Relationship between creep time dependent index and Paris Law parameters for bituminous mixtures

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Bituminous mixtures undergo cracking, either top-down or bottom-up, as a consequence of the repeated application of traffic loads, thermal cycling or a combination of the two mechanisms. Cracking is considered as one of the major distress modes in asphalt pavements.

This study presents a method to characterise crack resistance of asphaltic mixtures containing waste materials using a semi-circular bending (SCB) fracture test. Three different bituminous mixtures containing incinerator bottom ash waste and one control mix, containing limestone, were tested under cycling SCB loading conditions at 5°C and the results were interpreted using Paris Law. The same mixtures were also tested under controlled stress creep conditions at the same temperature. This paper examines the link between the time dependent index from creep tests with the n parameter from the Paris Law model, based on visco-elastic continuum damage mechanics analysis and linear elastic fracture mechanics principles.

INTRODUCTION

 Burning municipal solid waste, results in a few by-products, the most common of which is bottom ash. It was not uncommon to dump this in landfills. However, due to European Union restrictions imposed in 2004 on landfill sites, alternative usage has become necessary. One such alternative is using bottom ash waste in asphalt for roads. Its properties have been studied mechanically, physically and environmentally (Hassan & Khalid 2010a). These properties have linked bottom ash to lightweight aggregates.

Numerous successful trials have been conducted worldwide to study its usage as a road construction material. However, a better understanding of its usage and behaviour is still required. It was found that substitution of virgin aggregate with up to 80% incinerator bottom ash aggregate (IBAA) waste resulted in mixtures with a higher binder content of up to 1.2%, lower resilient modulus values and satisfactory use in binder course and base layers on major roads (Hassan & Khalid 2010a&b; Ogunro et al. 2004; Vassiliadou & Amirkhanian 1999).

An IBAA content of up to 80% was found to improve the leaching properties and rutting resistance of bituminous mixtures (Hassan & Khalid 2010a). With regard to the crack resistance properties of mixtures containing bottom ash waste, there are very few previous studies (Hassan & Khalid 2010b) that have explored this area. In the latter study, it was shown that elasto-plastic material properties can be derived from elastic parameters using a correspondence visco-elastic principle and creep compliance of mixtures. This work examines the relationship between the Paris Law constant, n, and the creep compliance time exponent, m, for mixtures containing different bottom ash waste quantities.

MATERIALS

Two aggregates were used in this study – limestone to produce control bituminous mixtures, and bottom ash waste to replace limestone. The binder used was 100/150 Pen bitumen sourced from Venezuelan crude. These materials were utilised to produce hot bituminous mixtures containing 0%, 30%, 60% and 80% (named as OA, AA, BA and CA in sequence) bottom ash waste by weight.

The composition and volumetric parameters of each mixture and details of the mix design procedure were published elsewhere (Hassan & Khalid 2007).

SAMPLING AND TESTING

Cylindrical cores of nominal 150 mm diameter and 65 mm thickness were cored from 300 mm square asphalt slabs compacted in the laboratory using a roller segment. Each cylinder was then cut in half to obtain semi-circular samples. These were then sharply notched at mid-point in the direction of the load using a diamond-tip tile cutter.

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Specimens were then allowed to deform under a uniaxial compression stress. The cross-head was allowed to apply a constant load over samples for 1 800 seconds. This time was found to be adequate for mixtures to reach steady state conditions. In each test, the axial and radial strains over time were recorded.

For each applied stress, the stress-strain relationship was captured and recorded by a computer. The axial deformation of the specimens was measured by recording the crack length; and 

\[ \frac{da}{dN} = A(\Delta K)^n \]  

(1)

where: \( \frac{da}{dN} \) is the crack growth rate; \( \Delta K \) is the stress intensity factor range; \( A \) and \( n \) are constants that depend on the material and test conditions; \( a \) is the crack length; and \( N \) is the number of load cycle applications.

Asphalt is a visco-elastic material. Its fracture behaviour can be characterised by means of the J-Integral parameter. Thus, the Paris Law can be expressed in terms of the J-integral as follows (Rice 1986):

\[ \frac{da}{dN} = A_j(\Delta J)^n \]  

(2)

To calculate \( J \), Schapery (1984) integrated a non-linear visco-elastic constitutive equation and presented the result in Equation 3.

\[ J = \int (w d\tau - \delta \tau_{xx} d\tau) \]  

(3)

where: \( w \) is the strain energy density; \( \tau_{xx} \) is the stress vector acting on the contour; \( u \) is the displacement vector; \( ds \) is the increment along contour \( i \); and \( x \) and \( y \) are coordinates normal to the crack front.

For linear elastic conditions, \( J \) represents the energy made available at the crack tip, whereas for visco-elastic conditions, \( J \) no longer represents the available energy because of its dissipation. However, the corresponding principle of visco-elasticity, demonstrated by Schapery (1984), makes it possible to define a generalised time-dependent J-Integral by forming a \( J_\nu \), which is a pseudo-elastic J-Integral, with the linear elastic case as shown in Equation 3 (Kuai et al 2009). It has been shown (Kuai et al 2009) that the visco-elastic problem can be converted to an elastic problem with the pseudo stress and strain parameters. Then the generalised J-Integral is given as follows:

\[ J_\nu = \int (w^e d\tau - \delta \tau_{xx}^e d\tau) \]  

(4)

\[ J = E_p \int_0^1 \left( D(t - \tau) \right) \frac{\delta u^e}{\delta x} d\tau \]  

(5)

where: \( W^e \) is the pseudo strain energy density; \( u^e \) is the pseudo displacement vector;
ER is a reference modulus; \( \tau \) is the retardation time for the \( i \)th element; and \( D(t) \) is the creep compliance. Parameters were determined to be used in Equation 5 (Hassan & Khalid 2010b) and the results were presented as in Figure 4, from which new Paris Law constants, \( A_J \) and \( n_J \), were determined and presented as in Table 1.

Creep results
For all mixtures, axial and radial strains were recorded over time. Figure 5 shows creep compliance curves obtained at 5°C and stress of 1 000 kPa. The creep compliance, \( D(t) \), in Equation 5 is typically described in a power law form as follows:

\[
D(t) = D_o + D_1 t^m
\]

(6)

where \( D_o \) is the material’s glassy compliance; \( D_1 \) is the compliance coefficient of time; \( m \) is the compliance exponent; and \( t \) is loading time. The \( m \) values for the four mixtures can be seen from the power law equations in Figure 5 to be 0.3757, 0.3972, 0.3336 and 0.2850 for mixtures OA, AA, BA and CA respectively. Schapery (1981) derived a relationship between the exponent \( n_J \) from Equation 2 and \( m \) from Equation 6 under different scenarios.

\[
n_J = 3.4762 m + 0.7042
\]

(7)

The nature of the relationship differs from that reported by Schapery and its shape does not change when any outliers are deleted from the regression analysis, demonstrating that the relationship in Equation 7 is representative between the two parameters for the bottom ash waste mixtures.

CONCLUSIONS
From the work conducted in this study, it can be concluded that:

- Paris Law was found suitable to characterise crack growth properties of bottom ash waste bituminous mixtures using the J-Integral. The J-integral was evaluated from elastic fracture analysis using Schapery’s correspondence principle.
- Adding up to 60% bottom ash waste led to a significant increase in the number of cycles to failure in the cyclic SCB test.
- The Paris Law constant, \( n_J \), has been related to the creep compliance exponent of time, \( m \), through a linear regression equation that differs from that reported by Schapery for constant tensile strength and bond energy of the fracture surface.

REFERENCES


