Experimental Characterization of Self-Healing of Asphalt Materials

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Abstract Several efforts have been made by the research community to identify proper laboratory testing methods and develop various analytical interpretations to estimate the healing performance of asphalt materials at the binder, mastic, mortar, and mixture scales. Depending on the considered scale and the testing approach, the evaluation of healing can capture two distinct mechanisms: adhesive healing and cohesive healing. While adhesive healing considers the phenomenon at the binder-aggregate interface, cohesive healing refers to the rebonding action of the binder medium itself. The assessment of crack healing can be derived from a variety of testing modes used to induce damage in the material and allow for the self-healing phenomenon to manifest itself when the material is left at rest. In such a context, damage can be based on both fatigue or fracture modes, requiring different experimental protocols and theoretical approaches. When focusing on the rest phase, the testing methods can be generally classified as storage, intermittent and hybrid healing tests, depending on how rest period(s) are introduced in the overall testing protocol. Following these considerations, several healing parameters can be introduced to measure the healing performance of the asphalt materials.

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1 Adhesive Versus Cohesive Approaches

Two main types of crack propagation and healing mechanisms are recognized to occur within asphalt materials, referred to as adhesive and cohesive processes [11, 30, 61, 74]. The former considers the crack and healing phenomena that occur at the binder-aggregate interface due to the rebonding action of the binder phase to the mineral aggregate. The latter refers to the crack and healing phenomena that occur at the binder medium's microcrack faces only.

The adhesive failure at the binder-aggregate interface, in combination with cohesive failure in the binder medium, leads to severe decay of both the durability and mechanical performance of asphalt mixtures. Loss of adhesion typically involves thin film coatings of asphalt binder all around the aggregate surface, whereas loss of cohesion occurs in the case of thick film coatings [13]. Thus, the adhesive properties of the binder-aggregate bond and the cohesive properties of the binder exert an important influence on the service life of asphalt pavements [74].

To characterize adhesive healing, it is necessary to study the binder-aggregate system [13, 23]. Adhesion occurring at the binder-aggregate interface must be investigated to understand cracking and healing in asphalt mixtures comprehensively. When focusing on the scale of mastics, mortars and mixtures, the adhesive properties of the binder-aggregate system cannot be discriminated against those related to the cohesion of the asphalt matrix. In this context, researchers have implemented the binder bonding strength (BBS) test to grasp the bonding healing at the binder-aggregate interface. Williams and co-workers [74] explained the cohesive and adhesive bonding interactions of binder-aggregate systems through the Lifshitz-van der Waals interactions of electron shells of neighboring molecules and acid–base interactions between constituent molecules. Bhasin and Little [13] proposed a methodology to estimate the surface free energy components of aggregates using the microcalorimeter. The thermodynamic concepts have been similarly applied by Nejad and co-workers [42] to study the moisture sensitivity of asphalt mixtures in the case of hydrate lime-treated aggregate. In their study, Huang et al. [27] investigated the influence of pulling rate and binder film thickness on the bonding strength of binders mixed with different additives. They found that the pull-off tensile strength (POTS) of the modified binders was improved, and the self-healing ability of blends with crumb rubber and ethylene bis-stearamide (EBS) wax was improved in comparison with that of the base binder. Binder blends with increasing SBS modification levels tended to have higher POTS values but decreased healing rate. Similarly, Lv and co-workers [38] underlined that the SBS modification mostly led to lower adhesive healing percentages than neat asphalt binders. Moreover, they found that the mastic samples made up of limestone filler performed better than binder samples in the investigated healing conditions. Wang et al. [72] used a granite substrate in the presence of water and found overall positive effects on adhesive healing.

Cohesive healing is generally investigated by isolating the asphalt binder phase from the lithic one to exclude any confounding interaction between aggregate and asphalt binder [57, 58, 71]. Such an approach has the advantage of assessing more fundamental properties in the analysis of the overall damage behavior of the asphalt matrix. First detailed by Wool and O'Conner, it was theorized that thermoplastic polymers could heal through the diffusion of molecular chains into contacted crack surfaces [75]. Full healing occurs when the molecular chains fully integrate and randomize into the undamaged polymer matrix, this theory was later adapted to cohesive healing for asphalt materials. Research studies have demonstrated that cohesive healing in asphalt binders results from several processes occurring at crack interfaces, such as wetting, interfacial cohesion, interdiffusion, and randomization of molecules at the wetted interfaces [54]. This allows the crack to be repaired, thus returning the binder matrix to its original or "undamaged" state. Although, from a theoretical point of view, cohesive healing can only be assessed by considering the pure asphalt phase, it is widely recognized that the healing response of the mastic, mortar and mixture differs from that of the associated pure asphalt binder because of the discontinuity introduced by the presence of the aggregate. The cohesive property of the binder is altered by the interaction existing between the binder and the filler/sand fractions [40, 50]. A mixed mode of cohesive and adhesive healing should be considered in such cases. Nevertheless, some researchers also consider the binding part in the mixture (i.e., asphalt binder and filler) as a whole. Williams and co-workers [74] stated that the cohesive fracture can be promoted by high mastic volumes within the asphalt mixture, whereas a lower quantity of asphalt binder can encourage adhesive fracture. Thus, the proper selection of the scale of investigation is of primary importance when studying adhesive and cohesive healing processes. Cohesive healing can be studied on the binder scale only, whereas a mixed approach, comprising both adhesion and cohesion, is involved for the other scales of observation, such as mastic, mortar, and mixture. Alternatively, when investigating only adhesive healing, the interface of the binder-aggregate system should be evaluated.

2 Fatigue-Based Versus Fracture Mechanics Approaches

To assess healing, cracks need to be generated within the asphalt material to subsequently analyze the crack-closure process. Such cracks can originate from both fatigue-based damage and fractures.

Fatigue cracking is the consequence of repeated tensile stresses or strains occurring due to the cyclic passage of traffic wheels during the pavement service life. It occurs at first as microcracks that eventually coalesce to form macrocracks throughout the asphalt layer. Accelerated laboratory testing methods associated with the formation of microcracks are generally referred to as fatigue tests. Fatigue tests are carried out by subjecting the sample to a stress-controlled or strain-controlled load. In stress-controlled tests, the stress input is kept constant, and the strain increases, whereas strain-controlled tests apply constant strain to the sample and the stress is reduced [53]. For the healing assessment, the fatigue-based approach is generally modified by including unloading phases that facilitate the healing phenomena. Fatigue cracks typically initiate as microcracks and grow over time as dictated by the crack propagation process, including the coalescence of the microcracks [22]. When microcracks form macrocracks, fracture-based concepts can be introduced. The healing phenomenon can be studied through fatigue analysis if the microstructural changes are bounded within the domain of microcracks. When the healing phenomenon is considered after the propagation of macrocracks, fracture-based approaches are adopted [34]. Fracture-based tests deal with the complexity of the stress field around the crack tip. The purpose of such tests is to determine the potential course of action of a crack: to propagate or to arrest. This is carried out by considering the fracture energy, which represents the energy required to separate the material into two pieces. Fracture energy is a material-dependent property, measured as the ratio of the work of the fracture to the crack area, where the work of the fracture represents the area under the load–displacement curve [51]. In this context, the assessment of healing is conducted by visibly fracturing the material and by placing the broken pieces back in intimate contact. However, the normal forces applied to bring the two fractured surfaces in contact can cause irregularities to the fractured faces. This can lead to discontinuous contact caused by consequent permanent deformations inevitably occurring at the crack interface [64].

In both approaches, the resistance of the asphalt mixture against cracking depends on several factors, such as the asphalt binder type and content, the volumetric characteristic of the mixture, the aggregate gradation, lithic type and size, as well as the presence of modifiers. Moreover, the adhesive/cohesive forces and the internal friction also dictate the cracking resistance and the healing performance [51]. The two approaches can be applied at different scales, such as asphalt binder, mastic, mortar and mixture, but the basic assumptions for damage and healing are different.

