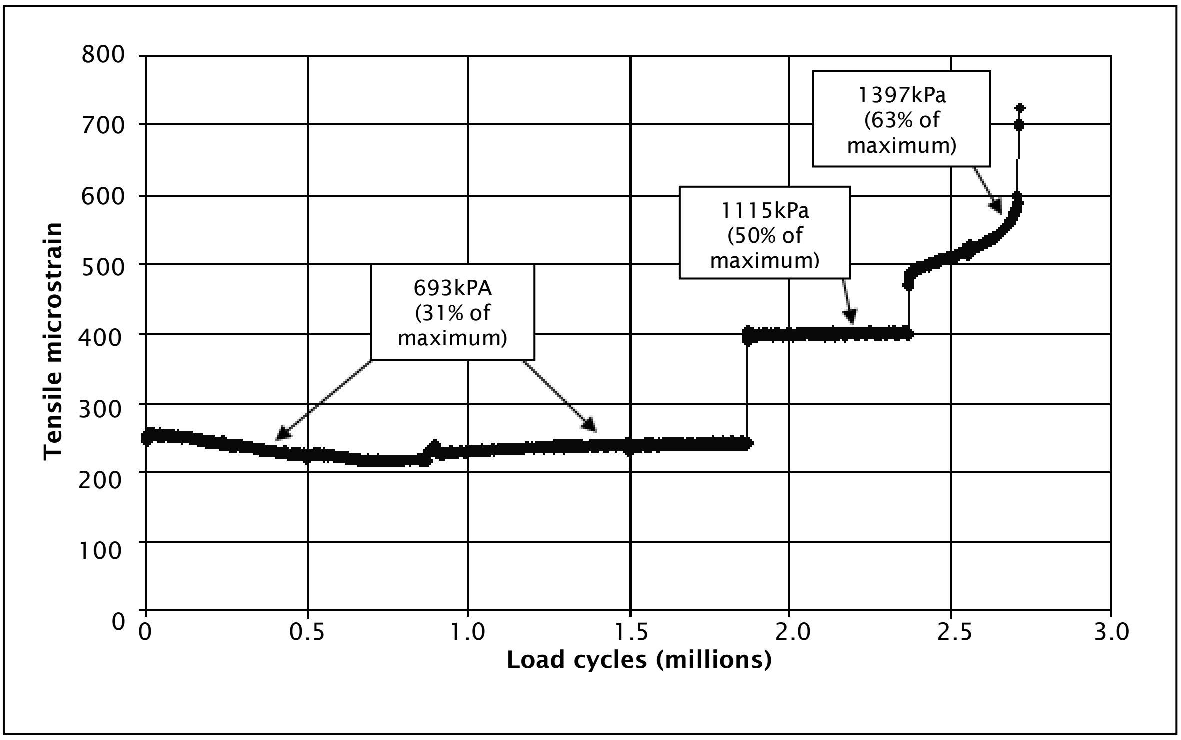


Figure C3 Fatigue results (modulus) for beam 110902 (CAPTIF + 4% cement): first stage

