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DEVELOPMENT OF A FOUR-POINT BEND TEST SYSTEM FOR BITUMINOUS MIXTURES

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ABSTRACT: One of the primary structural distress modes found in bituminous pavement layers, is fatigue cracking, resulting from repeated application of traffic-induced stresses. The development of a four-point bending (4PB) test arrangement to determine the dynamic mechanical properties of rectangular beam specimens (305x45x50mm dimensions) of bituminous mixture is discussed. The test fixture, which was integrated with a closed loop servo hydraulic feedback system, incorporates a constant clamping mechanism and uses a combined displacement and loading mode of control. The system also allows the crack damaged surfaces of beam specimens to be inspected and monitored digitally in-situ during fatigue tests. This digitally imaged information of fatigue cracking can be used to measure the extent of damage and rate of damage evolution within specimens. A series of four-point bending fatigue tests were performed on a Hot Rolled Asphalt (HRA) mixture and compared with indirect tensile fatigue data and theoretical models of fatigue damage. Longer fatigue lives were predicted with the four-point bending arrangement.

KEY WORDS: Bituminous mixture, fatigue, four-point bending, image analysis.

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INTRODUCTION

Fatigue cracking of the bituminous layer is a primary structural distress mode within flexible road pavement material systems. Increasing loads on the world's highways, together with a global move towards the use of centralised standards and test procedures, have intensified the importance of using fundamental, non-empirical mechanical tests to characterise the fatigue behaviour of these materials. This is particularly important when designing and predicting the in-service performance of bituminous road pavement mixtures.

Over the past forty years, many diverse test geometries have been developed to simulate the fatigue behaviour of bituminous road construction materials, with varying success (Roa Tangella et al, 1990). These devices can be categorised into; simple flexure (two, three and four-point bending), supported flexure, uniaxial, triaxial, diametral and wheeltracking fixtures.

Simple flexure tests are the most commonly used to obtain fatigue data. During this loading method a state of predominantly uniaxial tensile bending is created within the specimen. Different load configurations and specimen geometries have been used. Earlier devices made use of rotating cantilever (Pell, 1967) and trapezoidal cantilever fixtures (Van Dijk, 1975; Bonnot, 1986) powered by electric motors and electro-magnetic actuators. With the advances made in servo hydraulic and computer controlled pneumatic loading systems, the use of 3PB and 4PB fixtures with rectangular beam specimens have become more popular. Due to the amount of permanent deformation or sagging of the beams under gravitation, pure stress controlled tests have been avoided, especially when the specimen modulus is less than 3GPa (Van Dijk, 1975). Four-point bending is favoured since failure can initiate in an area of uniform stress between the

two centre loads. This method of loading is also said to be more sensitive to mixture variables such as binder type or aggregate grading (SHRP, 1992). Clamping of the specimen remains a delicate operation but the use of constant torque motors to apply a constant clamping force has increased the accuracy of the method.

To reproduce the in-situ stress conditions, researchers have supported test specimens with rubber mats (Majidzadeh et al, 1971) or air cushions (Jimenez and Gallaway, 1962) of known stiffness. This also helps to prevent the sagging of specimens at high temperatures due to gravitation. This support beneath the specimen is also said to reduce the effect of minor imperfections in the specimen and thus the scatter of results is less. Circular, slab and beam specimens have all been used with three-point and four-point loading. The method also makes it possible to apply an intermediate mode of load control without the use of complicated computer-controlled equipment. However, calculation of the stress state within the actual specimen is complex and failure is a function of the stiffness of the support, which might not be representative of in-situ condition. This method is more suited for mixtures that rely on aggregate interlock for providing strength, such as porous asphalt.

During direct axial tests, circular or rectangular beam specimens are loaded either by pure tension or tension-compression. These tests are less costly since they do not require special fixtures to load or clamp the specimen. Although the interpretation of results is simplified by the pure state of stress and the absence of shear, field stress and strain conditions are not duplicated particularly well. It is necessary to use precisely machined and aligned specimens and this can unduly complicate the method. Results from direct axial tests are said to be heavily influenced by the specimen's surface conditions (Read, 1996).

