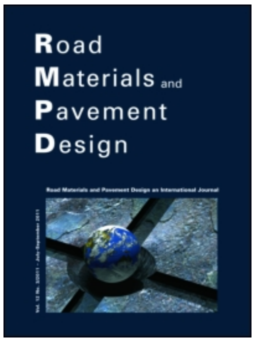

Road Materials and Pavement Design

ISSN: 1468-0629 (Print) 2164-7402 (Online) Journal homepage: https://www.tandfonline.com/loi/trmp20

Dilation behaviour of asphalt mixtures

Edgar A. Ossa & Andrew C. Collop

To cite this article: Edgar A. Ossa & Andrew C. Collop (2006) Dilation behaviour of asphalt mixtures, Road Materials and Pavement Design, 7:sup1, 93-109, DOI: 10.1080/14680629.2006.9690060

To link to this article: https://doi.org/10.1080/14680629.2006.9690060

Dilation behaviour of asphalt mixtures

Edgar A. Ossa — Andrew C. Collop

Nottingham Centre for Pavement Engineering
University Park
Nottingham
NG7 2RD, UK

Edgar.Ossa@upb.edu.co

Andrew.Collop@nottingham.ac.uk

ABSTRACT. *An extensive experimental study of the dilation behaviour of asphalt mixtures was performed. The effect of mixture composition (volume fraction, gradation, shape and size of aggregate) and test conditions (loading/unloading, temperature and confinement pressure) of idealized asphalt mixtures of various volume fractions of aggregate was performed. The volume fraction and angularity of aggregate was found to play an important role on the dilation behaviour whereas the experimental conditions were found to have no effect on the dilation behaviour of asphalt mixtures. A generic DBM mixture was fabricated with two different volume fractions of bitumen. It was found that an increase in bitumen content decreases the dilation gradient. An analytical model proposed by Goddard and Didwania (1998) was successfully used to predict the dilation gradient for mixtures with sub-spherical aggregate, but failed to predict the dilation behaviour of specimens with angular aggregate.*

KEYWORDS: *dilatancy, asphalt, deformation behaviour, granular materials, triaxial testing, temperature behaviour.*

Road Materials and Pavement Design. EATA 2006, pages 93 to 109

1. Introduction

An important factor in modelling the deformation behaviour of particulate (granular) materials such as asphalt is the phenomenon of *dilatancy*, which causes an increase of volumetric strain with distortional strain (Deshpande and Cebon, 1999). This phenomenon was first revealed by Reynolds (1885) and was later adopted in Rowe's *"stress-dilatancy"* theory (Rowe, 1962 and Rowe, 1972).

Reynolds (1885) stated that for a granular material in a state of maximum density, any contraction in one direction is accompanied by equal extensions in mutual perpendicular directions. Goddard and Bashir (1990) concluded that Reynolds dilatancy must be interpreted as an internal kinematic constraint reflecting the geometric effects which are operative in the quasi-static motion of the nearly rigid particles. In the absence of any such internal constraint, the volume or density of a compressible material is independent of its shape. Reynolds dilatancy theory can be written as:

$$H = s\,|\varepsilon_e|, \qquad [1]$$

where H is the volumetric strain, ε_e is the distortional strain and s is the dilation gradient. The distortional strain, ε_e, is given by $\varepsilon_e = \sqrt{2/3\,\varepsilon_{ij}^d \varepsilon_{ij}^d}$ where ε_{ij}^d is the deviatoric strain tensor.

Goddard and Didwania (1998) theoretically studied the dilatancy of 2-D and 3-D assemblies of rigid frictional spheres, with various sphere sizes and gradations. Under the assumption of fully dense random isotropic assemblies, they were able to derive the following analytical expression for the dilatancy of 2D assemblies:

$$s = \frac{H}{\varepsilon_e} = \frac{4(R_1 + R_2 + R_3)^{3/2}(R_1 R_2 R_3)^{1/2}}{\pi(R_1 + R_2)(R_1 + R_3)(R_2 + R_3)}, \qquad [2]$$

where R_1+R_2, R_2+R_3, R_1+R_3 are the sides of the representative triangle of three (nearly) touching disks of radius R_i.

In the special case of dense mono-size assemblies ($R_1=R_2=R_3$), equation [2] gives:

$$s = \frac{3^{3/2}}{2\pi} = 0.827, \qquad [3]$$

which can be compared with the Reynolds type estimate s=0.5 (Deshpande, 1997). According to Goddard and Didwania (1998), the only analytical solution for s for the case of 3-D, is for the special case of mono-sized spheres under uniaxial compression, giving:

$$s = \frac{3}{2\pi}\left(1 + \frac{1}{\sqrt{3}}\right) = 0.753 \qquad [4]$$

Note that the 2-D [3] and 3-D [4] solutions for s differ by about 10%, which is around the experimental error of the uniaxial and triaxial measured s values for mono-sized spheres by Deshpande (1997). A theoretical estimation of dilatancy for assemblies of angular shaped particles is still an unsolved and complex problem.

