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Exploring Damage Recovery in Bituminous Mixtures: An Analysis of Healing Technologies

TESIS DOCTORAL

Doctorando:

Pooyan Ayar

Directores:

Dr. Mª Carmen Rubio Gámez **Dr. Fernando Moreno Navarro**

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Exploring Damage Recovery in Bituminous Mixtures: An Analysis of Healing Technologies

A dissertation submitted by

Pooyan Ayar

In partial fulfilment of the requirements for the degree of Doctor of Philosophy (Ph.D.) in Civil Engineering

Supervisors:

Dr. Mª Carmen Rubio Gámez **Dr. Fernando Moreno Navarro**

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Declaration of authorship

Mr. Pooyan Ayar, as PhD Candidate, and Dr. Mª Carmen Rubio Gámez and Dr. Fernando Moreno Navarro, as PhD Supervisors and Professors of the University of Granada in Spain,

Guarantee by signing this thesis:

that the research work contained in the present report, entitled **Exploring Damage Recovery in Bituminous Mixtures: An Analysis of Healing Technologies**, has been performed under the full guidance of the PhD Supervisors and, as far as our knowledge reaches, during the work, it has been respected the right of others authors to be cited, when their publications or their results have been used.

Granada, Spain, 10/07/2017

PhD Supervisors:

Dr. Mª Carmen Rubio Gámez

Dr. Fernando M. Moreno Navarro

PhD candidate:

Mr. Pooyan Ayar

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Abstract

In recent years, the analysis of the recovery capability of bituminous mixtures has become an important research topic in the field of pavement engineering. This capability is recognized as a foundation for the development of long-life asphalt pavements. Nonetheless, if this ability is to be exploited to develop new rehabilitation techniques for road infrastructures, there still remain some questions that need to be addressed. The recovery of properties in bituminous materials mainly produced by various phenomena: reversible phenomena (e.g., thixotropy and heating,) and the healing phenomenon (understood as the reestablishment of the broken molecular bonds). However, in spite of the fact that there are many studies that have assessed the effect caused by these phenomena, relatively little is still known about their real efficiency, or which of these have the greatest impact on recovery capacity along with their repeatability (if they are to be used as a basis for developing rehabilitation techniques, these phenomena should be able to produce a similar level of damage recovery several times). In this respect, it is also interesting to consider that these phenomena are highly related to the damage state of the material (reversible phenomena are more prominent before crack initiation, whilst the healing phenomenon can appear when the crack is produced), and consequently it is necessary to determine the optimal damage state at which the rehabilitation techniques should be applied. Finally, it should be considered that the majority of rehabilitation techniques based on the recovery capability of asphalt materials are primarily affected by three variables (duration, temperature, and external forces), and because of this, it is of critical importance to determine the optimal conditions for these variables. These optimal conditions will be directly related to the characteristics of the asphalt material, and therefore it is also necessary to know the relationship between time, temperature and external forces, and the various types of bituminous binders.

Based on these considerations, this research aims to study the recovery capability of bituminous materials at various levels of damage, taking into account the influence of several variables such as time, temperature, external forces, and rest periods. Thus, to explore the recovery due to healing phenomenon, different types of asphalt mixtures were tested under various conditions until their macro-failure by employing the University of Granada Fatigue Asphalt Cracking Test (UGR-FACT), after which various conditions were applied in order to induce their recovery (applying heating and external forces) under different treatment durations. In addition, to explore the role of recovery capability due to reversible phenomena, the asphalt material was tested using UGR-FACT by introducing different types of rest periods.

The results indicated that among the variables that could affect the recovery capability of the material at the macro-crack level, the duration of the healing treatment has little impact, while the type and amount of binder could have more influence than temperature. Additionally, the presence of external forces during the healing treatment could increase the rate of recovery, but it is not sufficiently effective to recover the initial properties of the material. Thus, regardless of the type of treatment, the amount of fatigue life recovered in macro-damaged asphalt mixtures is low, prompting the suggestion that although applying these healing techniques can close the macro-crack, completely effective healing appears to be more difficult to achieve.

Furthermore, the results indicated that the presence of rest periods in the loading regime could lead to an increase in the fatigue life of asphalt mixtures when they are included before the appearance of cracks. In particular, it appears that an increment in the rest period duration and if they are included before the capacity to deform of the material is consumed could improve the resistance of the materials tested against cyclic loading. In this respect, the recovery produced during rest periods are not only related to reversible phenomena, but also to the delay of damage because of an increment in the plastic deformations produced (the inclusion of rest periods could increase the amount of deformations produced in the material, leading to a more ductile response and subsequently more number of load cycles can be supported).

Keywords: Bituminous mixture, Fatigue, Healing, Heating, Rest period, Thixotropy, UGR-FACT.

Resumen

En los últimos años, el análisis de la capacidad de recuperación de mezclas bituminosas se ha convertido en un importante tema de investigación en el campo de la ingeniería de pavimentos. Esta capacidad está reconocida como uno de los pilares en el desarrollo de pavimentos con una larga vida de servicio. No obstante, si se quiere usar esta habilidad en el desarrollo de nuevas técnicas de rehabilitación para infraestructuras de carretera, existen aún algunas cuestiones que necesitan ser resueltas. La recuperación de daño en materiales bituminosos está principalmente producida por dos tipos diferentes de fenómenos: fenómenos reversibles (i.e. tixotropía, calentamiento, etc.) y fenómenos de "healing" (entendidos como el restablecimiento de los enlaces moleculares rotos). Sin embargo, a pesar de que existen muchos estudios que han evaluado el efecto causado por estos, actualmente aún no se conoce su eficiencia real o cuáles de ellos tienen un mayor impacto en la capacidad de recuperación, como tampoco su repetibilidad (si se desea aplicarlos para dar lugar a técnicas de rehabilitación, estos fenómenos deben ser capaces de producir una recuperación de daño similar en diversas ocasiones). Respecto a esto, es también interesante considerar que estos fenómenos están muy relacionados con el estado de daño del material (los fenómenos reversibles están más presentes antes del inicio de la fisura, mientras que los fenómenos de "healing" pueden aparecer cuando se ha producido la misma), y por ello es necesario determinar el estado óptimo de daño en el que se aplicarán las técnicas de rehabilitación (con el objetivo de aprovechar los fenómenos más efectivos para la recuperación de daño). Finalmente, se debe tener en cuenta que la mayoría de las técnicas de rehabilitación basadas en la capacidad de recuperación de los materiales bituminosos se ven afectadas principalmente por tres variables (duración, temperatura y fuerzas externas) y, a causa de ello, la determinación de las condiciones óptimas para dichas variables es crucial. Estas condiciones óptimas estarán directamente ligadas a las características del material bituminoso y, por ello, será también necesario conocer la relación entre tiempo, temperatura y fuerzas externas, y los diferentes tipos de ligantes bituminosos.

Basándose en estas consideraciones, este trabajo pretende estudiar la capacidad de recuperación de materiales bituminosos para diferentes niveles de daño, teniendo en cuenta la influencia de diversas variables como tiempo, temperatura, fuerzas externas y periodos de descanso. De este modo, para explorar la recuperación debida a los fenómenos de "healing", distintos tipos de mezcla bituminosa fueron ensayados bajo diversas condiciones hasta su fallo por macro-fisuración empleando el "Ensayo para la evaluación del comportamiento a fisuración de mezclas bituminosas (UGR-FACT)", y tras ello, se aplicaron diferentes tipos de acondicionamiento para inducir su recuperación (aplicando calor y fuerzas externas) bajo distintas duraciones del tratamiento. Además, para explorar el papel de la capacidad de recuperación debida a fenómenos reversibles, el material bituminoso fue de nuevo ensayado usando el ensayo UGR-FACT introduciendo distintos tipos de periodo de descanso.

Los resultados indicaron que entre las variables que pueden afectar la capacidad de recuperación del material a nivel de macro-fisuración, la duración de los tratamientos de "healing" tiene poco impacto mientras que el tipo y la cantidad de ligante empleado puede tener más influencia que la temperatura. Sumado a esto, la presencia de fuerzas externas durante el tratamiento de "healing" puede incrementar la tasa de recuperación, pero no es lo bastante efectiva como para recuperar las propiedades iniciales del material. De esta forma, independientemente del tipo de tratamiento, la cantidad de vida de fatiga recuperada para mezclas bituminosas macro dañadas es baja y consecuentemente, se puede afirmar que aplicando estas técnicas de "healing", las macrofisuras pueden cerrarse pero parece difícil que se produzca la curación de estas de manera efectiva (los materiales no pueden recuperar sus propiedades iniciales).

Además, los resultados indicaron que la presencia de periodos de descanso durante el régimen de aplicación de cargas puede conducir a un aumento en la vida de fatiga de las mezclas bituminosas cuando estos se incluyen antes de la aparición de fisuras. En particular, parece que un incremento en la duración de los periodos de descanso y si estos son incorporados antes de que la capacidad de deformación del material se haya agotado, podría mejorar la resistencia de los materiales ensayados frente a cargas cíclicas. Respecto a esto, la recuperación producida durante los periodos de descanso

no está únicamente relacionada con los fenómenos reversibles sino que también lo está con el retraso del daño debido al incremento de las deformaciones plásticas producidas (la inclusión de periodos de descanso puede incrementar la cantidad total de deformaciones plásticas que se producen en el material dando lugar a una respuesta más dúctil y a una mayor cantidad de ciclos de carga soportados).

Palabras clave: Mezcla bituminosa, Fatiga, Healing, Calentamiento, Período de descanso, Tixotropía, UGR-FACT.

Contents

List of tables

List of figures

Notations

VA	Air Void
BOEF	Beam on Elastic Foundation
CII	Colloid Instable Index
DEA	Dissipated Energy Approach
DMA	Dynamic Mechanical Analyser
DSR	Dynamic Shear Rheometer
FAM	Fine Aggregate Matrix
FTIR	Fourier transform infrared spectra
4PB	Four-Point Bending Test
HI	Healing Index
IDT	Indirect Tensile Test
LVDT	Linear Variable Differential Transformer
MMHC	Methylene Plus Methyl hydrogen to Carbon Ratio
CH_2/CH_3	Methylene to Methyl Group Ratio
MMLS3	Model Mobile Load Simulator
PCI	Pavement Condition Index
PI	Penetration Index
3PB	Three-Point Bending Test
RAP	Reclaimed Asphalt Pavements
SEM	Scanning Electron Microscopy
SMA	Stone Matrix Asphalt
SBR	Styrene Butadiene Rubber
2PB	Two- Point Bending Test
TPH	Two-Piece Healing

Introduction

1 Introduction

1.1 Problem statement

In many countries, road transportation systems play an important role in socioeconomic development. The performance of these systems, therefore, can directly or indirectly affect the operation of a society's economy. Nonetheless, the performance of pavement infrastructures as an integral part of the road networks could also influence the whole performance and the efficiency of these systems.

Road pavements (which, worldwide, are mostly constructed using asphaltic materials) should sustain the traffic loads as well as be able to tolerate destructive environmental conditions (e.g. moisture, aging, fuel etc.). Additionally, pavement infrastructures must always provide an appropriate level of serviceability to meet the safety criteria of traffic flow and to satisfy the convenience of the road users.

As the age of the asphalt pavement increases, its serviceability declines, and to achieve an appropriate level of service a regular and efficient maintenance program is essential. In this respect, highway agencies spend a considerable proportion of their budgets on maintaining their pavement infrastructures. On some occasions, however, maintenance activities cause disruption to traffic flow, which may lead to certain economic and/or social consequences (particularly in arterial roads).

To overcome the social, environmental, and economic problems related to pavement maintenance, researchers have introduced various methods designed to maintain pavements in easy and effective ways. One of the most recent and notable methods for maintaining asphalt pavements is based on enhancing the recovery capability of the material through various rehabilitation technologies. In relation to this issue, some researchers have proposed that the recovery capability of asphalt pavements which essentially stems from the recovery capability of bituminous binder could be induced by certain healing technologies such as induction heating and healing agents.

The main idea that underpins the use of these healing technologies (e.g., the heating technique) is to induce the recovery capability of asphalt pavements, which could reduce the level of damage (i.e. recover some mechanical properties) and subsequently could extend the service life of the pavement as well preserve an adequate standard of serviceability. On the whole, these technologies are viewed as beneficial from both an environmental and economic standpoint.

However, it is necessary to remember that recovery of the mechanical properties in asphalt pavements is a complex issue. This is due to the fact that the recovery could occur as a result of different phenomena such as “real” healing and “reversibility” of the microstructures in the bituminous binder. In this respect, the effects of reversible phenomena are more obvious before crack initiation, whilst the healing phenomenon can appear when the damage has been generated in the bituminous material. It should also be noted that it is still not clear which of these phenomena has the greatest impact on recovery capability.

Therefore, it is important to focus on the distinction between these phenomena that are responsible for the recovery capability in asphalt pavements. Additionally, a better understanding of recovery capability in asphalt pavements could be of importance in helping to develop more realistic pavement designs. In fact, it is important to study which type of phenomena can potentially be effective and how they can influence the performance of asphalt pavements at different levels of damage, as well as which type of properties can be recovered as result of these processes. Given that a number of other factors could also influence the recovery capability, the study of these appears to be of paramount importance. Consequently, without a comprehensive understanding of the factors underlying the recovery capability of asphalt pavements, the feasibility and effectiveness of these healing technologies would remain unclear. In this context, one question of interest is whether application of healing technologies can effectively extend the service life or improve the level of serviceability, whilst a further important issue that also needs to be addressed is whether the resources used to apply healing technologies are technically and economically justifiable.

Taking into account these challenges, this research aims to explore the role of different phenomena in bituminous mixtures that could contribute to the recovery of mechanical properties and the subsequent extension of its service life at different levels of damage (i.e. micro and macro). Additional objectives of this study include are to examine the effectiveness of healing technologies in recovering mechanical properties under different service conditions (and using different materials), as well as finding the optimum conditions for applying these technology.

1.2 Content of the dissertation

This dissertation consists of eight chapters. The content of each chapter is described below:

Chapter 1 includes a concise introduction to clarify the necessity of the present work, as well as a brief description of the content of each chapter.

Chapter 2 provides a review of the related literature, which is important for defining the methodology of this research. This chapter reviews the state of the art of various fields including techniques for road maintenance based on the recovery capability of bitumen, studying the recovery capability of bituminous materials, factors influencing the recovery of properties in bituminous materials, along with healing technologies and other phenomena that can lead to the recovery of properties in bitumen. The end of this chapter presents an analytical conclusion of the reviewed literature.

Chapter 3 introduces the objectives of this research, which is based on the analytical conclusion of the literature presented in Chapter 2.

To meet the introduced objectives, Chapter 4 presents the methodology of this research. This description of the methodology serves to explain the materials and experimental procedures employed in this study. This chapter consists of two main sections, which separately describe the methodology used to study the recovery capability in bituminous mixtures at the macro and micro levels of damage.

Following the steps outlined in the methodology, the results are presented in Chapter 5. The results were analysed according to the findings of previous researchers, as well as the characteristics of the materials used.

Based on the analyses of the findings and in accord with the objectives, the overall conclusions of this study are presented in Chapter 6.

Chapter 7 presents some suggestions for a variety of future research lines that could potentially complete this study, particularly with respect to the recovery capability of bituminous mixtures. In fact, the novel lines of research suggested could provide a more effective contribution to current knowledge.

Chapter 8 is the final chapter of the current dissertation and lists the cited references that were used throughout all stages of this research.

State of the art

2 State of the art

2.1 Techniques for maintenance based on recovery capability of bitumen

Transportation systems can affect the patterns of urban and regional development (Iacono and Levinson, 2016) and generally these systems, including the highway network, can be considered as a vital component of a nation's economy, providing the mobility of people, goods, and services (Aldrich et al., 2015, Shatz et al., 2011). In this regard, pavement infrastructures constitute an inseparable part of the highway network and should be able to sustain traffic loads, as well as withstand degradations caused by environmental conditions (Van Dam et al., 2015).

Asphalt pavements are typically used for road construction (Tabaković & Schlangen, 2015), and more than 90% of roads in Europe and 92% in the U.S. have been constructed with asphalt materials (EAPA and NAPA, 2011). According to recent data, Europe and the U.S. produced 278.8 and 331 million tons of asphalt mixtures (i.e. hot and warm asphalt mixtures) respectively in 2015 (Figure 1) (EAPA, 2017).

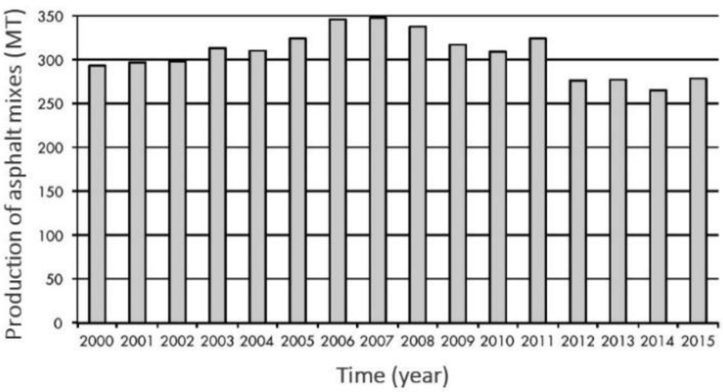

Figure 1: Total production of hot and warm asphalt mixtures (in Megatons) from 2000 to 2015 in the Europe (EAPA, 2017).

During the lifespan of the asphalt pavement, a series of factors (Figure 2), including traffic loads and temperature fluctuations, can accelerate the emergence of pavement distresses. Amongst the range of harmful effects that can occur as a consequence of pavement distresses, the most notable include a reduction in the service life of roads, a decrease in the efficiency of transport, and poorer standards of traffic safety. Among the various distresses, cracking is particularly harmful as cracks can degrade structural performance and vehicular speed, along with user comfort and safety (i.e. reduced tire friction) (Moreno-Navarro and Rubio-Gámez, 2013; Zhang et al., 2017; McDonald and McDonald, 2010). Accordingly, governments provide significant budgets to maintain their road infrastructures, as this is crucial for the growth and competitiveness of the country's economy (Tabaković and Schlangen, 2015). In this regard, it is worth noting that European countries spent almost 20,000 million Euros on maintenance for road infrastructures in 2011 (Philippe et al., 2013).

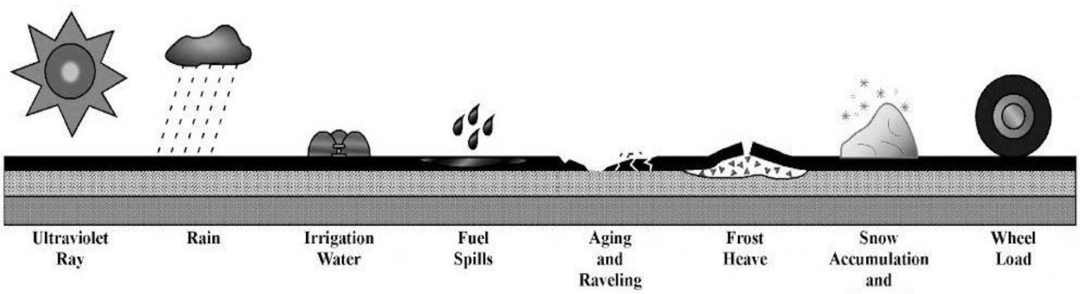

Figure 2: The typical causes of distresses in asphalt pavements (McDonald and McDonald, 2010).

From an environmental standpoint, the production of traditional asphalt mixes is accompanied by a considerable emission of greenhouse gases (Peng et al., 2015) and from the manufacturing of the mix through to the construction and maintenance processes involved with asphalt pavements, the adverse effects of energy consumption, bitumen production, and extraction of natural aggregates should be taken into consideration (Peng et al., 2015; Pérez-Martínez et al., 2014). Road pavements should be constructed and maintained in a way that ensures their longevity, due to their major impact on the economy of a nation (Peralta et al., 2012). Economic benefits of these infrastructures are achieved when their benefits exceed their cost (Thompson et al., 2008).

Given these critical issues, highway agencies have attempted to alleviate the environmental and economic impacts of asphalt pavements through different sustainability strategies such as identifying novel ways to improve their performance, reducing the temperature of production and construction (Rubio et al., 2012), reusing existing materials (Modarres and Ayar, 2014), increasing energy efficiency (Jamshidi et al., 2012) and protecting the environment by reducing harmful emissions (Pérez-Martínez et al., 2014).

However, some studies have recently emphasized the importance of developing long-life roads as a new sustainability strategy that can be applied in the field of pavement engineering (Tabaković and Schlangen, 2015). In particular, investigators believe that an asphalt pavement with an extended service life is an achievable aim, since the recovery capability of bitumen may be able to counter the development of micro-cracks (Karki et al., 2014; Roque et al., 2012). In this respect, the "recovery capability" of bituminous mixtures (which has commonly been considered as "healing capability") has been used as an important base for developing newfound technologies in order to prolong the service life of pavements. In fact, the main purpose of employing "healing technologies" is to enable/support materials to heal after the occurrence of damage (i.e. to reduce the level of damage and to extend or renew the performance and longevity of the damaged section) (Fischer, 2010). The application of healing technologies could potentially reap considerable environmental and economic benefits (e.g. preservation of natural resources, reducing energy consumption and greenhouse gas emission, lowering construction and maintenance budgets, and enhancing road safety) (Ayar et al., 2016; Tabaković and Schlangen, 2015). By conducting a life-cycle analysis, Butt et al. (2012) reported that using self-healing asphalt pavements could increase the service life of the road by 10% (from 20 to 22 years). Subsequently, this extension in the service life might reduce energy consumption by 3% (22 GJ), as well as CO_2 emissions by 3% (1.5 tons).

To clarify the idea of constructing long-life asphalt pavements that are developed on the basis of healing principles, a schematic diagram is presented in Figure 3. This figure shows the evolution of the Pavement Condition Index (PCI) versus pavement age (PCI is a value that is indicative of the structural condition of a pavement, and ranges from 0-100, where higher values indicate superior structural performance (Shahin, 1994)).

It can be observed from this figure that using a self-healing pavement could ensure superior serviceability during its life span, as well as increase the duration of its service life (in Figure 3 ΔT is the increased service life).

Therefore, to put this idea into practice, extensive research has focused on developing technologies for the repair and maintenance of asphalt pavements based on the principles governing the healing capability of bitumen. Healing technologies are generally thought to accelerate damage recovery through filling/rejuvenating the bitumen at the crack surfaces (e.g. using "microcapsules" to support wetting/diffusion as sub-mechanisms of the healing phenomenon), close the cracks by lowering the bitumen viscosity (e.g., using induction heating to support "flow/wetting" as sub-mechanisms of the healing phenomenon) and prevent the progress of damage (e.g. nanoparticles) (Ayar et al., 2016; Tabaković and Schlangen, 2015; Phillips, 1998).

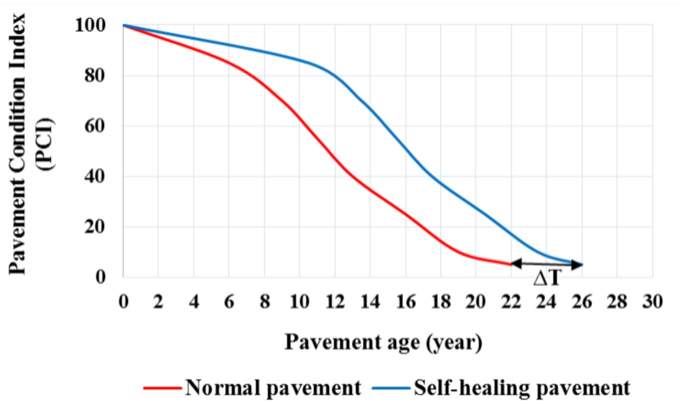

Figure 3: A schematic comparison of the PCI values of normal and self-healing pavements during their service life (depicted by the author).

It is important to note that real healing is mainly caused by the diffusion of molecular networks (restoring of the chemical bonds) at the crack surfaces. In spite of the effects of real healing, which reduce the level of damage and extend or renovate the performance and longevity of asphalt pavements (Phillips, 1998; Wool, 2008; Garcia, 2014), the recovery capability of healing technologies is still not well understood.

Among the various technologies that have been presented by researchers, induction heating stands out as the most developed healing technique, and is regarded as a novel approach for maintaining asphalt pavements (Tabaković and Schlangen, 2015). However, recent studies have shown that although healing technologies such as induction heating cause "crack-closure" by means of bitumen flow, the so-called repaired asphalt material cannot resist a high number of cyclic loads. This could imply that "real healing" cannot be achieved solely through crack-closure (i.e. "crack-gluing"), given that the flow is only a part of the healing mechanism, and it appears that inducing the critical determinant part of the healing mechanism (i.e. molecular diffusion) is not easily achieved by using healing technologies such as induction heating (Moreno-Navarro et al. 2015a). Additionally, a part of this apparent recovery as a result of using healing technologies cannot be considered as real healing, since it is caused by the reversibility of viscoelastic phenomena such as thixotropy or heating (Moreno-Navarro et al. 2015a).

When discussing the recovery capability of bituminous materials, this not only includes the healing phenomenon (understood as damage restoration), but also other reversible phenomena (e.g. thixotropy, heating). It should be pointed out that traditionally the word "healing" has been taken to encompass all of these phenomena, and in many studies, the recovery originating from reversible phenomena has been considered as healing (Soltani and Anderson, 2005).

In any case, it is necessary to note that previous investigators have created the foundations for developing these new technologies, and therefore it is necessary to review their works in order to have a deeper understanding of their development. Thus, the following section provides a review of the relevant literature concerning the study of recovery capability of bituminous materials.

2.2 Studying the recovery capability of bituminous materials

The recovery capability of bituminous materials has been studied at different levels, including bitumen, mastic, mortar, mixture, and asphalt pavement (Phillips, 1998; Qiu, 2012). Researchers have developed various methods to characterize the healing capability of bituminous materials in the laboratory, including fatigue-based healing tests, fracture-based healing tests, and non-destructive tests, whilst field tests have also been employed in some studies (Groenendijk, 1998; Nishizawa et al., 1997). Additionally, some researchers have utilized molecular dynamics simulation to assess the healing capability of bitumen (Xu and Wang, 2017; Bhasin et al., 2011).

The main approach for assessing the healing capability of bituminous materials is to compare the responses of materials under loading conditions with and without rest periods, which are known as fatigue-based methods. The fatigue-based healing experiments were used in several studies with two main loading conditions including interrupted and intermittent conditions under stress or strain-controlled tests (Qiu, 2012; Shen and Carpenter, 2007).

It should be noted that no universal method exists for either evaluating or quantifying healing capability in bituminous materials and the majority of studies are related to healing characterization. In this regard, some differences can be seen between the results of various studies, because some investigators chose to evaluate healing by examining only the bitumen, while others evaluated healing by examining the asphalt mixture or mastics (Roque et al., 2012). To explain this more clearly, Figure 4 represents the methods used for studying and measuring the recovery capability in bituminous materials.

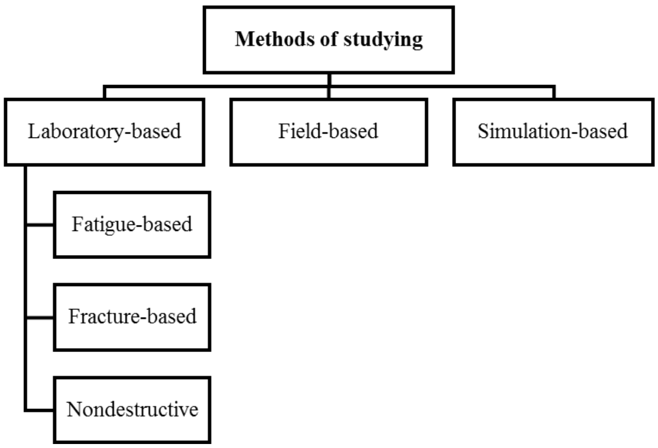

Figure 4: Methods for studying and measuring the recovery capability of bituminous materials.

In fatigue-based tests using the interrupted loading condition (Figure 5 (a)), the samples are subject to continuous load repetitions (as in a conventional fatigue test) for certain periods, except that the continuous load repetitions are interrupted with certain storage periods (intervals) during which the specimen is kept under a given set of conditions without loading (Qiu, 2012; Shen and Carpenter, 2007). An interrupted loading (group-rest healing) test is a short healing test in which different lengths of rest periods are inserted at different damage levels to determine a modulus or energy recovery as a function of rest period and damage level (Zeiada, 2012). Some researchers have applied this loading condition through a Two- Point Bending Test (2PB), Four-Point Bending Test (4PB) and Indirect Tensile Test (IDT) in order to evaluate the healing capability of asphalt concrete (Qiu, 2012; Shen and Carpenter, 2007).

In fatigue-based tests with an intermittent (pulse-rest) loading condition (Figure 5 (b)), each loading cycle is followed by a rest period (Shen and Carpenter, 2007; Zeiada, 2012). An intermittent loading condition (long healing test) appears to represent a more realistic test, because in real-life situations there is a rest period between load applications of the successive axles of passing vehicles (Qiu, 2012; Zeiada, 2012). This type of loading has been used in 2PB, Three- Point Bending Test (3PB), 4PB and uniaxial push-pull for the evaluation of healing capability in asphalt concrete (Qiu, 2012).

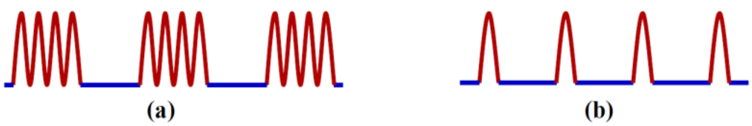

Figure 5: Loading conditions during fatigue tests (a) with rest intervals and (b) with intermittent loads (Zeiada, 2012).

In accord with previous studies, fracture-based healing methods were carried out to evaluate the healing ability of two fractured surfaces of a bituminous body. In addition, non-destructive healing tests, used in some investigations, could be divided into two main techniques: wave-based and image-based techniques. Non-destructive tests can be applied in order to assess the structural changes, and to predict the fatigue life and crack healing of bituminous materials in both the laboratory and field (Qiu, 2012). Furthermore, according to the current literature, the number of field investigations is limited in comparison with laboratory investigations (Roque et al., 2012).

2.2.1 Studying the recovery capability of bitumen, mastic, and mortar

Generally, studying the healing capability at bitumen, mastic, and mortar levels is important, since healing is an intrinsic capability of bitumen. In addition, it is important to study the behaviour of asphalt mixtures at mastic or mortar levels, as the fatigue and healing phenomena mainly occur at these levels of material (Izadi et al., 2011; Kim and Little, 2005; Kim et al., 2003).

The majority of studies investigating the healing potential of pure bitumen, mastic, and mortar have been conducted using Dynamic Shear Rheometer (DSR) and fatigue-based experiments (Qiu, 2012). These tests have commonly been conducted at temperatures in the range of 5 to 25 °C and frequencies between 1.59 and 41 Hz. In addition, a stress level of 60 to 400 kPa and a strain level of 0.3 to 20% have been applied for stress and strain controlled tests respectively (Qiu et al., 2011; Tan et al., 2012). This temperature range was used to ensure that the bitumen fails due to the effect of fatigue rather than instability flow (Shen et al., 2010). Among these studies, Little et al. (2001) used a fatigue-based test with and without rest periods on fine aggregate matrix (FAM) samples. In this study, the fatigue life was defined as the number of load cycles to failure. Additionally, the crack index parameter was calculated by means of a fracture mechanics-based method and the concept of dissipated pseudo-strain energy. To measure the healing in different materials, the rest periods were applied after different number of fatigue cycles. By comparing the crack index parameter obtained from the test with and without rest periods, the impact of healing can be measured. Moreover, some studies have assessed the recovery observed during rest periods using hysteresis loops of the materials. The changes in area (i.e. dissipated energy) and slope of the hysteresis loop during continuous cyclic loading and after rest periods could reflect the occurrence of damage and recovery (Sutharsan, 2010; Kim et al., 2001). In this regard, Figure 6 shows the hysteresis loops of sand-bitumen samples under a controlled shear strain at different loading cycles. According to this figure, the hysteresis loop of the

601th cycle shifted upwards after a rest period due to the recovery capability of bitumen (Kim et al., 2001).

