PONTIFICIA UNIVERSIDAD CATOLICA DE CHILE
ESCUELA DE INGENIERIA

ASSESSMENT OF MICROWAVE HEATING SELF-HEALING AS A SUSTAINABLE TECHNIQUE FOR ASPHALT PAVEMENT MAINTENANCE

KEVORK MICAEL NALBANDIAN GEYMONAT

Thesis submitted to the Office of Research and Graduate Studies in partial fulfillment of the requirements for the Degree of Master of Science in Engineering

Advisor:
ÁLVARO GONZÁLEZ V.

Santiago de Chile, (May, 2021)

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To the Armenian people and specially to the Armenians of Artsakh and their continuous struggle for survival in their homeland.

«Կանք, պիտի լինենք ու դեռ շատանանք»

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RESUMEN

Buscando alcanzar un desarrollo sustentable, varias alternativas han surgido para reducir el impacto de las actividades humanas. Siendo el transporte carretero y la industria de la construcción elementos fundamentales para el desarrollo, conllevando un alto impacto ambiental, económico y social, surge la tecnología de auto reparación mediante el calentamiento por microondas (ARMW) para pavimentos asfálticos como una alternativa hacia una infraestructura vial sustentable. Diversos estudios han probado su factibilidad técnica, sin embargo, hasta el momento no se ha realizado una evaluación completa que cuantifique su potencial efecto positivo en la sustentabilidad como alternativa de mantenimiento. Este trabajo tiene como objetivo investigar la sustentabilidad de la inclusión de la técnica de ARMW de pavimentos asfálticos en alternativas de mantenimiento en comparación con el mantenimiento tradicional. En la primera etapa de la investigación a partir de un estudio experimental y analítico, se propone una metodología que permite a través del parámetro de mecánica de fracturas Jc obtenido en laboratorio, establecer la extensión de vida de fatiga del pavimento al ser sometido a la ARMW. Se estima que esta técnica permitiría alcanzar un 20% de extensión de la vida de fatiga del pavimento. Luego a partir de los resultados de extensión de vida de fatiga y modelación con el software HDM-4 se establecen criterios para estrategias de mantenimiento de pavimentos asfálticos que incluyan la técnica de ARMW. Finalmente, se realizó un análisis de ciclo de vida ambiental, económico y social comparativo entre el mantenimiento tradicional y alternativas de mantenimiento incluyendo ARMW. Los resultados muestran que el mantenimiento utilizando ARMW en pavimentos asfálticos finos con mezclas convencionales tiene el potencial de reducir entre 28% y 52% el impacto en el cambio climático, al menos un 40% el consumo de materias primas y entre un 29% y 51% el consumo energético. También se identificaron efectos positivos a nivel socio-económico con potenciales reducciones en costos en el ciclo de vida (incluyendo inversión y costos de usuarios) de entre 17% y 42%, sumado a reducciones en niveles de ruido, accidentalidad, congestión y otros efectos que resultarían en una mejora en la calidad de vida de los usuarios de la vía y la comunidad circundante.

Palabras clave: auto reparación, microondas, pavimento asfáltico, sustentabilidad, análisis bibliométrico, Análisis de ciclo de vida, Análisis de ciclo de costos, sustentabilidad social.

ABSTRACT

Seeking to achieve sustainable development, several alternatives have emerged to reduce human activities' impact. As road transport and the construction industry are fundamental elements for development, causing high environmental, economic and social impact, asphalt pavement microwave heating self-healing technology (MW-SH) arises as a maintenance alternative towards a sustainable road infrastructure. Several studies have proven MW-SH technical feasibility, however, to date a complete evaluation has not been carried out to quantify its positive effect on pavement sustainability as a maintenance alternative. This work aims to investigate the sustainability of the MW-SH of asphalt pavements as a maintenance method compared to traditional maintenance. In the first stage of the research, based on an experimental and analytical study, a methodology is proposed that allows, through the laboratory fracture mechanics parameter Jc, obtained through laboratory tests, to establish the fatigue life extension of the pavement when subjected to the MW-SH technique. It is estimated that this technique would allow a 20% extension of the fatigue life of the pavement to be achieved. Then, from the results of the fatigue life extension and modeling with the HDM-4 software, criteria are established for asphalt pavement maintenance strategies that include the MW-SH technique. Finally, a comparative environmental, economic and social life cycle analysis was carried out between traditional maintenance and maintenance alternatives including MW-SH. The results show that maintenance including MW-SH technique on fine asphalt pavements with conventional HMA mixtures has the potential to reduce; the impact on climate change between 28% and 52%, at least 40% the consumption of raw materials and between 29% and 51% energy consumption. Positive effects were also identified at the socio-economic level with potential reductions in costs in the life cycle (including investment and user costs) between 17% and 42%, added to reductions in noise levels, amount of accidents, congestion and other negative effects, that would result in an improvement in the quality of life of road users and the surrounding community.

Keywords: Self-healing, microwave, asphalt pavement, sustainability, bibliometric analysis, LCA, LCCA, social sustainability.

1. GENERAL INTRODUCTION

1.1. Background

In the context of climate change that the planet is suffering as a result of greenhouse gases (GHG) emissions (IPCC, 2007), hence it is necessary to apply globally policies aimed to improve the environmental performance of all human activities. In 2015, the member countries of the United Nations (UN) agreed on the 2030 Sustainable Development Goals (United Nations, 2015), as a platform to promote the necessary changes. Among the key areas established, there are some directly related to the construction industry. It is known that this industry consumes a high proportion of natural resources worldwide; for example, in the United States of America (USA), the construction industry is responsible for the consumption of 30% of raw materials and 25% of the water consumed annually (Kucukvar & Tatari, 2013). In addition, it is responsible for a third of GHG emissions globally (Xu et al., 2019). That is why improving the environmental performance of the construction industry would help to achieve a significant impact worldwide.

According to data from 2016, the transport sector ranked second worldwide as a producer of GHG, reaching a quarter of the total emissions (International Energy Agency, 2017). Then in 2018, the transportation sector was responsible for 28% of total GHG emissions in the USA, thus being the sector with the highest incidence in the total (EPA, 2018). Road transportation mode is estimated to be responsible for between 70% and 90% of these emissions (Egis, 2010; European Commission, 2014). In addition, the construction and maintenance of roads generates more than 13% of the total emissions related to construction worldwide (Mukherjee & Cass, 2012). CEPAL, 2010, specifies that the emissions in the life cycle of a road are made up of indirect emissions (emissions associated with the infrastructure life cycle, vehicle life cycle and fuel life cycle) and direct emissions (associated with the fuel consumption for propulsion). Forty percent of the emissions in the life cycle of a road are due to emissions associated with the infrastructure and 38% to the propulsion of vehicles. In addition, of the total emissions associated with infrastructure, 14% have to do specifically with its maintenance (CEPAL, 2010).

Pavement (Fig. 1.1) is the central element for road transportation infrastructure because offers the riding surface to vehicles. Studies have shown that during the operation phase of a road, the surface condition of the pavement directly affects the GHG emissions into the atmosphere from the vehicles' propulsion (Memarian et al., 2015). An improvement in properties such as pavement texture and surface irregularity can achieve a reduction of between 10% and 20% in fuel consumption by propulsion (Thiel et al., 2013). Similarly, congestion, particularly that caused by pavement maintenance and construction works, also contributes to an increase in vehicle emissions (Huang et al., 2009; Yu & Lu, 2012). Hanson & Noland, 2015, on the other hand, showed that depending on if a total closure of the road or partial closures is carried out for maintenance, a variation of 96% in GHG emissions can be achieved.

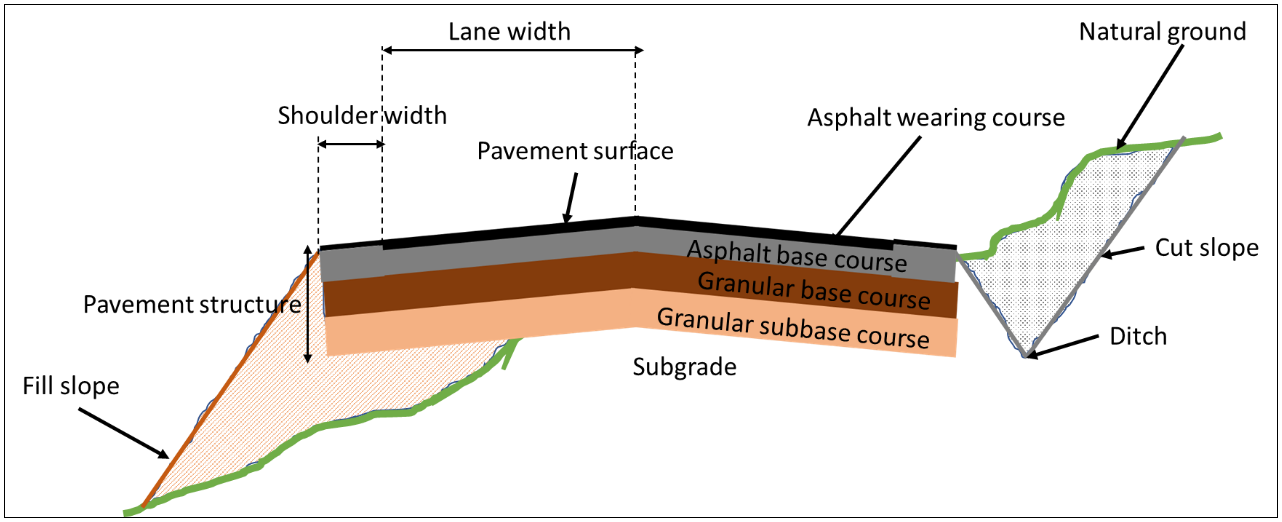

Figure 1.1 Typical asphalt road cross section

With regard to the latter, recently several countries around the world have begun to propose policies aimed at reducing emissions due to vehicle propulsion (García del Castillo, 2018). Germany, Denmark, France, Ireland, Norway and the United Kingdom, among others, plan to ban the sale of vehicles with combustion engines from 2025 to 2040 (Dugdale, 2018; Reuters, 2019; Staufenberg, 2016). In turn, several of the most important cities in Europe are restricting the circulation of vehicles with diesel or gasoline engine for the next few years (Ayuntamiento de Madrid, 2019; Behrmann, 2019). If this trend is confirmed, there will be a reduction in emissions associated with vehicle propulsion, thus emissions resulting from road construction and maintenance activities will become crucial to achieve sustainable road infrastructure.

Then it can be concluded that pavement maintenance or construction techniques, resulting in low GHG production due to the construction tasks and consumption of raw materials, which also allow to maintain a good surface condition of the pavement and generate little congestion, would have a positive effect in mitigating the environmental effect of the road transport sector.

Tabaković & Schlangen, 2016, state that pavements' self-healing techniques have the potential to reduce or eliminate the need for maintenance, minimize traffic disruption and CO_2 emissions during maintenance and drastically reduce the consumption of raw materials. Being asphalt the most common paving material worldwide, with a presence of 90% in China (Sultan & Guo, 2016) 92% in the US, around 90% in the European Community (EAPA & NAPA, 2011), and 86% in Chile (Subdirección de Desarrollo, 2017), it is important to analyze self-healing techniques for asphalt pavements.

It is widely recognized that asphalt concrete is a self-heling material (Liu et al., 2010; Tabaković & Schlangen, 2016), meaning that this material has the ability to recover its initial mechanical properties, such as dynamic modulus (Trigos et al., 2019). Once repetitive stress or strain induces damage to the asphalt mixture in form of nano cracks, the healing process occurs in three steps: i) wetting of the two faces of the nano crack; ii) beginning of the diffusion of molecules from one face to the other face of the nano crack; and iii) a randomization of the diffused molecules occurs in order to regain the original strength of the material (Little & Bhasin, 2007). However, long rest periods are needed in order to achieve the expected level of healing at normal ambient temperatures. It is clear that, in the context of a pavement in service, it is impossible to achieve these long periods of rest, for which various techniques have been developed to accelerate this phenomenon.

The ‘engineered’ healing process in asphalt materials can occur autonomously or through external stimuli (García, 2012). Knowing that high temperatures during a rest period increase the healing rate (Liu et al., 2010), procedures such as heating an asphalt pavement using electromagnetic induction (Apostolidis et al., 2016; Liu et al., 2010) or microwave radiation (Gallego et al., 2013; González et al., 2018b; Trigos et al., 2019) have been developed in the last decade. In addition, new autonomous self-healing techniques have been recently developed, such as the incorporation of nanoparticles, or rejuvenator agents, in microcapsules (Gonzalez-torre & Norambuena-contreras, 2020; Tabaković & Schlangen, 2016). These technologies involve the incorporation of new elements to the mix such as nanoparticles, microcapsules or metallic fibers in the case of microwave heating and electromagnetic induction. However, Trigos et al., (2019), González et al., (2019)y Sun et al., (2017), found that certain stone aggregates present in asphalt mixtures are heated with the application of microwave radiation, thus heating the mixture, without the need for the presence of metallic fibers. This implies that self-healing of asphalt pavements with microwaves is possible not only for new pavements (made with mixtures containing metallic fibers), but also for existing pavements, made with traditional mixtures, thus greatly increasing the potential field of application of this technique. Based on this fact, it can be stated that microwave heating self-healing technique, could have a significant effect on the volume of GHG emissions associated to transportation and road infrastructure.

Several studies have been carried out in relation to the self-healing of asphalt pavements with microwave radiation. Firstly, Gallego et al., (2013) proved its technical feasibility, confirmed among others, by studies such as that of Franesqui et al., (2017). Later, various investigations have been carried out studying the efficiency of self-healing when metal filler or raped are added to the asphalt mixture, , (González et al., 2018a, 2019; Li et al., 2018b, 2018a; Norambuena-Contreras et al., 2016, 2018; Phan et al., 2018; Zhu et al., 2017). Also, the effect of microwave self-healing on the properties of asphalt mixtures and binder aging has been studied (Flores et al., 2018; Norambuena-Contreras & Gonzalez-Torre, 2017). Additionally, studies were conducted comparing the efficiency of microwave self-healing with other self-healing methods, showing a better performance and higher healing effect (Liu et al., 2018; Norambuena-Contreras & Garcia, 2016). With regards to the environmental performance of asphalt pavements' self-healing techniques, Lizasoain-Arteaga et al., (2019), found that electromagnetic induction heating self-healing technique achieves a reduction in the impact in 12 of the 17 environmental impact categories analyzed, showing the positive effect of this self-healing technique. Regarding to microwave heating self-healing, Rodríguez-Alloza et al., (2019), carried out an hybrid input – output-assisted LCA analysis for thick asphalt pavement with metal slag addition. By arbitrarily defining the maintenance strategies to be compared, they concluded that a 16% reduction in GHG emissions is achieved compared to traditional maintenance techniques.

The literature review shows that the technical feasibility of self-healing asphalt pavements by means of microwave heating has been studied in the laboratory and the different parameters that may influence the efficiency the self-healing have been evaluated. However, at least two gaps are found. The first, is the application of this technique in the field. The second is the sustainability (environmental, economic, and social) of the maintenance of asphalt pavements when using the self-healing technique with microwave heating in thin pavements (asphalt concrete layer thickness ≤10cm, more frequent in developing countries) and with traditional Hot Mix Asphalt (HMA) mixtures without metallic fibers. The latter is highly relevant, as it will verify the effectiveness of the technology developed in responding to the need from which it arose.

1.2. Research questions

From the previous analysis, the following research questions arise. First, how should a maintenance strategy including microwave heating self-healing technique be made-up? Then, regarding the environmental effect, is a reduction in GHG emissions effectively achieved in the life cycle of the pavement by applying strategies that include microwave heating self-healing compared to traditional pavement maintenance, in pavements with low thickness of traditional HMA concrete? and if so, in what proportion will this reduction occur? An important factor considered by the road infrastructure managing agency when choosing maintenance alternatives is the cost of the road's maintenance, thus, which would be the economic impact of the inclusion of microwave heating self-healing technique in pavement maintenance? Finally, which would be the social impact of the implementation of microwave heating self-healing technique for pavement maintenance?

1.3. Hypothesis

The maintenance of thin asphalt pavements using microwave heating self-healing technique is more sustainable (environmental, economic and social) than traditional pavement maintenance techniques. Thus, allowing to achieve a 20% reduction in climate change impact and 15% in costs during pavement's life cycle.

1.4. Research Objectives

To verify the previously defined hypothesis the following general objective was established:

- To assess the environmental, economic, and social sustainability of asphalt pavement microwave heating self-healing maintenance technique compared to traditional pavement maintenance, understanding it's the potential impacts on the GHG emissions and economic cost.

Then, to achieve the general objective the following specific objectives were defined.

1. Identify the effect of microwave heating self-healing technique on asphalt pavement's fatigue life extension.

2. Establish asphalt pavement maintenance strategies including microwave heating self-healing technique.

3. Quantify the environmental impact of the established maintenance strategies including microwave heating self-healing technique compared to traditional asphalt pavement maintenance strategies.

4. Quantify the socio-economic impact of the established maintenance strategies including microwave heating self-healing technique compared to traditional asphalt pavement maintenance strategies.

1.5. Organization of dissertation

To address the previously mentioned objectives, the present thesis was arranged in the following way:

- Chapter 2. This chapter presents a bibliographic and bibliometric analysis of self-healing of asphalt pavements, which resulted in a paper titled "Analysis of the scientific evolution of self-healing asphalt pavements: Toward sustainable road materials" which was published in the Journal of Cleaner Production (Nalbandian et al., 2021).
- Chapter 3 (specific objective 1). This chapter investigates the ways to evaluate the self-healing efficiency of the developed self-healing techniques and seek to provide information about the pavement's life extension, valuable to design maintenance strategies. This chapter resulted in a paper titled "Assessment of self-healing asphalt pavement fatigue life using analytical Jc approach and laboratory results" which is currently under review in the Construction and Building Materials Journal.
- Chapter 4 (specific objectives 2, 3, 4). This chapter assesses the sustainability of the inclusion of the microwave heating self-healing technique in asphalt pavmemtn maintenance, addressing environmental sustainability through a LCA,

socio-economic sustainability through LCC analysis and a qualitative social sustainability assessment. This chapter resulted in a paper titled “Assessment of the sustainability of asphalt pavement maintenance with microwave heating self-healing technique” planned to be submitted to the Journal of Cleaner Production.

Finally, Chapter 5 presents the conclusions for this work, limitations and recommendations for future research.