In interpreting the results obtained from fatigue-based and fracture-based test methods, two main research approaches can be adopted: the phenomenological and mechanistic approaches. The phenomenological approach is quite simple, and it relates the fatigue life of the asphalt mixture to the initial pavement response in terms of stress or strain [35]. However, it does not consider the damage evolution process throughout the test, thus being strongly dependent on the material property, test type, and loading conditions [10, 32]. Mechanistic approaches are inherently more complex than the phenomenological approach because they are conceived to be potentially applicable to a broader range of loading and environmental conditions. Such approaches are based on fracture mechanics or continuum damage mechanics [30, 32]. Based on the type of approach adopted for the evaluation of healing, either fatigue-based or fracture-based approaches, the concepts of fracture mechanics or continuum damage mechanics can be implemented. As mentioned, the basic assumption in fatigue cracking is that microcracks are uniformly spread within the material. For such a situation, it is more appropriate to adopt the continuum damage mechanics concepts, which are based on stress–strain relationships. Continuum damage theories can be adopted to model the response of composite materials at different length scales. Those theories allow the characterization of material behavior using the net effect of microstructural changes on observable properties rather than microscale observations [66]. In doing so, they ignore the heterogeneity of the asphalt mixture by hypothesizing that all the damage within the material can be averaged and represented by phenomenologically defined internal state variables [31]. When such assumptions cannot hold due to the presence of a visible crack, it is preferable to use fracture mechanics concepts. The fundamental principles of fracture mechanics underline that cracking initiates in the vicinity of the crack tip in cases where the energy stored nearby exceeds the material crack resistance [59].

A way to bridge the gap between fracture mechanics and continuum damage mechanics is represented by the cohesive zone models used in crack initiation and propagation and, therefore, potentially adopted in the case of crack closure and healing [44]. Such a model implies a more physically sound approach that allows stress singularities ahead of the crack tip to be removed, thus better predicting its advancement during the damaging process [31]. However, the identification of the material constants associated with this approach is still very challenging.

3 Testing Configurations

Many test set-ups have been used to characterize the healing of asphalt binder, mastic, mortar, and mixtures by adopting fatigue-based and fracture-based approaches.

In the context of asphalt binders, cohesive healing is generally investigated through a variety of rheological measurements consisting of fatigue-based testing that all have in common the use of the dynamic shear rheometer (DSR), as presented in Fig. 1a [6, 17, 41]. Such tests are typically conducted on small disk-shaped specimens using a parallel plate configuration, where one DSR plate is fixed, and the other applies a shear force. Dynamic shear tests have also been implemented on two-piece samples to assess the material fracture-related properties. Such an approach is thought to simulate the crack healing process in which the crack is physically reproduced by the two halves of a sample that are brought in intimate contact to trigger the healing phenomena [14]. The direct tension test and the ductility test (Fig. 1b, d) have also been adopted on samples that are preliminarily cut into two equal parts and then placed in contact [48]. This allows the study of fracture-dependent healing behavior in the presence of visible cracks. The cohesive healing/failure of asphalt binders has also been assessed by means of the local fracture test, presented in Fig. 1c. Such a test is performed on an asphalt binder lens placed between two convex protuberances that simulate two aggregates [26].

Laboratory testing methods to investigate the healing behavior associated with the mastic phase have been conducted using dynamic shear tests (Fig. 2e), direct tension tests (Fig. 2g) and three-point bending tests (Fig. 2h). Such testing configurations evaluate the overall healing performances of asphalt mastic samples without separating healing phenomena related to adhesion or cohesion. Similarly, to asphalt binders, dynamic shear tests consist of rheological measurements conducted by imposing small amplitude loading on the sample [56]. Concerning fracture-based approaches, Al-Mansoori and co-workers [3] studied fracture healing on mastic beams that were broken in two pieces using three-point bending tests and then left to heal. In the same context, Qiu et al. [49] implemented the direct tension test to impart

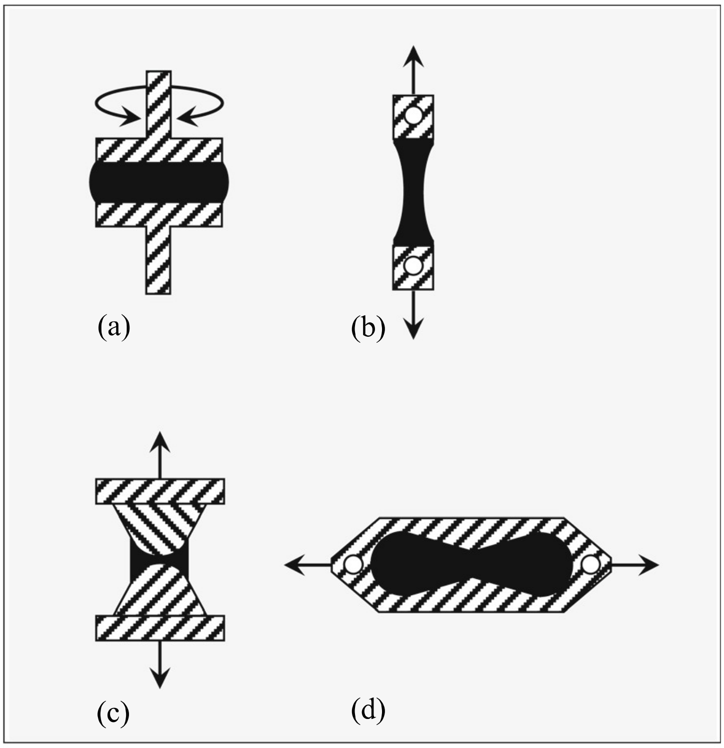

Fig. 1 Schematic representation of testing protocols on the binder scale: **a** dynamic shear test; **b** direct tension test; **c** local fracture test; **d** ductility test

multicracks to the mastic phase before healing. Another recent category of test used for the healing assessment is the binder bonding strength test, schematically presented in Fig. 2f. This configuration can be adopted for both asphalt binder and mastic. The former allows the assessment of the adhesive healing at the binder/aggregate interface [38, 72], while the latter refers to a mixed mode of healing comprising both adhesion and cohesion [27].

When referring to asphalt mortars, laboratory testing has much less tradition in the research community. Despite this, some healing studies are reported in the literature [68, 77]. Similar to the testing configurations adopted in the case of asphalt materials, some of the tests are related to dynamic shear tests and binder bonding strength tests, schematically represented in Fig. 3i, j, respectively. The former allows for the characterization of fatigue-related healing properties, whereas the latter is used in the context of fracture-based approaches. Other testing configurations involve the adoption of the semi-circular bending test and the three-point bending test, displayed in Fig. 3k, l, respectively. Apostolidis et al. [4] implemented the three-point bending test on beam specimens preliminarily broken in two pieces to evaluate the fracture-related healing performances. In the same context of fracture-based approaches, Pan et al. [43] used a notched semi-circular sample to be used for the semi-circular bending test.