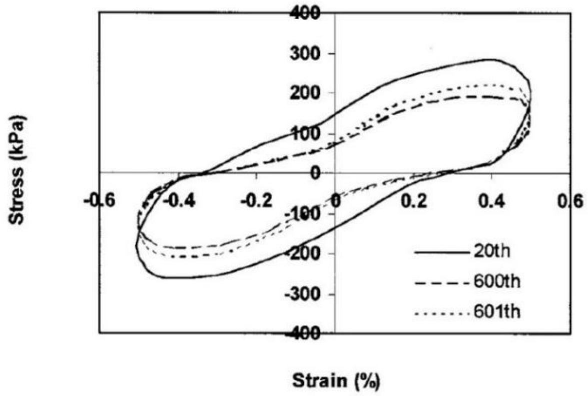

Figure 6:The hysteresis loops under torsional shear cyclic loading (Kim et al., 2001).

Fracture-based healing tests were also conducted to evaluate the healing capability of bitumen. In one fracture-based study, the bitumen was located between two hemispheric protuberances simulating two aggregate particles in the asphalt mixture (Figure 7). A strain-controlled tension loading condition was applied to the system at 0 ºC. After loading, the system returned to the initial gap-width between the spheres. Rest periods between 2 min and 2 h were then introduced to the system. In addition, a slight compression load of 50 N was applied to the sample holder. The results showed that after a 2 h rest period the bitumen almost recovered its initial fracture properties (Figure 8) (Hammoum et al., 2002), indicating that time could have a significant impact on the recovery of properties. However, the number of specimens tested and the type of binder used were limited and further research is needed.

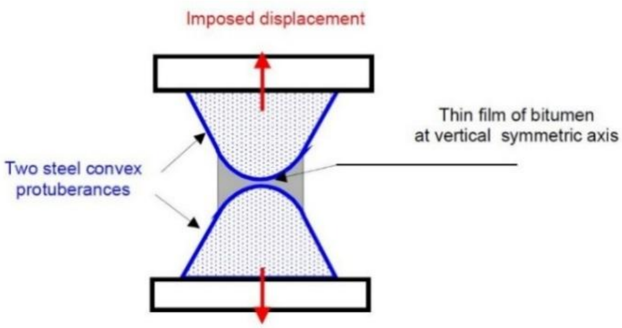

Figure 7: Schematic illustration of the local fracture test device (Hammoum et al., 2002).

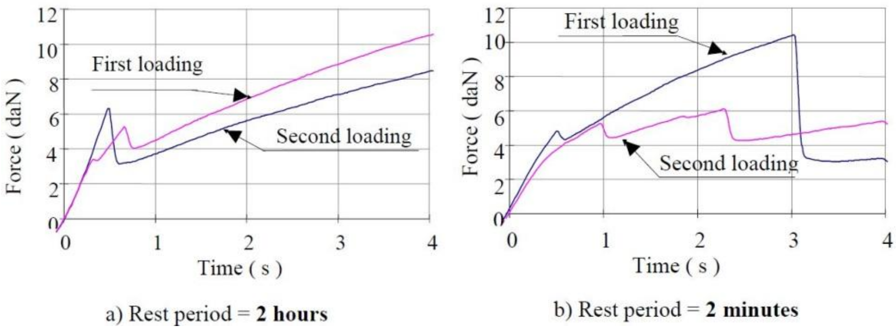

Figure 8: Results of the local fracture test: response of a 50/70 bitumen at 0 °C after (a) 2 h and (b) 2 min rest periods (Hammoum et al., 2002).

The researchers also introduced the Two-Piece Healing (TPH) test in order to directly simulate the crack healing process (Bhasin et al., 2008). They applied TPH at temperatures of 20 and 25 °C in a strain control mode. In this method, the DSR test was used to press the two pieces of bitumen together as a way of simulating the crack healing process. During the test, the change of the shear modulus was measured at strain level of 0.001% and constant compression force of 0.4 N. The results indicate that different asphalt binders had different intrinsic healing characteristics, and the initial healing values were obtained by means of gap closure (Bhasin et al., 2008). Similarly, Bommavaram et al. (2009) proposed a method to assess the intrinsic healing of bitumen. As mentioned previously, it is important to note that intrinsic healing depends on the properties of the materials. Since it is important to compare the healing capability among bitumens (or to study the effects of additives on the healing capability), it would be advantageous and reasonable to measure the intrinsic healing of bitumens (Little et al., 2015). In the study by Bommavaram et al. (2009), to measure the intrinsic healing of bitumen, the parallel plate geometry of DSR machine (diameter 25-40 mm) was used. In this procedure, bitumen with a thickness of 3.5 mm is attached on each one of the two plates (Figure 9 (a)). The surfaces of the two specimens are then brought into contact with each other, whilst the DSR applies a normal (small) force. Thereafter, the DSR measures and records the dynamic shear modulus (G*) at different points in time (usually 2-5 minutes) over a period of 1 hour. Measurements are conducted using a limited number of load cycles along with very small strain amplitude to minimize the disturbance of the interface. A control test method using a single specimen with twice the thickness was then repeated (Figure 9 (c)). Finally, the change in the shear modulus of the two-piece specimen normalizes the single specimen to obtain a dimensionless ratio that is representative of the percentage of healing (Bommavaram et al., 2009).

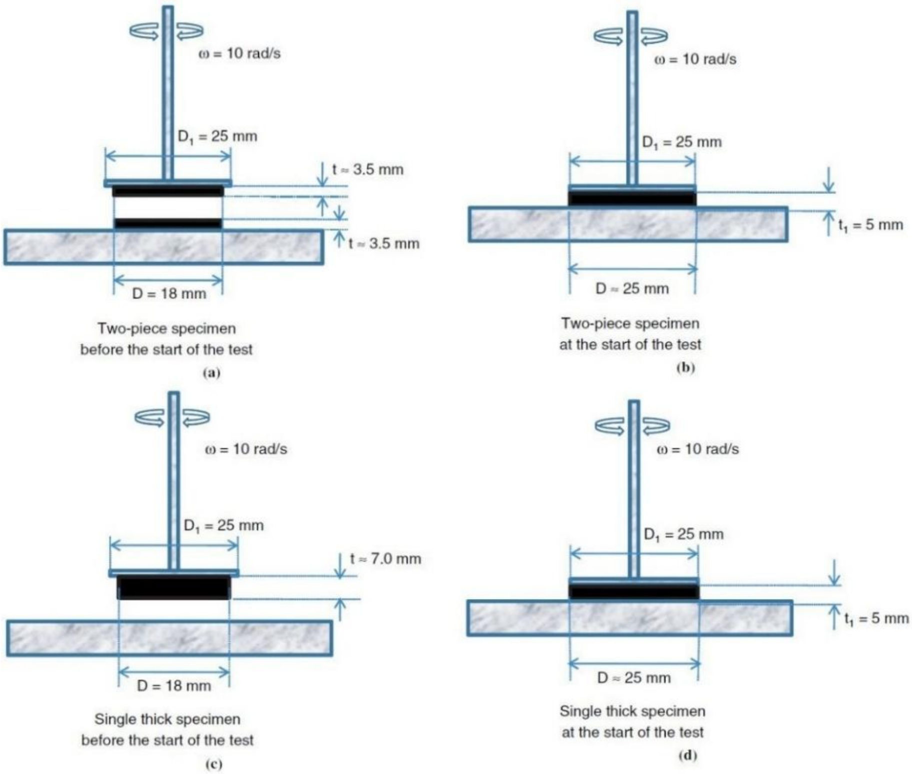

Figure 9: Schematic illustration of the test specimens used to determine intrinsic healing function: two-piece specimen (a) before and (b) after test start; single intact specimen (c) before and (d) after the start of the test (Bommavaram et al., 2009).

The results indicate that the healing occurs as a result of two different mechanisms. Short-term healing is mainly governed by the cohesive properties of the material (mainly surface energy) whilst long-term healing is governed by the molecular diffusion properties of the material (Bommavaram et al., 2009).

In addition, Qiu et al. (2011) used a TPH test to simulate healing stages through a DSR machine. They reported that the compressive normal pressure strongly promotes the development of healing. Further, Gaskin (2013) similarly confirmed the positive effect of compressive pressure on the healing capability of bitumen. Thus, the presence of the compressive pressure as an external effort could accelerate the healing process.

Qiu et al. (2012) presented a simple healing test procedure, including the fracture-healing-re-fracture test for bituminous mastics, which was successfully applied to investigate the healing capability of an open crack. This test was carried out using a direct tension test machine based on (ATS 900DTTS). In this study, the displacement speed for fracture and re-fracture was equal to 100 mm/min and periods of 3, 6, and 24 h were identified as those able to simulate healing conditions at 10, 20, and 40 C respectively. The results showed that the strength increased with an increase in both healing time and temperature. Moreover, Gaskin (2013) also used a similar test, in addition to using an environmental scanning electron microscope to evaluate the healing capability of bitumen. The results demonstrated that healing is both a viscosity-based and thermally accelerated phenomenon.

Non-destructive methods are also employed to measure the healing potential of bitumen. Atomic Force Microscopy spectroscopy experiments are used to measure the nano-scale adhesive and cohesive forces within asphalt mixtures in order to evaluate the mechanisms of healing (Das Kumar et al., 2012; Nazzal et al., 2012). Further, Scanning Electron Microscopy (SEM) has been utilized for the detection of bitumen healing stages (Lu, 2013; Qiu, 2012). Figure 10 depicts the healing process of a micro-crack within aged PG64-28 bitumen at different rest times, captured by field emission SEM equipment (Lu, 2013).

With regard to non-destructive tests, whilst non-destructive imaging techniques can provide a clear photo of nano and micro scale within the bituminous body in different conditions, adequate analysis of the results requires a comprehensive knowledge of mathematics, statistics, and image processing (Song et al., 2005).

Other studies monitoring healing in bituminous mastic specimens using X-ray Computed Tomography (X-ray CT) have provided both two-dimensional and three-dimensional images of the internal structure of a solid material or object in different phases of damage (Song et al., 2005; Tashman et al., 2004). Before monitoring the healing capability, samples were damaged with a Dynamic Mechanical Analyzer (DMA). The X-ray CT results are interpreted using a damage parameter that previously quantifies the percentage of voids (cracks and air voids) in a specimen, which is used as a means of characterizing healing. The damage parameter ξ can be calculated by the following equation (Equation 1):

$$\xi = \frac{1}{A}\sum_{i=1}^{N} A_{vi} \quad (1)$$

Where A_{vi}: the void area (cracks and air voids); A: cross-sectional area of a slice and N: the number of voids in a slice.

The results indicated that specimens with and without rest periods started with the same ξ value as expected or percentage of voids. Further, by introducing rest periods, the specimens exhibited a smaller ξ value (Song et al., 2005; Tashman et al., 2004).

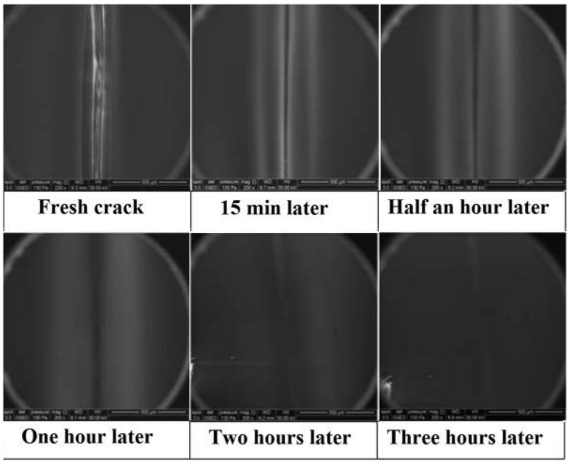

Figure 10: Healing process of a micro-crack (80 μm) within an aged PG64-28 bitumen for 3 h at 30 ºC taken by the field emission SEM equipment (Lu, 2013).

2.2.2 Studying the recovery capability of asphalt mixtures

The relationship between fatigue life extension and the presence of rest periods has been demonstrated using fatigue-based tests in a range of studies with different experimental procedures. The main reason for using fatigue-based tests in earlier studies was to evaluate and simulate the recovery capability during rest periods. Bazin and Saunier (1967) introduced various rest periods ranging from several hours to 100 days during a 2PB test at a frequency of 50 Hz and temperature of 10 ºC. They reported an increase in fatigue life as a result of including the rest periods. Similarly, Raithby and Sterling (1970) indicated that applying rest periods of 40 to 800 ms can increase the fatigue life by as much as five times. They used a sinusoidal tension compression test at temperatures of 10 and 25 ºC, and frequencies of 2.5 and 25 Hz. Other studies using the 3PB test at a frequency of 40 Hz have reported an increment in fatigue life when applying rest periods (Bonnaure et al., 1982; Van Dijk and Visser, 1977).

In recent years, investigators have made a number of attempts to quantify the recovery capability through fatigue-based tests and have also presented some healing indexes that are independent of test conditions (Kim and Roque, 2006; Si et al., 2002). For instance, Zhang et al. (2001) evaluated the healing capability of asphalt mixture using the Superpave IDT test. A haversine load with frequency of 10 Hz followed by a 0.9 s rest period was applied at a temperature of 10 ºC. Following a specified number of loading cycles, 12 h rest period was included at a temperature of 30 ºC, thus using a combination of interrupted and intermittent loading conditions. The results of this study demonstrated the existence of recovery capability during rest periods, whilst the authors also proposed a threshold concept based on a dissipated creep strain energy limit. Similarly, Grant (2001) used an IDT test by applying 0.1 s haversine loads followed by a 0.9 s rest period at the temperatures of 10 and 15 ºC. The normalized resilient modulus was used to measure damage accumulation, and a healing rate in terms of the recovered dissipated creep strain energy was determined. Further, Si et al. (2002) quantified the recovery capability of asphalt mixture using a continuum damage mechanical approach. A controlled-strain repeated cyclic uniaxial tensile fatigue test was applied to cylindrical specimens measuring 100 mm in diameter and 150mm in height. Additionally, recovery of pseudo stiffness after the introduction of rest periods was taken to indicate healing of the asphalt concrete (Equation 2).

$$HI = \frac{\varphi_{after} - \varphi_{before}}{\varphi_{before}} \qquad (2)$$

where HI is healing index, ϕ_{after} is the pseudo stiffness after a rest period and ϕ_{before} is the pseudo stiffness before a rest period. In a similar vein, Kim and Roque (2006) developed a hot mix asphalt fracture mechanic model to identify and quantify the healing capability of asphalt mixture based on the resilient modulus measured during the rest period. They used the IDT test, and 1000 cyclic loads were applied with a haversine load of 0.1 s and rest periods of 0.9 s. They found that the total healing rate was directly proportional to the rate of damage recovery. In addition, they proposed a method for measuring the damage recovery rate, which excludes the reduction of stiffness due to heating and steric softening. By following the paths of other researchers, Shen and Carpenter (2007) applied a 4PB fatigue test to evaluate the healing capability of asphalt mixture based on Dissipated Energy Approach (DEA) principles. They used a frequency of 10 Hz and temperature of 20 ºC through an intermittent loading condition with rest periods that included 0, 1, 3, and 9 s. They utilized DEA principles and obtained plateau values from healing tests with varying rest periods. The plateau value is a fundamental property of the material and could be used as an indicator of healing. This value is independent of mode of loading and testing condition. Mamlouk et al. (2012) also studied the fatigue and healing behaviour of asphalt mixture by using a 4PB fatigue test. They applied a deflection- controlled mode with both haversine and sinusoidal loading conditions at a frequency of 10 Hz. Further, they evaluated the effects at two strain levels of 400 and 800 microstrains, and three test temperatures of 4, 21, and 38 ºC. An Intermittent loading condition with 5 and 10 s rest periods were introduced during the fatigue test. The results of this experiment showed that sinusoidal loading shape is a more consistent and accurate way to study fatigue and recovery. Haversine strain and stress signals cannot be maintained during a test because of the viscoelastic nature of bitumen. Similar to previous studies, they signalled that application of rest periods reduces the loss of stiffness during the fatigue test.

Recently, Huang and Huang (2016) introduced a simple method to rank the healing capability of various asphalt mixtures. They generated a fatigue process using 4PB test under strain-controlled condition for the samples, after which the samples were healed through a specific condition. To heal a fatigued sample, a static load (12.51 kg) is placed over the samples by using a non-deformable rigid mould with the same shape as that of the sample. The samples were also exposed to a heating temperature of 60 °C for 24 hrs. Finally, the healed samples were re-tested by 4PB test, and to rank the healing capability of the mixtures, the difference between the trends of the two fatigue curves was considered. The closer the second curve (healed sample) to the first one (original sample), the stronger the healing ability. Based on these considerations, the Healing Index (HI) was defined as the damage rate ratio of the two fatigue tests, and can be calculated through the following equation (Equation 3):

$$HI = \frac{D_0}{D_1} \times 100 \qquad (3)$$

Where HI is the healing index (%); D_0, average damage rate related to the stiffness (slope of the stiffness curve) in the first test; D_1 the average damage rate related to the stiffness (slope of the stiffness curve) in the second test (after healing process). Figure 11 demonstrates these parameters that were used in the healing index formula. The results revealed that crumb rubber and polymer modified asphalt mixtures are able to obtain higher HI values.

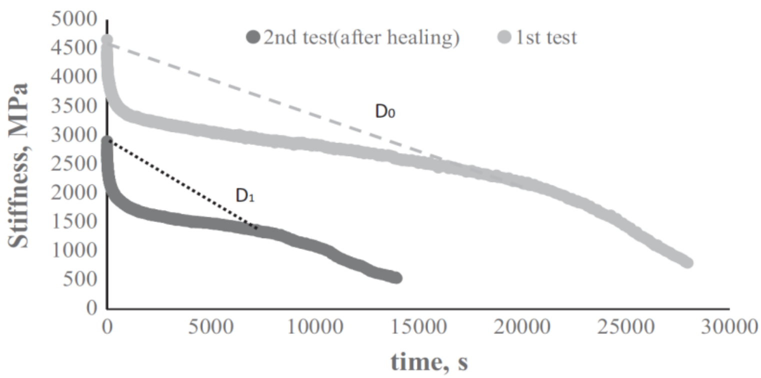

Figure 11: The evolution of stiffness over time before and after healing (Huang and Huang, 2016).

Regarding the fracture-based healing tests at mixture level, one of the preliminary experiments, Bazin and Saunier (1967) studied the healing capability of dense asphalt concrete beams which were formerly fractured by bending and uniaxial tensile loading. The dimensions of the prepared samples were equal to 4×3×10 cm. During the tensile tests, beam samples were stretched at the speed of 120 mm/min along the longest dimension and the tensile strength and strain in the failure point were measured. Additionally, the bending test was conducted using a dynamic two-point bending apparatus with a frequency of 50 Hz at 10 ºC until fatigue failure occurred. The two fractured pieces were then put in contact and the samples were stored vertically resting on the smallest base, whereupon the upper piece induced a compressive pressure of 1.48 kPa at the rupture interfaces due to its weight. Following this, the stored samples were exposed to temperatures of 10, 18, 25 °C at different rest periods ranging from 1 to 300 days. Finally, the samples were re-fractured under the same loading conditions to obtain the new tensile strength and strain in the uniaxial tensile test and the new fatigue life in the bending test. In this regard, Figure 12 shows the recovery of the tensile strength (R'T/RT) at different rest periods. According to this figure, the mixture type and temperature can considerably affect healing capability. In addition, Figure 12 shows that after a three-day rest period at 25 °C the asphalt concrete recovered 90 % of its primary tensile strength. Moreover, Bazin and Saunier (1967) indicated that the results of identical tests for samples that had been stored horizontally during the rest periods (without a compressive pressure) were widely sporadic. Consequently, it can be suggested that the presence of a compressive pressure increases the healing capability. Regarding the positive effects of compressive pressure, these results are compatible with the multi-step healing mechanism that emphasizes the role of consolidating stresses (Phillips, 1998). Similarly, the positive effects of compressive pressure have been reported when the healing capability was studied at the bitumen scale (Gaskin, 2013).

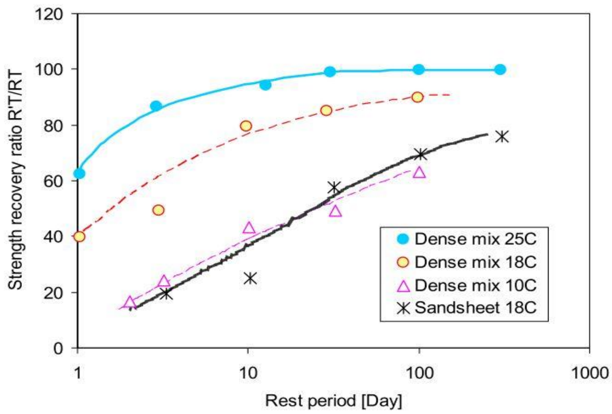

Figure 12: The recovery of tensile strength after different rest periods and temperatures (cited from Qiu, 2012).

With respect to the results of the cyclic fatigue test, Bazin and Saunier (1967) have illustrated that after a one-day rest period, the asphalt mixture with a very soft binder (Penetration Grade: 200) can recover 50% of its original fatigue life. This study presented a logarithmic recovery with time and a shift to shorter healing times at higher temperatures.

A flexural test was utilized by Uchida et al. (2002) in order to evaluate the healing capability of macro-cracks in asphalt concrete through a fracture-based test. In this study, the crack was formed in a wheel tracking test sample by bending the slab with a steel bar situated at the bottom of a sample, after which the sample (slab) was recovered to its original geometry for producing crack closure. The sample was then exposed to sunlight for a number of days. Additionally, the samples were subject to a passing wheel to simulate the kneading effect of the tires of vehicles to facilitate the possible healing at the upper part of the sample. Finally, the slabs were divided into strip (beam) specimens to measure the flexural strength at a temperature of 5 °C with a loading rate of 50 mm/min. This test was conducted at three outdoor exposure times (1, 3, 6, and 12 months), three wheel passing temperatures (20, 40, and 60 °C) and two cracking situations (with and without crack). Figure 13 shows the steps for preparing these samples, whilst the results are illustrated in Figure 14.

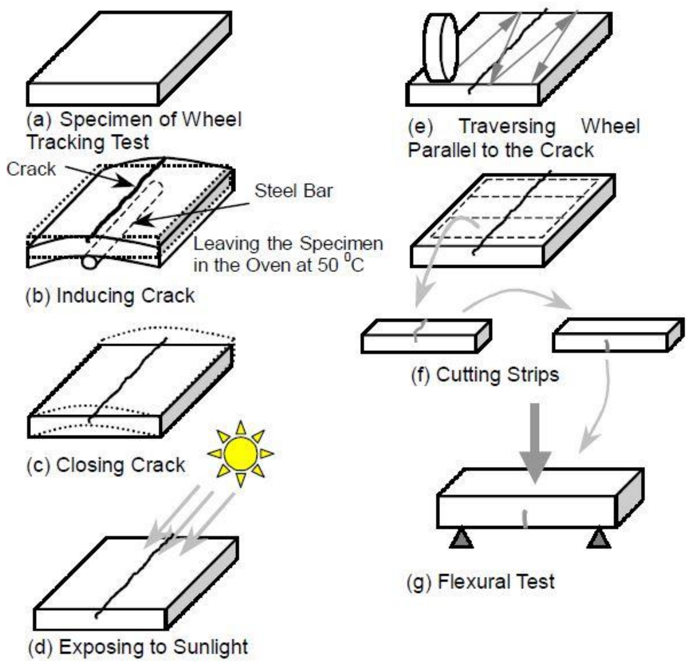

Figure 13: The steps for preparing healing test samples (Uchida et al., 2002).

According to these results, although the effects of exposure are not clear, the data indicate that healing capability increased with trafficking temperature. Further, the results indicated that high temperature had a negative effect through aging and, simultaneously, a positive effect on healing capability (Uchida et al. 2002).

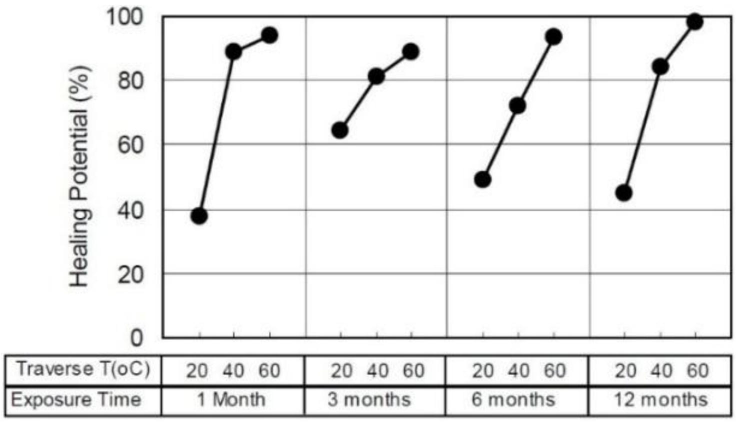

Figure 14: The effects of traverse (trafficking) temperature and outdoor exposure time on healing potential (Uchida et al., 2002).

Qiu et al. (2012) introduced a new fracture-based test to investigate the healing capability of asphalt concrete. They glued a notched asphalt concrete beam to the elastic foundation setup, after which they applied symmetric monotonic load and unloading cycles. The healing capability was quantified in terms of the recovery of both the strength and the crack opening displacement. They reported that at the beginning of the rest period, the healing process consists of viscoelastic recovery, whilst at higher temperatures and with the passage of time, healing was led by viscous flow.

Nevertheless, some investigators have found that the recovery observed during rest periods with and without application of heating could occur mainly due to reversible phenomena (such as thixotropy or heating). Further, the recovery observed in asphalt mixtures during the rest periods at the micro-damage levels is higher than recovery observed at macro-damage levels, since the effects of reversible phenomena fade out during the course of the fatigue test (Moreno-Navarro et al. 2015a). It is worth mentioning that although bitumen flow as a result of heating application during rest periods can totally or partially close the cracks at both micro and macro-damage levels, the original properties of the asphalt concrete cannot be completely recovered. Given that plastic deformations and the distance between aggregates cannot be exclusively re-established because of bitumen flow (i.e. from Figure 15 (Moreno-Navarro et al., 2015a) it can be understood that $d_d = d_h$ (Menozzi et al., 2015; Moreno-Navarro et al., 2015a). Interestingly, the stresses generated in the area close to so-called glued cracks (σ_h) are higher than that in the initial state (σi), and thus the material cannot sustain a high number of cyclic loads (Moreno-Navarro et al. 2015a) (Figure 15). According to Figure 15, the stresses (σ) generated in the material because of load application (F) change as a consequence of the variation of the section (geometry) where it is applied. Thereafter, in the closed part of the macro-crack there is an increase in the stresses suffered by the material following the healing treatment (heating technique) (Moreno-Navarro et al. 2015a).

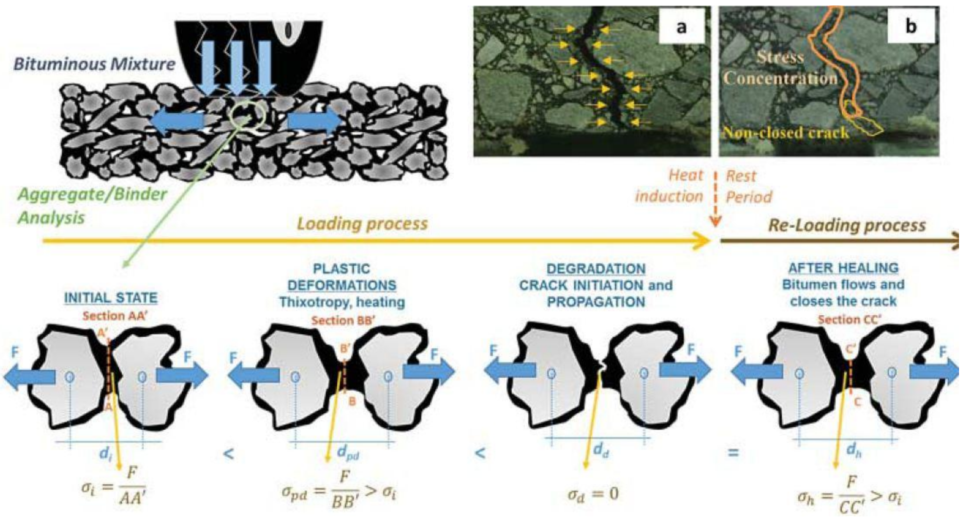

Figure 15: Image of a macro-crack both before (a) and after (b) application of the heating technique (Moreno-Navarro et al. 2015a).

The Ultrasonic method — which measures both the pulse velocity from the time of ultrasonic pulse transmission through the tested material and the distance between the transducer and receiver — has been used for assessing the healing capability of asphalt mixtures, and it is regarded as a non-destructive technique (Abo-Qudais and Suleiman, 2005). Other studies have used X-ray CT for monitoring both the internal structure and healing capability of asphalt mixtures at different phases of damage (Menozzi et al., 2015).

2.2.3 Studying the recovery capability of asphalt pavements

There are only a few studies that have evaluated the recovery capability of asphalt pavements. In one such study, a comparison of the measured responses in four thick pavements showed that fatigue cracking did not occur due to the recovery compensation effect in low-strain and low-damage levels (Nishizawa et al., 1997).

Another study was conducted in order to evaluate the effects of rest periods on pavement stiffness recovery using a surface wave measurement technique. The results showed that after introducing 24 h rest period, the pavement stiffness was increased, which was probably related to micro-crack healing processes (Williams et al., 2001).

Further, the Falling Weight Deflectometer (FWD) can be used for evaluation of the healing response. Groenendijk (1998) applied FWD measurements during accelerated pavement testing using a linear tracking apparatus under a range of temperatures between 0 and 30 ºC. In this study, a rest period was imposed whereby the continuous load repetitions were interrupted from each Friday afternoon to the following Monday morning. The results showed that pavements could recover their stiffness by application of this rest period.

Over the years, several studies have been conducted in connection with the recovery capability of bituminous materials (which include some of the important studies discussed previously in this section). The results reported by researchers employing different methods have revealed that the recovery capability of bituminous materials can be affected by different influencing factors such as temperature and rest period. Consequently, the next section discusses the factors influencing the recovery capability of these materials.

2.3 Factors influencing the recovery of properties in bituminous materials

As demonstrated in the studies previously presented, there are many factors that could influence the recovery potential of bituminous materials. In this regard, influencing factors can be divided into internal (i.e. bitumen characteristics, asphalt mixture characteristics and the presence of modifiers) and external factors (i.e. temperature, loading condition and damage level, rest periods and pavement geometry) (Ayar et al., 2016).

2.3.1 Internal factors

2.3.1.1 Bitumen characteristics

Some researchers have found that the characteristics of the bitumen play an important role in the recovery capability of asphalt pavements (Liu, 2012; Qiu, 2012), with soft bitumen having a higher recovery capability compared with hard bitumen. In other words, bitumen with a higher penetration grade is more desirable for recovery (Van

Dijk et al., 1972; Bonnaure et al., 1982). This issue is better understood when discussed with respect to the chemical composition of the material. In fact, hard bitumen contains more molecules with higher weight (i.e. asphaltenes) (Nicholls, 1998) (Figure 16) and this may reduce the molecular mobility as an important sub-mechanism of the healing phenomenon. According to previous studies, the molecular mobility and subsequent capability of diffusion is related to the lower molecular weight composition in bitumen (Bhasin et al., 2011). In polymers, which are materials similar to bitumen, when the molecular weight increases, the molecular mobility, wetting, and diffusion could be restricted (Ghosh, 2008).