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2. ANALYSIS OF THE SCIENTIFIC EVOLUTION OF SELF-HEALING ASPHALT PAVEMENTS: TOWARD SUSTAINABLE ROAD MATERIALS

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Abstract

Although researchers have investigated the concept of self-healing asphalt materials for decades, only recently has scientific interest in methods triggering self-healing properties of asphalt increased. Self-healing technologies are expected to increase the service life of materials and reduce their maintenance, decreasing raw materials consumption, greenhouse gas emissions, and negative effects of construction on climate change. Self-healing of asphalt materials has the potential to make important changes in the road construction materials industry, making it more sustainable; however, the literature has not exactly reported a quantitative analysis of the progress or evolution of this scientific topic. Bibliometric and science mapping analyses are methodologies to study through quantitative analysis, the scientific evolution of any knowledge area. Hence, this paper presents a bibliometric and science mapping analysis of the self-healing technology of 292 selected documents found in widely accepted scientific databases, using SciMAT open access software. In addition, the article presents a

description of the most important articles based on SciMAT analysis. The results of the study show that the production of documents related to self-healing has been growing since 1994, reaching a peak in 2018 with 60 published articles (21% of the total). In addition, China and the USA have an outstanding performance in the production of documents followed by the Netherlands, UK, Spain, and Chile, although the European continent has the largest number of countries actively developing this research area. The analysis also showed that the most productive authors in the topic of study are Wu, S.P., Little, D.N., Lytton, R.L., and Garcia, A. In addition, analysis showed an increasing development of self-healing pavements topics in new and more specific research areas such as microwave heating, nanocomposites, and microcapsules. Overall, this analysis shows that self-healing asphalt materials technology has been catching the scientific interest of many researchers in recent years; hence, there are many techniques and areas that are being developed and are expanding the branches and different niches in this research area. Therefore, opportunities for researchers to work in this field are developing and are also far from reaching a stage of maturity.

2.1. Introduction

Roads are of paramount importance for the development of any country or region, as they enable the transportation of goods and people, resulting in social and economic development (Balaguera et al., 2018). In addition, roads represent a large part of the infrastructure worldwide. Therefore, road construction and maintenance are crucial for governments and inhabitants of all states, countries, and regions. However, roads are part of the construction materials industry, which is one of the main natural resources exploiters, consuming 60% of the raw materials extracted from the lithosphere (Spence and Mulligan, 1995) and accountable for nearly a third of greenhouse gas (GHG) emissions (Xu et al., 2019). Thus, in the context of sustainable development, a concern has risen about how new practices and technologies can be applied in order to minimize the negative effects of construction on the environment (Ding, 2008). As a result, researchers on construction materials have made efforts to develop innovative technologies in order to make construction and road industry practices more sustainable. For instance, researchers have investigated the use of sustainable materials and their design (Plati, 2019), in-place pavement recycling, pavement preservation strategies and preventive treatments, pavement layers with very-high reclaimed asphalt pavement (RAP) content, and industrial wastes and byproducts (Santos et al., 2019). In addition, researchers have conducted studies on recycled and stabilized granular materials (González et al., 2018a), porous concrete pavements technology (Elizondo-Martínez et al., 2020), self-healing asphalt pavements (García, 2012; Tabaković and Schlangen, 2016), and cold in situ recycled pavements (González et al., 2010).

Asphalt is the most common material used in the road construction industry (González et al., 2018b). Hence, innovative techniques developed for construction and maintenance of asphalt pavements have a great beneficial potential for roads. Particularly, self-healing technologies have the potential to make important changes in this industry (Tabaković and Schlangen, 2016): for instance, reducing or eliminating maintenance needs, reducing the consumption of natural resources, decreasing the disruption of traffic and CO_2 emissions during maintenance, and increasing road safety (Tabaković and Schlangen, 2016). Fig. 2.1 illustrates the maintenance of traditional and self-healing asphalt pavements. Traditional maintenance needs machinery and natural resources, human intervention with workers in the field, and partial or total road closure, which generates traffic interruption, congestion, and more emissions to the atmosphere. Conversely, a self-healing pavement should have the ability of repairing distress by itself, or with minimum intervention.

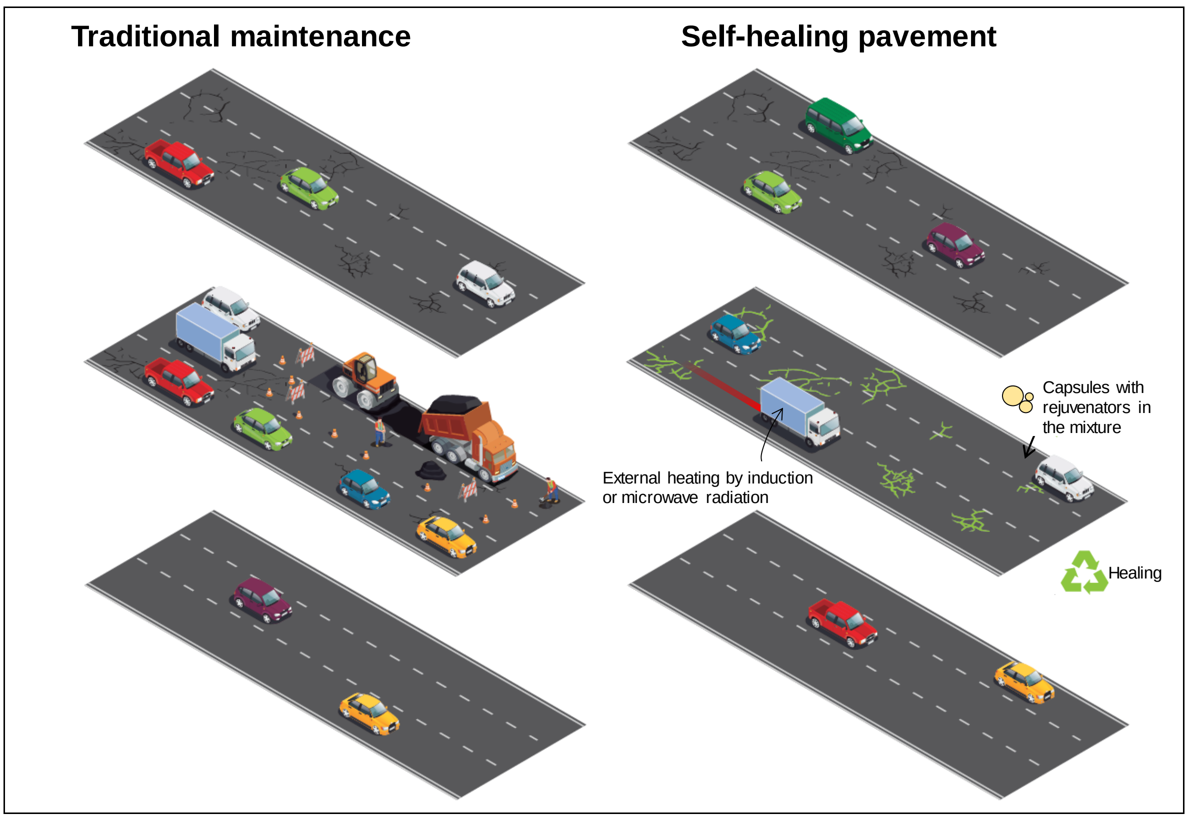

Figure 2.1 Traditional pavement maintenance vs self-healing maintenance techniques

The concept of self-healing comes from nature; e.g., when a branch of a tree is broken, the tree recovers from that injury, or when someone's finger is cut while cooking, if the cut is not very deep it will stop bleeding spontaneously and heal (García, 2012; Qiu et al., 2009). Similarly, it is widely recognized that asphalt concrete is a self-heling material (Liu et al., 2010; Tabaković and Schlangen, 2016), meaning that this material has the ability to recover its initial mechanical properties, such as dynamic modulus (Trigos et al., 2019). After stress or strain induces damage to the asphalt mixture, the healing process occurs in three steps: first, wetting of the two faces of the nano crack; second, diffusion of molecules from one face to the other begins; and, third, a randomization of the diffused molecules occurs in order to regain the original strength of the material (Little and Bhasin, 2007). However, long rest periods are needed in order to achieve the expected level of healing at normal ambient temperatures (Little and Bhasin, 2007). As it is usually impossible to leave an asphalt pavement road unused for a long period, researchers have recently developed techniques to accelerate this process.

The healing process in asphalt materials can occur autonomously or through external stimuli (García, 2012). Knowing that high temperatures during a rest period increase the healing rate (Liu et al., 2010), procedures such as heating an asphalt pavement using electromagnetic induction (Apostolidis et al., 2016; Liu et al., 2010) or microwave radiation (Gallego et al., 2013; González et al., 2018c; Trigos et al., 2019) have been developed in the last decade. In addition, new autonomous self-healing techniques have been recently developed, such as the incorporation of nanoparticles, or rejuvenator agents, in microcapsules (Tabaković and Schlangen, 2016).

In order to understand the state of the art of any area of knowledge, like the self-healing of asphalt pavements, there are several strategies or techniques; one of them is bibliometric analysis. This analysis quantitatively studies the scientific research production (Gauthier, 1998). Bibliometric analysis is mainly composed by performance analysis and science mapping. The former, evaluates scientific actors such us, universities, countries, journals or researchers, and the impact of their activity based on a large quantity of bibliographic data. Science mapping goal is to show the structural and dynamic aspects of scientific research through graphical maps (science maps) (Cobo et al., 2011a), as further described below. Thus, bibliometric analysis has been applied to multiple areas of knowledge such as computer science, psychology, marketing, and management (Rodríguez-bolívar et al., 2018), sustainable building assessment (Díaz-López et al., 2019), e-government (Alcaide–Muñoz et al., 2017), industry 4.0 (Cobo et al., 2018), urban heat islands (Carpio et al., 2020) and others. However, such methodology has not been applied to self-healing asphalt and, as a result, the authors identify a necessary research opportunity that needs to be fulfilled.

Therefore, this paper presents: i) an analysis of the scientific evolution of self-healing asphalt materials, conducted through a performance bibliometric analysis and science mapping applied to selected scientific articles, and based on the previous analysis ii) a brief description of the most important published documents. The analysis aims to achieve a comprehensive understanding of the development of this area of knowledge, and to identify the trending topics and gaps that might help and guide researchers on sustainable road infrastructures.

2.2. Methodology of analysis

2.2.1. General methodology

First, it is important to mention that bibliometric analysis is mainly based on statistical analysis as it is shown in the multiple articles previous published where this methodology is used (Aparicio et al., 2019; Cobo et al., 2018, 2011a; Díaz-López et al., 2019; López-robles et al., 2019; Rodríguez-López et al., 2019). Thus, in this work the analysis is made based predominantly on statistics, however there is also a brief content analysis of the most cited articles in the data base. The scientific evolution analysis conducted for this paper consists of two parts, a performance bibliometric analysis, and science mapping analysis. The performance bibliometric analysis was conducted using bibliometric indicators, such as the number of published documents, citations, h-index, most cited documents, most cited authors, and geographical distribution of publications (Cobo et al., 2015). Moreover, science mapping (SM) analysis was conducted through the use of SciMAT, a SM tool (Cobo et al., 2012).

The methodology consists of the six stages described below.

- *Definition of the search parameters: period, key terms, and journals.* The period for the bibliometric analysis was limited to materials from 1970 (oldest records in Web of Science, WOS) to 2019. The key terms that represent the main topic of this work were "self-healing asphalt", "self-healing flexible pavement", "self-healing bitumen", and "healing asphalt mixture". The search included scientific journal articles only because the authors focused their work on the scientific evolution of self-healing asphalt.

- *Search and depuration.* The second stage consisted of searching documents to be analyzed. Although this can be done through multiple sources of scientific knowledge, in this work the authors selected SCOPUS and WOS databases, as these are the most complete and widely used in similar investigations (Cobo et al., 2015; Díaz-López et al., 2019; Rodríguez-López et al., 2019). The initial number of pertinent articles found was 1,008. Nevertheless, most of these articles were duplicated, out of topic, or found in only one of the databases. After a manual one by one second filtering, 292 articles remained suitable for bibliometric analysis.
- *Software and manual processing of the information.* Using specific computer tools of SciMAT, and non-automatic data processing done without any specific tools, the information was made uniform, merging authors and journal names as well as grouping singular and plural key words.
- *Performance bibliometric analysis.* From the database stored in SciMAT, the performance of authors, documents, and journals was analyzed based on bibliometric performance indicators.
- *Science Mapping analysis*. Finally, the database was examined using SciMAT algorithms to develop the SM analysis.
- *Conclusion*. Conclusions and recommendations are based on the results of the previous phases of the methodology.

2.2.2. Science mapping methodology

SM or bibliometric mapping is a "spatial representation of how disciplines, fields, specialties, and individual papers or authors are related to one another" (Small, 1999). Many SM software tools have been developed such as CiteSpace, VOSviewer, HistCite, and SciMAT, among others (Cobo et al., 2011b; Pan et al., 2018). The authors chose SciMAT for this research because it is an open-source software (Cobo et al., 2012) developed for researchers who usually must use more than one software to conduct a bibliometric analysis. SciMAT produces science maps based on co-occurrence of keywords and enables identifying the evolution of keyword clusters (topic or themes), their importance in different periods, and the link between different keywords. Four diagrams are output by the SciMAT SM analysis: The overlapping graph, the evolution map, the strategic diagram, and the cluster network (Fig. 2.2).

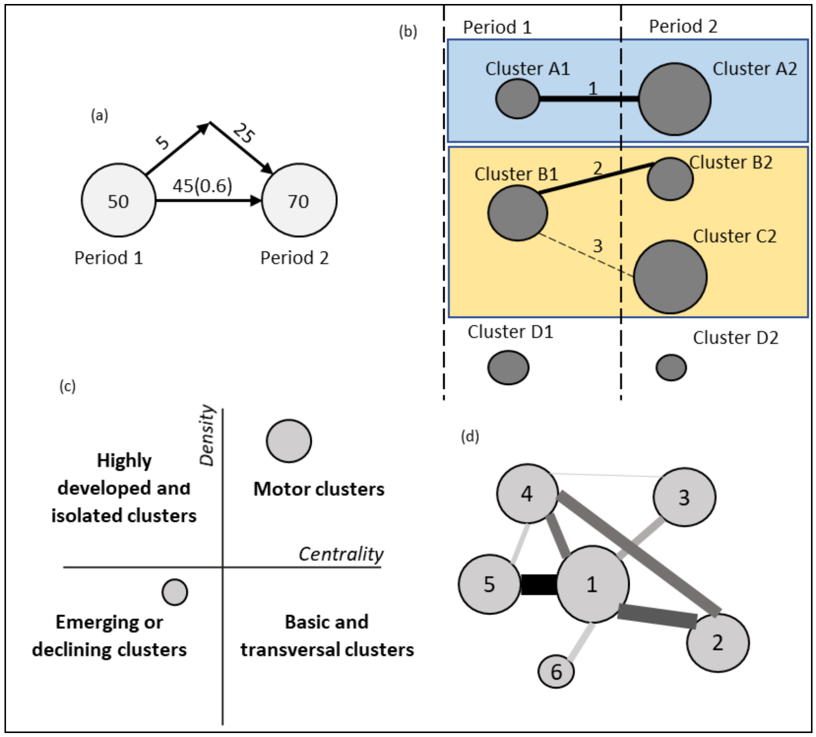

Figure 2.2 Outputs of SciMAT analysis: (a) overlapping graph; (b) evolution map; (c) strategic diagram; and (d) cluster network. Adapted from (Cobo *et al*., 2012)

In order to run the SM analysis, the authors defined four periods. The first was from 1994 (publication year of the first article in the database) to 2009, when there began a first substantial increase in the number of papers per year. The second period was from 2010 to 2014 with an average production of 12.4 articles per year; the third period was from 2015, the year of the agreement of the 2030 sustainable development agenda (United Nations, 2015), to 2017, which is a period when a large increase in the production was observed. Finally, the fourth period was from 2018 to 2019, the last two years, in order to analyze new trends in self-healing asphalt materials research.

2.2.2.1. Overlapping graph

The first output diagram is the overlapping graph (Fig. 2.2a), which shows the entrance (arrows coming from outside the diagram) or disappearance (arrows going outside the diagram) of keywords. In this graph, the number of words that "survive" from the current to the next period are represented by the horizontal arrows. The number of keywords that enter, disappear, or survive within each period are shown above each arrow. The stability index is the value in parenthesis and is a measure of the overlapping topics between two consecutive periods.

2.2.2.2. Thematic evolution map

The evolution map (Fig. 2.2b) shows the development of themes, and the links between themes in one period and the next period. The importance of each link is measured by the inclusion index (Cobo et al., 2011a). Circles represent the different various clusters, in which the diameter of each circle is proportional to the number of publications. The lines connecting the circles represent the types of links. Solid lines mean that the linked themes are labeled with the same keywords, or the label of one theme is part of the other theme name. Dotted lines indicate that the circles share elements that are not part of the theme name. Finally, the thickness of the line is proportional to the inclusion index (Cobo et al., 2011a).

2.2.2.3. Strategic diagrams

The bibliometric indicators (i.e., number of documents, citations, *h-index*, etc.) of each theme are related to each other; hence, they are analyzed together using the strategic diagram (Fig. 2.2c) by its density and centrality (Cobo et al., 2011a). Centrality, is a measure of the amount of interaction of one theme with the others and the strength of its ties and, as a result, represents the importance of the theme in the analyzed area of knowledge (Cobo et al., 2011a). On the other hand, density measures the strength of internal ties within a thematic cluster and can be used as a measure of the theme's level of development. Hence, the strategic diagram is a two-dimensional space where thematic clusters are plotted according to their centrality (x axis) and density (y axis). Each thematic cluster is represented by a circle whose diameter is proportional to the number of documents. According to their relative position in the diagram, themes can be classified as: motor themes (high centrality and high density); basic and transversal themes (high centrality and low density); highly developed and isolated themes (low centrality and high density); and merging or declining themes (low centrality and low density).

2.2.2.4. Thematic network

The thematic network is the last map delivered by SciMAT (Fig. 2.2d). It shows the keywords and their interconnections and draws a graph. Each network is named for the most significant keyword in the theme; in addition, each keyword is represented by a circle whose diameter is proportional to the number of documents, and the thickness of the linking lines between key words is proportional to the equivalence index (Cobo et al., 2011a).

2.2.3. Terminology and date of analysis

In order to understand correctly the results of this analysis, it is necessary to clarify the use of some terms listed below.

- *Documents*: articles or papers that have been selected from the above specified databases in order to conduct the research.
- *Publications*: Journals in which the documents were published.
- *Themes, thematic clusters, clusters*: clusters formed by keywords as a result of the co-occurrence keyword analysis.

The analysis presented in this article was performed in 2019; however, the temporal distribution of documents was updated to the 23rd August 2020.

2.3. Results of the performance bibliometric analysis

2.3.1. Temporal distribution of documents

Figure 2.3 shows the temporal distribution of 365 published articles. Between 1994 and 2009, only 20 documents related to self-healing asphalt materials were published (5.5% of the total). From 2010, a steady increase was observed, from an average production of two documents per year, to more than 10 annually between 2010 and 2014. From 2014 until 2018, the number of published documents has increased every year, showing a growing interest from the multiple stakeholders regarding self-healing asphalt pavements. Despite the large increase between 2009 and 2010, it must be noted that a notorious increment in the production of documents has occurred after 2015, reaching a total of 261 articles from 2016 to august 2020, which represents 71.5% of all papers selected. It should be noted that in 2015, the 2030 agenda for sustainable development was adopted at a special United Nations summit (United Nations, 2015). This international agenda is apparently encouraging more research in this and other topics that promote sustainable materials. Finally, it can be stated that, as shown in Figure 2.3, self-healing asphalt pavements is a topic that has captured the attention of world researchers and due to the development of this area of knowledge for the last three years has been the focus of a large and constant production of articles.

