Characterisation of Uniaxial Creep Deformation Behaviour of Asphalt Mixtures

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ABSTRACT: Compressive uniaxial creep and creep recovery tests have been conducted on two generic UK asphalt mixtures over a range of temperatures and stress levels. Instantaneous elastic, viscoelastic (delayed elastic) and viscoplastic behaviour have been observed and volumetric changes have been studied. The elastic modulus of the DBM was found to be greater than that of the HRA. The viscoelastic strain was found to increase approximately in proportion to the total stain up to a certain point, above which it tends towards a constant level. The steady state viscoplastic deformation behaviour of the mixtures was found to be nonlinear with exponents of 2.5 and 5.4 for the HRA for the DBM respectively. Both mixtures were found to dilate under creep loading with more dilation exhibited by the DBM mixture due to increased aggregate interlock. The dilation ratio was found to be independent of stress level and dependent on the type of mixture and test temperature.

KEY WORDS: Creep, strain rate, volumetric strain, dilation

1 INTRODUCTION

Premature rutting of asphalt pavements still represents a serious practical problem for heavily trafficked roads, particularly under high temperature conditions. While the incidence of wheel track ruts in the highway does not usually imply structural failure, particularly in heavy-duty pavements, it does represent a serviceability failure, since ruts cause a hazard to traffic, particularly in wet weather. In the UK, the Highways Agency have adopted an approach to pavement design which provides a long life structure and the opportunity to periodically renew the surfacing using appropriate maintenance treatments. Traditional Hot Rolled Asphalt with pre-coated chippings, although still used for surfacings, is rapidly being replaced by Stone Mastic Asphalt (SMA) or thin treatments of the type developed in France in recent years. While these new mixtures appear to offer good rut resistance, the layer immediately below (binder course) is still of the traditional dense bitumen macadam type and could be susceptible to rutting.

Over the years, a number of different approaches have been used for the prediction of permanent deformation in flexible pavement structures. The simplest approach has been to use empirical relationships relating measured surface rutting to the level of compressive stress or strain calculated at the top of the subgrade using layered elastic models (eg Claessen *et al.*, 1977; Shook *et al.*, 1982). In this type of approach rutting in the asphaltic layers is not explicitly calculated, although it is inherently included in the empirical relationship.

More advanced approaches include the use of viscoelasticity and viscoplasticity. In the viscoelastic type of approach moving wheel loads can be considered with time dependent material properties to define the state of stress and strain in the pavement structure (Elliot & Moavenzadeh, 1971; Collop *et al.*, 1995; Blab & Harvey, 2002). Non-linear theories provide a more realistic representation of material behaviour but are more complex often requiring Finite Element (FE) implementation (eg Sousa *et al.*, 1993; Schapery, 1999; Lee & Kim, 1998; Long *et al.*, 2002; Hornych *et al.*, 2002; Shields *et al.*, 1998).

Viscoplasticity-based models have also been used for modeling permanent deformation in asphaltic materials (eg Schapery, 1999; Erkens *et al.*, 2002; Uzan *et al.*, 1985; Uzan, 1996). Typically, in this type of approach, a-priori postulated flow rule is used to determine the viscoplastic strain and a surface is used to define the geometric locus of states of stress corresponding to the same level of viscous flow (Blaauwendraad & Scarpas, 2000). One of the limitations associated with the more sophisticated techniques is that application to practical pavement problems requires implementation of the constitutive model in a Finite Element (FE) framework (Kasbergen *et al.*, 1999). This has limited the applicability of these more complex models and to-date no accepted methodology is used in the UK.

The objective of this paper is to describe uniaxial compressive creep and creep recovery testing that has been undertaken to provide data from which material parameters can be determined for an elasto-visco-plastic constitutive model developed jointly between the Universities of Nottingham and Delft (see Collop *et al.*, 2002 for details). Instantaneous elastic, viscoelastic (delayed elastic) and steady state viscoplastic deformation behaviour for two types of asphaltic mixture are presented and volumetric changes as a result of creep loading are discussed.

