Characterization and Modelling of Self Healing of Bituminous Materials towards Durable Asphalt Pavement

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ABSTRACT

The traffic volume and the number of heavy vehicles are growing enormously nowadays. There is a need for designing a durable asphalt pavement with innovative technologies. Pavement structures and materials with self healing and self repairing capability are believed to be very useful in such a system. This paper is aiming to understand the self healing behaviour through mechanical testing and finite element modelling. Instead of a complex and time consuming fatigue involved self healing investigation, a more effective test method was developed for bituminous materials using the Direct Tension Test (DTT) with a monotonic loading-healing-reloading procedure. The results indicate that the self healing behaviour is a viscosity driven process and it is dependent on time, temperature and crack sizes. A visco-elastic coupled damage-healing (VEDH) model was developed using a smeared crack approach under finite element code FEMMASSE. By defining both visco-elastic and local damage-healing properties, the damage and healing behaviour of bituminous mastics can be simulated successfully. Based on the research findings, recommendations are also given for durable asphalt pavement with self healing technologies.

Keywords: Bitumen, Healing, Visco-elasticity, Finite Element Model, Durable asphalt pavement

1 INTRODUCTION

Self healing of bituminous materials has been known for more than forty years [1]. Asphalt pavements are believed to heal under long rest periods and hot summers, hence healing will extend the service life. It has been indicated that the self healing property is complex and very dependent on rest duration, temperature, crack phases and material properties like viscosity.

In this paper, the self healing capability of bituminous mastics was characterized using the Direct Tension Test (DTT). Under a special monotonic loading-healing-reloading procedure, the damage and healing behaviours of bituminous mastics were investigated. Furthermore, a finite element model was introduced then to further understand the self healing phenomenon observed from the mechanical testing. With the model in hand, the self healing phenomenon of bituminous mastics shown in the experimental work was simulated. In the end, the possibility of designing durable asphalt pavement using the self healing ideas was also discussed.

2 EXPERIMENAL CHARACTERIZATION

2.1 Materials

A standard 70/100 penetration grade Kuwait Petroleum bitumen was used in this paper with a penetration of 93 (0.1mm) at 25°C and a softening point of 45°C. The bituminous mastics were produced by mixing the bituminous binders with Wigro limestone filler with a mass ratio of 1:1. In this paper, the 70/100 penetration bituminous mastics is called the PBmas.

2.2 Experimental procedure

Figure 1 shows the parabolic shaped specimen used in the DTT test. The parabolic shape guaranteed that the stress concentration in the middle of the specimen was such that the cracking and healing occur at the same position [2].

As also shown in Figure 1, a post-peak unloading-reloading cycle procedure was applied to the specimen and the procedure is explained as follows:

a) Loading

The specimens were subjected to a direct tension loading at 0°C with a displacement speed of 10mm/min. Various target elongations (TE_{after}) were set in order to develop different phases of cracks in the specimen. The DTT machine was programmed to stop at a TE_{after} of 1mm, 2mm, 3mm, 3.5mm and totally broken respectively.

b) Healing

The specimens were unloaded at each TE_{after} and then placed back into the silicon rubber mould in order to heal. Healing times of 5 minutes, 30 minutes and 3 hours in a temperature chamber of 20°C were applied.

c) Reloading

After the healing period, the specimens together with the silicon rubber mould were conditioned back at 0°C for at least 2 hours. The reloading was applied with a displacement speed of 10mm/min at 0°C till total failure. For comparison, a reference specimen was reloaded immediately after unloading from TE_{after} without any healing procedure.