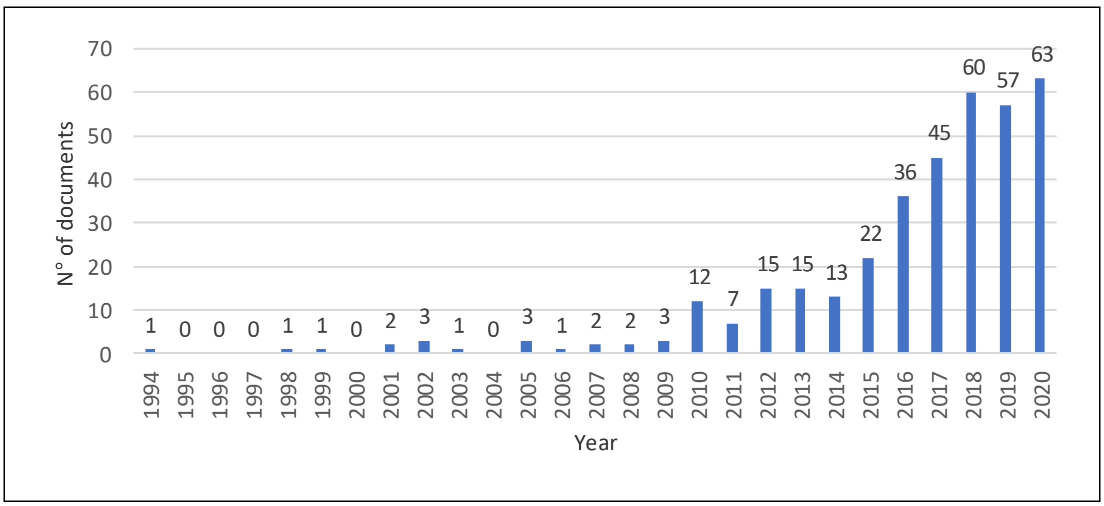

Figure 2.3 Number of documents published per year

2.3.2. Geographical distribution of documents

Regarding geographical origin of the scientific production, analysis was conducted considering the country of affiliation reported by the authors (Fig. 2.4). The countries with largest production of scientific articles concerning self-healing asphalt are China and the United States of America (USA), with 138 and 131 articles each, many of which were conducted in cooperation between researchers in both countries. The Netherlands is in second place, with 54 papers, many of them only by authors affiliated with Dutch universities, but also a large number were conducted in cooperation with China, Chile, Spain, and other countries. In the third place, the analysis found the United Kingdom (UK), Spain, and Chile, each one within a range of 23-33 documents, and in the fourth place, Iran, South Korea, Switzerland, and Sweden with approximately 15 documents each.

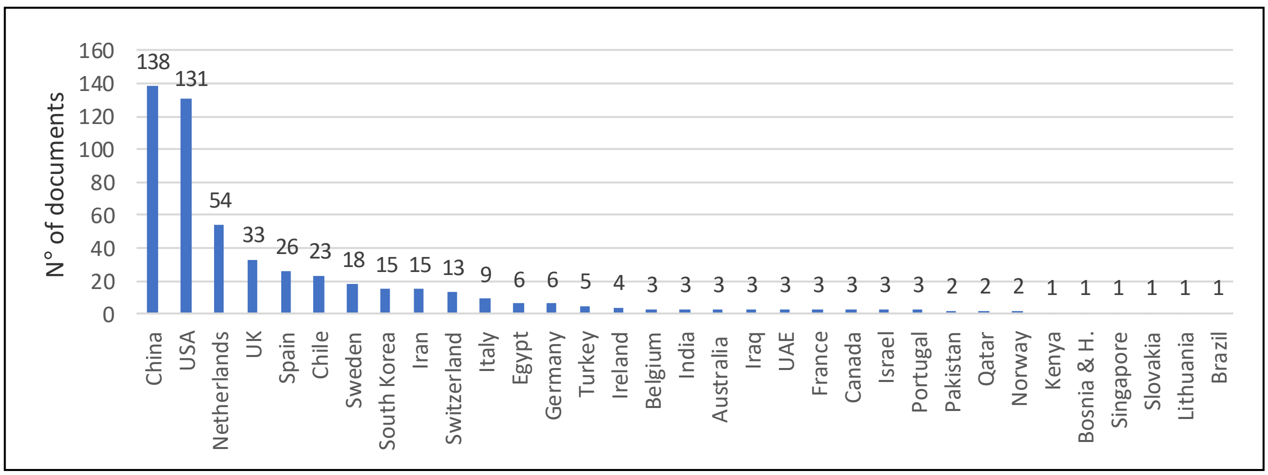

Figure 2.4 Number of documents published per country

At a continental level, Chile ranks first in South America (Fig. 2.5), being the main country researching self-healing asphalt pavement materials. In Europe (Fig. 2.5), despite many countries working in this field, the Netherlands is a hub of scientific production, sharing its ranking with the UK and Spain. In Asia (Fig. 2.6), as expected, China is by far the most relevant country in terms of number of published documents, although South Korea and Iran also have made an important contribution to the development of knowledge in the field of self-healing asphalt with 15 articles per country. These statistics can be explained primarily by the amount of investment in research and development of each country. For example, the USA and China are the two countries in the world that invest most in research and development, followed by UK, Netherlands, Spain, and South Korea, among the first 15 places (UNESCO, 2020). In addition, they rank highest by the number of paved roads and specifically asphalt surfaced roads in each country, which is a crucial factor influencing and pushing scientists to conduct research on asphalt pavement technologies. These naturally follow the interests of governments, states, and other stakeholders to maximize the benefits of these infrastructures and reduce construction and operation costs. In Europe approximately 90% of the paved roads are surfaced with asphalt, while in the USA this amount reaches 92% (European Asphalt Pavement Association and National Asphalt Pavement Association, 2011). In China, since 1997, semi-rigid base asphalt pavements are the most common pavement structure, reaching 90% of the total of paved surfaces (Sultan and Guo, 2016). According to Elvidge *et al.* (Elvidge et al., 2007), China and the USA are the two countries with the highest amount of constructed impervious area, and the UK, Iran, and Spain, are found in the top 20.

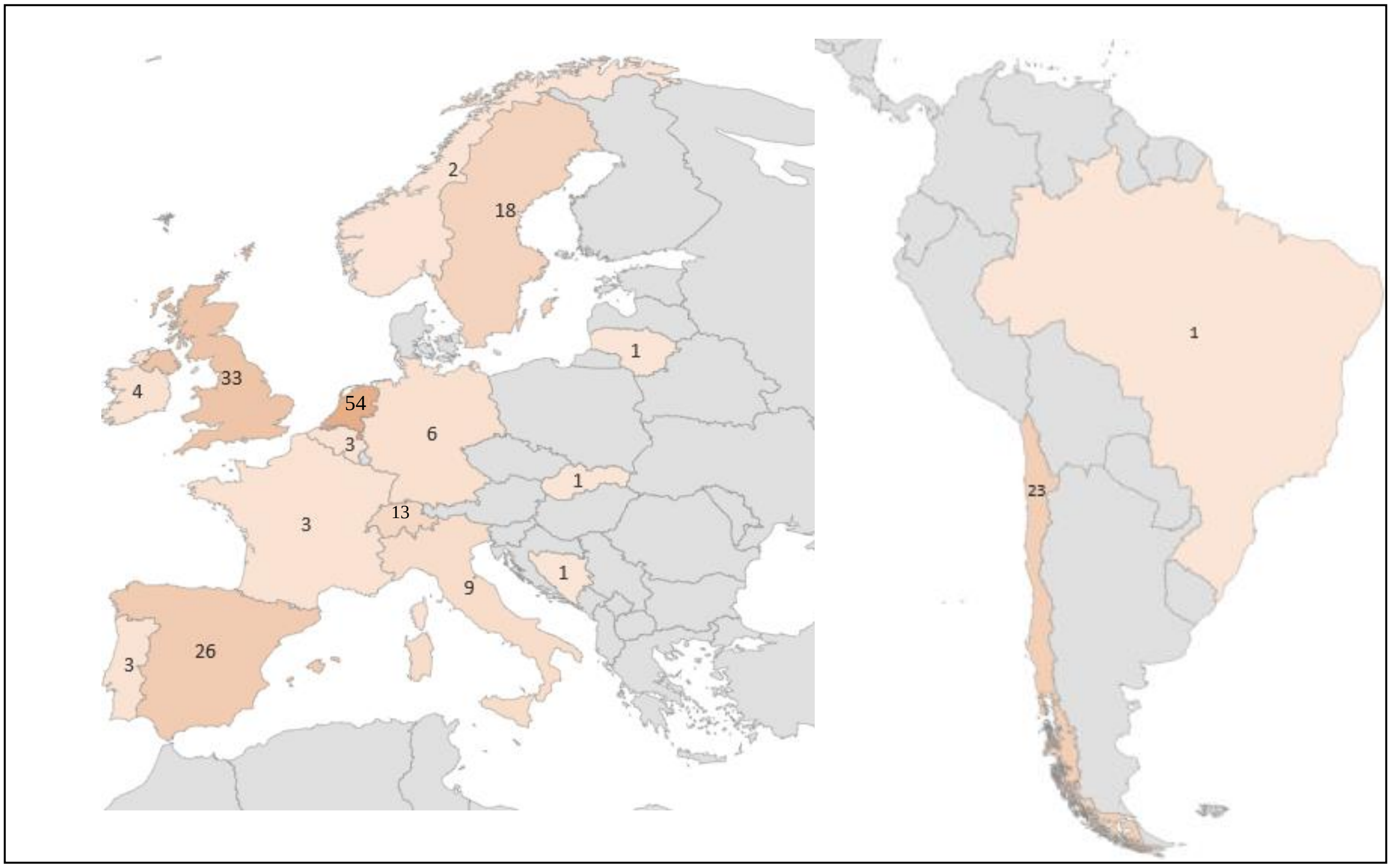

Figure 2.5 Number of documents published in Europe (left), and South America (right)

Figure 2.6 Number of documents published in Asia

2.3.3. Most productive authors in the research field

From 502 authors identified, 10 authors have the largest number of published articles (Table 2.1). The number of documents and the h-index (Hirsch, 2005), which measures the impact of a researcher's work, were used to analyze the authors' productivity. It can be appreciated that Wu, S.P. is the most productive author with 36 documents and an overall h-index of 41. However, Little, D.N., holds the highest h-index (48), being one of the most influential scientists in the list. Likewise, Table 2.1 shows, for each author, their most cited document. Little, D.N. as well as Lytton, R.L. prove to be the most cited, each with 201 citations for their most important document (Kim *et al*., 2003), which was written by them together. Finally, the performance of Garcia, A. reached second place with 34 articles and a total of 188 citations in his most cited document (García, 2012). It is interesting to see that the most cited documents for six out of the ten most productive authors are related to the self-healing of asphalt materials as a sustainable maintenance technique by external heating or microcapsules.

2.3.4. Most cited documents

Table 2.2 shows the 10 most cited documents arranged from the most to the least cited. The most recent work in this list is from 2012, while the vast majority of all articles analyzed were published after 2014 (71.9%), showing that articles need some time in order to achieve a high number of citations. Nevertheless, it must be observed that the majority of the topics are generic about fatigue, healing, mechanical behavior, and properties of asphalt mixture or mastic (Al-Rub et al., 2010; Bahia et al., 1999; Daniel and Kim, 2001; García, 2012; Kim et al., 2003; Krishnan and Rajagopal, 2005; Lee and Kim, 1998). However, only a few articles report on a specific technique of self-healing asphalt (García *et al*., 2009; Liu *et al*., 2010) and three of them are related to self-healing as a sustainable maintenance technique.

2.3.5. Publications with the largest number of documents

The conducted search identified 64 publications. Table 2.3 shows eight journals containing the highest number of articles published on self-healing asphalt as well as their most cited document. From the 292 articles in this study, 70% were published in the journals listed in Table 3. The journal with the leading number of publications, *Construction and Building Materials (CBM)* contained 102 articles, 35% of the total. Second place was the *Journal of Materials in Civil Engineering (JMCE)* with 31 articles and 11% of the total. *Construction and Building Materials* and the *Journal of Materials* *in Civil Engineering* are mentioned six times in Table 2, indicating that an important percentage of the most cited articles on self-healing asphalt have been published in these two journals. The *Journal of Cleaner Production* published seven documents on self-healing, with the most cited article being a general state of the art review on the topic.

The Scientific Journal Rating (SJR) is a widely recognized measure of a journal impact and quality (González-Pereira *et al*., 2010). Table 2.3 confirms that *CBM* is a journal with high impact and a large number of publications on the self-healing of asphalt materials. Other journals with high impact in the list are the *Journal of Cleaner Production* (JCP) and *Materials and Structures/Matériaux et Constructions*; however, these journals only published 7 and 11 articles on the topic of self-healing asphalt, respectively. Also, the journal *Transportation Research Record*, with a relatively low SJR indicator, is in the third place with 20 publications. In other words, the analysis shows that the journals with a high number of articles published may not have the largest impact, although *CBM* holds a high SJR of 1,491 and the largest number of published articles.

Table 2.1 Most productive authors

	Name	N° of documents	h-index*	Most cited document	Document's year	N° of citations of the document **
1	Wu, S.P.	36	41	Investigating self-healing behavior of pure bitumen using dynamic shear rheometer	2011	50
2	Garcia, A.	34	27	Self-healing of open cracks in asphalt mastic♦	2012	188
3	Liu, Q.	31	20	Induction heating of electrically conductive porous asphalt concrete♦	2010	144
4	Schlangen, E.	31	39	Induction heating of electrically conductive porous asphalt concrete♦	2010	144
5	Norambuena-Contreras, J.	24	18	Induction healing of dense asphalt concrete♦	2013	92
6	van de Ven, M.F.C.	17	23	Induction heating of electrically conductive porous asphalt concrete♦	2010	144
7	Su, J.-F.	15	28	Stability investigation of self-healing microcapsules containing rejuvenator for bitumen♦	2013	58
8	Little, D.N.	13	48	Fatigue and healing characterization of asphalt mixtures	2003	201
9	Zhu, X.	13	24	Intrinsic temperature sensitive self-healing character of asphalt binders based on molecular dynamics simulations	2018	48
10	Lytton, R.L.	12	33	Fatigue and healing characterization of asphalt mixtures	2003	201

*Scopus 23/08/2020, **Scopus 23/08/2020, ♦Article related to self-healing as a sustainable maintenance technique.

Table 2.2 Most cited articles

	Title	Athors	Journal	Year	N° of citations**
1	Fatigue and healing characterization of asphalt mixtures	Lytton, R.L., Little, D.N., Kim, Y.-R.	Journal of Materials in Civil Engineering	2003	201
2	Self-healing of open cracks in asphalt mastic♦	Garcia, A.	Fuel	2012	188
3	Non-linear viscoelastic and fatigue properties of asphalt binders	Zhai, H., Bonnetti, K., Kose, S., Bahia, H.	Asphalt Paving Technology: Association of Asphalt Paving Technologists-Proceedings of the Technical Sessions	1999	168
4	Induction heating of electrically conductive porous asphalt concrete♦	Garcia, A., Liu, Q., Schlangen, E., van de Ven, M.F.C.	Construction and Building Materials	2010	144
5	Viscoelastic continuum damage model of asphalt concrete with healing	Lee, H.-J., Kim, Y.Richard	Journal of Engineering Mechanics	1998	134
6	Electrical conductivity of asphalt mortar containing conductive fibers and fillers♦	Garcia, A., Liu, Q., Schlangen, E., van de Ven, M.F.C.	Construction and Building Materials	2009	133
7	Unique effects of hydrated lime filler on the performance-related properties of asphalt cements: Physical and chemical interactions revisited	Little, D.N., Petersen, J.C.	Journal of Materials in Civil Engineering	2005	131
8	A micro-damage healing model that improves prediction of fatigue life in asphalt mixes	Little, D.N., Abu Al-Rub, R.K., Darabi, M.K., Masad, E.A.	International Journal of Engineering Science	2010	110
9	Laboratory evaluation of fatigue damage and healing of asphalt mixtures	Daniel, J.S., Kim, Y.Richard	Journal of Materials in Civil Engineering	2001	105
10	On the mechanical behavior of asphalt	Krishnan, J.M., Rajagopal, K.R.	Mechanics of Materials	2005	96

Table 2.3 Journals with the highest number of documents published

	Name	SJR 2019***	N° of documents	Most cited article	N° of citations of the document **
1	Construction and Building Materials	1,491	102	Induction heating of electrically conductive porous asphalt concrete♦	144
2	Journal of Materials in Civil Engineering	1,035	31	Fatigue and healing characterization of asphalt mixtures	201
3	Transportation Research Record	0,540	20	Surface energy measurement of asphalt and its application to predicting fatigue and healing in asphalt mixtures	89
4	Road Materials and Pavement Design	0,967	13	A framework to quantify the effect of healing in bituminous materials using material properties	81
5	Materials	0,647	11	Investigation of the self-healing behaviors of microcapsules/bitumen composites by a repetitive direct tension test♦	18
6	Materials and Structures/Matériaux et Constructions	1,369	11	Induction heating of mastic containing conductive fibers and fillers♦	73
7	International Journal of Pavement Engineering	0,806	10	On the existence of wax-induced phase separation in bitumen	92
8	Journal of Cleaner Production	1,886	7	The healing capability of asphalt pavements: A state of the art review	81

*** SCImago Journal Rank measures weighted citations received by the journal. Citation weighting depends on subject field and prestige (SJR) of the citing journal (Scimago Journal & Country Rank, 2020).

**Scopus 23/08/2020.

2.4. Results of the science mapping analysis

2.4.1. Overlapping graph and thematic evolution map

The overlapping graph shows the introduction and disappearance of keywords from one time period to the next. In Figure 2.7, from left to right it can be observed that the number of keywords substantially increases since 1994, from 38 in the first period (1994-2009) to 106 in the fourth period (2018-2019), resulting in a 278.9% increase, and showing the diversification of topics and the development and growth of research in this research area.

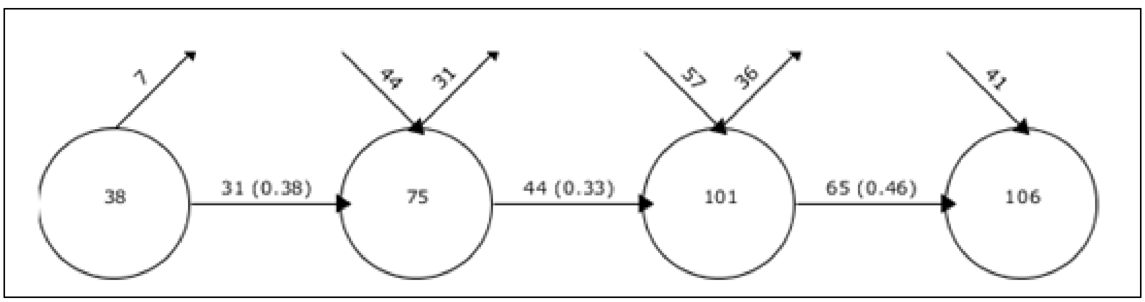

Figure 2.7 Overlapping graph of keywords, each circle is one period

The above mentioned keywords, are grouped in thematic clusters through the simple centers algorithm, in the context of co-word analysis as explained in Cobo *et al.* (Cobo et al., 2011a). After this process is completed, the thematic evolution map (Fig. 2.8) is constructed showing the evolution from a cluster to another in the next period.