When considering the scale of asphalt mixtures, several fatigue-based testing methods predominantly involve the use of cylindrical samples (Uniaxial Tension–Compression (also called pull–push test occasionally) and indirect tensile fatigue tests, pictured in Fig. 4m, n, and prismatic beam samples (three-point bending test and four-point bending test, represented in Fig. 4q, r). Ashouri et al. [5] adopted the

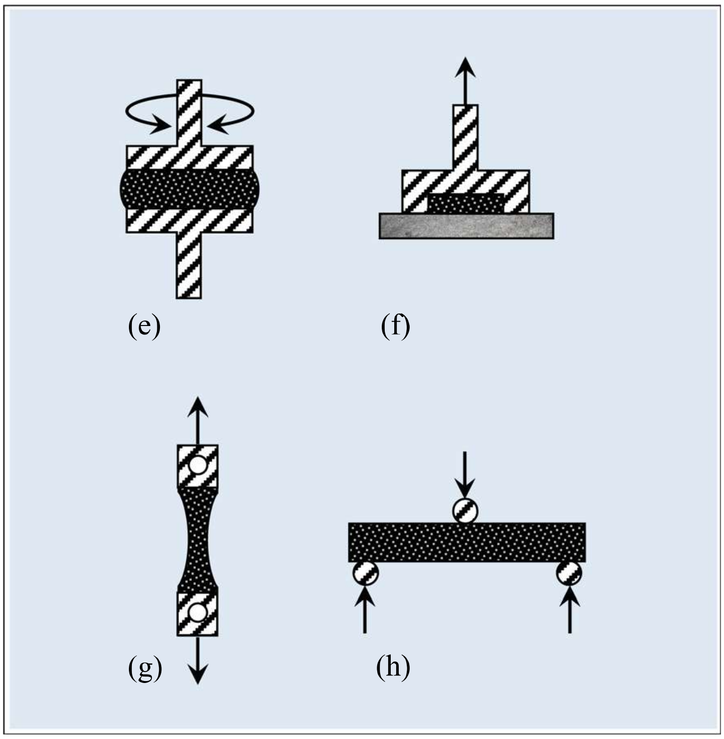

Fig. 2 Schematic representation of testing protocol on the mastic scale and at the binder/mastic-aggregate interface: **e** dynamic shear test; **f** binder bonding strength test; **g** direct tension test; **h** three-point bending test

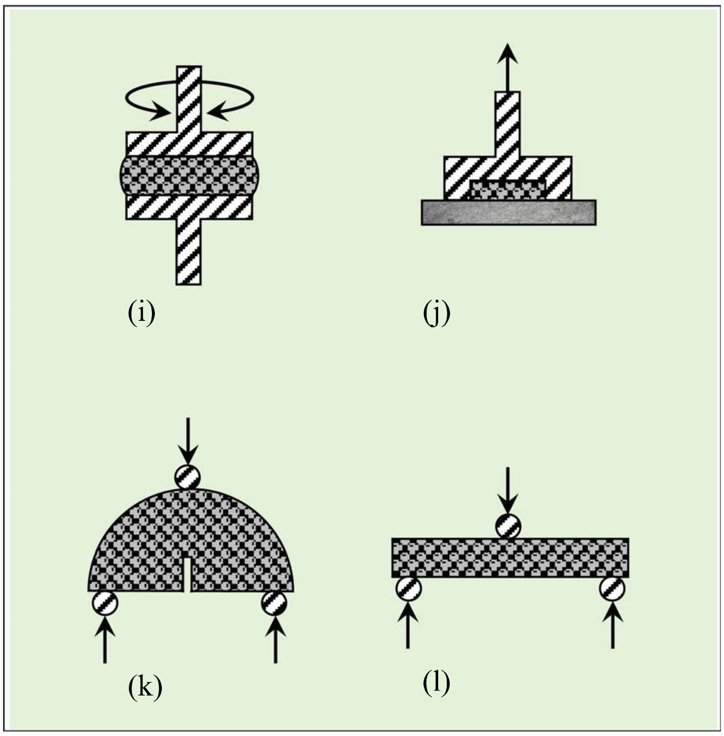

Fig. 3 Schematic representation of testing protocol on the mortar scale: **i** dynamic shear test; **j** binder bonding strength test; **k** semi-circular bending test; **l** three-point bending test

zero-mean stress-controlled testing configuration (Uniaxial Tension–Compression test) in which the haversine loading consisted of a 0.1-s loading pulse with rest periods ranging from 10 to 270 s. Similar loading conditions are adopted for the indirect tensile fatigue test, although the load is applied diametrically, while in the

Tension–Compression test, it is imposed on the cylindrical faces of the specimen. The three-point bending (3PB) and four-point bending (4PB) tests refer to fatigue-healing approaches when adopting rest periods to conventional fatigue procedures. However, they differ due to the location of the maximum bending moment and stresses along the prismatic beam. In the 3PB, the maximum stress occurs under the loading anvil, whereas in the 4PB, the maximum flexural stress is spread all over the beam section between the two loading points [29, 70]. In the same context of beam tests, another fatigue-based approach is the two-point bending test, displayed in Fig. 4p. Such testing configuration involves the use of trapezoidal samples that are clamped at one end to the testing frame and subjected to cyclic loading at its free end [69]. The three-point bending test can also be adopted in fracture-based studies by notching the sample's bottom face to promote predictable crack propagation [21]. Another fracture-based approach involves the use of the semi-circular bending test displayed in Fig. 4o. In this testing configuration, the fracture-healing test is performed by using notched semi-circular samples [29].

Beyond these mechanical testing methods that cause damage to the material, healing non-destructive tests exist. The two main techniques are related to the use of waves and images. Such tests can be applied to evaluate structural changes and to

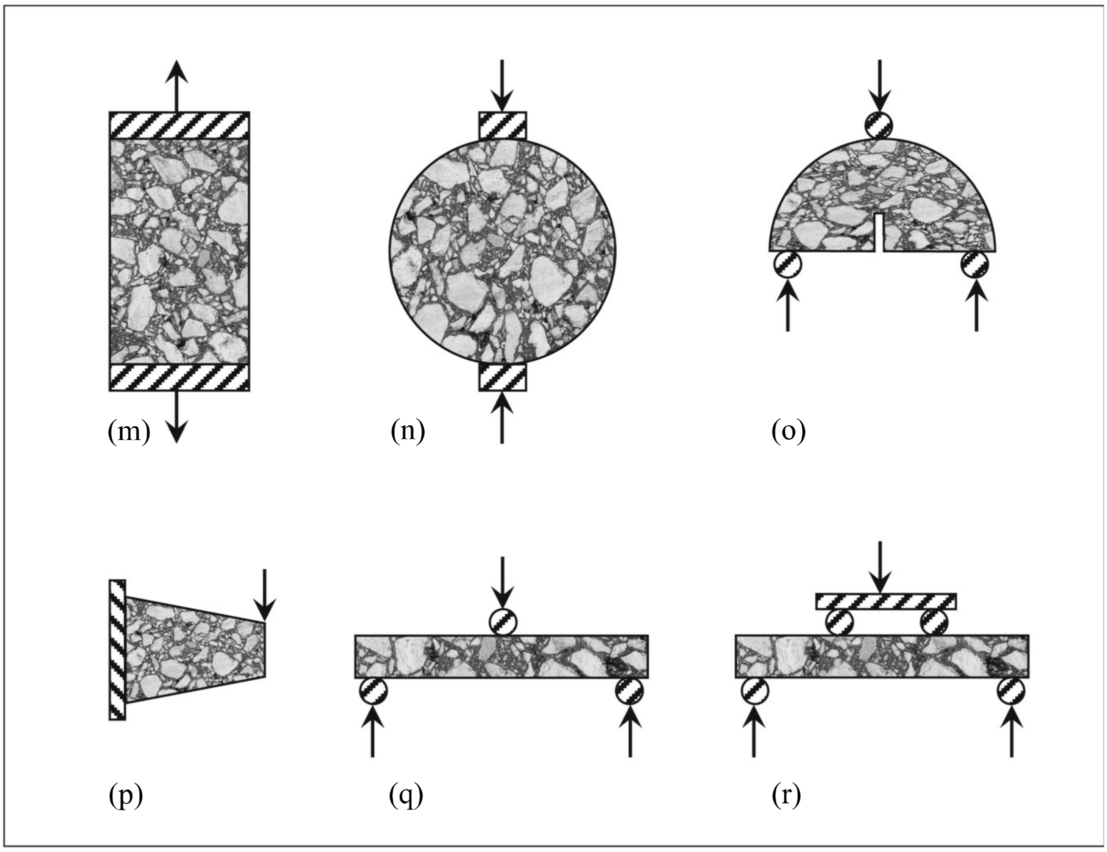

Fig. 4 Schematic representation of testing protocol on the mixture scale: **m** uniaxial Tension–Compression test; **n** indirect tensile test; **o** semi-circular bending test; **p** two-point bending test; **q** three-point bending test; **r** four-point bending test

predict the fatigue life and crack healing of asphalt materials [8]. Studies conducted by [7] and [78] utilized non-invasive ultrasonic propagation measurements to evaluate the fatigue and restoration properties of both unmodified and polymer-modified asphalt mixes using a uniaxial Tension–Compression fatigue-healing test. Ultrasonic transducers were placed axially at both ends of the cylindrical specimens, and a high-frequency (150 kHz) pulse was transmitted through the specimen at regular intervals, the time signals were processed using both time- and frequency-domain methods to evaluate changes in material integrity during loading and rest periods. Using a similar technique, Zhao [78] used the ultrasonic pulse propagation technique coupled with an "interrupted" ideal cracking test (CT) to evaluate the crack-healing ability of asphalt mixes loaded diametrically.