2 MATERIALS AND SPECIMEN PREPARATION

Two generic types of asphaltic mixture were chosen for this study; a 10mm Dense Bitumen Macadam (DBM) (BS 4987: Part 1 2003) and a 30/10 Hot Rolled Asphalt (HRA) (BS 594: Part 1, 2003). These mixtures were chosen because different types of behaviour were anticipated; the DBM is a continuously graded mixture that relies primarily on aggregate interlock for its strength whereas the HRA is a gap graded mixture that relies more on the properties of the bitumen/sand/filler mortar. Granite aggregates and a 70/100 Penetration grade of bitumen were used to produce both mixtures. The target air void content was chosen to be 4% for both mixtures and binder contents of 5.5% and 8% (by mass) were chosen for the DBM and HRA respectively.

Cylindrical specimens, 100mm in diameter and 100mm in height, were manufactured for the testing programme. They were produced by coring from a 150mm diameter Gyratory specimen compacted at a temperature between 150^{o}C and 156^{o}C. Both ends of the core were then trimmed and the air void content was measured. Only specimens with an air void content between 3% and 5% were selected for testing. The specimens were stored in a cold room (5˚C) until required for testing. Prior to testing, two pips were glued diametrically opposite each other at the mid height of the specimen for use with the radial strain measurement system.

3 TEST EQUIPMENT AND PROCEDURE

An Instron 1332 loading frame with a temperature-controlled cabinet (–5˚C to 50˚C) and a servo-hydraulic actuator with a load capacity of ±100 KN and ±50mm movement was used for the testing programme. Figure 1 shows the experimental set-up for the uniaxial compressive creep testing undertaken in this study. It can be seen from this figure that the specimen is placed between two polished chrome plates. To minimize lateral confinement due to the friction between the plates and the specimen ends, a friction reduction system was used which comprised a layer of plastic film sandwiched between two layers of soap. Two LVDTs, positioned on the top plate were used to measure the axial deformation of the specimen. An LVDT mounted on the collar was used to measure radial deformation at the mid-height of the specimen.

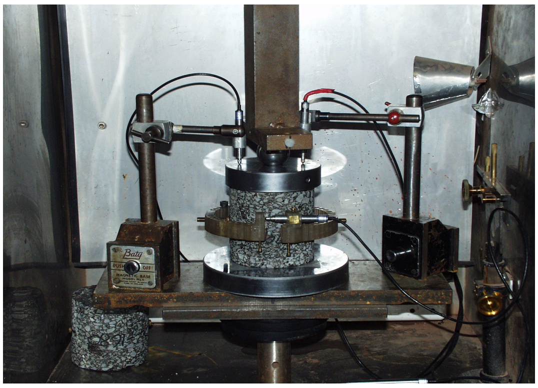

Figure 1: Test Set-up

Immediately prior to testing, the specimen was placed in the temperature-controlled cabinet for at least 12 hours to ensure it reached a uniform temperature. Before commencement of the test, a conditioning load (2% of the main load) was applied to the specimen for 10 minutes to ensure the loading plates were seated correctly on the specimen.

4 TEST RESULTS

Uniaxial creep and creep recovery testing were undertaken over a range of temperatures and stress levels. Figure 2 shows a result from a typical creep test on the DBM mixture (20˚C, 1MPa) where axial strain is plotted versus time. It can be seen this figure that the axial strain curve can be divided into three regions; a primary creep region where the strain rate decreases, a secondary creep region where the strain rate is approximately constant and a tertiary creep region where the strain rate increases as the specimen approaches failure. Results from typical creep recovery test (not shown for brevity) showed that on unloading, elastic and viscoelastic strains were recovered leaving a certain amount of permanent (viscoplastic) strain.

Results from the creep and creep recovery tests have been used to determine a number of parameters that are required by a constitutive model developed jointly between the Universities of Nottingham and Delft (see Collop *et al.*, 2002 for details). The model shares the same framework as classical viscoplasticity where the strains (and strain rates) are additive:

$$\varepsilon(t) = \varepsilon_{el}(t) + \varepsilon_{ve}(t) + \varepsilon_{vp}(t) \quad (1)$$

where e_{el}, e_{ve}, e_{vp} are the elastic, viscoelastic and viscoplastic strains respectively. Full details of the model can be found in (Collop *et al.*, 2002 and will not be repeated here for brevity. In this paper elastic strains are assumed to occur immediately upon loading and are fully recoverable upon unloading. Viscoelastic strains are assumed to occur as a function of loading time but are also fully recoverable. Viscoplastic strains are also assumed to occur as a function of loading time but are irrecoverable. The following sub-sections describe behaviour in each of these areas.

