Intrinsic Self-Healing of Asphalt Pavements

Greet Leegwater, Ferhat Hammoum, Amir Tabaković, Orazio Baglieri, and Hassan Baaj

Abstract Intrinsic self-healing refers to the inherent ability of asphalt materials to autonomously repair micro-cracks and damage, without the need for external interventions or special additives. Healing contributes to a longer service life of pavement, and it is commonly incorporated into the pavement design procedure by using lab-to-field factors. Such an approach is often too simplistic and based on past experiences with traditional materials. Advanced approaches are needed for a better and more reliable assessment of self-healing properties, especially for unconventional and innovative pavement materials. This requires an adequate understanding of healing phenomenon, including the relevant aspects at physic-chemical level and the driving mechanisms acting at different scales. This chapter explores the fundamental principles and recent developments in the study of intrinsic self-healing of asphalt pavements.

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H. Baaj and O. Baglieri (eds.), *Crack-Healing of Asphalt Pavement Materials*, RILEM State-of-the-Art Reports 45, https://doi.org/10.1007/978-3-031-99443-2_2

1 The Relevance of Self-Healing for Asphalt Pavement Performance

One of the major deterioration modes affecting the service life of asphalt pavement is fatigue cracking due to repetitive loading of traffic. It is well recognized that part of the fatigue damage caused by loading is restored during rest periods between loading repetitions. Therefore, not only is fatigue damage relevant when assessing the service life of asphalt mixtures, but also the ability of the material to reduce this damage during rest periods. This ability is commonly referred to self-healing.

For this reason, research on self-healing is a relevant topic in asphalt pavement engineering. This chapter focuses on intrinsic self-healing, which is defined as the ability of an asphalt material to autonomously repair (micro)-cracks without the need for external interventions or additives [1]. The intrinsic healing properties of asphalt mixes are linked with their viscoelastic nature. Asphalt binder, the primary binding material in these mixes, exhibits unique rheological characteristics that allow the material to flow and adapt at the molecular level in response to damage. This inherent ability to self-repair micro-level fissures and imperfections forms the basis of the healing process.

However, the mechanisms behind the healing of asphalt have not been fully understood. As a result, a standardized healing test that can predict the healing behaviour of an asphalt mixture is not available yet [2, 3]. Therefore, it is not possible to irrefutably demonstrate that new materials are better or worse healers compared to existing ones. This results in two challenges. The first challenge is that the healing ability of newly developed materials, which are, for instance, more environmentally friendly, are unknown. As a result, existing design rules for healing cannot be applied to these new materials, which presents a hurdle for large-scale application. The second challenge is that it is not possible to demonstrate the effectiveness of newly developed materials that are engineered to demonstrate improved self-healing behaviour.

In asphalt mixes, different cracks can manifest at various levels, ranging from macroscopic scale (asphalt mix) to mesoscopic scale (mortar)/microscopic scale (mastic/binder), each presenting its distinct characteristics and implications. By delving into the principles and mechanisms underlying the healing process at a different scale, the aim is to shed light on the transformative potential of healing in restoring the original properties of asphalt mixes. Ultimately, understanding the healing capabilities of these materials holds the premise of longer-lasting, more resilient, and environmentally sustainable asphalt pavements.

2 The Incorporation of Self-Healing in the Design of Pavement Structures

The most important criterion in the design of pavement structures is the resistance to fatigue cracking. The repetitive loading of heavy vehicles causes tension at the bottom of the pavement, which can lead to failure. Therefore, the resistance of a material to fatigue loading is input for the design calculation. The main question asked here is "How do we consider the phenomenon of the recovery (linked to rest periods) in pavements design method?".

During laboratory fatigue tests, the tested specimen is subjected to continuous cyclic stress or strain signals. However, in actual traffic conditions, the time between the axles of heavy vehicles is typically followed by a so-called rest period. Some researchers proposed to modify the protocol of the standardized fatigue test by inserting a rest phase between each loading phase. The modified protocol highlights a gain in the life duration of asphalt specimens tested under alternating loads.

Fatigue-based mechanistic pavement design methods are widely used to determine the optimal thickness of asphalt pavements. This approach relies on calculating the tensile strain at the bottom of the asphalt layer due to the stresses imposed by traffic loads. The resulting tensile strain value serves as a key input in fatigue analysis, determining the pavement's resistance to repetitive loading cycles before failure occurs. To establish a robust fatigue relation for each mixture type, laboratory fatigue tests are conducted, generating experimental data as input for the design process. If the computed number of load repetitions to failure falls short of the required design threshold, an adjustment in the design is needed. Typically, this involves increasing the pavement thickness to reduce the strain level ε and consequently extend the pavement's service life.

It has been shown that self-healing significantly increases the fatigue life of pavement [4–10], and is one of the important explanations for why the fatigue performance observed in the lab is less compared to practice [11].

To take this positive effect into account and prevent the over-dimensioning of pavement structure, healing has been incorporated into most pavement design methods by the introduction of a healing factor [10].

Notably, in the Shell Pavement Design Manual [12], a "shift factor" is introduced to consider the influence of healing properties and the lateral dispersion of traffic (where not all wheels follow the same track). In the French pavement design method [13], a shift factor is introduced to consider the self-healing contribution in the calibration coefficient. This method consists of adjusting the results obtained in the laboratory with fatigue tests and the development of cracks observed in-situ. The asphalt's fatigue life used in practice can be listed as follows:

$$N_{field} = N_{lab} * SF \tag{1}$$

where,

SF: shift factor due to some effects (testing method, healing, residual stresses, resilient dilation, etc.).

A summary of healing and general shift factors proposed in literature is provided by Van den Bergh [10] and reproduced in Table 1. The table shows that the healing factors in design guidelines range from 2 to 20.

A review of the different pavement design methods over the world reveals two different methods to take into account the self-healing effects:

(a) Shift factor obtained from the experimental testing in the lab: [17] expressed that the shift factor is dominated by healing and is a function of the number of rest periods, the time between load cycles, and the rest period duration. The strong variation in healing factors per country or method can be explained by a combination of reasons. Firstly, the healing factor is merely an experimentally determined fudge factor that describes the difference in test results with and without healing periods. Secondly, the determined healing differs per test method used [5]. Thirdly, every design procedure prescribes a different method to assess fatigue and healing.
(b) Shift factor obtained from the full-scale validation: In the French pavement design [13], the correction factors k_c which is associated with the healing contribution varies between 1 and 1.3, and is a fitting factor based on full-scale validation. This correction factor k_c is converted to equivalent shift factor SF by the relation $SF = (k_c)^5$ and varies between 1.6 and 3.7. The full-scale validation introduces real conditions with rest periods between axle loads.

The healing behavior of airport pavements, as discussed in the literature, differs from that of conventional road pavements, particularly in terms of the required rest period for recovery: (i) the spacing of twins and aircraft landing gear differs from heavy trucks. (ii) Landing and take-off speeds are no longer of the order of those

Table 1 Healing and general shift factors according to different design procedures [10]

References	Type of test	Load mode[a]	Individual factors			General shift
			Healing	Crack propagation	Traffic wander	
Asphalt Institute						13
[12]	Variable	D	2–10	1	2.5	10–20
[13]	2-point bending	D				1.6–3.7
[14]						10–13
[15]	2-point bending	F	7.1	3	1–2.5	7.1
[16]	4-point bending	D	4			

[a]F = Force controlled; D = Displacement controlled

encountered on the road. (iii) The time intervals between aircraft movements are longer than those between two heavy vehicles. Based on some calculation, Marchand [18] concluded that the equivalent shift factor for airfield pavement varies between 4 and 5.

3 Basic Observations on the Healing Phenomenon

In the first period of healing research from 1960 to 1980, healing was often studied as a part of fatigue research [19–23]. These researchers showed that a short rest period after each loading cycle resulted in significantly longer fatigue lives. During this period, it has been hypothesized by some of the researchers that the mechanism behind healing is not actual material healing but simply viscoelastic recovery.

The first overview of healing research was presented in 1982 [5]. The work up until this point is summarized, and trends are reported and verified on asphalt mixtures. The observed trends are the following:

- All studies showed a significant amount of healing when rest periods were introduced. This is well illustrated in a figure [24], reproduced here as Fig. 1. On the horizontal axis, Tr/Tw is the ratio between loading and rest periods. On the vertical axis, Nr/Nw is the ratio of the fatigue life with rest periods to fatigue life without rest periods. As a result of intermitted healing tests, healing factors were observed from 1.5 up to 20.

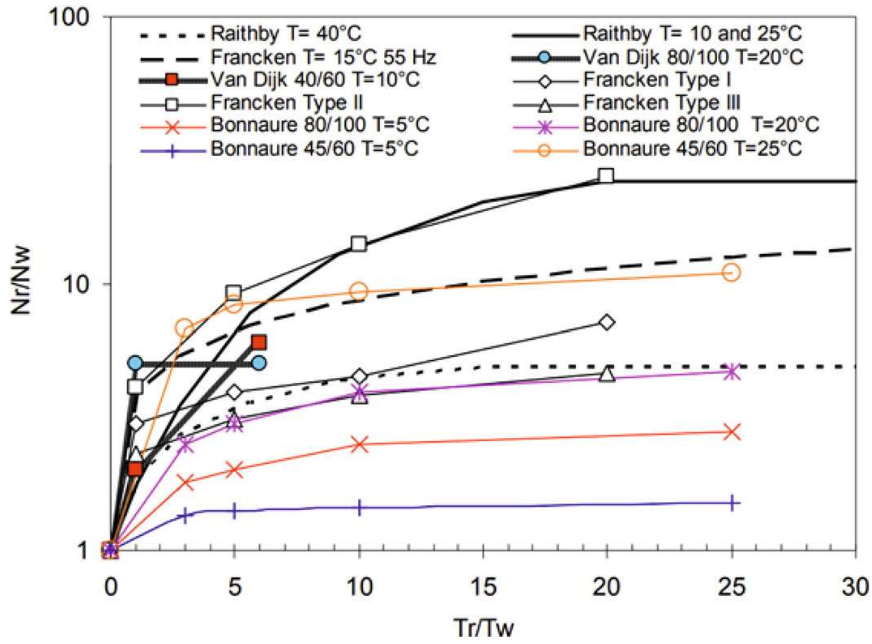


Fig. 1 Overview of reported healing from 1960's to 1980's, with the ratio of number of loads to failure with and without rest periods on the vertical axis and on the horizontal axis the rest to load ratio [24]

- Healing increases with increasing resting time. Initially, the increase in healing, with increasing healing time, is steep. However, there seems to be an upper limit to the effect of rest periods on the number of loads to failure. This can also be observed from the results presented in Fig. 1. The figure shows that even with very long rest periods (a rest-to-load ratio of 20 or more), specimens under fatigue loading will eventually fail.
- For all but one research, the amount of healing increased as the temperature increased (tests are performed between − 5 to 40 °C).
- Asphalt mixtures with a lower stiffness, usually manufactured using a softer binder, show a higher healing capacity.
- Healing tests performed under stress-controlled conditions result in more healing compared to healing tests under strain-controlled conditions when similar damage levels are considered.
- No general quantitative relations can be formulated to relate the amount of healing to the loading conditions and materials used.