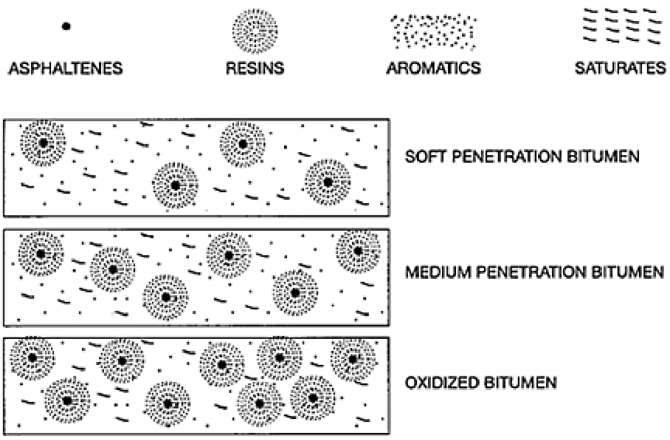

Figure 16: A schematic representation of the soft, medium and hard (e.g. oxidized) bitumen based on its colloidal nature (Nicholls, 1998).

In addition, viscosity may be a critical factor in determining the healing capability of bitumen. It can thus be hypothesized that lower viscosity can enhance the healing process in bitumen (Garcia et al., 2014; Kim et al., 2003). These claims are also in accordance with the multi-step healing mechanism introduced by Phillips (1998). In fact, the bitumen with lower viscosity has a higher flow capability and it was previously discussed that the flow is considered as the first step in the healing mechanism. However, viscosity is directly related to the chemical composition of bitumen and maltenes (e.g. saturates, aromatics) are responsible for viscosity and fluidity of the bitumen (González, 2010). Again, this could be taken to imply that a higher concentration of the molecules with lower weight can enhance the fluidity and consequently the molecular mobility, which is necessary for the occurrence of the healing phenomenon (i.e. the recovery of damage).

A number of authors have directly studied the effects of the chemical composition of bitumen on its healing capability (Little et al., 1999; Schmets et al., 2010). In particular, it has been demonstrated that bitumen with low amphoteric and high aromatic content (low molecular weight fractions) has a higher healing capability (because low molecular weight fractions can enhance the molecular mobility). Indeed, there is a direct relationship between aromatic content in terms of the acid base component of surface energy and long-term healing rate (Little et al., 1999). Hypothetically, the bitumens with "mobile aromatic" have a greater tendency to heal than bitumens, which are polar, where the polarity is "immobilized" through a high, interactive asphaltene content (which is perhaps enhanced by the presence of amphoterics). Nevertheless, previous studies have shown that amphotencs play an important role in building the polar-polar bonds that give asphalt its unique properties (Little et al., 1999).

Recently, Sun et al. (2017a), using a grey relational analysis, showed that the amount of the recovery observed during the rest period can be affected by the number of major chemical components (asphaltenes (As), saturates (S), aromatics (Ar) and resins (R)) in the bitumen. The decreasing order of the grey relational grade between the four components and recovery achieved can be expressed as Ar > S >R>As. The grey relational grade between Ar and recovery reaches values as high as 0.9414. It is important to bear in mind that Ar has a smaller molecular weight than the other three components (the small molecule enables bitumen to heal faster). Unlike the higher amounts of asphaltenes and resins (As + R), which could represent the large molecule in bitumen, could decrease the recovery capability. Nonetheless, the grey relational grade between (As + R) and recovery capability was smaller than that between recovery capability and Ar. Therefore, they concluded that recovery capability is most sensitive to the content of aromatics in the four components (i.e. the effect of small molecules on recovery capability is much greater than that of large molecules). The surface free energy density can be divided into two parts, including the Lifshitze-Van der Waals and the Lewis acid-base components. The Lewis acid-base component has a positive effect on long-term healing, whilst the Lifshitze-Van der Waals component can negatively affect short-term healing (Figure 17) (Lytton, 2000; Williams et al., 2001).

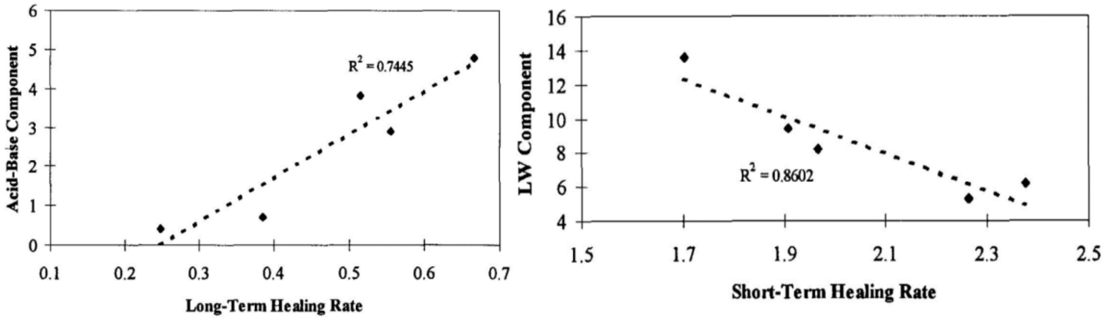

Figure 17: The effects of Lifshitze-Van der Waals and the Lewis acid-base components on the healing capability in bitumen (Williams et al., 2001).

Additionally, heteroatom content promotes healing since sulphur, oxygen, and nitrogen promote the polarity of the binder. The wax content is also helpful for healing due to the Van derWaals force of the interactions between long chains of hydrocarbons and aliphatic molecules within the wax (Schmets et al., 2010; Williams et al., 2001). According to the above-mentioned literature, a summary of the influencing factors related to physical and chemical characteristics of bitumen and the effects on recovery capability is provided in Table 1.

Table 1: A summary of influencing factors related to physical and chemical characteristics of bitumen and their impacts on recovery capability.

Determining characteristics	Desirable properties	Description
Penetration grade	High	Soft bitumen (which contains a lower concentration of the molecules with high molecular weight).
Viscosity	Low	Bitumen with lower viscosity has a higher flow capability
Aromatic content	High	Aromatic (as low molecular weight) fraction has a higher healing capability compared to other fractions in bitumen.
Amphoteric content	Low	e.g., Aged bitumens are not desirable
Asphaltenes and resins content	Low	Large molecules in bitumen are not desirable for recovery to occur.
Surface energy: Lewis acid base content	High	Positively affects long-term healing
Surface energy: LifshitzeVan der Waals content	Low	Negatively affects short-term healing
Wax content	Enough	Van derWaals force within the wax can promote healing

The morphology of bitumen — which directly originates from its chemical composition — could affect recovery capability. Based on the chemical composition of bitumen, Kim et al. (1990) introduced two parameters (using Fourier transform infrared spectra (FTIR)) to quantify the molecular mobility of bitumen including methylene plus methyl hydrogen to carbon ratio (MMHC) and the methylene to methyl group ratio (CH_2/CH_3), which are related to the amount of the branching in chains (at constant carbon number) and the length of chains (at constant branching) respectively. In addition, Kim et al. (1990) have reported that the diffusivity and rate of healing increases with the decrease of MMHC ratio (the amount of branching). A summary of these results is depicted in Figure 18.

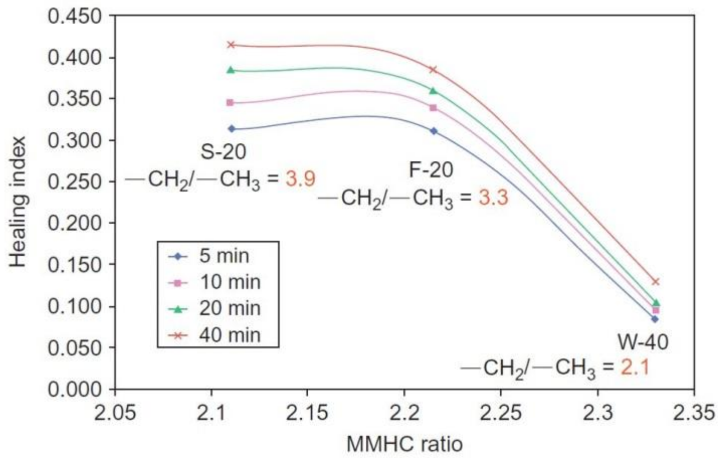

Figure 18: The variations of healing index versus MMHC ratio cited from (Little et al., 2015).

Bhasin et al. (2011) also found a correlation between these two parameters (CH_2/CH_3 and MMHC) and the diffusivity rate as an indicator of healing in the bitumen. The results reported by Bhasin et al. (2011), produced through molecular dynamics simulation, were in accordance with those found by Kim et al. (1990). Bhasin et al. (2011) modelled different bitumens by changing the relative proportions of saturates, napthene aromatics, and asphaltenes, as well as by varying the chain length of the molecule used to represent the saturates. In this regard, different combinations of molecules are used in molecular dynamic simulations (Table 2).

Table 2: The compositions of bitumens used for molecular dynamics simulation (Bhasin et al., 2011).

Number	Chain length of saturates	Approximate proportions of asphaltene, naphthene, and saturates
1	n-C_{23}	20-40-40
2		20-20-60
3	n-C_{33}	20-40-40
4		20-20-60

In this regard, Figure 19 and 20 display the variations of CH_2/CH_3 and MMHC with the molecular diffusivity in the modelled bitumen respectively. It is important to bear in mind that chains refer to saturates as well as (alphatic) appendages to aromatic and other larger molecules. Nevertheless, diffusivity indicates the movement of molecules across a wetted crack when there is a density gradient across the interface (Bhasin et al., 2011).

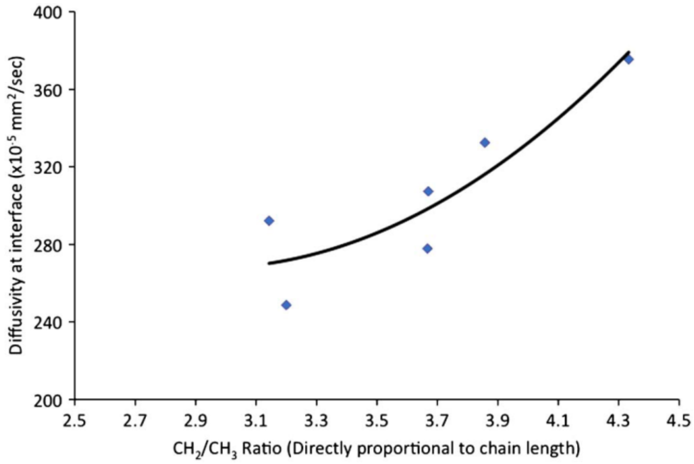

Figure 19: The variations of CH_2/CH_3 ratio of binders (created using average molecule structure) versus diffusivity of molecules at the crack interface (Bhasin et al., 2011).

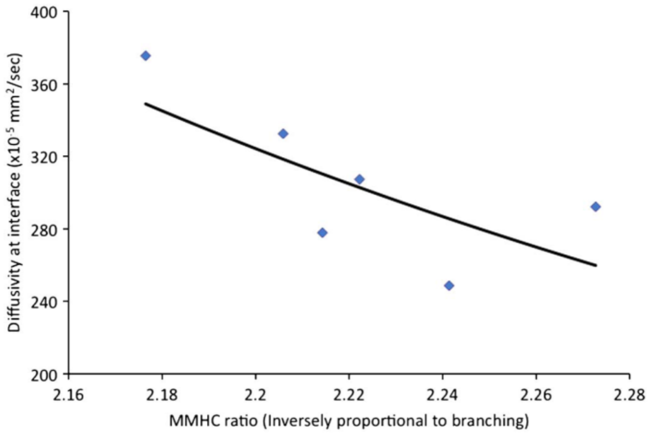

Figure 20: The variations of MMHC ratio of binders (created using average molecules structure) versus diffusivity of molecules at the crack interface (Bhasin et al., 2011).

According to Santagata et al. (2009) saturate/ aromatic ratio (S/Ar) could be used as an indicator of the recovery capability in bitumen based on its chemical compositions (saturates frequently contain long aliphatic chains and the aromatics mainly have compact ring structures). The results indicated that with the increased S/Ar ratio, there is a corresponding increase in the capability of the oil phase of the bitumen to heal micro-cracks. A few years later, these results were confirmed by Sun et al. (2017a), and they also found that with the increase of the penetration grade of bitumen, S/Ar increases gradually. In fact, the molecular structure of bitumen with a higher S/Ar value tends to be longer and thinner, which results in a smaller hindering effect between one molecule and another when they diffuse. In other words, with a higher S/Ar value, cracks in bitumen will be healed more rapidly (Figure 21).

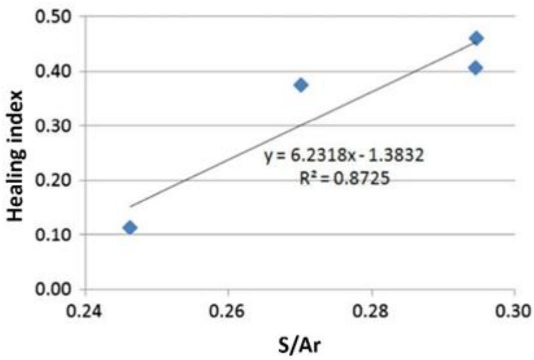

Figure 21: The correlation between S/Ar ratio and healing index (i.e. recovery in complex shear modulus during the rest period) (Sun et al., 2017a).

In addition, the percentages of asphaltenes and resins can represent the quantity of large molecules. With more large molecules, the average molecular weight is higher. Therefore, the molecular motion of bitumen will be slower and the recovery capability will be decreased, with the crack in the asphalt taking a longer time to heal (Sun et al., 2017a). However, Sun et al. (2017a) showed that the recovery capability is more sensitive to the molecular structure than the large molecule content. On the basis of the results reported by the above-mentioned researchers, a summary of influencing factors related to morphological characteristics of bitumen and the effects of these factors on recovery capability is provided in Table 3.

Table 3: A summary of influencing factors related to the morphological characteristics of bitumen and their impacts on recovery capability.

Determining characteristics	Desirable properties	Description
MMHC ratio	Low	Molecular branching
CH_2/CH_3 ratio	High	Chain length
S/Ar	High	The ratio of long molecules to ring shaped molecules

Considering the colloidal systems of bitumen that affect the visco-elastic response, it could be assumed that Sol type bitumen with a lower stiffness and a higher phase angle shows a higher recovery capability. Give that in Sol type bitumen there is a sufficient amount of resins and aromatics (i.e. lower molecular weight compositions), the molecular mobility could increase and this can help the occurrence of the healing phenomena (Van Gooswiligen et al., 1994; Liu, 2012; Read and Whiteoak, 2003).

In the same context, Sun et al. (2017a) have found a correlation between the Colloid Instable Index (CII) value and the recovery capability of bitumen, where a lower CII value could, to a certain extent, lead to an increase healing capability. In fact, with a smaller CII, bitumen is more likely to be Sol type material and its colloidal microstructure is more stable. This index can be calculated using the following equation:

$$\mathrm{CII} = \frac{\mathrm{As+S}}{\mathrm{R+Ar}} \qquad (4)$$

Where asphaltenes (As), saturates (S), aromatics (Ar) and resins (R) are the weight percentage of different fractions in bitumen, which are obtained from a chromatogram (Sun et al., 2017a). Additionally, it was reported that with an increase in the penetration grade of bitumen, the CII and the content of large molecules (As + R) decreases (Sun et al., 2017a). This means that softer bitumen is more likely to be Sol type material, resulting in a better recovery capability.

2.3.1.2 Aging

Like other organic materials, bitumen compositions evolve over time, which is known as the aging phenomenon (Zhang et al., 2012). In this regard, some researchers have reported the negative effects of aging on the healing capability in bituminous materials (Little et al., 1999; Liu et al., 2012a).

These results have been confirmed in a study by Xu and Wang (2017), in which a molecular dynamics simulation was used to assess the effect of oxidative aging on the properties of bitumen. They found the diffusivity of molecules in aged bitumen reduces due to the increased molecular size in asphaltene, resin, and aromatics along with the reduction of free volume space for saturates (Xu and Wang, 2017). These results imply that aging could reduce molecular mobility (i.e. a higher asphaltene concentration could reduce the ability to flow) (Xu and Wang, 2017; Qiu, 2012).

According to Figure 22, for the both virgin and aged bitumen, the diffusivity of molecules increases by increasing the temperature. Moreover, it can be understood from this figure that the diffusion coefficient of virgin bitumen is higher than that of aged bitumen. Similarly, by utilizing a field emission scanning electron microscopy method, Shen et al. (2016) has observed the negative effects of aging on the healing capability.

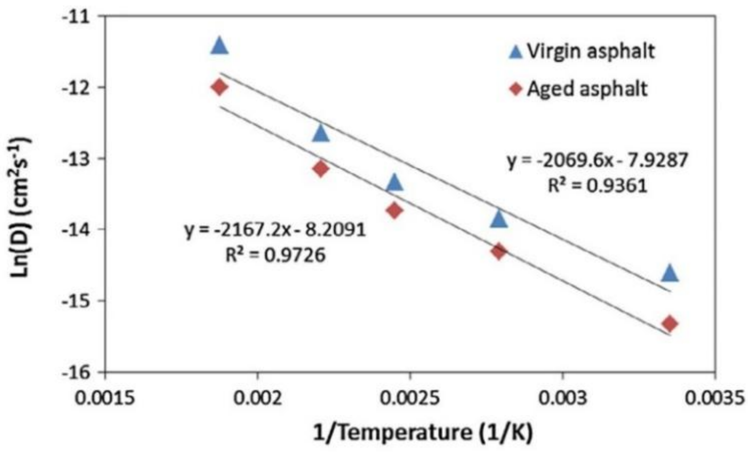

Figure 22: The variations of diffusion coefficient versus temperatures for virgin and aged bitumen (using molecular dynamics simulation and D: diffusion coefficient (cm^2/s)) (Xu and Wang, 2017).

Further, Van den Bergh (2011) revealed a distinct difference between the recovery capability of a laboratory-aged and a field-aged mortar sample. They also pointed out that the field-aged mortar sample (i.e. the mortar contacting the extracted bitumen from Reclaimed Asphalt Pavements (RAP)) has the lowest recovery capability. Although some researchers have shown (theoretically and experimentally) the negative effects of aging on the recovery capability in bitumen, these effects could be changed when modified binders or different aging processes are used (Canestrari et al. 2015; Lv et al., 2017).

2.3.1.3 Asphalt mixture characteristics

Some researchers have reported the effects of the mixture characteristics such as bitumen content, gradation size, and air void content on the recovery capability of asphalt concrete (Ayar et al., 2016).

Among the bitumen and aggregates that make up bituminous mixtures, only bitumen has the ability to recover properties. Thus, it is clear that the recovery capability of bitumen could allow the asphalt mixture to recover at least some properties. Nonetheless, the typical amount of bitumen ranges from 4 to 6% by weight of the mixture, depending on the specifications and intended use of the pavement (EAPA and NAPA, 2011), which is very low when compared with the quantity of aggregates. In this context, some studies have shown that the asphalt mixture with higher bitumen content has a higher healing rate (Molenaar, 2007; Van Gooswiligen et al., 1994, Lee et al., 2000; Lee et al., 1995).

Furthermore, Grant (2001) stated that the recovery of properties (measured in terms of stiffness) within the coarse-graded asphalt mixture is much faster than that within the fine-graded mixture at 15 °C. In this regard, Abo-Qudais and Suleiman (2005) also reported that at a specific air void content, the mixture with a higher maximum nominal aggregate size shows a better capacity for fatigue life recovery after applying a rest period, since the coarse gradation with a lower surface area can provide a thicker bitumen film and fewer transition zones between aggregate and bitumen. This condition therefore favours the improvement of crack healing (Abo-Qudais and Suleiman, 2005).

Additionally, the healing capability of asphalt mixtures can also be affected by aggregate interlock, film thickness, and Voids in Mineral Aggregate (VMA), particularly at low to intermediate temperatures (0-20 ºC) (Kim and Roque, 2006). In relation to Air Void (VA) content, it can be concluded that the mixture containing a lower VA has superior healing capability regardless of the type of bitumen, aging, and temperature (Luo, 2012). In addition, healing capability increases with an increase in Voids Filled with Asphalt (VFA), a decrease in the VMA, and a decrease of VA content (Qiu, 2012; Van den Bergh, 2011). However, these volumetric parameters can be affected by the bitumen content of the mixtures.

In relation to this issue, Liu (2012) has linked the healing rate (i.e. the recovered dissipated creep strain energy per unit time) to the structural properties of asphalt mixtures using the VFA/(VMA×VA) index based on data produced by previous studies (Figure 23).

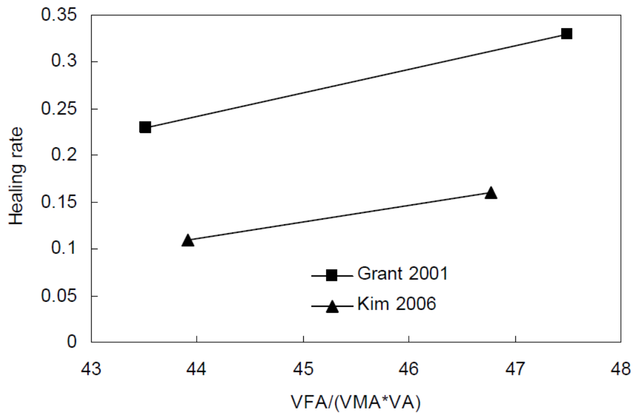

Figure 23: The connection between healing rate and VFA/(VMA×VA) at 15 ºC (Liu, 2012).

Recently, Gómez-Meijide et al. (2016), by applying the induction heating technique, found that the dense asphalt mixture has a superior healing capability. With respect to the above-mentioned studies, Table 4 provides a summary of the influencing factors related to asphalt mixture characteristics and their effects on recovery capability.

Table 4: A summary of influencing factors related to asphalt mixture characteristics and their effects on recovery capability.

Determining characteristics	Desirable properties	Description
Bitumen content	High	High bitumen content such as Stone Mastic Asphalt (SMA)
Gradation size	High	Lower surface area could provide a thicker bitumen film
Air void (VA)	Low	Associated with bitumen content and mineral skeleton
Voids in Mineral Aggregate (VMA)	Low	Associated with bitumen content and physical properties of the aggregate/mix
Voids Filled with Asphalt (VFA)	High	Associated with VA and VMA

2.3.1.4 The use of modifiers

This section discusses the effects of modifiers, particularly polymeric modifiers, which are widely used to improve the performance of bituminous materials (Zhu et al., 2014). However, there are some important challenges in relation to utilizing polymeric modifiers in bituminous materials (Zhu et al., 2014) such as their influence on recovery capability (Qiu, 2012), molecular mobility, and macroscopic segregation (Polacco et al., 2015). In addition, the results obtained by researchers regarding the impacts of polymeric modifiers on the recovery capability of bituminous mixtures are not very clear and further studies are needed.

In relation to this topic, Lee et al. (2000) showed that the recovery capability of asphalt concrete could be improved by applying modifiers. They indicated that using Gilsonite, Styrene Butadiene Rubber (SBR) polymer, and SBS polymer improved the healing capability of asphalt concrete. It should be noted that the SBS modified asphalt concrete achieved the highest healing capability compared with the other mixtures. Further, Shen and Carpenter (2007) also reported the positive effects of polymer-modified bitumen on the healing capability of asphalt concrete. The results of a study based on the DSR fatigue test showed that the healing rate of the polymer modified bitumen PG 70-28 is greater than that of the neat bitumen PG64-28 (Shen et al., 2010). Additionally, Kim and Roque (2006) found that healing rates were more strongly affected by the aggregate structure characteristics, than by polymer modification. In other words, although SBS polymer modification reduced the rate of damage accumulation, it had a relatively limited effect on the healing rate of the asphalt concrete. Following this series of investigations, Canestrari et al. (2015) have also reported the positive effects of using SBS modifier for bitumen during monotonous cyclic loading with multiple rest periods, and offered the suggestion that this is linked to the increase in elastic component due to the better rearrangement capability of polymer chains, and could reduce the non-reversible damage and enhance its thixotropic characteristics. Further, Huang and Huang (2016) have demonstrated the positive effects of SBS on the stiffness recovery of asphalt mixtures after applying rest periods.

Recently, Sun et al. (2017b) have studied the effects of the SBS polymer on the healing capability of bitumen by monitoring crack healing through a fluorescence microscope, as well as using a phenomenological model. They found that the required crack healing time for SBS modified binder was less than that of neat bitumen, particularly during the wetting stage. Since the SBS modified bitumen has a higher surface tension compared to neat bitumen due to its larger molecular weight, it has a maximum wetting rate (i.e. higher thermodynamic cohesion). Some of the results of this study are displayed in Figure 24, which represents the evolution of the crack area with the crack healing time for different types of bitumen at 25 °C.

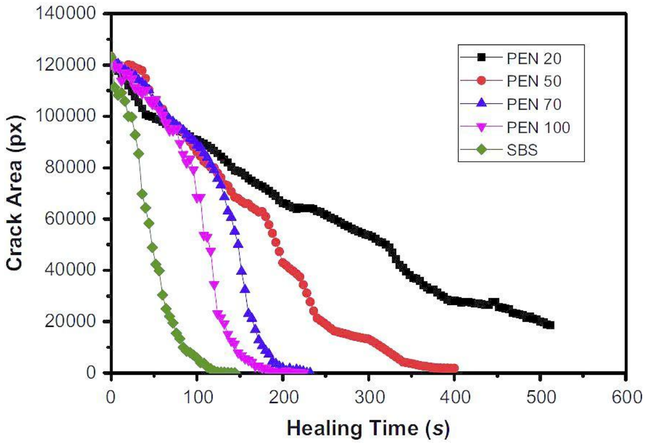

Figure 24: Evolution of the crack area with time in different bitumens at 25 °C (Sun et al., 2017b).

In contrast, Little et al. (1999) concluded that using SBS polymer modifier leads to a slight reduction in the healing capability of asphalt concrete. They suggested that polymer could act as a filler that limits the potential of bitumen to re-establish contact and heal. Moreover, it appears that the existence of a polymer network probably causes a reduction in diffusion of bitumen. Hence, a partial absorption of compatible components of the bitumen into the polymer network could occur (i.e. polymer can be swollen due to absorption of the light oil components in bitumen) and the rest of the bitumen remains with a higher asphaltene concentration, which reduces the flow capacity. In fact, the absorption of the light oil components could reduce molecular mobility, since these components are responsible for the molecular mobility, which is of critical importance in the healing mechanism (Qiu, 2012; Bhasin et al., 2011). However, an increase in polymer content may have a significant effect on healing capability, depending on polymer chain mobility and the interaction between bitumen and polymers (Newman, 2004).

Similarly, Qiu (2012) concluded that SBS polymer modification has a negative effect on the healing capability of bituminous mastic when considering the healing of an open crack (at macro-crack level) (Qiu, 2012, Qiu et al., 2012). In relation to this issue, Figure

25 illustrates some results of this study. It can be seen that the PBmas (bituminous asphalt with limestone filler and 70/100 pen bitumen) could achieve complete healing in much less time than the SBSmas (bituminous mastic with limestone filler and SBS polymer modified bitumen). This could possibly be due to the fact that the fractured SBS molecules could cause disorder in wetting and diffusion processes in bitumen, particularly at lower temperatures (Qiu et al., 2012).

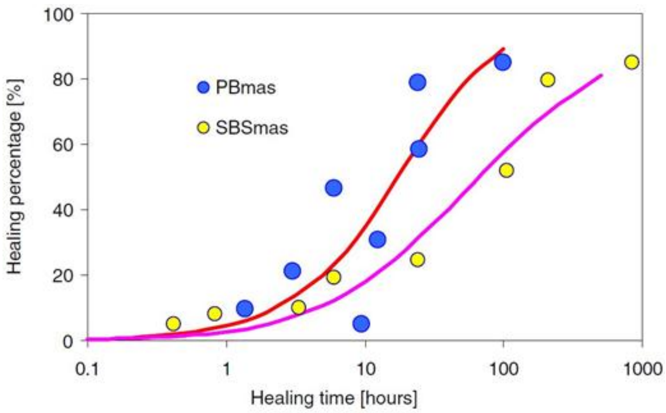

Figure 25: The healing master curves of bituminous mastics at 20°C (which are considered as the ratio (%) of fracture strength after the healing process divided by original fracture strength) (Qiu et al., 2012).

With respect to other modifiers, lime could affect the rate and level of cracking, healing, and plastic and viscoelastic flow in both mastics and mixtures within a wide range of temperatures (Little and Petersen, 2005). In conjunction with recovery capability, Little et al. (1999) concluded that lime could interact with the more polar asphaltene fractions in the binder, which could accelerate flow and healing properties. In fact, the removal of amphoteric fraction in bitumen by adsorption on the surface of the lime could improve the healing capability (since it could affect the surface energy of the binder) (Little and Petersen, 2005).

Finally, it should be noted that size, mixing method, compatibility, testing method, concentration, level of damage (micro or macro) and diffusion ability are all properties of the modifiers (specifically polymers) which might affect the results of healing experiments (Qiu, 2012; Roque et al., 2012; Polacco et al., 2006). Based on morphological properties and rheological perspectives, the concentration of modifier is one of the most critical aforementioned properties, and could strongly influence the viscoelastic properties of the bitumen (Polacco et al., 2006). Nevertheless, these negative effects of polymeric modification on the bitumen healing reported previously may be attributed to the thermodynamic incompatibility of polymers and bitumen, because the fundamental properties of the latter are different (e.g., in terms of density, polarity, molecular weight and solubility). Thermodynamic incompatibility could negatively affect the bitumen performance and particularly causes delamination of the composite during thermal storage (Fang et al., 2013). Based on the results of the above-mentioned studies, a summary of the influencing factors related to the use of modifiers on the recovery capability of asphalt pavements is provided in Table 5.

Table 5: A summary of the influencing factors related to the use of modifiers and their effects on the recovery capability in bituminous materials.

Modifier	Effect	Description
Gilsonite	Positive	-
Styrene Butadiene Rubber (SBR)	Positive	-
styrene-butadiene-styrene (SBS)	Positive/Negative	It is possible that the different properties of polymers used (e.g. size, mixing method, compatibility, diffusion), their concentration, testing methods, and the level of damage (i.e. micro or macro) resulted in different conclusions.
Lime	Positive	It could affect the chemical composition of bitumen to favour healing.

2.3.2 External factors

2.3.2.1 Temperature

The healing capability of asphalt concrete is linked to the temperature of service, such that an increase in temperature increases its healing capability (Daniel and Kim, 2001; Kim and Roque, 2006). In this regard, Grant (2001) concluded that healing can occur immediately, given sufficiently high temperatures, whilst Kim and Roque (2006) reported that the temperature sensitivity of the healing rate is highly nonlinear. In fact, the healing rate increased with increments in temperature, particularly in mixtures with high bitumen content. Additionally, by analysing the healing progress of open cracks in bituminous mastic, García (2012) found that the speed of the healing phenomenon increases when the temperature increases (Figure 26) a variation that can also be linked to the Arrhenius equation. Chemically, heating leads to the separation of chains in the molecular network of bitumen, resulting in the formation of Sol colloidal structure, which reduces the viscosity and consequently enhances the flow as an important sub-mechanism of healing (i.e. heating could enhance the capillarity flow). In other words, heating could promote molecular mobility, stimulating flow and possibly diffusion, which, together, could lead to the healing of cracks.

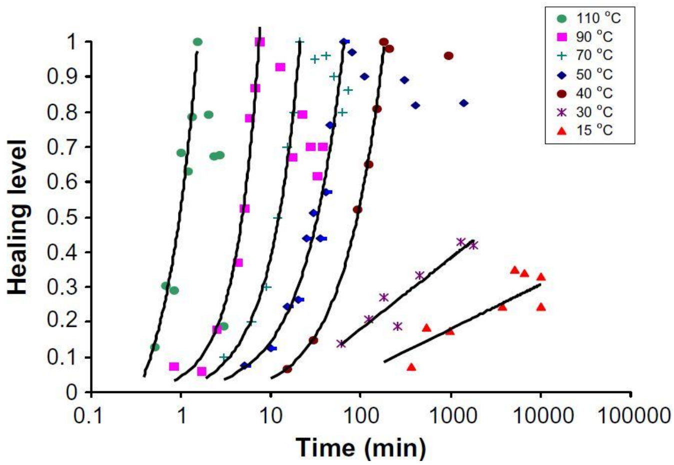

Figure 26: The evolution of healing levels in bituminous mastic with time at different temperatures (García, 2012).