In triaxial tests a confining pressure is applied to the circumference of a test specimen (usually cylindrical) using either air, water or vacuum. Axial loads are applied directly through loading platens. This represents the in-situ stress conditions well although triaxial tests require specialised equipment that is costly and time consuming to set up. Triaxial tests are generally considered to be more appropriate for characterising permanent deformation than for fatigue.

The diametral fatigue test is conducted by repetitively loading a cylindrical sample with a compressive load acting parallel to and along the vertical diametral plane. A relatively uniform state of tensile stress, which eventually causes failure, develops along a plane that is parallel to the loading axis. The main advantage of this configuration is that the test can be performed on laboratory compacted or field cored specimens. According to Read (1996) failure initiates from the centre of the specimen and thus is not affected seriously by the surface conditions of a specimen. However, at the points of load application stress concentrations do occur while unacceptable shear and compression failures can occur at elevated temperatures. With diametral loading it is not possible to vary the ratio of the vertical to the horizontal stress components in the centre of the specimen. It is not possible to cyclically reverse the stress and consequently permanent deformation will accumulate. This result in specimens not failing solely by fatigue. Diametral tests are less sensitive to mixture composition than flexural tests and the number of cycles to failure is generally fewer than when flexural tests are used (SHRP, 1992).

Wheel tracking test facilities are often used to better simulate the dynamic effects of a rolling wheel on the pavement and to better understand the sequence of crack initiation and propagation. In such a device a loaded wheel with a solid rubber or pneumatic tyre is rolled over an asphalt concrete slab that is supported on a rubber foundation. The tyre/specimen contact area can be varied by changing either the load or the inflation pressure of the tyre. This test procedure

allows for the interaction between other forms of pavement distress and fatigue damage to be investigated. It also allows special pavement structures, like geo grid reinforcement of an asphalt layer, to be tested.

While many different configurations are available, simple flexure tests seem to be the most appropriate for simulating fatigue damage, which originates at the bottom of an asphalt layer. More specifically, four-point bending should be used since this allows failure to initiate in a region of uniform stress that is remote from loading attachments. The experimental equipment and techniques that are required to load and control static 4PB tests on asphalt beam specimens are relatively simple. However, under dynamic loading conditions, viscoelastic effects and permanent deformation of the beams complicate clamping and load cycle controls. The present paper describes a 4PB fixture that was designed, manufactured and integrated with an Instron 8501 computer controlled servo hydraulic loading system. A series of 4PB tests was conducted to evaluate the fatigue strength of a standard Irish Hot Rolled Asphalt mixture and compared with data obtained from a diametral test system. Results indicated longer fatigue lives were measured with the 4PB arrangement.

DESIGN OF FATIGUE TEST FIXTURE

A specific requirement when designing the fixture concerned the monitoring of fatigue damage during a test. A variety of different techniques were considered for measuring crack propagation, namely crack foil measurement, crack opening displacement (COD) measurement, indirectly by measuring the change in force, displacement or compliance of the specimen and

calibrating it against the crack length through finite element analysis and visual measurement using a travelling microscope. Initial experiments with 3PB and 4PB fixtures indicated that it would be particularly difficult to measure fatigue damage. Within the bituminous mixture cracks tend to form network patterns, initiating at more than one point, vanishing behind aggregates or separating around them. As remarked by Read (1996), the lineal crack length is quite different to the crack depth as the cracks follow meandering paths around aggregate, this being especially true for mixtures with a more continuous grading or having larger aggregates. A technique that would accommodate such crack behaviour and which was developed in this present investigation involved photographing damaged areas and subsequently analysing the captured images. Due to the uniform maximum stress state that would exist between the two central loading points of the 4PB arrangement, failure was expected to occur in this region. Accordingly, this area was digitally photographed at different increments of fatigue life. The image capturing process is described later but it is important to realise that the lateral face of the beam specimens had to be kept clear of all clamping obstructions so as to accommodate in-situ photography during testing. The final design of the fixture has a completely open front side that not only makes photography possible but also simplifies the placing and location of the specimens within the fixture. This is simpler and more convenient for in-situ damage detection than either of the products (MTS, 2000; ELE, 2000) that have been developed subsequent to the SHRP A-003A programme (SHRP, 1992).