4 Physicochemical Aspects of Self-Healing

4.1 Chemical Drivers for Intrinsic Self-Healing

Different research groups pose different theories behind the healing mechanisms of asphalt. Kim et al. [25] start by observing that more work is needed to open a crack after a rest period. They indicated that this is partly due to viscoelastic recovery and partly due to chemical healing. In the article, chemical healing is investigated further. The article refers to mechanisms behind the healing of polymers. It takes this as a starting point for reasoning how asphalt materials might heal [26]. To validate this hypothesis, the healing indexes of three different asphalt binders were analyzed and correlated to two parameters that indicate chain length (methylene (CH_2) to methyl (CH_3) ratio) and extent of branching in asphalt binder (MMHC ratio). The results are presented in Fig. 2, from which it can be argued that that longer chain lengths and less branching increase the healing potential.

Another perspective on the driving mechanism for healing relates to surface energy. The concept of surface energy is used for problems of cohesion and interfacial adhesion. In 1989, Schapery introduced surface energy density to explain cracking and self-healing processes. Later, Lytton et al. [27] offered an interpretation of asphalt binder cracking and self-healing based on Schapery's theory and used the concept of surface energy density. The surface energy density essentially depends on the contents of different components of asphalt binder (aromatic, amphoteric and paraffinic).

The surface energy of asphalt binder is obtained from wetting and dewetting angle measurements using the Wilhemly plate. The wetting surface energy is directly related to the self-healing potential.

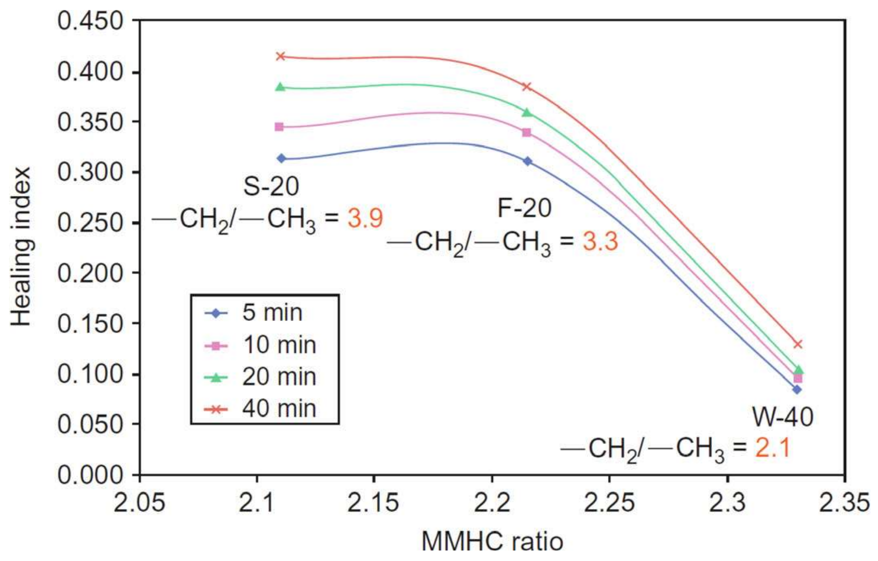


Fig. 2 Correlation of MMHC ratio and healing index [7]

Kim et al. [28] and Little et al. [29] conducted mechanical tests to evaluate the self-healing of five asphalt binders at the specimen scale (combined effect between wetting and inter-diffusion). After a cyclic loading phase, a rest phase is introduced, and several rest times are tested. A pseudo-strain energy obtained from the area under the stress–strain curve is used to estimate the damage in the specimen at each cycle. The self-healing parameter (healing index) H is calculated after each rest phase as follows:

$$H = \frac{\emptyset_A^R - \emptyset_B^R}{\emptyset_A^R} \tag{2}$$

with $\emptyset_A^R$ and $\emptyset_B^R$ respectively representing the strain pseudo-energy after and before a rest period measured during the cyclic loading test. The results are presented in Fig. 3.

According to the work of [29], the short-term self-healing kinetics in asphalt binder (the first 10 s of the rest period) is inversely proportional to the non-polar component of surface tension or Lifshitz-van der Waals parameter.

Similarly, the self-healing kinetics (after the first 10 s) is directly proportional to the polar component of the surface tension of the asphalt binder or Acid–Base component. These two components of surface energy for wetting and dewetting are identified by [30]: Lifshitz-Van der Waals and Lewis Acid–Base. In the literature, these two components explain cohesion and adhesion in asphalt mixtures. In summary, an asphalt binder that has a high self-healing potential has maximum polar energy and minimum non-polar energy [11].

Building on this work Bhasin et al. [31], have further in investigated healing and surface energy using the two-piece healing method [31]. In this test, two pieces of asphalt binder are brought together in a Dynamic Shear Rheometer (DSR), and the measured stiffness in shear of the combined two pieces is compared to the response

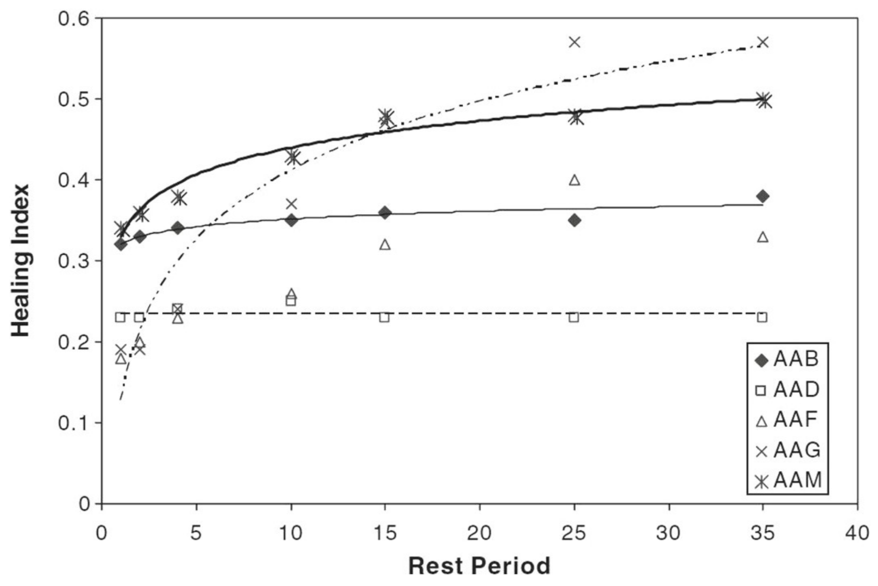


Fig. 3 Intrinsic self-healing of asphalt mixes evaluated with different binders [29]

of a single piece of asphalt binder. At the start of the test, two pieces of asphalt binder are pushed together. It is assumed that the total area is instantly in contact. Measured healing is assumed to consist of an instant part that can be related to surface energies and a time-dependent part that is linked to diffusion. The ARC quarterly report of April to June 2008 [32] presented a graph showing the measured healing of five different binders from the SHRP program, as shown in Fig. 4.

They propose the following formula (Eq. 3) to describe intrinsic healing:

$$R_h(t) = R_0 + p\left(1 - e^{-qt^r}\right) \quad (3)$$

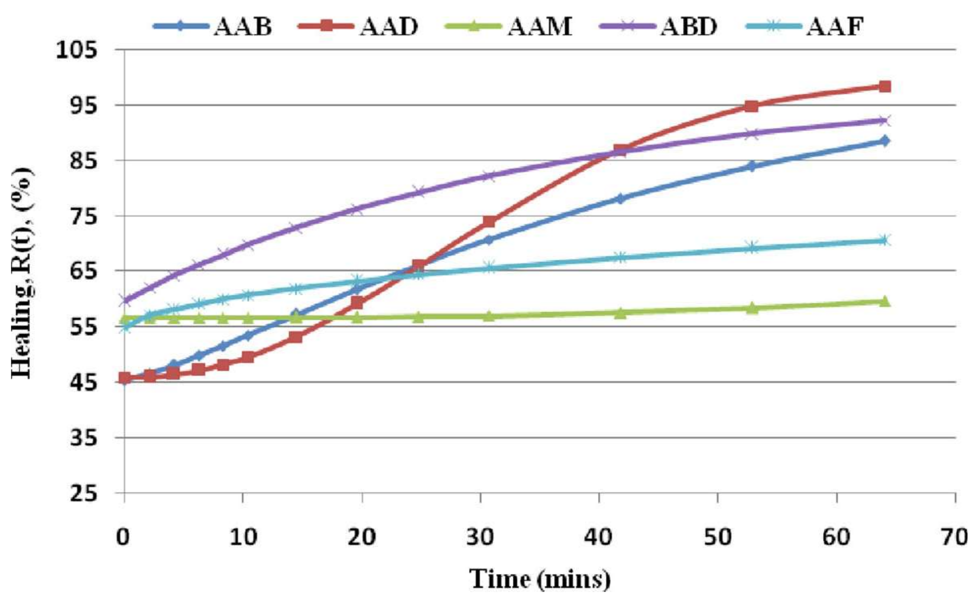


Fig. 4 Healing measured with two-piece healing methods [32]

where R_0 is the instant healing based on the material's surface energy, the other part is the time-dependent part. The R_0 levels correlate very well with the surface energies determined by the Wilhelmy Plate Method [7].

Qiu [33] also performed tests using this two-piece healing method. He has demonstrated that the pressure level during the tests influences the shear resistance measured. This influence of pressure could imply that part of the shear resistance that is measured is caused by friction. When the two pieces of asphalt binder are pressed together, the surface roughness of the asphalt binder samples will influence the amount of shear resistance that is measured. Even though asphalt binder looks smooth, Atomic Force Microscopy (AFM) images show that on an extreme scale, asphalt binder indeed has surface texture [34].

The link between chemical composition and the healing potential of binders has also been highlighted by several other authors [35, 36]. They related stiffness recovery of binders in DSR fatigue tests to, amongst others, SARA analysis. These tests demonstrate that the healing potential of binders increases when more small molecules are present in the asphalt binder. They show that as the Saturates/Aromatics ratio increases, the observed healing also increases.

More recently, it has been demonstrated by AFM that micro-cracks form and disappear in the stress concentration zone [37, 38]. Also, by using AFM, it has been found that additives can affect the rate of crack closure in asphalt binders [39]. Furthermore, Song et al. [40] showed self-healing in asphalt mastics through a reduction in the percentage of voids after rest periods using X-ray computer tomography.