Soil mechanics theories such as those by Taylor (1948) and Terzaghi and Peck (1948) have found a dependence of dilatancy on confining pressure. This behaviour has been recently confirmed by numerical analysis using Discrete Element Modelling (DEM) by researchers like Sitharam (1999) and Collop *et al.*, (2005) for particulate materials representing soils and asphalt, respectively. However, despite those theoretical studies, no conclusive experimental study has been conducted to confirm the dependence of dilatancy on confining pressure or temperature for asphaltic materials.

Scope and motivation of the study

The aim of this study is to understand the effect of the different variables involved in asphalt mixture composition (volume fraction, size, shape and gradation of aggregate) and experimental conditions (loading/unloading, temperature and degree of confinement) on the dilation behaviour of asphalt mixtures.

First, an extensive experimental programme on various idealized and generic asphalt mixtures will be described. Then the effects of the experimental variables on the dilation behaviour will be discussed and comparisons between measurements and analytical predictions from the model of Goddard and Didwania (1998) (eq. [2]) will be given.

2. Experimental investigation

Idealized asphalt mixtures with various volume fractions of aggregate with different sizes and shapes were prepared and tested under uniaxial and triaxial axisymetric conditions and the dilation behaviour was measured. A generic asphaltic mixture corresponding to a 10mm Dense Bitumen Macadam (DBM), BS 4987: Part 1 (25) was also fabricated with two different volume fractions of bitumen using (i) the amount specified in the standard (5.5% by mass) and (ii) an increased amount of binder (8% by mass) in order to asses the effect of an increase in binder content on the dilation behaviour of these mixtures.

2.1. *Materials*

2.1.1. *Bitumen*

A 50/70 penetration grade (pen) bitumen, with Penetration and Softening Point values of 53dmm and 53.5°C, respectively, was used for all of the idealized mixtures studied. A softer 70/100 penetration grade bitumen, with penetration and softening point values of 88dmm and 45°C, respectively, was used for the two DBM mixtures studied. The choice of a harder bitumen for the idealized mixtures was motivated by the fact that the low aggregate volume fraction mixtures are soft and can represent problems for the load measurement system of the testing equipment.

2.1.2. *Idealized asphalt mixtures*

Following a similar investigation procedure to Deshpande and Cebon (2000), nine types of mixtures consisting of bitumen and different volume fractions of aggregate were prepared and tested. These are listed in Table 1. Mixes AS and BS were low volume fraction dispersions, whereas mixes CS, CA, DS, ES and EA were fully dense mixtures (see Finney (1970), German (1989) and Deshpande and Cebon (2000)). The mixture preparation and testing procedures are detailed in the following sections.

2.1.3. *DBM mixtures*

The generic DBM mixture was chosen because it is a continuously graded material that relies primarily on aggregate interlock for its strength whereas the idealized mixtures are more close to gap-graded materials that rely more on the properties of the bitumen/sand/filler mortar. The two different DBM mixtures were made using angular granite aggregate with a maximum nominal size of 10mm. Figure 1 shows the design grading and the specification grading envelopes for the 10mm DBM. The target air void content was chosen to be 4.0% for both mixtures and the binder contents were chosen to be 5.5% and 8.0% (by mass) for the DBM1 and DBM2 mixtures respectively.

2.2. *Specimen preparation*

Different specimen preparation techniques were employed in this study depending on the type of mixture. That is, for the low dispersion mixtures AS and BS (see Table 1) a "*sintering*" process was followed. Double plunger compaction was followed for the remaining idealized mixtures (see Table 1), while gyratory compaction was used to fabricate the DBM mixtures. A brief description of each of these specimen preparation procedures will follow.

Table 1. *Description of idealised mixtures studied*

Mixture	*Vol fraction aggregate*	*Vol fraction voids*	*Aggregate gradation*
AS	40%	3.0%	Sub-spherical sand 1.18-2.36mm
BS	52%	3.0%	Sub-spherical sand 1.18-2.36mm
CS1	64%	4.0%	Sub-spherical sand 300-600µm
CS2	64%	4.0%	Sub-spherical sand 1.18-2.36mm
CA1	64%	0.5%	Angular sand passing 75µm sieve
CA2	64%	2.0%	Angular sand 150-300µm
DS	75%	4.0%	(1) Sub-spherical sand 300-600µm (35%) (2) Sub-spherical sand 1.18-2.36mm (35%)
ES	85%	4.0%	(1) Sub-spherical sand 150-300µm (11%) (2) Sub-spherical sand 1.18-2.36mm (18%) (3) Rounded stones 10 mm (56%)
EA	85%	9.0%	(1) Sub-spherical sand 150-300µm (11%) (2) Sub-spherical sand 1.18-2.36mm (18%) (3)Angular stones 10 mm (56%)