It is important to note that when a steady state temperature is reached, the internal pressure related to the flow and surface tension is dissipated and thus the binder could flow downward due to gravity, causing ineffectiveness of the heating in creating crack closure (Gómez-Meijide et al., 2016).

Additionally, the softening point can be considered as the optimal healing temperature for bitumens in a penetration grading system (Tang et al., 2016). Taken together, these findings indicate the importance of considering the optimum time and temperature of the heating technique to induce the recovery capability in asphalt concretes.

2.3.2.2 Loading condition and damage level

Load amplitude is considered to be one of the important influencing factors on the healing capability of asphalt pavement. Various studies have shown that a high tensile stress/strain level has a negative effect on healing capability (Van Dijk et al., 1972; Castro and Sanchez, 2006).

Further, the healing capability is high when the damage level is low (Song et al., 2005; Zhang et al., 2001). During the phase in which macro-cracks occur, it becomes difficult to recover the properties of the material by means of healing phenomena (Molenaar, 2007; Zhang, 2000).

Recently, some researchers reported that inducing healing capability of asphalt mixtures by means of applying heating could be effective, but only at a specific level of damage (which is known as the optimum moment), when the fatigue damage is not highly destructive (Menozzi et al., 2015).

Based on observations through field emission scanning electron microscopy, Shen et al. (2016) reported that in a neat bitumen, cracks with a width of less than 80 μm can heal themselves much faster in comparison with wider cracks (160 μm). This finding emphasises the effects of damage level. Interestingly, this result has been validated by a molecular dynamic simulation method. According to results achieved based on this method, it can be seen from Figure 27 that with an increase in crack width, a longer time is needed for the cracked sample to obtain the density of the un-cracked sample (i.e. the crack width of 5 Å and 20 Å could be healed completely and almost achieve the same density of an un-cracked sample after 20000 fs) (Shen et al. (2016)).

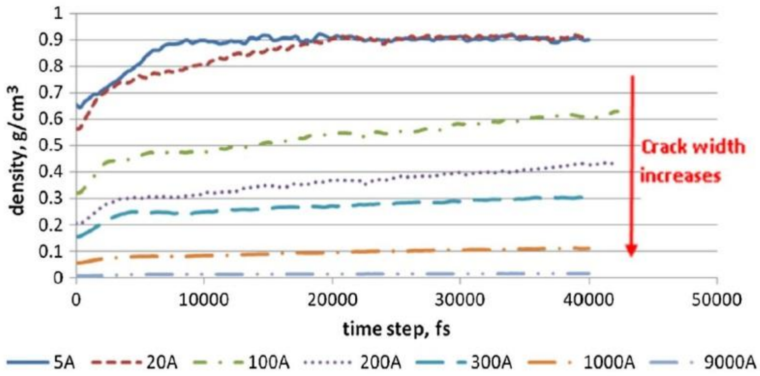

Figure 27: Variations of the density of simulated system at 298 K for the models with different crack widths (5 Å, 20 Å, 100 Å, 200 Å, 300 Å, 1000 Å, and 9000 Å) (Shen et al., 2016).

2.3.2.3 Rest periods

Many researchers have acknowledged the beneficial effects of rest periods on recovery capability in bituminous materials under different loading conditions. The longer rest periods lead to better recovery in mechanical properties (Kim et al., 2002; Van Dijk et al., 1972; Liu, 2012). In this respect, the length of rest period required for recovery to occur in the laboratory depends on both loading condition (Qiu, 2012) and type of asphalt mixture (Castro and Sanchez, 2006). Typically, researchers in the field agree that the optimum rest time should be approximately ten times the loading time (Castro and Sanchez, 2006).

However, the occurrence of the healing phenomenon could be independent of the presence of the rest periods and recovery might even occur during damage accumulation (Ashouri, 2014; Little et al., 2015). In addition, it is important to consider that a substantial part of the recovery achieved during rest periods could occur as result of viscoelastic reversible phenomena (e.g. heating and thixotropy) in bituminous materials (Ashouri, 2014; Moreno-Navarro et al., 2015a) which should be distinguished from real healing.

2.3.2.4 Moisture

According to pervious investigations, moisture generally has a negative effect on healing capability. However, some studies have reported that the effects of water can change during the healing time. Although water could temporarily enhance the speed of healing, since the hydrogen atoms (in water) have a good affinity with the Lewis acid and base components of the surface energy (Lv et al., 2017; Zollinger, 2005), it could eventually have a negative impact on healing capability. Given that water has a high affinity for the aggregates, infiltrated water in fractured aggregates near the crack can negatively change the general mechanical response of the material.

2.3.2.5 Pavement geometry

Concerning the geometric characteristics of the asphalt pavement, a thicker pavement can be expected to have a higher healing capability. In this regard, Nishizawa et al. (1997) evaluated the measured responses of four thick asphalt pavements and the results indicated that fatigue cracking did not easily occur, owing to the compensatory effects of healing on crack growth at low-strain and low-damage levels.

There has been no specific study that has examined the effects of recovery capability at different depths of asphalt pavement. However, it can be argued that this capability could be more manifest at the surface course layer, which usually has a higher bitumen content compared with the base course. Additionally, some findings in the literature suggest that the compression and traffic kneading effects that may enhance healing capability are more effective in the surface course (Gaskin, 2013; Ayar et al., 2016). According to the results of the above-mentioned studies, a summary of the external influencing factors and their effects on the recovery capability of bituminous materials is provided in Table 6.

Table 6: A summary of the external influencing factors and their impacts on the recovery capability in bituminous materials.

Determining characteristics	Desirable properties	Description
Temperature	High	Higher temperature leads to lowering the viscosity of bitumen.
Damage level	Low	The recovery is more effective at lower levels of damage.
Rest period	Long	Rest period provides an opportunity to rearrange microstructures (e.g. thixotropy).
Moisture	Low	Negatively affects the recovery capability of bitumen.
Pavement thickness	High	When the level of damage is lower, the recovery capability could be more efficient.

The following section presents a brief review related to the healing technologies in bituminous materials.

2.4 Healing technologies

Healing technologies can be defined as technologies that stimulate or induce the healing capability of bitumen by considering the principles that govern the healing mechanism. In this respect, healing technologies can be classified into three groups including, healing agents, encapsulation technique and heating technique (i.e. mainly induction heating) (Ayar et al., 2016; Tabaković and Schlangen, 2015). In fact, healing agents, encapsulation technique and heating technique were used to control damage levels, reduce the viscosity and accelerate the flow as influencing factors respectively, resulting in a better recovery capability of the bitumen.

2.4.1 Healing agents

It is important to use appropriate and efficient modifiers, additives or general agents to improve the healing capability of bituminous materials. For this purpose, Qiu et al. (2009) have suggested the following criteria for selecting the possible healing agents for asphalt mixtures:

a) Good compatibility with bitumen

b) High temperature stability

c) Ability to survive mixing and construction conditions

d) Healing temperature between -30 °C and 40 °C.

e) Capable of continuous/multi-time healing

Nanoparticles that are used to upgrade the mechanical response of the bituminous materials have also been utilized as a possible agent to improve the healing capability. Regarding their influence on this capability, it is assumed that nanoparticles could halt the progress of cracks (Qiu et al., 2009). In this regard, Qiu et al. (2009) assessed the effects of nanorubber on the healing capability of bitumen, reporting that their influence depends on the type of nanomaterial used. According to Tabatabaee and Shafiee (2012), the organo-clay-modified bitumen can increase fatigue life when rest periods were included, which could indicate the beneficial effects of nano-clay on the recovery capability. In addition, Santagata et al. (2015) indicated that the effectiveness of the carbon nanotubes to improve the recovery capability is considerably influenced by the properties of the base bitumen. Recently, Li et al. (2016) have fabricated a light-induced healing agent (OXE-CHI-PUR network) to be utilized in bitumen. They believed that when the bitumen cracks, certain chemical bonds in the OXE-CHI-PUR network could break and as a consequence release free radicals. Thus, by applying UV light, these free radicals could regroup and the damage could eventually be repaired.

2.4.2 Encapsulation technique

Using rejuvenators for the recovery of properties in aged bitumen is a well-known technique, and it can also be used for improving the healing capacity of asphalt pavements (Menozzi et al., 2015; Su et al., 2013a). In this respect, capsules containing rejuvenator have been used in asphalt mixtures to improve their healing capability. To this end, researchers have tried to produce microcapsules with a proper resistance to high temperatures and mixing stress during the process of asphalt mixture production (Su et al., 2013b). The mechanism of microcapsule performance within the body of the asphalt pavement is illustrated in Figure 28. According to this figure, this mechanism has three levels consisting of: (1) the capsule tolerates the traffic loading over the years, (2) by increasing the stiffness of the bitumen the load distribution in the capsule's shell changes. Consequently, the shell will tear due to repetition of traffic loading and bitumen aging (i.e. the fracture energy at the tip of the crack opens the capsule and releases the healing agent (Tabaković and Schlangen, 2015)), and (3) because of an increase in permanent deformation within the capsule, the pressure inside the capsule increases and the rejuvenator (oil) will flow. Finally, it decreases the aging level by diffusion of the rejuvenator into the bitumen structure and could also fill the cracks (Chung et al., 2015; García et al., 2011).

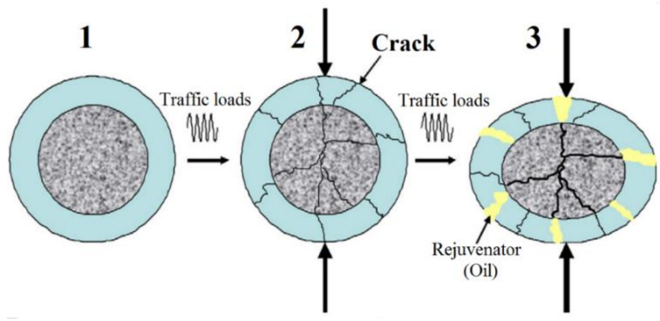

Figure 28: The mechanism of microcapsule performance in asphalt pavements (García et al., 2011).

Different types of microcapsule have been developed with sufficient thermal and mechanical stability to sustain the asphalt mixture production process. In this respect, prepolymer of melamine-formaldehyde modified by methanol has been successfully used to produce stable microcapsules (Su et al., 2013b; Su and Schlangen, 2012; Garcia et al., 2009).

Regarding healing tests, Su et al. (2013a) evaluated the healing capability of bitumen containing 5 and 10% microcapsules by means of a mechanical test conducted at 0 ºC for 24 h. The results demonstrated that the bitumen samples with microcapsules were able to show a recovery of their mechanical properties. Moreover, Su et al. (2015a) investigated the healing capability of bitumen containing microcapsules through a modified beam on elastic foundation (BOEF) test. A symmetric monotonic load was applied with loading–unloading–healing–reloading cycles. By demonstrating the load–strain curves, it was shown that the healed samples have a higher load and strain values, which could indicate the positive role of rejuvenators inside microcapsules. According to recent work, the capsule size should be less than the thickness of bitumen films between aggregates, which is approximately 50 μm. By adopting such a criterion, the capsules can be preserved against squeezing or pulverizing effects during the production and compaction processes of asphalt mixes (Su et al., 2013c; Su et al., 2015a). According to Su et al. (2015a), microcapsules smaller than 10 μm are not able to contain a sufficient amount of rejuvenator for healing purposes. Regarding microcapsule content, Su et al. (2015a), based on a Fluorescence microscope morphological method, have concluded that the optimum content of microcapsules should not exceed 30% by total volume of bitumen. Given that adding high amounts of microcapsules to the bitumen causes the segregation of the interface between microcapsules and bitumen, unanticipated structural defects could occur. Following these studies, Su et al. (2015b) pointed out the beneficial usage of microcapsules containing waste cooking oil as rejuvenator. They produced mechanically and thermally stable microcapsules that can effectively rejuvenate the aged bitumen based on the results obtained through penetration, softening point, and viscosity tests, as well as a Fluorescence microscope morphological approach.

Tabaković et al. (2016) introduced a new approach to encapsulate the rejuvenator by sodium alginate compartmented fibres. In this regard, the major advantages of alginate compartmented fibres as materials for encapsulation aims include low preparation cost, organic nature (low environmental impact) and self-degrading properties. The results indicated that alginate compartmented fibres could survive during asphalt mix production. Regarding the healing property of alginate compartmented fibres containing rejuvenator, it was reported that the use of alginate-compartmented fibres improves the strength of the bituminous mastic by 36%.

In contrast to the results obtained by researchers in relation to the use of microcapsules containing rejuvenator, Garcia et al. (2016) reported the infectiveness of using large capsules (0.60 to 5.6 mm) containing rejuvenator (which was sunflower oil) in asphalt mixtures as a healing agent. To make these capsules, Garcia et al. (2016) embedded rejuvenator in the cavities of porous sand (i.e. porous sand containing rejuvenator used as core materials) and then to produce a cover for the core materials, cement Type I 52.5R glued by a liquid epoxy resin was used (i.e. the shell (wall) of the capsule manufactured by a cement-epoxy resin materials). Although the capsules were successfully prepared for use in asphalt mixture, the mechanical analysis in terms of indirect tensile strength, stiffness and indirect tensile fatigue tests revealed the inefficiency of using these types of capsules, particularly with larger sizes. Given that not all capsules resist the mix production process, the rejuvenator will be released and the bitumen tends to be softened. Thereafter, the stiffness reduces because due to the softening of the bitumen. Similarly, Micaelo et al. (2016) have reported that macro-capsules release a small amount of rejuvenator during the fabrication of the asphalt mix, which could negatively affect the overall resistance to permanent deformations.

2.4.3 Heating technology

The healing capability of bituminous materials is a temperature-dependent phenomenon, and this capability increases with an increase in temperature (as an external influencing factor) during the rest periods. The healing process of asphalt pavements is very slow at ambient temperature, and can begin at temperatures between 30 and 70 °C, depending on the type of bitumen used and according to Tang et al., (2016), the softening point is the optimal healing temperature for bitumen in the penetration grading system.

Based on these facts, researchers have demonstrated a feasible way to enhance the healing capability of asphalt concrete by increasing its temperature (Liu et al., 2012a; Menozzi et al., 2015). In particular, some studies have applied induction heating as a method that can be used for improving the healing capability of asphalt pavements. This method is currently considered to be a potential preventive maintenance approach (Liu et al., 2012a). It is important to note that the major healing mechanisms in the induction heating technique are the capillary flow and diffusion of the bitumen at high temperatures (García, 2012).

When applying the induction heating method, electrically conductive and/or magnetically susceptible particles (e.g. carbon fibres, graphite, steel fibres, steel wool, iron oxide nanoparticles and conductive polymer polyaniline) should be used in the bituminous materials (Wu et al., 2006; Tabaković and Schlangen, 2015; Jeoffroy et al., 2016). Concentration and type of conductive particles, as well as their forms (e.g., fibre or powder forms) can considerably affect healing efficiency (Apostolidis et al., 2016). Based on the results of new studies, Iron oxide nanoparticles can also be used to manufacture the conductive asphalt mixes. By using a very low content of these nanoparticles, the temperature of the bitumen through magnetic hyperthermia can rapidly increase (Jeoffroy et al., 2016).

In this technology, an induction heating apparatus generates alternating electromagnetic fields and it can heat the conductive particles in asphalt concrete. Thus, the bitumen indirectly heats up and could flow (Dai et al., 2013). A pictorial diagram of the induction heating mechanism for asphalt pavements is shown in Figure 29. It appears that induction heating is a rapid way to increase the temperature within the asphalt concrete (Liu et al., 2010). Induction heating can also be applied to a conductive asphalt mixture through microwaves and infrared radiation (Gallego et al., 2013; Gómez-Meijide et al., 2016).

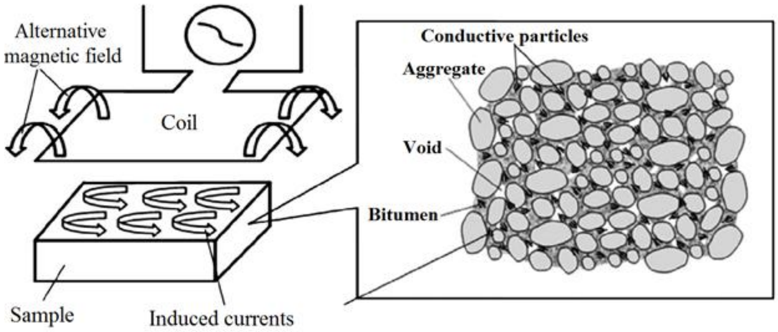

Figure 29: The pictorial diagram of the induction heating mechanism in asphalt pavements (Dai et al., 2013).

In the Netherlands, Liu et al. (2012b) evaluated the healing capability of steel wool reinforced porous asphalt. The steel wool content employed was equal to 1.27% (mass content of the total mixture). The results showed that induction heating increased the healing rate of the porous asphalt beams, and that the healing was highly microstrain-dependent i.e. there is a higher healing rate at higher levels of microstrain. It was also demonstrated that the optimum heating temperature is 85 ºC. Further, the fatigue life of porous asphalt was significantly extended by multiple periods of induction heating (Liu et al., 2012b; Liu, 2012).

Additionally, Liu et al. (2011) quantified the effects of induction heating of asphalt mixes containing steel through the following equation (Equation 5). They used an indirect tensile fatigue test at 5 ºC. Firstly damage was induced in the materials (i.e. the fatigue test was conducted until a 70-80% drop in the original stiffness, where the number of cycles needed to induce damage is C_1)). Secondly the process was followed by a 2 min induction heating phase and then 24 hrs rest period. Finally, the samples were tested under identical conditions until a 70-80% drop of its initial value was observed for a second time (the number of cycles after healing: C_2) (See Figure 30). In some cases, they reported that applying induction heating (approximately 120 ºC after 2 min of heating) followed by 4 h rest period can considerably recover the stiffness of the material (by up to 99.1% of the original stiffness).

$$HI = \frac{C_2}{C_1} \qquad (5)$$

where HI is the Healing Index (%); (HI= 100% denotes the occurrence of complete healing and HI= 0% denotes no healing; C_1 is the number of cycles during the first loading application; and C_2 is the number of cycles during the second loading application.

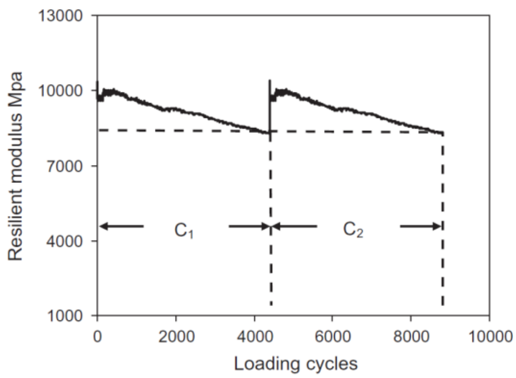

Figure 30: The fatigue life recovery of cylindrical asphalt samples (Liu et al., 2011).

Dai et al. (2013) also studied the healing capability of mastic and dense-graded asphalt concrete beam samples through induction technology. In this study, 8 and 5.66% steel wool fibres by volume of binder were utilized for preparing electro-active asphalt concrete and mastic respectively. The mastic and asphalt beams were tested by fracture-healing cycles under the 3PB test and induction healing process. It was found that the micro-cracks in the mastic samples could be effectively healed at the heating temperature of 60 ºC, whilst 100 ºC was identified as the optimum induction heating temperature for asphalt concrete. Nonetheless, a heating temperature between 60 and

80 ºC is also acceptable, due to the fact that after six fracture-healing cycles more than 50% of strength was recovered.

Moreover, Menozzi et al. (2015) also conducted a study related to induction heating in asphalt concrete. The findings indicated that the lifetime of specimens subjected to fatigue damage could be extended by up to 31% by applying induction heating, although this procedure could only heal cracks of a certain width (low width cracks). These results have since been confirmed by Bueno et al. (2016) who analysed the efficiency of induction heating of long asphalt slabs damaged by the Model Mobile Load Simulator (MMLS3). Bueno et al. (2016) pointed out that induction heating could be effective when applied at the early stages of deterioration in asphalt pavements (i.e. before emergence of irreversible damage).

A recent study was carried out by Gómez-Meijide et al. (2016) to assess the effects of gradation and void content on the induction heating effectiveness, using electromagnetic field and infrared radiation. Regarding the energy efficacy issue, they reported the superior benefits of electromagnetic induction heating compared with infrared radiation. The reason for this is that in the electromagnetic induction the bitumen can be directly heated, in contrast, infrared radiation also heats aggregates. In terms of the effects of gradation type, they found that the maximum healing level was lower for dense asphalt mixtures. This could be due to the generation of more broken aggregates in a dense mix compared with the semi-dense or porous mix. One of the most important findings was that when a steady state temperature was reached (when the temperature of the mix becomes stable), the internal pressure (i.e. pressure related to the flow and surface tension) is dissipated and thus the binder could flow downward due to gravity. Finally, the cracks remain open and the overall strength of the materials decreases, whilst there is an increase in the air void content of the mixture in the upper parts of the sample (Gómez-Meijide et al., 2016).

Norambuena-Contreras and Garcia (2016) compared the effects of induction heating using microwave and electromagnetic field methods on the crack healing ability of asphalt mixes. To create a conductive dense asphalt mix, various quantities of steel wool fibres were added to the mix (2%, 4%, 6% and 8%). From Figure 31, it can be observed that independent from the heating mechanism (microwave or electromagnetic induction), the surface temperature of the asphalt samples increases with an increase in exposure time and fiber content. According to Figure 31 (a), the existence of polar molecules in asphalt mix causes a rise in temperature when applying the microwave technique, even if there are no conductive particles. However, the efficiency of heating in this case is low and the bitumen can reach very high temperatures before losing its heat to the aggregates and the environment. As a result, it is difficult to control the temperature of bitumen during microwave heating. In addition, although the surface temperature of the mix exposed to the microwave radiation is not very high compared with the induction method, based on the thermogravimetric analysis it was shown that the temperature of the binder could exceed the flash point. Thus, overheating as a result of microwave radiation could damage the asphalt mix and it was recommended that the exposure time to this method should not exceed 40 s (Norambuena-Contreras and Garcia, 2016).

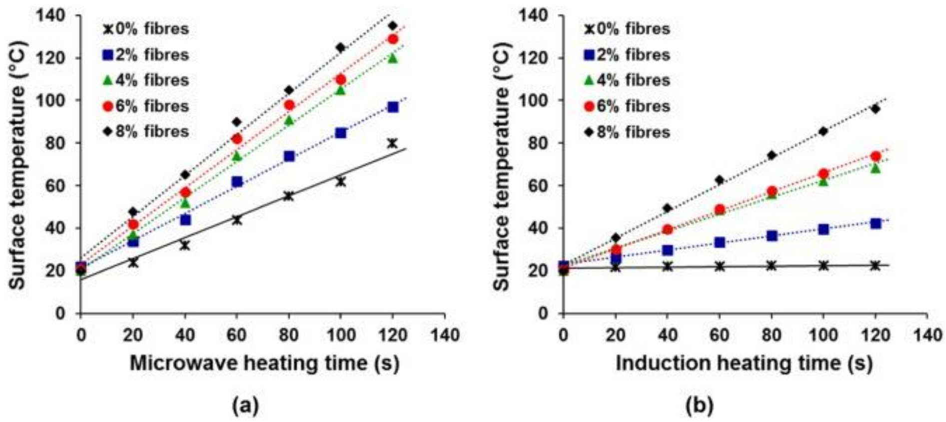

Figure 31: Surface temperature of the samples after exposure to (a) microwave, and (b) electromagnetic filed (Norambuena-Contreras and Garcia, 2016).

Moreover, it was revealed that microwave radiation could affect the air void structure inside the mix and this could result in a decline in strength. Interestingly, by applying different healing-loading cycle using a 3PB test it was shown that the higher healing level is achieved when microwave radiation applied. In addition, the healing level was reduced with each healing cycle, regardless of whether microwave or induction heating techniques were used. This could due to the changes of the void content-position as a consequence of heating (Norambuena-Contreras and Garcia, 2016).

As observed, many researchers have investigated the recovery capability in bituminous materials. Considering the fact that the recovery of properties could occur owing to different phenomena, it seems important to review these phenomena. Thus, the next section provides some information related to the recovery of properties in bituminous materials, considering related phenomena.

2.5 Phenomena that cause the recovery of properties in bitumen

There are many scientific references that discuss the recovery of properties in bituminous materials. However, from a technical viewpoint, it should be clarified that recovery could happen due to a range of different phenomena. Therefore, there is an important need to consider a comprehensive approach to understanding the recovery concept in bituminous materials (Ayar et al., 2016). Although studying the recovery capability of bituminous mixtures as complex multi-phase composite materials is not easy, recent studies have attempted to explore the role of different recovery efforts within bituminous materials (Mazzoni et al., 2016, Moreno-Navarro et al., 2015a).

Normally, the “predicted fatigue life” of asphalt pavements in the lab is less than their “real fatigue life” in the field. Thus, in fatigue based mechanistic design procedures some shift factors are used to calculate a reliable prediction of the fatigue life for asphalt pavements (Figure 32) (Guo, 2007).

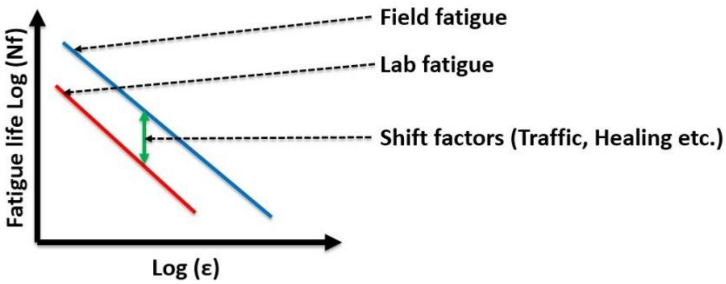

Figure 32: A schematic comparative diagram of the field and laboratory fatigue laws in asphalt pavements (depicted by the author).

For more than half a century, various experimental results have shown that during fatigue tests on asphalt concrete, the fatigue life is extended when rest periods are included between the successive loading signals (Van den Bergh, 2011). Furthermore, some researchers believed that the difference between predicted fatigue life and field fatigue life is, at least in part, related to the compensatory effects that could occur during the rest periods between load applications of successive traffic axles (Kim and Roque, 2006; Shen and Sutharsan, 2011; Al-Qadi and Nassar, 2003). In order to have a better understanding of rest periods, Figure 33 shows a schematic view of traffic loading application in a real pavement cross-section. It can be seen from this figure that different factors including vehicle speed, axle configuration, and headway can affect the duration and spacing of traffic pulses (Zeiada, 2012). In this context, headway is the time that elapses between the arrival of the same point of the leading vehicle and the following vehicle at the designated test point (in figure 33 headway is: T5+T4+T3+T2+T1) (Zhang et al., 2007).

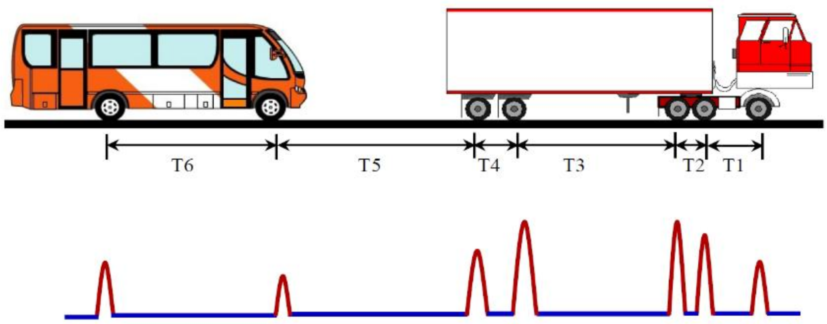

Figure 33: The schematic view of traffic loading application in a real pavement (Zeiada, 2012).

The recovery of mechanical properties owing to the existence of rest periods is not the only reason for the difference between predicted and real fatigue life of asphalt pavements. In fact, the following major factors may also directly contribute towards the difference between predicted and real fatigue life in asphalt pavements (Al-Qadi and Nassar, 2003):

1. Difference between calculated versus measured strains.

2. Difference between the state of stress in the field and in the laboratory.

3. The influence of the traffic wander.

4. Difference between laboratory-compacted specimens and field compaction.

Although many researchers have traditionally connected the recovery observed during rest periods to the healing phenomena (Ayar et al., 2016; Van den Bergh, 2011), the recovery can also be observed as a result of the reversibility of viscoelastic phenomena (i.e. dissociation/deformation of molecular bonds such as thixotropy and/or heating) during rest periods. In fact, healing is related to the recovery of structural damage (mainly micro-cracks) while reversible phenomena such as heating or thixotropy (which occur because of the rearrangement of the molecular network). Moreover, the material does not necessarily need to be damaged in order to observe the reversible phenomena (Ashouri, 2014; Butt et al., 2012; Mouillet et al., 2012; Moreno-Navarro and Rubio-Gámez, 2016), whilst the effects of reversible phenomena in viscoelastic materials could temporarily recover the some properties (i.e. stiffness, phase angle) during rest periods (Ashouri, 2014; Moreno-Navarro et al., 2015a). In relation to this issue, some studies have indicated that the recovery in stiffness is not directly related to fatigue life extension (Gaskin, 2013; Lu et al., 2003). These results revealed that during rest periods the stiffness of the asphalt concrete could be improved by means of reversible phenomena. Since this improvement is not due to damage reparation, it cannot significantly contribute to the fatigue life extension. In relation to this issue, Figure 34 shows a tangible example that was obtained by testing different bitumens using DSR equipment. In this case, three types of bitumen were fatigued to 50% of initial complex modulus (Fatigue 1), unloaded for four hours, re-fatigued to the pre-rest modulus level (Fatigue 2), and subsequently unloaded for 17 hours before re-fatigue (Fatigue 3). It can be seen that although the stiffness can considerably be recovered during the rest period (i.e. unloading period), the recovery of fatigue life did not correspondingly change and remained at a low level (Lu et al., 2003, Gaskin, 2013).

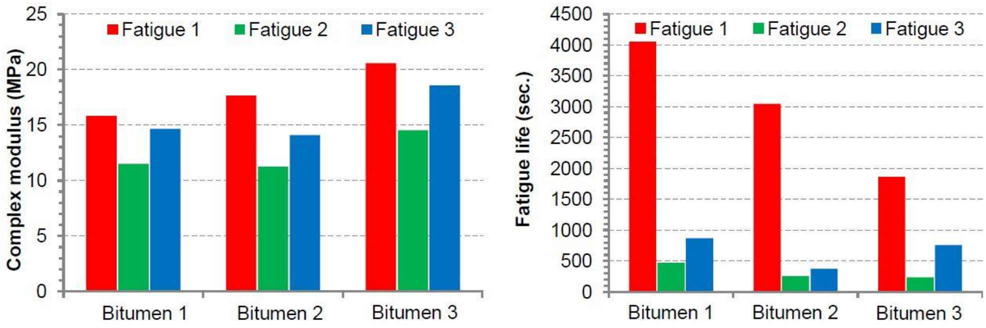

Figure 34: The effects of the rest periods on the stiffness and fatigue life recovery cited from Gaskin (2013).

To understand the different efforts leading to the recovery of properties in bituminous materials (i.e. reversible phenomena and real healing), Figure 35 presents a general outline of this issue. Knowing that the recovery could occur as a result of both reversible phenomena and healing, the next section describes these phenomena.