4.2 Influence of Thermal Expansion Self-Healing

For the case where physical cracks are present, the meso to macro scale, Grossegger [41] shows that thermal expansion of asphalt materials, e.g. asphalt binder and aggregates, is one of the main factors influencing asphalt self-healing. According to Grossegger, the self-healing process follows these steps, which have been summarized in Fig. 4:

1. When a crack opens in asphalt, the surface of the cracks is smoothened due to asphalt binder's surface tension.
2. Asphalt may heat up due to solar irradiation; if that occurs, asphalt binder and aggregates may expand, which brings the cracks together and creates contact points.
3. Due to surface tension, gravity, and further thermal expansion, mastic may flow into the cracks and fill them from these contact points.
4. The material that fills the crack is a mixture of asphalt binder and fine aggregates; the fine content and composition may change the expansion coefficient and viscosity, affecting how cracks are filled.

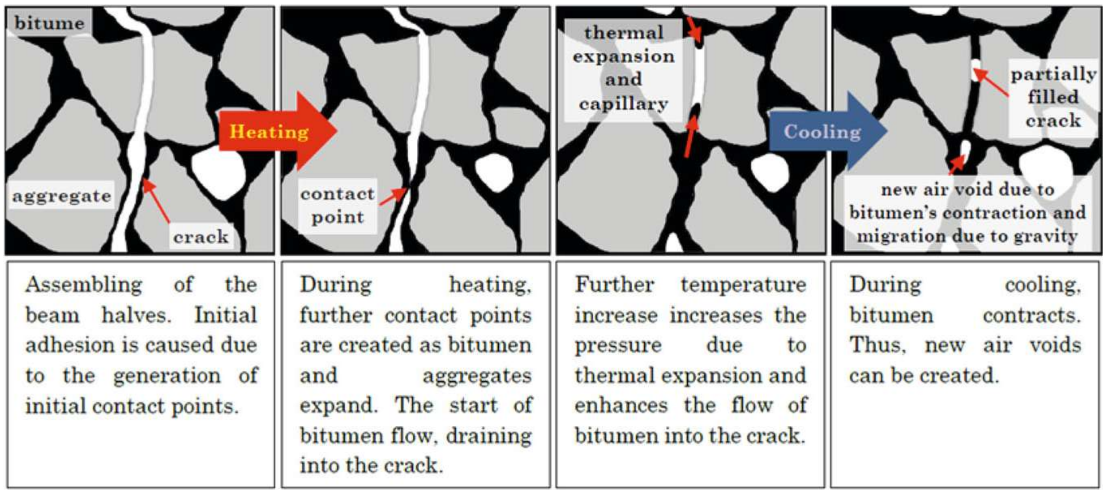


Fig. 5 Scheme of the natural self-healing process [43]

5. During heating, cracks will continue filling until a thermal equilibrium is reached. When the thermal equilibrium is reached, asphalt binder will drain due to gravity, which may open additional voids in the areas close to the surface. A similar effect was noted by [42] that used induction heating to accelerate the mending of cracks, once the asphalt reached the thermal equilibrium, new pores opened in the asphalt, and its strength was reduced; regardless of the high temperature of the asphalt.

Furthermore, Grossegger et al. [43] reported that the presence of water in the cracks hindered the self-healing process due to water having a similar density to that of asphalt binder, preventing the drain of asphalt binder into the cracks, as presented in Fig. 5.

Based on this, it can be deduced that aggregates and binders with higher thermal expansion coefficients will accelerate asphalt self-healing. Additionally, using asphalt binder with lower viscosity can accelerate the healing process, as it allows the binder to flow more easily into cracks, facilitating repair. The amount of asphalt binder available to flow and drain into the cracks will influence the asphalts self-healing, which may be why porous asphalts shows higher self-healing capacity than denser materials [44]. The self-healing of cracks in asphalt derives from the complex interplay between asphalt binder viscosity, the thermal properties of aggregates and asphalt binder, and the aggregate gradation. Based on these insights, one of the most promising measurements of the natural self-healing capacities of asphalt may derive from simply measuring its thermal expansion coefficient.

5 Healing Mechanisms at Different Scales

An asphalt mixture is a heterogeneous composite material, composed of gravel, sand, filler and asphalt binder. For the design of asphalt pavements, knowledge is required of the self-healing behaviour of full asphalt mixtures. However, studying asphalt mixtures is quite complex, as the material is heterogenic with numerous interfaces between different constituents, which also exhibit a broad range of sizes.

Mineral aggregates (gravel, sand, and filler) will not restore any strength after damage under the conditions present in pavements. Therefore, the restoration in asphalt mixtures can be assumed to originate from the asphalt binder. As a result, it is expected that the restoration behaviour of asphalt binder has predictive power for the restoration behaviour of a mixture.

It should be kept in mind that mixture composition and chemical interactions between the binder and the aggregates can influence the restoration of an asphalt mixture. For instance, Little et al. [45] showed that certain binders show more healing when combined with specific aggregate types. When damage occurs on the interface between mineral aggregates and the binder, the aggregates might also affect the interaction between the newly created surfaces. Hence, to fully assess healing behaviour, both the behaviour of the binder and the mixture is relevant. A possible approach can also be to study healing in an asphalt mortar. In this case, all the chemical interactions are present in a highly reproducible environment due to a lack of gravel reducing the anisotropy in the material.

As a result of the driving influence of the binder on healing, combined with the expected interactions with aggregate surfaces, healing research has been conducted on all scales; asphalt binder, a mix of asphalt binder, a mix of asphalt binder and filler (mortar), filler and sand (mastic) and the whole asphalt mix. Through this research executed at different scales it has also demonstrated that correlations between the different scales are not easily established [24].

Several researchers have adopted a healing model from polymer science [3, 6, 7, 31]. The polymer healing model interprets the self-healing of a crack as a series of five processes that occur subsequently: (i) surface rearrangement, (ii) surface approach, (iii) wetting, (iv) diffusion and (v) randomization [46]. These processes are visualized in Fig. 6. As a result of these processes, two mechanisms that determine the interaction between two crack interfaces have been identified. First, surfaces must be in contact with each other to be able to transfer load, this is named wetting. Second, the force that the contact area can transmit is dependent on time. As a result of adhesion, there will be an instant ability of the contact area to transfer a load. This initial strength will increase over time as molecules diffuse over the crack interface and increase interaction between the two crack phases. Therefore, it is concluded that the macroscopically observed healing is the convolution of the amount of area in contact and the load-bearing capacity of this contact.

To translate the conceptual model of healing into equations that could be used to assess healing at the macroscale, Wool and O'Connor introduced a parameter. This parameter is defined as the ratio of the material's mechanical properties after

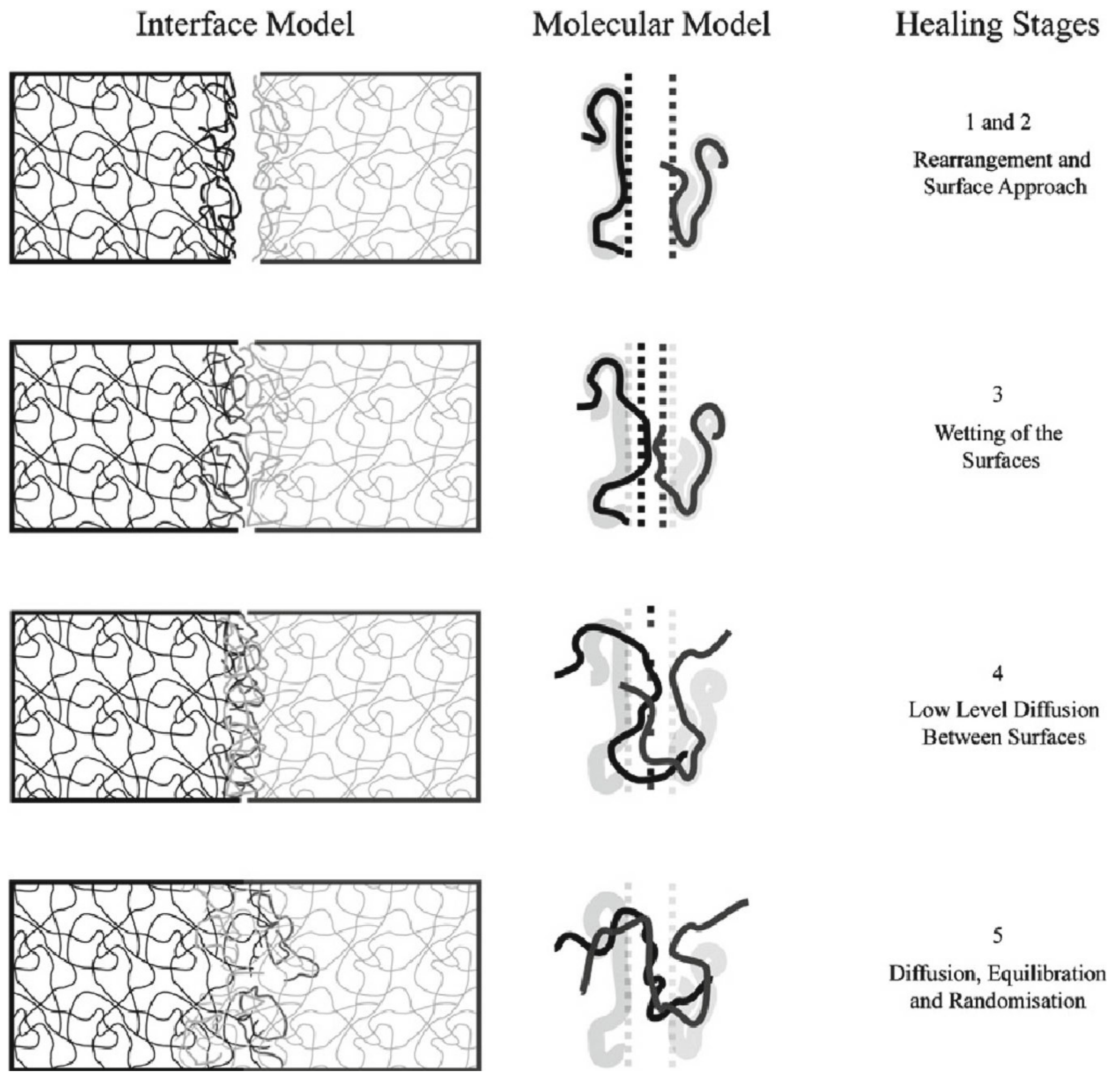


Fig. 6 Five steps in the healing process [46, 47]

a rest period to its mechanical properties in the original state. The value of R, by definition, varies between 0 and 1. These mechanical properties include fracture stress, failure strain, tensile modulus, and fracture energy. The recovery parameter, R, is represented as a convolution integral of the intrinsic healing function $R_h(t)$ and wetting distribution function $\varphi(t, X)$ given by

$$R = \int_{\tau=-\alpha}^{\tau=t} R_h(t-\tau)\frac{d\varphi(\tau, X)}{d\tau}d\tau \quad (4)$$

