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BITUMEN FILMS IN TENSION

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Abstract

This paper discusses adhesive testing of bitumen films in order to determine their fracture behaviour. Both brittle and ductile films are examined, and the ductile-brittle transition is located.

Introduction

Cracking of asphalt road surfaces is normally a fatigue phenomenon. It is useful to understand the fracture process in any one cycle before attempting to study fatigue. Observations of crack surfaces in asphalt test specimens have revealed that in most cases cracks run through the binder film rather than along the aggregate binder-interface, or through the aggregate itself [1]. Bitumen is a viscoelastic material and is sensitive to variations in temperature and strain rate. This project explores cracking in bitumen films. In particular, the films are tested in tension over a band of temperatures and strain rates including those common in-situ.

Test regime

Testing methods used for adhesives were adapted to examine the fracture properties of pure bitumen, since this is the primary constituent of the binder in asphalt. Bitumen films of thicknesses ranging from 0.5mm to 3mm were tested in two geometries.

The “double cantilever beam” (DCB) joint comprised a pair of 3mm aluminium plates with a layer of bitumen sandwiched between them, and a very thin crack initiator (0.05mm) in the centre of the bitumen layer at the loading end, see Figure 1. This test models a crack running through the binder under the influence of forces acting at right angles to the crack face. Such mode I loading emulates the conditions between aggregate particles near the bottom of the bound layers of a flexible pavement, where cracks are thought to initiate. The adherend thickness had to be sufficiently small that the beams were able to bend under the restraint of the adhesive. Aluminum was chosen since its elastic modulus is comparable to that of common aggregates.

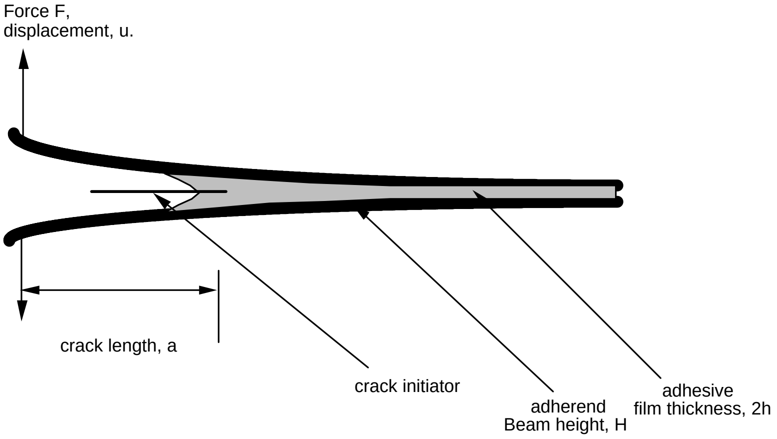

Figure 1. A double cantilever beam joint

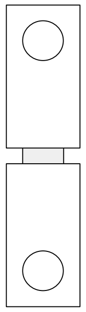

Figure 2. A butt joint: bitumen adhesive layer between aluminium blocks.

The "butt joint" test models the bitumen-aggregate contact within the flexible pavement under load, in which the aggregate particles move apart. This specimen configuration consists of a pair of aluminium blocks, with square faces, joined by a film of bitumen (Figure 2). These blocks were 25mm square in plan, and no crack initiator was used. The films ranged in thickness from 0.5mm to 3mm.

Both types of adhesive joints were pulled apart in a hydraulic testing machine at constant speeds ranging from 0.1mms^{-1} to 100mms^{-1}, inside an environmental chamber which allowed a temperature variation of -30°C to 30°C.

Brittle fracture

Brittle fracture in both double cantilever and butt joints is characterised by a linear load displacement curve, which is suddenly truncated. The fracture surfaces are often flat and shiny. For some conditions the alternating crack surfaces are observed, in which the crack periodically switches from one interface to the other.

Critical strain energy release rate

The critical strain energy release rate G_{IC} of butt joints can be estimated as the area under the load-displacement curve, divided by the area of new crack surface created in the broken specimen [2].

In the DCB joints the amount of energy needed to start a crack is the important parameter, since brittle cracks are often uncontrolled after initiation. The load measured at crack initiation was used to calculate the energy input per unit area of crack surface.