Due to bituminous material's viscoelastic nature, which causes a beam specimen to sag under its own weight, 4PB fixtures for testing asphalt beam specimens have generally been designed with fairly complicated clamping mechanisms. Monismith and Deacon (1969) used spring loaded screw clamps while Airey (1995) bolted his specimens to his fixture at a specific torque.

More recently, the SHRP 4PB fixture (Tayebali et al, 1996) and the MATTA fatigue tester (Austroads, 1998) relied on precision torque motors to automatically re-adjust the clamping of the specimen during testing. A prototype test fixture was constructed to evaluate this basic technology. The prototype 4PB fixture consisted of four freely rotating clamps that prevented translation movement. Hand tightening the clamps to a specific torque was insufficient to prevent a specimen from translation movement within the fixture; this was due to sagging of the specimen around the clamping area. A spring-loaded mechanism showed some improvement but was still inadequate as it could not accommodate the large amount of slack and required re-adjustment during testing. An automatic clamping mechanism using torque controlled DC motors was investigated and finally incorporated into the design of the fixture. The DC motors, fitted with stepped gearboxes, were controlled using separate servo controllers. The motor controllers were set to a cut-off current that would achieve a finger tight lock of the clamps on the specimen.

The basic design of the fixture is shown in Fig 1. The two centre loading clamps are mounted on a frame that is connected to the bottom actuator of the loading machine. The outer reaction clamps are connected to the loadcell on the crosshead via an aluminium frame and guide rod that extends through an access hatch in the environmental chamber.

The specimen clamping mechanism is described in detail in Fig 2. The DC motors are fixed on a guide plate fitted with a linear bearing that runs along a guide rod extending from the top of the clamp. The rotating axle of the motor is connected to a threaded bar that screws into the clamp frame and pushes the clamp face onto the specimen. The clamps are connected to the upper and lower aluminium frames through a set of roller bearings to allow free rotation around the x-axis. Free translation movement on three of the clamps is achieved through two linear

bearings running along the y-axis. The fourth clamp is fixed in the y-direction to stabilise the system. The clamping procedure involved aligning the bottom clamp faces, inserting the beam specimen with the bottom face pointing downwards and then locking the outer clamps first before clamping the inner loading points. The clamping was applied throughout the duration of a test and adjusted automatically when the specimen experienced deformation. The complete 4PB test facility is shown in Fig 3.

EXPERIMENTAL TEST SETUP

An Instron 8501 servo hydraulic loading system into which the different fixtures for static and dynamic tests are placed, was used to load and control both the static and fatigue tests. This machine operates as an electro-hydraulic feedback closed-loop servo system where load is applied by a servo-controlled hydraulic actuator mounted on the table of a loading frame. Pressure and flow of the hydraulic fluid to the servo valves and actuator are provided by a hydraulic power pack (80 litres/minute at 207 bar pressure). Load on the beam specimens and displacement of the actuator is sensed by a loadcell situated on the crosshead and an internal LVDT running on the actuator. For the dynamic tests an external LVDT was mounted to measure central beam specimen deflections. Signals from the load and displacement transducers are conditioned and controlled via the interface and data acquisition board situated in the control console. Purpose designed software for fatigue tests allowed feedback from the input transducers to be monitored and adjusted by a microcomputer. Customised software (Instron, 1995) was used to control fatigue experiments where a specimen was cyclically loaded at levels below its

ultimate static strength until failure. Limitations on the capacity of the data acquisition board in the control console meant that a maximum cyclic frequency of 4Hz could be achieved in the combined mode of control. A standard Instron environmental chamber was used; this incorporates access hatches to connect the fixtures to the actuator and loadcell. The chamber is controlled from a separate temperature controller that can achieve temperature stability to within ± 0.5 °C over the range of -73 to 315 °C.