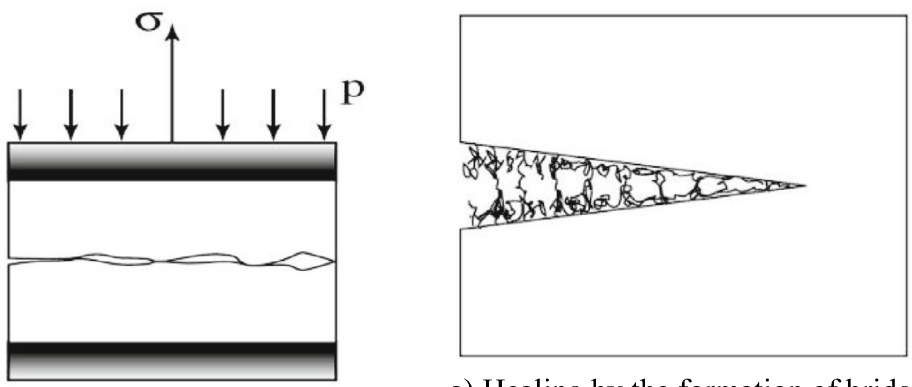
Here, τ is the time variable, and t is the present time. This intrinsic healing function defines the rate at which the self-healing occurs among two wetted surfaces and the portion of the original strength recovered. Hence, this intrinsic healing function is additively decomposed to include the intrinsic self-healing due to short-term wetting and the intrinsic healing due to long-term diffusion and is represented using

$$R_h(t) = R_0 + Kt^{0.25}\xi(t) \tag{6}$$

where, R_0 is the instantaneous strength gain, K is a constant, and t is time. $\xi(t)$ represents the effect of surface rearrangement of molecules. This crack healing model through inter-diffusion is further studied by Kim et al. [48], who conducted studies based on crack healing theory at the polymer–polymer interface. While this model has been validated for polymers, the extent of validation for asphalt binder is limited at this moment [3, 7]. It is also likely that the model should be adjusted to serve as a model for asphalt binder, as the types of molecules present in asphalt binder differ from polymers.

6 Closing of Cracks

Stiffness and strength loss in asphalt materials is a consequence of the formation of micro cracks. To heal this real damage, the two sides of the micro crack must regain contact. This process requires the displacement of material into the crack to ensure proper wetting. Following this, the contact area can homogenize to reestablish molecular bonds, restoring the material's strength and toughness (see Fig. 7). Asphalt binder, being a very viscous liquid, can flow inside a crack and reinstall contact above its glass transition temperature (T_g). There can be variety of forces triggering this flow, such as an external applied compressive force, gravity, a compressive force as a result of temperature expansion, surface energy, etc. As the flow properties of asphalt binder are very temperature-dependent, this will happen faster at higher temperatures. In intrinsic healing, this flow is the natural flow of the binder, while in the case of extrinsic healing, attributes are brought into the material or the system to speed up this process.



a) Bringing the lips of the crack in contact

a) Healing by the formation of bridges between molecular chains

Fig. 7 Principle of intrinsic self-healing of a crack

The crack can close fully or partially, depending on the time given and the effectiveness of the self-healing process. The extent of the closing of the crack has a strong influence on the observed material response. Figure 8 presents an example of a crack, which appears to have disappeared after a period without loading.

Figure 9 shows microscopic images of the self-healing of a fully cracked dog-bone sample made of asphalt mastic while it is kept under controlled conditions. It demonstrates that after a healing period of 18 h, the original crack is hardly detectable using this technique. In his work [24], also proves that the strength of these samples restores over time.

In relation to the crack closure at the micro and macro levels, it has been demonstrated that the initial properties of asphalt concrete cannot be fully recovered only using heating [50]. The authors concluded that healing through heating cannot

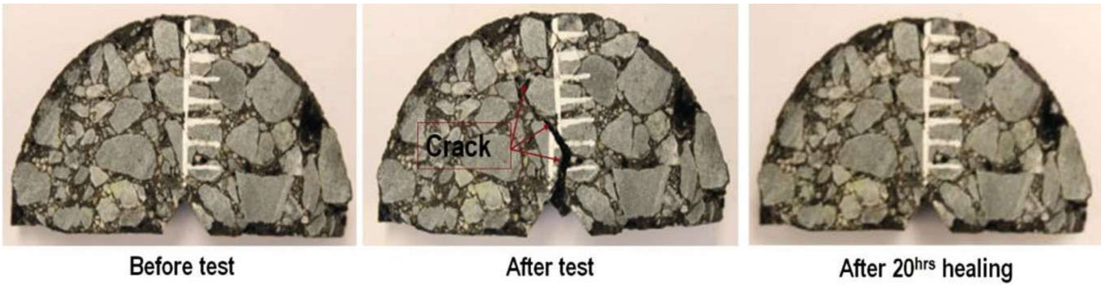


Fig. 8 SCB test specimen crack closure/healing [49]

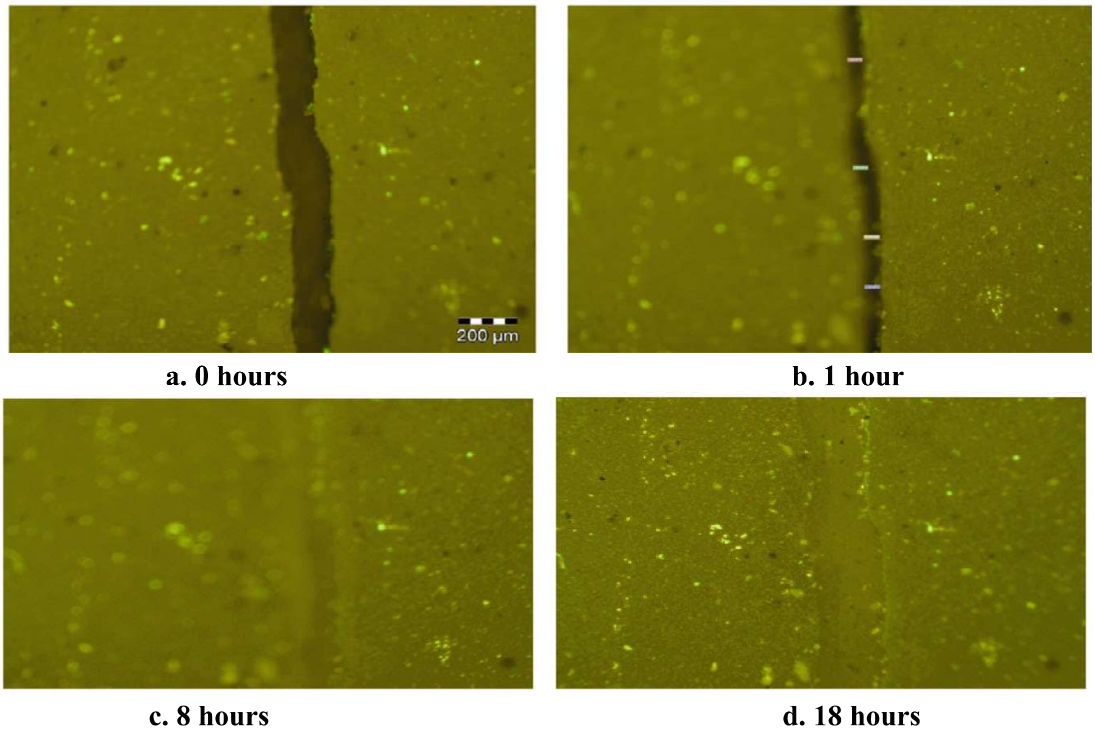


Fig. 9 Fluorescence microscopic pictures of an asphalt mastic specimen at a healing temperature of 25 °C with different healing times [24]

recover all types of cracks, as in case of significant plastic deformations, the binder flow is not extensive enough to re-establish the contact between aggregates. Consequently, although the cracks were closed (crack damage was repaired) due to the binder flow, the stresses generated in the area close to them were higher than those in the rest of the material.

There are several tests developed to assess the healing ability of cracks in asphalt binders. [51, 52] propose applying a load on an asphalt binder sample in a plane/plane shear configuration using a conventional Dynamic Shear Rheometer (DSR) test. The test would be conducted at a specified frequency and under low levels of deformation until the stiffness of the specimen reduces to half of its initial, virtually undamaged value obtained at the start of the test. Then, they introduce a rest phase (T_R) of variable duration before loading the sample again (Fig. 10).

Figure 11 shows that the insertion of rest phases, as well as the increase in their duration compared to the duration of the stress, makes it possible to increase the life duration of the specimen. [52] deduce a favorable effect of the duration of the rest phase on the self-healing of the asphalt binder.

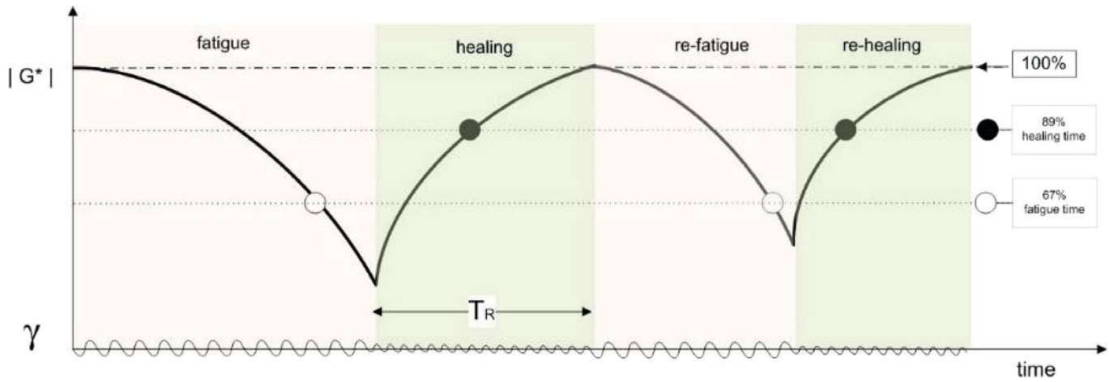


Fig. 10 Insertion of rest period between loading phases [51]

