Terms and Definitions on Crack-Healing and Restoration of Mechanical Properties in Bituminous Materials

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Abstract Fatigue damage is one of the main modes of deterioration of bituminous materials that leads to the failure of flexible pavements. However, it is well known that bituminous materials have some capability of recovering inflicted damage to some extent due to their viscoelastic nature. This process has been referred to as "self-healing". Recently, research on crack-healing of bituminous materials has gained more importance and popularity due to the development of self-healing materials by materials scientists and engineers, that have been used in several applications. The Rilem Technical Committee TC 278-CHA (Crack-Healing of Asphalt Pavement Materials) was created in 2016 to tackle the challenges related to testing and evaluating the crack-healing properties of bituminous materials. However, the committee members noticed that there is no clear agreement within the scientific community about some basic terms to use when it comes to this new area of interest. Hence, this paper aims to clarify some of the concepts related to crack-healing and propose some common terms to the researchers and pavement engineers.

Keywords Crack-healing · Restoration · Recovery · Bituminous materials · Self-healing materials · Terminology

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H. Di Benedetto et al. (eds.), *Proceedings of the RILEM International Symposium on Bituminous Materials*, RILEM Bookseries 27,
https://doi.org/10.1007/978-3-030-46455-4_6

1 Introduction

During (cyclic) mechanical loading a reduction of strength and stiffness can be observed in bituminous materials [1]. Interestingly, in many cases, this loss in strength and/or stiffness of bituminous materials can be totally or partially restored [2]. When first discovered, the restoration of mechanical properties in asphalt was called “Healing” or “Self-healing”. As this effect is significantly large, several pavement design methods address this effect by using an empirical healing-factor [3, 4]. Even though the restoration of mechanical properties is regularly observed, there is no consensus or clear agreement regarding the mechanism that drives this restoration.

The reason why it is challenging to understand the restoration, it that there are many mechanisms occurring at the same time that are hard to untangle. Therefore, in order to facilitate the scientific discussions and improve the understanding within the scientific community, we should start by having a clear and concise terminology. In this paper, an introduction to the different phenomena is given and a framework of definitions is proposed.

This set of terms and definitions for restoration and crack-healing in bituminous materials will also assist interaction with other research domains. In the field of materials science, in the beginning of this century, a research movement started aiming at designing materials that are able to restore damage autonomously, creating the domain of “self-healing materials”. Since then, the research on self-healing materials has moved into the field of bituminous materials and several researchers have started investigating different types of solutions to improve self-healing capabilities of asphalt mixes and binders, Fig. 1. As a result, terminology of the self-healing world has entered to bituminous materials field. Creating one set of definitions will make pavement engineering publications and discussions more comprehendible for people outside the pavement engineering community.

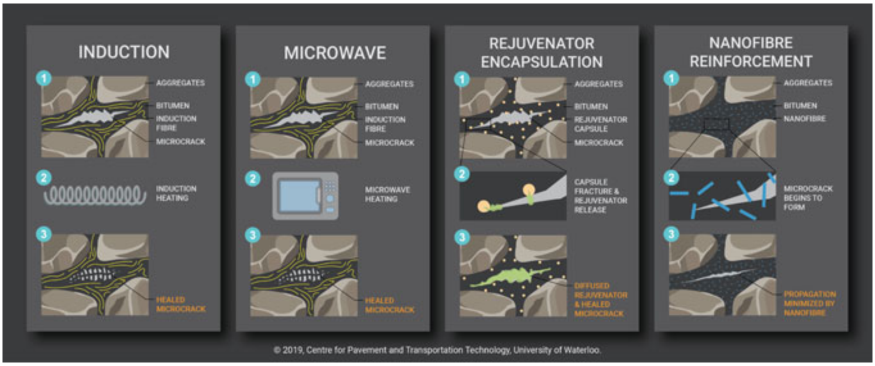

Fig. 1 Different approaches to introduce additional self-healing performance (extrinsic) to bituminous materials

2 Rheological Response of Bituminous Materials to Cyclic Loading

Especially in cyclic loading (typically imposed in so-called fatigue tests), there are several mechanisms that come into play with respect to the loss and consequently the restoration of mechanical performance [5–8]. Therefore, the purpose of this section is to provide a small introduction to the response of bituminous materials subjected to cycling loadings. This response depends on several mechanisms related to the time- and temperature-dependant nature of bituminous materials. When interpreting the response, it is important to discriminate loss in mechanical properties due to formation of micro-cracks from loss due to other undesired biasing effects, more specifically local heating, thixotropy and non-linearity. There is still debate about the relative impact of each these phenomena, however the main phenomena that may occur during cyclic loading tests are briefly introduced below.

Non-linear viscoelasticity (NLVE)—Bituminous materials start exhibiting a strain dependent visco-elastic behaviour, commonly referred to as NLVE, when applied strain exceeds a characteristic threshold value (LVE limit). Determination of LVE limit for bituminous materials is generally not trivial. Moreover, it must be taken into account that binder located within inter-aggregate spaces in mixtures is subjected to strain levels significantly higher than the overall mix strain, resulting in non-linearity when an asphalt mix is subjected to relatively small strain levels [9]. As a consequence of non-linearity, proportionality between stresses and strains is no longer valid resulting in a difference in observed stiffness, however this does not imply any damage and is therefore purely biasing effects in the test.

Self- or Local Heating—Application of repeated loading to bituminous materials may cause an increase of internal temperature of tested sample due to energy dissipated by visco-elastic effects. As a consequence of this higher temperature, the material shows a stiffness reduction. This phenomenon occurs mainly in the initial stage of loading at a relatively high rate [5]. Self-heating has been proven by several authors measuring temperature variations on bituminous binders [10, 11] and mixtures [12].