Fatigue tests were performed at a temperature of 20 °C using a sinusoidal load waveform at a frequency of 4Hz, without rest periods. These tests were purposely carried out using a combined load and displacement mode of control. Load control without reversal leads to excessive permanent deformation while displacement control inhibits the development of complete fracture. The combined control involved a fatigue cycle in which the beam was loaded from its datum conditions to a target load and displaced back to its zero displacement position. The typical variations of load and deflection during a fatigue test under this combined mode of loading are illustrated in Fig 4.

Initial sagging of the specimen occurs with the effect that the load amplitude increases and additional load is required to force the specimen back to its zero deflection position. With increasing fatigue cycles the recovery load reduces gradually and the total deflection increases as the structural integrity of the specimen deteriorates. Fig 5 provides further insight into the behaviour of the material and control mode during the test. It shows the typical variation of the mode factor (MF) with number of load cycles for the combined mode of control. The mode factor was defined by Monismith and Deacon (1969) as:

$$MF = \frac{|A| - |B|}{|A| + |B|} \quad (1)$$

where

MF = mode factor,

$|A|, |B|$ = the percentage change in strain and stress, respectively, for an arbitrarily fixed reduction in stiffness.

During most of the test it is displacement control that is the dominant control mode since the rates of load reduction and deflection increase remain stable. However, in the latter stages of a test, the deflection increase occurs more rapidly and the control mode changes to load control.

SAMPLE PREPARATION

The bituminous mixture used during the commissioning of the experimental facility was a 30% 14mm Hot Rolled Asphalt (HRA) mixture (BS 594: Part 1 1992). A binder content towards the lower end of the design spectrum (7.3 % by wt.) was purposely chosen to obtain fatigue prone mixtures. Raw materials were sampled, conditioned and mixed as described elsewhere by Hartman (2000) and Hartman et al (2001). The standard Coopers Research Technology Roller Compactor was used to compact the loose material with a segment of a roller that allow the aggregate particles to move relative to one another and orientate themselves in a manner similar to in-situ material. The precise depth of the slab can be pre-set enabling the target density (4% voids) to be achieved. The slabs that were produced measured 305x305x50mm and required roughly 11kg of mix. Before beams (305Lx50Wx45Dmm) were machined from these slabs, they were cured at 60°C in a forced draft oven for 24 hours inside the compaction moulds. The bottom faces of the beams, that were exposed to the maximum tensile stresses under bending and

from which cracks would initiate, were also machined away. This was done to ensure a more uniform initial flaw size and reduce scatter of results. Specimens were water cooled during machining and subsequently they were air dried for 24 hours before being weighed to determine their void content. Voids were determined from dimensions measured with a Vernier calliper (accuracy $\pm 0.01\text{mm}$). After determining their void content, the fatigue specimens were painted with a white emulsion spray paint to ensure that any crack damage would be visible as black markings on a white background.

MONITORING AND ANALYSIS OF CRACKING

The use of sophisticated digital imaging techniques has become more common in recent years to investigate the behaviour and condition of civil engineering materials (Oren et al, 1994; Groenendijk et al, 1997; Kuo and Freeman, 1998). In 1996 Read used such techniques to measure asphalt cracking in laboratory beam specimens. This made it possible to monitor the increase in crack length, and thus to determine the total length of a crack path as opposed to an equivalent crack depth that is indirectly measured by mechanical or electrical devices such as COD gauges and crack foil circuits.

Image capturing

Prior to testing, all beam specimens were painted with a quick drying road marking spray paint. Any cracks or damage were therefore expected to become visibly apparent as black against

a white background. A sufficient number of thinly painted layers were applied until a completely white surface was obtained.