4 Loading Pattern and Rest Periods

Generally, the investigation of healing requires rest period(s) to be introduced during the test. Two different categories of test methods can be distinguished based on how rest period(s) are introduced. One category loads a sample until damaged and then put to rest for a certain period of time. This type of healing test will be referred to as a storage self-healing test. The second category introduces a rest period after each load application in a fatigue test. This type of healing test is referred to as an intermittent self-healing test.

It should also be noted that self-healing can also occur without the introduction of rest periods. In a cyclic test, there is a harmonic load signal. Consequently, the loading varies during the test, and there are periods with decreasing strain or even opposite strain. As a result, cracks that have formed during the largest load peak can be closed later in the loading cycle, which can result in a restoration of strength [36, 45].

The first step of a storage healing test is to introduce (micro)cracks in a specimen. After damage is introduced, the next step is to allow the specimen to rest under controlled conditions: at a certain temperature, for a specific time, and under a certain normal force. After this, the performance of the specimen can be tested and compared to the undamaged performance. It is important to note that, at least in this context, "damage" is intended as a deterioration of the volume of mechanical properties of materials, as it can be evaluated using a continuum mechanics approach. The relation between damage and the formation of microcracks within the material is an interpretation of the observed variation of material properties .

The magnitude and extension of the damage induced to the material can be the result of any kind of cracking introduced to the sample; micro-cracking induced by dynamic fatigue loading [12], a partially cracked sample [26], a fully cracked sample [28, 57] or even by using two separately produced samples [14, 33].

In many cases, a fatigue load is chosen to introduce damage simulating the conditions under which the material would experience wear, before being allowed to heal. An example of the response of a storage healing test is presented in Fig. 5. The black

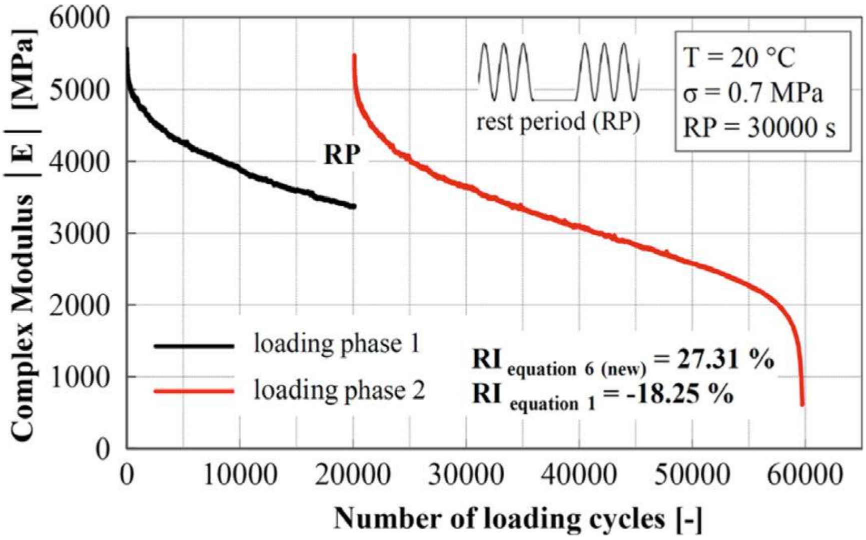

Fig. 5 Stiffness measured in a uniaxial tension–compression fatigue test with a rest period of 30.000 s [28]

line in the figure represents the stiffness reduction due to repeated loading. After a certain stiffness reduction, a rest period (RP) of 30,000s (~ 8 h) is introduced. The red line shows the response of the specimen after the test is started again. The initial stiffness in the second loading phase, just after the rest period, is almost the same as the initial stiffness in the first loading phase. The red line has a slightly higher inclination compared to the black line, which could imply that damage development proceeds faster in an already damaged specimen.

Such a loading condition has been adopted in fatigue-based dynamic shear tests (Figs. 1a and 2e), for asphalt binders and mastics, Tension–Compression test, indirect tensile test, three-point bending test, and four-point bending test (Fig. 4m, n, q, r) to assess the healing performance of asphalt mixtures.

With intermittent healing tests, the purpose is to create a loading pattern which matches the loading in practice more closely. This is carried out by introducing a rest period after each loading period. By definition, this type of protocol is part of a fatigue test. The rest period is usually a multiple of the loading period, such as 10 times the loading period. Such a loading condition was adopted in dynamic shear test, in the case of asphalt binders and mastics, and for the asphalt mixture uniaxial Tension–Compression test, indirect tensile test, and four-point bending test (Figs. 1a, 2e, 4m, n, r).

A disadvantage of this type of test is that it is very time-consuming. Normal fatigue tests are already time-consuming, as one test takes up multiple hours. By also adding a rest period, which multiplies the test time by at least a factor of 10, a single test may take several days. While these types of protocols are considered relevant for research purposes, they are not suitable for inclusion in pavement design protocols. It is also a challenge to apply a representative load signal in between the rest periods due to the load control technology in place in a testing machine for cyclic loading, as these machines often require a number of loading cycles to realize the prescribed

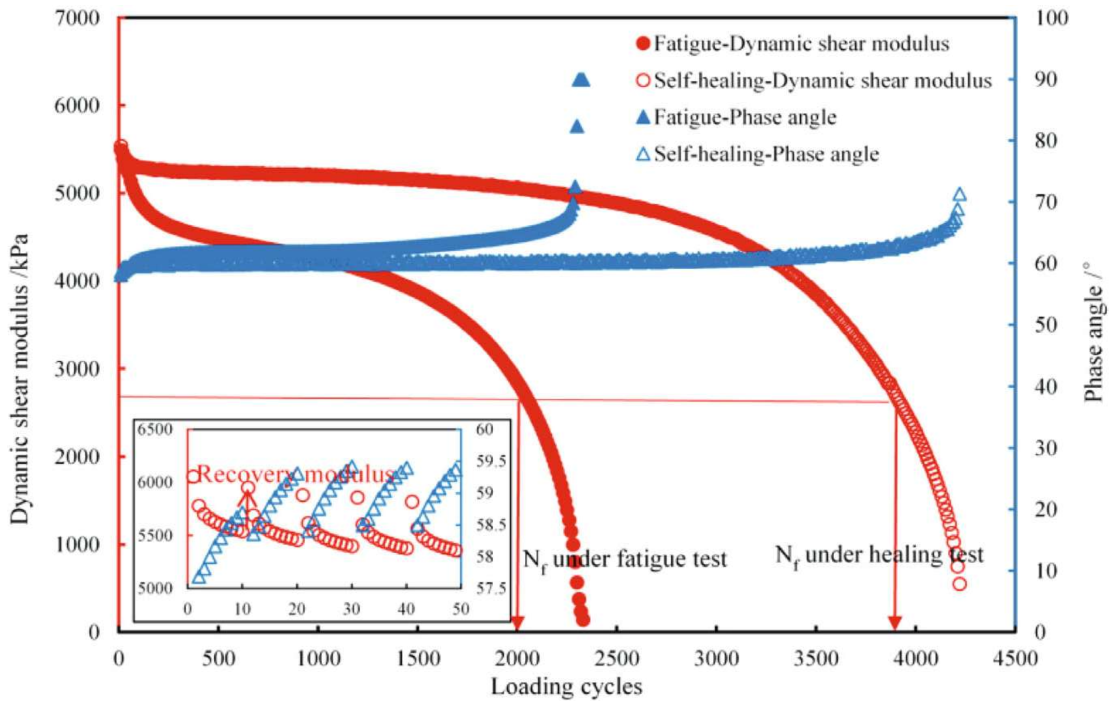

Fig. 6 Stiffness measured in dynamic shear fatigue test with intermittent rest periods of 2 s [60]

load level [67]. With these types of tests it is very important to double-check if the applied load signal is similar to the prescribed load signal as it may affect test results and lead to wrong conclusions.

