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Quasi-Static Characterisation of Asphalt Mixtures

EXECUTIVE SUMMARY

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1. Introduction

For most pavement design purposes, extensive use has been made of linear elastic theory applied to layered systems [Shell International Petroleum, 1978; Brown and Brunton, 1986]. However, such approaches, many of which are routinely used in road engineering to assess pavement deterioration, ultimately do not fully describe the complex behaviour of asphaltic materials, and generally involve simplifications of the pavement structure. Whilst satisfactory results may be obtained for pavements of relatively thick asphalt construction, provided the stiffness of the asphalt layer is accurately specified, linear elastic analysis is inappropriate for pavements of thinner asphalt construction, where the non-linear characteristics of the pavement are more prominent [Brown, 1997]. Typically, thin or low volume pavements account for much of the lightly trafficked road network, a sector that represents approximately 95% of pavements in the UK [British Road Federation, 1999]. The application of inappropriate analysis tools for this category of a road has resulted in the use of uneconomic standards, in a sector where funds are particularly restricted [Dunhill *et al.*, 2000]. Therefore, if improved design standards are to be developed, alternative analysis and evaluation methods that can fully describe the behaviour of asphaltic and other paving materials are required.

The use of constitutive modelling is well established in many fields of engineering, such as soil or rock mechanics and concrete technology. However, asphaltic materials represent a difficult medium for the engineer to model due to their complex physical structure and correspondingly complex behaviour. It is well documented that asphaltic materials are both loading rate and temperature dependent and exhibit elastic, viscous and plastic behaviour. Traditionally, the numerically intensive computer simulations required to model such complex material behaviour were prohibitive in terms of computation processing time and storage space. However, the continuing increases in computing power and advances in numerical procedures now facilitate the implementation of complex constitutive models into incremental numerical techniques such as finite element (FE) methods. To apply this approach to pavement structures, a constitutive model capable of describing the elastic and inelastic strain rate, temperature and stress dependent nature of asphaltic materials is required. The development of such constitutive models for asphalts and other paving materials, once implemented in FE codes, will provide versatile tools to facilitate the analysis and study of pavement response, performance and damage modes, such as rutting and cracking.

2. ACRe Constitutive Model

One such, three-dimensional, strain rate sensitive, history and temperature dependent constitutive model for asphaltic and other paving materials has been developed at Delft University of Technology [Scarpas *et al.*, 1997; Scarpas and Blaauwendraad, 1998]. This dynamic plasticity based asphalt concrete response (ACRe) model retains the fundamental classical plasticity notions of flow surface, decomposition of strains, and hardening and/or softening to produce a unified modelling approach for materials such as asphalts, that exhibit rate dependent inelastic deformations. The model utilises two independent flow surfaces, the first, based on work by Desai *et al.* [1986], to control material hardening and overall material softening and the second to control the tensile cracking response. In this study, research focus was placed on the determination of the model parameters concerned with the first flow surface.

The model has been implemented in a three-dimensional FE code (CAPA-3D) and used to simulate damage response in Dutch pavement structures. A prerequisite to enable this model to be used for the investigation of the mechanisms that lead to damage modes within UK pavements is the availability of model parameters describing realistic UK asphalt mixtures. The objective of this study is therefore to experimentally determine and numerical verify the model material parameters necessary for the characterisation of UK asphalt design mixtures for use in this constitutive model.

3. Experimental Work

The first stage in the development of any constitutive model is the availability of experimental data for the determination, calibration and verification of the model and the material parameters. Thus, a key element in the development of the constitutive model has been the development of appropriate material characterisation tests to determine the necessary model input parameters [Erkens and Poot, 1998 and 2000]. A three-dimensional response model should be based on the generalisations of numerous stress states. However, the response of asphalt mixtures is state of stress dependent, therefore to evaluate a one-to-one relationship between a state of stress and the corresponding response, the state of stress in any representative laboratory test must be uniform. This excludes many standard pavement engineering tests, such as the indirect tensile fatigue test, where a non-uniform stress state exists. Thus, in this study, characterisation is undertaken using data from quasi-static, monotonic uniaxial compression and tension laboratory experiments, carried out over a range of displacement rates and temperatures. Two asphalt mixtures were chosen for full characterisation. These being a continuously graded 10 mm dense bitumen macadam [British Standards Institution, 1993] and a gap graded type F 30/10 hot rolled asphalt [British Standards Institution, 1985], selected to represent the two generic types of asphalt mixtures traditionally utilised in the construction of UK lightly trafficked pavements. To enable an unbiased investigation into the effect of aggregate gradation on the mixture response, and hence material parameters, the same penetration grade bitumen was used. Therefore, both mixtures comprised andesite aggregate and 100 penetration grade bitumen, with a binder content by mass of 5.5% and 7% for the DBM and HRA mixtures respectively.

