MICROSTRUCTURAL SELF-HEALING OF BITUMINOUS MATERIALS: COMBINED EXPERIMENTAL AND NUMERICAL STUDY

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ABSTRACT

Bituminous materials form a class of materials that possess the intrinsic ability to self-heal. This self-healing capability is evidenced by the observation that the service life of these materials 'in the field' exceeds the service life as predicted by standard mechanical laboratory tests. This mismatch between laboratory prediction and field service life is usually accounted for by applying a shift or healing factor.

In this contribution we demonstrate a model that is based on the observation that bitumen possesses a microstructure on the micrometre length scale, as can be observed by atomic force microscopy (AFM). On this scale bitumen can be regarded as a two-phase material, where the phases have a distinct stiffness. . One of the phases has a very typical appearance and is often referred to as 'bee-phase' [1-3]. The interface between the phases can be regarded as a manifold that is defined by stiffness gradient in the material. From mechanical considerations damage will initiate within this manifold. Modest variations in thermodynamic conditions (thus without melting the material) will already lead to rearrangement of phases, and a new damage initiation manifold, meanwhile the accumulated damage is erased.

Starting from two experimental microstructural arrangements, one before and one after phase rearrangement, a finite element mesh is produced. For both phases a viscoelastic constitutive model is implemented. The interface manifold is treated equally, but is allowed to acquire damage, as are the other phases, to a lesser extent. In this way, using experimental observations as a starting point, it is demonstrated that the effect of healing in bituminous materials can be treated micromechanically, and leads to quantitative results. This opens the way to quantify the healing potential of a bituminous material upon its microstructure. Optimal manifolds to accommodate the healing behaviour can then be derived. The experimental challenge will be to engineer the interface manifold in accordance with the desired healing potential of the material.

1. INTRODUCTION

Worldwide the most common pavement material is asphalt concrete. Asphalt is well known to display healing behaviour. The intrinsic healing characteristic of asphalt is utilized in asphalt pavement design. In the Netherlands healing factors are included for calculating the layer thickness of roads (higher healing factor, thinner layer). However,

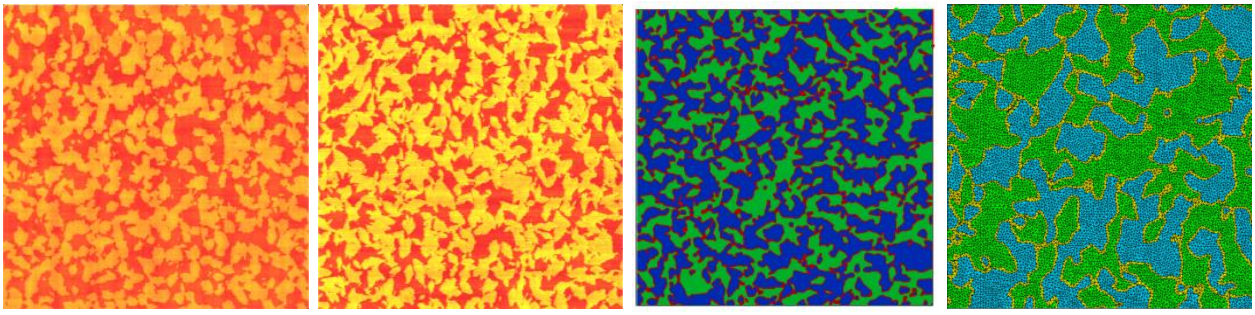
this (design) healing factor happens to be a rather random property of mixes, and is therefore usually estimated conservatively.

This healing propensity of asphalt does depend on many parameters, a.o. temperature, maximum load levels, loading rates and it can be associated with an intrinsic healing property of one of the material's components. Usually this healing property is attributed to the bituminous binder, which is both the 'weakest link' in the asphalt concrete composite and the component that possesses the highest amount of 'physico-chemical mobility'. Mobility on the microscopic scales at service temperatures, is commonly regarded as a necessary condition for healing to occur.