Analyzing the number of core documents, the most important keyword cluster in the first period (1994-2009) is “mixtures”, evolving to “asphalt” (solid line), and then to “bitumen”, “pavements”, “self-healing materials”, “material-property”, and “ageing” (dotted line). In the period 2010-2014, “asphalt” appears as the keyword cluster with the largest number of documents, evolving in the period 2015-2017 to “self-healing”, “concretes”, and “rest-periods” (solid line), in addition to “aggregates”, and “numerical model” (dotted line). Finally, it can be noticed that “self-healing” is the predominant thematic cluster in the period 2015-2017, evolving primarily to the “self-healing” cluster, and to the “cracks” cluster (solid line), and the “mechanical-properties” cluster.

It should be noted that the themes “acoustic-emissions” and” fatigue loadings” that appear in the second period are new themes that were discontinued in the following period. In addition, the cluster “pavements” starts in the first period and continues to evolve in the second and third periods, delivering new themes (i.e., “self-healing materials”, “self-healing properties”, and “microwaves”) to be finally discontinued in the fourth period. It is also important to observe that new and more specific thematic clusters are developed after each period, showing that self-healing asphalt pavements is a topic that has recently developed and is growing. Hence, as shown in Figure 2.8, during the third and fourth periods, thematic clusters regarding self-healing techniques such as “microwaves”, “nanocomposites”, “high temperatures”, and “curing-agents” emerge. To conclude, it should be noted that the topic “self-healing”, as a cluster per se, appears to be developing in the third period, evolving from “asphalt”, “bitumen”, and “self-healing materials”, and continues growing in importance through the 2018-2019 period, showing that self-healing has become an individual subject in asphalt pavement materials.

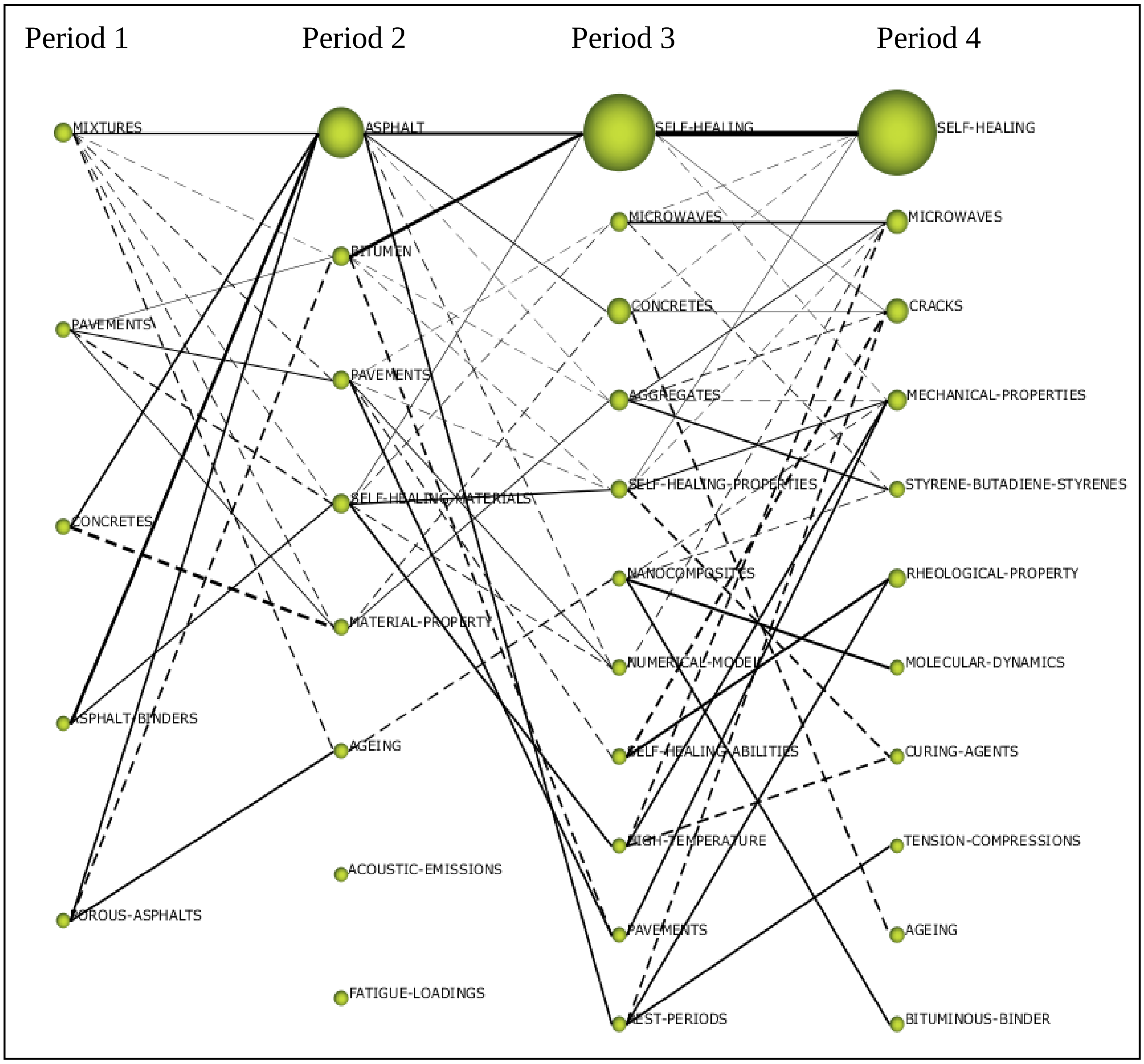

Figure 2.8 Thematic evolution map

2.4.2. Strategic diagrams and description of most important documents

Each thematic cluster is characterized by its calculated centrality and density, thus the strategic diagrams are plotted (Cobo et al., 2011a) as shown in Figure 2.9. Four kinds of themes are identified: motor themes (upper-right quadrant); highly developed and isolated themes (upper-left quadrant); basic and transversal themes (lower-right quadrant); and emerging or declining themes (lower-left quadrant). Analysis is made from the strategic diagrams (Fig. 2.9) and performance indicators for each cluster presented in Table 2.4, for each studied period. Also, the main outcomes of the most cited articles are noted.

2.4.2.1. First period (1994-2009)

According to the diagram presented in Figure 2.9, from the 20 publications analyzed, there were five research themes identified: asphalt-binders, pavements, mixture, porous asphalts, and concretes. One of them is a motor theme (pavements), two are basic and transversal themes (mixtures and concretes), and two of them are highly developed and isolated themes (asphalt binders and porous asphalt). Regarding the performance of each thematic cluster (Table 2.4), it can be appreciated that "pavements" is the most relevant cluster presenting the highest number of documents, h-index, and by far the largest number of citations.

During this period, 7 of the 10 most cited articles (Table 2.2) were published, including the first one "Fatigue and healing characterization of asphalt mixtures" by Kim, Little, and Lytton (Kim et al., 2003), with 201 citations .

Regarding to the most relevant works of this period, first, Lee & Kim (1998), successfully modeled damage accumulation under uniaxial tensile cyclic loading and microdamage healing during rest periods. Then, Bahia *et al*. (Bahia et al., 1999), while studying non-linear viscoelastic and fatigue properties of asphalt binders, found that rest periods showed a significant positive effect on recovery from accumulated fatigue damage. The authors stated that healing was the most probable mechanism explaining this phenomenon, and that this process depends on the composition of the asphalt and the type of modifiers. Kim *et al.* (Kim et al., 2003), showed, through dynamic mechanical analysis tests, that during rest periods healing is possible for sand-asphalt mixtures to extend their fatigue life. Finally, based on studies showing that self - healing during rest periods is increased with higher temperatures (Daniel and Kim, 2001), García *et al.* (García et al., 2009) investigated the effect of the addition of conductive fillers and fibers to sand asphalt mastic to enable heating asphalt mixtures with electromagnetic induction. The authors discovered that conductivity of these mixtures is highly dependent on the sand-asphalt ratio, and that the addition of conductive fibers is more efficient than adding fillers in order to reach the desired conductivity. Optimum conductivity is reached with fibers, but the optimum amount of fibers depends on various parameters such as type of aggregates, sand-asphalt ratio, length and thickness of fibers, and type of filler, among others. Lastly, it is stated in this work that even with a minimum content of conductive fibers, heating with electromagnetic induction is possible and that the heating ratio grows as the resistance increases. It is important to mention that García *et al.* (García et al., 2009) is one of the first studies regarding the development of a technique to augment the self-healing effect on asphalt mixtures by external heating. Hence, this period stablished the fundamentals for the development of self-healing asphalt techniques as an alternative maintenance technique for more sustainable pavements.

2.4.2.2. Second period (2010-2014)

According to the diagram presented in Figure 2.9, from the 62 publications analyzed, there were 8 research themes identified: asphalt, bitumen, pavements, acoustic-emissions, material-property, fatigue-loadings, self-healing materials, and ageing. Three of them are motor themes (asphalt, bitumen and pavements), two are basic and transversal themes (self-healing materials, ageing), two are highly developed and isolated themes (acoustic-emissions, material-property), and only one emerging or declining theme (fatigue-loadings). Regarding the performance measures, the “asphalt” cluster must be highlighted because it has the largest number of documents within the period (49), several times more than the second (7). Furthermore, it presents the greatest number of citations (1749) and the highest h-index (24) of all the periods analyzed. During this period the remaining three documents from the top 10 most cited were published, García (García, 2012) Liu *et al.* (Liu et al., 2010) and Al-Rub *et al.* (Al-Rub et al., 2010). On the one hand, some of the most cited articles belonging to this period, aim to explain or comprehend the self-healing phenomenon (Al-Rub et al., 2010; Bhasin et al., 2011; García, 2012; Shen et al., 2010) . Al-Rub *et al.* (Al-Rub et al., 2010), propose a model to predict micro-damage healing and a phenomenological healing equation for the evolution of the micro-damage healing internal state variable. This model was validated by comparing its predictions with experimental data. Shen *et al.* (Shen et al., 2010), studied binder healing through the analysis of dissipated energy recovery during dynamic shear rheometer testing with resting periods. The authors found that binder type, strain level, and temperature have an important impact on the healing achieved. Finally, García (García, 2012), the second most cited article of the entire data base analyzed with 188 citations, mentions that the existing theories to that date cannot explain fully the healing mechanism of asphalt pavements, thus the main objective of the author was to investigate this phenomenon. The healing capability as well as the healing process of a sand asphalt mixture with metallic fibers was studied, and the activation energy for flow and capillary flow were investigated. After a series of tests, the author finds first that the healing rate of asphalt mastic increases as the healing temperature increases. Then, the mastic´s mechanical resistance can be fully restored with sufficient healing time and heated at a certain temperature above the temperature in which asphalt begins to behave as a Newtonian fluid. Also, this article states that healing begins from the points of contact between the two faces of a crack. Lastly, as a result of the investigation, it can be mentioned that the Arrhenius equation can be used to predict the healing time at different temperatures, meaning that an activation energy defines the healing capacity of asphalt mastic, which also depends on the type of asphalt and aging level.

In this period, a great number of studies also began to explore different techniques or technologies to accelerate the process of self – healing, such as induction heating (Liu et al., 2011, 2010), microwave heating (Gallego *et al*., 2013) or microcapsules with rejuvenators (García *et al*., 2010). Liu *et al*. (Liu et al., 2010), folowing the steps of García *et al*. (García et al., 2009), studied the behavior of porous asphalt concrete with the addition of conductive fibers regarding conductivity, tensile strength, and self-healing capability through induction heating. Porous asphalt cylindrical samples were molded, and resistivity tests, indirect tensile test, microscope image analysis and induction healing tests were carried out. The results showed that steel wool was better than short steal fibers to make porous asphalt concrete electrically conductive, but the short fibers have a better strength reinforcement capacity. Also, the authors find that an optimum amount of steel wool exists (10% by volume unit of binder), which makes porous asphalt concrete conductive and enables a fast induction heating rate. The same authors one year later released another article in which they explain that fractured asphalt mastic beams containing steel wool can be completely healed multiple times through induction heating. In addition, it is shown that porous asphalt concrete with steel wool is more fatigue resistant than traditional porous asphalt concrete, and that fatigue damage can be not only completely but also rapidly healed by induction heating. This means that fatigue life of the pavement can be extended. As a result, traditional maintenance and reconstruction activities can be reduced, thus decreasing the amount of CO_2 emissions and energy consumption in pavement management activities (Liu *et al*., 2011).

Another way of extending asphalt pavement life is to counter the aging of the asphalt binder. Applying rejuvenators on the surface is a well-known technique, but with three main problems, difficulty to penetrate the pavement surface, the reduction of skid resistance and potential of environmental pollution. To solve these problems García *et al.* (García et al., 2010), proposed the introduction of micro capsules containing rejuvenators into the asphalt mixture. In their work, they propose an encapsulation system to incorporate asphalt binder rejuvenators into the mixture finding that the capsules can substitute part of the sand, also are resistant to high temperatures and tension being successfully mixed in porous asphalt concrete. So, by this addition the three previous mentioned complications can be addressed.

Towards the end of this analysis period, another self-healing technique emerges with promising results. Gallego *et al.* (Gallego et al., 2013), based on the previous knowledge that high temperatures during rest periods accelerate the healing process of asphalt concrete pavements, propose an alternative, the use of microwave heating. The researchers found that it is possible to heat asphalt concrete using microwaves, and that the amount of steel wool needed is only 10% of the amount needed for induction heating; finally, they found that the quantity of energy required for microwave devices is less than needed to produce the same effect with induction heating.

Worth mentioning is that up to this moment pavement sustainability was mentioned mainly as a motivation for the development of the self-healing technology. However, although not in the articles analyzed, Butt el *al.* (Butt et al., 2012), made a first approach to a life cycle assessment (LCA) of a self-healing pavement. The authors conclude that a better understanding of healing capacity of bitumen could lead to extending asphalt pavements life and as a result, have a significant impact on the energy consumption and environmental impacts during its life cycle.

To conclude, this was a period in which researchers continued to propose and validate models to understand the self-healing phenomenon, but at the same time, self-healing enhancing techniques started to be developed, mainly induction heating.

2.4.2.3. Third period (2015-2017)

According to the diagram presented in Figure 2.9, from the 103 documents analyzed, there were 11 thematic clusters identified: self-healing, microwaves, concretes, aggregates, self-healing properties, nanocomposites, numerical-model, self-healing-abilities, high temperature, pavements, and rest periods. From these themes, six are considered motor themes (self-healing, aggregates, concrete, microwaves, nanocomposites, and self-healing properties), and five emerging or declining themes (numerical-model, self-healing abilities, pavements, high temperature, and rest periods). Figure 2.9 shows that there are no highly developed and isolated themes or basic and transversal themes during this period. This fact, together with the increment in the number of documents per year during this period (Fig. 2.3), proves that 2015-2017 is a period of strong development of self-healing asphalt knowledge, growing from a new and unknown topic to a trending topic. Taking into account the performance measures (Table 2.4), the "self-healing" cluster shows its paramount importance, gathering 86 documents (83.5% of the period documents) and the second largest number of citations (1500) and h-index (22) of the four analyzed periods. As earlier noted, in this period many new themes emerge, which have little impact in terms of number of documents, h-index, or citations.

Regarding the most relevant works in this period, it should be noted that self-healing technique-related papers achieve a paramount importance with three of the six most cited documents, one comparing microwave and induction heating (Norambuena-Contreras and Garcia, 2016), another exclusively about induction healing (Menozzi *et* *al*., 2015), and finally an article about microcapsules (Su *et al*., 2015). However, there are also two articles regarding ageing and healing theory (Hou *et al*., 2014; Xu and Wang, 2017) and one is a state-of-the-art review (Ayar *et al*., 2016) showing that the self–healing asphalt theme at this point has reached a critical number of studies that deserve a summarizing review.

Menozzi *et al.* (Menozzi et al., 2015), followed the path of induction heating, researching the ability of this technique to heal fatigue damage. Marshall asphalt mixture specimens were prepared with 6% by volume of cast steel particles and exposed to fatigue through indirect tensile fatigue test, then induction heating was applied and the healing effect was evaluated by tomography scan tests and loading cycles to fatigue before and after heating process. This study results showed that, fatigue damage life can be extended up to 31% through induction heating, but healing occurs only in cracks of limited width. Thus, there exists an optimum moment to apply this technique when cracks are still thin enough to be healed. Also, authors found that there is a recommended temperature over which healing will not be as efficient; moreover, asphalt binder could be temperature damaged which could affect mixture's healing capacity.

Su *et al.* (Su et al., 2015), studied the self-healing mechanism of aged bitumen using microcapsules. The behavior, performance, and healing effect of microcapsules of prepolymer of melamine-formaldehyde modified by methanol, filled with dense aromatic oil as rejuvenator agent was observed. This research proved mainly that microcapsules can survive in hot bitumen, being stable, and consequently can be successfully used. Likewise, microcapsules are broken by microcracks releasing the rejuvenator, which enables capillary flow and fills the cracks. As a result, aged bitumen can recover its original properties. Finally, it was shown that a higher volume of microcapsules augments the speed of the rejuvenator's longitudinal movement.

As one of the first studies to compare two heating techniques in order to achieve self – healing, Norambuena-Contreras & Garcia (Norambuena-Contreras and Garcia, 2016), evaluate the self–healing performance of dense asphalt mixture with steel wool fibers through microwave and induction heating applied to samples tested multiple times on three point bending tests. Results showed that microwaves heat the asphalt binder, but using electromagnetic induction, heating can only be achieved through the presence of steel fibers. Additionally, it was observed that for the same surface temperature, microwave heating had better healing results than induction heating. Regarding the effect of multiple healing cycles, this study suggested that the healing rate decreases with every healing cycle; however, the healing reduction was less when microwaves were used. X-ray microtomography was used to evaluate changes in the sample's microstructure, which enabled the researchers to note that microwave heating changes the air voids structure inside the asphalt mixture. Induction heating did not change the number of air voids, but after heating, voids in a different position. The authors explained that these changes in the structure of the asphalt mixture could be one of the reasons behind the reduction of healing level in the successive heating cycles.

As mentioned earlier, Ayar *et al.* (Ayar et al., 2016), wrote a state-of-the-art review, analyzing the evolution until 2016 of this area of knowledge and described potential gaps in research. The authors noted that despite several techniques having been tested in the laboratory, researchers have to start testing these techniques at field scale. Then, they noted that one unified method should be defined to quantify the healing effect. Finally, it is stated that the practicality of induction heating should be evaluated in the field, based on life cycle assessment, together with its long-term effects on the pavement structure.