The experimental testing programme was undertaken at three displacement rates of 0.1, 1 and 10 mm/s and three temperatures of 5, 20 and 35°C. Three repeats per set of test conditions were undertaken resulting in a data set of 108 uniaxial compressive and tensile test results. Cylindrical test specimens were used for the compression tests with 'dog bone' shaped specimens being used for the tension tests. Based on work undertaken by Erkens and Poot [1998], a lubrication system comprising a soap - plastic film - soap sandwich, at each of the specimen/loading platen interfaces during the uniaxial compressive tests, ensured a true measure of the material properties. Tests conducted with this arrangement were observed to display up to a 25% reduction in peak load and to exhibit a change in the mode of failure from barrelling followed by shear failure, to a more uniform dilation of the compressive specimen, followed by vertical axial splitting.

The observed failure mode for the compressive specimens during the initial phase of the specimen response, up to and past peak load, was that of axial splitting. The HRA mixture was found to have higher compressive strengths ranging from 1.42 to 31.09 MPa compared to 1.07 to 29.20 MPa for the DBM mixture. Each of the mixtures displayed an increase in compressive strength with increasing strain rate and/or decreasing temperature. The data indicated that the apparent strength of asphalt mixtures was sensitive to both binder content and binder type (penetration grade), with increases in binder content/decreases in binder penetration grade producing increases in the compressive strength of a mixture. At low stiffness conditions (high temperatures and/or slow displacement rates) the apparent strengths of all the asphalt mixtures were comparable. For each of the mixtures, and for all test conditions, the stress-stain response is similar, comprising an ascending portion until peak stress, followed by a descending portion. It is therefore possible to generalise the stress-strain response of the asphalt mixtures. The stress-strain response curves for the DBM mixture generally exhibited more pronounced, sharply defined (brittle) peak stress-strain response curves compared to the less pronounced and more rounded (ductile) peak stress-strain response curves of the HRA mixture. This is reflected in the substantially lower peak strain values obtained for the DBM mixture compared to those found for the HRA mixture.

The strain rate and temperature dependent relationship developed by Erkens and Poot [2000] to describe the strength response of a Dutch Sand asphalt mixture has been successfully used to describe the strength response of the UK DBM and HRA asphalt mixtures. However, based on the analysis of the non-linear regression parameters, it is recommend that, at this stage in the model development, the regression parameters are considered valid only within or close to the strain rates and temperatures used in the experimental testing programme. The apparent stiffness of the mixtures was found, as expected, to increase as a function of decreasing temperature and/or increasing displacement rate. It was therefore possible to utilise a similar relationship to that employed for the compressive strength to describe the apparent stiffness modulus of the DBM and HRA mixtures. An approximately linear relationship was found to exist between compressive strength and apparent stiffness; thus providing the possible opportunity to define the apparent stiffness modulus of the mixtures based on the more easily measurable mixture compressive strength. Similar values for Poisson's ratio were found for both the DBM and HRA mixtures. The values ranged from 0.2 to 0.46 for the DBM mixture and 0.22 to 0.46 for the HRA mixture. A slight trend of increasing Poisson's ratio with decreasing mixture stiffness was also found.