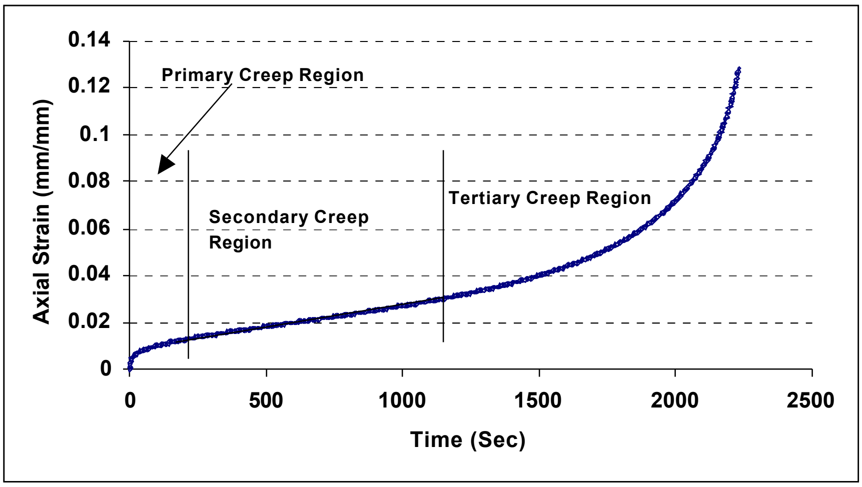

Figure 2: Typical Creep Curve for the 10mm DBM (20˚C, 1MPa)

4.1 Elastic behaviour

The elastic response was determined using the unloading portion of the creep recovery curve. A fast rate of unloading (35 microseconds) was used to be able to distinguish elastic behaviour from viscoelastic behaviour. The elastic modulus was determined as the slope of the stress strain curve during the unloading process as shown in Figure 3.

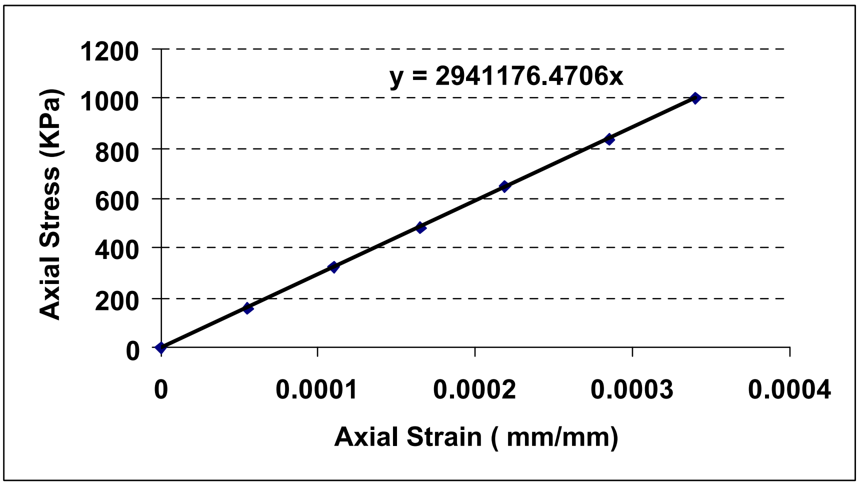

Figure 3: Stress versus strain during the unloading process for the 10mm DBM (20˚C, 1MPa)

Figure 4 shows the values of the elastic modulus for HRA30/10 and 10mm DBM plotted as a function of stress level for different test temperatures. It can be seen from this figure that the elastic modulus of the DBM is greater than that of the HRA and, for the both mixtures, the elastic modulus does not depend on stress level but, as expected, depends on the temperature.