An example of the response of an intermittent healing test is presented in Fig. 6. The two red lines in the figure represent the stiffness reduction as a result of pulse cycles and pulse-rest cycles. In the case of healing, the applied rest period is 2 s. The comparison among the red lines shows the gain in the material resistance due to healing.

The literature also presents hybrid healing tests, which are a combination of both healing test types, storage and intermittent healing tests. These protocols include multiple loading cycles followed by multiple rest cycles. In some cases, a hybrid loading regime is required as test equipment cannot realize one loading signal with several rest periods with sufficient accuracy. This was the case for tests performed by Van den Bergh [68]. To address this, he selected a protocol with 30 loading cycles followed by 90 rest cycles, giving him a loading-to-healing ratio of 3. However, a hybrid protocol can also aim to introduce not 1 large but 10 small rest periods of 2 min during a fatigue test [30].

Abo-Qudais and Suleiman [1] adopted the indirect tensile fatigue test by applying a cyclic constant load of 0.1s followed by a 0.4s rest period. When the stiffness was reduced by a quarter of the initial stiffness, samples were subjected to rest periods of 1 day and 3 h, 3 days, 7 days, and 14 days at five different temperatures (0, 15, 30, 45 and 60 °C), and retested again by the indirect tensile fatigue test. These specific test protocols are usually combined with a specific method to calculate the healing factor.

It can be claimed that the intermittent healing test resembles loading in practice closest. This loading application is thought to simulate better the intermittent nature of passing vehicles' axles. In reality, there is always a rest period between the loading of one axle to the next one and, of course, rest in between each truck passage. Unlike in intermittent testing, rest periods will not be constant but will vary depending on the moment in the day and days of the week. In practice, the load levels from trucks will vary, whereas they remain constant in laboratory conditions.

The healing measured using the storage healing method is not directly related to the load pattern in practice. It is sometimes suggested that this type of healing is representative of healing that occurs during the night when the loading frequency is reduced. However, more importantly, storage healing is assumed to correlate with healing that occurs in shorter rest periods and can distinguish between well and poor healing asphalts.

5 Healing Parameters

The analysis and modeling of data gathered by the testing configurations reported above comprise multiple data post-processing procedures based on different theoretical principles that practically determine the success of the methods.

From a general point of view, healing is defined as the measured performance of a damaged specimen after a healing period (f_{healed}), divided over the initial performance ($f_{initial}$), which results in a healing ratio (Hr) presented as Eq. (1).

$$Hr = \frac{f_{healed}}{f_{initial}} \tag{1}$$

When this formula is used, the healing ratio ranges from 0 to 1, where a healing ratio of 0 indicates no recovery, and a healing ratio of 1 indicates full recovery. Different material parameters can be evaluated to establish the restored performance. This strongly depends on the variables associated with the adopted testing methods. In most cases, stiffness-related parameters (S) are considered before and after the rest period. These can also be measured during the rest, thus tracking the evolution of the material restoration [55]. The same formula can be used to establish the restoration of the number of loads to failure (N). In this respect, it should be mentioned that most studies show a higher healing ratio when the stiffness is evaluated, compared to the number of loads to failure [36, 41, 46]. To address these shortcomings, many other techniques have been proposed to analyse the data of the healing tests based on energy ratios (dissipated energy (DE), dissipated energy ratio (DER), the ratio of dissipated energy change (RDEC)) [18, 28] or pseudo stiffness and internal state variables (S_d) [5, 36]. Such parameters can be adopted in fatigue-based tests such as dynamic shear tests in the context of asphalt binders, mastics and mortars. By specifically referring to two-piece asphalt specimens used in fracture-based dynamic shear tests, healing is assessed using the intrinsic healing function (R), which is related to the strength gain due to interfacial cohesion and interdiffusion of molecules at the microcrack faces. For asphalt mixtures, such parameters are linked to uniaxial tension–compression tests, three-point bending and four-point bending tests. In fracture-based approaches, the evaluation criteria adopted in the case of notched three-point bending tests include the peak load at fracture (F_p). Three and four-point bending tests are also implemented to determine the material flexural strength or bend strength (S_h) of a sample, representing the highest stress experienced within the material at its moment of rupture. In the case of semi-circular bending tests, the evaluation of healing includes multiple parameters: the peak load (F_p of the load–displacement curve; the fracture energy (E, which is the energy required to disrupt the interfacial adhesive and cohesive forces; the fracture toughness (FT, describing the material resistance to the propagation of the crack; the secant modulus (MS, dependent on the load–displacement curve; the deformation growth rate (D and the tensile strain growth rate (ε_r) of the material under load.

The peak load (F_p) of the load–displacement curve is also considered when considering the local fracture test of asphalt binders. In the case of the binder bonding strength test implemented at the scale of observation of binders, mastics, and mortars, the pull-off tensile strength (BS) is adopted for the healing assessment. When ductility tests are implemented, the length of break (L) is the considered parameter, which deals with the property of the binder undergoing plastic deformation when a pull force is applied without breaking. In the case of healing of asphalt binders and mastics based on a direct tension test, the fracture strength (S_h) of the original sample is compared to that of the re-fractured sample.

When evaluating the performance after a rest time, it should be kept in mind that it is also possible that the specimen gains strength or stiffness due to the aging process, which is taking place in the sample simultaneously. A test setup should be designed to correct this effect.

Regarding the degree of healing, storage healing tests using fatigue damage often don't report full restoration of the original mixture properties [19] unless rest periods are weeks or longer [12]. However, factors that improve the level of healing have been identified, such as an increased temperature during rest periods [9, 24].

In intermittent healing tests, the healing factor is usually defined as the ratio between the number of loads to failure with and without rest periods (N). If the healing factor is equal to 1, this indicates that the number of loads to failure has not increased by introducing rest periods, implying that no healing has occurred. As such a healing factor from this type of test cannot be compared to a healing factor from a storage healing test, as mentioned in Eq. (1), as a healing ratio of 1 will indicate full healing. Such a healing factor based on N can translate the result of a continuous fatigue test to a test with healing periods. These types of healing observations are often used to determine a healing factor that can be used in a pavement design procedure to translate the result from a continuous fatigue test in the laboratory to a performance in practice [67]. Such a factor can be used in dynamic shear tests and uniaxial Tension–Compression tests. Moreover, a hybrid healing test, combining both storage and intermittent healing approaches, can adopt the parameter N. In the indirect tensile test, the healing assessment can be defined based on the resilient modulus (MR), which is defined as the ratio of the applied stress to the recoverable strain during the application of repeated loads. As a non-destructive method, the ultrasonic pulse velocity (UPV) can be used to evaluate the material strength by measuring the velocity of an ultrasonic pulse passing through the mixture [7, 78]. In the case of the four-point bending fatigue test procedure, the ratio of dissipated energy change (RDEC) has been adopted. This is defined as the difference in dissipated energy between two successive loading cycles divided by the total number of cycles. The RDEC value at the 50% stiffness reduction point, referred to as plateau value (PV), is also considered a healing parameter.

