Fracture and Fatigue Strength of Grouted Macadams

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ABSTRACT: Grouted macadams form a class of material which provides significant advantages in comparison to both concrete and conventional asphalt, having both rut resistance and a degree of flexibility. This paper presents a series of laboratory tests on several grouted macadam mixtures, for stiffness, fatigue and low temperature fracture. The variables explored include binder grade and content, aggregate size and gradation, and grout strength. Although the material is found to perform fundamentally as an asphalt, there are several significant differences in the form of fatigue behavior found compared to that usually expected from an asphalt. In particular the effect of varying binder content is found to be markedly different. The results are discussed in terms of optimizing mixture design in order to obtain the most desirable combination of properties (stiffness, fatigue strength, low temperature fracture resistance). Discussion is also presented regarding the possible role of grouted macadams as base or binder courses within highway pavements, and the conclusion is drawn that they are likely to provide an economical solution in many circumstances owing to their superior mechanical properties.

KEY WORDS: Grouted Macadam, Mixture Design, Stiffness, Fatigue, Thermal Cracking.

1 INTRODUCTION

Grouted Macadams are materials that comprise a voided asphalt skeleton which is then filled with high fluidity cementitious grout. Grout penetration is achieved by manual spreading and the resultant air void content in the mixture is close to zero. These materials constitute a poorly understood branch of pavement technology and have generally been relegated to a role in certain specialist pavements whose performance is predicted on purely empirical evidence. On the other hand, these specialist pavements include aircraft stands, bus stations, port pavements, industrial hard-standings and warehouse floors, and it is clear that grouted macadam is used by industry as a real alternative in all circumstances where Portland Cement Concrete might normally be used. The reasons for this are the material's near total deformation resistance and its ability to survive oil spillage, combined with a welcome lack of the need for formed joints. Yet grouted macadams are rarely 'designed'; they tend to be specified based on successful past performance. This has led to quite different mixtures being used in different countries, apparently for no better reason than a lack of observed problems.

In the UK, Collop and Elliott (1999) carried out a series of tests to determine the mechanical properties (stiffness, compressive strength, fatigue resistance, deformation susceptibility) of a commonly used European product. They derived a stiffness modulus for design purposes and a fatigue characteristic (load-controlled indirect tensile test), and also concluded that deformation was likely to be negligible. In parallel, a similar series of tests was carried out by Anderton (2000) on so-called 'Resin-Modified Pavement', a form of grouted macadam developed in the US having a much broader aggregate grading than that used in Europe. Boundy (1979) reported an earlier test series on another specific grouted macadam mixture. However, none of these studies investigated in any depth the effect of varying the different mixture parameters. This paper is intended to go some way toward redressing the situation by presenting a range of laboratory test data on a series of grouted macadam mixtures, drawing attention to some of the real issues and potential ways in which such mixtures might be designed and optimized for particular climatic and traffic conditions. The work has recently been carried out at the University of Nottingham in the UK.

2 EXPERIMENTAL PROGRAMME

2.1 Materials

In this investigation, a 'standard' grouted macadam material was defined and the effect of varying different mixture parameters from this standard was then investigated. The standard mixture comprised a nominally single-sized 10mm granite aggregate (75% by mass between 6.3mm and 10mm), 4.1% of 200pen bitumen, with 3.7% fibers (by mass of binder) to prevent binder drainage. After compaction, this produced a void content of 25-30%, which was then filled with a 110MPa compressive strength grout. Grout shrinkage was measured at approximately 0.33%.

Differences from the standard mixture were investigated as follows:

- Binder penetration: 50pen
- Binder content: 1.5%, 3% (fiber content adjusted accordingly)
- Nominal aggregate size: 14mm, 20mm
- Aggregate gradation: graded 20-6.3mm
- Grout: 35MPa compressive strength grout

In the case of variations in aggregate size this was done in two ways; firstly, the binder content was altered to retain the same binder film thickness, giving 3% and 2% binder contents for 14mm and 20mm nominal stone sizes respectively; secondly, the 4.1% binder content used in the standard mixture was used for both, thereby giving increased binder film thickness.