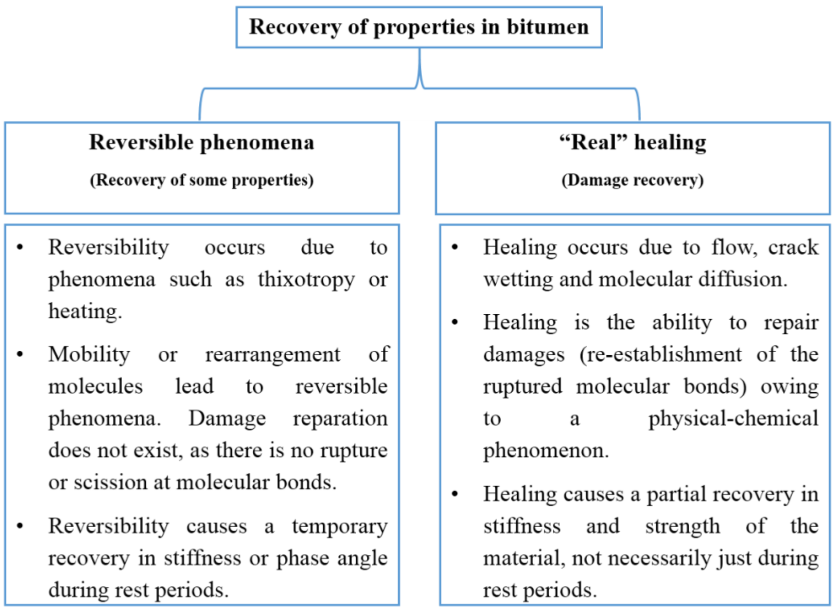

Figure 35: Outline of the recovery concept in bituminous materials.

2.5.1 Reversible phenomena

As previously expressed, the reversible phenomena (e.g. thixotropy, heating) can temporary recover the properties (i.e. stiffness, phase angle) of bituminous materials during rest periods. To understand the role of reversible phenomena in the mechanical response, it is important to understand why they occur in bituminous materials. In this respect, it is fundamental to know the structure of bitumen.

Bitumen has traditionally been regarded as a colloidal system consisting of high molecular weight asphaltene micelles dispersed or dissolved in a lower molecular weight oily medium (maltenes) (Figure 36). The micelles are considered to be asphaltene clusters together with an absorbed layer of high molecular weight aromatic resins that act as a stabilizing solvating medium. Away from the centre of the micelle there is a gradual transition to less polar aromatic resin and saturate layers which extend outwards to the less aromatic oily dispersion medium (Read and Whiteoak, 2003). In Figure 36, the asphaltene micelles are pictured as spherical to illustrate the concepts of solvation layer (resin shell) and effective volume. The oily dispersion medium is known as maltenes (Gaskin, 2013; Lesueur, 2009).

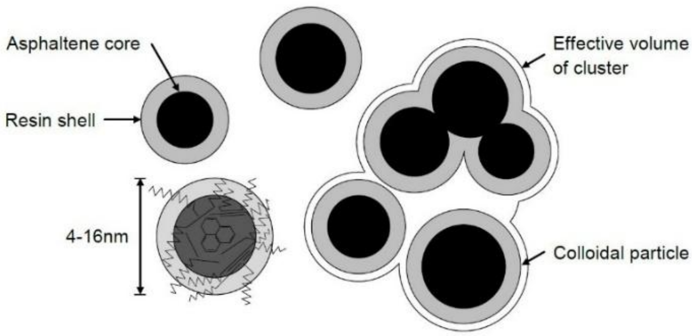

Figure 36: The simplified concept of the colloidal structure of bitumen (Gaskin, 2013).

According to this colloidal structure, the bitumen can be divided into three categories including Sol bitumen, Gel bitumen and Sol-Gel bitumen. The Sol bitumen has a sufficient amount of resins and aromatics, with enough solvating power to fully peptize the asphaltenes. Therefore, the resulting micelles have good mobility in the bitumen. The Gel bitumen has insufficient aromatic/resin fractions to peptize the micelles. The asphaltenes can become further associated in Gel type bitumen. This can lead to an irregular open packed structure of linked micelles. The rest of the space is filled with an intermicellar fluid of mixed constitution. In practice, most bitumens show an intermediate colloidal character, known as Sol-Gel bitumen. Figure 37 illustrates a schematic representation of Sol (a) and Gel (b) type bitumen (Read and Whiteoak, 2003).

In this regard, Sol bitumens could represent a more Newtonian behaviour, while Gel bitumens (i.e. commonly blown types) illustrate highly non-Newtonian behaviour. From a novel perspective, the non-Newtonian behaviour could be characterized as delayed elasticity together with some non-linearity in the viscoelastic properties (Lesueur, 2009).

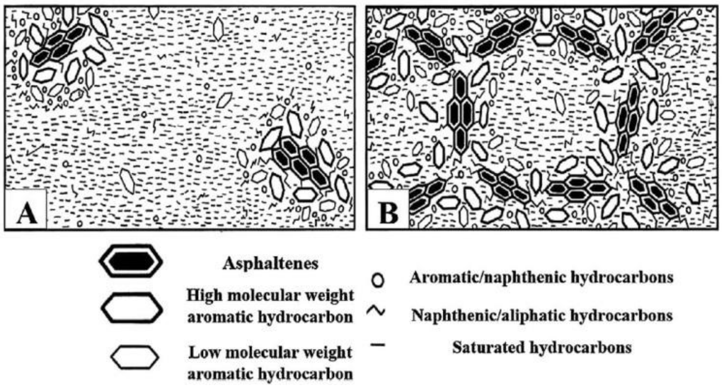

Figure 37: A schematic representation of Sol (A) and Gel (B) type bitumen (Read and Whiteoak, 2003).

Some researchers have pointed out that the Penetration Index (PI) can be used as an indicator of the colloidal nature of bitumens. A PI higher than + 2 could indicate a gel structure of elastic properties and a thixotropic nature, while a PI less than − 2 could indicate a Sol structure of Newtonian properties. However, bitumen with satisfactory rheological properties should have a PI between +1 and –1. To calculate PI the following equation can be used (Speight, 2015):

$$PI = 10 \times \frac{(2-50A)}{(1+50A)} \qquad (6)$$

Where the PI is the penetration index and A is the slope of the temperature sensitivity related to the logarithm of the penetration. In fact, A can be obtained by measurement of the penetration at two different temperatures or by the relation between the penetration and the softening point temperature. A can be calculated using the following equation (Speight, 2015):

$$A = \frac{d \log Penetration}{dt} \qquad (7)$$

Since the 1930s researchers have attributed the thixotropic behaviour of bitumen to its colloidal nature (Figure 36), which depends on the source of the bitumen, the degree of processing, and the temperature. This behaviour can be detected in many colloidal systems (Qiu, 2012). In this regard, thixotropy — as an intrinsic property of a viscoelastic material — indicates the capability to recover its microstructure from the un-cracked part of the material (Mewis and Wagner, 2009). In other words, thixotropy as a reversible phenomenon has been introduced as the tendency of a material's viscosity to decrease with time under loading condition (flow/stress) and to recover during the time when the loading is removed (i.e. during rest periods). It should be remembered that thixotropy could affect the entire performance of the bitumen, but particularly fatigue, healing, and high temperature performance (Shan et al., 2011). In addition, this non-Newtonian response is attributed to the dissociation and deformation of inter and intra-molecular bonds (microstructural changes) (Gaskin, 2013; Moreno-Navarro and Rubio-Gámez, 2016). Thixotropic effects can be seen at relatively high temperatures 15 °C (Castro and Sanchez, 2006), since at lower temperatures the molecules have less mobility (Moreno-Navarro and Rubio-Gámez, 2016) which can be affected by the size of the molecules (Khabaz and Khare, 2015).

The main point in this context is that during a repetitive loading process, thixotropic property of bitumen causes a progressive change from a gel to a sol structure (ascribed to the dissociation and deformation of inter- and intra-molecular bonds) while during rest periods the gel structure starts to reform (Gaskin, 2013; Moreno-Navarro and Rubio-Gámez, 2016).

In relation to this issue, Figure 38 shows a schematic outline of the behaviour of the thixotropic materials. In thixotropic material, applying a sheared condition results in the breakdown (i.e. separation) of the gel networks, while under a stationary condition (i.e. during rest periods) the regelation process occurs (the regelation process is slower when materials are subjected to higher shear rates) (Jyoti and Baek, 2015).

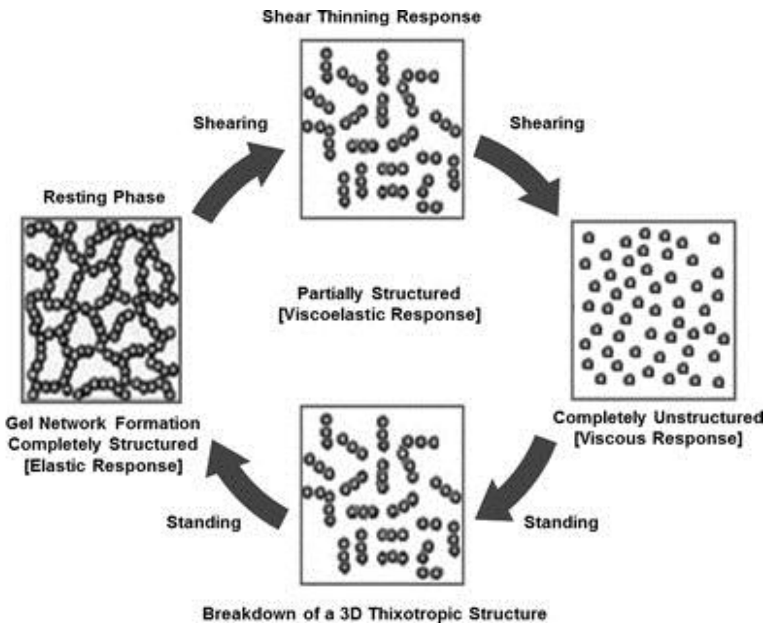

Figure 38: A schematic outline of the thixotropic behaviour in viscoelastic materials (Jyoti and Baek, 2015).

In theory, thixotropic materials can be fully viscous or viscoelastic, resulting in different types of results under a shear test. Many models have been developed for the correlation and prediction of the thixotropic response in materials, such as the structural kinetics approach (Mortazavi-Manesh, 2015). Figure 39 shows the response of a thixotropic material that is purely viscous under a shear condition, compared to thixotropic material that also possesses viscoelastic properties (Mortazavi-Manesh, 2015).

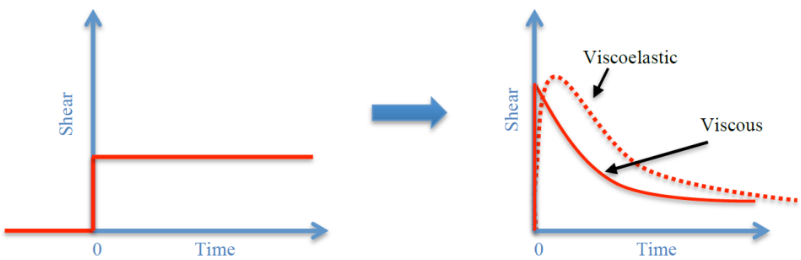

Figure 39: The response of a thixotropic material that is purely viscous under the shear condition, compared to thixotropic material that also possesses the property of viscoelasticity (Mortazavi-Manesh, 2015).

Another reversible phenomenon that could affect the performance of bitumen during fatigue process is heating. The molecular friction during the loading process causes the emergence of the heating phenomenon. Heating leads to chain separation as a result of thermal expansion and consequently a reduction in the secondary intermolecular forces. The mechanical appearance of the heating phenomenon is the reduction in stiffness of the material during loading process (known as self-heating), which can be recovered when the loading processes stop and the molecular temperature is restored (called as self-cooling) (Bazyleva et al., 2010; Sperling, 2005; Traxler and Coombs, 1936). Heating may be neglected for in situ loadings due to the available rest periods. However, during cyclic fatigue tests in the laboratory with a large number of loading cycles being applied to the sample over a short time period, self-heating cannot be neglected (Riahi et al., 2017).

According to the new approach to analysing the fatigue response in asphalt concrete presented by Moreno-Navarro and Rubio-Gámez, (2016), some phenomena related to molecular mobility such as plastic deformations or reversibility (e.g. thixotropy, heating) that co-exist with damage, cannot be neglected during cyclic loading. In this respect, three different stages can be observed during a fatigue process due to cyclic loading in asphalt mixtures including (Figure 40): (1) accumulation of permanent deformations; (2) reversible degradation (thixotropy) and initiation of irreversible damage (micro-cracks); (3) crack propagation (the coalescence of micro-cracks produces the localization and propagation of macro-cracks) (Moreno-Navarro and Rubio-Gámez, 2016).

Figure 40: A global sketch of different phases during a fatigue process in asphalt mixtures (Moreno-Navarro and Rubio-Gámez, 2016).

The above-mentioned fatigue stages can be interpreted from a mechanical viewpoint. In fact, the emergence of these phenomena (including reversible phenomena) during the cyclic loadings in asphalt mixtures can be specified by the variations generated in the phase angle and modulus (stiffness) (Moreno-Navarro and Rubio-Gámez, 2016). According to Figure 41 (Moreno-Navarro and Rubio-Gámez, 2016), in the first stage, a quick reduction of the modulus and increase of the phase angle that is related to plastic deformations, along with reversible phenomena such as thixotropy and heating, can be detected. Then, in the second stage, a quasi-stationary evolution is observed because of a slight change in these parameters (as a result of the fatigue cracking initiation and also reversible phenomena), and the effects of reversible phenomena (e.g. heating and thixotropy) during this part of the responses are not predominant. Ultimately, in the third stage, a rapid reduction of modulus and phase angle occurs (due to fatigue cracking propagation) (Mazzoni et al., 2016; Moreno-Navarro and Rubio-Gámez, 2016).

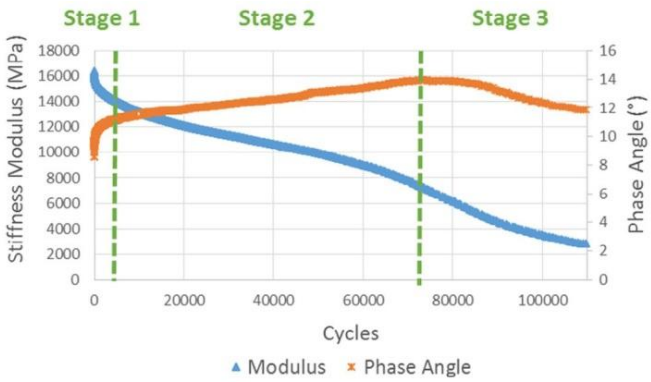

Figure 41: The typical results observed in a strain-controlled fatigue test on asphalt mixtures using four-point bending method (Moreno-Navarro and Rubio-Gámez, 2016).

2.5.2 Real healing

Materials that possess healing ability when exposed to damage through thermal, mechanical, ballistic or other means are able to heal and recover themselves and restore their original set of properties (i.e. restoring the fractured molecular bonds) (Liu, 2012; Wool, 2008; Yang, 2016; Li and Meng, 2015). Materials generally considered to have healing ability include polymers, metals, ceramics and their composites (Wool, 2008), glass, concrete, and bitumen (Qiu, 2012; Shen and Carpenter, 2007). Among these materials, researchers have intensively focused their efforts on examining the healing capability of polymers. As an interesting experiment, some studies concluded that bullet holes in a plastic plate would heal up instantly. When a high velocity projectile could penetrate the polymer plate, the hole would heal faster than the eye could see via elastic recovery followed by interdiffusion and sealing (Kalista et al., 2007). More specifically, this type of healing can be seen in poly (ethylene-co-methacrylic acid) copolymers (Wool, 2008; Kalista et al., 2007).

As mentioned in the previous paragraph, in some few types of materials, however, the ability to heal as an intrinsic property can be observed (Wool, 2008), and the majority of studies have focused on the use of novel self-healing systems, particularly in the case of polymers for the repair of damage (Liu, 2012; Bekas et al., 2016). Some of these systems have a shell structure with an embedded liquid (such as microcapsules, hollow fibres, and microvascular networks) and when a crack passes through it, the shell tears and the embedded liquid flows to fill and repair the crack (Joseph et al., 2009; Qiu, 2012). Figure 42 shows the mechanism of the hollow fibers embedded in materials, which can deliver a healing agent to the crack plane and subsequently the recovery in properties may occur (Banea et al., 2014).

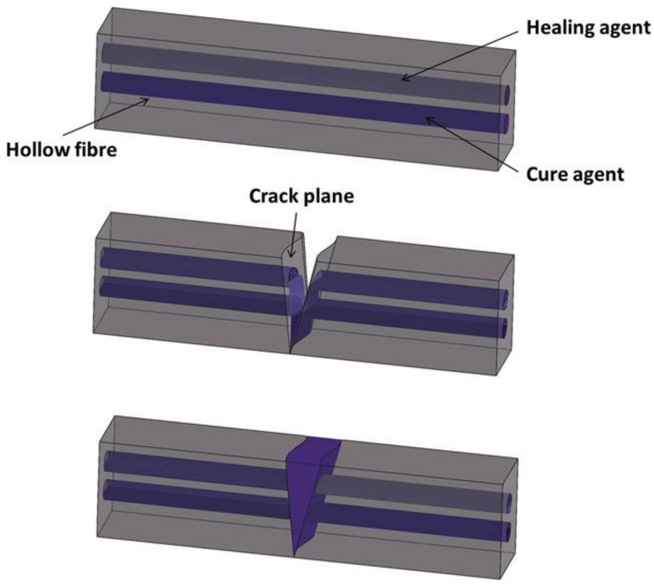

Figure 42: A schematic view of self-healing hollow fibres used in the materials to repair damage (Banea et al., 2014).

The mechanism thought to underlie healing remains unclear (Qiu, 2012), and there is no exact definition of healing capability in bituminous materials. However, healing capability is generally regarded as the intrinsic response of bitumen to diminish the generated cracks by reformation of molecular bonds, which consequently initiates the partial recovery of its original properties over time (Canestrari et al., 2015; Shen and Carpenter, 2007; Ayar et al., 2016). It is important to note that healing is a time dependent phenomenon and some researchers have confirmed this fact through imaging techniques, as well as mechanical analysis (García, 2012; Qiu et al., 2012). Since the healing process can be explained through distinct viewpoints and levels of analysis (i.e. mechanical and chemical), researchers have defined different models for the healing mechanism in bitumen. Among these models, the multi-step healing model — which has essentially been derived from the multi-step healing mechanism in polymers — has been highlighted in many studies (Ayar, et al., 2016, Qiu, 2012). According to the multi-step healing mechanism in polymers (Figure 43), the healing mechanism is introduced in five stages of the model including surface rearrangement, surface approach, wetting, diffusion, and randomization (Wool and O'Connor, 1982; Wu et al., 2008).

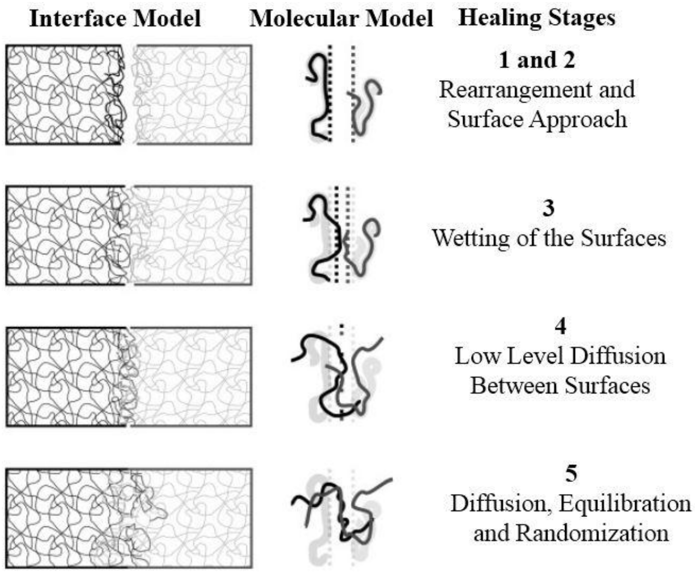

Figure 43: The multi-step healing mechanism in polymers (Wool and O'Connor, 1982; Wu et al., 2008)

According to Wool and O'Connor (1981), the healing phenomenon in materials has been characterized by combining an intrinsic healing function of the material with a wetting distribution function through a convolution integral (Equation 8).

$$R = \int_{\tau=-\infty}^{\tau=t} \mathrm{R}_h(\mathrm{t}-\tau)\frac{d\phi(\tau,\mathrm{X})}{d\tau}d\tau \qquad (8)$$

where R is the net macroscopic healing, R_h (t) is the intrinsic healing function of the material, φ(t, X) is the wetting function, and τ is the time variable. In this equation, the lower limit of negative infinity denotes healing even when there is a micro-damage at the crack tip that has not yet propagated to the crack opening stage. In fact, at t=0 the crack is closed and could be partially healed.

Because of the similarity between the bitumen and polymer materials, Phillips (1998) divided the healing mechanism in bituminous materials into three steps (Figure 44): (1) surface approach due to the consolidation of stresses and flow of bitumen, (2) wetting (adhesion of two crack surfaces driven together by surface energy) and (3) the complete recovery of mechanical properties due to diffusion and randomization of asphaltene structures (Phillips, 1998).

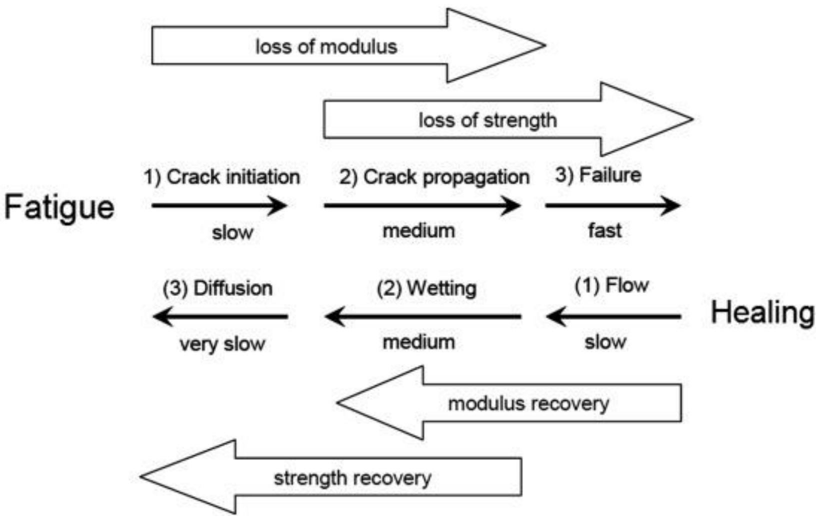

Figure 44: A schematic diagram of the three-step healing mechanism in bitumen cited from Qiu (2012).

Other researchers have similarly explained the healing phenomenon based on the capillary diffusion theory. In fact, during the wetting step, the capillary force could apply a considerable impact on the healing efficiency. When the bitumen is sufficiently liquid it could encounter one of the propagating cracks including the contact points and the empty space, and could finally enter the cracked surfaces driven by capillary force. Thereafter, this condition may provide an opportunity for wetting the cracked surfaces, diffusing into the fractured matrix driven by gradients of pressure or of concentration, and entangling with the matrix molecules by surface energy difference or thermodynamic driving force. The capillary action begins from the contact points between the both crack surfaces and then develops across the crack (Sun et al., 2017b).

The mechanism of the healing phenomenon based on capillary diffusion is shown in Figure 45 (Sun et al., 2017b).

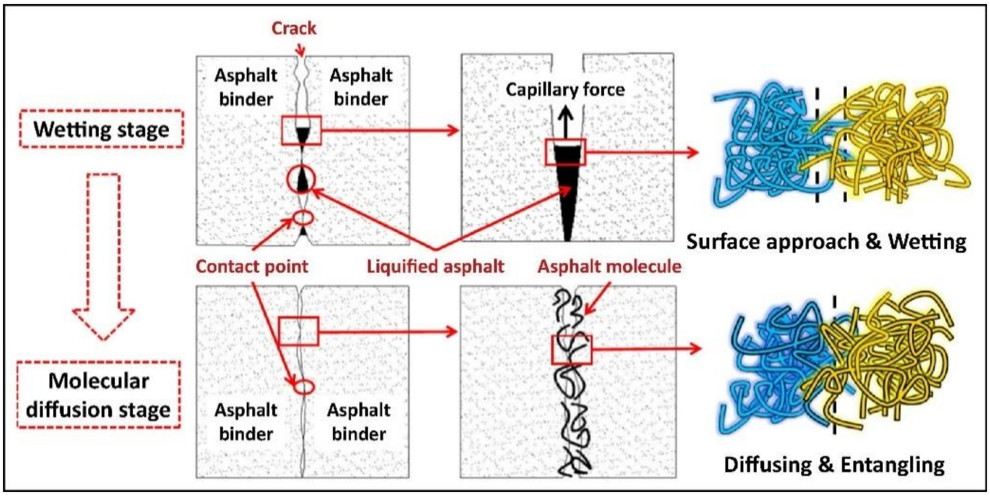

Figure 45:The mechanism of healing phenomenon in asphalt concrete based on capillary diffusion theory (Sun et al., 2017b).

In the healing mechanism, wetting is the ability of two crack surfaces to make contact (i.e. crack closure) (Little and Bhasin, 2007). Wetting ability is related to the fundamental characteristics of materials such as mechanical properties, surface energy, geometric features of the crack, viscosity and temperature (Ashouri, 2014; Little et al., 2015; Sun et al., 2017b). As mentioned previously (Section 2.3.1), bitumen containing fewer molecules with high molecular weight has a higher wetting capability, since this type of bitumen can flow easily (Garcia et al., 2014; Sun et al., 2017a).

Additionally, the capability of diffusion (i.e. connection between the molecular chains) (Wool, 2008) is directly related to the mobility potential of the molecules in the bitumen, which can be affected by the morphology. In fact, bitumen containing more molecules with longer chains and fewer branches has higher molecular mobility (in maltenes components) (Bhasin et al., 2011).

Furthermore, the ratio of long molecules to ring shaped molecules could enhance the mobility and subsequently the diffusion capability of the bitumen (Sun et al., 2017a). According to Sun et al. (2017a) the recovery capability in bitumen is more sensitive to the molecular structure (morphology) than the large molecule content (Sun et al., 2017a). This could indicate the importance of diffusion effects (as the final and determinative stage) on the healing mechanism.

According to the multi-step healing mechanism in bitumen, wetting and intrinsic healing (diffusion capability) act as key factors (Little et al., 2015). As a conclusion, the simplified interrelationship between material properties and the healing mechanism in bituminous materials is explained in Figure 46 (Little et al., 2015).

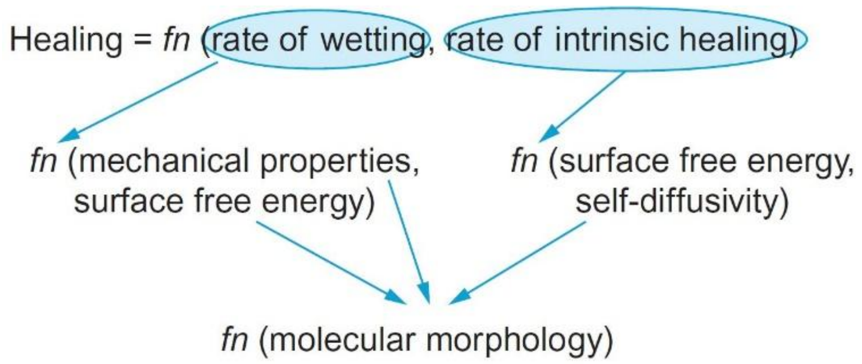

Figure 46: The simplified interrelationship between material properties and the healing in bitumen (Little et al., 2015).

2.6 Conclusions of the state of the art and the motivations for research

The recovery of properties in bituminous mixtures is a complex concept, as evidenced by the various phenomena such as microstructure reversibility (e.g. thixotropy or heating) and healing (i.e. restoring the structural damage) (Moreno-Navarro and Rubio-Gámez; 2016; Ayar et al., 2016; Soltani and Anderson, 2005), phenomena that could also coexist with fatigue processes during cyclic loading (Moreno-Navarro and Rubio-Gámez; 2016).

When analysing the recovery of properties, it is important to consider the level of damage (i.e. micro or macro crack) during the loading process, since the recovery capability of bituminous mixtures can be affected by this aspect (Moreno-Navarro et al., 2015a; Ayar et al., 2016; Menozzi et al., 2015). Thus, it is also important to apply the healing techniques as rehabilitation measures at the optimal damage state of the material.

Similarly, recovery capability can also be affected by other factors such as temperature, compressive pressure (Gaskin, 2013), types of material, and duration of the technique (time) (Moreno-Navarro et al., 2015a). Therefore, to apply healing techniques, the optimal conditions should be selected in order to achieve the maximum possible recovery. Normally, these techniques are used for restoring macro-damage, and it is therefore necessary to evaluate efficiency of these techniques at this level of damage.

However, without adequate knowledge of the phenomena that lead to the recovery in asphalt pavements at different states of damage, it will not be easy to design and implement the healing technologies on a real scale. Furthermore, the efficiency of each of these phenomena to recover damage and properties should also be studied. Regarding the information presented by previous researchers, some important questions related to the recovery capability of bituminous mixtures still remain unanswered.

On the one hand, it is important to study whether the asphalt concrete can recover its initial and/or previous mechanical properties when the macro-damage failure happens. Moreover, it is necessary to investigate the capability and efficiency of healing technologies (e.g. heating technique, external force) for inducing the recovery of properties (e.g. fatigue life, visco-elastic properties) in bituminous mixtures. More specifically, it should be clarified whether or not gluing macro-cracks (i.e. crack closure) by inducing healing through the heating technique is able to restore the visco-elastic properties in bituminous mixtures (Moreno-Navarro et al., 2015a) and also it is necessary to study the time-dependency feature of this technique. In the same vein, the effects of internal influencing factors (e.g. type of binder, the use of modifier, mixture characteristics), and external influencing factors (e.g. testing condition) on the recovery capability at the macro-damage level should be assessed.

Further, the suitable conditions for applying healing technologies (e.g. temperature, time) and their effects on the efficiency of recovery are worthy of investigation. Given that the healing techniques have been considered as a possible rehabilitation method for asphalt pavements (Ayar et al., 2016), their repeatability under different service conditions should be examined.

On the other hand, the potential for restoring initial mechanical properties at the micro-damage level in bituminous mixtures remains unclear (Ayar et al., 2016). In fact, it is important to reveal which types of phenomena (e.g. reversibility, healing) can (separately or simultaneously) contribute to recover the mechanical properties when cyclic loading is interrupted (i.e. during rest periods). In addition, some questions still remain that must be addressed:

Are rest periods included before damage initiation able to increase fatigue life or should they be included before the loss of deformation capacity in the material?

How do the characteristics of rest periods (duration and number of load repetitions applied between them) affect the fatigue life?

Is the increment in fatigue life due to the recovery of lost properties (molecular restructuring to the original position as in Sol-Gel transformation) or is this due to other mechanisms?

Finally, could the effects of the molecular mobility produced by these phenomena be compared with those produced by plastic deformations or are they very small in comparison?

Objectives

3 Objectives

On the basis of the conclusions presented in the previous section, the main objective of this research is to study the recovery capability in bituminous mixtures, paying attention to the effect of healing techniques to induce this capability.

To accomplish the main objective, the following secondary aims were established for this research:

- To evaluate the recovery of mechanical properties in bituminous mixtures at the macro and micro levels of damage, considering the role of different phenomena (i.e. thixotropy, heating, healing etc.).
- To assess the role of internal influencing factors (e.g., the use of modifiers, mixture characteristics), and external influencing factors (e.g., testing conditions) in the recovery capability of bituminous mixtures at the macro-damage level.
- To examine the influence of the main variables that affect the healing technologies (temperature, time, and external force) in the recovery capability of bituminous mixtures at the macro-damage level.
- To analyse the repeatability of the induced recovery achieved by applying healing techniques for bituminous mixtures.
- To assess the mechanisms underlying the fatigue life extension during rest periods, and to investigate the effects of rest period characteristics (i.e. duration and the number of load repetitions applied between them) on the recovery capability of bituminous mixtures.

Methodology

4 Methodology

As previously mentioned, the level of damage can have an impact on the recovery capability of asphalt concrete (Ayar et al., 2016; Moreno-Navarro, 2015). Accordingly, in this study, the experimental program to explore the recovery capability of asphalt concrete has been conducted at two different levels of damage (i.e. macro and micro levels). Further, to meet other objectives of this study, the impact of influencing factors (e.g. materials, service condition) and healing technology (i.e. heating technique) on the recovery capability was assessed in some cases.