6 Summary

Table 1 summarizes some of the studies carried out on the healing performances of asphalt binders (represented in italic), mastics (represented in bold), mortars (represented in bolditalic) and mixtures (represented in unbold roman, regular). Each study is characterized by the specific testing configurations schematically presented in Figs. 1, 2, 3, and 4, in the case of binder, mastic, mortar and mixture, respectively. Based on the scale of observations and the testing configuration, the healing potential (cohesive or adhesive) can be assessed. The testing configurations also determine the type of approach (fatigue-based or fracture-based) and the healing category (storage, intermittent or hybrid). Finally, based on the post-processing of data, the healing performance is defined through specific healing parameters.

Table 1 Research studies carried out on asphalt binder (represented in italic), mastic (represented in bold), mortar (represented in bolditalic) and mixture (represented in unbold roman, regular)

Authors	Healing mechanism	Damage approach	Testing configuration	Healing category	Healing parameter
Hammoum et al. [26]	*Cohesive*	*Fracture*	*(c)*	*Storage*	F_p
Lu et al. [37]	*Cohesive*	*Fatigue*	*(a)*	*Storage*	*S, N*
Lu et al. [37]	*Cohesive*	*Fatigue*	*(a)*	*Intermittent*	*N*
Bodin et al. [15]	*Cohesive*	*Fatigue*	*(a)*	*Storage*	*S*
Bhasin et al. [14]	*Cohesive*	*Fracture*	*(a)*	*Storage*	*R*
Shen and Sutharsan [58]	*Cohesive*	*Fatigue*	*(a)*	*Intermittent*	*RDEC*
Qiu et al. [48]	*Cohesive*	*Fatigue*	*(a)*	*Storage*	*S*
	Cohesive	*Fracture*	*(b)*	*Storage*	S_h
	Cohesive	*Fracture*	*(d)*	*Storage*	*L*
Tan et al. [65]	*Cohesive*	*Fatigue*	*(a)*	*Storage*	*S*
Santagata et al. [55]	*Cohesive*	*Fatigue*	*(a)*	*Storage*	*S, N*
Canestrari et al. [17]	*Cohesive*	*Fatigue*	*(a)*	*Storage*	*N*
Santagata et al. [54]	*Cohesive*	*Fatigue*	*(a)*	*Storage*	*N*
Pan et al. [43]	*Cohesive*	*Fracture*	*(b)*	*Storage*	F_p, *S, E*
Wang et al. [73]	*Cohesive*	*Fatigue*	*(a)*	*Storage*	S_d
Zhang et al. [76]	*Cohesive*	*Fatigue*	*(a)*	*Storage*	*S, N, DE*
	Cohesive	*Fracture*	*(d)*	*Storage*	*L*
Miglietta et al. [41]	*Cohesive*	*Fatigue*	*(a)*	*Storage*	*S, N*
Aurilio [7]	*Cohesive*	*Fracture*	*(a)*	*Storage*	*E*
Qiu et al. [50]	**Cohesive and adhesive**	**Fracture**	**(g)**	**Storage**	**Sh**
Qiu et al. [49]	**Cohesive and adhesive**	**Fracture**	**(g)**	**Storage**	**Fp**
Santagata et al. [56]	**Cohesive and adhesive**	**Fatigue**	**(e)**	**Storage**	**DE**
Huang et al. [27]	**Cohesive and adhesive**	**Fracture**	**(f)**	**Storage**	**BS**
Lv et al. [39]	**Adhesive**	**Fracture**	**(f)**	**Storage**	**BS**
Al-Mansoori et al. [3]	**Cohesive and adhesive**	**Fatigue**	**(h)**	**Storage**	**F**

(continued)

Table 1 (continued)

Authors	Healing mechanism	Damage approach	Testing configuration	Healing category	Healing parameter
Lv et al. [38]	**Adhesive**	**Fracture**	**(f)**	**Storage**	**BS**
Wang et al. [72]	**Adhesive**	**Fracture**	**(f)**	**Storage**	**BS**
Shi et al. [60]	**Cohesive and adhesive**	**Fatigue**	**(e)**	**Intermittent**	**S**
Van den Bergh and Van de Ven [68]	***Cohesive and adhesive***	***Fatigue***	***(i)***	***Hybrid***	***N***
Apostolidis et al. [4]	***Cohesive and adhesive***	***Fracture***	***(l)***	***Storage***	***F***
Pan et al. [43]	***Cohesive and adhesive***	***Fracture***	***(k)***	***Storage***	F_p, ***S, E***
Grossegger and Garcia [25]	***Cohesive and adhesive***	***Fracture***	***(l)***	***Storage***	***F***
Zhang et al. [77]	***Cohesive and adhesive***	***Fracture***	***(j)***	***Storage***	***BS***
Breysse et al. [16]	Cohesive and adhesive	Fatigue	(p)	Intermittent	S
Abo-Qudais and Suleiman [1]	Cohesive and adhesive	Fatigue	(n)	Hybrid	UPV
Carpenter and Shen [18]	Cohesive and adhesive	Fatigue	(r)	Intermittent	RDEC, PV
Cheng et al. [20]	Cohesive and adhesive	Fatigue	(n)	Storage	MR
Riara et al. [52]	Cohesive and adhesive	Fracture	(o)	Storage	F_p, FT, S, E
Aguirre et al. [2]	Cohesive and adhesive	Fatigue	(q)	Storage	S_h
Jiang et al. [29]	Cohesive and adhesive	Fracture	(o)	Storage	N, MS, RDEC, D, ε_r
Sun et al. [63]	Cohesive and adhesive	Fatigue	(n)	Intermittent	MR
Xiang et al. [70]	Cohesive and adhesive	Fatigue	(r)	Storage	S, N
Ashouri et al. [5]	Cohesive and adhesive	Fatigue	(m)	Intermittent	S_d
Aurilio [7]	Cohesive and adhesive	Fatigue	(m)	Intermittent	S_d, N, UPV

(continued)

Table 1 (continued)

Authors	Healing mechanism	Damage approach	Testing configuration	Healing category	Healing parameter
Zhao [78]	Cohesive and adhesive	Fatigue	(m)	Intermittent	S, UPV
Zhao [78]	Cohesive and adhesive	Fatigue	(n)	Intermittent	S, UPV

BS pull-off tensile strength, *DE* dissipated energy, DER dissipated energy ratio, *D* deformation, *E* fracture energy, *F* fracture force, F_p peak load, *FT* fracture toughness, *L* length at break, *MR* resilient modulus, *MS* secant modulus, *N* number of loading cycles, *PV* plateau value, *R* intrinsic healing, *RDEC* ratio of dissipated energy change, *S* stiffness-related parameter, S_d internal damage state variable, S_h strength, *UPV* ultrasound pulse velocity, ε_r tensile strain