2.2 Testing Procedures

Two principal pieces of test equipment were used, namely a 4-point bending rig and a thermal cracking rig. The 4-point bending equipment (Figure 1) was purpose designed for this project (Oliveira, 2006) and tested a 50mm×50mm×300mm beam, with loading points spaced 90mm apart. Five specimens of each mixture were tested, all at 20ºC. Initially, the stiffness modulus was recorded, at 5 and 10Hz; each specimen was then subjected to a displacement-controlled fatigue test, at a different strain level for each of the five beams. In this paper, failure is defined as the number of cycles required to achieve a 50% reduction in apparent material modulus, in line with common practice in asphalt testing. The full complexities of grouted macadam fatigue behavior will be treated thoroughly in a later paper.

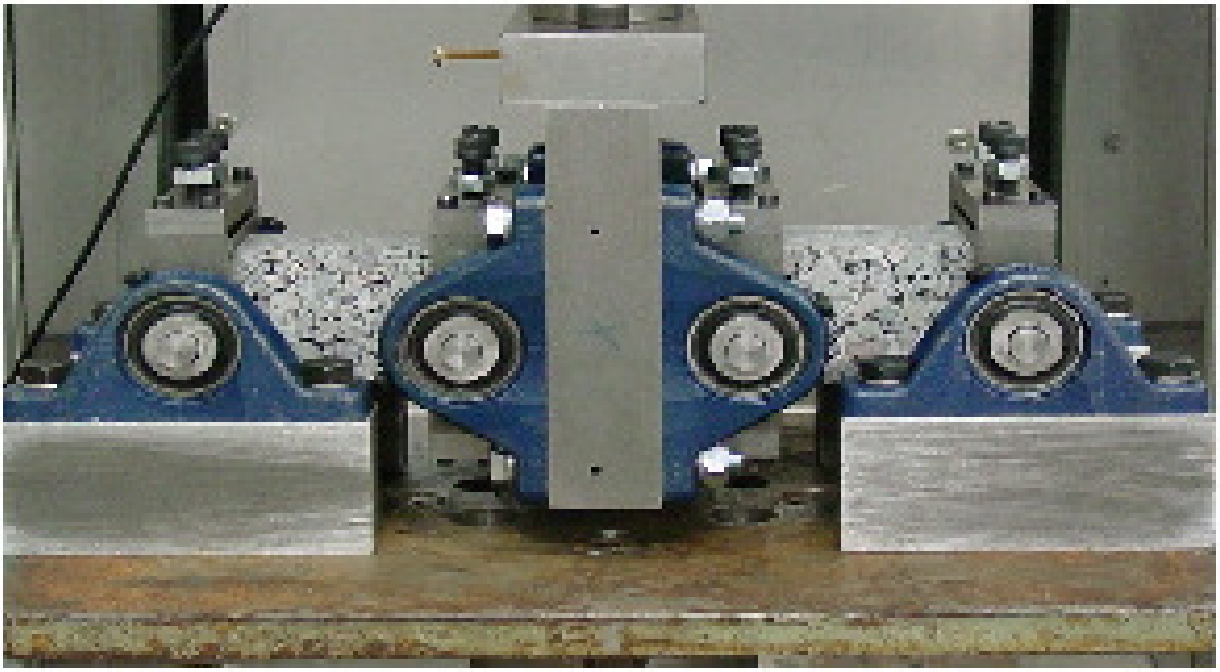

Figure 1: Four-point bending equipment in use on grouted macadam specimen

The thermal cracking equipment has been described previously (Brown et al, 2001) and a schematic is included as Figure 2. It allows two types of test: true simulation of a thermally induced reflective crack is achieved by tack-coating an asphaltic layer onto a split concrete base; a controlled tensile test is achieved by gluing a necked specimen to end plates. In both cases, the test is carried out ultra-slow, typically by inducing a millimeter or so of movement over an 8 hour period, and at a low temperature, in this case –5ºC. In this paper, results from pure tensile tests are reported.