On the one hand, to assess the recovery capability at the macro-damage level, the macro-cracks were exposed to an accelerated healing process since this is required to recover macro-cracks, and under such a level of damage rest periods would not be helpful (Ayar et al., 2016; Moreno-Navarro, 2015). Therefore, the accelerated healing process is designed based on the principles of the healing mechanism. In fact, this process could accelerate two sub-mechanisms of the healing phenomenon including "flow" and "wetting" (Phillips, 1998) by means of techniques such as "heating" and "external force" respectively (Figure 47).

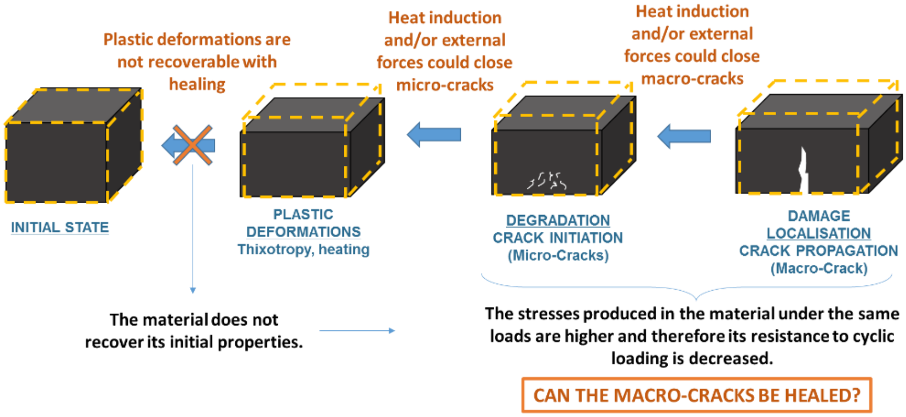

Figure 47: Sketch of the degradation and recovery stage in asphalt materials considering healing process for the recovery of macro-cracks.

On the other hand, to analyse the recovery capability at the micro-damage level, rest periods are included in the loading regime, since rest periods provide an opportunity for the appearance of different phenomena such as reversible phenomena (e.g. thixotropy, heating etc.), or healing. In general, all these phenomena are supposed to play an important role in the recovery of properties in asphalt concrete. (Ayar et al., 2016; Moreno-Navarro, 2015; Moghadas-Nejad et al., 2016) (Figure 48).

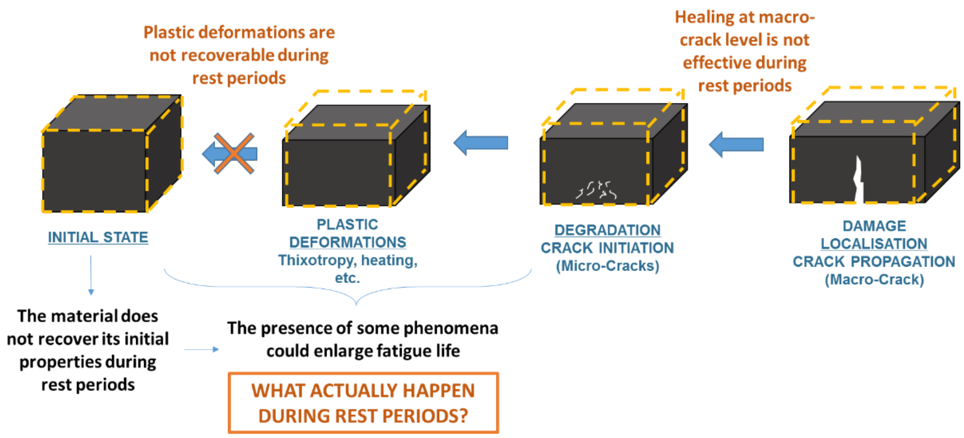

Figure 48: Sketch of the degradation and recovery stage in asphalt materials considering rest periods for the recovery of micro-cracks.

In this regard, the following sections explain the methodology, which has been divided into two main parts including “Exploring the damage recovery in bituminous mixtures at the macro-crack level: the role of healing process (heating, time and external force)” and “Exploring the damage recovery in bituminous mixtures at the micro-crack level: the role of rest period”. Each of these two parts separately describes the materials and testing plan applied in this study.

4.1 Exploring the damage recovery in bituminous mixtures at the macro-crack level: the role of healing process (heating, time, and external force)

4.1.1 Materials

To accomplish the aims of study at the macro-crack level, four different asphalt mixtures, two AC 16 (EN 13108-1) and two BBTM 11 (EN 13108-2), manufactured with different types of bitumens (SBS polymer modified bitumen, crumb rubber modified bitumen, and conventional bitumen) were used. The use of different types of bitumen as influencing factors can meet some of the objectives presented in this study. Table 7 illustrates the properties of bitumen used.

However, it should be noted that the main reason for using SBS polymer modified and crumb rubber modified bitumens is the uncertainty of their effects on the mechanical recovery in asphalt mixtures, which has been reported by some researchers (Ayar et al., 2016; Qiu, 2012). Adopting a different point of view, Tabaković and Schlangen (2015) classified the polymer and rubber modification of binders as possible healing technologies for asphalt pavements, and the effects of bitumen modification as a healing technology on the recovery capability of asphalt mixtures were also evaluated in the present study.

Table 7: Properties of the bitumens employed for studying the recovery capability of asphalt mixtures at the macro-crack level.

Bitumen type	Modifier	Penetration (0.1 mm) EN 1426	Softening point (°C) EN 1427	Elastic Recovery (%) EN 13398
B	-	55	51.2	11
PMB	SBS Polymer	53	61.2	87
CRMB-1	Crumb Rubber	57	55.8	69
CRMB-2	Crumb Rubber	52	61.2	82

It should be stated that AC16 and BBTM 11 consist of continuous-graded and gap-graded mineral skeletons respectively, which can be considered as the most commonly used mixtures in the construction of asphalt pavements (this makes the study more representative). In fact, these two types of gradation curves as internal influencing factors were selected to assess the effects of the mineral skeleton on the recovery capability of asphalt mixtures at the macro-crack level. Nonetheless, the aggregates used to manufacture these asphalt mixtures were the same; ophitic aggregates in the coarse fraction, and limestone aggregates in the fine and filler fractions. Figure 49 shows the gradation curves used for studying the recovery capability of asphalt mixtures at the macro-crack level.

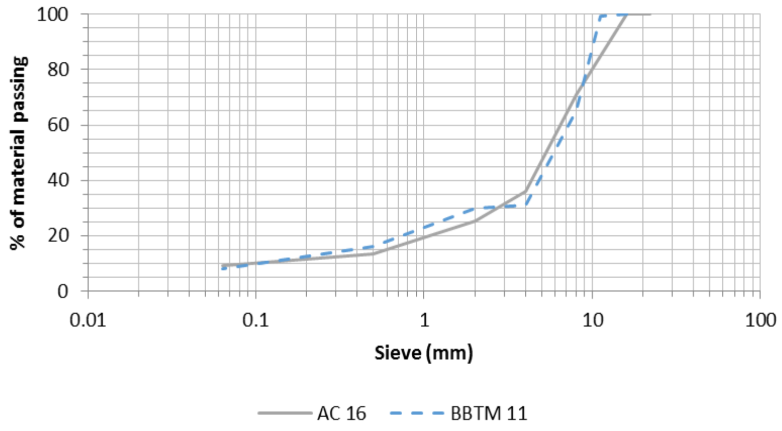

Figure 49: Gradation curves used in this study.

In addition, some characteristics of the four asphalt mixtures are summarized in Table 8. As can be observed, the designed mixtures have similar density, bitumen and void content, in order to reduce the influence of these variables when studying the recovery capability of these materials.

Table 8: Properties of the mixes manufactured for studying the recovery capability of asphalt mixtures at the macro-crack level.

Mixture	Bitumen type	Bitumen content (%)	Bulk density (g/cm³) EN 12697-6	Air voids (%) EN 12697-8	Indirect tensile strength at 15 ºC (kPa) EN 12697-23
AC-I	B	5.0	2.387	4.50	2263
AC-II	CRMB-1	5.0	2.367	4.50	2024
BBTM-I	PMB	5.5	2.390	4.25	1864
BBTM-II	CRMB-2	5.5	2.374	4.81	1578

4.1.2 Experimental Plan

The recovery capability of the asphalt mixtures in this research was analysed using the University of Granada – Fatigue Asphalt Cracking Test (UGR-FACT). This test method was developed at the Construction Engineering Laboratory of the University of

Granada (LabIC.UGR) (Moreno-Navarro and Rubio-Gámez, 2013; Moreno-Navarro and Rubio-Gámez, 2014).

The UGR-FACT was primarily utilized to induce a macro-crack in the asphalt concrete samples through a fatigue effort, and afterwards to evaluate the effectiveness of the healing process applied to the induced macro-crack. The UGR-FACT reproduces the conditions that lead to the appearance of fatigue cracking in asphalt pavements (i.e. combination of traffic loads and thermal gradients) and can also classify the different steps of the response of materials under a fatigue process (Moreno-Navarro and Rubio-Gámez, 2013).

Additionally, the results obtained by the UGR-FACT method of analysis can provide information regarding the mobility produced at molecular and bonding level, as well as the produced damage caused by the fracture of molecular bonds (Moreno-Navarro and Rubio-Gámez; 2016).

The device consists of a base (Figure 50 (a)), two supports where the specimen is fixed over them (Figure 50 (b)), and a load application plate (Figure 50 (c)). The base has a platform that is composed of two sloping surfaces with two rails that allow for the sliding of the supports, and of two vertical spindles that are used to measure vertical deformations in the upper part of the test specimen (Figure 50 (d)). The two supports are composed of a carriage that is adapted to the shape of the rail at the base (leading to effective load transmission), and of a support plate (to which the test specimen is attached over it with epoxy resin) where horizontal Linear Variable Differential Transformers (LVDTs) are located (Figure 50 (e)). Furthermore, under these support plates, two elastic elements (rubber pads) are introduced in order to allow the flexion of the specimen (Figure 50 (f)) along with a spring that simulates the foundation layers (Figure 50 (g)) (Moreno-Navarro et al., 2015b).

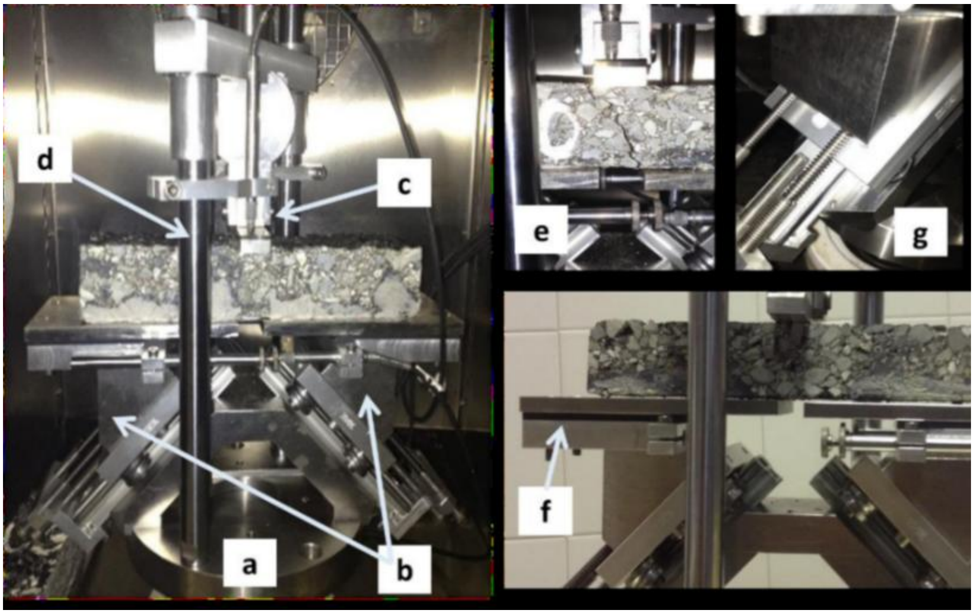

Figure 50: The UGR-FACT equipment (Moreno-Navarro et al., 2015b).

The distance between the supports can vary, depending on the type of deterioration that needs to be reproduced (e.g. a crack, pre-crack, dilatation joint, pothole, etc.). Moreover, the head of the load application is composed of a piece of steel that is thick enough to prevent deformations during the load application (thus avoiding differential errors due to its own deformation and which are not related to the test specimen) (Figure 50 (c)) whilst providing a flat surface for the vertical LVDTs (Figure 50 (f)). It should be noted that the UFR-FACT specimens used in this study had dimensions of 200 (length) × 60 (width) × 40 (thickness) mm. However, samples of different thickness corresponding to its real thickness in a pavement system can be tested by UGR-FACT equipment. In this research, a thickness of 40 mm was selected since the BBTM mix is usually laid at a thickness of 30-40 mm (Nikolaides, 2014).

The simple geometry of the test device is capable of generating horizontal as well as vertical deformations in the test specimen, which reproduce the bending and shear stresses induced by traffic loading, as well as tensile strains due to the effect of thermal gradients (Moreno-Navarro and Rubio-Gámez, 2013; Moreno-Navarro et al., 2015b).

Figure 51 represents the sketch of the mechanical efforts induced in the asphalt concrete samples using the UGR-FACT test device.

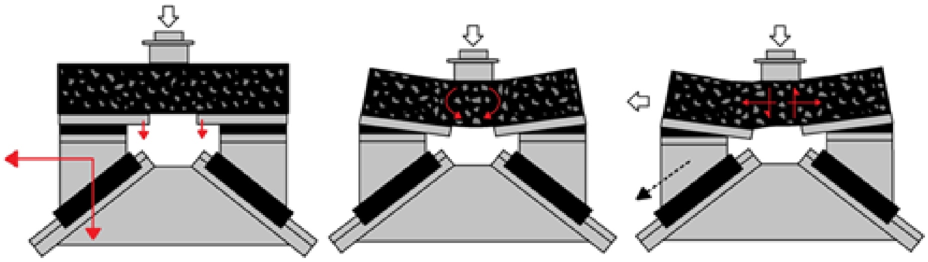

Figure 51: The sketch of the mechanical efforts induced in the asphalt concrete samples using the UGR-FACT equipment (Moreno-Navarro et al., 2015b).

For this purpose, a combined load function is used (Figure 52): a main up and down ramp that simulates thermal effects (with lower frequencies and higher amplitude) and a secondary verse-sine that represents traffic loads (with higher frequencies and lower amplitudes) (Moreno-Navarro et al., 2015b).

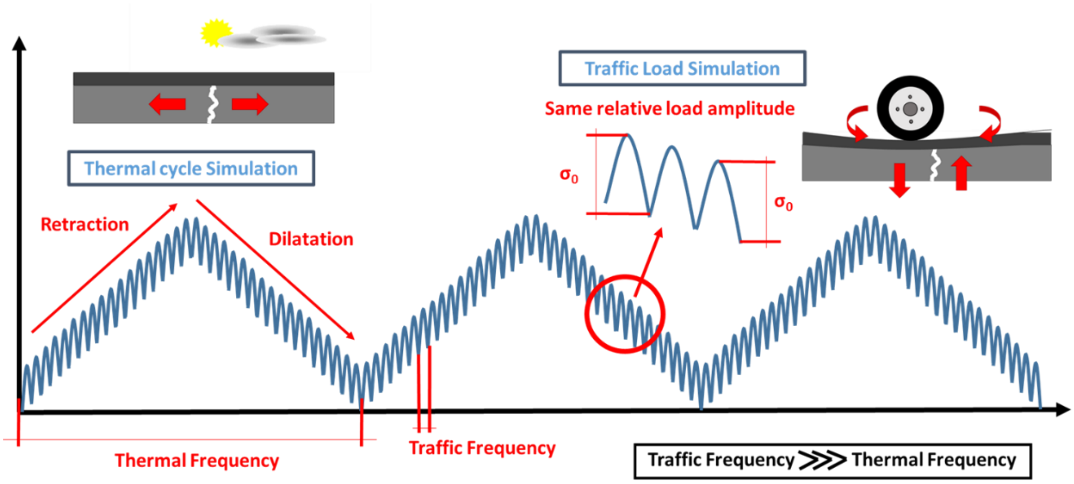

Figure 52: Outline of the loading function employed in the UGR-FACT test (Moreno-Navarro et al., 2015b).

In addition, the different states of the material behaviour during the fatigue process (initial state: plastic deformations, thixotropy, heating, etc.; micro-damage; and macro-damage) can be evaluated through the displacements produced in its geometry (Figure 53) (Moreno-Navarro et al., 2015a).

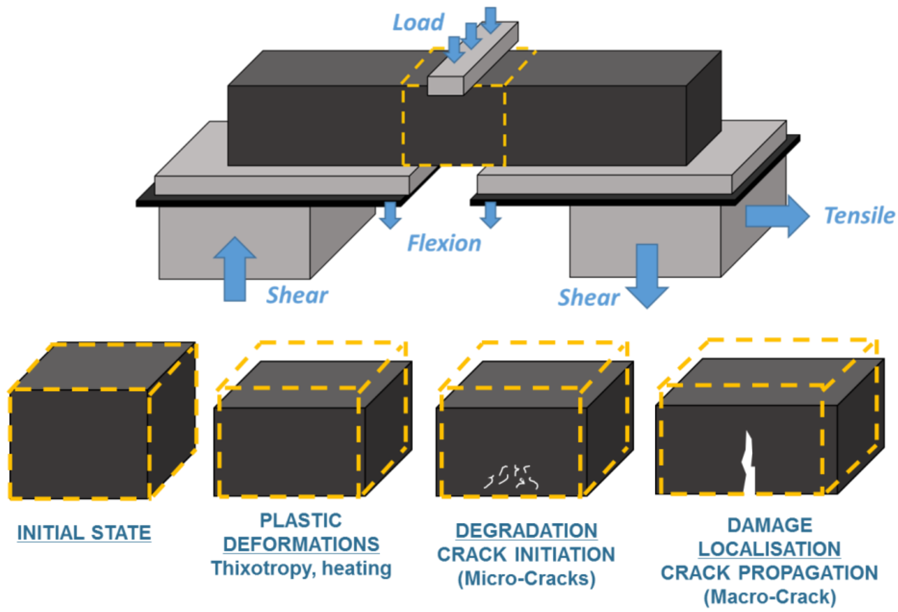

Figure 53: Scheme of the efforts induced with the UGR-FACT test device and the different states of the volume tested during the fatigue process (Moreno-Navarro et al., 2015a).

As can be seen from Figure 50, four LVDTs (one vertical and one horizontal in each side of the specimen) are used in order to control the vertical and horizontal displacements produced in the material in each load cycle. Based on the measures taken by LVDTs, two different types of displacements can be observed in each direction (horizontal and vertical) and load cycle: a "permanent" displacement (hi, vi) that remains after the load cycle and is related to the non-recoverable deformations or the damage produced in the material; and a "relative" displacement (Hi, Vi) that is related to the consistency (stiffness) or damage state of the material in a given cycle (Figure 54).

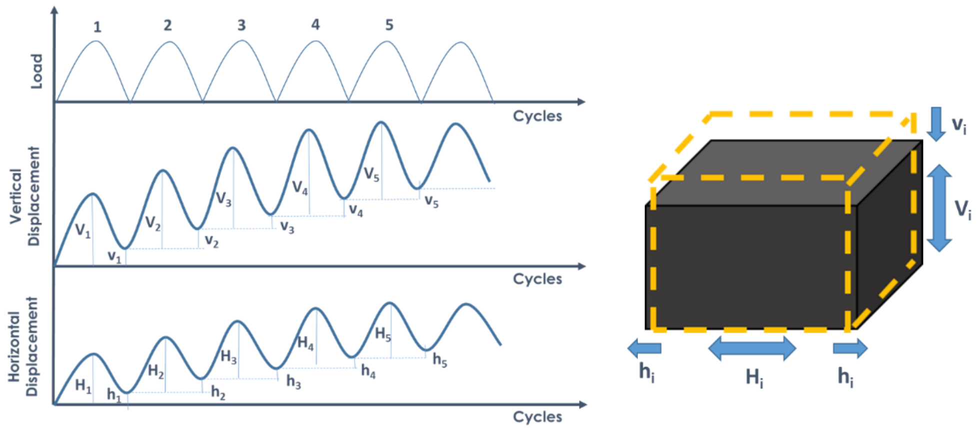

Figure 54: Outline of the displacements produced in the volume during the UGR-FACT test (Moreno-Navarro et al., 2015a).

The evolution of the fatigue cracking process is examined by using a combined analysis of the dissipated energy in each load cycle (calculated from the area of the hysteresis loop described in the "relative" displacements, (Equation (9)) and the variation of the geometry (Δεi) of the material in the zone where the fatigue phenomenon takes place (calculated from the "permanent" displacements in both directions measured in an unitary volume (Equation (10)). Using this information, different stages of the fatigue process can be clearly identified in the material (Moreno-Navarro & Rubio-Gámez, 2016). Thus, it is possible to assess the behavioural phases (degradation state) of the material tested whilst the effectiveness of the healing process can be analysed.

$$\omega_i = \omega_{hi} + \omega_{vi} \qquad (9)$$

Where ω_i is the dissipated energy in cycle i (in J/m^3); ω_{hi} is the horizontally-dissipated energy in cycle i (in J/m^3); and ω_{vi} is the vertically-dissipated energy in cycle i (in J/m^3).

$$\Delta\varepsilon_i = \frac{|(1+\delta_{hi})\cdot(1-\delta_{vi})|-1}{1} \cdot 100 \qquad (10)$$

Where $\Delta\varepsilon_i$ is the variation of the geometry of the specimen in the cycle i for an initial unitary volume; δ_{hi} and δ_{vi} are the horizontal and vertical dimension changes measured in the specimen in the cycle i.

Figure 55 illustrates the typical results obtained when representing the two parameters obtained in each load cycle of the UGR-FACT test (dissipated energy on the horizontal axis, and the variation of the geometry on the vertical axis). As can be observed, the different stages of the fatigue process (plastic deformations, thixotropy, etc.; micro-damage; and macro-damage) can be clearly identified in each material tested. During the first part of the fatigue test, high variations are produced in the geometry of the material (vertical axis), which are reduced as the number of applied load cycles increases (due to plastic deformations), until they generate molecular breakage. In spite of this considerable variation in the geometry of the material, the dissipated energy measured in each load cycle during this first part does not correspond to any change (the first part of the curve almost represents a vertical descent). This implies that the variations produced in the material due to the cyclic loads do not produce damage, as the levels of dissipated energy do not change considerably from the first cycle (which represents the viscoelastic response of the undamaged material). In the second part of the test, the variations in the geometry of the material become very small, and the dissipated energy measured in each additional cycle begins to increase. In this stage, strain hardening causes a reduction in the molecular mobility capacity of the materials and each additional load cycle does not produce plastic deformations or other visco-elastic phenomena such as thixotropy; rather, they begin to produce micro damage due to molecular rupture (damage initiation). Finally, after a certain number of cycles, the dissipated energy begins to increase considerably by maintaining the changes produced in the geometry (which signals the initiation of the macro-crack due to the coalescence of micro-cracks), up to a point at which the values of $\Delta\varepsilon_i$ begin to increase again (due to the propagation of the macro crack), until total failure of the specimen is reached (Moreno-Navarro & Rubio-Gámez, 2016).

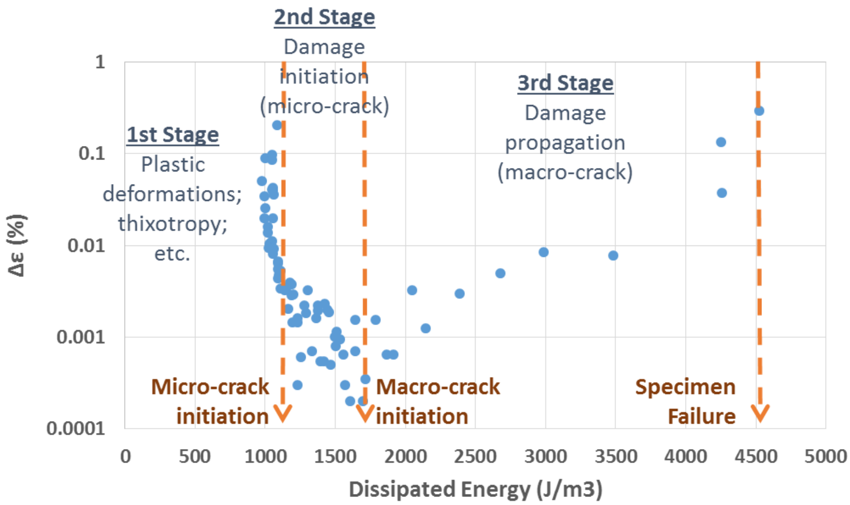

Figure 55: Example of the results obtained in the UGR-FACT test when the dissipated energy and the variation of the geometry of the specimen are represented.

Concerning the information presented in the state of the art section, since the recovery capability of two fractured surfaces (crack surfaces) of asphalt mixtures is assessed, the experimental method of this part of study can be classified as a fracture-based healing method. In this context, relatively few investigations have analysed the healing capability of macro-cracks (specifically open cracks) in asphalt concrete (Ayar et al., 2016; Qiu, 2012). Nonetheless, there are two studies that have assessed the healing capability of macro-crack in asphalt mixtures, conducted by Bazin and Saunier (1967) and Uchida et al. (2002). However, Bazin and Saunier (1967) employed a very soft bitumen to manufacture asphalt mixes (which could not be considered very representative), and Uchida et al. (2002) also induced macro-cracks through a static failure before analysing healing capability by a flexural test, whereas in reality the combination of traffic loads and thermal gradients leads to cracking in asphalt concrete (Moreno-Navarro and Rubio-Gámez, 2013).

In order to assess the effect of recovery capability at the macro-damage level, the asphalt concrete samples were subjected to different steps of testing (i.e. fracture-healing-fracture test). During the first step, the samples were tested using the UGR-FACT until their macro-crack failure was reached (Figure 56).

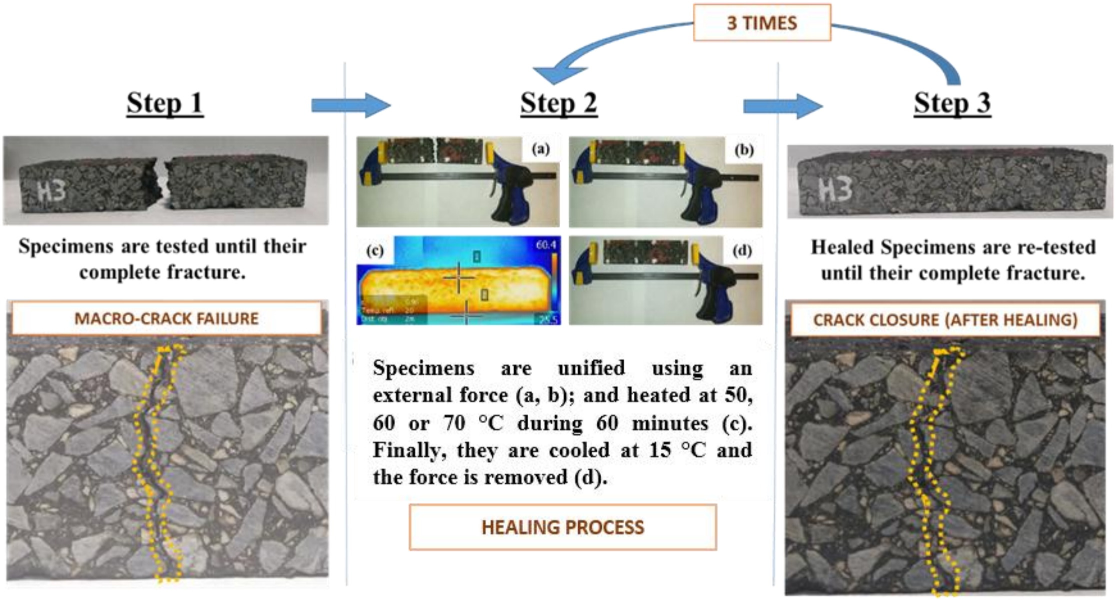

Figure 56: Detail of the steps followed during the testing of each specimen during the healing process (Moreno-Navarro, 2017).

In a second step, an accelerated healing process was then applied to the fractured samples. This process is designed based on the principles of the healing mechanism in bitumen. In fact, to accelerate the "flow" and "wetting" as two sub-mechanisms of healing phenomenon, "heat conditioning" and "external force" were employed (Figure 57). It is worth noting that applying a small compression stress on the crack surface could induce the healing capability by means of promoting surface approach and wetting as principal parts of the healing mechanism (Gaskin, 2013; Bazin and Saunier, 1967; Qiu, 2012), as well as reducing the variability of the results (Bazin and Saunier, 1967). Moreover, the heat conditioning could reduce the viscosity and it can thus accelerate the capillary flow of the bitumen (García, 2012). Previously, it has been stated that the healing process of asphalt pavements is very slow at ambient temperature, and can begin at temperatures between 30 and 70 °C, depending on the type of bitumen (Menozzi et al., 2015).

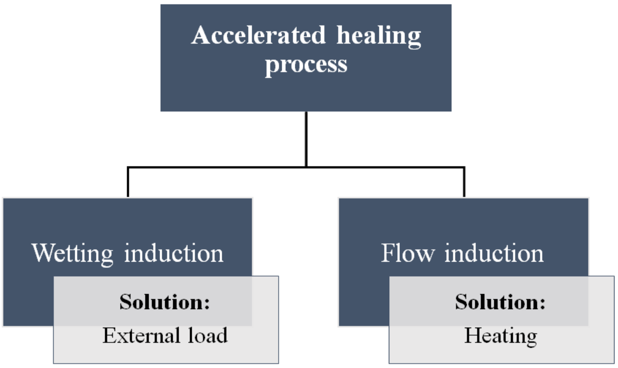

Figure 57: The general outline of the accelerated healing process employed to recover the macro-cracks.

To apply the healing process (i.e. healing treatment), the specimens were subjected to an external force (the fractured specimens were restored to their original length by using a clamp that guarantees a constant contact pressure between the crack surfaces) together with a heating conditioning procedure in a climatic chamber for 60 minutes (Figure 56). In relation to the amount of external force that was applied by clamp, this was equivalent to the minimum force needed to obtain the primary length of the non-fractured specimen (i.e. the length of the specimen at the beginning of Step 1).

Additionally, to evaluate the impact of the heating technique on the recovery capability of the mixtures and to also find the optimum temperature, different conditioning temperatures were used during this process (50, 60 and 70 °C).

During the heating process, the specimens were placed on rigid and thick metallic plates in a climatic chamber to prevent possible deformations, whilst the heating process was controlled by a thermal imaging infrared camera (Figure 58). At the end of the second step, the specimens were cooled for 24 h.

Figure 58: The control of the heating process with a thermal imaging infrared camera (FLIR E40 ®).

In a third step (following the healing process), the healed specimens were then re-tested (re-fractured) by UGR-FACT under the same conditions, and the degree of recovery reached was measured (Figure 56). Similarly, in order to analyse the repeatability of the healing processes (to be considered an effective pavement rehabilitation solution, the process must produce similar results when its application is repeated several times), Steps 2 and 3 were repeated three times on every test (Figure 56).

In addition, to analyse the influence of other variables that could affect the healing capability of the mixtures at macro-damage level (such as the presence of an external force or the time of heat conditioning), some additional tests were applied to the mixture BBTM-II. The steps used were the same as those described previously, but in this case, the healing technique was modified by removing the external force (i.e. the clamp was not used before applying the heating process) and the conditioning time was extended to 3600 minutes (Table 9).

Given that one of the most important aspects in the mechanical response of asphalt materials is the service temperature (Moreno-Navarro et al., 2015b), different test conditions were used for each mixture (Table 9). Further, using different testing conditions (i.e. temperature, stress amplitude) as influencing factors could clarify the effectiveness of the healing process as a possible rehabilitation method to recover the properties of asphalt concrete. In this regard, Moreno-Navarro et al. (2015b) have shown that when designing a rehabilitation solution for asphalt pavement, it is critical to evaluate the performance under conditions similar to those that will affect it during its service life.