The tensile stress-strain response curves displayed a trend of increasing tensile strength with increasing displacement rate and/or decreasing temperature, up until peak fracture strengths of approximately 6.1 and 6.8 MPa for the DBM and HRA mixtures respectively, after which a decrease in strength was observed with further increases in stiffness. It is possible to distinguish two main modes of tensile failure. Ductile failures, at high temperatures and slow displacement rates, and brittle failures, at low temperatures and fast displacement rates. The type of failure mode (ductile or brittle) was linked to binder stiffness. Brittle type failures occurred for test conditions where binder stiffness was greater than or equal to 60 MPa. Ductile type failures where observed to occur if test conditions resulted in binder stiffness moduli less than or equal to 30 MPa. For intermediate stiffness ranges, mixed failure conditions occurred. The response of the DBM and HRA mixtures are therefore dependent on the applied stress in a manner analogous to that for bituminous binders, i.e. if the test conditions are sufficient to induce large stiffness moduli, the specimen will fail in a brittle manner, otherwise for low stiffness moduli, failure will take place in a ductile manner. The same strain rate and temperature dependent relationship that was used to describe the compressive strength response was used to describe the tensile strength response of the asphalt mixtures. However, a dual set of non-linear regression parameters, segregated on the basis of binder stiffness was used to describe the tensile failure response in the ductile and brittle zones.

4. Determination of Material Parameters

Based on the uniaxial compression and tension test results, the basic material parameters needed for the model were determined. The peak strength data was used to define the failure envelopes for each of the test conditions from which the model parameters γ and R were determined together with general expressions for these parameters as functions of uniaxial strength, temperature and strain rate. The volumetric response of both mixtures, after a small initial compaction phase, was found to be dilative under all test conditions. Values for parameter n (apex of the flow surface) were therefore determined at the state of stress corresponding to the onset of dilative response as a function of temperature and strain rate with identical values being used for both the DBM and HRA mixtures.

Non-linear regression analysis on the inelastic hardening phase of the experimental data allowed the parameters describing hardening to be determined as both functions of plastic work and equivalent plastic strain. A general trend for parameter α (hardening parameter) was found to exist for all test conditions, however, the relative magnitudes varied for different test conditions. The evaluated parameters for the hardening function were found to exhibit both temperature and strain rate dependent characteristics, for both specifications of the expression. Non-linear regression analysis on the degradation phase of the experimental data allowed the parameters describing softening to be determined both as a function of post fracture plastic work and post fracture equivalent plastic strain. The parameter K, evaluated as a function of post fracture plastic work, was found to exhibit a strong strain rate and temperature dependency. However, the residual strength parameter A, and parameter κ, evaluated as a function of post fracture equivalent plastic strain were found to exhibit no consistent strain rate or temperature dependencies.

Similar families of flow surfaces were obtained for the DBM and HRA mixtures, particularly under high stiffness test conditions (low temperatures and high strain rates), where the mixture binder properties dominate mixture response. Similar yield and hardening surfaces were obtained for either plastic work or equivalent plastic strain specifications of the hardening function. For all uniaxial compressive test conditions, for both the DBM and HRA mixtures, the model flow surface exhibits growth potential and therefore is suitable for modelling the observed compressive hardening response of asphalt mixtures. For all uniaxial tensile test conditions, for both the DBM and HRA mixtures, the yield and failure surfaces coincide. Therefore, the model exhibits no potential growth capabilities for tensile states of stress. This may be suitable for simulating the observed tensile response of the asphalt mixture for high stiffness conditions ($S_b \geq 60$ MPa), where the mixtures exhibit little material hardening. However, it is not suitable for simulating the ductile type tensile response for low stiffness conditions ($S_b \leq 30$ MPa), during which the response of the asphalt mixtures were characterised by necking and hence exhibited material hardening.

Overall the predicted compressive stress-strain response for both asphalt mixtures was found to be comparable to the experimental data under all test conditions. The model was found to successfully predict the peak strength as well as the softening and particularly the hardening response of the asphalt mixtures. Similar hardening responses were predicted irrespective of whether plastic work or equivalent plastic strain was used to specify the hardening parameters. A better fit for the degradation response was generally obtained when the post fracture equivalent plastic strain was used to define the softening parameters, although this was found to over-predict the post peak radial strains for high stiffness test conditions, particular for the DBM mixture.

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