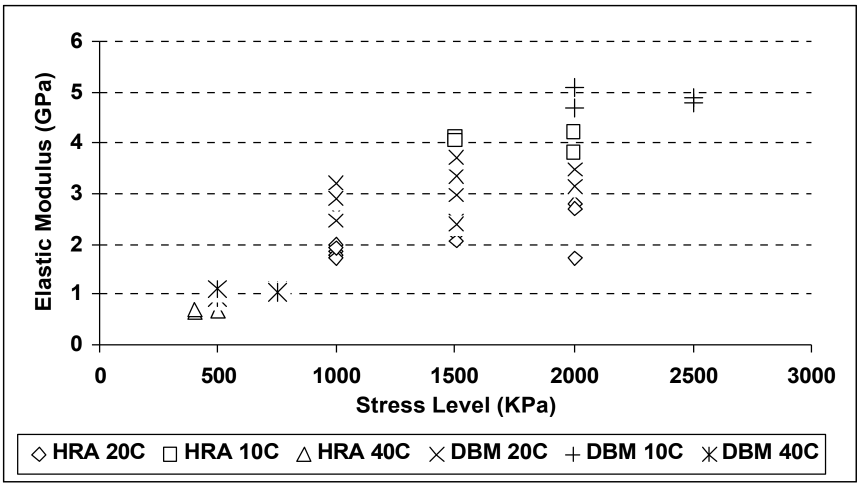

Figure 4: Elastic Moduli of the HRA and DBM Specimens

4.2 Viscoelastic behaviour

The viscoelastic strain was determined from the creep recovery tests. After initial elastic recovery has taken place, the viscoelastic strain is defined as the remainder of the recoverable strain.

Figure 5 shows the viscoelastic strain plotted as a function of total strain calculated immediately prior to unloading. It can be seen from this figure that the recovered strain increases approximately in proportion to the total stain up to a certain point, above which it tends towards a constant level. It can also be seen from Figure 5 that the recovered strain is greater for the HRA mixture. It was also found that strain rate during recovery depends on the type of mixture and temperature. The rate of recovery was found to be greater at higher temperatures.

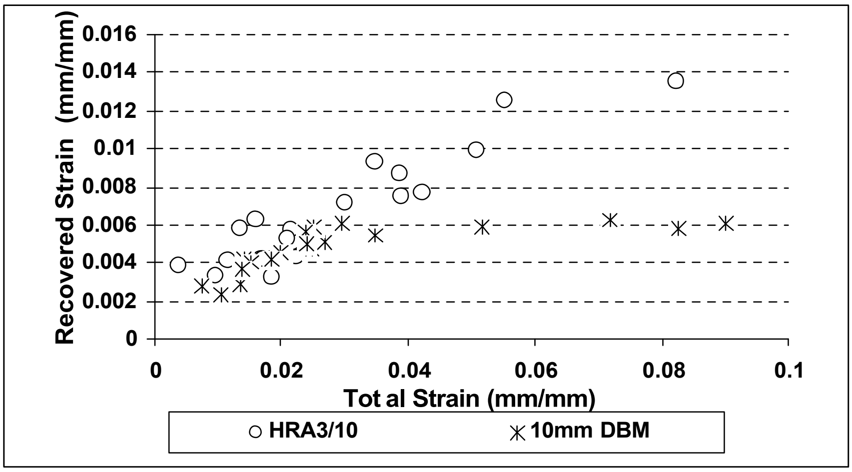

Figure 5: Viscoelastic Strain Versus Total Strain

4.3 Viscoplastic behaviour

Steady-state viscoplastic behaviour was determined from the secondary region of the creep test where the strain rate can be considered to be approximately constant. It was observed that the steady state strain rate for both the HRA and DBM mixtures occurs at an axial strain level of approximately 0.015 (1.5%).