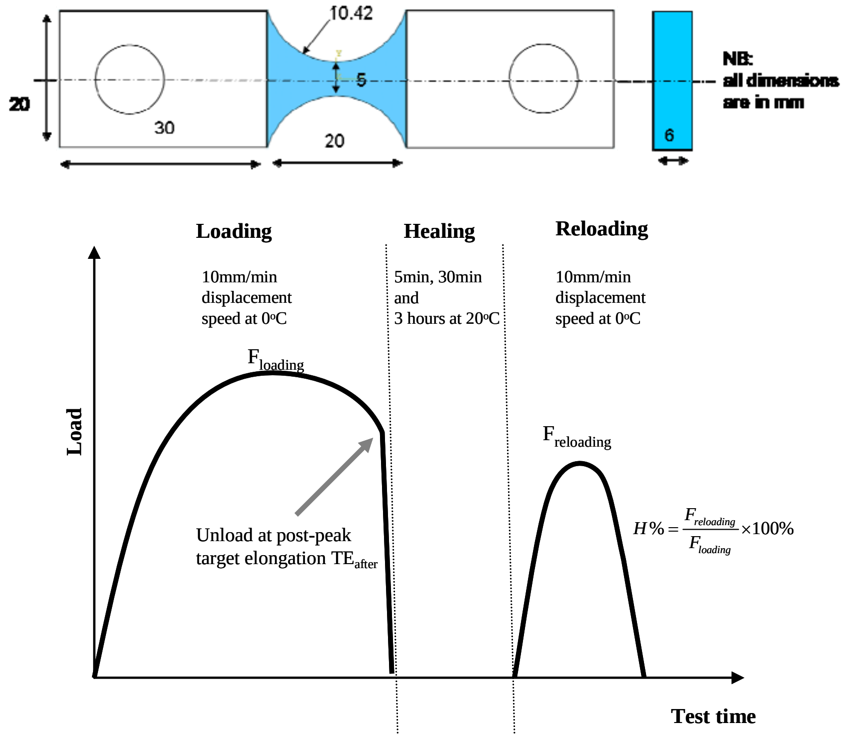


Figure 1 Illustration of the parabolic shaped specimen (upper) and the test procedure (lower) used in the DTT test

2.3 Experimental results

Figure 2 shows the experimental results of the damage and healing characterizations of bituminous mastics using the DTT. When comparing the trends of damage with the trend of healing, they are clearly opposite.

The immediate reloading curve from different target elongations can be regard as the development of damage. The development of damage is not only concerning the strength decrease and also the decrease of the displacement and the area of the curve. When comparing different target elongations, a target elongation before the peak load causes almost no damage to the immediate reloading curve compared to the original curve. After peak load, a gradual decrease of the strength can be observed with the increasing target elongations.

The reloading after different rest periods can be regard as the development of healing. A clear time dependency of the development of the reloading curve can be observed. Among this, the initial healing period of 0.1h plays a major role in both recovery of the reloading strength and the reloading displacement.

It can also be observed that the damage and healing process is coupled with visco-elastic behaviour. However, the influence of the visco-elastic behaviour on the damage and healing process is not clear.

In order to further understand the damage and healing behaviours and the influence of the visco-elastic property, a finite element modelling (FEM) is needed.

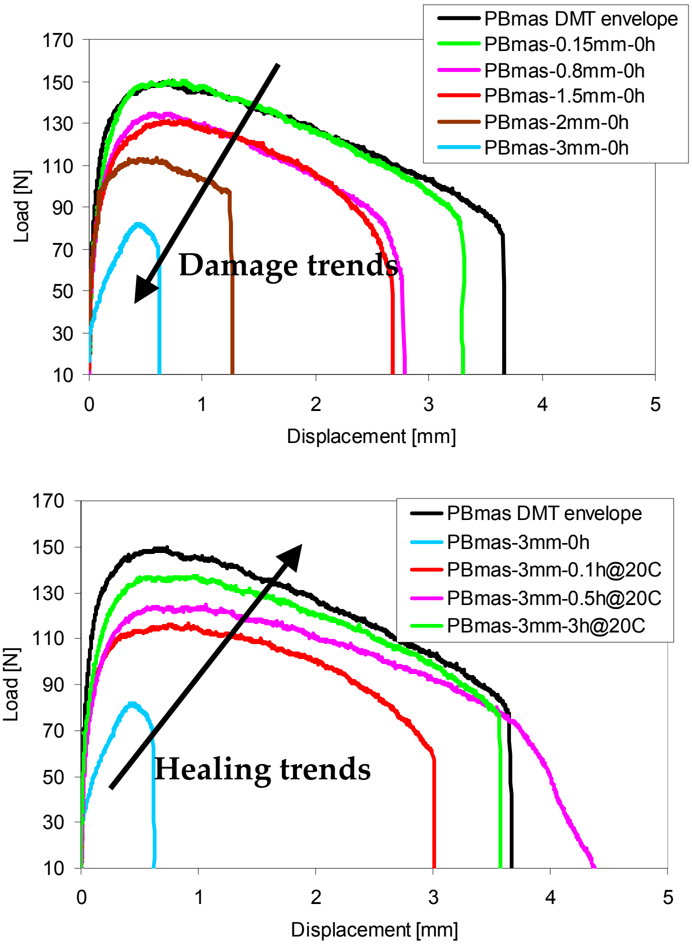


Figure 2 Developments of damage (upper) from immediate reloading and healing (lower) from reloading after rest periods