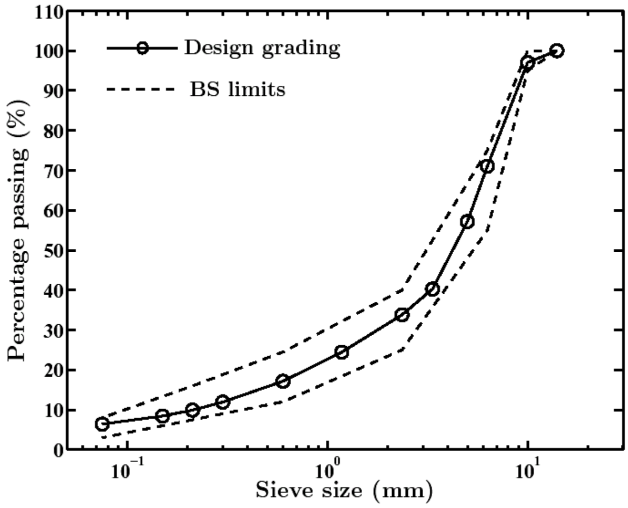

Figure 1. *Aggregate grading for the 10 mm DBM1 and DBM2 mixtures*

2.2.1. *Preparation procedure for specimens of types AS and BS*

Asphalt mixtures are usually prepared by mixing hot bitumen with hot dry aggregate. Deshpande and Cebon (2000) found that the main problem in the preparation of specimens with an aggregate volume fraction less than the maximum random packing density[1] is that the aggregate settles, leading to poor homogeneity of the specimen. To overcome this problem they prepared these mixes using a "*sintering*" process. That specimen making technique was followed in this study.

A cylindrical mould was manufactured and used to cast and compact the specimens. The internal diameter of the cylinder was 38.5mm and the ratio of height to diameter of the specimen was of about 2. A lubricant consisting of a mixture of natural soap and glycerine (see Cheung (1995)) was applied to the inner surface of the mould to avoid sticking of the mixture. A piece of non sticking silicone paper was placed in the bottom surface of the plungers to ease removal of the specimen after compaction. Crushed cold bitumen was mixed with the correct amount of sand (40% or 52% volume fraction) and then poured into the mould. The powdered mix was then compacted in a mechanical press (at room temperature) and then heated in a furnace for 1 hour at 55C[2]. This soft mixture (still in the mould) was further compacted at 5MPa for 5min to allow the bitumen to fill the air voids and bond with the sand. The mould was then placed in a freezer to cool down the specimen to about 0^{o}C. Finally, the cold specimen was slowly extruded from the mould. The final homogeneity of the specimens was checked using X-ray tomography, with good results (see Ossa *et al*., 2004 for details).

2.2.2. *Preparation procedure for specimens of types CS, CA, DS, ES and EA*

Double plunger compaction in one layer was selected as the compaction technique for mixtures CS, CA, DS, ES and EA in this study. The same cylindrical mould used for mixtures AS and BS was used to cast the specimens of mixtures CS, CA and DS, while a cylindrical mould of internal diameter of 70mm was used to cast the ES and EA specimens, keeping the ratio of height to diameter of the specimen of about 2. A mixture of the correct amounts of bitumen and aggregate (64%, 75% or 85% volume fraction) was heated to melt the bitumen. The mixture was then well stirred, poured into the mould, and compacted in a mechanical press at a pressure of 15 MPa. After the mixture had cooled down to room temperature, the specimen was slowly extruded from the mould and stored at sub-zero temperature, following the same procedure described by Deshpande and Cebon (2000).

2.2.3. *Preparation procedure for specimens of types DBM1 and DBM2*

Cylindrical specimens, 100mm in diameter and 100mm in height, were manufactured for the testing programme of the DBM1 and DBM2 mixtures. They

---

[1] The maximum random packing density for single sized spheres is about 64% (Finney, 1970).

[2] This is the approximate *softening point* of the 50/70 Pen bitumen used.

were produced by coring the central section from a 150mm diameter Gyratory specimen compacted at a temperature between 150°C and 156°C. Both ends of the core were 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 at 5°C until required for testing.

2.3. *Equipment*

Compressive tests on the cylindrical shaped specimens were performed in a hydraulic testing machine. The top and bottom surfaces of the loading platens of the testing machine were lubricated with a mixture of soap and glycerine in order to reduce friction between these surfaces and the specimen and thus reduce barrelling. The load was measured with a 2kN load cell for specimens of 40 to 75% volume fraction of aggregate, while a 20kN load cell was used for the higher volume fraction of aggregate specimens (ES, EA, DBM1 and DBM2). The measured load was used to calculate the nominal stress in the specimen. The load line displacement was used to calculate the nominal axial strain. The radial strains were measured by fitting a *Hall effect* radial transducer to the specimens of mixtures AS, BS, CS, CA and DS. A non-contact laser scan micrometer was used to measure the radial strains of mixtures ES and EA specimens. A collar mounted LVDT was used to measure radial deformation of the DBM1 and DBM2 specimens. The test temperature was controlled by an environmental chamber with a resolution of ±0.5°C. Prior to testing, all specimens were kept in the environmental chamber for about 2 hours to allow them to attain the test temperature. Experimental results from tests at temperatures from 0°C to 40 °C are reported here. A number of spot repeat tests confirmed the repeatability of the tests. For the sake of brevity, these results are not presented.