Fig. 6 illustrates the digital image capture arrangement that was developed. A black and white digital CCV camera was set up inside a camera box that was fixed to the environmental chamber in order to provide identical optical distance and repeatable lighting conditions during specimen photography. The capturing of images was controlled from a microcomputer fitted with a frame grabber card. The software that controlled this card uses Visual Basic code to program data capture subroutines. A subroutine was programmed so as to photograph the side face of a beam specimen between the two loading points at set time intervals. A high shutter speed was used in order that images could be captured during fatigue tests. These images were linked to specific cycle intervals so that the incremental crack growth could be analysed after a test had been captured.

Image processing and analysis

Image processing refers to the manipulation of the captured digital images to extract the monitored feature and to emphasise its quality. A digital image consists of a two-dimensional grid made up of picture elements or pixels that vary in intensity. Pixels in a grey-scale image range from black (value = 0) to white (value = 255) while pixels in a colour image consists of three components (red, blue, green) each with an intensity ranging between 0 and 255.

The digital photographs of the beam specimens were 768x576 pixels in size and stored as greyscale bitmaps (.BMP). These images were first converted to a compressed format (.JPG) using Ulead PhotoImpact (Ulead Systems, 1996) and then imported into UTHSCSA Image Tool

(1996). Using the dimensions of the beam specimen for spatial calibration, direct dimensional measurements could be made from the digital images. An algorithm was developed to automatically select the side face of the beam from the original image. The grey scale images were subsequently converted into binary format (consisting of only pure white and pure black pixels) by applying a threshold value. The selection of this threshold value was achieved by applying a range of thresholds and then manually selecting the value that best represented the crack damage. The same threshold was then applied to all subsequent images. In order to calculate the total area of cracks, an algorithm was used to count the number of black pixels. This number of cracked pixels was converted to an area of damage by means of spatial calibration.

4PB FATIGUE RESULTS

Fig 7 illustrates the fatigue response for the HRA mixture under conditions of different initial strain amplitudes. For comparison purposes, the figure also includes data from fatigue tests carried out on the same material using the Indirect Tensile (IT) test. The indirect tensile fatigue tests were also carried out at 20°C but these used pulsed loading at a frequency of 0.67 Hz (Hartman 2000). An empirical growth rate relationship was used during the regression analysis:

$$N = k_1(\varepsilon_T)^{k_2} \quad (2)$$

where

- N = number of strain applications to failure,
 ε_T = initial tensile strain (μ strain),
 k_1, k_2 = empirical coefficients listed in Table 1.

The 4PB fatigue tests predicted longer fatigue lives than the IT tests. For an initial loading of 100 μ strain, the 4PB fatigue test predicted a fatigue life that was 48 times greater than that predicted via the IT test. This order of magnitude difference in predicted fatigue life can be attributed to the difference in loading mode, test frequency, load waveform and the manner of load application (pure bending as opposed to indirect tension). The shift in fatigue lines produced by the different test procedures can also be attributed to the different stages of fatigue damage that are simulated by each of these tests. The specific loading method and mode of load control utilised by the IT test are such that this test predominantly characterises the number of fatigue cycles to crack initiation. Only a small percentage (10%) of the cycles to failure represent the crack propagation stage (Read, 1996). The four-point bending test, on the other hand, characterises both the initiation and propagation stages of damage evolution.

Analysis of the fractured specimens and the captured digital images during fatigue tests revealed that all specimens failed at or near the central pair of loading clamps. Typical examples of beam failures are shown in Fig 8. Failure did not occur preferentially beside any particular loading position but rather was seen to vary between the two central clamps and in some instances failure appeared at both locations. Small opening tensile cracks, that were aligned in a direction perpendicular to bending, were observed on the bottom tensile face of the beams between the loading clamps, shown typically in Fig 9. This would indicate that the bearings in the clamps did allow specimens to bend in a manner similar to in a classic 4PB test. It appears

that under a small clamping force the curved clamp faces almost always induce damage because of stress concentrations from which fatigue damage grows.

