Full Length Research Paper

Effect of secondary aggregates on relationship between creep time dependant index and Paris Law parameters

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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 dependant 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. The Paris Law constant, \( n_J \), has been related to the creep compliance exponent of time, \( m \).

Key words: Cracking, bottom ash, visco-elasticity, semi-circular bending (SCB), Paris Law, creep.

INTRODUCTION

Burning municipal solid waste in energy from waste plants results in a few of by-products. One of these is Bottom Ash waste which is the most common by-products. It was not uncommon to dump it 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 to produce new materials for roads. Its properties have been studied mechanically, physically and environmentally (Hassan et al., 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. Nevertheless, higher usage and more behaviour understanding are still required. It was found that substitution of virgin aggregate with up to 80% Incinerator Bottom Ash Aggregate (IBAA) waste resulted in mixtures with 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 et al., 2010; Ogunro et al., 2004; Vassiliadou et al., 1999). Up to 80% IBAA content level was found to improve leaching properties and rutting resistance of bituminous mixtures (Hassan et al., 2010a). With regard to crack resistance properties of mixtures containing Bottom Ash waste, there are very few previous studies (Hassan et al., 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 was used 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...
Table 1. Mixture details.

<table>
<thead>
<tr>
<th>Mix reference</th>
<th>Optimum binder content (%)</th>
<th>Bottom ash content (%)</th>
<th>CDM (g/cm$^3$)</th>
<th>VIM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OA</td>
<td>4.5</td>
<td>0</td>
<td>2.380</td>
<td>7</td>
</tr>
<tr>
<td>AA</td>
<td>5.5</td>
<td>30</td>
<td>2.293</td>
<td>7.4</td>
</tr>
<tr>
<td>BA</td>
<td>6.5</td>
<td>60</td>
<td>2.177</td>
<td>11</td>
</tr>
<tr>
<td>CA</td>
<td>7.5</td>
<td>80</td>
<td>2.063</td>
<td>14</td>
</tr>
</tbody>
</table>

Figure 1. SCB test schematic diagram.

and details of the mix design procedure were published elsewhere; however, shown in Table 1 (Hassan et al., 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 saw tile cutter. Notch length was 15 mm to produce a notch to radius ratio of 0.2. Samples were then stored in an incubator at 5°C until test commencement. Cyclic Semi Circular Bending (SCB) tests were conducted in which the mixtures were tested under a cyclic load of 1.5 kN under a haversine load frequency of 1 Hz and 5°C temperature. For all tests, triplicate samples were used. Figure 1 shows a schematic of the SCB test.

Alternatively, cylindrical asphalt mixture samples of 67 mm diameter and 134 mm height were manufactured. Firstly, a laboratory roller compactor was used to produce 305 × 305 mm asphaltic slabs of 100 mm height. The slabs were compacted at four different pressures, namely 175, 275, 345 and 495 kPa. Each pressure was applied for 10 passes over each slab. The slabs were then cut into two halves. Each half was turned on its side and cored to produce cylinders of 67 mm diameter and 150 mm height. Each cylinder was then trimmed from both ends to 134 mm height. Three samples were used for each creep test. Figure 2 shows the equipment arrangement for the creep tests, which comprises a temperature controlled cabinet (-20 to 50°C) mounted on a loading frame, an axially mounted 10 tonne load cell, the specimen and its instrumentation, and a linear variable differential transducer (LVDT) with its conditioning box connected to a data logger.

Specimens were tested at 5°C. To ensure uniformity of temperature, samples were conditioned in a temperature control cabinet, at the testing temperature, for at least 12 h preceding the test. Specimens were then placed between two steel platens, smeared with silicon grease, to reduce friction, and a small pre-load was applied to take out any relaxation in the system. Specimens were then allowed to deform under a uniaxial compression stress. The cross-head was allowed to apply a constant load over samples for 1800 s. 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 via recording the cross-head movement.

RESULTS AND DISCUSSION

SCB results

Figure 3 shows the measured crack lengths against the
The axial deformation of the specimens was measured via recording the cross-head movement.