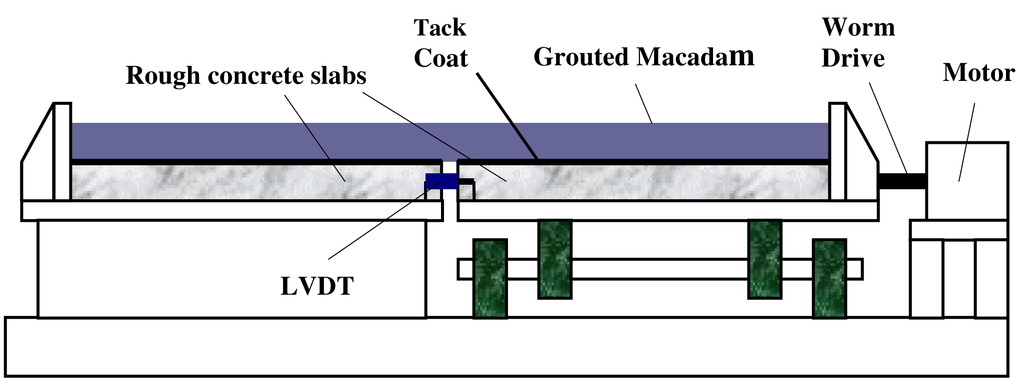

Figure 2: Thermal cracking equipment in reflective crack simulation mode

3 PRESENTATION OF TEST DATA

3.1 Stiffness Modulus and Phase Angle

The full set of results (each an average of five tests) is shown in Figures 3 and 4.