2.4.2.4. Fourth period (2018-2019)

According to the diagram presented in Figure 2.9, from the 107 documents analyzed, there were 11 research themes identified: self-healing, microwaves, cracks, mechanical-properties, styrene-butadiene-styrene, rheological properties, molecular dynamics, curing agents, tension-compression, ageing, and bituminous binder. Four of these are motor themes (self-healing, microwaves, molecular dynamics, and mechanical properties). Three can be cataloged as emerging or declining themes (aging, bituminous binder, and rheological properties). However, in this period, contrary to the third period, there are highly developed and isolated themes (tension-compression and curing agents) and basic and transversal themes (cracks, and styrene-butadiene-styrene). As a result, it appears that in this last period, deeper and more specific research has been done, showing more specificity and a growing interest and investment of resources in developing this area of knowledge. Regarding the performance measures, four thematic clusters must be mentioned for their values: self-healing, microwaves, cracks, and mechanical properties. The first contains 97 documents (90.6% of the total of the period) as well as the highest h-index (9) and citations (355) of the fourth period. The other three are in a lower level (average of 12 documents, citations between 36 and 71, and average h-index 4). To finalize, it also should be noticed that in this period, as well as in the third, several small and more specific clusters have appeared.

With regard to the most cited articles of this fourth period, in agreement with what is stated above, self–healing technique related articles prevail over the development of healing mechanism models. In this period, Sun *et al.* (D. Sun et al., 2018), published the most cited article, in which the researchers used modeling, simulation, and laboratory tests to learn about the microscopic process of self-healing and to study the influence of temperature in this process. However, the majority of the published work in this period is related to capsules containing rejuvenators (Al-mansoori *et al*., 2018; Xu *et al*., 2018), induction heating (Lizasoain-arteaga et al., 2019), comparing microwave and induction heating (Y. Sun *et al*., 2018), and with notorious importance on microwave heating (González *et al*., 2018c; Jahanbakhsh *et al*., 2018) as shown in the strategic diagram (Fig. 2.9).

Sun *et al.* (D. Sun et al., 2018), through molecular dynamics simulation and the usage of Dynamic Shear Rheometer based fatigue-healing-fatigue test, verified that self-healing is directly related to temperature, and that a higher temperature will allow a larger molecular diffusion rate and range. This diffusion rate results in a higher level of healing at higher temperatures, where full healing can be achieved. Finally, the authors noted the existence of an optimal healing temperature because low temperatures do not allow full recovery and too high temperatures might result in permanent deformation. This optimal temperature is near to the phase transition temperature as was previously stated by other researchers.

Regarding to the encapsulated rejuvenators technology, Al-Mansoori *et al.* (Al-mansoori et al., 2018) and Xu *et al.* (Xu et al., 2018), studied the inclusion of calcium alginate capsules with rejuvenator agents in asphalt mastic mixtures, testing the behavior of these capsules within the mixture and the effect on self-healing. Both studies show that using these capsules is plausible as they have the ability to resist heating and mixing processes, mainly being broken by external stress produced by cracking of the asphalt mastic mixture. Also, these works confirmed that healing levels in asphalt mastic samples with the presence of microcapsules were higher than in samples without them. Additionally, healing levels depended on rejuvenator concentration inside the capsules as well as the temperature at which the healing occurs (Al-mansoori *et al*., 2018). To conclude, Xu *et al.* (Xu et al., 2018) affirm that there is an optimum dosage of capsules that must be determined in future research. Moreover, they stated that this technique could be used together with induction heating, counteracting its aging effect on asphalt binder.

Although not in the data base analyzed, it is worth mentioning that following this last recommendation, Xu *et al.* (Xu et al., 2020) recently found that it is possible to successfully mix these two technologies, applying them to porous asphalt concrete mixture. The results of their experiments prove that induction heating and the inclusion of microcapsules with rejuvenator agents have a synergic effect, resulting in higher healing levels than the ones achieved by these techniques applied separately.

Once again in this period, microwave and induction heating were compared for instance by Y. Sun *et al.* (Y. Sun et al., 2018). In this case, the ability of these techniques to be utilized under snowy and freezing conditions were contrasted. Researchers found that self-healing asphalt pavement (containing steel fibers) under the effect of induction or microwave heating improved significantly their ice and snow melting performance, even compared with the results with pipe heating systems. However, the healing results during the melting process were poor due to the presence of water on surface of the cracks; thus, the researchers suggested using a second heating stage after melting to achieve good healing results.

During this period, microwave heating continued its development as a self – healing technique. Jahanbakhsh *et al.* (Jahanbakhsh et al., 2018), addressing steel wool fibers' negative effects on the asphalt mixture, such as increment of air voids resulting in less durability and uneven distribution in the mixture leading to uneven heating, proposed an alternative. The authors suggested that modifying the asphalt binder with carbon black instead of adding steel wool fibers could bring some benefits to asphalt mixtures, for instance, more rutting resistance, and oxidation ageing resistance together with the microwave heating self - healing ability. This study's results showed that carbon black can augment the conductivity and sensitivity of asphalt mixture to electromagnetic radiation, and that microwave heating rates of carbon black modified asphalt concrete mixtures are between 25% and 47% higher than unmodified asphalt concrete mixtures. Also, carbon black can improve rheological and mechanical performance of asphalt concrete. In addition, the authors found that, as in other cases, the healing ratio decreases with the successive healing cycles, and, last but not least, carbon black modified asphalt in quantities more than 10% by weight of binder could reduce low temperature cracking resistance.

On the other hand, González, Norambuena-Contreras, *et al.* (2018c), in an effort to achieve a more sustainable technology, tested microwave heating on a hot asphalt mixture including RAP and metal shavings (a waste material from the metal industry) instead of steel fiber wool. They proved that despite having a more irregular shape than traditional steel wool fibers, which results in an increment of air voids inside the mixture, metal shavings are also useful to produce self-healing asphalt mixtures. Also, their research results showed that even though the inclusion of RAP reduces the healing effect, asphalt mixtures including RAP and metal shavings have the potential to be healed through microwave heating as an alternative to achieve environmentally sustainable pavements. Finally, the authors acknowledge that responsible LCA and life cycle cost analysis (LCCA) should be carried out in order to support that conclusion. In this way the authors brought awareness about the lack of these previously mentioned analyses, which can truly prove the sustainability of self-healing techniques.

In agreement with this previous statement, finally Lizasoain-Arteaga *et al.* (Lizasoain-arteaga et al., 2019), did a LCA study for a self-healing asphalt pavement, where induction heating was included as an activity part of the maintenance strategy. In this work, researchers compared the environmental performance of a traditional asphalt mixture pavement maintained with traditional techniques (mill and overlay) against a self-healing asphalt mixture pavement (including steel fibers) maintained with induction heating and eventually mill and overlay. The LCA functional unit was defined as 1 km of a two lane per direction road, the analysis period was 30 years including production of materials, construction, use and end-of-life stages. After completing the life cycle inventory with information from various sources, a hierarchical characterization method was used to calculate the environmental impacts. The results showed that induction heating is a fast and less intensive maintenance technique that minimizes traffic disruption. Also, they found that in 12 of 17 midpoint impacts analyzed induction heating technique had a better performance than traditional maintenance. Moreover, the positive effects of pavement life extension and lack of maintenance activities were far more significant than the negative effects of the production of the steel fibers needed to elaborate the self-healing pavement. Hence, positive results were achieved in the three end point impacts studied (damage to human health, damage to ecosystem diversity, and damage to resource availability).

Overall, in this period not only was asphalt healing mechanisms theory developed, but the three main self-healing enhancing techniques (induction and microwave heating and the use of microcapsules filled with rejuvenating agents) were extensively studied. It should be noted that also during this period environmental sustainability went from being only a motivation to a topic of research itself, wherein researchers through LCA try to prove whether self-healing is truly a plausible alternative to achieve sustainable asphalt pavements.

2.4.2.5. Most recent publications (2020)

Numerous articles were published after the fourth period of analysis, in 2020. The microcapsules technique took more relevance in 2020 with numerous publications (Gonzalez-Torre and Norambuena-Contreras, 2020; Li et al., 2020; Shu et al., 2020; Tian et al., 2020; Zaremotekhases et al., 2020). Also, Norambuena-contreras et al. (2020), studied the potential use of bio-oils obtained from liquefied agricultural biomass waste as encapsulated rejuvenating agents. The authors found that the self-healing effect is achieved and that capsules show adequate morphology and stability for self-healing asphalt mixtures. In addition, Li et al. (2020), investigated the survival and activation behavior of microcapsules in self-healing asphalt mixtures. The authors studied the key factors for the success of microcapsules concluding that microcapsules size and mixing temperature are critical for their survival, recommending further research on the type and thickness of the capsule shell suggesting that the optimization of the microcapsules would enable future mass production and field implementation. Lastly, other types of encapsulation were studied as explained by Gonzalez-torre and Norambuena-contreras (2020). For instance, Zaremotekhases et al. (2020) analyzed the effects of sodium alginate fibers containing rejuvenator agents on the cracking of asphalt mixtures, showing that self-healing was achieved and also the resistance to cracking and rutting increased.

In 2020, several articles on the microwave and induction heating techniques for self-healing were published. Some continued the investigation on different additives to enhance self-healing capability such as ferrite, fly ash and steel slag (Atakan, 2020; Concretes, 2020; Karimi et al., 2020a; Zhu et al., 2020). Others studied the influence of the mixture components, such as aggregates (Trigos et al., 2019) finding that andesite and ophite are highly susceptible to microwave heating while limestone and quartzite are not very susceptible. Also, Jahanbakhsh et al (2020) studied the bitumen rheological properties in self-healing asphalt mixtures, showing that zero shear viscosity is a key characteristic to achieve heating self-healing. Another relevant topic addressed was the effect of moisture and freeze-thaw damage on microwave healing of asphalt mixtures (Kavussi et al., 2020). The authors analyzed the effect of cracking temperature, moisture, and freeze-thaw damage on the healing capability of the mixture, and found that low temperature cracking reaches a higher level of healing than intermediate temperature cracking. In addition, moisture and freeze-thaw damage cycles decreased the microwave healing capability of asphalt concrete. It is important to mention that researchers started to question if the methods to evaluate the self-healing of asphalt mixtures are accurate. For instance, Karimi et al. (2020b), proposed a novel energy-based approach to compare induced heating capability of different asphalt concretes. Finally, a new literature review was published towards the end of 2020 (Liang et al., 2021), in which the self-healing techniques, the healing mechanisms, and the critical factors affecting the self-healing of asphalt materials were reported.

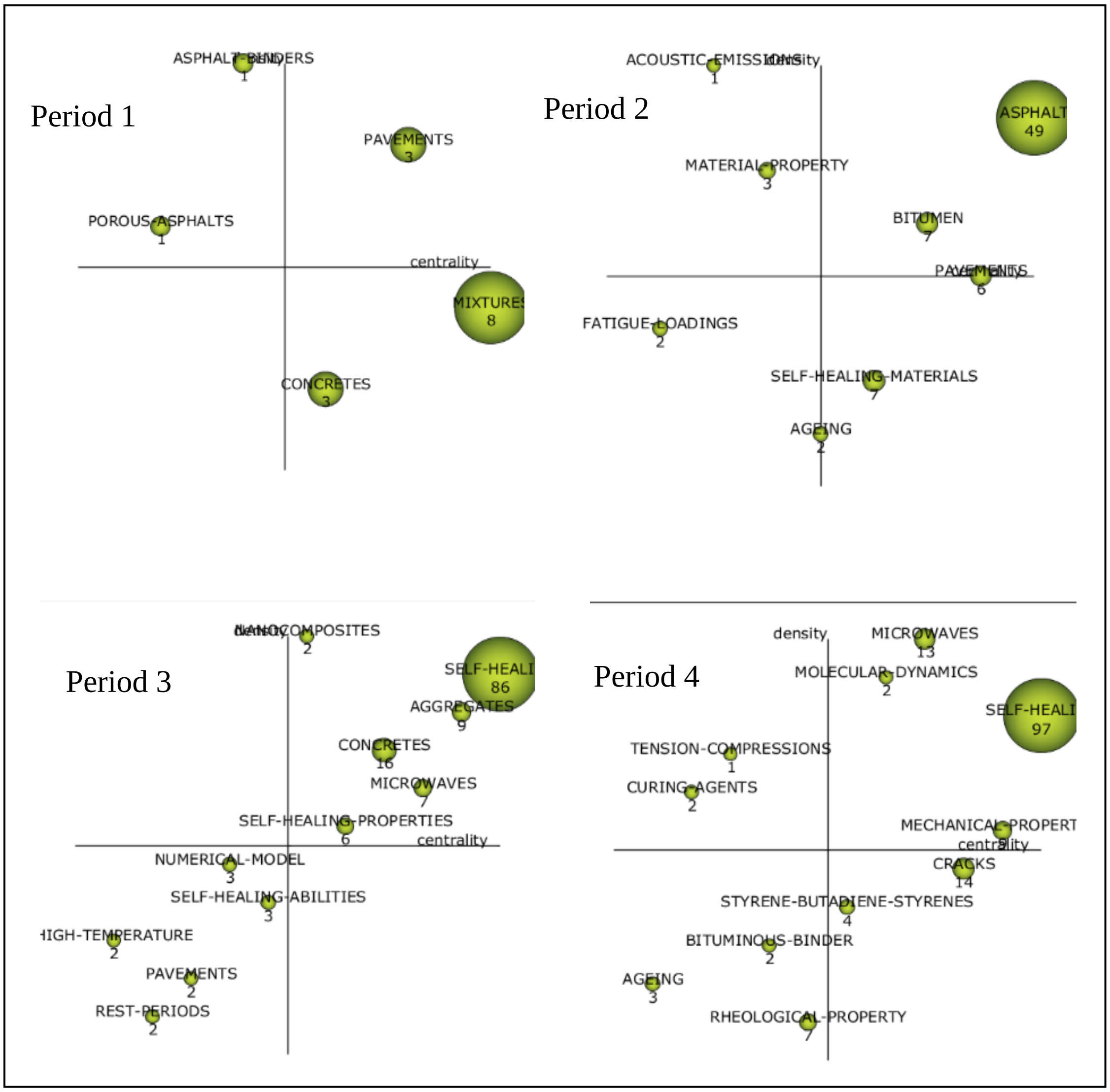

Figure 2.9 Strategic diagrams by period

Table 2.4 Performance analysis of themes clusters by period

Cluster	N° of documents	N° of citations (29/10/19)	h-index	Centrality	Density
1st period (1994-2009)					
Mixtures	8	648	7	80.43	53.39
Pavements	3	333	3	36.13	135.83
Concretes	3	220	3	29.25	27.31
Asphalt-binders	1	38	1	16.00	150.00
Porous-asphalts	1	10	1	10.00	100.00
2nd period (2010-2014)					
Asphalt	49	1749	24	151.34	62.35
Bitumen	7	250	7	70.67	41.02
Pavements	6	119	5	89.55	36.25
Self-healing-materials	7	317	7	64.97	27.16
Material-property	3	143	3	25.28	58.33
Ageing	2	77	2	38.26	25.00
Acoustic-emissions	1	15	1	5.57	100.00
Fatigue-loadings	2	17	2	2.15	33.33
3rd period (2015-2017)					
Self-healing	86	1500	22	174.41	68.98
Microwaves	7	108	7	56.97	41.52
Concretes	16	199	9	55.79	41.90
Aggregates	9	117	6	69.42	48.65
Self-healing-properties	6	115	6	48.29	33.26
Nanocomposites	2	51	2	34.10	92.86
Numerical-model	3	37	3	29.82	32.50
Self-healing-abilities	3	63	3	33.81	29.17
High-temperature	2	31	2	7.90	22.22
Pavements	2	10	2	11.41	13.33
Rest-periods	2	44	2	11.23	12.50
4th period (2018-2019)					
Self-healing	97	355	9	180.29	52.73

Microwaves	13	71	5	51.27	80.95
Cracks	14	36	3	81.47	22.77
Mechanical-properties	9	48	3	96.70	30.48
Styrene-butadiene-styrenes	4	21	4	36.28	22.52
Rheological-property	7	19	2	32.40	10.62
Molecular-dynamics	2	3	1	39.46	54.00
Curing-agents	2	4	2	7.10	33.33
Tension-compressions	1	5	1	9.87	33.33
Ageing	3	7	2	6.16	20.00
Bituminous-binder	2	8	1	14.12	22.22

2.4.3. Thematic network

Finally, the thematic network of each keyword cluster can be analyzed. Figure 2.10 presents the thematic network of the self-healing theme corresponding to the last period, which is, as mentioned earlier, the most relevant thematic cluster of the 2018-2019 lapse. This graph represents the network formed by all the keywords grouped in a cluster and the strength of their bounds.

Four main keywords can be identified: asphalt, self-healing materials, asphalt mixtures, and mixtures. These words, despite having a strong link with self-healing, also show thick linking lines among each other; for example, mixtures and asphalt mixtures, and asphalt and self-healing materials. Furthermore, minor keywords inside this graph are strongly linked as well, such as bitumen and bituminous materials, asphalt and self-healing properties, microcapsules and asphalt and self-healing properties, and fibers and bituminous materials. As a result, it appears that the self-healing theme according to the definition given in Cobo *et al*. (Cobo et al., 2011a) presents great internal strength, thus a high density, showing its high level of development.

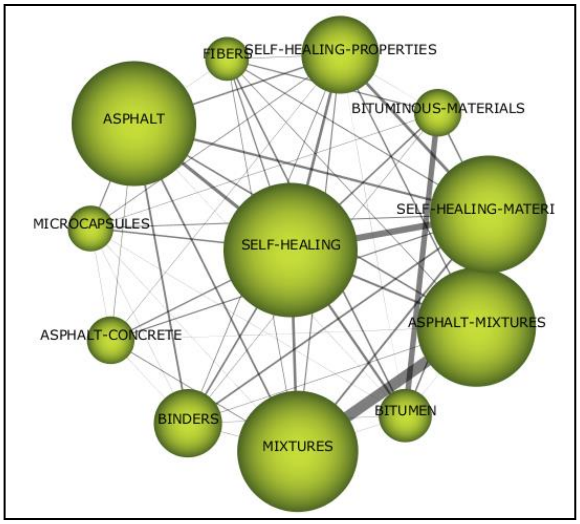

Figure 2.10 Thematic network "self-healing" of fourth period (2018-2019)

2.5. Conclusions

This article presents the scientific evolution of self-healing asphalt materials through a performance and science mapping analysis of a total of 292 articles retrieved from SCOPUS and WOS. Also, the most cited articles of each analysis period were reviewed. From the analysis, the following conclusions can be drawn:

- The production of documents related to self-healing has been growing since 1994. In particular, since 2015, this number has dramatically increased, reaching a peak in 2020 of 63, although the articles were counted only until August 2020.
- China and the USA have an outstanding performance in the production of documents followed by the Netherlands, UK, Spain, and Chile. Nevertheless,

Europe is the continent with the largest number of countries active in the development of this area of knowledge.