3 FEM MODEL

3.1 Introduction to cohesive zone model

A so-called cohesive zone model (CZM), was developed based on non-linear fracture mechanics [3]. As shown in Figure 3, a cohesive zone is defined in front of the crack tip with certain traction-separation behaviour. When the local stress applied is higher than the maximum traction force σ_{max}, the cohesive zone model is active. The post-peak softening is followed until the traction diminishes at a distance of δ. The cohesive zone model was used to simulate the fracture process of asphalt mixtures at low temperatures with success [4]. Attempts were also made to simulate the fracture process in a visco-elastic medium with a phenomenological visco-ealstic cohesive zone model [5].

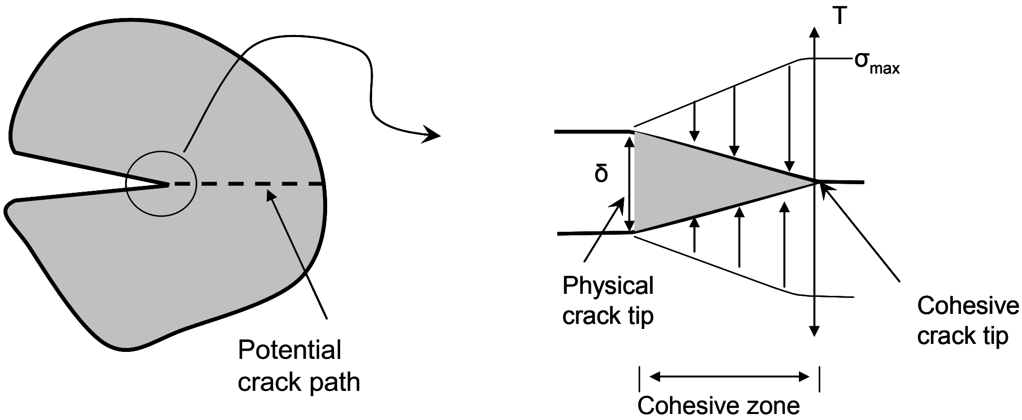


Figure 3 Illustration of cohesive zone model

In this paper, the damage and healing behaviour of bituminous mastics was modelled with the smeared type CZM approach using a commercially available finite element code FEMMASSE [6]. The advantage of the smeared type CZM approach is that this is probably more realistic and it does not assume the pre-existence of the cohesive element during simulation.

3.2 FEMMASSE model

FEMMASSE is a finite element code with an abbreviation of Finite Element Modules for MAterials Science and Structural Engineering [6]. It embeds both features of visco-elasticity and the smeared crack model.

A 5-term Maxwell model was used to model the visco-elastic behaviour by means of Prony series and the expression of the relaxation modulus is shown in Equation 1. Table 1 lists the material properties of the bituminous mastics. The data was back-calculated from the complex modulus master-curve of the sample at a test temperature of 0°C [2].

$$E(t) = E_0 \cdot \sum_{i=1}^{n} \left(1 - \alpha_i \left(1 - \exp\left(t / \tau_i \right) \right) \right) \quad (1)$$

Where:

$E(t)$ is the time dependent relaxation modulus as a function of time, t [MPa]; E_0 is the stiffness of instantaneous response [MPa]; α_i is the model parameter, i.e ith Prony modulus reduction ratio [-]; τ_i is the model parameter, i.e. relaxation speed of the ith component [hours]; n is the number of components in the model [-]

Table 1 List of material parameters of bituminous mastics

E0	2306 MPa	Poisson's ratio	0.35	Strength	5 MPa
5-Term Maxwell model					
i	1	2	3	4	5
τ_i [hours]	5.98454E-07	1.28933E-05	0.000277778	0.005985	0.128933
α_i	0.523185976	0.322064934	0.132783536	0.020001	0.001964

Figure 4 shows the input local damage curve. A nonlinear damage hardening and softening curve was used to define the effect of local damage on the strength-crack width relation. When the local stress is higher than the material strength, the stress will decrease following the local damage relation. The parameters were obtained by fitting the global monotonic load-displacement curve, which will be shown in Section 4.1. In addition, an Alfa factor of 0 was used to consider the crack closure path to zero during unloading.