Previous research (Cheung & Cebon, 1997, Deshpande & Cebon, 1999, Collop & Khanzadeh, 1999) has shown that the steady state behaviour of asphalt mixtures is linear at low stress level ($\dot{\varepsilon} \propto \sigma$) and nonlinear at higher stress levels ($\dot{\varepsilon} \propto \sigma^n$). Figures 5 and 6 show a plot of steady state strain rate versus stress level for the HRA and DBM mixtures respectively. The steady state strain rate for each test was obtained directly from the slope of creep curves in secondary creep region. It can be seen from Figures 5 and 6 that both mixtures display non-linear behaviour with an exponent (n) of approximately 2.5 for the HRA and approximately 5.3 for the DBM. It can also be seen from these figures that as the temperature is increased the strain rate increases for the same applied stress level.

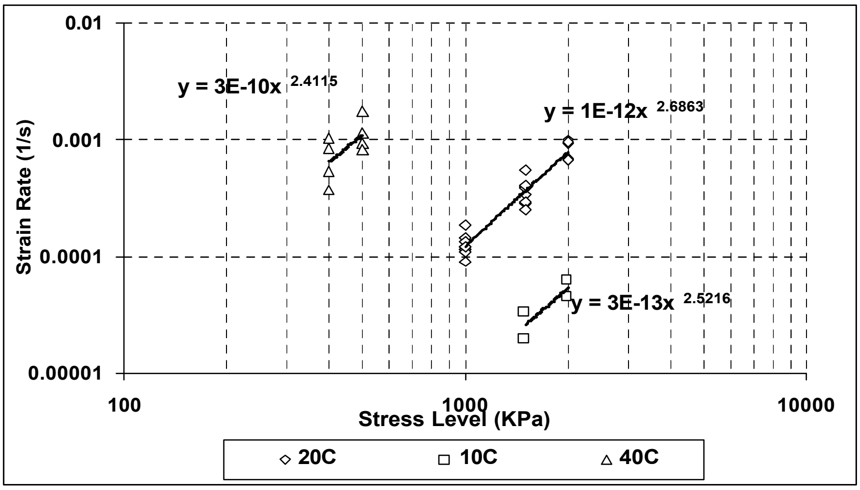

Figure 5: Steady state Behaviour of the HRA

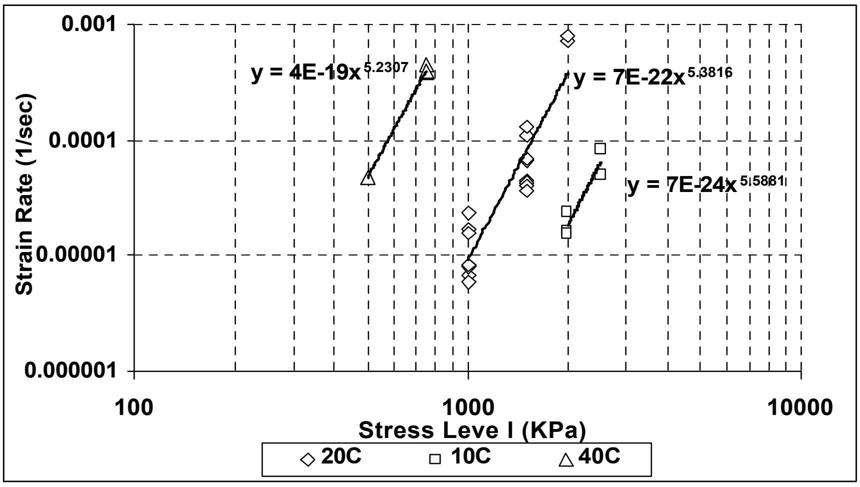

Figure 6: Steady state Behaviour of the DBM

4.4 Dilation

Measurements of radial deformation were used to study volumetric changes during creep loading. Figure 7 shows a typical plot of radial strain versus axial strain for the same test as shown in Figure 2. It can be seen from this figure that the gradient of the resulting curve gradually increases to an approximately constant value as the test progresses. Very early in the test (ie when the load is applied) the ratio of radial to axial strain tends towards Poisson's ratio for the material.