**Figure 2.** Creep test arrangements.

**Figure 3.** Crack length against number of cycles.
number of cycles, for the four tested mixtures, in which it is shown that each mixture had a stable crack growth phase. It is evident that adding bottom ash waste up to a certain amount has led to an increase in the number of cycles to failure.

LEFM analysis has been used to characterise crack growth rate by means of the well known Paris Law (Paris et al., 1963), in which the rate of crack propagation is a function of the stress intensity factor. This law is given by the following expression:

$$\frac{da}{dN} = A (\Delta K_I)^n$$

where: \(\frac{da}{dN}\) is the crack growth rate; \(\Delta K_I\) is mode I stress intensity factor range \((K_{max} - K_{min})\); \(A\) 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.

As asphalt is a viscoelastic material, its fracture behaviour can be characterised by means of the J-Integral parameter. Thus, Paris’ Law can be expressed in terms of the J-integral as follows (Rice, 1986).

$$\frac{da}{dN} = A_J (\Delta J)^{n_J}$$

To calculate Schapery (1984) integrated a non-linear viscoelastic constitutive equation and presented the result in Equation 3.

$$J = \int_{t_0}^{t} \left( W^e \, dy - T_j \frac{\partial u^e}{\partial x} \, ds \right)$$

where: \(W^e\) is the strain energy density; \(T_j\) is the stress vector acting on the contour; \(u^e\) 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 viscoelastic condition, \(J\) no longer represents the available energy because of its dissipation. However, the correspondence principle of viscoelasticity, demonstrated by Schapery (1984), makes it possible to define a generalized time-dependent J-Integral by forming a \(J_e\), 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 by Kuai et al. (2009) that the viscoelastic problem can be converted to an elastic problem with the pseudo stress and strain parameters. Then the generalized J-Integral is given as follows:

$$J_e = \int_{t_0}^{t} \left( W_e \, dy - T_j \frac{\partial u^e}{\partial x} \, ds \right)$$

$$J = E_R \int_{t_0}^{t} (D(t - \tau) \frac{\partial u^e}{\partial \tau} d\tau) = \int_{t_0}^{t} (D(t - \tau) \frac{\partial u^e}{\partial \tau} d\tau)$$

where: \(W^e\) is the pseudo strain energy density; \(u^e\) is the pseudo displacement vector; \(E_R\) is a reference modulus; \(\tau\) is the retardation time for the \(j^{th}\) element and \(D(t)\) is the creep compliance.

Parameters were determined to be used in Equation 5 (Hassan et al., 2010b) and results were presented in Figure 4, from which new Paris Law constants, \(A_J\) & \(n_J\), were determined and presented in Table 2.
Table 2. Paris Law constants using J-Integral.

<table>
<thead>
<tr>
<th>Mix</th>
<th>OA</th>
<th>AA</th>
<th>BA</th>
<th>CA</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_j$</td>
<td>0.377</td>
<td>1.3989</td>
<td>0.6312</td>
<td>2.5508</td>
</tr>
<tr>
<td>$n_J$</td>
<td>1.7016</td>
<td>2.032</td>
<td>2.562</td>
<td>1.3583</td>
</tr>
<tr>
<td>$R^2$</td>
<td>0.6434</td>
<td>0.4257</td>
<td>0.6121</td>
<td>0.3165</td>
</tr>
</tbody>
</table>

Figure 5. Creep compliance curves for the four mixtures.

Creep results

For all mixtures, axial and radial strains over time were recorded. Figure 5 shows creep compliance curves obtained at 5°C and stress of 1000 kPa. The creep compliance, $D(t)$, in Equation 5 is typically described in a power law form as follows (Lytton, 2010).

$$D(t) = D_0 + D_1 t^m$$  \hspace{1cm} (6)

where $D_0$ is the material’s glassy compliance; $D_1$ is compliance coefficient of time; $m$ is 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.

Schapery (1981) found that, if the tensile strength of the material and bond energy of fracture surface were constant during the fracture process, then $n_J = 1 + 1/m$. From regression analysis, the two parameters are related as in Equation 7.

$$n_J = 6.2 - 1/m$$  \hspace{1cm} (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:

1. 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.
2. Adding up to 60% bottom ash waste led to a significant increase in the number of cycles to failure in the cyclic SCB test.
3. The Paris Law constant, $\eta_p$, 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