References

1. Abo-Qudais, S., & Suleiman, A. (2005). Monitoring fatigue damage and crack healing by ultrasound wave velocity. *Nondestructive Testing and Evaluation, 20*(2), 125–145.
2. Aguirre, M. A., Hassan, M. M., Shirzad, S., Cooper, S., Jr., Mohammad, L. N., & Negulescu, I. I. (2019). Laboratory testing of self-healing fibers in asphalt mixtures prepared with recycled materials. *Transportation Research Record, 2673*(4), 513–523.
3. Al-Mansoori, T., Norambuena-Contreras, J., Micaelo, R., & Garcia, A. (2018). Self-healing of asphalt mastic by the action of polymeric capsules containing rejuvenators. *Construction and Building Materials, 161*, 330–339.
4. Apostolidis, P., Liu, X., Scarpas, A., Kasbergen, C., & Van De Ven, M. F. C. (2016). Advanced evaluation of asphalt mortar for induction healing purposes. *Construction and Building Materials, 126*, 9–25.
5. Ashouri, M., Wang, Y., Choi, Y. T., & Kim, Y. (2021). Development of healing model and simplified characterization test procedure for asphalt concrete. *Construction and Building Materials, 271*, 121515.
6. Aurilio, R. M., Aurilio, M., & Baaj, H. (2021). The effect of a chemical warm mix additive on the self-healing capability of bitumen. *Journal of Testing and Evaluation, 50*(2).
7. Aurilio, R. M. (2023). *Investigating and developing fatigue-healing characterization of asphalt materials* [Ph.D. Thesis]. University of Waterloo.
8. Ayar, P., Moreno-Navarro, F., & Rubio-Gámez, M. C. (2016). The healing capability of asphalt pavements: A state of the art review. *Journal of Cleaner Production, 113*, 28–40.
9. Baaj, H. (2002). *Comportement à la fatigue des matériaux granulaires traités aux liens hydrocarbons*. INSA.
10. Bahadori, A. M., Mansourkhaki, A., & Ameri, M. A. (2014). Phenomenological fatigue performance model of asphalt mixtures based on fracture energy density. *Journal of Testing and Evaluation, 43*(1), 133–139.
11. Bahia, H. U., Zhai, H., Bonnetti, K., & Kose, S. (1999). Non-linear viscoelastic and fatigue properties of asphalt binders. *J Assoc Asph Pav Tech, 68*, 1–34.
12. Bazin, P., & Saunier, J. (1967). Deformability, fatigue and healing properties of asphalt mixes. In *International conference on the structural design of asphalt pavements*.
13. Bhasin, A., & Little, D. N. (2009). Application of microcalorimeter to characterize adhesion between asphalt binders and aggregates. *Journal of Materials in Civil Engineering, 21*(6), 235–243.
14. 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*(sup1), 219–242.

15. Bodin, D., Soenen, H., & de La Roche, C. (2004). Temperature effects in binder fatigue and healing tests. In *Eurasphalt & Eurobitume Congress, Vienna* (Vol. 82).
16. Breysse, D., De La Roche, C., Domec, V., & Chauvin, J. J. (2003). Influence of rest time on recovery and damage during fatigue tests on bituminous composites. *Materials and Structures, 36*(10), 648–651.
17. Canestrari, F., Virgili, A., Graziani, A., & Stimilli, A. (2015). Modeling and assessment of self-healing and thixotropy properties for modified binders. *International Journal of Fatigue, 70*, 351–360.
18. Carpenter, S., & Shen, S. (2006). Dissipated energy approach to study hot-mix asphalt healing in fatigue. *Trans Res Rec, 1970*, 178–185.
19. Castro, M., & Sánchez, J. A. (2006). Fatigue and healing of asphalt mixtures: Discriminate analysis of fatigue curves. *Journal of Transportation Engineering, 132*, 168–174.
20. Chen, Y., Simms, R., Koh, C., Lopp, G., & Roque, R. (2013). Development of a test method for evaluation and quantification of healing in asphalt mixture. *Road materials and pavement design, 14*(4), 901–920.
21. Dai, Q., Wang, Z., & Mohd Hasan, M. R. (2013). Investigation of induction healing effects on electrically conductive asphalt mastic and asphalt concrete beams through fracture-healing tests. *Construction and Building Materials, 49*, 729e737.
22. Di Benedetto, H., de La Roche, C., Baaj, H., Pronk, A., & Lundström, R. (2004). Fatigue of bituminous mixtures. *Materials and Structures, 37*(3), 202–216.
23. Gong, M., Yang, J., Wei, J., & Zhu, W. (2015). Characterization of adhesion and healing at the interface between asphalt binders and aggregate using atomic force microscopy. *Transportation Research Record, 2506*(1), 100–106.
24. Grant, T. P. (2001). *Determination of asphalt mixture healing rate using the Superpave indirect tensile test*. University of Florida.
25. Grossegger, D., & Garcia, A. (2019). The effect of water and pressure on the self-healing of macro cracks in asphalt mortar beams. *Construction and Building Materials, 229*, 116941.
26. Hammoumm, F., Piau, J., & Stefani, C. (2002). *Experimental investigation of fracture and healing of bitumen at pseudo-contract of two aggregates.*
27. Huang, W., Lv, Q., & Xiao, F. (2016). Investigation of using binder bond strength test to evaluate adhesion and self-healing properties of modified asphalt binders. *Construction and Building Materials, 113*, 49–56.
28. Isailović, I., Wistuba, M. P., & Falchetto, A. C. (2017). Influence of rest period on asphalt recovery considering nonlinearity and self-heating. *Construction and Building Materials, 140*, 321–327.
29. Jiang, J., Ni, F., Wu, F., Sadek, H., & Lv, Q. (2019). Evaluation of the healing potential of asphalt mixtures based on a modified semi-circular bending test. *Construction and Building Materials, 196*, 284–294.
30. Kim, Y. R., Little, D. N., & Lytton, R. L. (2003). Fatigue and healing characterization of asphalt mixtures. *Journal of Materials in Civil Engineering, 15*(1), 75–83.
31. Kim, Y., Allen, D. H., & Little, D. N. (2007). Computational constitutive model for predicting nonlinear viscoelastic damage and fracture failure of asphalt concrete mixtures. *International Journal of Geomechanics, 7*, 102–110.
32. Lee, H. J., Daniel, J. S., & Kim, Y. R. (2000). Continuum damage mechanics-based fatigue model of asphalt concrete. *Journal of Materials in Civil Engineering, 105*, 1005–1112.
33. Leegwater, G. A., Scarpas, A., & Erkens, S. M. J. G. (2018). The influence of boundary conditions on the healing of bitumen. *Road Materials and Pavement Design, 19*, 571–580.
34. Leegwater, G., Taboković, A., Baglieri, O., Hammoum, F., & Baaj, H. (2020). Terms and definitions on crack-healing and restoration of mechanical properties in bituminous materials. In *RILEM international symposium on bituminous materials* (pp. 47–53). Springer.
35. Li, Q., Jong, L. H., & Kim, T. W. (2012). A simple fatigue performance model of asphalt mixtures based on fracture energy. *Construction and Building Materials, 27*(1), 605–611.
36. Little, D. N., Bhasin, A., & Darabi, M. K. (2015). Damage healing in asphalt pavements: Theory, mechanisms, measurement, and modeling. In *Advances in asphalt materials: road and pavement construction.*