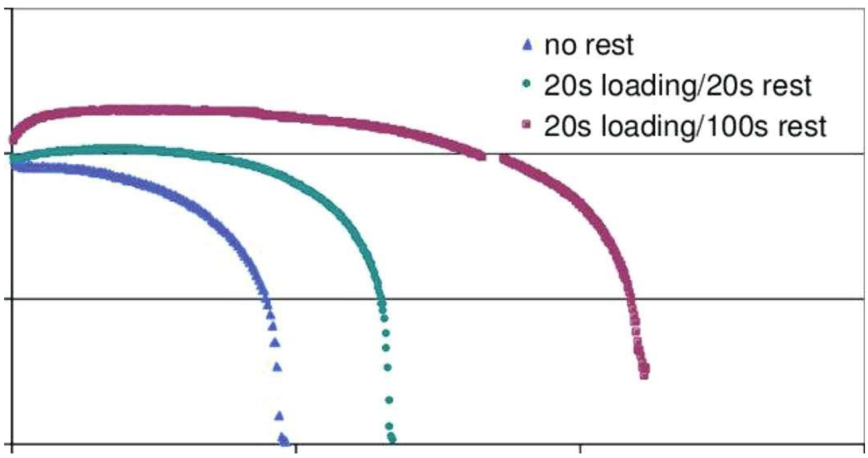


Fig. 11 Effect of rest periods on fatigue tests (DSR) of Asphalt Binder (unaged) at 210 kPa stress, 25 Hz and 15 °C [52]

In their work, Bhasin et al. [53] state that the growth of a micro-crack is linked to the creation of new fracture surfaces originated by accumulated damage in the vicinity of the crack tip. This damage is related to the deformation and rearrangement of molecules in this failure zone. The authors hypothesize that the self-healing mechanism could be seen as the reversal of crack initiation and propagation. To explain this mechanism at a micro-scale, a theoretical approach was proposed where fracture mechanics were used to model the micromechanics of crack growth and self-healing in asphalt composites by quantifying time-dependent healing. Two distinct phases across a crack interface are differentiated: wetting and intrinsic healing (or rate of strength gain processes). According to this model, wetting is related to the material's mechanical properties and surface-free energy. In contrast, intrinsic healing is considered a time-dependent phenomenon associated with the self-diffusion of asphalt molecules across the crack interface. It was experimentally proved that the rate of crack closing or wetting rate depends on the crack geometry, mechanical properties of the binder or mixture, and the surface free energy of the binder.

At the University Gustave Eiffel, the repeated local fracture test on asphalt binder is the device used to study cracking and self-healing behavior [54]. This device consists of two steel sample holders whose central protuberances, when placed face to face, represent the contact zone between two aggregates, see Fig. 12. Each protuberance consists of a truncated cone terminated by a spherical cap. This geometry ensures, in a specimen without crack, a concentration of 90% of the stresses in a cylinder with a radius of 3 mm and an axis coincident with that of the protuberances (spherical part of the test device). Consequently, this geometry facilitates the initiation of a crack in the center of the specimen.

After each tensile cycle obtained from an imposed displacement, the specimen returns to its initial configuration. To study self-healing, the rest time is fixed after a loading phase, and an ultrasonic technique is used to monitor the reattachment phase of the lips of the crack.

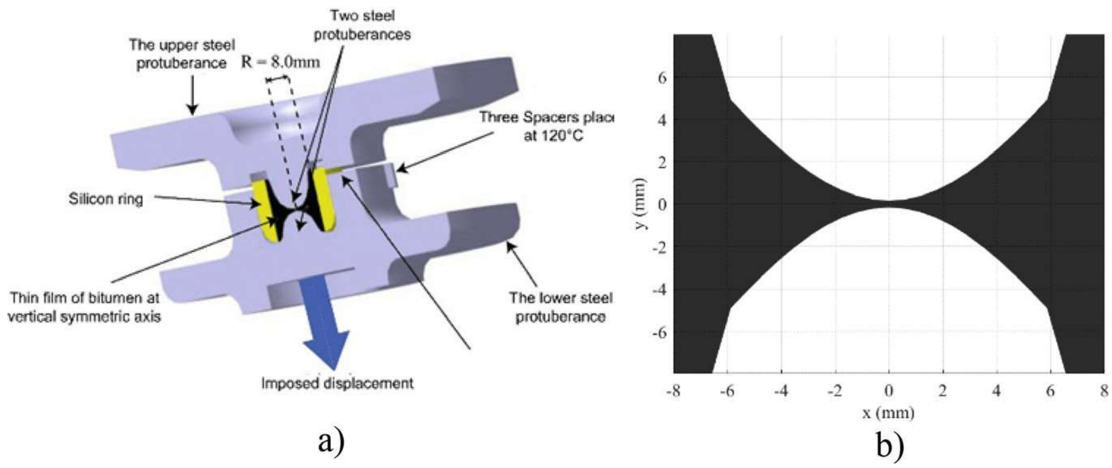


Fig. 12 The local fracture test: **a** test device and **b** sample geometry [55]

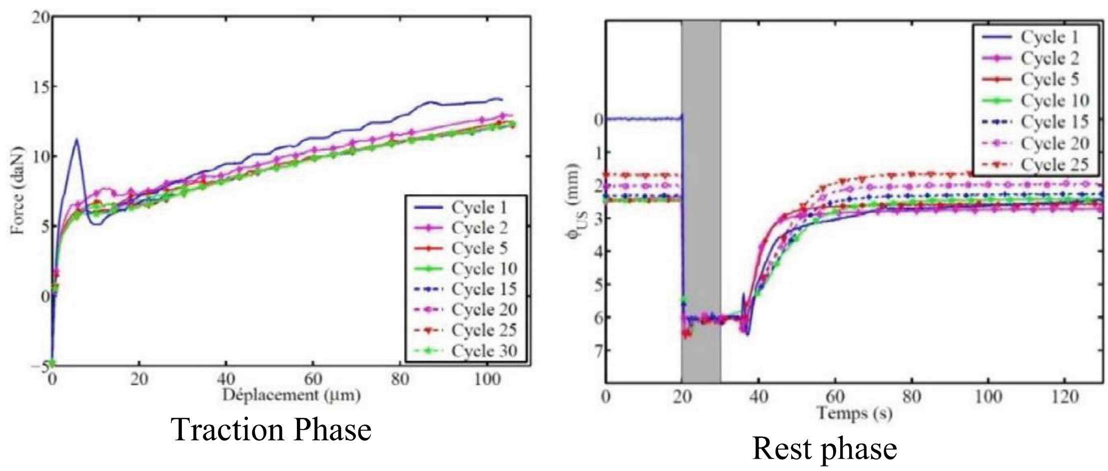


Fig. 13 Self-healing of modified asphalt binder by polymer at 0 °C—local fracture test [56]

This device made it possible to study the kinetics of reattachment at the edge of a crack during the rest phase. Experimental tests show that kinetics depend on experimental conditions and the nature of the used asphalt binder [56], see Fig. 13.

Care must be taken when interpreting results from tests conducted at low strain levels and/or long rest periods, as changes in material properties may be attributed to either nonlinear behavior or physical hardening of the material.

7 Biasing Effects in Fatigue and Healing Testing

Healing tests can be executed using many approaches. When self-healing is measured after a period of fatigue loading, the stiffness recovery after a rest period is often close to 100%. This can be observed in the example shown in Figure. Next to this case, there are many other reports of this phenomenon [57–60]. However, despite this strong restoration of stiffness after a healing period, the number of loading cycles to failure is often significantly reduced compared to the original performance. A plausible explanation for this phenomenon is that asphalt materials lose stiffness in repetitive loading before any damage in the material occurs. This specific loss of stiffness is due to phenomena other than damage, and therefore is fully reversible.

In order to avoid gross errors in estimating the fatigue and healing performance of materials, it is thus very important to isolate transient and reversible non-fatigue phenomena that occur during repeated loading [61–63]. The concept of “biasing effects” have been proposed to define this type of phenomenon. The biasing effects generally treated in the literature are non-linearity, heating and thixotropy.

Non-linearity refers to the phenomenon where the response of asphalt material depends on the level of strain applied. If the strain is different during the test, the detected stiffness also varies. Heating of the test specimen occurs because of energy dissipation during cycling loading. As the response of asphalt materials is very temperature-dependent, a small increase in temperature will result in a loss of stiffness.

The phenomena behind thixotropy requires a bit more explanation. According to the "International Union of Pure and Applied Chemistry" (IUPAC), the application of finite shear stress to a system after a long period of rest can cause a decrease in its viscosity or consistency. If this decrease persists when the stress is interrupted, the behaviour is called "work softening". At the same time, if the original viscosity or consistency is recovered, the behaviour is called "thixotropy" (IUPAC website). The accepted explanation of thixotropy is linked to the hypothesis of a microstructure that slowly forms in the material at its molecular level due to the weak forces of attraction between the particles. The concept of intermolecular forces as a driver for asphalt binder behaviour has already been suggested by chemists who studied asphalt binders [64, 65]. Considering the nature of these intermolecular and the large molecules composing the asphalt binder, it seems very plausible that ordering over time is likely. In this sense, it is also very possible that the application of a flow (shear) causes rupture and reorganization of this network between the particles [66]. Experimental evidence of thixotropic behaviour has been found for asphalt materials [67–70]. It has been shown that thixotropy can have a major influence on the variation of the mechanical properties of asphalt mastics during fatigue tests compared to heating [71]. The same observation was made for asphalt mixes [72, 73].

To study these biasing effects, ENTPE has developed a tension–compression test protocol called ALFABET, "Advanced Laboratory Fatigue and Biasing Effects Test") [74–77]. This test approach makes it possible to isolate different phenomena that contribute to stiffness loss and recovery during laboratory fatigue tests. Figure 14 shows the results of stiffness development during five consecutive load and rest cycles. Each load cycle entails 100,000 load cycles, and low-strain measurements are executed during the rest period to assess the recovery. Using this approach, the stiffness loss is assigned to various biasing phenomena and a recoverable component. The figure shows that the unrecoverable part is relatively minor compared to the biasing effects. This observation is confirmed for all five damage and restoration periods in Fig. 15.