A standard axi-symetric triaxial cell of the type commonly used in soil mechanics was used in the triaxial experimental investigation. It had a maximum allowable confining pressure of 1.5MPa. The fluid used in the triaxial cell was water for the idealized asphalt mixtures, while air was used as pressurising fluid for the DBM mixtures. The axial and radial strains of the specimens were also measured for the triaxial tests.

A pressure transducer was fitted directly to the bottom of the triaxial cell in order to monitor the confining pressure applied to the specimen. The outputs of the radial transducer, axial LVDT, load cell and pressure transducer were logged by a personal computer through an analogue to digital converter.

2.4. *Test protocol*

Compressive stress controlled (creep) tests on the different asphalt mixtures were performed in order to study the effect of the different variables (volume fraction of aggregate, temperature, confinement pressure and aggregate gradation, size and shape) on the dilation gradient behaviour. Creep tests with constant confinement pressure (stress ratio) were performed in order to characterise the overall dilation gradient of the different mixtures. Creep recovery tests were performed to study the effect of unloading on the dilation gradient, while tests with varying confinement pressure (stress ratio) and temperature were performed to asses the effect of these variables on a given specimen. A change in test conditions for a given mixture specimen allows to estimate dilation gradient variations without the experimental scatter associated with complex particulate mixtures as asphalt.

2.4.1. *Creep tests with constant confinement pressure*

Compressive creep tests were performed under uniaxial and triaxial conditions. The test procedure was the same in both cases with the constant applied confinement pressure being the only difference.

After the target hydrostatic pressure (in the triaxial tests) was reached and was stable, an axial load was applied *instantaneously* [3] and maintained at that constant value. The axial load, axial displacement, radial strain and hydrostatic pressure were logged for the duration of the test. The axial load Q and the hydrostatic pressure P are related to the principal stresses (see Figure 2) by:

$$\sigma_{33} = Q/A + P, \tag{5}$$

$$\sigma_{22} = \mathrm{P}, \tag{6}$$

$$\sigma_{11} = \mathrm{P}, \tag{7}$$

where A is the nominal cross-sectional area of the specimen. Thus,

$$\sigma_{\mathrm{m}} = \sigma_{kk}/3 = P + Q/3A, \tag{8}$$

$$\sigma = \sigma_{33} - \sigma_{11} = Q/A, \tag{9}$$

are the mean and deviatoric stresses respectively. The tests were performed over a range of hydrostatic and deviatoric stresses. The stresses were applied such that for a particular deviatoric stress σ, the stress ratio $\eta=\sigma_m/\sigma$ was constant. The stress ratio η was varied from $\eta=1/3$ (uniaxial) to $\eta = 1$ ($P = 2Q/3A$).

---

[3] The typical loading time was of about 0.5s.

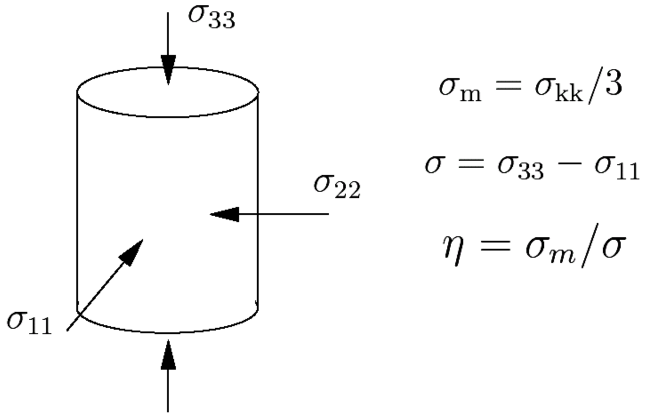

Figure 2. *Stresses on the cylindrical specimen and definition of stress ratio* η

2.4.2. *Creep tests with varying confinement pressure*

In order to study the effect of confinement pressure on the dilation behaviour of the different asphalt mixtures, tests were performed with increasing and decreasing stress ratio η. After an initial target hydrostatic pressure was reached and was stable, an axial load was applied *instantaneously* and maintained at that constant value. The specimen was allowed to creep under constant load to a given axial strain. After this strain the stress ratio η was further increased (or reduced) to a given value, keeping the axial load constant. This procedure was repeated until a maximum (or minimum) stress ratio η and axial strain were reached. The axial load, axial displacement, radial strain and hydrostatic pressure were logged for the duration of the test.