AFM evidence indicates the presence 2 or 3 microstructural phases of bitumen [2]. Because the phases possess different mechanical stiffnesses, damage may originate at the interfaces between them, when subjected to mechanical loading. When bitumen undergoes relatively modest temperature changes (20-45 °C), the phases already tend to rearrange themselves into new configurations, Figures 1a and 1b. Phase rearrangements will then lead to 'erasure' of earlier damage, and hence improved service life characteristics. The necessary thermal variation of 25 °C for this to happen, is within the typical daily temperature variations experienced by real pavements.

2. MATERIALS AND METHODS

For this study the bitumen AAK from the SHRP bitumen library [4] was selected. Initially a 30×30 µm AFM (tapping mode) image was recorded at 20 °C, Figure 1a. Then the sample was slowly heated to 45 °C, cooled again to 20 °C and subsequently imaged again by AFM, Figure 1b. The AFM images were then digitally processed Figure 1c, displaying clearly the two phases and the interface (red) between them. Finally, finite element meshes consisting of three material types, were generated using Simpleware©, Figure 1d.



(a) **(b)** **(c)** **(d)**

Figure 1 : AFM phase images (a and b), image-processed AFM image (c) and detail of the finite element mesh derived from the latter (d).

The viscoelastic Zener material model which consists of two parallel components, an elastic spring and a Maxwell component has been utilized for constitutive modelling. Additionally the standard model has been extended to include damage simulation. To allow for damage the second Piola-Kirchhoff stress S in the reference configuration is modified as:

$$S_{eff} = (1-d)S \qquad (1)$$

where $d = 0$ in absence of damage and $d = 1$ for the case of complete damage. In this implementation damage is made a function of the total work W in the Zener component, and is expressed as:

$$d = 1 - \exp\left(-k\,W^{r}\right). \qquad (2)$$

Here k and r are parameters, and the total W is the total work. This model is then implemented within the finite element framework CAPA-3D to simulate the response of bitumen to a triangular, stress controlled (σ_{max} = 2.5 MPa, i.e. about 1% strain) repeated loading scenario with 15 load-unload cycles. The applied load was uniaxial in the vertical y-direction.

The material parameters like relaxation modulus E were derived from values obtained by dynamic shear rheometer (DSR) tests: the overall (averaged) parameters correspond to the DSR-derived values, whereas the range of properties 'per phase' were estimated from quantitative AFM measurements, Table 1. The damage parameter k was chosen to be in the range 1 to 5, while the parameter r was fixed to 1 for all simulations. The Poisson ratio is taken throughout as 0.4.

Table 1 : Parameter ranges as used in the FEM simulations for the 3 distinct phases. Between parentheses: the actual values used for the simulations of Figure 2.

	Bee-phase ('green' in Fig 1c)	Interface-phase	Continuous phase
E (E_0=110 MPa)	1-4 E_0 ($2E_0$)	1-2 E_0 ($1.45E_0$)	1-3 E_0 (E_0)
Viscosity (η_0 = 5 MPa.s)	$10\eta_0$	$5\eta_0$	η_0
Damage parameters k ; r	1-5 (3) ; 1	1-5 (5) ; 1	1-5 (1) ; 1

For the simulation presented in Figure 2, the damage parameters of the interface were chosen such as to make this phase to be most prone to developing early stage damage ($k = 5$). Furthermore, the continuous phase was given the lowest value ($k = 1$), with the 'bee phase) in between these extreme values ($k = 3$). The order of magnitude of the damage parameters was selected such as to show a noticeable decrease of mechanical response within 15 load repetitions.

3. RESULTS AND DISCUSSION

In Figure 2 the results of the finite element simulation for one particular cyclic loading scenario is presented. After every full loading-unloading cycle, a value for the temporal stiffness was obtained by evaluating the ratio of total applied force and displacement. In Figure 2 surface displacements at 5 different surface locations (nodes) are shown. The stiffness shows a similar decreasing trend as a function of load cycle, with a maximum decrease of about 24% after 15 cycles. The spatial distribution of damage accumulated after 15 cycles is shown in the bottom right insert in Figure 2. Damage is most prominent in interface and bee phases. As the maximum strain is at the order of 1%, no discrete discontinuities are introduced into the material. Then the material was subjected to a temperature cycle of 25 °C.