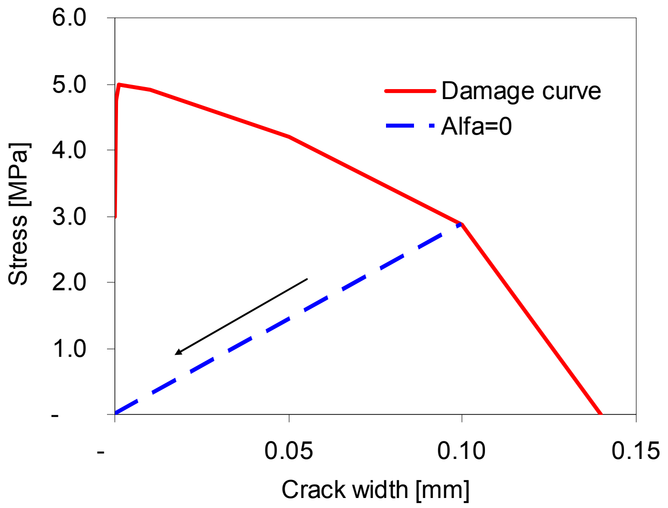


Figure 4 Illustration of the local damage criteria

Figure 5 shows the bituminous mastic specimen and its modelling. The corresponding meshes and the boundary conditions in the FEMMASSE program are also shown. The aluminium top and the bottom caps were simulated as well. A damage-healing zone was defined with a height of 5mm in Red for further healing investigation. Initially, both parts of the bituminous mastics follow the same damage rule. During the healing process, the material properties within the damage-healing zone can be changed, which will be discussed later. In addition, the simulation results of the tensile stress distribution and the crack propagation are also presented in Figure 5.

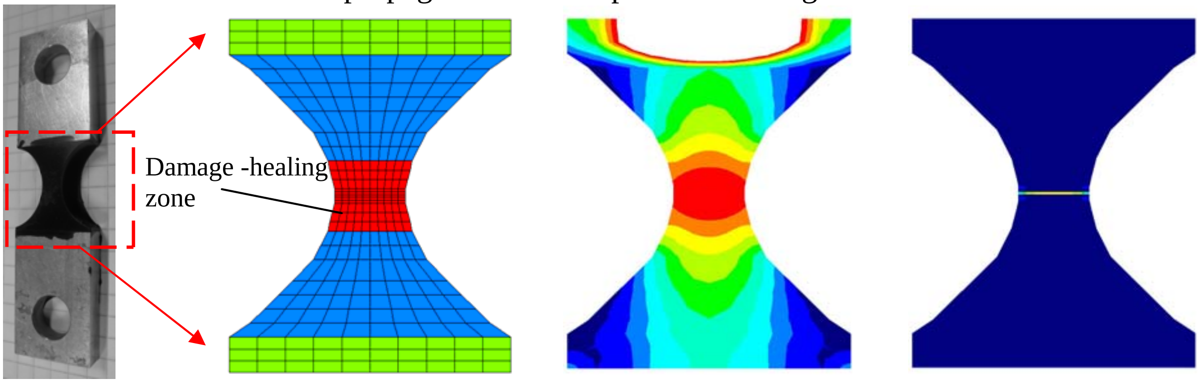


Figure 5 FEM model of the DTT specimen
(a) DTT specimen; (b) FEM meshes; (c) Tensile stress distribution; (d) Crack propagation

4 MODELLING OF DAMAGE BEHAVIOUR

4.1 Monotonic curve

Figure 6 shows the modelling results of the monotonic DTT test at $0^{o}C$ with a displacement speed of 10mm/min. It can be observed that the measured curve can be simulated very well. The development of the crack width is also similar to the development of the crack width as observed in the experiment by using a fluorescence microscope. It should be noted that the experimental curve was shifted a little bit in order to correct for differences between the experimental displacement speed at the very beginning of the test and the constant speed of 10mm/min was assumed in the simulation. The differences were caused by the fact that in the very beginning of the test the equipment was unable to give a constant displacement speed of 10mm/min.