- The most productive authors in the topic of study are Wu, S.P., Little, D.N., Lytton, R.L., as well as Garcia, A. The journal *Construction and Building Materials* is the journal with the highest number of articles on the topic.
- The science mapping analysis shows that an increasing development of self-healing pavements research is noticeable. In addition, new research areas are more specific, and particularly linked to new techniques and technologies such as microwave heating, nanocomposites, and microcapsules.
- From 1994 to 2015, researchers were developing self-healing knowledge. However, predominantly from 2015, research themes became more specific and related to self-healing and the healing ability of asphalt mixtures were studied as an opportunity to achieve sustainable pavements, enhancing their service life through diverse self-healing promoting techniques.
- Numerous studies have been done to understand self-healing phenomena and to develop self-healing techniques in the laboratory. In addition, research proved that these techniques reduce the consumption of natural resources and emission of GHG among other positive effects on environmental impacts, allowing self-healing techniques to be an alternative to achieve a sustainable road infrastructure.
- Future research should deepen on the optimization of self-healing techniques, link the laboratory findings to the field behavior of asphalt concrete pavements

and thus provide tools to design pavement maintenance strategies in order to conduct comprehensive LCA studies.

- Overall, this research has shown that self-healing asphalt pavements have been catching the interest of many researchers in recent years; hence, there are many techniques and areas that are being developed and expanding the branches and different niches in this research area. Therefore, opportunities for researchers to work in this field are still growing and developing, and this research is also far from reaching a stage of maturity.

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3. ASSESSMENT OF SELF-HEALING ASPHALT PAVEMENT FATIGUE LIFE USING ANALYTICAL JC APPROACH AND LABORATORY RESULTS

A paper submitted to the journal Construction and Building Materials

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Abstract

Self-healing asphalt pavements are an alternative sustainable road infrastructure. Through a literature review and laboratory tests, authors aim to develop a methodology to study the efficiency of asphalt pavement self-healing techniques, giving pavement managers a valuable tool to establish maintenance strategies. Results show that commonly used Healing Indexes could overestimate the effectiveness of self-healing techniques. A novel methodology using the semicircular bending test and the fracture mechanics parameter Jc is proposed to estimate pavement fatigue life extension when self-healing techniques are applied. Following this novel methodology, results show that microwave heating of conventional asphalt achieved a 20% fatigue life extension.

3.1. Introduction

Facing the threat of climate change resulting from the increase in greenhouse gases (GHG) emissions (IPCC, 2007), various initiatives have emerged to mitigate its effects, as well as to prevent it from continuing to deepen. Road transport is a sector with broad responsibility in the generation of GHG (Egis, 2010; European Commission, 2014). In particular, the construction and maintenance of roads is responsible for more than 13% of the worldwide emissions related to construction (Mukherjee & Cass, 2012).

Pavement is the central element of the road infrastructure that requires maintenance. Thus, techniques have been developed to make pavements more sustainable, such as the use of sustainable materials (Plati, 2019), recycling on site (A. González et al., 2010), developing and using long-lasting pavements, and recycled and stabilized granular materials (A. González, Chamorro, et al., 2018), using porous concrete pavements (Elizondo-Martínez et al., 2020), and developing self-healing techniques (García, 2012; Tabaković & Schlangen, 2016). Asphalt is the most widely used material for paving worldwide (A. González, Norambuena-Contreras, et al., 2018a): for instance 90% of paved roads in China (Sultan & Guo, 2016), 92% in the US, and 90% in the European Community (EAPA & NAPA, 2011) are built with asphalt materials. Therefore, it is important to study and develop techniques and materials with less environmental impact. Self-healing asphalt pavements recover their mechanical properties under specific conditions slowly and progressively (Little & Bhasin, 2007). Enhancing this ability to obtain faster healing results and achieve a greater recovery of the original properties would reduce the use of raw materials, traffic congestion, and greenhouse gas emissions resulting from maintenance (Tabaković & Schlangen, 2016). The most recent self-healing techniques for asphalt mixtures include the incorporation of microcapsules with binder rejuvenating agents (Gonzalez-torre & Norambuena-contreras, 2020; Lv et al., 2016; Su et al., 2015; D. Sun, Li, et al., 2018) and external heating by means of electromagnetic induction (Apostolidis et al., 2016; Liu et al., 2010) or microwaves (Gallego et al., 2013; A. González, Norambuena-Contreras, et al., 2018b; Trigos et al., 2019). The joint effect of these techniques has been studied, showing excellent synergistic potential (Xu et al., 2020).

The knowledge production in this area has been growing in recent years, reaching a record in the number of indexed scientific publications in 2020 (Nalbandian et al., 2021). In recent decades, research evolved from understanding the fundamentals and factors that affect the phenomenon of self-healing to studying the effectiveness of self-healing techniques that seek to enhance this phenomenon. However, the majority of these published studies are based on the analysis of laboratory experimental results; with few exceptions, these studies do not clearly show the potential positive effect of self-healing techniques in the field (Nalbandian et al., 2021). One of these exceptions is the investigation by Lizasoain-Arteaga et al., 2019 (Lizasoain-Arteaga et al., 2019), in which a Life Cycle Analysis (LCA) is carried out to demonstrate the sustainability of induction healed asphalt mixtures developed in the HEAL-ROAD project. In this case, laboratory data and multiple databases were used in addition to field data collected from the construction of a pilot section where an induction heater prototype was used. Literature shows that there are two possible methods to validate the effectiveness of such novel pavement techniques: full-scale accelerated testing of asphalt pavements, or long-term testing of trial sections. The main drawback of both of these methods is the large amount of resources required in addition to the testing time required to obtain reliable results (Alvaro González et al., 2012).

The literature review on self-healing asphalt mixtures indicates that studies focus on the comparison between the strength of mixes before and after healing. However, few studies have focused on the effect of the healing process on the fracture energy or resistance to cracking (Fan et al., 2018; Jahanbakhsh et al., 2018), which would allow the prediction of pavement fatigue life and performance.

This work aims to identify a material parameter obtained from simple laboratory tests using analytical methods that are performed on asphalt mixtures to estimate the fatigue life of self-healing asphalt pavements in the field. The results of this study can be used to estimate the benefits of adopting self-healing materials based on the fatigue life of asphalt pavements and to define maintenance strategies that include self-healing techniques such as microwave external heating, as further detailed in this article.

3.2. Crack healing, fracture toughness indicators, and Jc

Various models attempt to explain the phenomenon of fatigue cracking and self-healing of asphalt materials. These models are based on different theories and explain the phenomenon of self-healing at different levels such as nano or micro cracks (10^{-9} to 10^{-6} m), meso cracks (10^{-4} m), and macro cracks, which are visible to the human eye. The latter can also be classified into cohesive cracks (cracks in the asphalt or mastic) and adhesive cracks (at the mastic - aggregate interface). Regarding the self-healing process, molecular diffusion, surface energy (for micro and nano cracks), and capillary flow (for macro cracks) models can be mentioned (D. Sun, Sun, et al., 2018). These models explain the healing phenomenon for the different crack sizes based on the properties of the asphalt mixture and its components.

Darabi, Al-rub, & Little, 2012 (Darabi et al., 2012) developed a mathematical model to describe the healing process of cracks in asphalt mixtures. They proposed the following equation to describe the healing rate:

$$\dot{h} = \Gamma(1-\varphi)^{a}(1-h)^{b} \qquad (1)$$

where $\dot{\boldsymbol{h}}$ is the healing rate, $\boldsymbol{\varphi}$ is the damage density representing the proportion of the damaged area (healed and not healed) over the total surface, h is the level of healing as the fraction of the healed area over the damaged area, and **a**, **b, Γ** are material properties. This model shows the recovery rate decreases as the density of damage, and, therefore, the damaged (cracked) area increases.

Fracture mechanics studies the generation and propagation of cracks. To describe the cracking behavior of materials, three critical parameters are measured experimentally. These include: the stress intensity factor Kc, based on the intensity of the stress; the rate of release of energy Gc or J-integral (Jc) based on the concepts of energy release and consumption; and the Crack-Tip Opening Displacement (CTOD (δ_c)) based on the correlation between the resistance to fracture and the crack tip geometry (S. Tang, 2014). Each of these fracture parameters are appropriate for analysis according to the mechanical behavior of the material (linear elastic or elasto-plastic) and the size of the cracked area.

Tang, 2014 (S. Tang, 2014), analyzed in detail which of the three critical parameters mentioned above is more suitable for describing cracking in asphalt mixtures. Particularly, the author shows that J-integral and CTOD have a greater range of application as parameters that describe cracking behavior and are applicable to analyze materials with linear elastic or elasto-plastic behavior with small or large-scale deformations. Zhu & Joyce, 2012 (Xian-kui Zhu & Joyce, 2012), had previously indicated that in the case of asphalt mixtures subjected to intermediate temperatures, J-integral and CTOD are the most appropriate choices. Additionally, due to their elasto-plastic or viscoelasto-plastic nature, linear elastic models do not correctly describe the behavior of asphalt mixtures, and the J-integral concept is the most appropriate for the modelling of asphalt cracking. In addition, several authors have used J-integral to study the propagation of fatigue cracking in asphalt mixtures, proving that it is possible to use this J-integral or characterize cracking behavior (M.A. Mull et al., 2002; Mary Ann Mull et al., 2005) .

The concept of the J-integral was initially proposed by Rice, 1968 (Rice, 1968) and consists of a mathematical expression (Eq.2) referring to a homogeneous body subjected to a two-dimensional field of deformations (plane) so that all the stresses $\boldsymbol{\sigma_{ij}}$ are expressed in two Cartesian axes x and y, being x parallel to the flat faces of the crack (Fig. 3.1). This expression represents the contour or surface integral around the tip of the crack from one side of the crack to the other in a counterclockwise direction. Rice shows that this integral is independent of the path and enables study of the field of deformations and stresses around the crack.

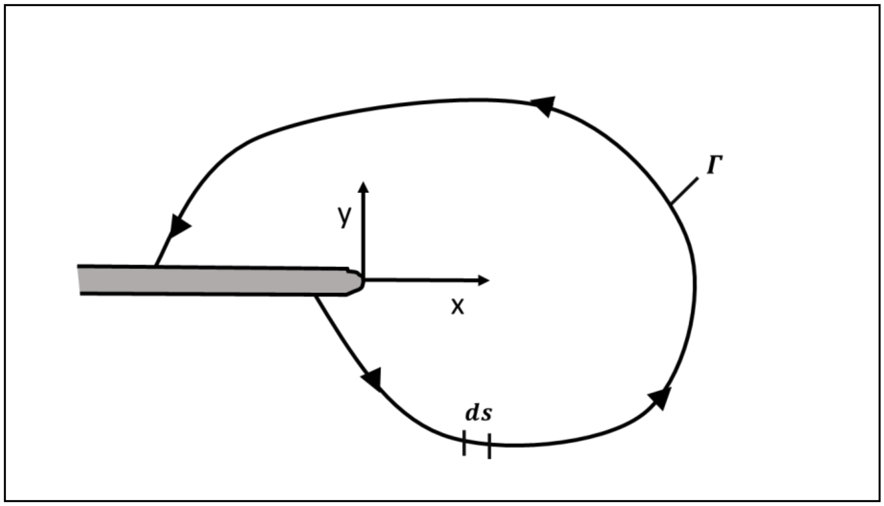

Figure 3.1 Arbitrary contour around the crack tip used in the definition of the J-integral

Rice´s proposed expression was:

$$J = \int_{\Gamma} \left(w dy - T_i \frac{\partial u_i}{\partial x} ds \right) \qquad (2)$$

Where

w= strain energy density

T_i= components of the traction vector

u_i= displacement vector components

ds=length increment along the contour Γ

The strain energy density is defined as:

$$w = \int_0^{\varepsilon_{ij}} \sigma_{ij} d\varepsilon_{ij} \qquad (3)$$

where $\boldsymbol{\sigma_{ij}}$ y $\boldsymbol{\varepsilon_{ij}}$ are stress and strain tensors, respectively.

The components of the traction vector representing the stress acting on the edges of the element surrounded by $\boldsymbol{\Gamma}$ in the case of making a free-body diagram, are calculated at each point as

$$T_i = \sigma_{ij} n_j \qquad (4)$$

With $\mathbf{n_j}$ components of a unit vector normal to $\boldsymbol{\Gamma}$.

Rice showed that this expression represents the rate of released energy or work done per unit fracture surface area in a non-linear elastic body containing a crack (Xian-kui Zhu & Joyce, 2012).

Based on Rice´s and other authors´ work (Begley & Landes, 1972), it can be stated that the J-integral can be interpreted as the difference of potential energy between two bodies identically loaded with neighboring crack sizes. This can be expressed mathematically by thickness unit by the following equation:

$$J = -\frac{\partial U}{\partial l} \qquad (5)$$

Where **U** is the potential energy and ***l*** the crack´s length in a plain body situation (Begley & Landes, 1972). Generalizing for a body of thickness **B**, then the equation results:

$$J = -\frac{1}{B}\left(\frac{\partial U}{\partial l}\right) \qquad (6)$$

Where **U** is represented by the area below the force vs. displacement curve (Fig. 3.2a). The parameter Jc is defined as the critical value of the J-integral and considers the energy until failure or the critical strain energy release rate, that is, when the peak is reached in the force vs. displacement curve (Fig. 3.2a). This concept (Jc) is pointed out by Wu et al., 2005 (Wu et al., 2005) as an indicator of the fracture resistance of asphalt mixtures, and, in particular, of the initiation of cracking (S. Tang, 2014).

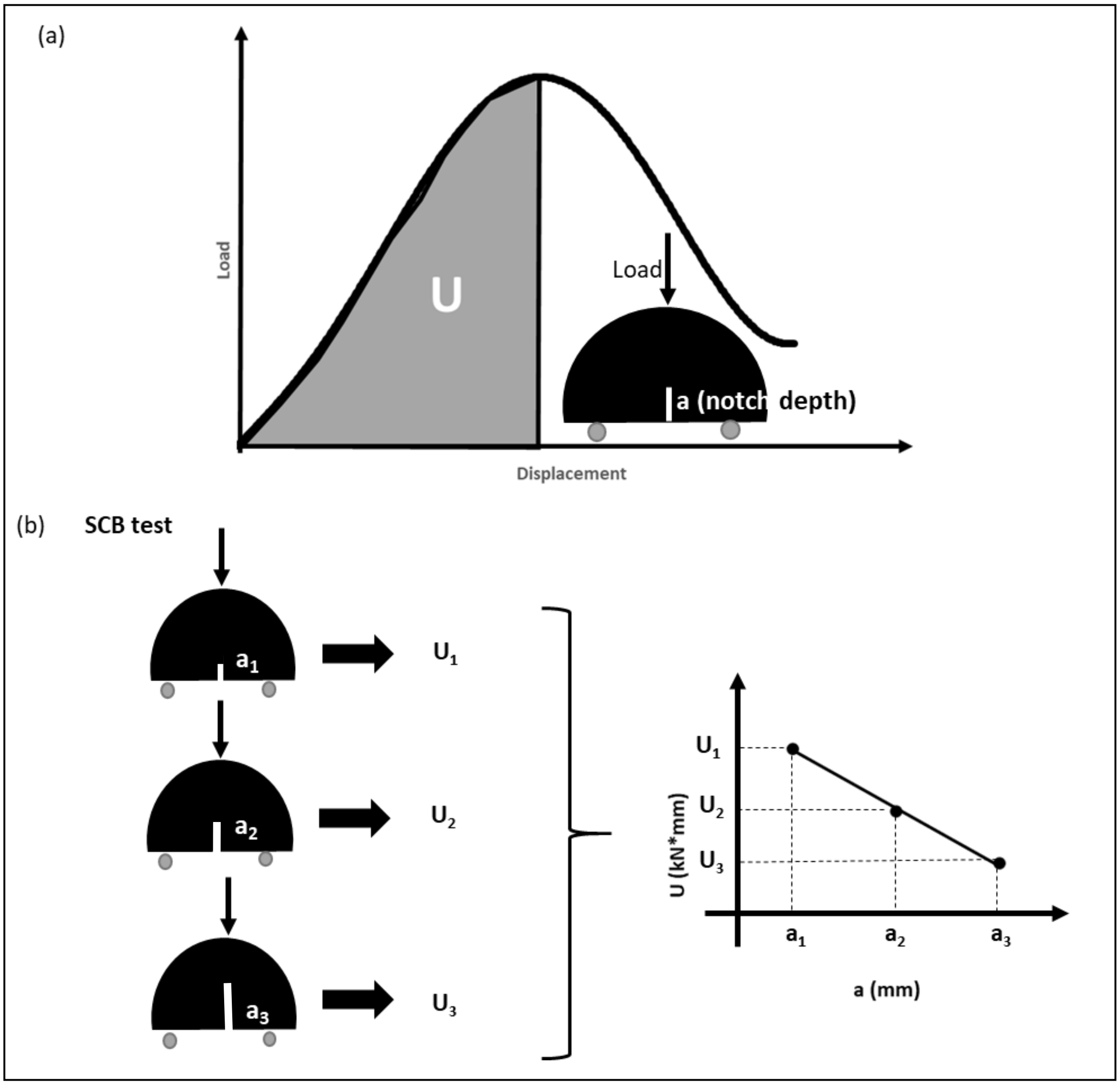

Figure 3.2 (a) Load vs displacement curve, value of U correspondent with Jc/ SCB test sample, **(b)** SCB test method for Jc

The value of the J-integral can be estimated by applying the definition of the Rice contour integral, but it is usually difficult to instrument the asphalt sample in order to obtain all the necessary measurements. Also, it can be obtained through analysis with finite element models (Anderson, 2005). However, researchers have sought an experimental laboratory method that enables easily obtaining this J-integral value for asphalt mixtures, through studying the cracking resistance of asphalt mixtures from the bending test of semicircular specimens (SCB) (Elseifi et al., 2012; L N Mohammad et al., 2004; M.A. Mull et al., 2002; Mary Ann Mull et al., 2005; Wu et al., 2005). Originally used in rock mechanics (Kim et al., 2012), this method consists in applying equation (6) as follows:

$$Jc = -\frac{1}{B}\left(\frac{\partial U}{\partial a}\right) \qquad (7)$$

Where **Jc** is the critical strain release rate (kJ / mm^2), **B** is the thickness of the specimen (mm), **a** is the notch depth (mm) (Fig. 3.2a), **U** is the energy of deformation until failure (area under the curve force - displacement to the peak) (Fig. 2a) and $\frac{\partial U}{\partial a}$ is the variation of strain energy with the notch depth. The methodology proposed by the authors then consists in performing the SCB test for at least three different notch depths, calculating **U** and making the **U** vs **a** graph, from which through a linear regression the value of $\left(\frac{\partial U}{\partial a}\right)$ can be estimated (Fig. 3.2b).