Thixotropy—Thixotropy is associated to shear-induced reorganizions of the material's microstructure resulting in a viscosity decrease [13]. When left to rest, due to Brownian motion, the elements of the microstructure are able to slowly regain their more favourable energy positions and the microstructure is rebuilt recovering the original viscosity. The whole process is completely reversible. Evidences of thixotropy occurrence in bituminous materials have been shown [14] and methods to separate thixotropy from fatigue process have been proposed [8, 15].

Micro-cracking—Fatigue cracking is traditionally described as a two-stage process, including the (I) initiation phase, in which micro-cracks appear in a diffuse way to form a network and the (II) propagation phase, in which micro-cracks coalesce and grow until macro-cracking occurs [1]. Beginning of cracks has been related to micro-compositional flaws in the binder medium [16] that grow slightly in each load cycle. Cracks can grow as both adhesive fractures (between the binder and the aggregates) and cohesive fractures (within the thin film of binders). In this document, deleterious structural changes related to micro-crack initiation and propagation are referred to as damage. This definition of damage implies the use of continuum damage mechanics.

3 Continuum Damage Mechanics Versus Fracture Mechanics

In the analyses of cracking damage, different approaches can be taken. An important facet of the damage analyses is whether principles from fracture mechanics are used or continuum damage mechanics [17]. As seen in the previous section where micro-cracks are assumed to be smeared over a wide region, which more typical in fatigue cracking, the use of continuum damage mechanics is more appropriate. However, fracture mechanics is well suited for the analysis of structures and materials that contain a single crack, which is the case when micro cracks coalesce to one macro crack in fatigue or in the case of thermal cracking.

The perspective taken when analysing the damage, should also be considered when evaluating healing, as this is by definition revering he consequences of the damage.

4 Restoration and Crack-Healing During Rest

As mentioned before, the restoration of the mechanical properties can be readily observed in bituminous materials if the mechanical loading is interrupted and the specimen is left to rest. When the cyclic loading is stopped during a fatigue test, the effect of local heating and thixotropy immediately starts to diminish. This part of the restoration is not interpreted as a change in material behaviour or performance, but is regarded as the return to the original state of the material. This part of the restoration is therefore by definition limited to the reversible experimental biasing effects and "recovery" is seen as a suitable term for this part of the restoration. Next to this, the closing and repair of cracks due to the viscous nature of bitumen is also expected to contribute to the restoration [18–21]. We propose to call this part of the restoration "self-healing". The contribution of recovery and self-healing to the restoration is schematically shown in Fig. 2. The relative contribution of each of these phenomena to the restoration is still an active research topic and is shown to be test dependent [8].

Based on current insights, it is expected that the restoration due to self-healing is slower compared to restoration due to recovery. Next to this, the scientific community assesses that it is likely that the self-healing of cracks affects performance in the

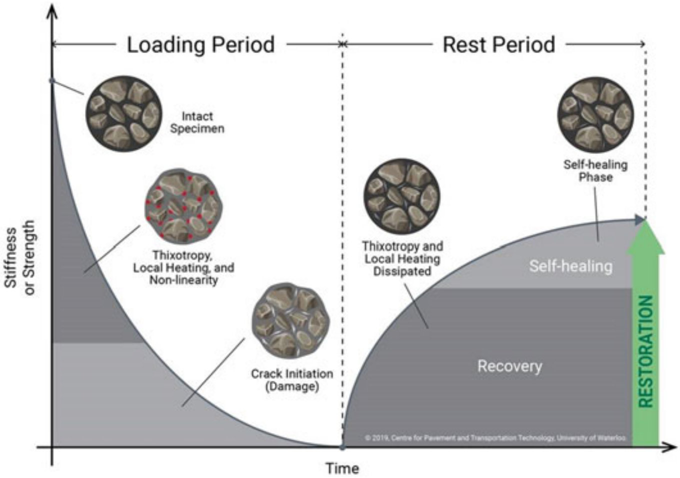

Fig. 2 Schematic overview of contributions to the restoration of performance of different phenomena

field, while the biasing effects in fatigue tests are very much related to the unrealistic loading, which is needed for accelerated laboratory testing.

5 Conclusion: Proposed Definitions

The main conclusions of this paper are the definitions on crack-healing that aim to help the community to have a clear discussion on restoration of mechanical properties and crack-healing. These definitions are formulated for the use in this specific domain, as for instance other domains e.g. aging of bituminous materials will have their own definition of damage. By separating restoration in recovery and self-healing these definitions are also applicable to healing of cracks that are not the result of fatigue loading, but caused by e.g. temperature cracking.

Damage: Loss of original mechanical properties, i.e. the strength or the stiffness, due to the initiation, coalescence and propagation of micro-cracks within the material.

Restoration: The total observed change in mechanical properties after a period of rest.

Recovery: Component of the restoration that can be attributed to changes in response resulting from cyclic loading, more specifically heating and thixotropy.

Self-healing: Component of the restoration that can be attributed to the closure and repair of (micro) cracks.

Intrinsic (Self-)healing: Aspect of the self-healing behaviour that is inherent to the material used.

Extrinsic (Self-)healing: Aspect of the self-healing behaviour that can be attributed to an added phase or action that is specifically used to improve self-healing capabilities, to trigger crack-healing or prevent crack propagation.

Acknowledgments The authors would like to acknowledge the members of the Rilem TC 278-CHA (Crack Healing of Asphalt) and the members of Cluster F (Bituminous Materials and Polymers) for their comments, suggestions and contributions to the very constructive discussions during the different TC and Cluster meetings.

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