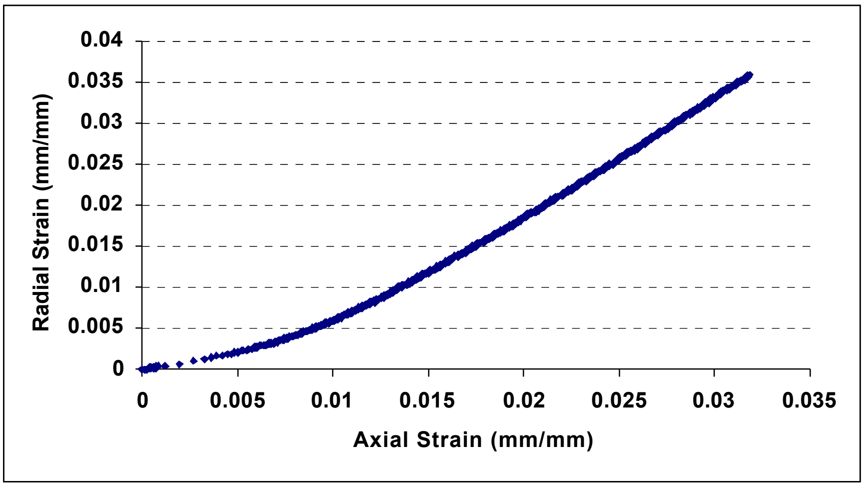

Figure 7: Radial Strain Versus Axial Strain for the 10mm DBM (20˚C, 1MPa)

Figure 8 shows these Poisson's ratio values for both mixtures at the different test temperatures. For comparison, the values recommended by TRL (Nunn, 1995) are also shown in this figure. It can be seen from Figure 8 that Poisson's ratio increases with temperature and is independent of the stress level. It can also be seen from this figure that the measured values agree well with the TRL recommendations.

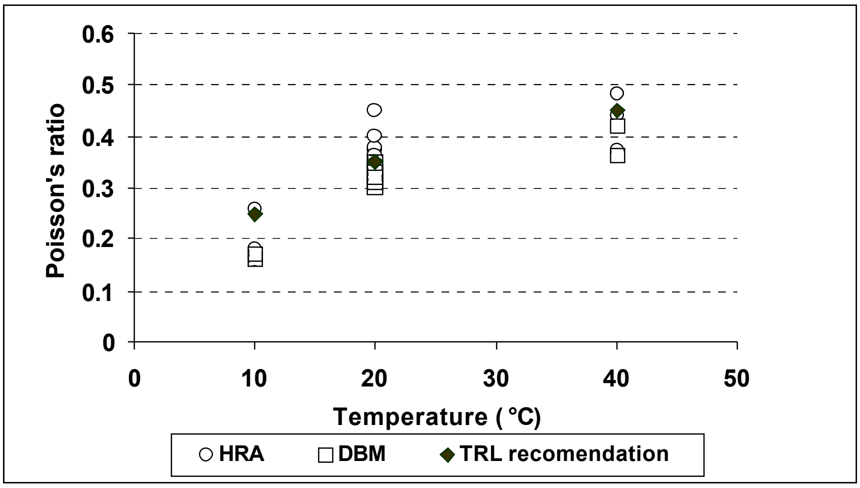

Figure 8: Poisson's Ratios

The gradient in the linear region in Figure 7 was calculated for the mixtures at all test conditions. It was found that this gradient is dependent on the type of mixture and independent of the stress level. The gradients varied from 1.31 for the HRA at 10˚C to 2.6 for the DBM at 40˚C. Although the values do not change from 10˚C to 20˚C, the values at 40˚C were higher than those at 10 and 20˚C.

Figure 9 shows a plot of volumetric strain versus shear strain for the same test as shown in Figures 2 and 8. The volumetric (e_V) and shear strains (e_S) were calculated from the radial (e_r) and axial strains (e_a) using the following equations.