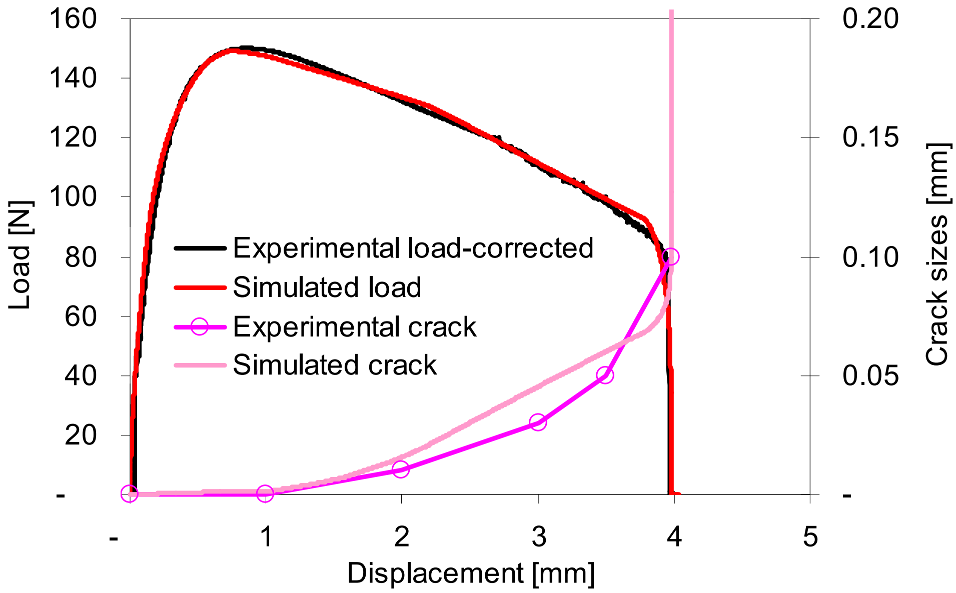


Figure 6 Modelling of the VED full curve of bituminous mastic with Alfa=0 (0^oC and 10mm/min displacement speed)

4.2 Immediate reloading

Figure 7 shows the example of local damage criteria for immediate reloading. As it is shown from the experimental results, an extra damage can be observed when reloading applies after unloading. It is very likely that the reloading curve is overestimated when this extra damage is not taken into account. Hence, a damage term was introduced to the local damage criteria. The reloading curve follows the same route as the unloading curve but continuously follows the re-damage curve by which the effect of the extra damage is simulated.

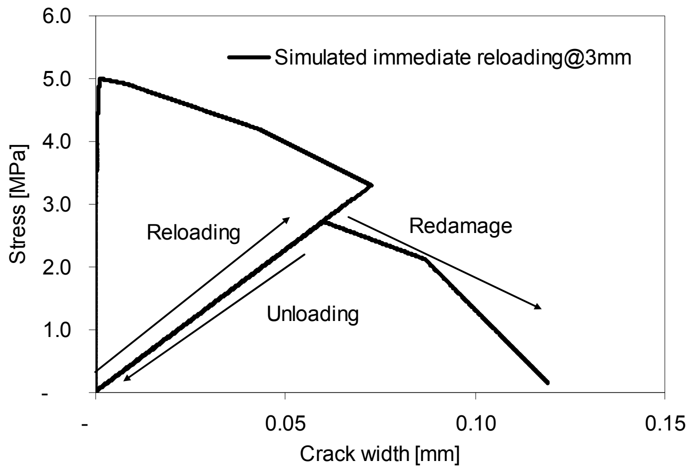
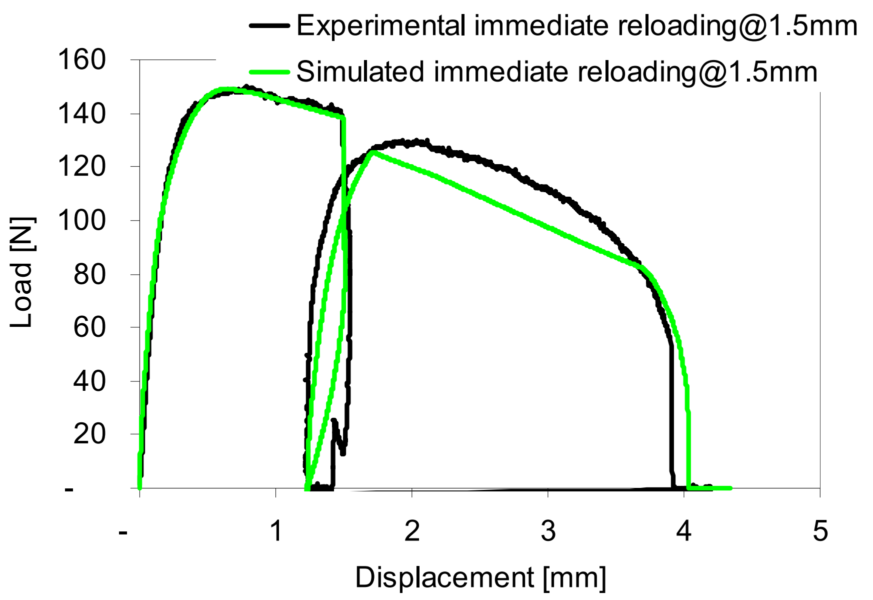