During the course of the 4PB fatigue tests, digital images were captured of the side face of each beam, i.e., between the centre loading points where fracture was expected to occur. These images made it possible to monitor fatigue crack development through the depth of each specimen. Image analysis procedures were applied to the sets of images and the growth in crack area was thereby determined. Fig 10 shows a typical example of the development of crack area for a specimen.

CHARACTERISATION OF FATIGUE BEHAVIOUR

An effort was made to characterise 4PB fatigue behaviour by applying a linear elastic fracture mechanics (LEFM) approach to the crack area data as determined from the digital image analysis procedure. By normalising the cracked area against the specimen depth (d), an equivalent crack length (c_{DIA}^{eq}) was determined:

$$c_{DIA}^{eq} = d \cdot \sqrt{\frac{A_c}{A_t}} \quad (3)$$

where

A_c = total area of cracks at cycle N ,

A_t = total area of cracks at failure.

Fig 11a shows typical data obtained for HRA specimens tested at high and low load levels. A power law regression fit was determined for each set of measurements allowing the rate of crack

propagation to be determined at the specific recorded load cycle and represented in the form of a Paris growth rate equation (Paris and Erdogan, 1963):

$$\frac{dc_{DIA}^{eq}}{dN} = A\Delta K^n \quad (4)$$

where

- c_{DIA}^{eq} = equivalent crack length (mm),
- N = number of load cycles to fatigue failure,
- A, n = material coefficients,
- ΔK = cyclic stress intensity factor range (N/mm^{1.5}).

The relationship between the stress intensity factor and the equivalent crack growth rate for these two particular HRA specimens is shown in Fig 11b, while the combined data of a total of ten HRA specimens are shown in Fig 12. In general, the data for the HRA mixture is seen to obey the LEFM model for fatigue life well ($R^2=0.93$).

CONCLUSIONS

A four-point bending arrangement, which was integrated with a closed loop servo hydraulic feedback system, was purposely designed, constructed and used to determine the fatigue properties of a Hot Rolled Asphalt mixture. Compared to Indirect Tensile fatigue the four-point bending arrangement produced data that predicted longer fatigue lives. An image processing system was developed to characterise cracks by analysing digitised photographs of the side face

of a beam specimen. This approach showed considerable promise and was used to evaluate a linear elastic fracture mechanics model. Subsequent work will use this fixture to evaluate the static and fatigue flexural properties of bituminous mixtures.

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APPENDIX 2 – FIGURE CAPTIONS

FIG 1. Schematic layout of dynamic 4PB fixture which was designed to fit inside an experimental chamber of a servo hydraulic testing machine.

FIG 2. Detail of specimen clamping arrangement in 4PB fatigue fixture.

FIG 3. Overall layout of 4PB testing system: (a) Instron control console; (b) environmental chamber temperature control unit; (c) specimen clamping DC motor controller unit; (d) environmental chamber; (e) dynamic 4PB fixture with calibration perspex beam; (f) test control and data acquisition via microcomputer.

FIG 4. Typical variation of load and deflection during 4PB fatigue test.

FIG 5. Typical variation of the control mode during a combined mode fatigue test.

FIG 6. Schematic of arrangement for digital photography (S: sample; C: CCV camera; L: light source; I: frame grabber and image processing).

FIG 7. Four-point bending (4PB) and Indirect Tensile (IT) fatigue life data for HRA mixture.

FIG 8. Typical examples of beam failures close to the central loading noses. Compressive and tensile stress states exist along the top and bottom edges of the beam specimens, respectively.

FIG 9. Example of tensile cracks on the bottom tensile face of beam specimen between central loading clamps.

FIG 10. Progressive development of fatigue cracks from bottom tensile face to top compressive face in a typical beam specimen.

FIG 11. (a) Development of the equivalent crack length with number of load cycles;
(b) propagation data for HRA.

FIG 12. Equivalent crack propagation data fitted to the Paris equation.