The results of the last fatigue stage of the ALFABET test were analyzed to determine the fatigue life of the asphalt mixes. Four criteria were used: DER (Dissipated Energy Ratio), maximum of the phase angle and local criteria, related to the relative deviations of the deformation amplitude (± 25%) and the phase angle (± 5°) between the three extensometers. The fatigue life Nf was determined as the mean of the values of the four lifespans obtained with each criterion. The variations of |E*| and φ throughout the test were analyzed in terms of damage. The DIIIC approach, developed by a research team from ENTPE [78–81] was applied to correct the results of the ALFABET trial for biasing effects. The results obtained were compared with the estimates of the biasing effects made during the five fatigue loops and the corresponding rest periods, with both analyses give consistent results. The corrected values do not show a significant increase in damage during the first four fatigue stages, while they indicate a rapid deterioration of Liner Viscoelastic (LVE) properties during the

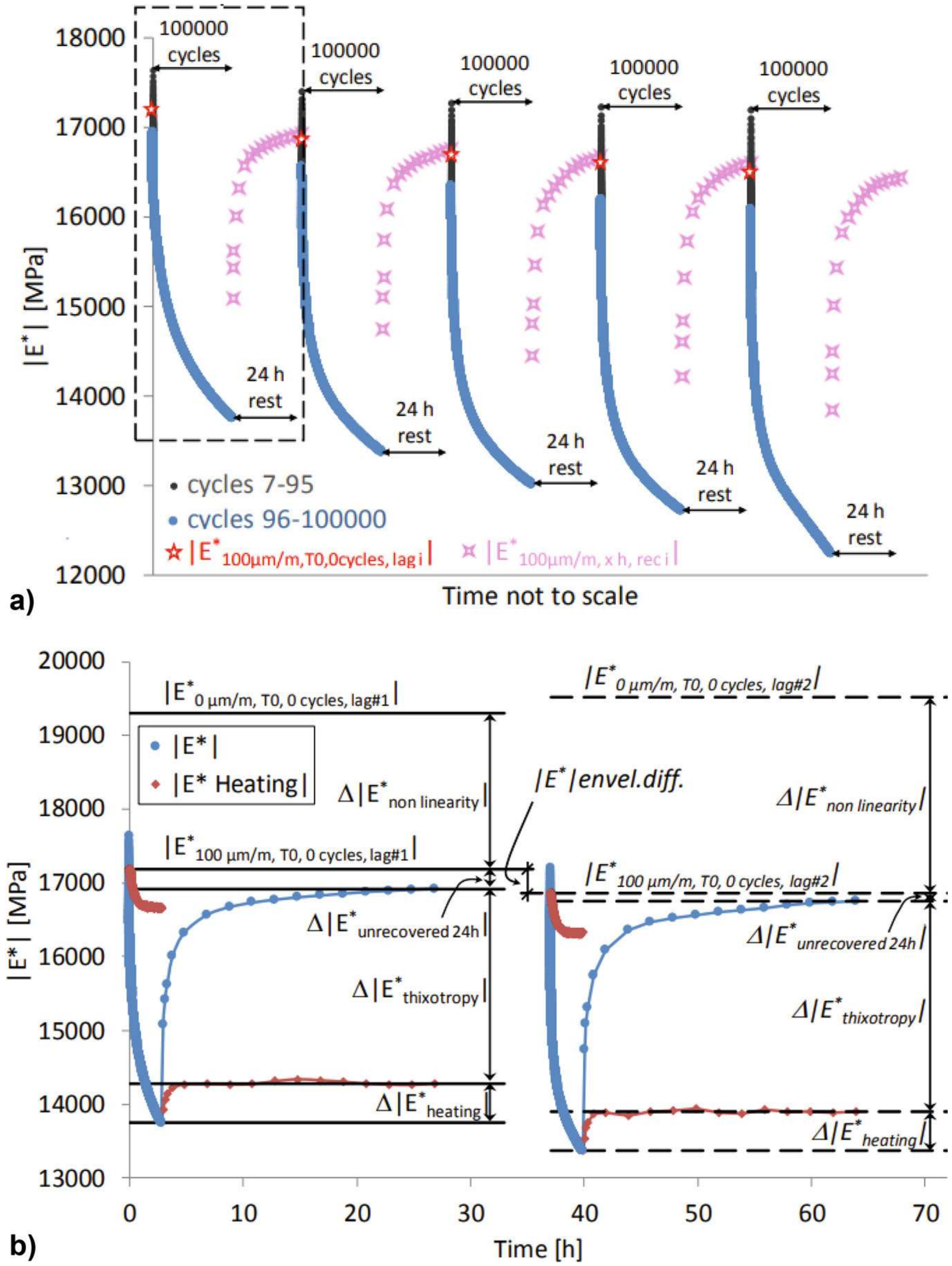


Fig. 14 Example of results obtained with the ALFABET test: (**a**, top) evolution of |E*| during loading and rest periods of fatigue test; (**b**, bottom) quantification of biasing effects and unrecovered variations during cyclic loading and rest periods #1 and #2

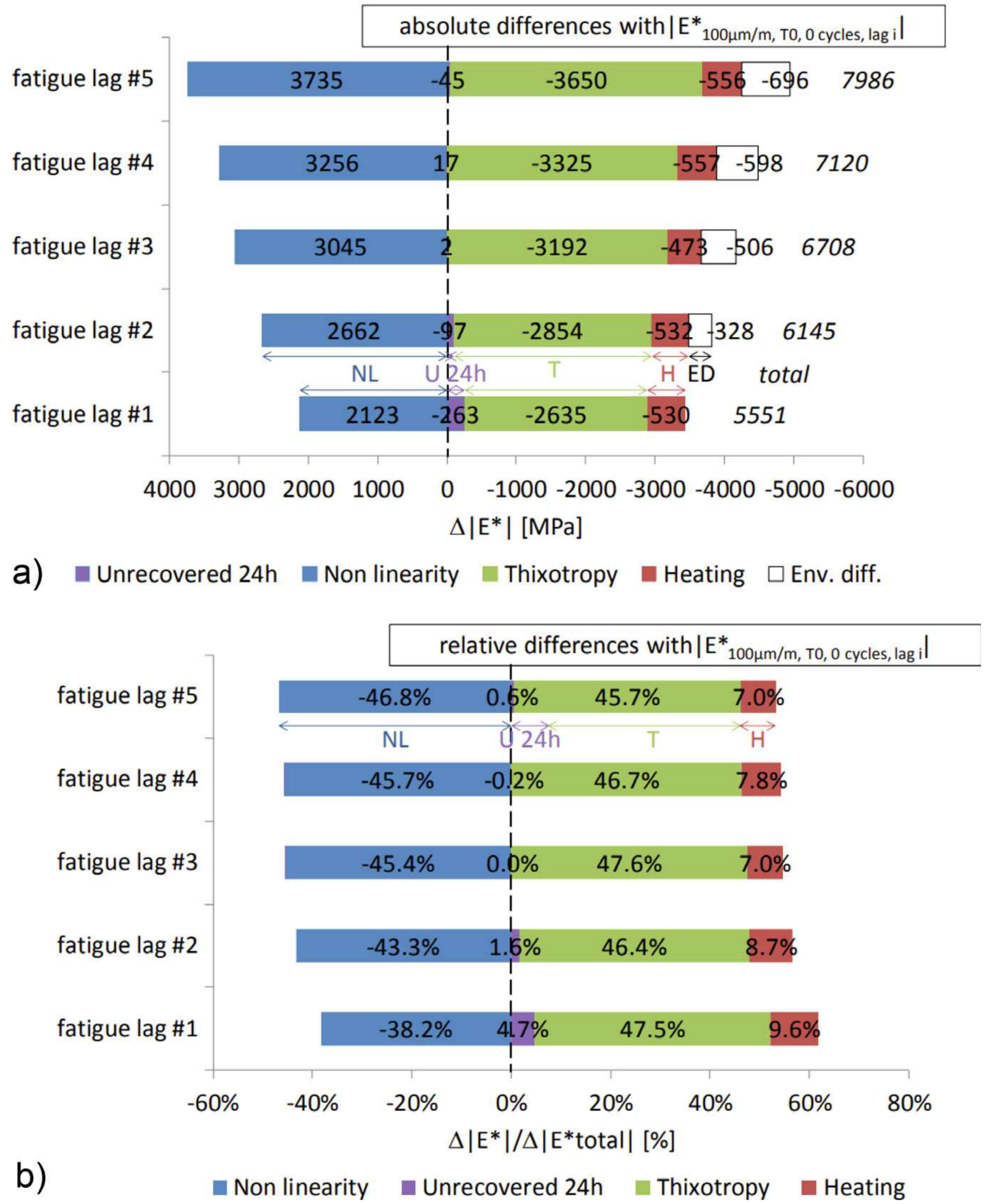


Fig. 15 Example of quantification of bias effects and unrecovered variations of |E*| obtained with the ALFABET test: (**a**, top) variations of |E*| in absolute terms; (**b**, bottom) relative variations to total variation (per period of cyclic loading)

fifth and especially the final fatigue stage. This demonstrates that the loss in stiffness is not relevant for true fatigue failure.

8 Terms and Definitions on Self-Healing and Restoration

To clarify the biasing effects (such as thixotropy, local heating, and non-linearity) as well as actual damage and healing, specific terms and definitions have been developed in relation to crack-healing [1]. As these definitions will aid in having a specific discussion about the mechanisms, the definitions and a visual representation are reproduced here. The total restoration of material properties after healing involves the recovery of performance due to the reversal of biasing effects and the self-healing of (micro) cracks within the material (see Fig. 16). The related definitions are presented below the figure.

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.

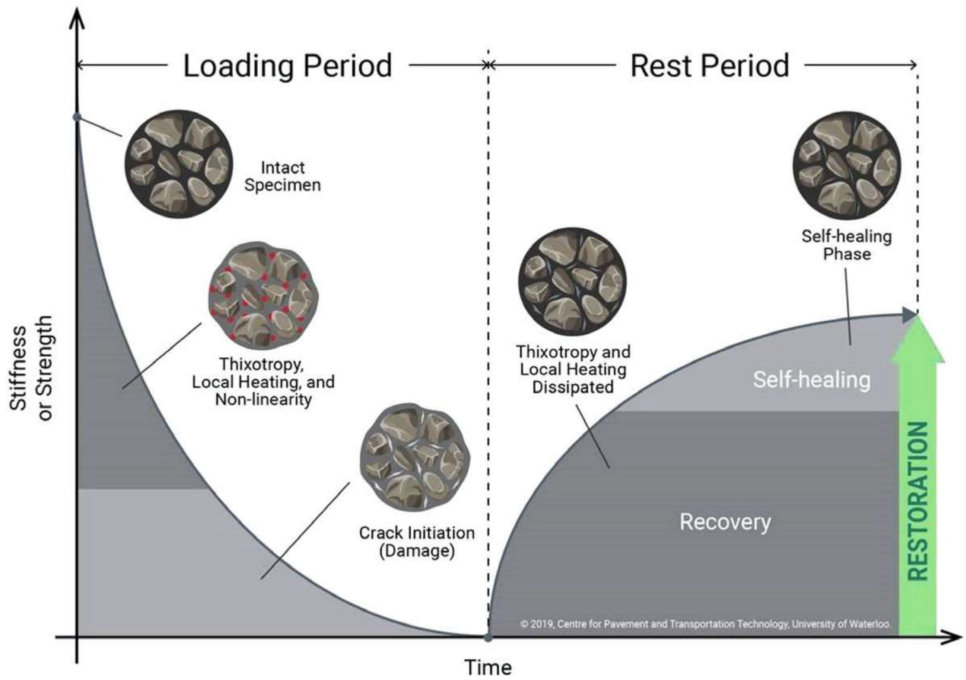


Fig. 16 Schematic overview of contributions to the restoration of performance of different phenomena [1]

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.

9 Summary

The recovery strength of specimen after a rest period has been observed in many situations. This is a widely recognized property of asphalt materials and is consequently integrated into many pavement design approaches. However, the behavior is not yet fully understood. This is partly caused by differences in self-healing performance when the same material is tested with different healing tests. However, there are some general trends in healing; healing increases with longer rest periods, at higher temperatures, is more efficient with smaller damages, the materials have a higher penetration grade or a higher binder content.