Table 9: Summary of the test conditions used for exploring damage recovery in bituminous mixtures at the macro-crack level.

Type of Study	Mixture tested	Test Conditions (Steps 1 and 3)	Conditions Healing Process (Step 2)
Analysis of the influence of the type of gradation curve, type of bitumen, test conditions and conditioning temperature on the healing capability	AC-I; AC-II; BBTM-I; BBTM-II	Temperature : 10 ^{0}C Frequency: 5 Hz Stress amp.: 0.6 MPa	Time: 60 min Temperatures: 50, 60 and 70 ^{0}C External force: Yes
	AC-I; AC-II; BBTM-I; BBTM-II	Temperature : 20 ^{0}C Frequency: 5 Hz Stress amp.: 0.4 MPa	Time: 60 min Temperature: 50, 60 and 70 ^{0}C External force: Yes
	AC-I; AC-II; BBTM-I; BBTM-II	Temperature : 30 ^{0}C Frequency: 5 Hz Stress amp: 0.2 MPa	Time: 60 min Temperature: 50, 60 and 70 ^{0}C External force: Yes
Analysis of the influence of external forces and conditioning time on the healing capability	BBTM-II	Temperature : 20 ^{0}C Frequency: 5 Hz Stress amp: 0.6 MPa	Time: 60 min Temperature: 60 ^{0}C External force: Yes and No
	BBTM-II	Temperature : 20 ^{0}C Frequency: 5 Hz Stress amp: 0.6 MPa	Time: 3600 min Temperature: 60 ^{0}C External force: No

4.2 Exploring the damage recovery in bituminous mixtures at the micro-crack level: the role of rest periods

4.2.1 Materials

To assess the recovery capability of the asphalt concrete at the micro-crack level, a BBTM mixture (EN 13108-2) was manufactured with 5% (by total weight of the mix) conventional bitumen (50/70 Penetration Grade). The main properties of this bitumen are presented in Table 10.

Table 10: The properties of bitumen used in this part of the research.

Bitumen type	Modifier	Penetration (0.1 mm) EN 1426	Softening point (°C) EN 1427	Elastic Recovery (%) EN 13398
50/70	-	50	52	-

Moreover, the composition of the mineral skeleton and gradation curve employed in this part of the study are similar to the BBTM 11 mix that has been introduced in the previous section (4.1.1). Some physical and mechanical properties of the mix are displayed in Table 11.

Table 11: Properties of the mix manufactured for studying the recovery capability of asphalt mixtures at the micro-crack level.

Mixture	Bitumen type	Bitumen content (%)	Bulk density (g/cm³) EN 12697-6	Air voids (%) EN 12697-8	Indirect tensile strength at 15 ⁰C (kPa) EN 12697-23
BBTM	50/70	5.0	2.418	6.79	1630

4.2.2 Experimental Plan

To study the damage recovery in bituminous mixtures at the micro-crack level, the asphalt samples have been tested through an "uninterrupted" loading regime (i.e. stress-controlled fatigue test without applying rest periods) under specific testing conditions (Temperature: 20 ⁰C; Frequency: 5 Hz; Stress Amp. 0.3 MPa) (Figure 59 (a)). In addition, to analyse the effects of phenomena that occur during rest periods and their potential to recover lost properties in these materials, the same test conditions were used but applying an "interrupted" loading regime (i.e. stress-controlled fatigue tests with different types of rest periods) (Figure 59 (b)). In this respect, Figure 59 presents a scheme of the testing types used to study the recovery capability of asphalt pavements at the micro-damage level.

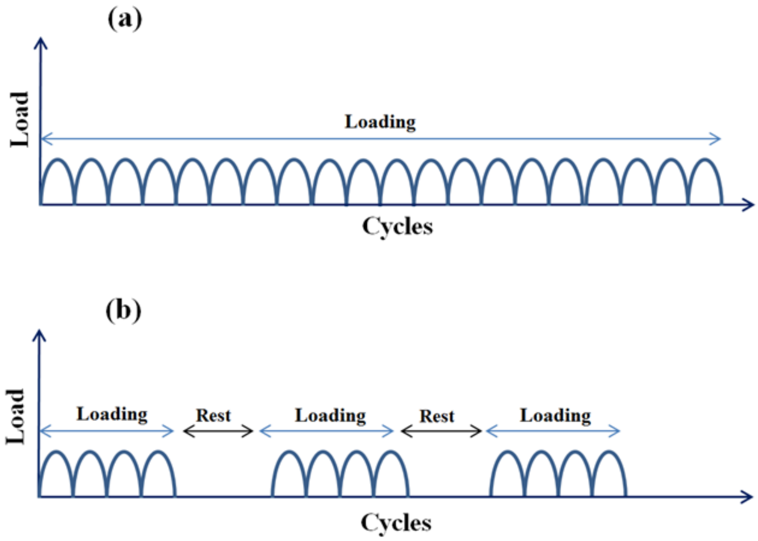

Figure 59: Scheme of testing types used to study the recovery capability of asphalt pavements at micro-damage level: (a) uninterrupted loading and (b) interrupted loading regimes.

According to previous studies (Moreno-Navarro and Rubio-Gámez, 2016; Mazzoni et al., 2016), the recovery potential produced by rest periods should mainly occur in the initial cycles of loading (before 2^{nd} stage in Figure 55), since phenomena that could cause recovery are supposed to have a higher potential when the material is un-cracked (Mewis and Wagner, 2009). Therefore, the effect of the rest periods is examined when there is no structural damage in the material. Subsequently, the end of the first stage in Figure 55 has been determined as the limit of the number of load cycles to include rest periods in the loading regime. Figure 60 shows an example with the limit of the cycles associated with the end of the first stage (N_{1st}) based on the outputs of the UGR-FACT method.

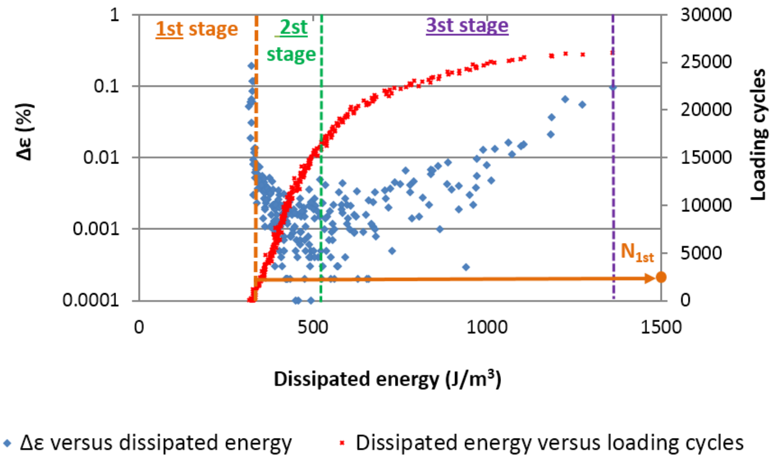

Figure 60: Limit of cycles associated with end of the first stage (N_{1st}) based on the outputs of the UGR-FACT method.

Additionally, to understand the effects of the application of rest periods with different characteristics (i.e. different number of load repetitions between them), other limits were also established ($N_{1st}/2$ and $N_{1st}/8$). Using these limits could help to clarify the effects of different number of load cycle repetitions between rest periods on the recovery capability in asphalt concrete. Furthermore, to assess the effects of the duration of rest periods on the fatigue response and the recovery capability, 1, 5, and 10 min rest periods were introduced to the loading regimes. Considering the above-mentioned points, Table 12 summarises the general testing conditions employed to study the recovery capability of the asphalt concrete at micro-damage level.

Table 12: Testing conditions employed to study the recovery capability at the micro-crack level.

Loading regime				
Uninterrupted	Interrupted			
Without rest period (continues loading)	1 min rest period at every N_{1st} cycles	10 min rest period at every N_{1st} cycles	1 min rest period at every $N_{1st}/2$ cycles	5 min rest period at every $N_{1st}/8$ cycles
No. of specimens tested				
6	6	6	6	6
Testing condition (Temperature; Frequency; Stress Amp.)				
20 ^{0}C; 5 Hz; 0.3 MPa	20 ^{0}C; 5 Hz; 0.3 MPa	20 ^{0}C; 5 Hz; 0.3 MPa	20 ^{0}C; 5 Hz; 0.3 MPa	20 ^{0}C; 5 Hz; 0.3 MPa

Analysis of the results

5 Analysis of the results

The current chapter presents the analysis of the results obtained from the experiments conducted according to the methodology used. This chapter can be broadly divided into two sections, which provide the analysis of the results from "Exploring the damage recovery in bituminous mixtures at the macro-crack level: the role of healing process (heating, time, and external force)" and "Exploring the damage recovery in bituminous mixtures at the micro-crack level: the role of rest period".

5.1 Exploring the damage recovery in bituminous mixtures at the macro-crack level: the role of healing process (heating, time, and external force)

This subsection presents the analysis of the results related to the recovery capability of asphalt concrete at the macro-level damage. Additionally, an analysis of the effects of applying the healing process under different conditions is provided.

5.1.1 Study of the influence of the type of mineral skeleton, type of bitumen, test conditions, and heating on the healing capability of asphalt mixtures at macro-damage level

Figures 61-64 show the average results obtained from the various UGR-FACT tests in terms of amount of fatigue life recovered (expressed as a ratio of the total number of load cycles supported by the materials in Step 3 divided by the total number of load cycles supported in Step 1, as a percentage) (Equation 11):

$$\text{Recovered fatigue life (\%)} = \frac{\text{Total number of load cycles in Step 3 (After healing process)}}{\text{Total number of load cycles in Step 1 (Primary fatigue test)}} \tag{11}$$

As a general conclusion, it is worth noting that regardless of the type of mixture, bitumen, or healing process used, the amount of fatigue life recovered at macro-damage level is considerably low (always below 5% of recovery). Nonetheless, it has also been demonstrated that variables such as the test conditions, or the type of binder could have a slight impact on the level of healing achieved.

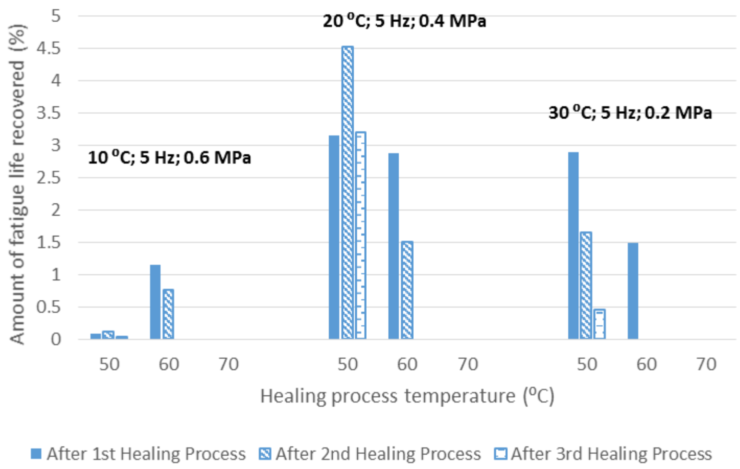

Figure 61: Rates of recovered fatigue life in the mixture AC-I under the different test conditions.

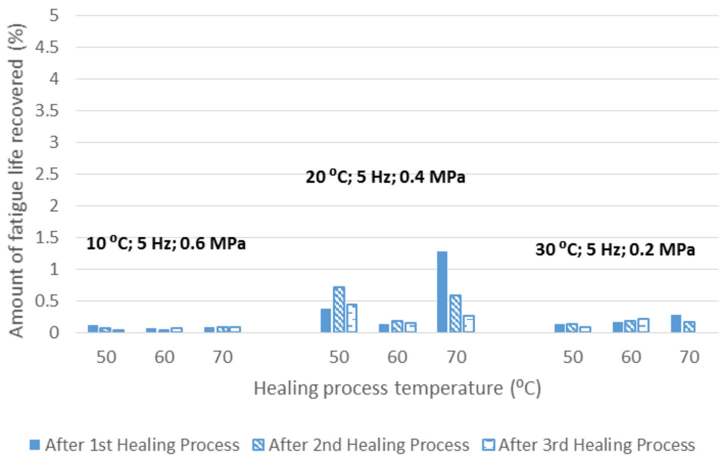

Figure 62: Rates of recovered fatigue life in the mixture AC-II under the different test conditions.

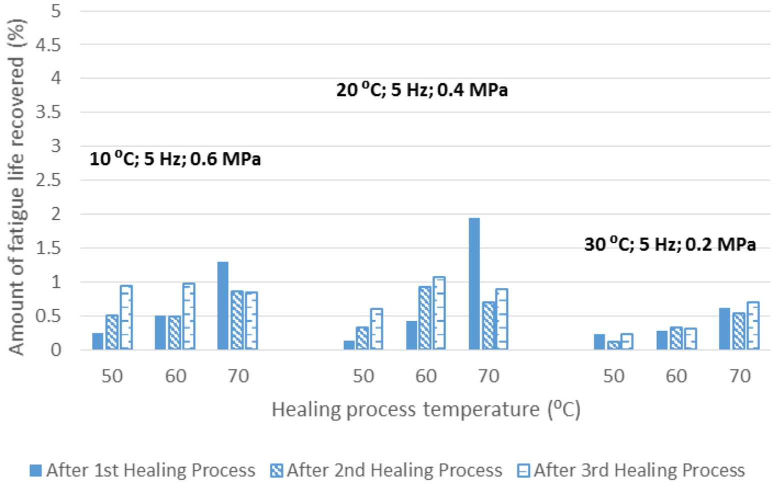

Figure 63: Rates of recovered fatigue life in the mixture BBTM-I under the different test conditions.

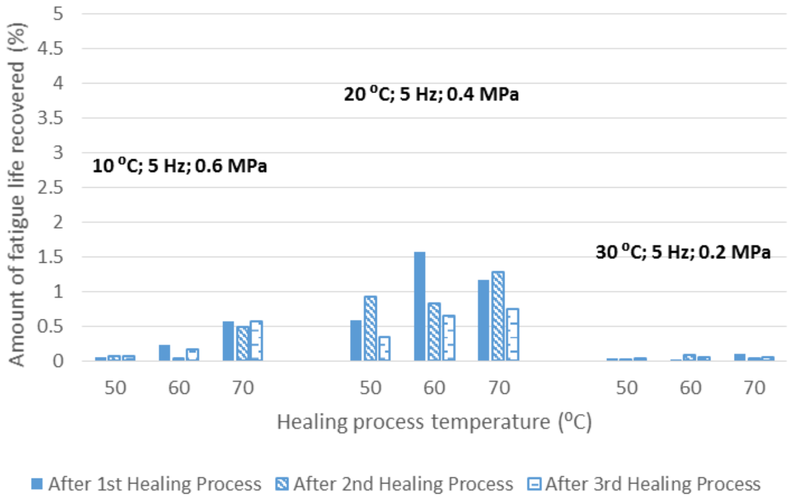

Figure 64: Rates of recovered fatigue life in the mixture BBTM-II under the different test conditions.

It can be observed that the mixtures tested at a temperature of 20 ^{0}C showed a slightly higher recovery rate than when tested at 10 or 30 ^{0}C, which implies that the service conditions of the road could affect the effectiveness of healing treatments. Similarly, the heat conditioning during the healing process also has an impact on the amount of fatigue life recovered. In particular, it has been observed that as the temperature increases, the rate of recovery also increases (which could be due to a better flow and wetting (Phillips 1998)). However, as mentioned previously, the amount of growth is not marked. Moreover, for the case of some of the mixtures, when the samples were heated at high temperatures (as in the case of the AC mixtures) the healing process had a negative impact, producing excessive deformations in the specimen and considerably reducing the amount of recovery.

In terms of the mineral skeleton, it appears that there was no significant impact on the rate of recovery achieved. In contrast, the type of bitumen used appears to exert a greater influence, since it can be seen that the use of a conventional binder could provide a higher recovery rate (which is in accord with the results of previous investigations (Moreno-Navarro et al., 2015a)). Finally, the results show that the repeatability of the healing process appears to be satisfactory. However, if the temperature used during the healing process is sufficiently high to produce deformations in the specimen (as in some cases of the AC mixtures, Figures 61 and 62), the healing processes have a negative impact when applied several times.

Figures 65-68 represent the average results of the two parameters obtained in each load cycle of the UGR-FACT test, in Step 1 (fatigue test) and Step 3 (fatigue test following the healing treatments conducted at different temperatures) of the methodology previously described. As observed in the tests applied to the AC mixtures (Figures 65 and 66), the different healing techniques were unable to recover the initial properties of the tested specimens. In particular, following the treatments, the viscoelastic properties of the materials remained in the third stage of the fatigue process (in the damage propagation stage), which signals that any healing induced in these materials is not sufficiently effective (they maintained high levels of dissipated energy and high rates of variation in geometry).

Further, it is observed that the capability of the material to deform before breaking (ductility) has disappeared (the initial part of the tests carried out in Step 3 do not follow a vertical descent as in the case of the initial part of the test in Step 1). It has thus been demonstrated that after the application of the healing processes at the macro-crack level, the resulting materials are more brittle and less resistant (higher dissipated energies under the same load conditions), and therefore the amount of recovered fatigue life is too low. Finally, it is worth noting that the temperature used in the heating process appears to have minimal influence on the results obtained, while the use of conventional binders allows for a higher recovery (some of the tests carried out with the conventional binder appear to restore the viscoelastic properties to those observable at the stage of damage initiation). This finding is in accord with previous studies concluding that a binder with lower viscosity offers higher healing rates (Qiu, 2012).

In fact, polymer modifier could act as a filler that limits the potential of bitumen to re-establish contact and heal (Little et al., 1999). Since the existence of a polymer network is likely to cause a reduction in flow and diffusion of bitumen. Hence, a partial absorption of compatible components of the bitumen into the polymer network could occur and the rest of the bitumen remains with a higher asphaltene concentration, which reduces the flow capacity (Qiu, 2012). Additionally, a similar account could be used to explain the lower healing capability of crumb rubber modified binder compared with conventional binder (Ibrahim et al., 2013).

In the case of the BBTM mixtures (Figures 67 and 68) high rates of variation in geometry are also observed after the healing treatments (which means that the material is strongly affected by the loads applied, and it cannot recover its initial properties, as its deformational responses have been changed). However, in these cases the curves obtained in Step 3 show a similar trend to that described in Step 1 (with an initial vertical descent, followed by a horizontal displacement). Similarly, the viscoelastic properties of the materials are partially restored to those observed in the first stage of the fatigue process. These aspects of the results demonstrate that the healing treatments are more effective when applied to the BBTM mixtures in comparison with the AC mixtures (possibly as a consequence of their higher bitumen content (Molenaar, 2007)), in spite of the level of fatigue recovery being low (Figures 63 and 64) due to the already extensive fatigue life of these materials (as they are manufactured with polymer modified binders). Nonetheless, it is necessary to note that the high rates of variation in geometry obtained in Step 3 (after the healing treatment) show that the materials have a lower ductility than that observed in the original test materials (Step1). In addition, the resistance of the molecular bonds of the healed materials appears to be lower, as the rate of increment of dissipated energy with the number of load cycles is much higher in Step 3. These facts can supply an explanation for the ineffectiveness of the healing techniques applied at macro-damage level. Finally, it should be noted that in the case of the BBTM mixtures, the temperature of the healing process appears to have a higher impact (an increase in temperature induces better wetting and boosts the recovery of viscoelastic properties).

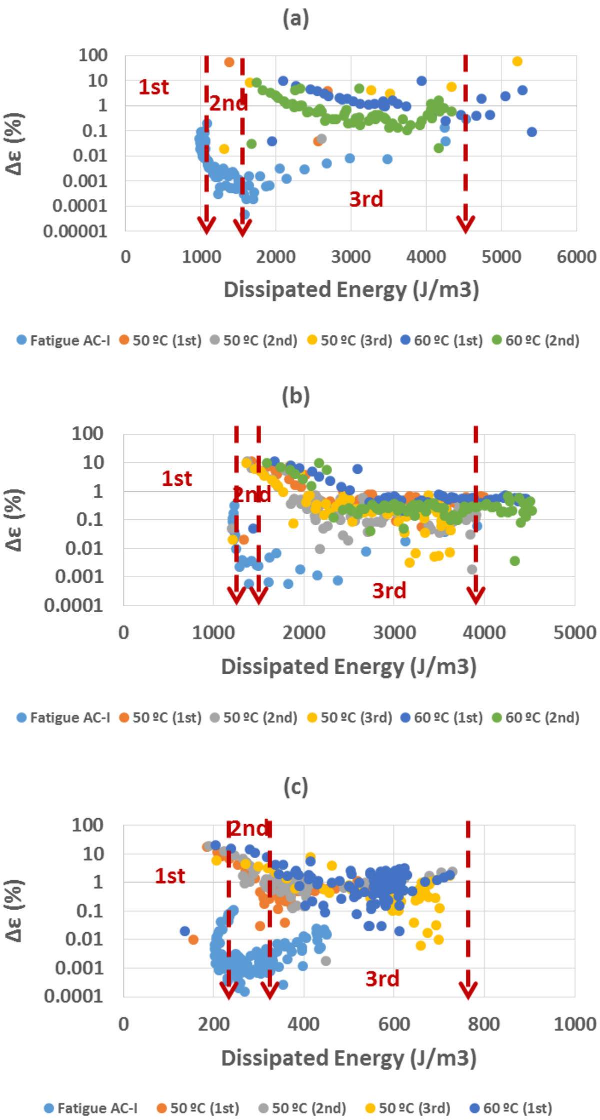

Figure 65: Average result obtained for the mixture AC-I in the different steps of the UGR-FACT test: Step 1 (Fatigue AC-I); Step 3 first healing treatment at 50 ^{0}C (50 ºC (1st)); Step 3 second healing treatment at 50 ^{0}C (50 ºC (2nd)), etc. (a) tests carried out at 10 ^{0}C, 5 Hz and 0.6 MPa; (b) tests carried out at 20 ^{0}C, 5 Hz and 0.4 MPa;(c) tests carried out at 30 ^{0}C, 5 Hz and 0.2 MPa.

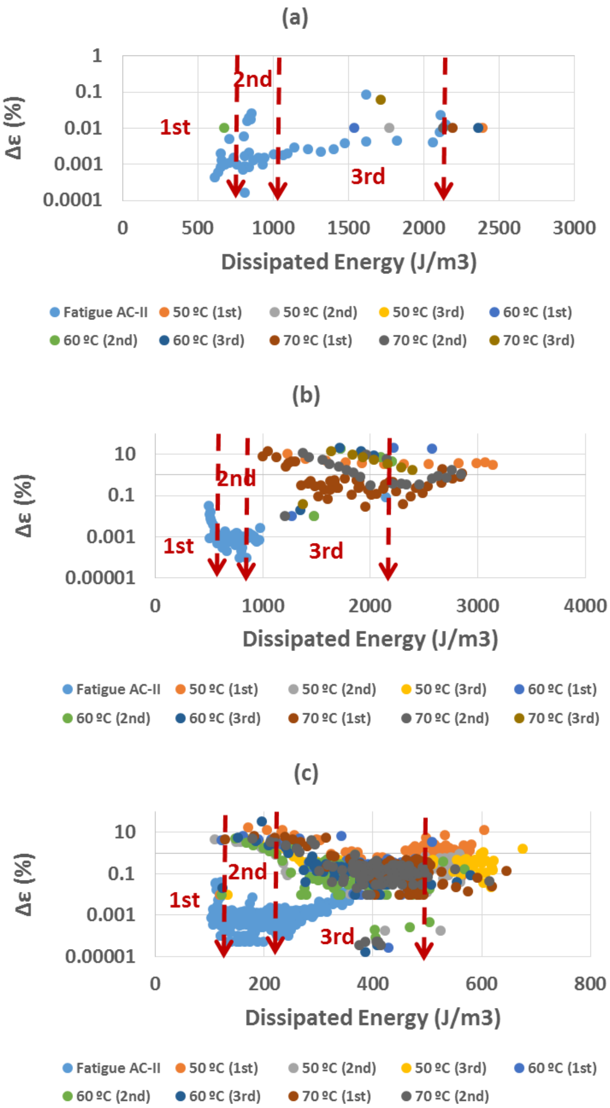

Figure 66: Average result obtained for the mixture AC-II in the different steps of the UGR-FACT test: Step 1 (Fatigue AC-II); Step 3 first healing treatment at 50 ^{0}C (50 ºC (1st)); Step 3 second healing treatment at 50 ^{0}C (50 ºC (2nd)), etc. (a) tests carried out at 10 ^{0}C, 5 Hz and 0.6 MPa; (b) tests carried out at 20 ^{0}C, 5 Hz and 0.4 MPa;(c) tests carried out at 30 ^{0}C, 5 Hz and 0.2 MPa.

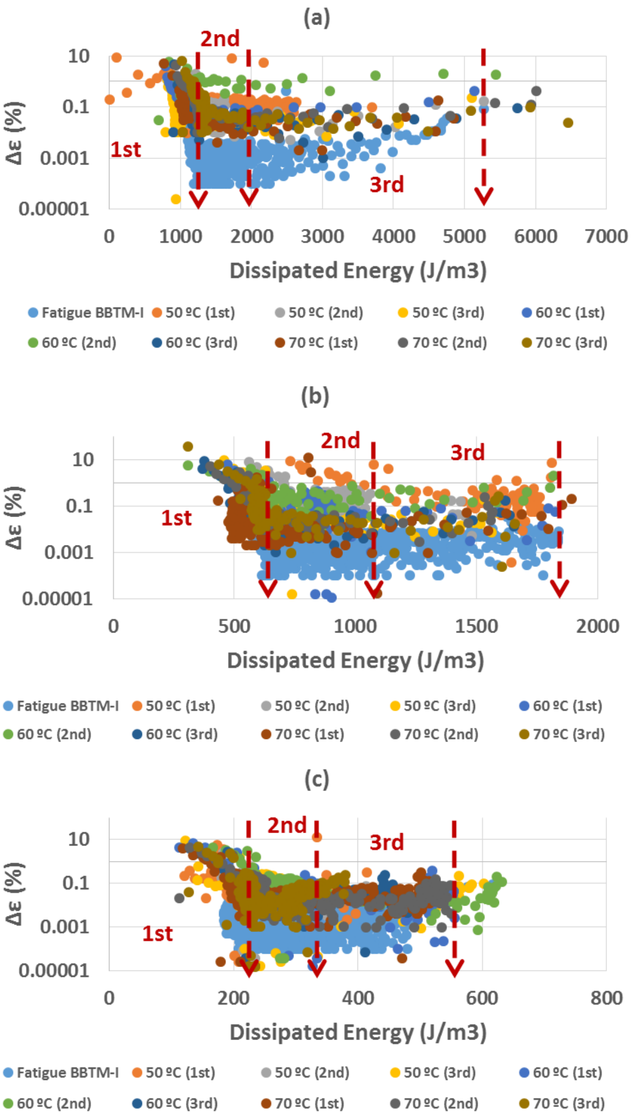

Figure 67: Average result obtained for the mixture BBTM-I in the different steps of the UGR-FACT test: Step 1 (Fatigue BBTM-I); Step 3 first healing treatment at 50 ^{0}C (50 ºC (1st)); Step 3 second healing treatment at 50 ^{0}C (50 ºC (2nd)), etc. (a) tests carried out at 10 ^{0}C, 5 Hz and 0.6 MPa; (b) tests carried out at 20 ^{0}C, 5 Hz and 0.4 MPa;(c) tests carried out at 30 ^{0}C, 5 Hz and 0.2 MPa.

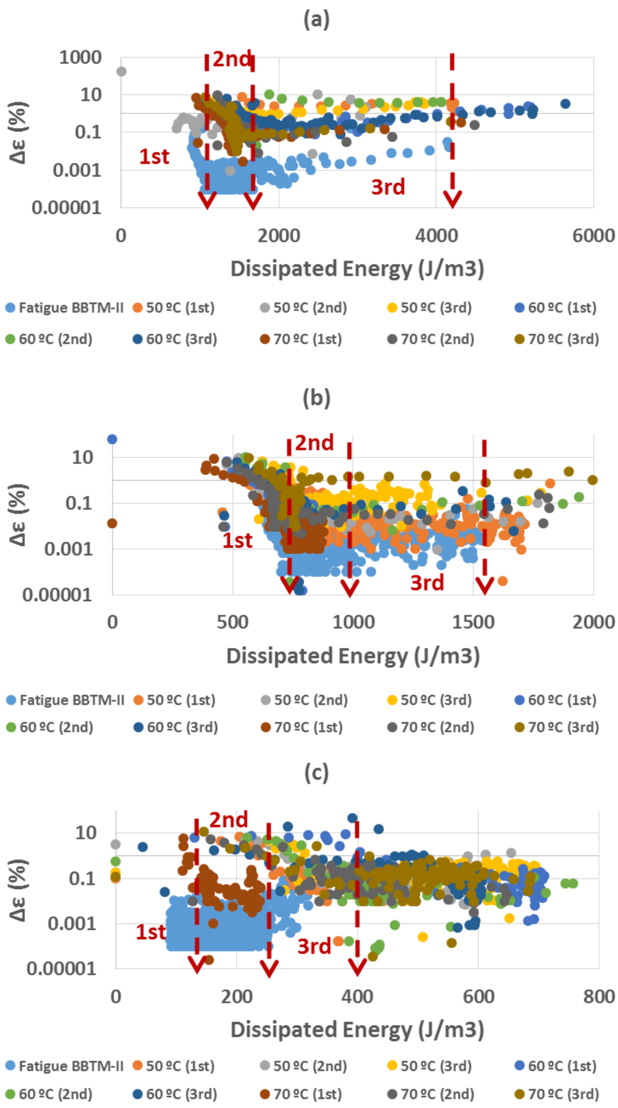

Figure 68: Average result obtained for the mixture BBTM-II in the different steps of the UGR-FACT test: Step 1 (Fatigue BBTM-II); Step 3 first healing treatment at 50 ^{0}C (50 ºC (1st)); Step 3 second healing treatment at 50 ^{0}C (50 ºC (2nd)), etc. (a) tests carried out at 10 ^{0}C, 5 Hz and 0.6 MPa; (b) tests carried out at 20 ^{0}C, 5 Hz and 0.4 MPa;(c) tests carried out at 30 ^{0}C, 5 Hz and 0.2 MPa.

5.1.2 Study of the influence of external forces and conditioning time on the healing capability of asphalt mixtures at macro-damage level

Figures 69-70 show the effect of the external force and the duration of the healing treatment on the amount of fatigue life recovered in the mixture BBTM-II (as a percentage of the total number of load cycles supported by the material). Once again, the results obtained show that the total amount of fatigue life recovered after the healing treatment at the macro-damage level is too low. Nonetheless, it is notable that the presence of an external load contributes towards increasing the rate of recovery, while the increase of the time of heating conditioning seems to have no significant effect.

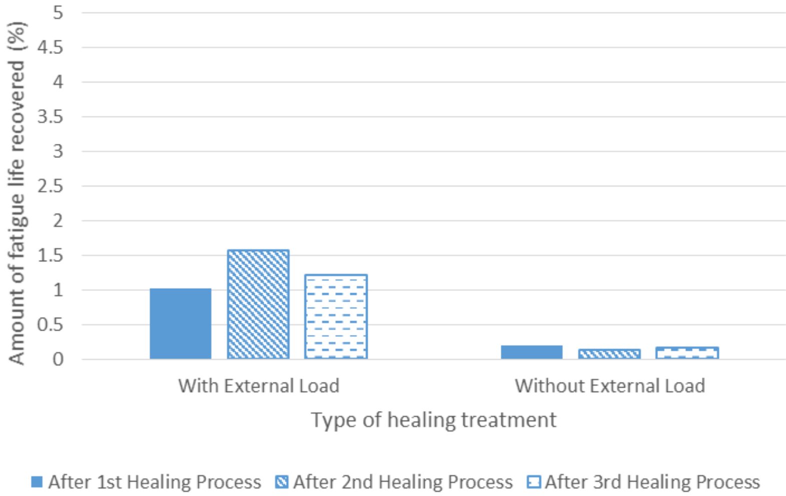

Figure 69: Rates of recovered fatigue life in the mixture BBTM-II with and without the presence of external loads during the healing treatment (Carried out at 60 ^{0}C, for 60 minutes).