$$e_V = 2e_r + e_a \tag{2}$$

$$e_S = \frac{2}{3}(e_r - e_a) \tag{3}$$

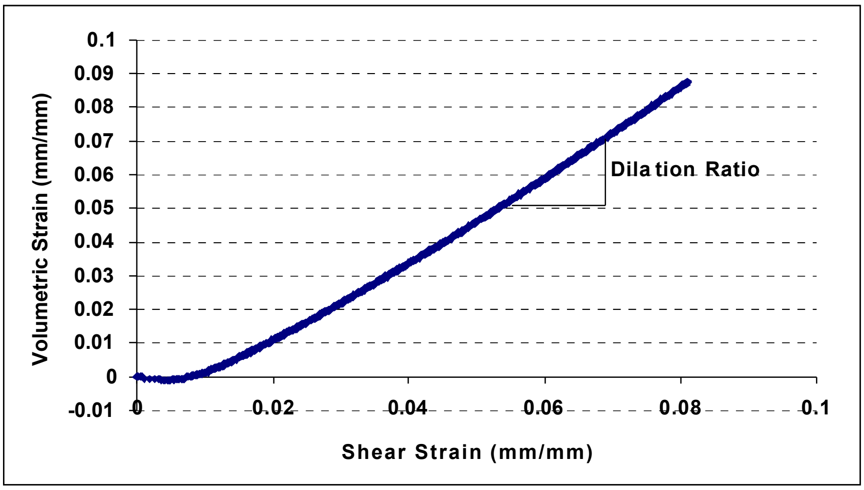

Figure 9: Volumetric Strain Versus Shear Strain for the DBM (20˚C, 1MPa)

It can be seen from Figure 9 that the volumetric strain at the beginning of the test is negative which indicates that the volume of the specimen is decreasing. After this initial phase, the volumetric strain increases indicating that the mixture is dilating. It can also be seen from Figure 9 that at higher shear strain levels volumetric strain increases approximately in proportion to the shear strain. The constant of proportionality, known as dilation ratio, was found to be dependent on the type of mixture and temperature and independent of stress level.

Figure 10 shows the values of dilation gradient for the mixtures at all test conditions. It can be seen from this figure that the dilation ratios measured from the DBM mixtures are generally greater than those measured from the HRA mixtures due to increased aggregate interlock in the DBM mixtures. Figure 10 also shows that the dilation ratios for both mixtures are slightly greater at 40˚C compared to those at 10˚C and 20˚C.

5 CONCLUSIONS

- The elastic modulus of the DBM is greater than that of the HRA. Neither was found to depend on applied stress level but they are both dependent on temperature.
- The viscoelastic strain increases approximately in proportion to the total stain up to a certain point, above which it tends towards a constant level.
- The steady state viscoplastic deformation behaviour of the mixtures was found to be nonlinear with exponents of 2.5 and 5.4 for the HRA for the DBM respectively.
- Both mixtures were found to dilate under creep loading with more dilation exhibited by the DBM mixture due to increased aggregate interlock.

- The dilation ratio was found to be independent of stress level and dependent on the type of mixture and test temperature.

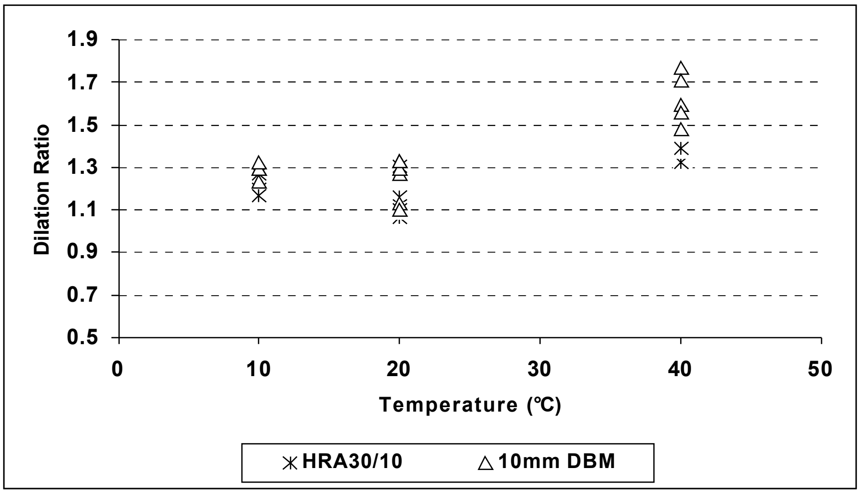

Figure 10: Measured dilation Ratios

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