This toughness parameter, for bitumen, was obtained from results of tests at low temperatures (-10°C to -30°C), where the material is brittle. The calculation of G_{IC} for a double cantilever beam joint has evolved from the work of Mostovoy *et al.* [3]. The American Society for Testing of Materials standard for DCB tests (ASTM D3433, [4]) is based on this research. More recent publications have refined the calculation technique. Whereas Ripling *et al.* [5] have approximated the DCB to a simple cantilever fixed at the crack tip, others allowed for crack tip rotation by representing the DCB as a beam on an elastic foundation. This approach has been enhanced for relatively thick adhesive layers by treating the DCB as a composite. In the present tests, the bitumen film thickness was comparable to the depth of the aluminum plate, and therefore the latter refinements were explored.

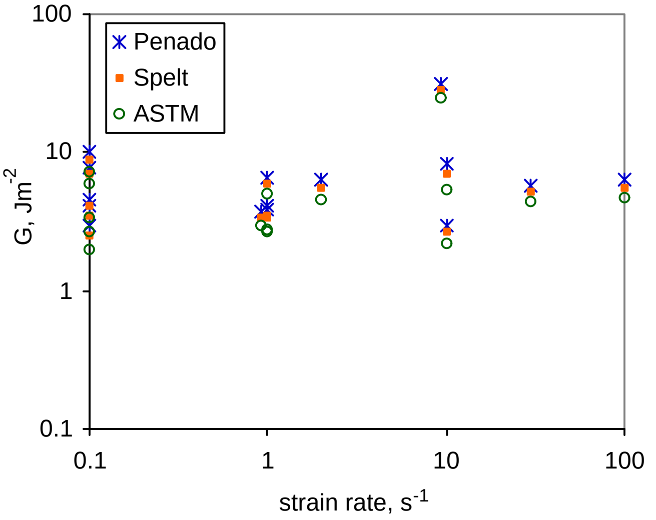

Figure 3. Fracture energy in DCB specimens calculated by the different methods

Spelt's calculation ([6], [7]) models the beam as a composite of adhesive and adherend, supported on a composite elastic foundation. Penado's model, [8] consists of a beam of the adherend material on a composite foundation. When the crack in the bitumen DCB specimens is on the point of growing, there is a region of pure aluminium in bending, and a region of bitumen – in contact with aluminium – also in bending. Thus the two approaches give the limits to the experimental case.

The bitumen tests were done at a fixed displacement rate according to the ASTM standard [4]. For a beam of width B, and depth H, with an initial crack of length a, in the adhesive layer, G_{IC} can be estimated from the load F, measured at crack initiation according to [4]:

$$G_I = \frac{12F^2a^2}{EB^2H^3}\left(1 + \frac{(1+u)}{4}\frac{H^2}{a^2}\right)$$

For aluminium alloy adherends Poisson's ratio is approximately 0.3, and the elastic modulus is 71GPa.

Film thickness

The calculation methods for G_{IC} , based on the beam on an elastic foundation include the film thickness as a parameter. Thus, there is a dependence of beam compliance on film thickness which translates into a dependence of G_I on film thickness. Penado [8] showed that this relation is sensitive to the ratio of moduli of adhesive to adherend. For the materials used, the ratio is approximately 0.007 – the modulus of the aluminium alloy being 71GPa and that of bitumen being about 0.5GPa (The modulus of bitumen was measured at a temperature of -20°C using a high frequency acoustic method). For this ratio, there is an increase in beam compliance and fracture energy with film thickness in the load-based formula. This is shown in Figure 4 as Spelt (F). An alternative testing procedure is to use a fixed crack opening displacement instead of fixed end displacement rate. Such tests are usually carried out by driving a wedge through the adhesive layer. In this case, G_{IC} can be calculated using the displacement-controlled method described by Spelt ([6], [7]). It is labelled Spelt(d) in Figure 4. G is seen to decline with film thickness when calculated in this way. The estimate presented here is based on a measurement of the average opening displacement at the load points when the crack begins to run. The ASTM formula [4] is independent of adhesive thickness (Figure 4), and was chosen for this research, in order that the more complex effects of adhesive thickness on ductile fracture behaviour could be clearly identified.