2.4.3. *Creep recovery tests*

The creep recovery dilation behaviour of the mixtures was investigated by performing single load/unload tests. A compressive axial load was applied rapidly to the specimen and then held constant. The specimen was allowed to creep to a specified total axial compressive strain ε^{T}. At this strain, the axial load was released and the compressive strain monitored until the strain rate was zero $\dot{\varepsilon} \approx 0$. The axial and radial strains were logged for the duration of the test. This kind of test was performed at various stress ratios η to asses the effect of stress ratio on the recovery portion of the dilation behaviour.

2.4.4. *Creep recovery tests with varying temperature*

Creep recovery tests with varying temperature were performed to evaluate the effect of temperature in the dilation behaviour of the mixtures. Prior to testing, the specimen was kept in the environmental chamber for about 2 hours to allow it to attain the initial specified test temperature. A compressive axial load was applied rapidly to the specimen and then held constant. The specimen was allowed to creep to a specified total axial compressive strain ε^T. At this strain, the axial load was released and the temperature in the environmental chamber increased (or reduced). The specimen was allowed to reach the new target temperature for about 2 hours. The specified axial load was again applied to the specimen and held constant until a maximum defined axial strain was reached at this new temperature. The axial and radial strains were logged for the duration of the test.

3. Experimental results

Creep and recovery tests with constant or variable stress ratios and temperatures were performed on the different mixtures studied (idealized and DBM). However for the sake of brevity only selected results will be shown as the general dilation behaviour for the different mixtures was found to be similar.

The aim of this study was to estimate the effect of the different variables affecting the dilation behaviour of asphalt mixtures. Therefore, the creep deformation behaviour of the mixtures will not be addressed here. For a complete study of the uniaxial and triaxial deformation behaviour of asphalt mixtures the reader is referred to Deshpande and Cebon (2000), Collop and Khanzada (2001), Ossa et al. (2004) and Ossa *et al.*, (2005).

For the cylindrical specimens, the volumetric strain H is given by:

$$H=2\varepsilon_{11} + \varepsilon_{33}, \tag{10}$$

where ε_{11} and ε_{33} are the radial and axial strains, respectively. The distortional or Von Mises effective strain ε_e is given by:

$$\varepsilon_e = \varepsilon_{33} - \frac{H}{3} = \frac{2}{3}(\varepsilon_{33} - \varepsilon_{11}). \tag{11}$$

The relationship between distortional and volumetric strain for a selected recovery test on mixture DS (75%) is shown in Figure 3. The behaviour is similar to that observed for soils (Taylor, 1948). There is an initial reduction in volumetric strain due to compaction of the specimen. The volumetric strain then increases in proportion to the distortional strain with slope *s*, which is called the dilation gradient. After removal of the load there is a small amount of hysteresis, after which the strains recover with the same slope *s* as for the loading path.

Table 2 shows the dilation gradient measured for the different mixtures studied. Note that the fully dense mixtures (volume fraction of aggregate > 64%) show $s>0$ while mixtures AS (40%) and BS (52 %) show $s \cong 0$, in line with the observations of Deshpande and Cebon (2000). It is also worth noting here that for the fully dense mixtures there is a considerable scatter in the measured values of dilation gradient. This scatter was expected for a complex particulate composites such as asphalt.

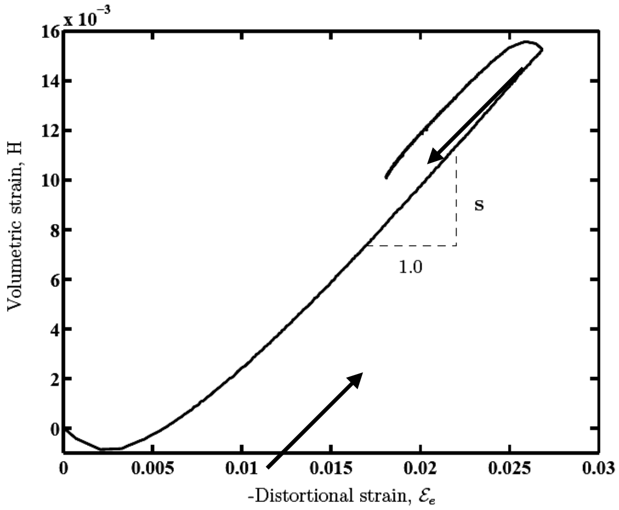

Figure 3. *Variation of volumetric strain with distortional strain for mixture DS (75%). Creep recovery test result, $\sigma = 0.47MPa$ and $\eta=1/3$ (uniaxial) at 10^oC. The arrows indicate loading and recovery paths*

Table 2. *Measured and predicted (equation [2] where apply) dilation gradients for the asphalt mixtures studied. Values obtained from uniaxial tests*