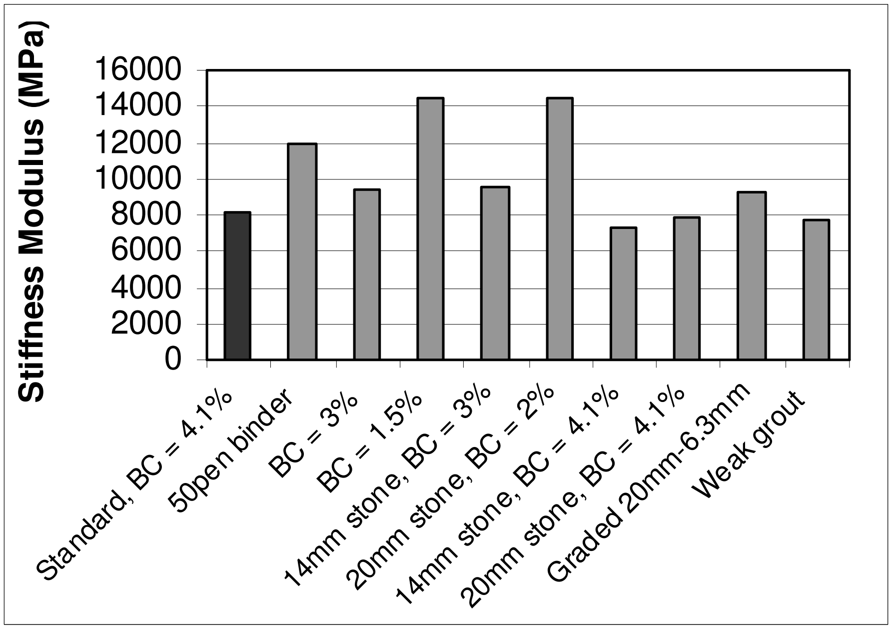

Figure 3: Stiffness modulus data, 20ºC, 10Hz

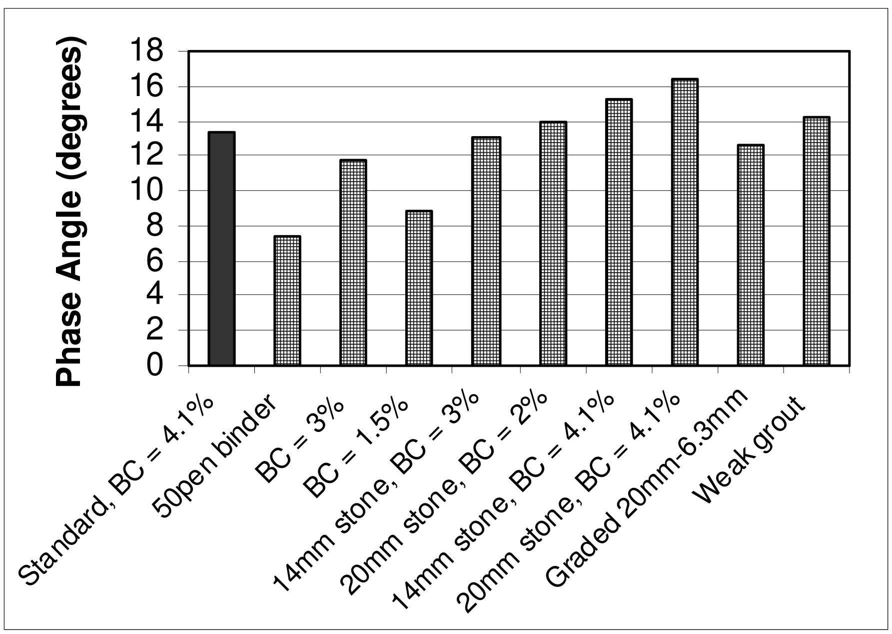

Figure 4: Phase angle data, 20ºC, 10Hz

The following points emerge from this set of data.

- As expected, use of a harder binder (50pen) increases stiffness modulus, but the ratio between the 50pen and 200pen results is much smaller than would be expected in a conventional asphalt.
- Reducing the binder content also increases stiffness modulus. This is expected since binder volume is directly replaced by grout and so the Voids in Mineral Aggregate (VMA) reduces accordingly (although the suitability of the VMA parameter for such mixtures is open to question).
- This point is also evident in the 14mm and 20mm aggregate size results. The two cases where the binder content is maintained at 4.1% show a similar stiffness modulus to the standard case; where the binder content is reduced, the stiffness modulus increases.
- The graded aggregate case reveals a slightly increased stiffness modulus, even with 4.1% binder, although the statistical significance is low.
- Use of a weak grout does not appear to have affected stiffness modulus.
- The phase angle appears to be directly related to binder film thickness and, as expected, binder grade. Figure 5 illustrates, where the calculated binder film thickness assumes single sized spherical aggregate particles of the nominal stone size and should therefore only be seen as a relative measure.

At this stage therefore, and if stiffness modulus were the only criterion, reducing the binder content and increasing binder hardness both improve material properties. Neither increasing stone size nor moving to a broader grading appear to have any effect beyond that expected due to binder content, although the consequent changes in binder film thickness also affect the phase angle. Furthermore, grout strength appears to be of little importance for material stiffness. In comparison with a conventional asphalt, the standard mixture (200pen, 4.1%) gives a similar stiffness modulus to that expected from a 25-35pen asphalt concrete.