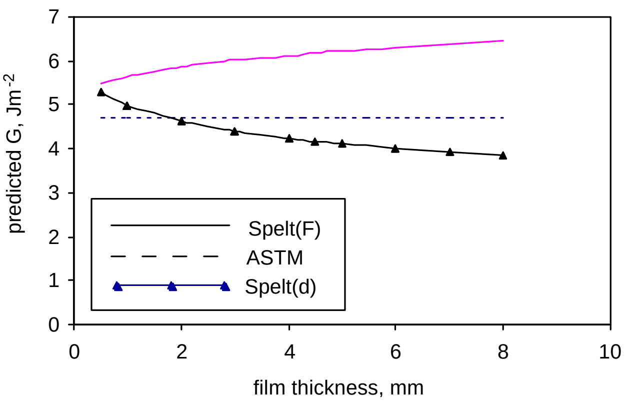

Figure 4. Effect of film thickness on estimated fracture energy

Crack tip sharpness

In DCB joints, the starter crack was not razor sharp, since the crack initiator had a finite thickness at the crack tip. In the butt joints the crack starts from a random flaw – the crack 'tip' itself is blunt. This variation in crack tip sharpness may be representative of the range of starter crack conditions in a road pavement. Due to healing in the binder, at temperatures which allow the material to flow, an existing crack tip becomes blunt over time. However, at the moment when a moving crack stops advancing (the moment of crack arrest), it is likely that the crack tip is very sharp. This effect is shown in Figure 5, where the first peak corresponds to the first initiation at the starter notch, and the second and third peaks correspond to initiation from points of arrest. Cracks will most easily initiate from a sharp flaw. Therefore, there is a range of crack initiation energies, which may be encountered in practice. This range is encompassed by the variation of G_{IC} from the high values measured in butt joint tests (minimum value of 10Jm^{-2}) to the low values associated with crack arrest in DCB joint tests. The lowest value of G_{IC} observed for crack reinitiation from an arrest, as in Figure 5, was 5Jm^{-2}. This agrees with the results of DCB tests at -30°C, and indicates that the crack initiator used was sufficiently sharp. The range of G_{IC} for bitumen films is therefore 5 Jm^{-2} to 10 Jm^{-2}.

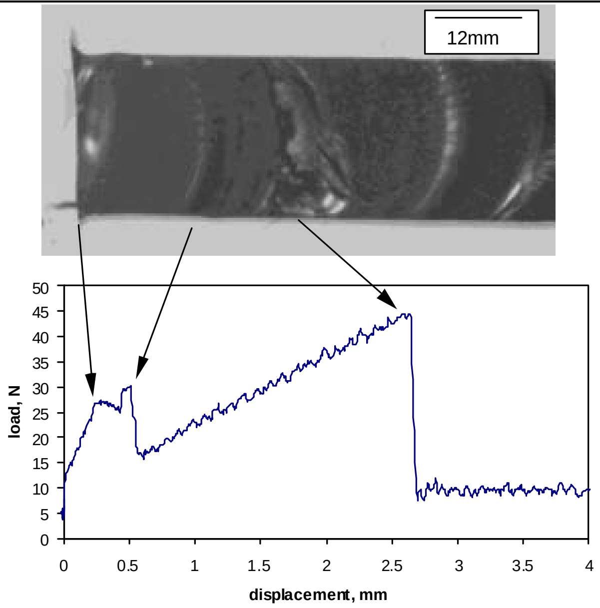

Figure 5. Crack arrest on a fracture surface and associated loading curve

Ductile fracture

At high temperatures and low strain rates, the behaviour of bitumen is so ductile that conventional cracks are not observed. The film material in the butt joint flows inwards from the edge and necks down to form a point at rupture. Alternatively, voids form within the film. These voids join together, leaving ligaments of material between them. In DCB's the equivalent of a single ligament is a wall of material extending across the width of the specimen. In other tests, there was evidence of voiding, as a number of finger-like projections constituted the crack surface. All the load-displacement curves were non-linear, and it was necessary to observe the DCB tests carefully, to verify that the crack began to advance at the point where the load reached its peak. In these tests, there was a very blunt crack mouth (instead of a sharp tip) and a process zone of deforming material moving in advance of the mouth. Crack initiation was considered, for the purposes of this study, to be the point at which the mouth was widest, and just about to translate forwards.