At the end of the temperature cycle, phase rearrangement has erased damage (loss of memory). The response of the 'healed' material, Figure 1b, leads then to an increase in stiffness ('healing'), followed by a decrease with subsequent load cycles.

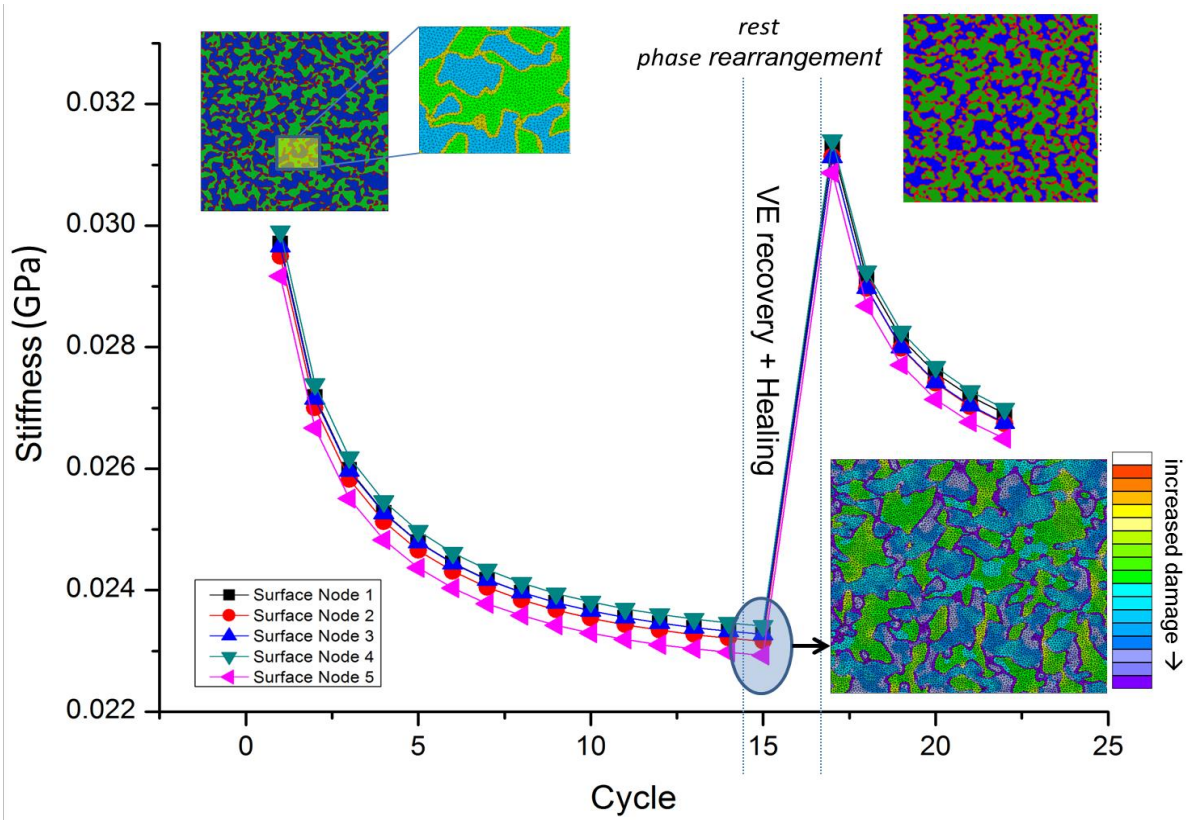


Figure 2 : Results of FEM simulations. Inserts show FEM meshes and damage after 15 stress controlled load cycles.

4. CONCLUSION

In a combined experimental and numerical study a possible scenario for the intrinsic healing phenomenon in bituminous materials is introduced. This scenario is based on the existence of microstructural phases in bituminous materials, and the AFM observation that moderate thermodynamic changes to the system lead to rearrangement of the phases and with accompanying loss of memory for moderate levels of straining. This was demonstrated by an increase of mechanical response of the material after moderate thermal cycling, leading to phase rearrangement.

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