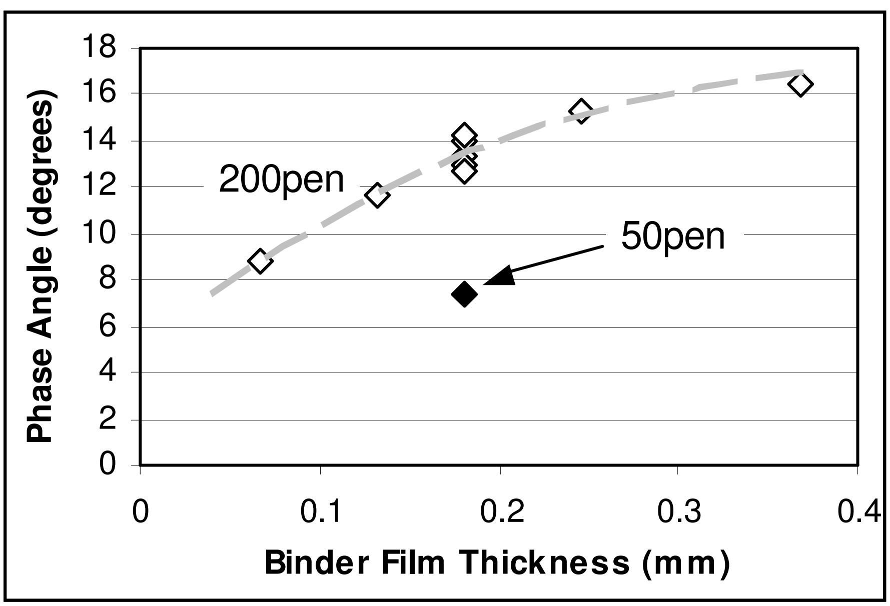

Figure 5: The dependence of phase angle on binder film thickness

3.2 Fatigue Life

The fatigue behavior of grouted macadams, notably the pattern of stiffness reduction during fatigue, is significantly different from that of conventional asphalts, which makes direct comparison difficult. However, this is a large subject in itself and will not be pursued further in this paper. Figure 6 plots fatigue lives derived in the conventional way, that is with failure defined as a 50% reduction in stiffness and, for comparison, data from a conventional Dense Bitumen Macadam (DBM) is also included. All the tests shown were carried out at a frequency of 10Hz. The grouted macadam specimens were tested at 20ºC; the DBM was tested at 10ºC. However, investigation into the effect of test temperature on the fatigue of grouted macadam indicated very little difference over the range 0 to 20ºC. The following are the key points to emerge from Figure 6.

- Almost all the grouted macadam mixtures tested gave results which lay on a single fatigue characteristic. This included results for both 50pen and 200pen binder, binder contents between 1.5 and 4.1%, two different grout strengths, two different nominal aggregate sizes and a more broadly graded aggregate.
- There is a factor of about 2 (on the x axis) between the majority of the grouted macadam data and that for conventional DBM.
- The only data which does not fit the common fatigue characteristic is that for 20mm stone size; this is thought likely to be due to the rather small ratio between stone size and specimen dimension.

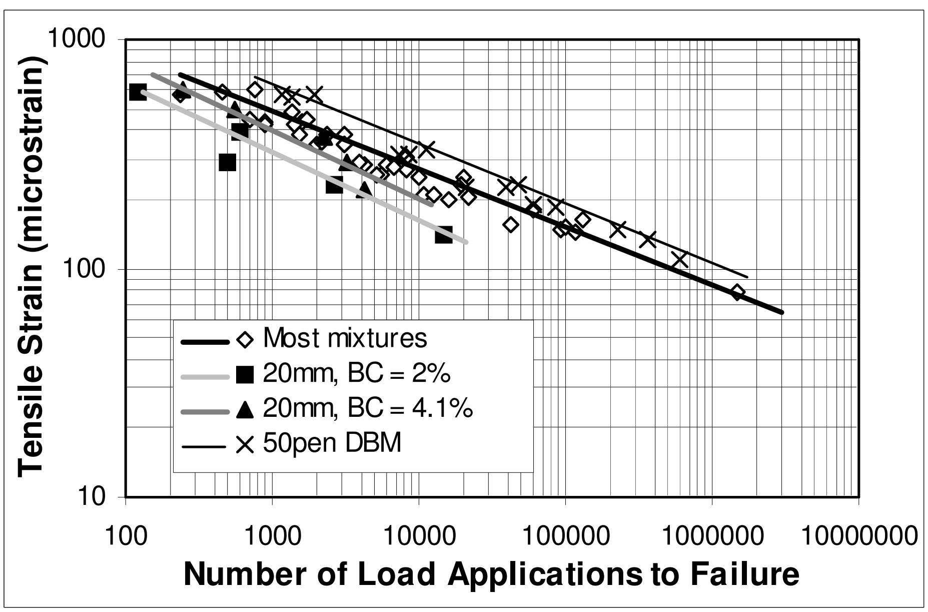

Figure 6: Fatigue data derived from 4-point binding tests

Whilst it should be appreciated that this data does not tell the full story, and probably understates the true fatigue resistance of grouted macadam in the field, particularly grouted macadam which uses soft binder, it does allow certain interim conclusions to be drawn. Since fatigue looks to be effectively independent of all the mixture variables investigated with the possible exception of stone size, the logical approach to design is therefore to maximize the stiffness modulus and therefore to reduce the strain which develops under load. As noted above, this implies that improved properties are achieved by reducing the binder content and/or increasing the binder hardness.