Figure 7 Example of local damage criteria

Figure 8 compares the simulated immediate reloading with the experimental results. It can be seen that the simulation is in line with the experimental results. However, the simulated reloading curve seemed to be larger than the experimental curve at a higher reloading displacement level. This may due to the rapid crack accumulation during the experiment.



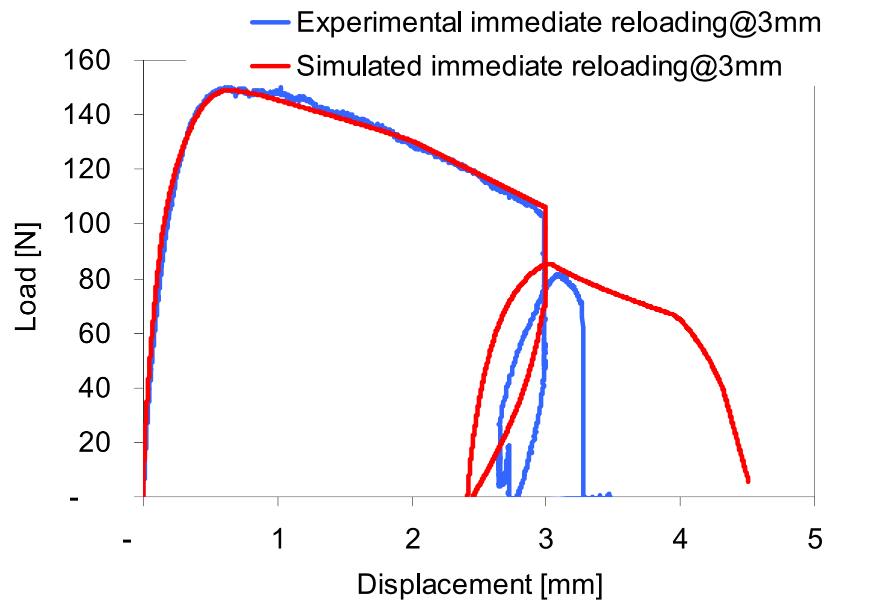


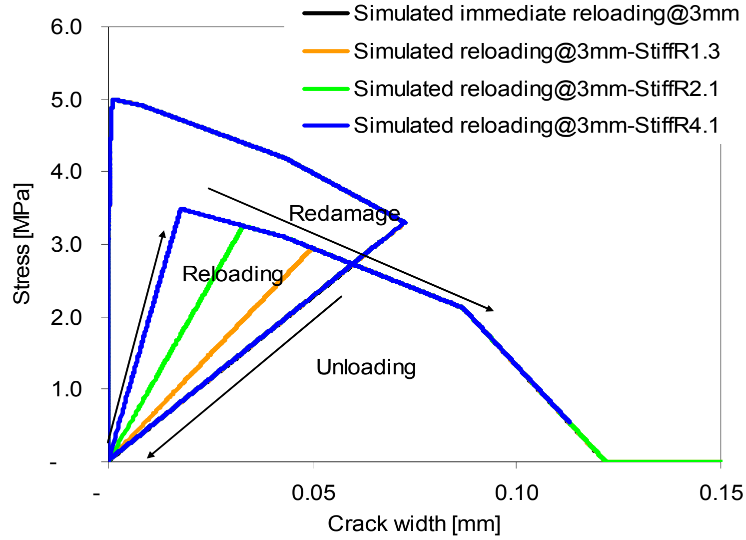
Figure 8 Simulation of immediate reloading at displacement of 1.5mm (upper) and simulation of immediate reloading at displacement of 3mm (lower)

5 MODELLING OF HEALING BEHAVIOUR

5.1 Healing decomposition

As indicated above, the time dependent visco-elasticity is very important for the damage behaviour of bituminous mastic. It would be expected that visco-elasticity will also influence the healing process as represented by the reloading curves after healing periods. As a result, the healing process can be de-composed into visco-elastic recovery (VER) and damage recovery. The two processes are interacted with each other. And the VER is faster than the damage recovery. From the definition of the model, the VER is defined as the pure visco-elastic recovery without taking into account any damage development. The damage recovery can be divided into the stiffness recovery (StiffR) and the strength recovery (StrenR).