37. Lu, X., Soenen, H., & Redelius, P. (2003). Fatigue and healing characteristics of bitumens studied using dynamic shear rheometer. In *6th RILEM Symposium PTEBM* (Vol. 3).
38. Lv, Q., Huang, W., Zheng, M., Hao, G., Yan, C., & Sun, L. (2020). Investigating the asphalt binder/mastic bonding healing behavior using bitumen bonding strength test and X-ray Computed Tomography scan. *Construction and Building Materials, 257*, 119504.
39. Lv, Q., Huang, W., Zhu, X., & Xiao, F. (2017). On the investigation of self-healing behavior of bitumen and its influencing factors. *Materials and Design, 117*, 7–17.
40. Mazzoni, G., Stimilli, A., Cardone, F., & Canestrari, F. (2017). Fatigue, self-healing and thixotropy of bituminous mastics including aged modified bitumens and different filler contents. *Construction and Building Materials, 131*, 496–502.
41. Miglietta, F., Tsantilis, L., Baglieri, O., & Santagata, E. (2021). A new approach for the evaluation of time-temperature superposition effects on the self-healing of bituminous binders. *Construction and Building Materials, 287*, 122987.
42. Nejad, F. M., Hamedi, G. H., & Azarhoosh, A. R. (2013). Use of surface free energy method to evaluate effect of hydrate lime on moisture damage in got mix asphalt. *Journal of Materials in Civil Engineering., 25*(8), 1119–1126.
43. Pan, C., Tang, P., Riara, M., Mo, L., Li, M., & Guo, M. (2018). Effect of healing agents on crack healing of asphalt and asphalt mortar. *Materials (Basel), 11*, 1373.
44. Park, K., & Paulino, G. H. (2013). Cohesive zone models: A critical review of traction–separation relationships across fracture surfaces. *Applied Mechanics Reviews, 64*, 1–20.
45. Pronk, A. C.: Partial healing—a new approach for the damage process during fatigue testing of asphalt specimen. In *Asphalt concrete: simulation, modeling, and experimental characterization* (2006).
46. 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.
47. Qiu, X., Cheng, W., Xu, W., Xiao, S., & Yang, Q. (2020). Fatigue evolution characteristic and self-healing behaviour of asphalt binders. *International Journal of Pavement Engineering*, 1–12.
48. Qiu, J., Van de Ven, M. F. C., Wu, S., Yu, J., & Molenaar, A. A. A. (2009). Investigating the self healing capability of bituminous binders. *Road Materials and Pavement Design, 10*(sup1), 81–94.
49. Qiu, J., Van de Ven, M. F., Wu, S., Molenaar, A. A., & Yu, J. (2014). Self-healing characteristics of bituminous mastics using a modified direct tension test. *Journal of Intelligent Material Systems and Structures, 25*, 58–66.
50. Qiu, J., Van de Ven, M., Wu, S., Yu, J., & Molenaar, A. (2012). Evaluating self-healing capability of bituminous mastics. *Experimental Mechanics, 52*(8), 1163–1171.
51. Radeef, H. R., Abdul Hassan, N., Zainal Abidin, A. R., Mahmud, M. Z. H., Mohd Satar, M. K. I., Mohd Warid, M. N., & Al Saffar, Z. H. (2021). Determining fracture energy in asphalt mixture: A review. *Conference Series: Earth and Environmental Science, 682*(1), 12069 (2021).
52. Riara, M., Tang, P., Mo, L., Javilla, B., Chen, M., & Wu, S. (2018). Systematic evaluation of fracture-based healing indexes of asphalt mixtures. *Journal of Materials in Civil Engineering, 30*(10), 04018264.
53. Rondón, H. A., Zafra, C. A., & Reyes, F. A. (2021). Fatigue in asphalt mixtures—A summary to understand the complexity of its mathematical modeling. *Journal of Physics: Conference Series, 2118*, 012009.
54. Santagata, E., Baglieri, O., Dalmazzo, D., & Tsantilis, L. (2017). Investigating cohesive healing of asphalt binders by means of a dissipated energy approach. *International Journal of Pavement Research and Technology, 10*(5), 403–409.
55. 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.
56. Santagata, E., Baglieri, O., Tsantilis, L., Dalmazzo, D., & Chiappinelli, G. (2016). Fatigue and healing properties of bituminous mastics reinforced with nano-sized additives. *Mechanics of Time-Dependent Materials, 20*(3), 367–387.

57. Shen, S., Chiu, H. M., & Huang, H. (2010). Characterization of fatigue and healing in asphalt binders. *Journal of Materials in Civil Engineering, 22*(9), 846–852.
58. Shen, S., & Sutharsan, T. (2011). Quantification of cohesive healing of asphalt binder and its impact factors based on dissipated energy analysis. *Road Materials and Pavement Design, 12*(3), 525–546.
59. Saha, G., & Biligiri, K. P. (2015). Fracture damage evaluation of asphalt mixtures using Semi-Circular Bending test based on fracture energy approach. *Engineering Fracture Mechanics, 142*, 154–169.
60. Shi, C., Luo, R., Liu, H., & Yang, J. (2021). Evaluation of self-healing characteristics of asphalt materials by intermittent loading tests. *Road Materials and Pavement Design.*
61. Song, I., Little, D. N., Masad, E. A., & Lytton, R. L. (2005). Comprehensive evaluation of damage in asphalt mastics using X-ray CT, continuum mechanics, and micromechanics (with discussion). *Asphalt Paving Technology, 74.*
62. Sun, G., Hu, M., Sun, D., Deng, Y., Ma, J., & Lu, T. (2020). Temperature induced self-healing capability transition phenomenon of bitumens. *Fuel, 263*, 116698.
63. Sun, G., Sun, D., Guarin, A., Ma, J., Chen, F., & Ghafooriroozbahany, E. (2019). Low temperature self-healing character of asphalt mixtures under different fatigue damage degrees. *Construction and Building Materials, 223*, 870–882.
64. Sun, D., Sun, G., Zhu, X., Guarin, A., Li, B., Dai, Z., & Ling, J. (2018). A comprehensive review on self-healing of asphalt materials: Mechanism, model, characterization and enhancement. *Advances in Colloid and Interface Science, 256*, 65–93.
65. Tan, Y., Shan, L., Kim, Y. R., & Underwood, B. S. (2012). Healing characteristics of asphalt binder. *Construction and Building Materials, 27*(1), 570–577.
66. Underwood, B. S., Kim, Y. R., & Guddati, M. N. (2010). Improved calculation method of damage parameter in viscoelastic continuum damage model. *International Journal of Pavement Engineering, 11*(6), 459–476.
67. Van den Bergh, W. (2011). *The effect of ageing on the fatigue and healing properties of bituminous mortars.*
68. Van den Bergh, W., & Van de Ven, M. F. C. (2012). The influence of ageing on the fatigue and healing properties of bituminous mortars. *Procedia-Social and Behavioral Sciences, 53*, 256–65.
69. Varma, R., Balieu, R., & Kringos, N. (2021). A state-of-the-art review on self-healing in asphalt materials: Mechanical testing and analysis approaches. *Construction and Building Materials, 310*, 125197.
70. Xiang, H., Zhang, W., Liu, P., & He, Z. (2020). Fatigue-healing performance evaluation of asphalt mixture using four-point bending test. *Materials and Structures, 53*, 1–10.
71. Xie, W., Castorena, C., Wang, C., & Kim, Y. R. (2017). A framework to characterize the healing potential of asphalt binder using the linear amplitude sweep test. *Construction and Building Materials, 154*, 771–779.
72. Wang, C., Chen, Y., & Gong, G. (2021). Cohesive and adhesive healing evaluation of asphalt binders by means of the LASH and BBSH tests. *Construction and Building Materials, 282*, 122684.
73. Wang, C., Xie, W., & Underwood, B. S. (2018). Fatigue and healing performance assessment of asphalt binder from rheological and chemical characteristics. *Materials and Structures, 51*(6), 1–12.
74. Williams, D., Little, D. N., Lytton, R. L., Kim, Y. R., & Kim, Y. (2001). *Microdamage healing in asphalt and asphalt concrete, volume II: Laboratory and field testing to assess and evaluate microdamage and microdamage healing.* No. FHWA-RD-98-142.
75. Wool, R. P., & O'Connor, K. M. (1981). A theory crack healing in polymers. *Journal of Applied Physics, 52*, 5953–5963.
76. Zhang, H., Bai, Y., & Cheng, F. (2018). Rheological and self-healing properties of asphalt binder containing microcapsules. *Construction and Building Materials, 187*, 138–148.
77. Zhang, H., Li, H., Abdelhady, A., Mo, D., Yang, B., & Harvey, J. (2019). Optimum filler–bitumen ratio of asphalt mortar considering self-healing property. *Journal of Materials in Civil Engineering, 31*(8), 04019166.

78. Zhao, D. (2023). *Development and evaluation of testing protocols for fatigue damage and crack-healing of bituminous mixtures [Ph.D. Thesis]*. University of Waterloo.