Rate dependence of ductile fracture

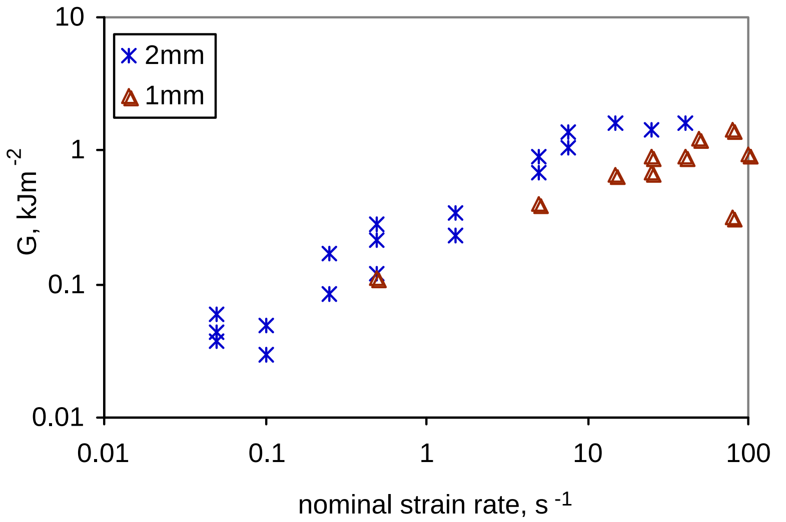

Figure 6. Fracture energy depends on both strain rate and film thickness

In the ductile region, the non-linear viscous aspect of the stress-strain response of bitumen dominates and *G* depends on both the strain rate and the film thickness, as shown in Figure 6. Bitumen film tests show an increase in failure load with increases in strain rate. Consequently, more energy is required to separate the adherends at higher strain rates. The strain rates imposed in tests at any given temperature can be adjusted in order to covert them to an equivalent strain rate at a reference temperature (chosen to be 0°C for this study). This allows a greater range of behaviour to be represented on a single pair of axes. The adjusted strain rates $\dot{\varepsilon}_a$ were calculated using a model for the uniaxial behvaiour of bitumen by Cheung [9]:

$$\dot{\varepsilon}_a = \dot{\varepsilon}\exp\left(\frac{-Q}{R(T_0 - T_1)}\right)$$

where Q is the activation energy and R is the universal gas constant. T_0 is the reference temperature and the test is carried out at a temperature T_1, in Kelvins.

Crack bridging

The ductile DCB specimen behaves as if a complex viscoelastic foundation has replaced the elastic one described earlier. This situation is almost impossible to represent analytically for a material like bitumen, which displays an intricate constitutive behaviour. A crack bridging approach is therefore proposed. The spring units can be visualised as being replaced by crack bridging units, each having the behaviour of a simple bitumen film in tension. The butt joint tests thus define a bridging law or ‘spring law’ for the viscoelastic foundation. Before adopting this viewpoint, it is necessary to verify that the fracture behaviour of the DCB’s and butt joints coincide.

Figure 6 highlights that the results are affected by film thickness. A new parameter, *G/2h* can be used to represent ductile toughness. *G/2h* measures the energy per unit volume required to separate the adherends. This parameter conforms with the crack bridging visualisation, implying that thicker films contain longer ‘spring units’ showing the same stress-strain response as their shorter counterparts. A plot of *G/2h* against adjusted strain rate is shown in Figure 7.

It can be seen that the data, for films 0.5mm to 3mm thick, collapse onto a single line. Furthermore, the butt joint and DCB test results lie on the same line, which shows a by a power law dependence on strain rate.

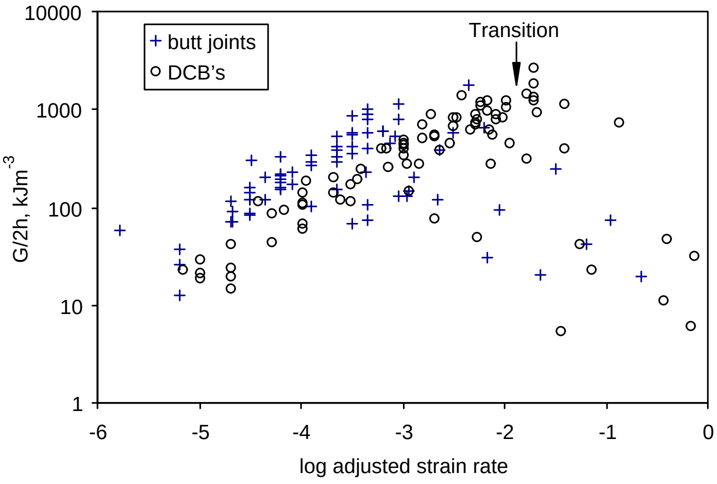

Figure 7. Energy per unit volume is a function of strain rate only

Ductile-brittle transition

Figure 7 shows a transition from ductile to brittle behaviour at an adjusted strain rate of $0.01s^{-1}$. The position of the ductile-brittle transition may be estimated by considering the size of the process zone over a range of strain rates. At very low adjusted strain rates, the process zone is large, extending well ahead of the crack mouth. As strain rates increase, the length of this zone shrinks, until it is comparable with the film thickness. When the zone is sufficiently small that it no longer interacts with the adherend-adhesive interface, it is possible for a brittle crack to develop. This locates the onset of the ductile-brittle transition.