3.3. Laboratory tests to quantify healing performance and healing index

3.3.1. Definition of healing index and healing performance tests

In the last decade, researchers have developed laboratory tests to evaluate the effectiveness of various self-healing techniques. The most common method to assess healing performance is by healing indexes (HI) that relate a mechanical property of a mixture before damage and the same mechanical property after damage and i-th cycles of healing. The HI is normally expressed using the general equation form:

$$HI_i(\%) = \frac{\zeta_i}{\zeta_0}.100\% \qquad (8)$$

Where HI_i is the healing index after the i-th cycles of damage and subsequent healing, ζ_0 is the value of the mechanical property measured on an undamaged test sample, and ζ_i is the same mechanical property measured after the i-th cycles of damage and subsequent healing (see example on semicircular bending samples in Fig. 3.3).

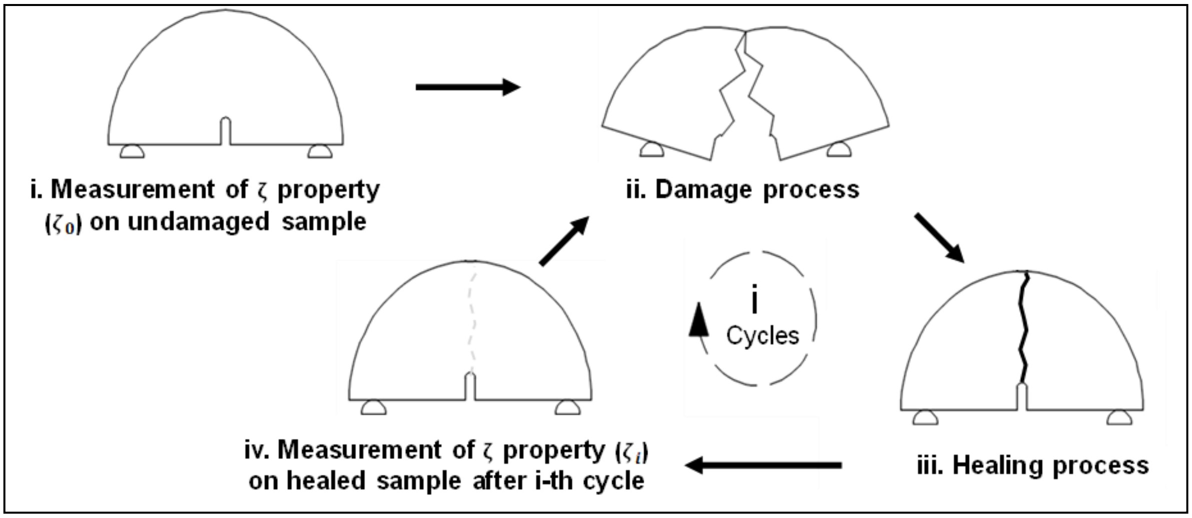

Figure 3.3 Example of testing sequence for the measurement of the healing index in semicircular bending samples

For the modelling of pavement field cracking, researchers have proposed two phases based on experimental observations (de Solminihac et al., 2018). The first is the initiation phase, in which the surface cracked area is less than 0.5%, and the second is the progression phase in which cracking increases steadily from 0.5% up to 100%. Laboratory tests aim to study the behavior of asphalt mixtures in the two phases of pavement cracking (Fan et al., 2018). For example, the fatigue three-point bending test (FTPB), which relates the applied stress or strain applied with the number of loading up to material failure, simulates the fatigue crack initiation of the mixture. Conversely, fracture tests such as the semicircular bending test (SCB) or the disk shape compact tension test (DCT) are used to study the propagation of cracking from an initial crack (Fan et al., 2018). From the literature review made by the authors, the used tests can be grouped in two: cyclic load tests and monotonic load tests (A. González et al., 2019; Liu et al., 2012; Vo et al., 2020; Xiang et al., 2020; Xu et al., 2020; Xingyi Zhu et al., 2019).

3.3.2. Cyclic loads tests

Recently, various authors (Garcia et al., 2020; Xiang et al., 2020; Zhao et al., 2017; Xingyi Zhu et al., 2017) have used the FTPB and the fatigue four point bending test (FFPB), respectively, to study the fatigue performance of asphalt mixtures after self-healing. From these tests, HIs were developed considering the fatigue life extension (Eq. 9) or the ratio between stiffness modulus (Eq. 10):

$$HI_N = \frac{N_2}{N_1}.100\% \qquad (9)$$

$$HI_s = \frac{(S_2 - S_S)}{(S_1 - S_S)}.100\% \qquad (10)$$

Where HI_N is the healing index related to the extension of fatigue life, N_1 is the number of loading cycles until reaching the fatigue condition of the new beam sample and N_2 is the number of loading cycles until fatigue after the healing process. In addition, HI_s is the healing index related to the stiffness modulus, S_1 is the initial stiffness modulus (stiffness at the end of the 50th loading cycle for the new beam), S_S is the stiffness when the new beam reaches the fatigue condition and S_2 is the initial stiffness of the healed beam (at the 50th loading cycle).

Another way to quantify the healing achieved through self-healing techniques with the FFPB (H. Wang et al., 2020) is the ratio of the areas under the stiffness modulus vs. loading cycles curves (Fig. 3.4, Eq. 11). This perspective combines the extension of the fatigue life with the evolution of the stiffness modulus (it is considered that fatigue is reached when the stiffness modulus is reduced to 50% of its initial value (H. Wang et al., 2020)).

$$HI_{area} = \frac{A_p}{A_p + A_{after}} . 100\% \qquad (11)$$

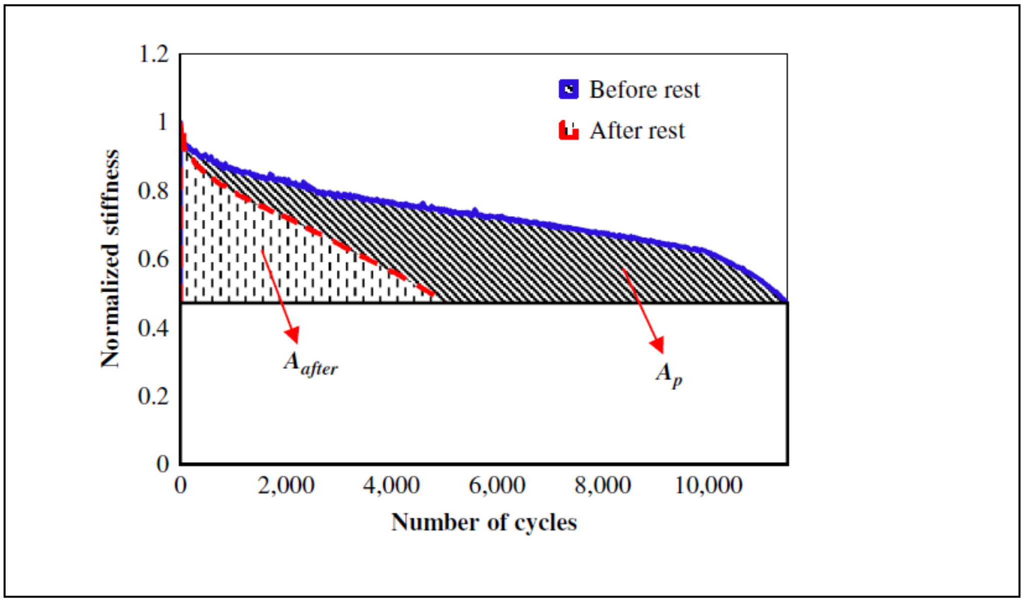

Figure 3.4 Areas used to calculate HI in Wang et al. 2020 (H. Wang et al., 2020). Before rest refers to the curve of the original material; after rest refers to the curve of the material after the healing process (heating and rest period)

These fatigue life extension indicators may permit study of the effect that the self-healing process has on the field fatigue behavior of the pavement. However, these laboratory tests require complex testing machines, long testing periods, and are not frequently used by researchers, as shown in Table 3.1. The most frequently used tests seem to be the monotonic loads tests, described below.

3.3.3. Monotonic loads tests

The three-point bending test (TPB) measures the maximum or peak load of undamaged asphalt specimens and damaged asphalt specimens after i-th healing cycles (Y. Sun et al., 2016, 2017, 2018). Hence, a healing index has been developed using this test:

$$HI_{TPB}(\%) = \frac{F_{TPBi}}{F_{TPB0}} . 100\% \qquad (12)$$

Where F_{TPB0} is the peak load reached by undamaged samples in the TPB test, and F_{TPBi} is the peak load after i-th healing cycles.

Indirect Tensile Strength (ITS) has also been used by diverse authors to estimate the healing index, sometimes from the ratio of the ultimate force before and after healing (Gulisano, Crucho, Gallego, & Picado-Santos, 2020; Jahanbakhsh et al., 2018) and others from the stiffness modulus (Tabaković et al., 2019). Moreover Xingyi Zhu et al., 2019 (Xingyi Zhu et al., 2019) and G. Sun et al., 2019 (G. Sun et al., 2019) used this test in its fatigue variant to study the fatigue life extention of self-healing techniques.

As shown in Table 3.1 the most frequently used laboratory test is the SCB (A. González et al., 2019; A. González, Norambuena-Contreras, et al., 2018b, 2018a; Norambuena-Contreras et al., 2018; Norambuena-Contreras & Garcia, 2016; Norambuena-Contreras & Gonzalez-Torre, 2017; Phan et al., 2018; Vo et al., 2020; Xu et al., 2020; H. Zhu et al., 2020), which adopts the following HI:

$$HI_{SCBFi} = \frac{F_{maxSCBi}}{F_{maxSCB0}} . 100\% \qquad (13)$$

Where $F_{maxSCB0}$ and $F_{maxSCBi}$ are the peak loads reached on undamaged samples and on damaged samples after the i-th healing cycle, respectively.

From the parameters that can be measured with the SCB test, it is also possible to establish healing indexes from the calculation of parameters that are more directly related to the fatigue cracking behavior of asphalt mixtures, related to fracture mechanics, and that are more suitable for describing asphalt pavement cracking behavior (M.A. Mull et al., 2002). This is the case of the study by Fan et al., 2018, in which three different HIs are proposed. The first, mentioned above, is established as the ratio between the maximum forces before and after healing. The second and third are related to the previously described concepts of fracture mechanics such as the fracture energy and Jc, which as explained in Section 3.2 is the most appropriate parameter to model the cracking of asphalt mixtures due to their elasto-plastic or viscoelasto-plastic nature.

The authors herein propose the HI_{SCBU} healing index as follows:

$$HI_{SCBUi} = \frac{U_i}{U_0}.100\% \qquad (14)$$

Where HI_{SCBUi} is the healing index related to the fracture energy, U_0 and U_i are the initial fracture energy and the fracture energy after the i-th healing cycle, being the fracture energy the area under the force-displacement curve (Fig. 3.2).

The other index is associated to the critical value of the J-integral:

$$HI_{SCBJci} = \frac{J_{ci}}{J_{c0}}.100\% \qquad (15)$$

Where HI_{SCBJci} is the healing index related to the critical value of the J-integral, J_{C0} and J_{ci} the critical value of J-integral of the test sample in the initial condition and in the test sample after the i-th healing cycle obtained as explained in Section 3.2 from the SCB test for three different notch sizes.

The use of laboratory tests that measure the resistance until failure of the test samples, prior to and after self-healing, make it possible to identify whether healing occurs or not, and to compare the effectiveness of the techniques or additives used to increase the healing capacity of the material. However, they do not make it possible to clearly establish the effect on the extension of pavement life or on the behavior of the pavement with regard to the progression of deterioration, in particular, cracking progression. In addition, as explained by Mull et al. 2002 (M.A. Mull et al., 2002), standard tests that evaluate ultimate strength and elastic modulus, are suitable for studying the behavior of homogeneous materials. Being a heterogeneous material, asphalt pavements cannot be correctly studied by these means, and fracture resistance characterization is more adequate (Section 3.2), enabling evaluation of crack propagation within the material.

Mohammad et al., 2012 (Louay N. Mohammad et al., 2012), studied the correlation of Jc with field cracking of asphalt pavements. These authors quantified the alligator cracking, as well as the transverse cracks in nine study sections in the state of Louisiana, United States, finding that there is a good correlation between this parameter and the measured cracks, verifying that the lower values of Jc correspond to the higher level of cracking. Moreover, Kim et al. 2012 (Kim et al., 2012), find that Jc values obtained from SCB tests show a good correlation with field cracking performance data, demonstrating the suitability of Jc parameter for estimating pavement cracking performance at intermediate service temperatures. Subsequently, Louay N., Mohammad Minkyum, Kim Harshavardhan, 2016 (Louay N., Mohammad Minkyum, Kim Harshavardhan, 2016), confirmed that the Jc obtained from SCB tests has a good correlation with the cracking index with an R^2 of 0.73, accounting for the potential use of this parameter to predict the cracking behavior of asphalt pavements. On the other hand, West et al. 2017 (West et al., 2017), despite stating that they could not find a relationship between Jc obtained from SCB tests and field cracking, confirm the trend that shows higher Jc values provide better fatigue cracking resistance.

These studies together with what is described in Section 3.2, which explains the suitability of Jc to describe the cracking behavior of asphalt mixtures, leads to the conclusion that the healing index calculated from Jc constitutes a good tool for evaluating the performance of the self-healing techniques and their effect on pavement cracking resistance.

Table 3.1 Tests and indicators used to quantify the healing degree

Title	Healing method	Laboratory test	Healing index/healing evaluating method	Reference
A novel self-healing system: Towards a sustainable porous asphalt	EMIH[1]/MWH[2]	SCB	maximum tensions ratio	(Xu et al., 2020)
Effects of asphalt types and aging on healing performance of asphalt mixtures using induction heating method	EMIH	SCB	maximum force ratio	(Vo et al., 2020)
Crack healing performance of hot mix asphalt containing steel slag by microwaves heating	MWH	SCB	maximum force ratio	(Phan et al., 2018)
Microwave Healing Performance of Asphalt Mixture Containing Electric Arc Furnace (EAF) Slag and Graphene Nanoplatelets (GNPs)	MWH	ITS	ITS ratio	(Gulisano, Crucho, Gallego, & Picado Santos, 2020)
Fatigue–healing performance evaluation of asphalt mixture using four-point bending test	COH[3]	FFPBT	Fatigue N ratio/ stiffness modulus ratio	(Xiang et al., 2020)
Evaluation of the induction healing effect of porous asphalt concrete through four-point bending fatigue test	EMIH	FFPBT	fatigue N ratio	(Liu et al., 2012)
Self-healing performance of asphalt mixtures through heating fibers or aggregate	MWH	TPBT	maximum force ratio	(Y. Sun et al., 2017)
Accelerated Healing in Asphalt Concrete via Laboratory Microwave Heating	MWH	FFPBT	ratio between area under stiffness-N° cycles curve / fatigue life extension ratio	(H. Wang et al., 2020)
Evaluation of Self-Healing Performance of Asphalt Concrete for Macrocracks via Microwave Heating	MWH	SCB	maximum force ratio	(H. Zhu et al., 2020)
Microwave self-healing technology as airfield porous asphalt friction course repair and maintenance system	MWH	ITS/ITSM	ITS ratio/ITSM ratio	(Tabaković et al., 2019)
Low temperature self-healing character of asphalt mixtures under different fatigue damage degrees	rest	ITS	variation of the resilient modulus	(G. Sun et al., 2019)
Low temperature self-healing character of asphalt mixtures under different fatigue damage degrees	COH	CTS	comparing images	(G. Sun et al., 2019)
Microwave crack healing on conventional and modified asphalt mixtures with different additives: an experimental approach	MWH	SCB	maximum force ratio	(A. González et al., 2019)
Influence of the Microwave Heating Time on the Self-Healing Properties of Asphalt Mixtures	MWH	SCB	maximum force ratio	(Norambuena-Contreras & Gonzalez-Torre, 2017)
Optimum moment to heal cracks in asphalt roads by means electromagnetic induction	EMIC	FTPBT	Fatigue life extension ratio	(Garcia et al., 2020)
The healing properties of asphalt mixtures suffered moisture damage	MWH	TPBT	bending strength ratio	(Y. Sun et al., 2016)
Snow and Ice Melting Properties of Self-healing Asphalt Mixtures with Induction Heating and Microwave Heating	EMIH/MWH	TPBT	maximum force ratio	(Y. Sun et al., 2018)
Self-healing properties of recycled asphalt mixtures containing metal waste: An approach through microwave radiation heating	EMIH/MWH	SCB	maximum force ratio	(A. González, Norambuena-Contreras, et al., 2018b)
Self-healing properties of ferrite-filled open-graded friction course (OGFC) asphalt mixture after moisture damage	MWH	FITS	fatigue life extension ratio	(Xingyi Zhu et al., 2019)
Self-healing of asphalt mixture by microwave and induction heating	EMIH/MWH	SCB	maximum force ratio	(Norambuena-Contreras & Garcia, 2016)
Self-healing efficiency of ferrite-filled asphalt mixture after microwave irradiation	MWH	FFPBT	fatigue life extension ratio/stiffness modulus ratio	(Xingyi Zhu et al., 2017)
Microwave-healing performance of modified asphalt mixtures with flake graphite and exfoliated graphite nanoplatelet	MWH	DCT	maximum force ratio	(Z. Wang et al., 2018)
High-Efficiency Heating Characteristics of Ferrite-Filled Asphalt-Based Composites under Microwave Irradiation	MWH	FFPBT	fatigue life extension ratio/stiffness modulus ratio	(Zhao et al., 2017)
Effect of RAP and fibers addition on asphalt mixtures with self-healing properties gained by microwave radiation heating	MWH	SCB	maximum force ratio	(A. González, Norambuena-Contreras, et al., 2018a)
Effect of metallic waste addition on the electrical, thermophysical and microwave crack-healing properties of asphalt mixtures	MWH	SCB	maximum force ratio	(Norambuena-Contreras et al., 2018)
Evaluation of Self-Healing Performance of Asphalt Concrete for Low-Temperature Fracture Using Semicircular Bending Test	COH	SCB	maximum force ratio/fracture energy ratio/ Jc ratio	(Fan et al., 2018)
Induction heating and healing of carbon black modified asphalt concrete under microwave radiation	MWH	SCB/ITS	maximum force ratio	(Jahanbakhsh et al., 2018)

(1) EMIH: Electromagnetic induction heating, (2) MWH: microwave heating, (3) COH: conventional oven heating

3.4. Relationship of Jc with pavement fatigue resistance

During recent decades pavement design methods have evolved from empirical to mechanistic-empirical, such as the well-known method published in the AASHTO Mechanistic-Empirical Pavement Design Guide (MEPDG) (AASHTO, 2008). The guide proposes the following fatigue relationship for asphalt layers:

$$N_f = k_{f1}(C)(C_H)(\varepsilon_t)^{k_{f2}}(E)^{k_{f3}} \qquad (16)$$

Where

N_f = Allowable number of axle-load applications for a flexible pavement and HMA overlays, until cracked area reaches 20% of the total area,

ε_t= Tensile strain at critical locations and calculated by the structural response model, in/in,

E= Dynamic modulus of the HMA measured in compression, psi

k_{f1}, k_{f2}, k_{f3} Global field calibration parameters (from the NCHRP 1-40D re-calibration; k_{f1} = 0.007566, k_{f2} = –3.9492, and k_{f3} = –1.281)

$$C=10^M \qquad (17)$$

$$M = 4.48\left(\frac{V_{be}}{V_a+V_{be}} - 0.69\right) \qquad (18)$$

Where;

V_{be} = Effective asphalt content by volume (%)

V_a = Percent air voids in the HMA mixture

C_H = Thickness correction term, dependent on type of cracking

For bottom-up cracking or alligator cracking

$$C_H = \frac{1}{0.000398 + \frac{0.003602}{1+e^{(11.02-3.49 H_{HMA})}}} \qquad (19)$$

H_{HMA} = Total thickness of asphalt layers

Based on the results of Louay N., Mohammad Minkyum, Kim Harshavardhan, 2016 (Louay N., Mohammad Minkyum, Kim Harshavardhan, 2016), and considering that asphalt mixtures are a complex composite material that shows a behaviour difficult to fully describe using a single parameter, Cao et al., 2018 (Cao et al., 2018) proposed a fatigue equation based on the MEPDG fatigue relationship (Eq. 16) including Jc, as follows:

$$N_f = k_{f1}(C)(C_H)(\varepsilon_t)^{k_{f2}}(E)^{k_{f3}}(J_c)^{k_{f4}} \qquad (20)$$

Where k_{f4} is a calibration parameter corresponding to Jc, and the rest of the parameters were defined above. In their work, the authors calibrated the model using data from 11 study sections tested at the pavement Accelerated Loading Facility (ALF) of the Federal Highway Administration (FHWA) of the United States (US) Department of Transportation and obtained the following values:

$k_1 = 3.57E12;\ k_2 = -2.141;\ k_3 = -4{,}327; k_4 = 1.587$

The authors found that the results obtained from this newly developed fatigue equation had a better correlation with the results of the ALF field measurements than the original MEPDG equation (Eq. 16).