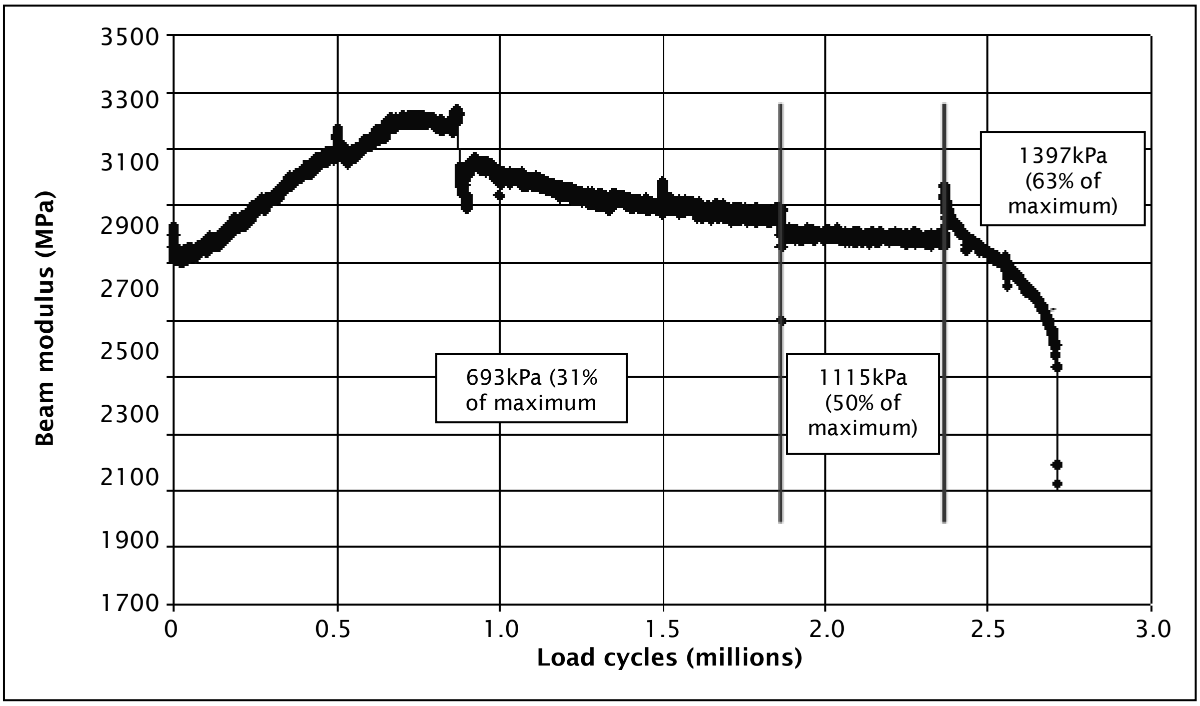
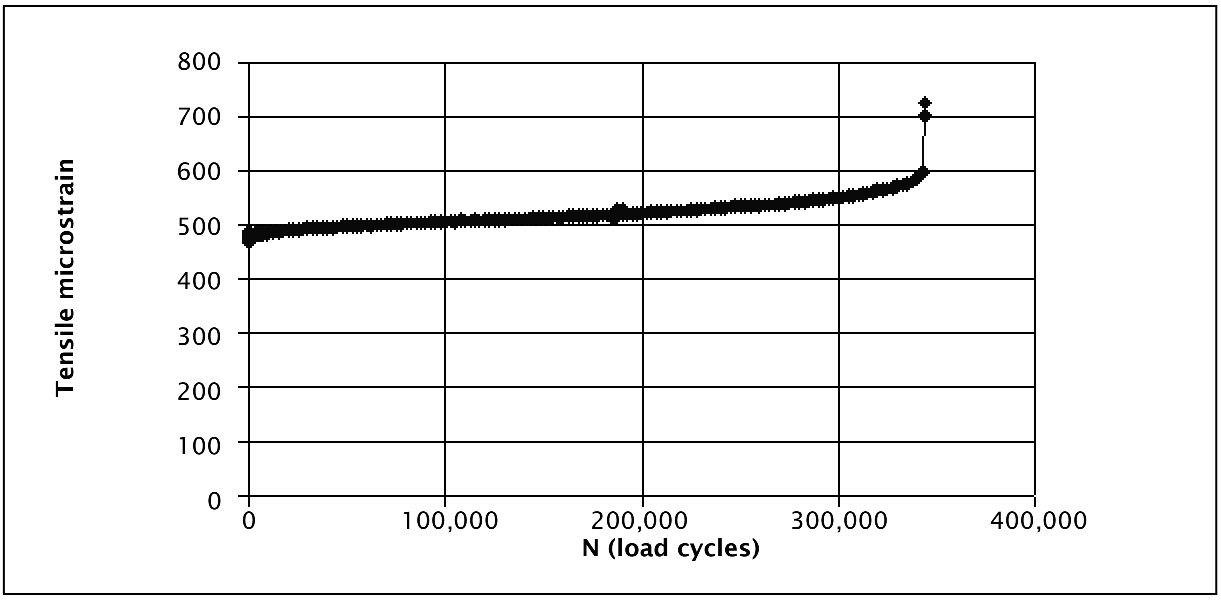


Figure C4 **Fatigue results (tensile microstrain) for beam 110902 (CAPTIF + 4% cement): second stage**



Tensile stress = 1397kPa (approximately 63% of maximum tensile strength)

Figure C5 **Fatigue results (modulus) for beam 110902 (CAPTIF + 4% cement): last stage**

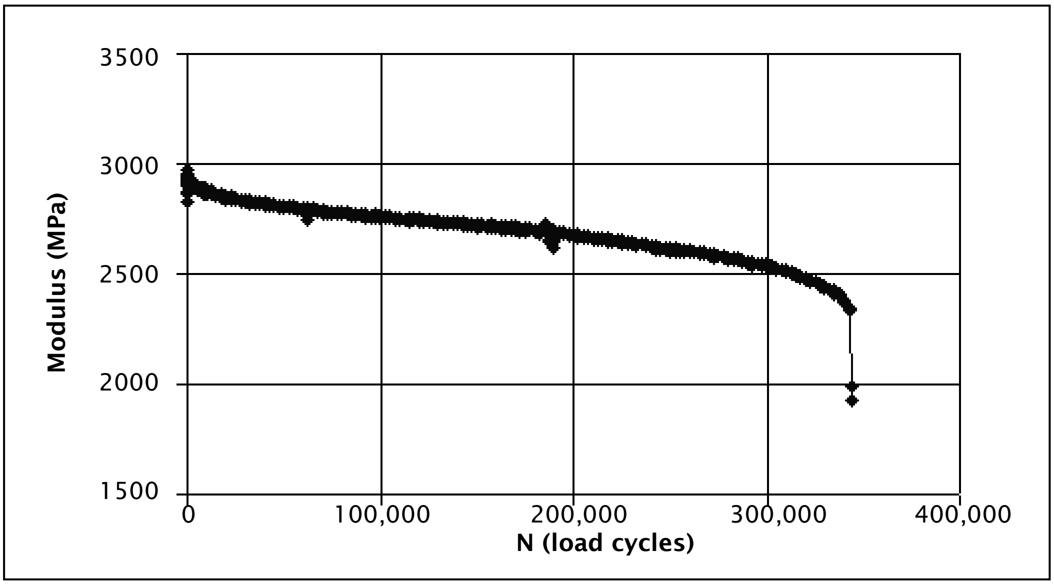


Table C4 Further beam fatigue test results for CAPTIF + 4% cement

Beam #	Tensile stress (kPa)	Tensile strain (mm)	Flexural modulus (MPa)	Number	Comment
110902c-g	693	242	2863	5,000,000	Estimated
110902j	1115	398	2800	1,000,000	Estimated
110902l	1395	490	2846	344,522	Actual
110907f	1115	378	2948	199	Actual
110906b	1116	296	3756	133	Actual

Figure C7 shows the beam fatigue test results plotted alongside tensile fatigue criteria derived from breakage tests (see the CIRCLY design criteria in table C3).

Figure C7 Beam fatigue test results and tensile fatigue criteria for CAPTIF + 4% cement beams