In the limit, a brittle crack tip is preceeded by a vanishingly small process zone and no attempt will be made to quantify the process zone length in the brittle region. In the ductile region, the conventional equation for process zone length may be slightly modified: replacing the uniaxial yield stress with the uniaxial steady state flow stress, s_f, measured for the bitumen used. A process zone length normalised by the film thickness, can be estimated as [10].

$$\frac{r_p}{h} = \frac{EG}{hp\,s_f^2}\ .$$

The modulus of elasticity was, as before, the low temperature-high frequency limit, and fracture energy, *G*, is calculated from DCB test results. Figure 8 shows the decline of normalised process zone length with strain rate, and the location of the onset of the transition from ductile to brittle fracture.

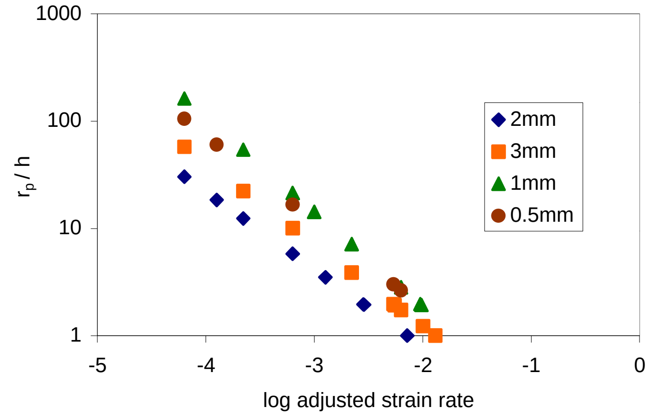

Figure 8. Plot of normalised process zone size over a range of strain rates

The results of all tests performed on the DCB specimens are shown in Figure 9 for twelve decades of adjusted strain rate. It clearly shows the three modes of behaviour: ductile, transition and brittle.

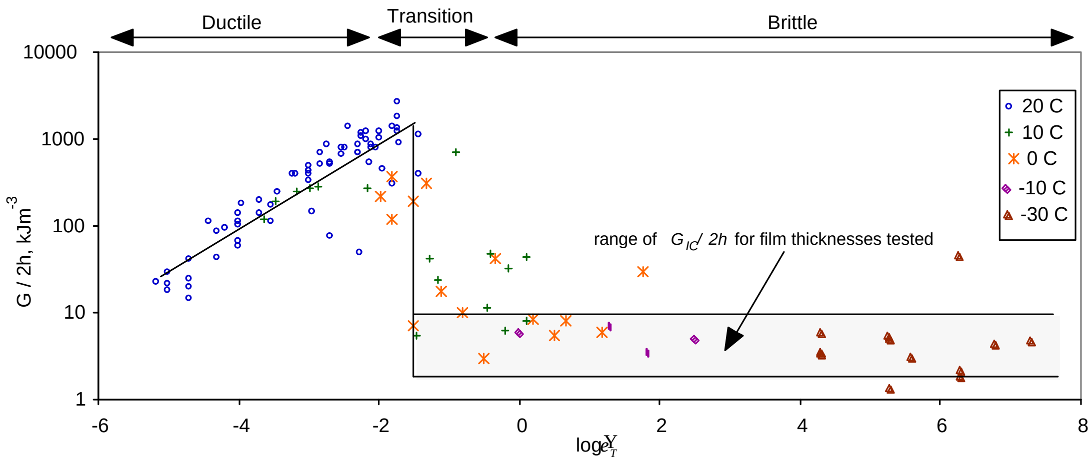

Figure 9. Master curve showing relation between *G / 2h* and $\dot{e}_a$ for different mechanisms in DCB's

Conclusions

Bitumen films show different failure mechanisms depending on the temperature and strain rate at which the load is applied. The range of fracture behaviour in bitumen films is summarised on the master curve shown in Figure 9. At low temperatures or very high strain rates, brittle fracture occurs. The critical strain energy release rate ranges from $5Jm^{-2}$ to $10Jm^{-2}$, depending on the sharpness of the crack tip. At very high temperatures or low strain rates, films show ductile, viscous behaviour, with high fracture energies. A single value of energy per unit volume of material separated is associated with any given strain rate. The transition from ductile-brittle behaviour begins at an adjusted strain rate of $0.01s^{-1}$.

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