3.3 Thermally Induced Cracking

Except in certain warehouse floor applications, grouted macadams are expected to withstand the effects of thermal cycles in the same way as any other asphaltic mixture. Indeed, one of their principal competitive advantages compared to Portland Cement Concrete (PCC) is the fact that they do not require the joints that PCC requires to accommodate thermally induced movements. It is therefore important to investigate the degree to which different grouted macadam mixtures perform under this sort of stress and strain regime.

The test equipment introduced in Section 2.2 was used to test 700mm long necked specimens (see Figure 7) at a temperature of –5ºC. The 'neck' consisted of a 100mm length over which the width of the specimen reduced from 150mm to 75mm. Specimen height was approximately 50mm. The test is a simple, controlled strain rate, tensile extension test and, for this test series, the extension rate used was 1mm in 8 hours. Failure always occurred in the necked region (for example Figure 8) and was determined by examining strain data measured on the upper surface of the specimen using a 'Demec' gauge. Figure 9 gives typical strain data and illustrates the point taken as 'failure' in each case. Depending on whether the principal crack developed within a particular gauge length or not, failure is seen as either a marked increase in strain rate or else a marked decrease.

This test is relatively time-consuming and so a restricted series was carried out, concentrating on those variations which gave high stiffness modulus. The test was therefore conducted on a standard mixture, on the 50pen binder variant and on the 1.5% binder content variant. Comparison was also made with earlier testing carried out on a 50pen DBM mixture under the same temperature and strain rate conditions. The result is given in Table 1 as a strain at failure and is the average from strain measurements in three locations.