Mixture Type	**Dilation gradient, *s*** ***Measurement***	**Dilation gradient, *s*** ***Prediction eq. [2]***
AS (40%)	~0	N.A.
BS (52%)	~0	N.A.
CS1 (64%)	0.70 – 0.90	0.827
CS2 (64%)	0.70 – 0.95	0.827
CA1 (64%)	1.00 – 1.35	N.A
CA2 (64%)	1.15 – 1.45	N.A
DS (75%)	0.60 – 0.75	0.705
ES (85%)	0.85 – 1.15	0.430
EA (85%)	0.80 - 1.00	N.A
DBM1	1.20 -1.40	N.A
DBM2	0.70 – 1.10	N.A

All dilation gradients measured from tests with constant stress ratios fell between the experimental scatter values shown in Table 2, indicating the independence of dilation gradient on stress ratio. However, in order to rule out possible small changes in dilation gradient covered up by experimental scatter, tests with varying stress ratios were performed (see Section 2.4.2.). Figure 4(a) shows the distortional strain plotted versus time for a creep test with decreasing stress ratios η on mixture DBM2. It can be seen from this figure that a reduction in stress ratio causes an increase in strain rate (and vice-versa). Figure 4(b) shows the volumetric strain plotted against the distortional strain for the same experiment. It can clearly be seen from this figure that there is no observable change in the dilation gradient with decreasing stress ratio. Tests where the stress ratio was increased were also performed with similar results for the different mixtures.

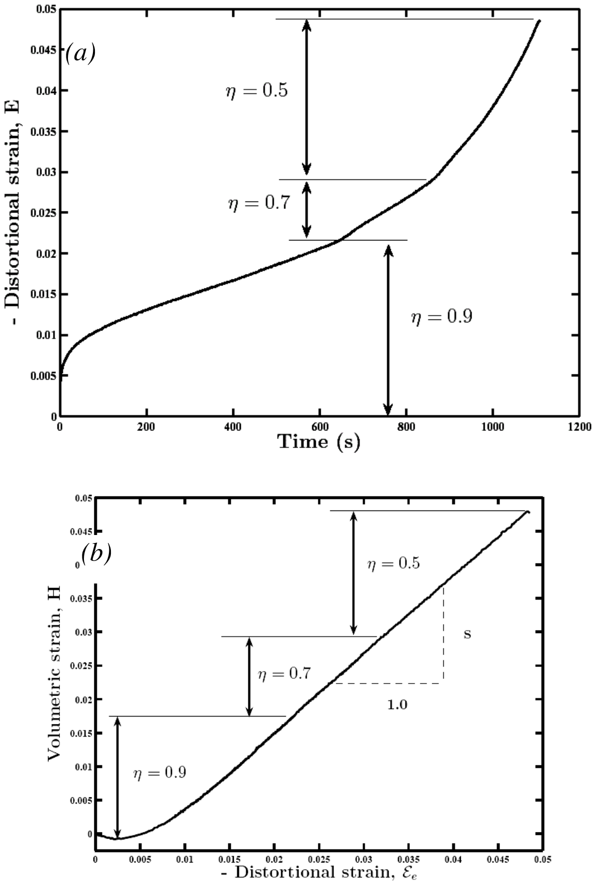

Figure 4. *Triaxial test result decreasing stress ratio (confining pressure) for DBM2 at 40^{o}C and constant deviatoric stress σ = 0.5 MPa. (a) Time versus distortional strain response, and (b) Distortional versus volumetric strain response*

Figure 5 shows volumetric strain plotted against distortional strain for a creep recovery test with decreasing temperature on mixture DBM1 (see Section 2.4.4.). It can be seen from this figure that, after the initial reduction in volumetric strain, the volumetric strain increases in proportion to the distortional strain with slope *s*. After removal of the load there is a small amount of hysteresis. After the 2 hour temperature conditioning period, the load was re-applied with the volumetric strain increasing in proportion to the distortional strain with the same slope *s* as for the initial loading path at 40°C. Tests where the temperature was increased were also performed with similar results for the different mixtures.