Theories from material science have been formulated to explain the mechanisms underlying self-healing behavior. Addressing what mechanism are at play in the closing of cracks, identifying that surfaces need to restore contact through a process of wetting and that time is required for the material at areas in contact to restore its original properties through a process of homogenization. This demonstrates that the formation and healing of cracks are continuous processes within the material, influenced by loading and rest conditions. This complexity highlights why capturing this healing behavior remains so challenging. These theories help formulate better test methods; however, they are also not fully verified. The presence of biasing effects, which cause changes in material behavior occurring during tests execution that are not related to damage, hampers identification of physical damage in the material and consequently the self-healing.

This all possess a challenge when the self-healing ability of innovative materials is needed to manage risks during application. More research on healing could help better understand the phenomenon and to formulate adequate test methods to assess healing behavior of innovative materials. The presented common set of definitions on self-healing of asphalt will contribute to a clearer scientific discussion while this research is being executed.

References

1. Leegwater, G., Taboković, A., Baglieri, O., Hammoum, F., & Baaj, H. (2022). Terms and definitions on crack-healing and restoration of mechanical properties in bituminous materials. In *Proceedings of the RILEM International Symposium on Bituminous Materials. ISBM 2020. RILEM Bookseries* (Vol. 27). Springer. https://doi.org/10.1007/978-3-030-46455-4_6
2. Pooyan, A., Moreno-Navarro, F., & Rubio-Gámez, C. (2016). The healing capability of asphalt pavements: A state-of-the-art review. *Journal of Cleaner Production, 113*, 28–40.

3. Leegwater, G., Scarpas, T., & Erkens, S. (2016). Direct tensile test to assess healing in asphalt. *Transportation Research Record, 2574*(1), 124–130.
4. Bazin, P., & Saunier, J. (1967). Deformability, fatigue and healing properties of asphalt mixes. In *International Conference on the Structural Design of Asphalt Pavements.*
5. Bonnaure, F. P., Huibers, A. H. J. J., & Boonders, A. (1982). A laboratory investigation of the influence of rest periods on the fatigue characteristics of bituminous mixes (with discussion). In *Association of Asphalt Paving Technologists Proceedings* (Vol. 51).
6. Richard Kim, Y., Little, D. N., & Benson, C. (1990). Chemical and mechanical evaluation on healing mechanism of asphalt concrete (with discussion). *Journal of the Association of Asphalt Paving Technologists, 59*
7. Little, D. N., Bhasin, A., & Darabi. M. K. (2015). Damage healing in asphalt pavements: Theory, mechanisms, measurement, and modeling. In *Advances in asphalt materials* (pp. 205–242). Woodhead Publishing.
8. Qiu, J. (2012). *Self-healing of asphalt mixtures, towards a better understanding.* Dissertation report. Delft University of Technology.
9. Miglietta, F., Shane, U. B., Tsantilis, L., Baglieri, O., & Santagata, E. (2023). Self-healing master curves of bituminous binders: A non-linear viscoelastic continuum damage framework. *Road Materials and Pavement Design, 24*(sup1), 124–144.
10. Van den Bergh, W. (2011). *The effect of ageing on the fatigue and healing properties of bituminous mortars.*
11. Williams, D., Little, D. N., Lytton, R. L., Kim, Y. R., & Kim, Y. (2001). Micro-damage healing in asphalt and asphalt concrete. In *Volume II Laboratory and Field Testing to Assess and Evaluate Micro-Damage and Micro-Healing, FHWA-RD-98-142.* Texas Transportation Institute, 182p.
12. Shell. (1978). *Shell pavement design manual—Asphalt pavement and overlays for road traffic.* Shell International Petroleum Company Limited.
13. LCPC. (1997). French design manual for pavement structures. In *Technical guide, LCPC/SETRA, translation of the French version December 1994*, 248p.
14. Von Quintus, H. L., Scherocman, J. A., Hughes, C. S., Kennedy, T. W. (1991). *Asphalt aggregate mixture analysis system.* NCHRP report 338, March 1991. ISBN 0-309-04861-3
15. Verstraeten, J. (1974). Loi de fatigue en flexion répétée des mélanges bitumineux. *Bulletin de Liaison des Laboratoires des Ponts et Chaussées*, n° 70, mars 1974
16. Groenendijk, J. (1998). *Accelerated testing and surface cracking of asphaltic concrete pavements.* Delft University of Technology, Delft, The Netherlands.
17. Lytton, R. L., Uzan, J., Fernando, E., Roque, R., Hiltunen, D., & Stoffels, S. (1993). *Development and validation of performance prediction models and specifications for asphalt binders and mixes.* Strategic Highway Research Program SHRP-A-357.
18. Marchand, J. P. (1981). *Influence du temps de repos sur le comportement à la fatigue des matériaux de chaussées.* LCPC Report in French, 10p.
19. Raithby, K. D., & Sterling, A. B. (1970). The effect of rest periods on the fatigue performance of a hot-rolled asphalt under reversed axial loading and discussion. *Association of Asphalt Paving Technologists Proceedings.*
20. Van Dijk, W., et al. (1972). The fatigue of bitumen and bituminous mixes. In *Third International Conference on the Structural Design of Asphalt Pavements, Grosvenor House, Park Lane, London, England* (Vol. 1), September 11–15.
21. Van Dijk, W., & Visser, W. (1977). Energy approach to fatigue for pavement design. In *Association of Asphalt Paving Technologists Proceedings* (Vol. 46).
22. Francken, L. (1979). Fatigue performance of a bituminous road mix under realistic test conditions. *Transportation Research Record, 712.*
23. Verstraeten, J., Veverka, V., & Francken, L. (1982). Rational and practical designs of asphalt pavements to avoid cracking and rutting. In *Fifth International Conference on the Structural Design of Asphalt Pavements* (pp. 45–58).
24. Qiu, J. (2012). Self-*healing of asphalt mixtures.* Master Thesis, Technical University Delft.
25. Kim, Y. R., Dallas, N. L., & Benson, F. C. (1990). Chemical and mechanical evaluation on healing mechanism of asphalt concrete. *Journal of the Association of Asphalt Paving Technologists, 59.*

26. Wool, R. P., & O' Connor, K. M. (1981). A theory crack healing in polymers. *Journal of Applied Physics, 52*, 5953–5963.
27. Lytton, R. L., Chen, C. W., & Little, D. N. (1998). *A micromechanics fracture and healing model for asphalt concrete.* FHWA Final Report. DTFH61-92-C-00170, Texas A&M University.
28. Kim, Y. R., Little, D. N., & Benson, F. C. (1990). Chemical and mechanical evaluation on healing mechanism of asphalt concrete (with discussion). *Journal of the Association of Asphalt Paving Technologists, 59*, 240–275.
29. Little, D. N., Lytton, R. L., Williams, D. A., & Kim, Y. R. (2001). Microdamage healing in asphalt and asphalt concrete. In *Microdamage and microdamage healing, project summary report, FHWA-RD98-141, June 2001* (Vol. 1, p. 88).
30. Good, R. J., Manoj, K., & Chaudhuryvan Oss, C. J. (1991). Theory of adhesive forces across interfaces 2. In L.-H. Lee (Eds.), *Interfacial hydrogen bonds as acid—Base phenomena and as factors enhancing adhesion, Fundamentals of adhesion.* Springer Science Business Media, LLC.
31. Bhasin, A., Little, D. N., Bommavaram, R., & Vasconcelos, K. L. (2008). A framework to quantify the effect of healing in bituminous materials using material properties. *International Journal of Road Materials and Pavement Design, EATA, 08*(2008), 219–242.
32. FHWA. (2008). ARC consortium quarterly technical progress report. In *QuarterlyReport_April–June*. FHWA.
33. Qiu, J. (2012). *Self-healing of asphalt mixtures.* Technical University Delft.
34. Nahar, S. N., et al. (2014). Microstructural changes in bitumen at the onset of crack formation. *European Polymer Journal, 56*, 17–25.
35. Santagata, E., Baglieri, O., Dalmazzo, D., & Tsantilis, L. (2009). Rheological and chemical investigation on the damage and healing properties of bituminous binders. *Journal of the Association of Asphalt Paving Technologists, 28*(2009), 567–595.
36. Sun, D., Fan, Y., Li, L., Lin, T., & Zhu, X. Y. (2017). Effect of chemical composition and structure of asphalt binders on self-healing. *Construction and Building Materials, 133*, 495–501.
37. Hou, Y., Wang, L., Pauli, T., & Sun, W. (2015). Investigation of the asphalt self-healing mechanism using a phase-field model. *Journal of Materials in Civil Engineering, 27*(3).
38. Nahar, S. N. (2016). *Phase-separation characteristics of bitumen and their relation to damage-healing.*
39. Nazzal, M., Kaya, S., & Abu-Qtaish, L. (2012). Evaluation of the healing properties of WMA using atomic force microscopy. In *Proceedings of the 7th RILEM International Conference on Cracking Pavements* (Vol. 4). Springer.
40. Song, I., Little, D. N., Masad, E. A., & Lytton, R. (2005). Comprehensive evaluation of damage in asphalt mastics using X-ray CT, continuum mechanics, and micromechanics (with discussion). *Association of Asphalt Paving Technologists, 74.*
41. Grossegger, D. (2021). Fatigue damage self-healing analysis and the occurrence of an optimal self-healing time in asphalt concrete. *Journal of Materials in Civil Engineering, 33*(6), 04021098.
42. Gómez-Meijide, B., Ajam, H., Lastra-González, P., & Garcia, A. (2016). Effect of air voids content on asphalt self-healing via induction and infrared heating. *Construction and Building Materials, 126*(2016), 957–966.
43. GrosseggerGarcia, D. (2019). Influence of the thermal expansion of bitumen on asphalt self-healing. *Applied Thermal Engineering, 156*, 23–33.
44. Salih, S., Gómez-Meijide, B., Aboufoul, M., & Garcia, A. (2018). Effect of porosity on infrared healing of fatigue damage in asphalt. *Construction and Building Materials, 167*, 716–725.
45. Little, D. N., Prapnnachari, S., Letton, A., & Kim, Y. R. (1993). *Investigation of the micro-structural mechanism of relaxation and fracture healing in asphalt.* Texas Transportation Inst College Station
46. Wool, R. P., & O'Connor, K. M. (1981). A theory of crack healing in polymers. *Journal of Applied Physics, 52*(10), 5953–5963.