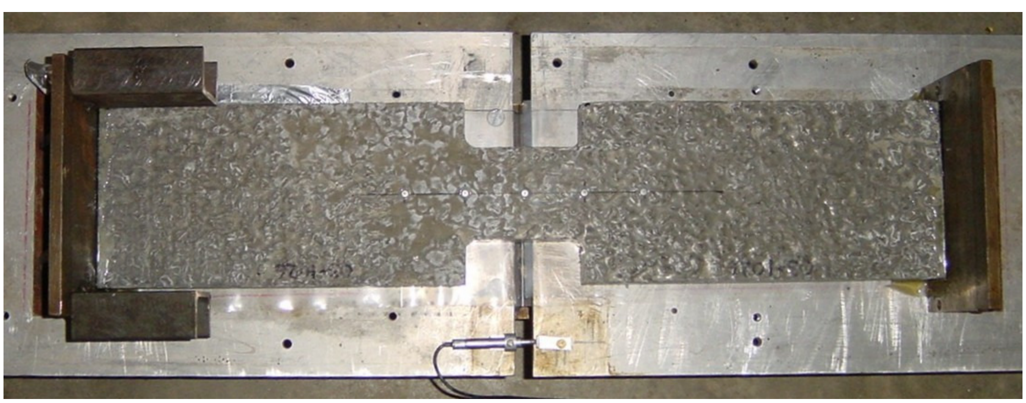

Figure 7: A necked specimen ready for testing

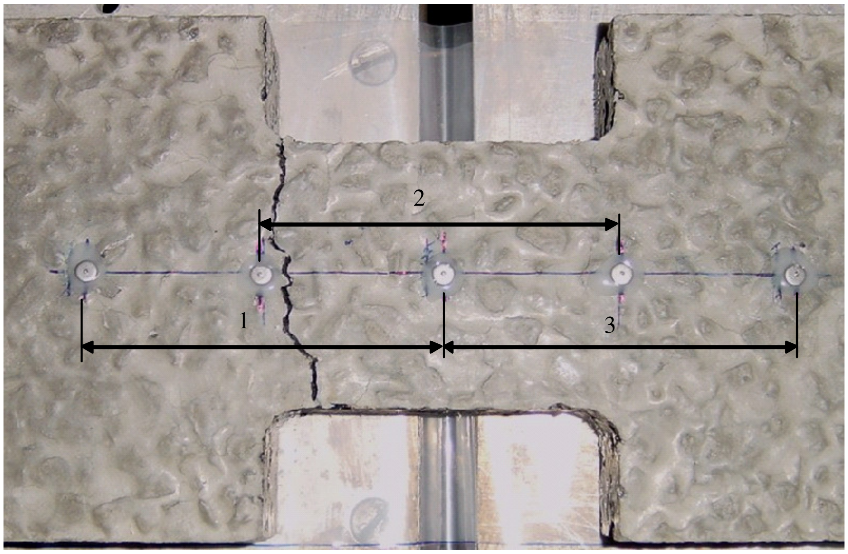

Figure 8: A typical specimen failure

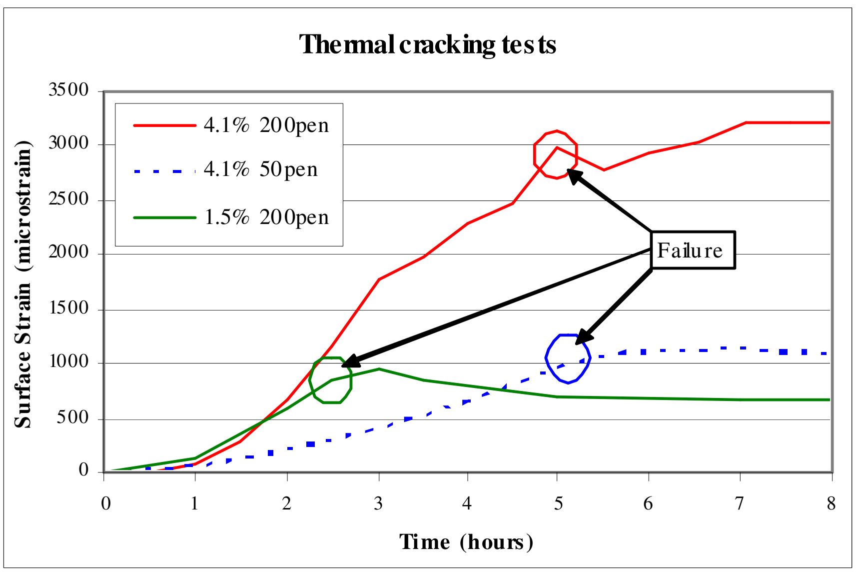

Figure 9: Examples of definition of 'failure'

Table 1: Average strains at failure – thermal cracking tests

Specimen	**Average strain at failure (microstrain)**
'Standard' grouted macadam (4.1%, 200pen)	3768
4.1% binder, 50pen	1267
1.5% binder, 200pen	1028
DBM, 50pen	3518

The implications of this test series are quite clear. Whereas the standard grouted macadam is approximately equivalent to a 50pen DBM in terms of its resistance to thermally induced cracking, this is certainly not the case if a reduced binder content is taken, nor if a harder binder is used. The advantage in stiffness modulus which these two variants bring therefore comes at the cost of much reduced resistance to thermal movement. The key issue is exactly what level of thermal crack resistance is required, and that will clearly be dependent on both climate and level within the pavement. However, a day/night temperature difference of 20ºC would equate to an induced strain of 360 microstrain, assuming a coefficient of thermal expansion of 18×10^{-6}, suggesting that a low-temperature failure strain of 1000 microstrain is likely to be adequate for a climate such as the UK. In support of this, a temperature data set was obtained from measurements taken over the course of a year about 20mm beneath the surface of an asphalt pavement in Nottingham, UK. The critical case appeared to occur from about February to April, where a large temperature difference is combined with a relatively low minimum. In a particularly extreme year, it is quite possible that a 30ºC temperature difference might be combined with a –5ºC minimum. This would approximately equate to the conditions during the test, at a strain of about 540 microstrain, and it further reinforces the point that, so long the failure strain is at least 1000 microstrain, there should be little chance of thermally induced failure. More severe climates, particularly those with much lower absolute minima, would of course demand increased low-temperature crack resistance.