Figure 9 shows the local definition of the stiffness recovery by means of changing the reloading slopes. The change of the slope also represents the recovery of the crack width. The local definition of the strength recovery is also shown. It can be seen that the recovery of the strength could result in a higher failure envelope.



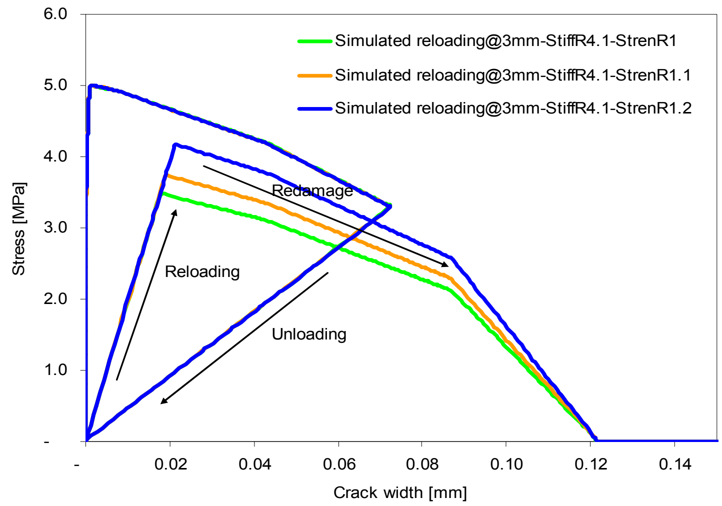


Figure 9 Modelling of stiffness recovery (upper) and strength recovery (lower) on local damage criteria

Figure 10 shows the healing decomposition in the global load-displacement curve. The following can be observed:

- The VER shows improvement in the pre-peak area of the reloading curve, but no change is observed in the reloading strength and the post-peak area. However, a lower reloading stiffness can also be observed.
- The Stiffness recovery shows improvement in both the reloading stiffness and the reloading strength. No change is observed in the reloading displacement.
- The Strength recovery shows improvement in the reloading strength. No change is observed in the reloading stiffness and the reloading displacement.

As observed from the experimental results, the reloading stiffness after healing was always higher than the one with immediate reloading. This suggests that the VER and stiffness recovery happen together at the beginning of the healing process, and then followed by the strength recovery.

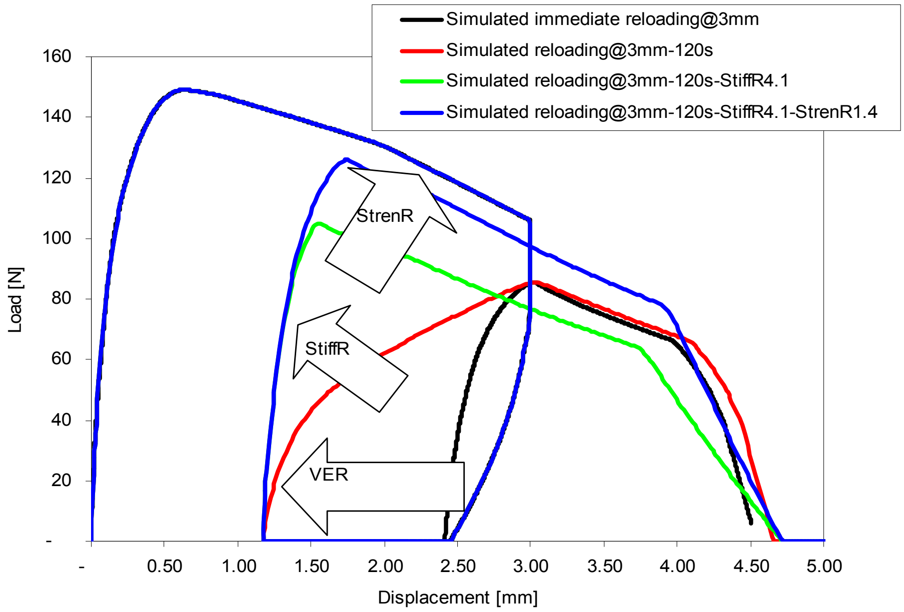


Figure 10 Illustration of visco-elastic coupled healing decomposition

5.2 Modelling of healing

Figure 11 shows the modelling results of the visco-elastic coupled healing. The results are in good agreement with the experimental observations.