47. Wu, D.-Y., Meure, S., & Solomon, D. (2008). Self-healing polymeric materials: A review of recent developments. *Progress in Polymer Science, 33*, 479–522.
48. Kim, Y. H., & Wool, R. P. (1983). A theory of healing at a polymer-polymer interface. *Macromolecules, 16*(7), 1115–1120.
49. Tabaković, A., Schuyffel, L., Karač, A., & Schlangen, E. (2017). An evaluation of the efficiency of compartmented alginate fibres encapsulating a rejuvenator as an asphalt pavement healing system. *MDPI Applied Sciences, 7*, 16.
50. Moreno-Navarro, F., Sol-Sánchez, M., Rubio-Gámez, M. C. (2015). Exploring the recovery of fatigue damage in bituminous mixtures: The role of healing. *Road Materials and Pavement*.
51. Phillips, M. C. (1999). Multi-step models for fatigue and healing, and binder properties involved in healing. In *Eurobitume workshop on performance related properties for bituminous binders*, Luxembourg.
52. Lu, X., Soenen, H., & Redelius, P. (2003). Fatigue and healing characteristics of bitumens studied using dynamic rheometer. In *6th RILEM Symposium PTEBM'03, Zurich* (pp. 408–415).
53. Bhasin, A., Pavaldi, S., & Little, D. N. (2011). Influence of aging and temperature on intrinsic healing of asphalt binders. *Transport Research Board, 2207*, 9.
54. Hammoum, F., de La Roche, C., Piau, J.-M., & Stefani, C. (2002). Experimental investigation of fracture and healing of bitumen at pseudo-contact of two aggregates. In *Ninth ISAP International Conference on Asphalt Pavements, Denmark*.
55. Tozzi, C., Hammoum, F., & Baglieri, O. (2023). *Evaluation and modelling of low temperature fracture properties of asphalt binders in thin film by means of the local fracture test, road materials and pavement design* (pp. 1–17).
56. Maillard, S. (2005). *Etude du comportement à la rupture sous chargements répétés du bitume en film mince*, PhD report in French, Ecole centrale de Nantes.
57. Hyun-Jong L., & Kim Y. R. (1998). Viscoelastic continuum damage model of asphalt concrete with healing. *Journal of Engineering Mechanics, 124*(11), 1224–1232.
58. Erkens, S., van Vliet, D., & Leegwater, G. (2012). *Healing van asfaltmengsels, onderzoek naar een pragmatische proefmethode.* InfraQuest.
59. Pronk, A. C., & Cocurullo, A. (2009). Investigation of the PH model as a prediction tool in fatigue bending tests with rest periods. In *Advanced testing and characterisation of bituminous materials, Loizos, Partl*. Taylor & Francis Group.
60. Baaj, H., Mikhailenko, P., Almutairi, H., & Di Benedetto, H. (2018). Recovery of asphalt mixture stiffness during fatigue loading rest periods. *Construction and Building Materials, 158*, 591–600.
61. Di Benedetto, H., Ashayer, M., Soltani, A., & Chaverot, P. (1996). Fatigue damage for bituminous mixtures: A pertinent approach. *Journal of the Association of Asphalt Paving Technologists, 65*, 142–158.
62. Di Benedetto, H., de la Roche, C., Baaj, H., & Pronk, A. (1994). Fatigue of bituminous mixtures. *Materials and structures, 37*, 202–216.
63. Lundström, R., Ekblad, J., & Isacsson, U. (2004). Influence of hysteretic heating on asphalt fatigue characterization. *Journal of Testing and Evaluation, 32*, 484–493.
64. Redelius, P., & Soenen, H. (2015). Relation between bitumen chemistry and performance. *Fuel, 140*, 34–43.
65. Petersen, J. C., Robertson, R.-E., Branthaver, J. F., Harnsberger, P. M., Duvall, J. J., Kim, S. S., Anderson, D. A., Christiansen, D. W., & Bahia, H. U. (1994). *Binder characterization and evaluation: Volume 1, Rep. No. SHRP-A-367, Strategic Highway Research Program.* National Research Council.
66. Mewis, J., & Wagner, N. J. (2009). Thixotropy. *Advances in Colloid and Interface Science, 147–148*, 214–227.
67. Gauthier, G., Bodin, D., Chailleux, E., & Gallet, T. (2010). Nonlinearity in bituminous materials during cyclic tests. *Road Materials and Pavement Design, 11*(Supp 1), 129–158.
68. Mouillet, V., de la Roche, C., Chailleux, E., & Coussot, P. (2012). Thixotropic behavior of paving-grade bitumens under dynamic shear. *Journal of Materials in Civil Engineering, 25*, 23–31.

69. Santagata, E., Baglieri, O., Tsantilis, L., & Dalmazzo, D. (2013). Evaluation of self-healing properties of bituminous binders taking into account steric hardening effects. *Construction and Building Materials, 41*, 60–67.
70. Shan, L. Y., Tan, Y. Q., Underwood, B. S., & Kim, Y.-R. (2011). Separation of thixotropy from fatigue process of asphalt binder. *Transportation Research Record: Journal of the Transportation Research Board, 2207*, 89–98.
71. Delaporte, B., Van Rompu, J., Di Benedetto, H., Chaverot, P., & Gauthier, G. (2008). New procedure to evaluate fatigue of bituminous mastics using an annular shear rheometer prototype. In I. L. Al-Qadi, T. Scarpas, & A. Loizos (Eds.), *Pavement cracking: Mechanisms, modeling, detection, testing and case histories: Proceedings of the 6th RILEM International Conference on Cracking in Pavements* (pp. 457–467). CRC Press/Balkema
72. Di Benedetto, H., Nguyen, Q. T., & Sauzéat, C. (2011). Nonlinearity, heating, fatigue and thixotropy during cycling loading of asphalt mixtures. *Road Materials and Pavement Design, 5*, 163–202.
73. Soltani, A., & Anderson, D. A. (2005). New test protocol to measure fatigue damage in asphalt mixtures. *Road Materials and Pavement Design, 6*, 485–514.
74. Nguyen, Q. T., Di Benedetto, H., & Sauzéat, C. (2012). Determination of thermal properties of asphalt mixtures as another output from cyclic tension-compression test. *Road Materials and Pavement Design, 13*, 85–103.
75. Mangiafico, S. (2014). *Linear viscoelastic properties and fatigue of bituminous mixtures produced with Reclaimed Asphalt Pavement and corresponding binder blends*. PhD report, ENTPE.
76. Mangiafico, S., Sauzéat, C., Di Benedetto, H., Pouget, S., Olard, F., & Planque, L. (2015). Quantification of biasing effects during fatigue tests on asphalt mixes: non-linearity, self-heating and thixotropy. *Road Materials and Pavement Design, 16*, 73–99
77. Nguyen, Q. T. (2011). *Comportement thermomécanique des enrobés bitumineux sous sollicitations cycliques dans les domaines linéaire et non-linéaire*. PhD report, ENTPE.
78. Baaj, H. (2002). *Comportement à la fatigue des matériaux granulaires traités aux liens hydrocarbonés*. Dissertation, Lyon, INSA.
79. Baaj, H., Di Benedetto, H., & Chaverot, P. (2005). Effect of binder characteristics on fatigue of asphalt pavement using an intrinsic damage approach. *Road Materials and Pavement Design, 6*, 147–174.
80. Di Benedetto, H., et al. (2004). Fatigue of bituminous mixtures. *Materials and Structures, 37*, 202–216.
81. Tapsoba, N., Sauzéat, C., & Di Benedetto, H. (2013). Analysis of fatigue test for bituminous mixtures. *Journal of Materials in Civil Engineering, 25*, 701–710.
82. Williams, D. et al. (2001). *Micro-damage healing in asphalt and asphalt concrete, volume II: Laboratory and field testing to assess and evaluate micro-damage and micro-damage healing*. No. FHWA-RD-98-14.
83. Sun, D., Yu, F., Li, L., Lin, T., & Zhu, X. Y. (2017). Effect of chemical composition and structure of asphalt binders on self-healing. *Construction Building Materials, 133*, 495–501.
84. Little, D. N., Bhasin, A., & Darabi, M. K. (2015). Damage healing in asphalt pavements: Theory, mechanisms, measurement, and modeling. In *Advances in asphalt materials* (pp. 205–242). Woodhead Publishing.
85. Nahar, S., Schmets, A., Kasbergen, C., Schitter, G., & Scarpas, A. (2016). *Microstructural changes in bitumen at the onset of damage-healing*. CROW InfraDagen.
86. Bhasin, A., Palvadi, S., & Little, D. N. (2011). Influence of aging and temperature on intrinsic healing of asphalt binders. *Transportation Research Record: Journal of the Transportation Research Board, 2207*, 70–78.
87. Kausch, H. H. (1987), Fracture mechanics studies of crack healing. In *Polymer fracture* (2nd ed.).
88. Boiko, Y. M., & Lyngaar-Jorgensen, J. (2004). Healing of interfaces of high and ultra-high molecular weight polystyrene below the bulk Tg. *Polymer, 45*(25), 8541–8549.

89. Kinloch, A.-J. (1987). Adhesion and adhesives. In *Science and technology* (2nd ed.). Chapman and Hall.
90. Bhasin, A., Little, D. N., Bommavaram, R., & Vasconcelos, K. (2008). A framework to quantify the effect of healing in bituminous materials using material properties. *Road Materials and Pavement Design, 9*, 219–242.
91. Hou, Y., Wang, L., Pauli, T., & Sun, W. (2015). Investigation of the asphalt self-healing mechanism using a phase-field model. *Journal of Materials in Civil Engineering, 27*, 04014118.
92. Leegwater, G., Scarpas, T., & Erkens, S. (2016). Direct tensile test to assess healing in asphalt. *Transportation Research Record: Journal of the Transportation Research Board* 124–30.
93. Little, D. N., Bhasin, A., & Darabi, M. K. (2015). Damage healing in asphalt pavements: Theory, mechanisms, measurement, and modeling. Theory, mechanisms, measurement, and modeling. *Advances in Asphalt Materials: Road and Pavement Construction.*
94. Nazzal, M., Kaya, S., & Abu-Qataish (2012). Evaluation of WMA healing properties using atomic force microscopy. In T. A. Scrpas (Ed.), *7th Rilem Conference on Advanced Testing and Characterization of Bituminous Materials* (pp. 1125–1134).
95. Santagata, E., Baglieri, O., Dalmazzo, D., & Tsantilis, L. (2009). Rheological and chemical investigation on the damage and healing properties of bituminous binders. *Asphalt Paving Technology-Proceedings, 28*, 567.
96. Soenen, H., Besamusca, J., Fischer, H. R., Poulikakos, L. D., Planche, J.-P., Das, P. K., Kringos, N., Grenfell, J. R. A., Lu, X., & Chailleux, E. (2013). Laboratory investigation of bitumen based on round robin DSC and AFM tests. *Materials and Structures* 1–16.
97. Song, I., Little, D., Massad, E., & Lytton, R. L. (2005). Comprehensive evaluation of damage in asphalt mastics using X-ray CT, continuum mechanics, and micromechanics. *Journal of Assoc Asphalt Paving Technology, 74*, 36.