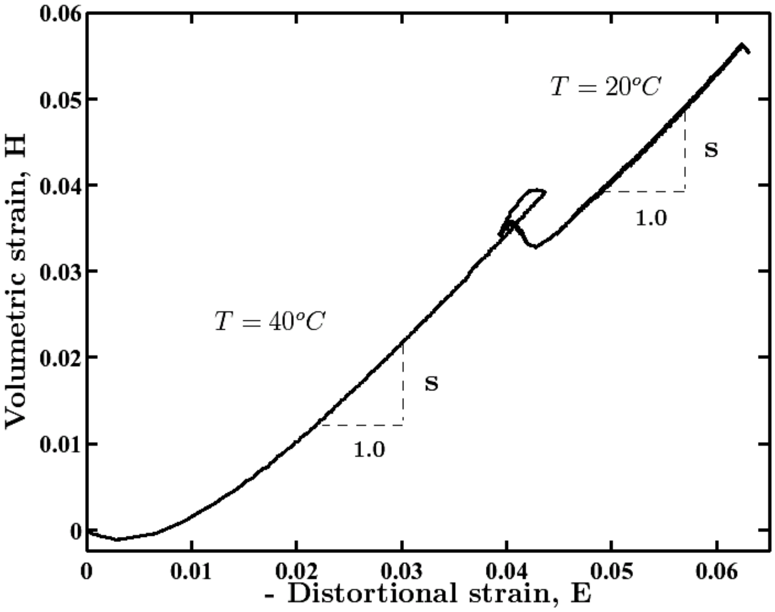

Figure 5. *Uniaxial test result decreasing temperature for DBM1 mixture, with constant deviatoric stress* $\sigma = 0.4$ *MPa*

4. Discussion

This study was focused on exploring the effect of the different variables involved in asphalt mixture composition (volume fraction, size, shape and gradation of aggregate) and experimental conditions (loading/unloading, temperature and stress ratio) on the dilation gradient behaviour. Idealized asphalt mixtures composed of one, two or three different particle sizes were manufactured to asses the effect of the mixture composition factors in a more *controlled* way. While generic continuously graded DBM mixtures with two binder contents were prepared to estimate the effect of this variable in the dilation behaviour of commonly used mixtures.

The low volume fraction of aggregate mixtures AS (40%) and BS (52%) did not experienced volumetric change during compression (see Table 2), behaving as incompressible solids. This kind of behaviour was expected as the dilation behaviour is caused by the kinematical constraint imposed by the *interlocking* of particles which does not occur in these low volume fraction dispersions.

Particle size was found to have no significant effect on the dilation behaviour of mixtures with the same volume of aggregate. However, particle shape was found to play an important role in the dilation behaviour of these mixtures, with the dilation gradient increasing by a factor of almost 2 for the angular CA1 and CA2 mixtures in comparison with the corresponding sub-spherical CS1 and CS2 mixtures (see Tables 1 and 2).

Experimental conditions were found to have no effect on the dilation behaviour of both the idealized and the "*real*" mixtures. The dilation gradient was found to be independent of the loading or recovery conditions applied to the specimen (see Figure 3) at different temperatures and stress ratios. Further, Ossa (2004) found that the dilation gradient was unchanged for continuous and pulse cyclic loading conditions for idealized mixtures similar to those described here.

The dilation behaviour of granular materials has been extensively studied using Discrete Element Modelling (see for instance: Cundall and Strack (1979), Mehrabadi *et al*., (1982), Sitharam (1999)) finding a strong dependence of stress ratio on the dilation gradient. In contrast, this extensive experimental study has found that the dilation behaviour of asphalt does not depend on confining pressure. This difference is likely to be due to the fact that bitumen films act as a binder between particles in an asphalt mixture restricting the effect of confinement pressure on the mobility of particles and hence interlocking.

An increase in the volume of bitumen for the generic DBM mixture showed a reduction in the dilation gradient. This can be explained by the increased thickness of the bitumen films between particles. Bitumen can act as *lubricant* between particles decreasing the interlocking effect caused by the continuous grading of angular particles of the DBM mixture. Furthermore, the increased thickness of the bitumen films is also believed to be responsible for the increased experimental scatter in the measurement of the dilation gradient of mixture DBM2 in comparison with mixture DBM1.

Table 2 shows the dilation predictions obtained using Equation [2]. The analytical model proposed by Goddard and Didwania (1998) is seen to predict accurately the dilation gradient s for the idealised mixtures made with sub-spherical aggregate up to 75% volume fraction of aggregate, but under predicts the dilation gradient of mixtures with angular aggregate and high volume fraction of aggregate. The model was derived from a theoretical study of the deformation of nearly touching disks, which explains why the model accurately predicts the behaviour of the mixtures containing rounded particles. The analytical prediction of dilation for angular aggregate mixtures is still an open research topic and is well beyond the scope of this study. Nonetheless, this study has shown that the volume fraction of bitumen plays an important role on the dilation behaviour of angular aggregate mixtures and should be considered in any further attempt to model theoretically the dilation gradient.

5. Concluding remarks

The effect of the variables involved on asphalt mixture composition and experimental conditions, on the dilation gradient behaviour were experimentally studied on different *idealized* and *real* asphalt mixtures with different compositions and aggregate shapes.

Mixtures with volume fractions of aggregate lower than the maximum random packing density (64%) showed no dilation behaviour whereas for mixtures with volume fractions higher than 64% the volumetric strain increased in proportion to the distortional strain in the stress controlled tests.

The size of the aggregate did not have a significant effect on the dilation behaviour of the asphalt mixtures whereas the angularity of the aggregate showed a dramatic effect, increasing the dilation gradient as the angularity of the aggregate is increased.