- The VER and the StiffR happen first during the healing process in a short time, which is related to crack closure and visco-elastic recovery.
- The StrenR happens after the short term healing process and lasts a longer time, which is related to further strength gain.

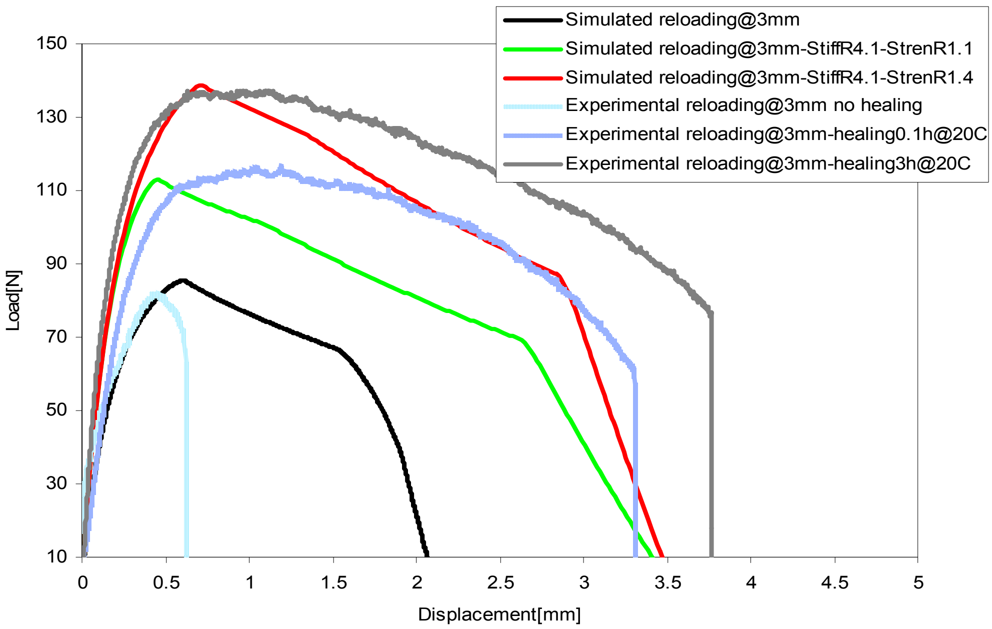


Figure 11 Modelling of visco-elastic coupled healing results
(Test was done at 0^{o}C and 10mm/min displacement speed, healing was done at 20^{o}C)

6 DISCUSSION

The possible healing can be very important for durable asphalt pavement. With the help of the healing behaviour, the crack can be repaired by itself. This process is also very sensitive to the environmental conditions such as temperatures, compressive stress etc. As a result, optimisation of the healing behaviour should be undertaken to enhance the durable pavement design.

- When considering the sizes of the cracks for the self healing phenomenon. A small size of the cracks is favourable for a fast healing. When the damage and healing are balanced or the healing process is dominant, a prolonged service life of asphalt pavement can be expected.
- When considering the difference between the modulus recovery and the strength recovery, the stiffness recovery probably not a good indicator for assessing the healing capability. The strength recovery is more appropriate. So the existing modulus based healing assessing methods (for example, fatigue related healing test) need to be improved.
- The complexity and artefacts during the self healing assessment should be taken good care of. Especially the visco-elastic behaviour, the geometry effect and the plastic behaviour, which are happening during the measurement.

7 CONCLUSIONS

The self healing capability of bituminous mastics was investigated experimentally using a modified direct tension test and a healing model was developed by combining the viscoelastic property and the smeared type cohesive zone model. Based on the research observations and the simulation results, the following can be concluded:

- The self healing process is a reverse process of the damage process, which indicates the ability to improve the stiffness in a short healing time, the strength in a long healing time.
- The viscoelastic coupled damage and healing behaviour of bituminous mastics can be simulated by defining both visco-elastic and the local damage-healing properties.
- The visco-elastic coupled healing process can be de-composed into visco-elastic recovery and damage recovery including stiffness recovery in a short healing time and strength recovery in a long healing time.
- An optimisation of the healing behaviour can be important to ensure a durable asphalt pavement.

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