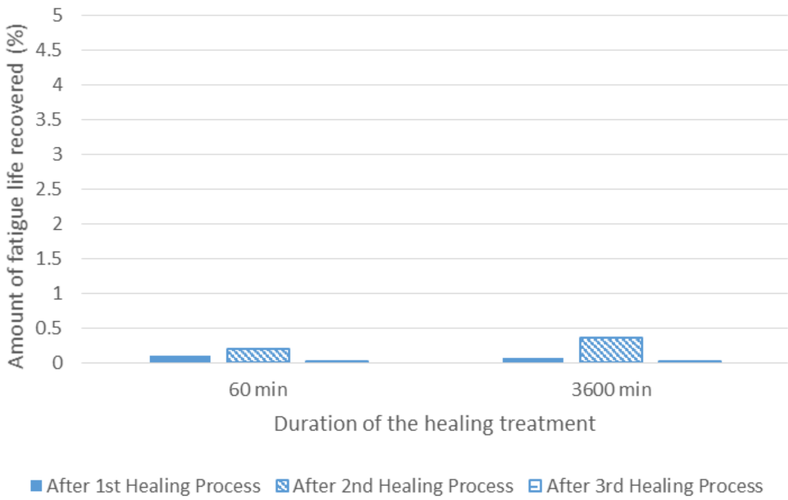

Figure 70: Rates of recovered fatigue life in the mixture BBTM-II with different durations of the healing treatment (carried out at 60 ^{0}C).

Figure 71 displays the average results of the two parameters obtained in each load cycle of the UGR-FACT test under these test conditions. These results suggest that external loads could have a considerable impact on the degree of recovery of the viscoelastic properties of asphalt materials. In particular, the specimens healed under the presence of an external load can show recovered viscoelastic properties that are similar to those offered by the original mixture during the first stage of the fatigue process (Figure 71a). This effect could be due to a better surface approach (Phillips 1998), which leads to a more effective healing process. In contrast, when no external load is applied and the only healing treatment is heat, the degree of recovery is considerably low. Thus, as shown in Figure 71a, following the healing treatment the viscoelastic properties of the materials remain comparable to those observed in the final stage of the fatigue process (damage propagation). In any case, it is worth noting that regardless of the action of an external load, the amount of fatigue life recovered at this level of damage (macro-crack) remains low (due to the lack of ductility of the material in comparison to its original properties).

Figure 71b clearly shows the minimal influence of increasing the duration of the healing process from 60 to 3600 minutes. In both cases, the materials tested remain in the last stages of their fatigue life (macro-crack stage) following the healing treatments.

Finally, the results indicate that the amount of fatigue life recovered in bituminous mixtures at the macro-damage level after applying the heating technique with or without an external force is considerably low (less than 5%) for all types of binders and under different testing conditions. This point suggests the unjustifiability of employing the heating technique to recover damage or even to effectively restore some initial visco-elastic properties at the macro-damage level. It should also be noted that the ineffectiveness of this technique to completely recover macro-cracks could primarily be a consequence of the fact that the plastic deformations cannot be recovered.

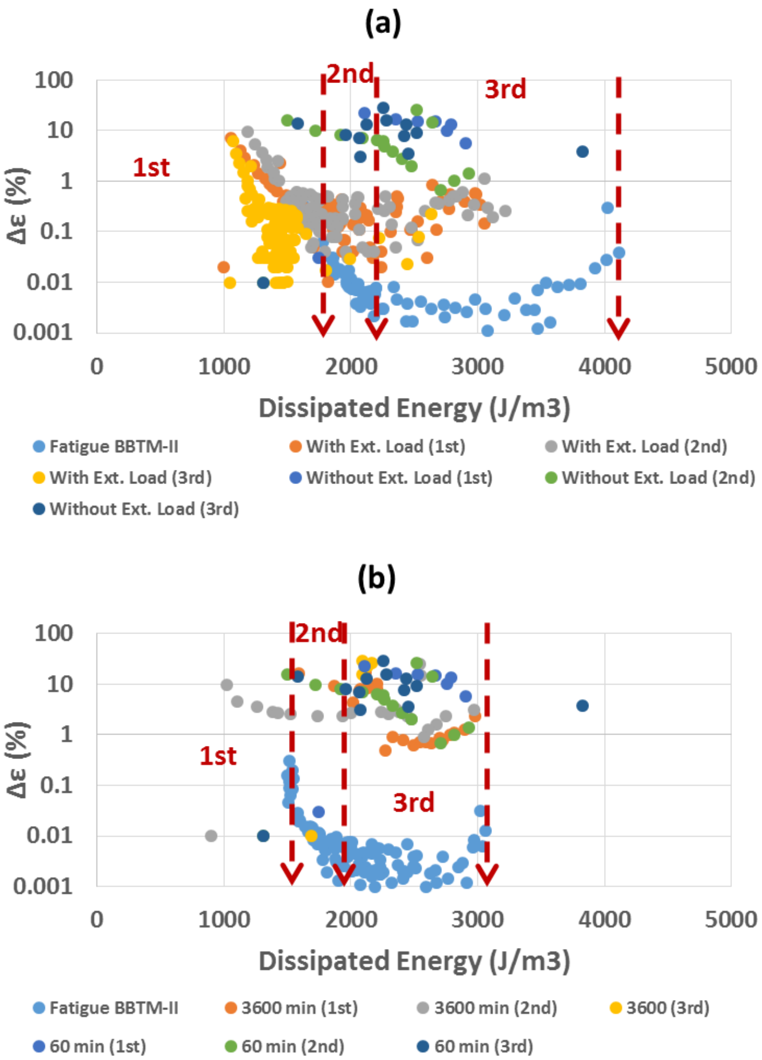

Figure 71: Average result obtained for the mixture BBTM-II in the different steps of the UGR-FACT test: Step 1 (Fatigue BBTM-II); (a) step 3 first healing treatment with external load (With Ext. Load (1st)); Step 3 first healing treatment without external load (Without Ext. Load (1st)), etc.; (b) Step 3 first healing treatment for 3600 min without external load (3600 min (1st)), step 3 first healing treatment for 60 min without external load (60 min (1st)), etc. The tests were carried out at 20 ^{0}C, 5 Hz and 0.6 MPa.

The duration, temperature, and the presence of the external force of the healing technique can influence the amount of fatigue life recovered at the macro-crack level. However, the impact of duration of the healing technique on the recovery obtained seems to be low (when considering times that could be applied as rehabilitation techniques, i.e. times that do not produce the closure of the road for a long period), in spite of that the recovery of the fatigue life and also visco-elastic response obtained is sensitive to the temperature and also the presence of the external force (since the temperature and external force could accelerate the flow and wetting respectively).

By using external force the amount of fatigue life recovered is higher, and the visco-elastic response after applying healing technique is more similar to the initial visco-elastic response, whilst the external force cannot sufficiently recover the initial visco-elastic response, since the variation of the geometry produced after the treatment remains higher. Nonetheless, the impact of treatment temperature as an external factor in both the fatigue life recovered and the visco-elastic response (after applying the healing technique) is relatively weak compared with the influence of internal factors (i.e. the type and the amount of the binder).

Phenomenologically, although the “heating” and “external force” techniques could accelerate “flow” and “wetting” as two preliminary sub-mechanisms of the healing phenomenon respectively, using these techniques to accelerate “molecular diffusion” as the ultimate and determinant sub-mechanism in this phenomenon seems to be very difficult at the macro-damage level. Thus, gluing macro-cracks (i.e. crack closure) by inducing healing through the heating technique does not necessarily lead to effective healing.

5.2 Exploring the damage recovery in bituminous mixtures at the micro-crack level: the role of rest periods

In this subsection, the analysis of the results related to the recovery capability of asphalt concrete at the micro-level damage has been presented (primarily the effects of different types of rest periods on the mechanical properties).

In the beginning and according to the methodology, the end of the first stage in the UGR-FACT output graph has been determined as the limit of the number of load cycles to include rest periods in the loading regime. For the mix used in this study, the 800th cycle was selected as the upper limit of the first stage (N_{1st}) (Figure 72) and therefore rest periods must be applied within this range of cycles. Consequently, the other limits for applying the rest period including $N_{1st}/2$ and $N_{1st}/8$ (see Table 12) were calculated as the 400th and 100th cycles

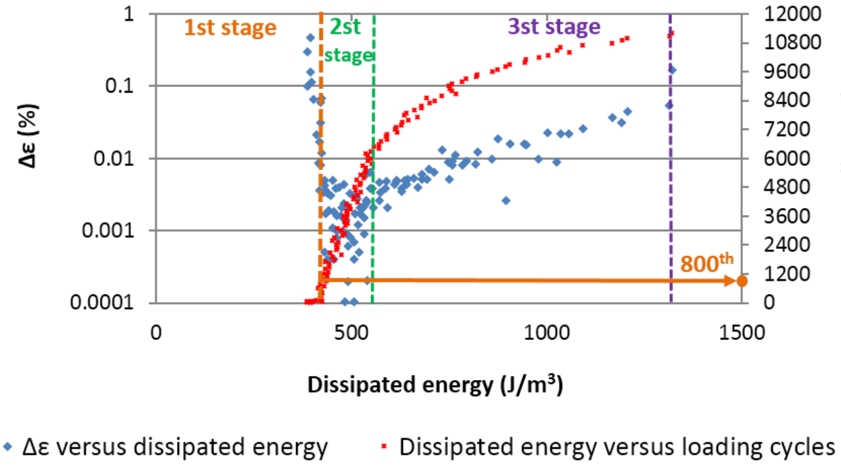

Figure 72: Determining the cycle associated with the end of the first stage for the mixture studied (N_{1st}=800th cycle).

To analyse the effect of rest periods on the fatigue life of the bituminous mixtures, the Fatigue Life Ratio (FLR) was calculated for all types of loading regimes using the following equation:

$$\textbf{Fatigue Life Ratio (FLR)} = \frac{\textbf{Average fatigue life obtained from interrupted test}}{\textbf{Average fatigue life obtained from uninterrupted test}} \quad (12)$$

Where FLR is the ratio of the average fatigue life obtained from interrupted test (when rest periods are included in the loading regime) to the average fatigue life obtained from uninterrupted test (the fatigue test with continuous loading cycles).

Figure 73 shows the FLR values for different types of loading regimes. Although the majority of previous investigations have reported the extension in fatigue life as a result of employing rest periods (Zeiada, 2012), according to Figure 73, not all types of rest periods necessarily extend the fatigue life of the asphalt concrete. As can be observed, when rest periods are included at the end of the 1st stage (800th cycle, just before the appearance of damage, Figure 72), their influence on the fatigue life of the mixture studied is not noticeable (the fatigue life span remains unaltered, with FLR values around 1). Nonetheless, as the rest periods are included far away from this limit (the 800th cycle) and closer to the beginning of test, their effects produce an increment in the fatigue life of the material. The lower the number of load cycles applied before the rest period, the bigger the resulting increment in fatigue life. In this respect, the results shown in Figure 73 demonstrate that in the interrupted fatigue test, including rest periods at every 400th cycle can increase the fatigue life of the material by 30%. In addition, if the duration of the rest periods is increased and they are included each 100 cycles, fatigue life span increases by 80% (which shows the positive effect of increasing the duration of the rest periods and introducing them much earlier than the end of the 1st stage). In this respect, previous studies have pointed out that when intermittent (pulse-rest) loading condition rather than interrupted loading (similar to the loading condition used in this study) is applied during cyclic testing, the recovery effects were more pronounced than plastic deformations (Moghadas-Nejad et al., 2016). It is therefore worth mentioning that intermittent (pulse-rest) loading appears to represent a more realistic condition, because in real-life situations there is a rest period between load applications of the successive axles of passing vehicles (Qiu, 2012, Zeiada, 2012). Indeed, the loading interruption not only occurs because of rest periods, but also as a result of traffic wandering, and eventually this generates the difference between the "real" and "predicted" fatigue life of asphalt pavements, whilst the effects of stress state and material properties should also not be forgotten (Al-Qadi and Nassar, 2003).

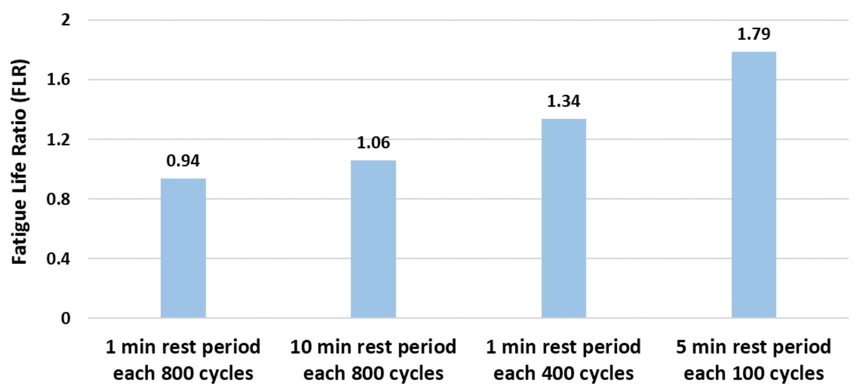

Figure 73: The FLR value for different types of loading regimes employed in this study.

Therefore, based on these considerations the inclusion of rest periods when the material has consumed its ability to deform (end of the first stage) has little effect on fatigue life. In contrast, rest periods of long duration combined with their inclusion after a low number of loads have been applied appears to result in the highest increment in fatigue life. The question now is to assess why this increment is produced or the mechanisms that cause it. Figure 74 represents the average of the accumulated dissipated energy as a function of the load cycles (which can be considered as a measurement of the evolution of the properties of the material) for the uninterrupted tests and for the tests that include rest periods of 5 min every 100 cycles. As can be observed, for a given number of load cycles, the amount of accumulated dissipated energy is lower in the case of the interrupted tests, which means that for the same amount of energy introduced in the material (load cycles), less quantity is consumed in changing its properties (and thus its fatigue life is longer under this test condition).

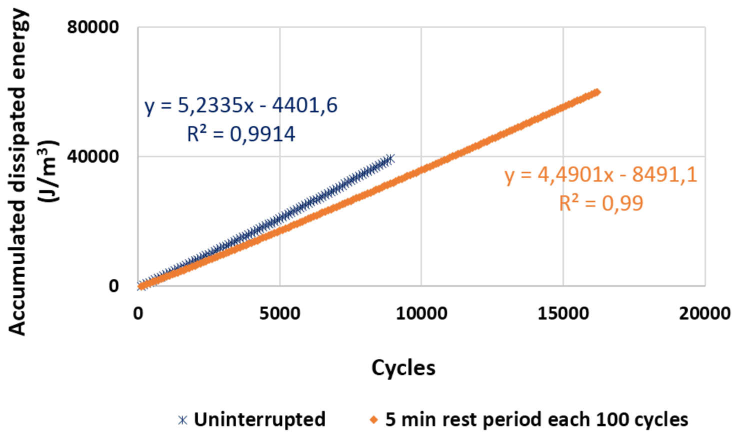

Figure 74: A comparison between the accumulated dissipated energy graphs of uninterrupted and interrupted (5 min rest period each 100 cycles) loading regimes.

Based on this analysis, if linear trend lines are assigned to the different average accumulated dissipated energy graphs for each type of test conditions (Table 13), it can be observed that the slope values decreases by including rest periods in loading regimes. This aspect of the results indicates that applying rest periods could prevent the progressive change in the properties of the material and could subsequently reduce the speed of damage propagation, except for the case in which a 1 min rest period is applied every 800 cycles.

Table 13: The linear trend lines of the accumulated dissipated energy graphs for each type of loading regime.

Loading regime	Trend line	R-squared value	Slope
Uninterrupted	y = 5.2335x – 4401.6	0.991	5.2335
1 min each 800 cycles	y = 5.4025x – 2484.7	0.995	5.4025
10 min each 800 cycles	y = 4.7083x – 1765.5	0.996	4.7083
1 min each 400 cycles	y = 5.2254x – 4045.1	0.990	5.2254
5 min each 100 cycles	y = 4.4901x – 8491.1	0.990	4.4901

However, according to the results shown in Figures 75-78 (which represent the average results of the variation of geometry (Δε) as a function of the number of load cycles), it can be observed that the deformations produced in the specimens tested under interrupted tests are higher (for the same amount of load cycles) than those produced in the specimen tested under the uninterrupted condition. These results show that higher variations occur in the geometry of the specimens (i.e. deformations) when rest periods are included at a lower level of loading (e.g., at every 400 cycles instead of every 800 cycles, or at every 100 cycles instead of every 400 cycles) (Figures 77 and 78).

In this regard, other researchers have also found that under interrupted loading regimes a growth in the deformations can be detected in comparison with uninterrupted regimes (Moghadas-Nejad et al., 2016).

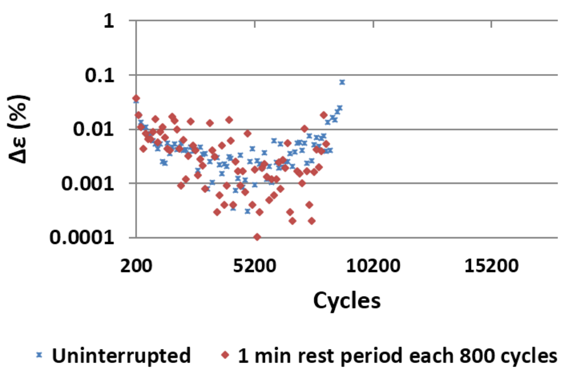

Figure 75: A comparison between Δε values of samples tested under interrupted (1 min rest period every 800 cycles) and uninterrupted loading regimes.

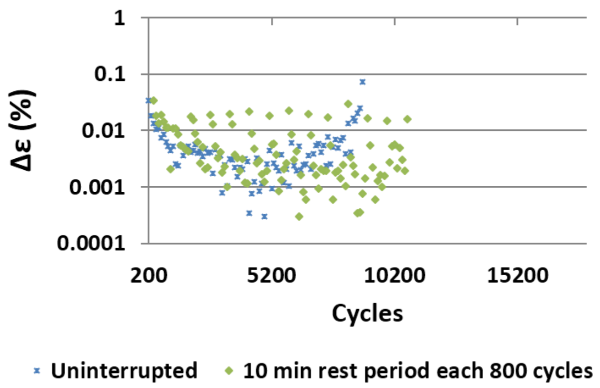

Figure 76: A comparison between Δε values of samples tested under interrupted (10 min rest period every 800 cycles) and uninterrupted loading regimes.

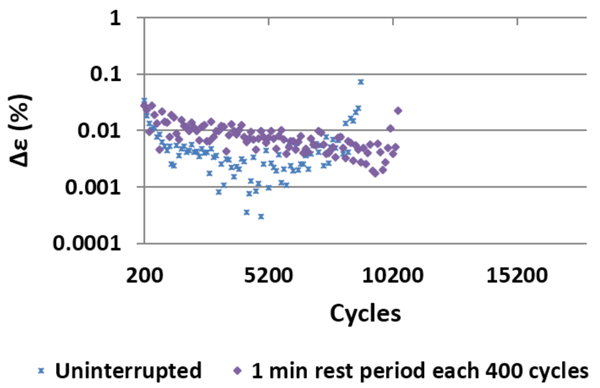

Figure 77: A comparison between Δε values of samples tested under interrupted (1 min rest period every 400 cycles) and uninterrupted loading regimes.

Thus, based on the analysis of the dissipated energy, the inclusion of rest periods prevents the changes produced in the visco-elastic response of the material during cyclic loading, but according to the evaluation of the variation of the geometry, rest periods can increase the deformation produced in the material. This implies that rest periods would not produce a variation in the mechanical behaviour of the material but they could induce a more ductile response during the fatigue process before the crack initiation (as more deformations are produced in the material).

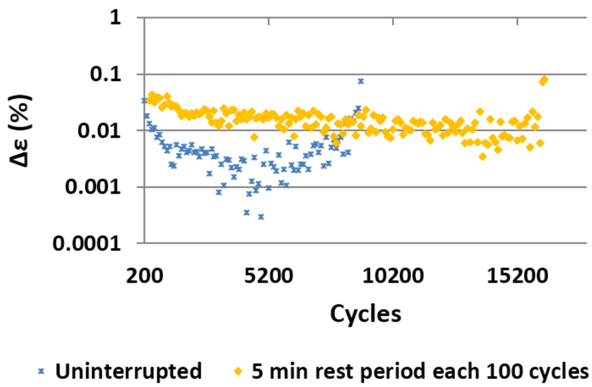

Figure 78: A comparison between Δε values of samples tested under interrupted (5 min rest period every 100 cycles) and uninterrupted loading regimes.

Figure 79 shows the evolution of hysteresis loops under the interrupted and uninterrupted regimes. In this figure it can be observed that at the initial loading cycle, materials have the same amount of global deformations. However, as the number of applied load cycles increases, these deformations are clearly higher under interrupted (5 min every 100 cycles) regime compared with the uninterrupted regime (which shows that rest periods provide a more ductile response in the material).

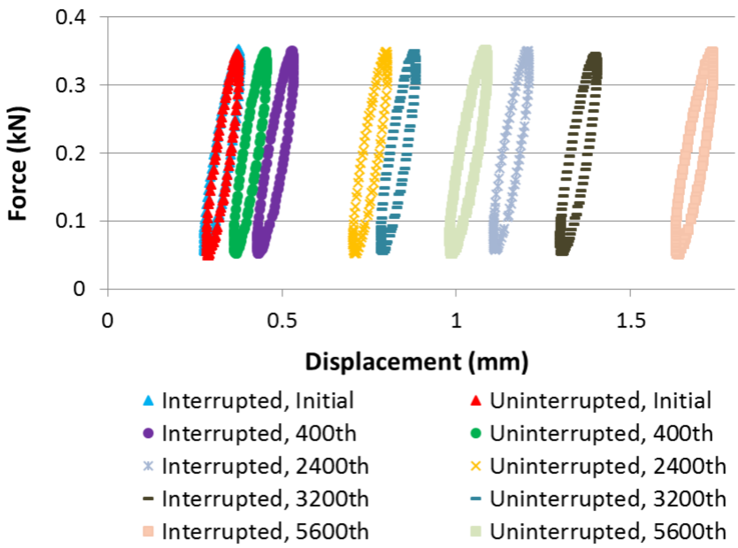

Figure 79: The evolution of the global deformations at different loading cycles under the interrupted and uninterrupted regimes.

Finally, if the normalized hysteresis loops of the material are analysed before and after the rest periods, it can be observed that some reversible phenomena can occur when rest periods are included, as part of the shape is recovered after these rest periods (i.e. the area of the loop after rest period decreases) (Figure 80). This could be due to the rearrangements of the molecular networks during rest periods as a result of thixotropy (i.e. Sol-Gel transformation) or self-cooling. Nonetheless, these reversible phenomena do not last when the materials are already damaged (under a high amount of load cycles), because the shape in the hysteresis loop cannot be recovered after the rest period (Figure 81). In fact, under a high amount of damage (in the case of the interrupted test and applying 5 min RP every 100 cycles when 30% of the fatigue life is reached) the evolution of the continuous hysteresis loops are similar to those tested under the uninterrupted condition and rest periods are not able to recover part of the shape (Figure 81). Thus, it can be stated that the effect of the reversible phenomena could have a higher impact under low levels of loading (before the material is highly deformed or damaged).

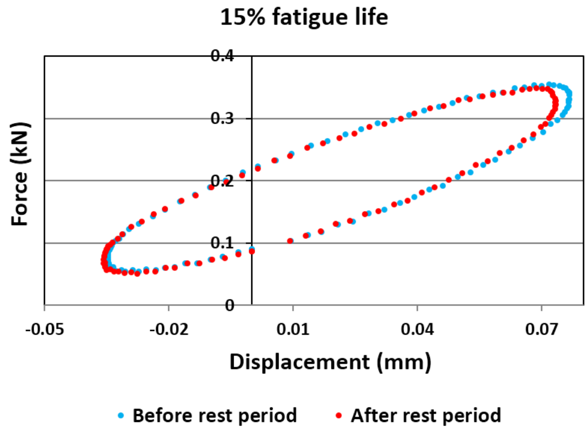

Figure 80: Continues hysteresis loops before and after applying rest period at 15% of the fatigue life when 5 min rest period each 100 cycles applied.

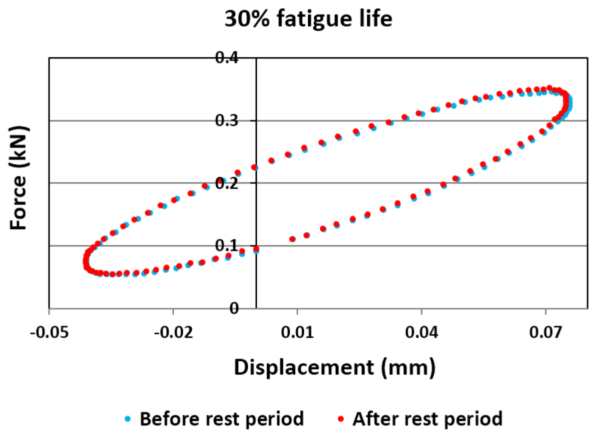

Figure 81: Continuous hysteresis loops before and after applying the rest period at 30% of the fatigue life when a 5 min rest period is applied at every 100 cycles.

Additionally, it is important to note that the recovery in hysteresis loops occurred only when a sufficient duration of rest periods is incorporated in the loading regime (i.e. 10 min rest period every 800 cycles and a 5 min rest period every 100 cycles).

This research has demonstrated that not all type of rest periods could extend the fatigue life of asphalt materials. If the rest periods are sufficiently long and a low number of loads are applied before their inclusion, a higher increment in fatigue life will be observed. In this respect, it also has been demonstrated that before its failure the deformations produced in the specimens are greater under these test conditions. Before their fracture, all materials deform as much as possible. Thus, the increment in the deformation ability of the materials produced by rest periods could be one of the reasons for having more resistance to fatigue loading (i.e. the increment of deformations can delay the appearance of damage). In addition, reversible phenomena such as thixotropy and self-cooling could also help to increase fatigue life, but only if they occur before the material is highly deformed or already damage

Conclusions

6 Conclusions

In recent years, the recovery capability of bituminous materials has been considered an important starting point from which to develop rehabilitation techniques that could extend the service life of road pavements. Nonetheless, the recovery of the mechanical properties of these materials is a complex issue, since the recovery could occur due to different phenomena (i.e. reversible phenomena, or the healing phenomenon).

In order to clarify some issues of uncertainty in this field, the current research aimed to investigate the recovery capability of bituminous mixtures at different levels of damage. In particular, several aspects that could influence this capability such as duration, temperature, external forces, and rest periods have been considered. Thus, to explore the role of the healing phenomenon in the recovery capability at the macro-crack level, different types of bituminous mixtures were tested under several conditions until their macro-failure by employing the UGR-FACT method. Various types of healing conditioning where applied in order to induce their recovery (applying heating and external force) with different treatment durations. Additionally, to explore the role of recovery capability originating from reversible phenomena (such as thixotropy, heating, etc.), the bituminous mixture was tested using UGR-FACT by introducing rest periods with different characteristics. Finally, on the basis of the results obtained, the following conclusions can be drawn:

- The results indicate that the various conditions employed in the healing technique including temperature, duration of the treatment, and presence of the external force could affect the recovery capability of bituminous mixtures at the macro-crack levels. Generally, as the temperature of treatment increases, the rate of recovery also increases (due to better wetting). However, if the temperature exceeds a certain level, the healing process could have a negative impact on the mechanical properties of the material, resulting in excessive deformations. Regarding the presence of the external force, the results indicate that it increases the rate of recovery during healing treatments (which could be due to a better wetting and surface approach) whilst the external force cannot sufficiently recover the initial visco-elastic response, since the variation of the geometry produced after the treatment remains higher. In contrast, an increment in the duration of the healing treatment appears to have little impact on the capacity for recovery at the macro-crack level.

- The type of bitumen used also appears to influence the recovery rate. In this respect, the use of a conventional (i.e. neat) binder could provide a higher recovery rate since the higher viscosity of the modified binders could negatively affect the flow and wetting. Moreover, a higher amount of binder (whether modified or not) could have a positive impact on the degree of recovery achieved in the properties of the materials following the application of a healing process.
- The type and amount of binder as internal factors could have more of an influence on the recovery capability at the macro-crack level compared with the treatment temperature as an external factor. Further, the recovery capability of bituminous mixtures at the macro-crack level appears to be sensitive to the service conditions (external factors). Therefore, these factors must be taken into account when evaluating the effectiveness of the healing treatment as a rehabilitation technique. The results also showed that the repeatability of the healing process, which is a requirement for applying rehabilitation techniques, appears to be satisfactory. Based on the results obtained during this study, the healing treatments can be carried out several times and similar degrees of recovery can be obtained on each occasion.
- Regardless of the influence of the different variables and conditions, it is worth noting that the amount of fatigue life recovered at the macro-damage level after applying an accelerated healing process in all the specimens evaluated in this study is considerably low (always below 5% of the total number of load cycles supported by the original materials). Thus, it can be concluded that the use of healing techniques is not justifiable at this advanced level of damage (the macro-cracks can be glued, but cannot be effectively healed). In fact, by applying the healing technique the materials cannot completely recover their initial properties and this

can even result in the materials becoming more brittle (less ductile) and less resistant, and therefore the amount of fatigue life recovered is very low.

- Not all types of rest periods are able to produce recovery and also extend the fatigue life of asphalt materials. When the duration of the rest periods are longer, and they are included after relatively few loads have been applied (i.e. when the material has not consumed its capacity to deform), the highest increment in fatigue life is observed. In this respect, it also has been demonstrated that before failure of the material, the deformations produced in the specimens are greater under these test conditions. Before their fracture, all the materials deform as much as possible. Thus, the increment in the deformation ability of the materials produced by rest periods could be one of the reasons for having greater resistance to fatigue loading (i.e. the increment in deformations delays the appearance of damage). This increment in deformations could be due to a redistribution of the stress field following rest periods.
- The reversible phenomena such as thixotropy and heating could also help to increase fatigue life, but only if they occur before the material is highly deformed or already damaged. However, reversibility (i.e. rearrangement in the micro-structure) seems to be a time-dependent response. For this to occur, sufficiently long rest periods are needed (i.e. 10 min rest period at every 800 cycles and 5 min rest period at every 100 cycles).
- Given that the effects of reversible phenomena and the increment in deformations primarily appear during the initial phase of the fatigue process (i.e. before the occurrence of damage and before the material has consumed its capacity to deform), it could be interesting to evaluate the effects of healing technology (e.g. heating technique) during this phase on the recovery capability of bituminous mixtures.

Future lines of research

7 Future lines of research

On the basis of the results obtained from this doctoral dissertation, a series of new lines for further investigations in this field have been presented. These future lines of research can be summarised as follows:

- Analysing the effects of heating techniques on the physical, chemical, and also structural properties of bituminous mixtures.

- Analysing the influence of intermittent (pulse-rest) loading regime on the recovery capability of bituminous mixtures.

- Assessing the effects of heating techniques at the initial phase of the fatigue process (i.e. before the occurrence of damage and before the material has consumed its capacity to deform) on the recovery capability of bituminous mixtures.

- Evaluating the effects of internal influencing factors (e.g., binder, mineral skeleton, aging) and external influencing factors (e.g. loading conditions, testing temperature etc.) on the recovery obtained during rest periods in bituminous mixtures.

- Investigating the recovery obtained by incorporating rest periods according to the properties of the bitumen (i.e. physical, chemical, and morphological properties).

- Monitoring the effects of the rest periods on the mechanical response in real pavements to find a more realistic shift factor that could be employed in design guidelines.

- Evaluating the effects of stress redistribution after rest periods on the deformation properties in asphalt mixtures.

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