The experimental conditions (loading/unloading, temperature and stress ratio) had no affect on the dilation gradient of the different mixtures studied. An increase in the amount of bitumen for a DBM mixture showed to decrease the dilation gradient as the bitumen films between aggregate particles was increased.

A simple analytical model proposed by Goddard and Didwania (1998) was used to predict the dilation gradient values of the idealized asphalt mixtures with sub-spherical aggregate with good results for volume fractions of aggregate lower than 75%. However, this model cannot be used to predict the dilation behaviour of angular aggregate mixtures where the interlocking effect is enhanced.

Acknowledgements

Support from the EPSRC Platform Grant awarded to the Nottingham Centre for Pavement Engineering (NCPE) is gratefully acknowledged. The authors would also like to thank Dr. D. Cebon and Dr. V. S. Deshpande from the Cambridge University Engineering Department for all their help and fruitful discussions about testing and fabrication of idealised asphalt mixtures.

6. Bibliography

Bashir Y. M and Goddard J. D., “A novel simulation method for the quasi-static mechanics of granular assemblages”, *J. Rheology.*, Vol. 35, No 5, 1991, pp. 849-885.

BS 4987, "Coated macadam for roads and other paved areas*", Part1. Specification for constituent materials and for mixtures*, British Standards Institution, London., 2003.

Cheung V. S., Mechanical behaviour of bitumens and bituminous mixes, PhD Thesis, Cambridge University Eng. Department, 1995.

Collop A.C and Khanzada S., "Permanent deformation in idealised "sand asphalt" bituminous mixtures", *Int. Journal of road materials and pavement design*, Vol. 2, No. 1, 2001, pp. 7-28.

Collop A. C., McDowell G. R. and Lee Y. "Modelling dilation in an idealised asphalt mixture using the distinct element method", *Submitted to Mechanics of Materials*, 2005.

Cundall P. A. and Strack O. D. L., "A discrete numerical model for granular assemblies", *Geotechnique*, Vol. 29, No. 1, 1979, pp. 47-65.

Deshpande V. S., Steady-state deformation behaviour of bituminous mixes, PhD Thesis, Cambridge University Eng. Department, 1997.

Deshpande V. S. and Cebon D., "Steady-state constitutive relationship for idealised asphalt mixes", *Mechanics of Materials*, Vol. 31, 1999, pp. 271-287.

Deshpande V. S. and Cebon D., "Uniaxial experiments on idealised asphalt mixes", *Journal of Materials in Civil Eng.*, Vol. 12, No. 3, 2000, pp. 262-271.

Finney J. L., "Random packings and the structure of simple liquids, i: The geometry of random close packing", *Proc. Royal Society London A.*, Vol. 319, 1970, pp. 479-493.

German R. M.. "Particle packing characteristics", *Metal Powder Industries Federation*, 1989, Princeton, N. J.

Goddard J. D. and Bashir Y. M., *Recent developments in structural continua*, Vol. 2, De Kee and Kaloni (eds). *Longman Scientific and Technical*, 1990, London, Chapter: On Reynolds dilantancy, pp. 23.

Goddard J. D. and Didwania A. K., "Computations of dilatancy and yield surfaces for assemblies of rigid frictional spheres", *Q. J. Mech. Appl. Math.*, Vol. 51, No. 1 1998, pp. 15-43.

Mehrabadi M. M., Nemat-Nasser S. and Oda M., "On statistical description of stress and fabric in granular materials", *International Journal for Numerical and Anayitical Methods in Geomechanics*, Vol. 6, 1982, pp. 95-108.

Ossa E. A., Deformation behaviour of bitumen and bituminous mixes, PhD Thesis, Cambridge University Engineering Department, 2004.

Ossa E.A., Deshpande V.S. and Cebon D., Uniaxial monotonic and cyclic behaviour of bituminous mixes, Cambridge University Engineering Department Report, CUED/C-MICROMECH/TR.95, 2004.

Ossa E.A., Taherkhani H. and Collop A.C., "Compressive deformation behaviour of asphalt mixtures", Submitted to: *Journal of the AAPT*, 2005.

Reynolds O., "On the dilatancy of media composed of rigid particles in contact, With experimental observations", *Phil. Mag.*, Vol. 20, 1885, pp. 469-481.

Rowe P. W., “The stress-dilatancy relation for static equilibrium of an assembly of particles in contact”, *Proc. Royal Society London A.*, Vol. 269, 1962, pp. 500-529.

Rowe P. W., *Theoretical meaning and observed values of deformation parameters for soil*, G. T. Foulis & Co., 1972, London, pp. 143-194.

Sitharam T. G., “Micromechanical modeling of granular materials: effect of confining pressure on mechanical behaviour”, *Mechanics of Materials*, Vol. 31, 1999, pp. 653-665.

Taylor D.W., *Fundamentals of soil mechanics*, Wiley Interscience, New York, 1948.

Terzaghi K. and Peck R. B., *Soil mechanics in engineering practice*, Wiley, 1948.