4 POTENTIAL GROUTED MACADAM APPLICATION

Grouted macadam has traditionally been used as a specialist surfacing, taking advantage of its excellent resistance to both deformation and fuel spillage. However, the evidence from this series of tests is that it has potential for use as a more significant part of the structure of the pavement. Furthermore, in a climate such as that of the UK, it would appear that significant advantage could be gained by reducing the binder content, perhaps to as little as 1.5%, thereby increasing the stiffness modulus of the material without compromising its fatigue resistance nor rendering it susceptible to thermally induced cracking.

At 1.5% binder content, the stiffness modulus at 20ºC was found to be over 14000MPa, which brings the material into the territory covered by so-called 'high modulus bases'. However, high modulus bases rely on the use of an unusually hard binder, down to 15pen, and there have been several problems reported with the durability of such materials, particularly if water is able to penetrate the layer. The problem appears to be that the water eventually leads to a break-down of the adhesion between binder and stone, an issue which is being addressed in the UK by the introduction of a purpose designed durability test (Collop et al, 2004). The advantage which grouted macadam brings to this type of design is that it is effectively waterproof, as well as being much more oil-proof than asphalt, and therefore no damaging durability issues would be expected.

A particular issue faced by all countries with developed road networks is that of pavement strengthening, and often the need for strengthening is restricted to a single lane of a multi-lane carriageway. The usual solution is a partial reconstruction, removing the existing materials to a certain depth, often in excess of 200mm, and replacing with an equivalent quantity of new asphaltic material. Grouted macadam opens up the possibility of dramatically reducing this partial reconstruction depth, saving on both materials and, potentially, time, although the two-stage nature of grouted macadam construction also has to be recognized. It also offers the possibility of achieving this without introducing a material of questionable durability.

5 CONCLUSION

The series of tests reported in this paper allows informed decisions to be taken on the most appropriate mixture design for grouted macadam in a particular climate. It allows suppliers to optimize their materials for minimum cost and maximum effectiveness, and it has led to the conclusion that, for some climates at least, it is acceptable to reduce the binder content significantly from the level commonly used without compromising performance.

It is also suggested, based on these findings, that grouted macadams may have applications outside their traditional role as a specialist deformation-resistant surfacing. Significant further work is required to optimize the construction method in situations where time is critical, but the findings open up the possibility of its use as a base layer in highway construction.

REFERENCES

Anderton, G., 2000. *Engineering Properties of Resin Modified Pavement (RMP) for Mechanistic Design*. Report ERDC/GL TR-00-2, U.S. Army Corps of Engineers, Vicksburg.

Boundy, R., 1979. *Development of a Resin/Cement grouted coated Macadam Surfacing Material*. MPhil Thesis, University of Nottingham, Nottingham.

Brown, S.F., Thom, N.H. and Sanders, P.J., 2001. “A study of grid reinforced asphalt to combat reflection cracking”, *Asphalt Paving Technology*, Vol 70.

Collop, A. and Elliott, R., 1999. *Assessing the mechanical performance of Densiphalt*. 3rd European Symposium of "Performance and Durability of Bituminous Materials and Hydraulic Stabilised Composites", Leeds, UK.

Collop, A., Choi, Y-K., Airey, G.D. and Elliott, R.C., 2004. *Development of the saturation ageing tensile stiffness (SATS) test*. Proceedings of the Institution of Civil Engineers, Transport 157, pp163-171.

Oliveira, J., 2006. *Grouted Macadam – Material Characterisation for Pavement Design*. PhD Thesis, University of Nottingham, Nottingham, UK.