Summarizing, from the previous sections, it is shown that a parameter known as the critical value of the J-integral (Jc), which represents the fracture resistance of asphalt mixtures, and is easily determinable from SCB tests, correlates well with the field cracking of asphalt pavements. Furthermore, researchers have successfully incorporated this parameter into a fatigue equation, which correlates well with field cracking. Hence, if Jc is obtained from the crack and healing laboratory tests, it is possible to assess the extension of the field fatigue life of asphalt pavements with self-healing capabilities.

3.5. Evolution of Jc with cracking and healing cycles and estimation of fatigue life extension

3.5.1. Previous research findings

Researchers have studied the evolution of Jc with failure and healing cycles. For instance, Fan et al., 2018 (Fan et al., 2018), evaluated the evolution of Jc through SCB testing, healing the samples at 100°C for eight hours in a conventional oven. Authors calculate the healing index with Jc, HI_{SCBJc1} =95% for conventional asphalt mixture and HI_{SCBJc1} =86% for a SCB modified binder mixture. On the other hand, Jahanbakhsh et al., 2018 (Jahanbakhsh et al., 2018), carried out SCB tests at 25°C on asphalt mixtures samples healed with microwave heating. Healing indexes calculated with the Jc parameter obtained from data presented in the mentioned article, may be calculated for three cycles of microwave healing reaching the following values: $HI_{SCBJc1} = 56\%$, $HI_{SCBJc2} = 38\%$, and $HI_{SCBJc3} = 40\%$.

However, it is likely necessary to carry out more such experiments, since only the two previously mentioned set of experiments were available in the literature. In addition, the tests found in the literature were conducted on specimens with specific aggregates and bitumen, and it is necessary to expand the available database in order to reach more general conclusions. Given the published research, more experimental investigations are warranted. Finally, the experimental results could be used to calculate Jc and hence estimate fatigue life of asphalt pavements. In other words, new results could be used to compare fatigue life of healed asphalt mixtures. Thus, the authors decided to carry out a new set of laboratory tests to investigate the evolution of the Jc parameter with cracking and healing cycles.

3.5.2. Materials and methods

3.5.2.1. Aggregates and bitumen

A standard dense asphalt mixture was used for preparing the laboratory test samples (Table 3.2). The aggregate was formed by blending four different fractions; crushed granitic rock 5mm-14mm (54%), crushed dust from the same granitic rock (36%), natural siliceous sand (9%), and Portland cement as mineral filler (1%). The particle size distribution curve is presented in Figure 3.5. The bitumen used was a conventional asphalt cement AC30 delivered by ANCAP (National Refinery Company of Uruguay), and the hot mix asphalt (HMA) was prepared by IDALAR S.A. in Montevideo, Uruguay.

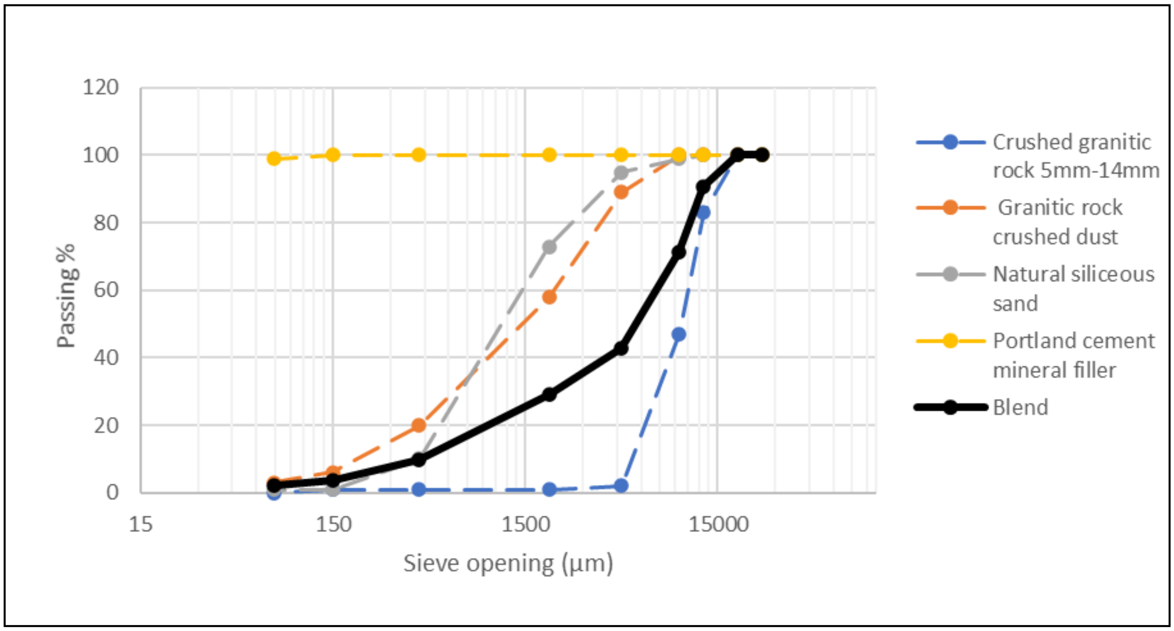

Figure 3.5 Particle size distribution of aggregates used in the HMA

Table 3.2 Asphalt binder AC30 physical properties and asphalt mixture properties

Bitumen Physical Properties	
Softening point (°C)	54.9
Flash Point (°C)	>240
Penetration 25°C (1/10mm)	36
Absolute Viscosity at 60° (Poises)	3220
Cinematic Viscosity at 135° (cSt)	426
Asphalt Mixture and Marshall Specimen Properties	
Asphalt content (%)	5.2
Bulk density (g/cm3)	2.355
Air voids (%)	4.2
VMA^{+} (%)	14.8
Stability (kg)	1550
Flow (mm)	390

(+) Voids in the mineral aggregate

3.5.2.2. Preparation of asphalt mixture specimens

The Marshall cylindrical specimens (100mm in diameter, 60mm thick) were compacted with 75 blows on each face following ASTM D6926 – 20 standard. Four semicircular specimens (50mm radius, 30mm height) were obtained by cutting one Marshall specimen, first with a 3mm saw through the plane parallel to the flat face at half of the height (Fig. 3.6b) and later through the 100mm diameter (Fig. 3.6c). Finally, a straight vertical notch was cut along the symmetrical axis of each semicircular specimen with a 2mm circular saw (Fig. 3.6d). Seven samples were prepared for each notch size (10mm, 15mm, and 20mm).

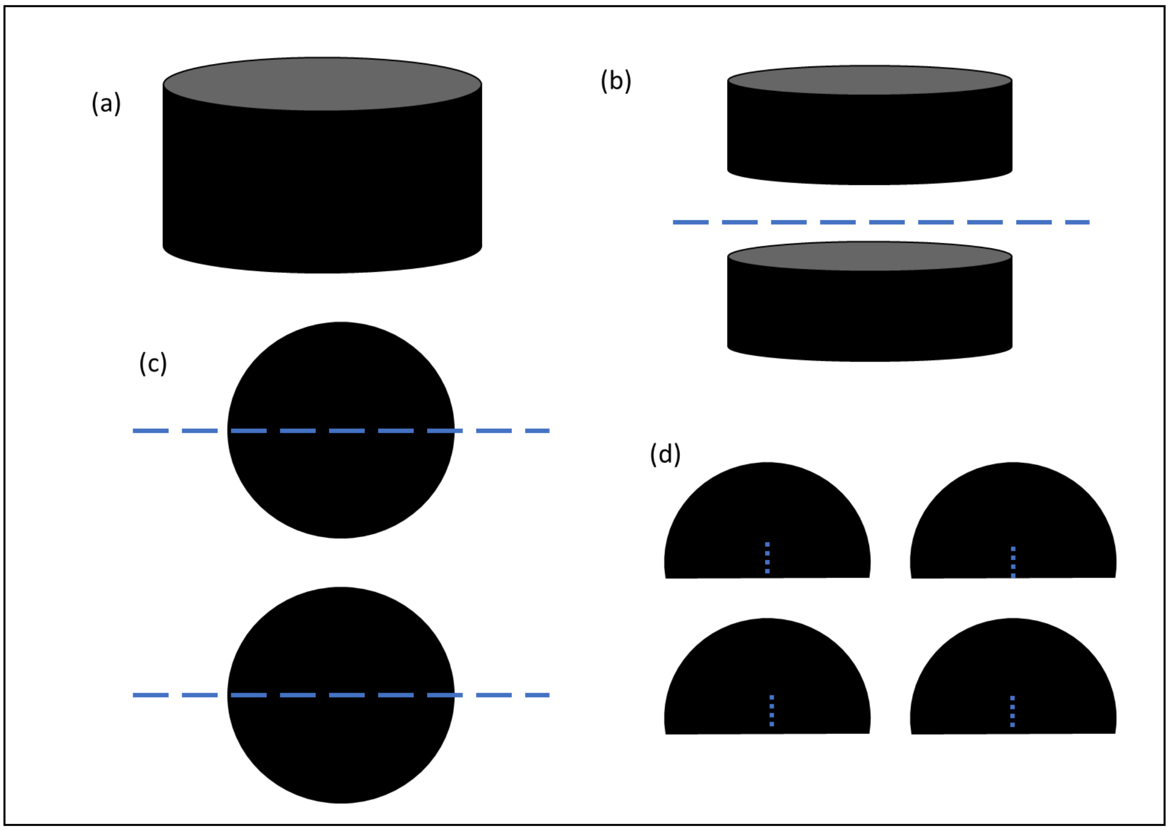

Figure 3.6 (a) Marshall specimen, **(b)** specimen sawed in two halves by the plane parallel to the flat face, **(c)** halves sawed by the diameter, **(d)** sawing of the notches

3.5.2.3. Jc testing and healing procedure

The semicircular asphalt samples were tested following the ASTM D8044-16 semi-circular bending test standard to evaluate asphalt mixture cracking resistance which is used to obtain the Jc value (Fig. 3.7a). The tests were conducted in a multispeed universal loading testing machine, with a load cell of 50kN. The average testing temperature was 22.8°C (SD=0.7°C), and the load was applied in displacement control mode with a speed of 0.5mm/min and continued until applied load was reduced to 50% of the peak load (Fig. 3.7b). After testing, semicircular specimens were heated in a 700W and 2450MHz microwave oven for 90s reaching an average temperature of 70.2°C (SD=5.5°C), and then let to cool down and heal at room air temperature, approximate 20°C-23°C for 18 hours. This process was repeated five times for each test sample. It should be highlighted that the temperature reached through microwave heating is higher than the softening point of the binder, which according to various authors (García, 2012; J. Tang et al., 2016) is recommended to activate the self-healing process.

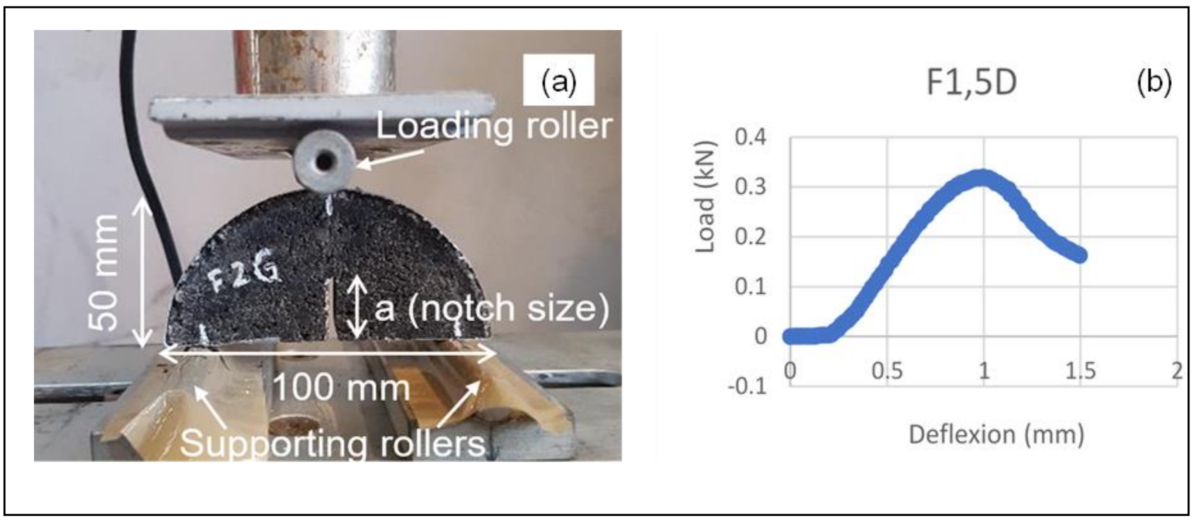

Figure 3.7 (a) Test sample, **(b)** Example of test measurement (F1,5D is the name of the test sample; F=type of mixture, 1.5=notch size in cm, D name of the sample)

3.5.3. Analysis and discussion of results

3.5.3.1. Evolution of the HI_{SCBF}

Figure 3.8a shows the average peak load achieved by the SCB samples with different notch sizes and Figure 3.8b shows the healing index HI_{SCBF}, which is one of the most used healing indexes according to the literature (Table 3.1). Figure 3.8a illustrates that the peak load applied to all the undamaged samples, regardless their notch size, decreases approximately 40% after the first healing cycle. However, after the first and until the 4^{th} healing cycle, the peak load remains relatively constant. Figure 3.8b shows that HI_{SCBF} is relatively constant in the order of 0.6 for all the healing cycles. Both results show that after breaking the original bonds of the undamaged sample, the strength of the new bonds formed in the healing process remains constant despite the number of break and healing cycles applied up to the 4^{th} cycle. These results are consistent with literature findings for asphalt mixtures without additives that promote external microwave heating (Fan et al., 2018; González et al., 2019, 2018b; Zhu et al., 2020). In addition, results from Figure 3.8a show that the peak load decreases with increasing notch size, which was expected because larger notches decrease the cross-section of the asphalt sample, increasing the tension produced by the bending of the sample during the test for the same load applied (Fan et al., 2018). However, Figure 3.8b suggests that HI_{SCBF} is independent from the notch size and remains near 0.6 for all the samples, as mentioned above, because this healing index is a ratio of relative strength obtained from the various peak loads.

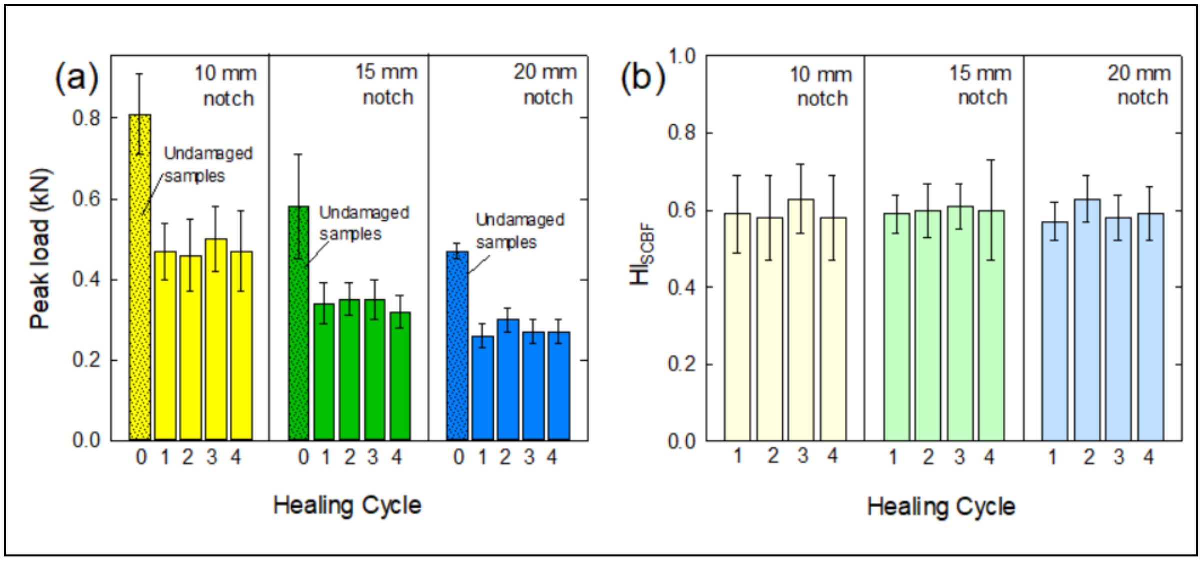

Figure 3.8 Results from semicircular bending tests: **(a)** peak loads and **(b)** HI_{SCBF}

3.5.3.2. Evolution of the Jc and HI_{SCBJc}

As described above, Jc is related to the cracking behavior of asphalt pavement. Hence, Fan et al. 2018 (Fan et al., 2018) proposed a healing index based on Jc. Figure 3.9a shows the Jc calculated from the undamaged and damaged samples for the first to fourth healing cycle. As expected from the peak load and healing index results detailed in the previous section, Jc for the undamaged samples (1.16 kJ/m^2) is higher than for the damaged and healed specimens. In addition, and similar to the previous results, Jc remains relatively constant from the first to the fourth healing cycle (between 0.31 and 0.51 kJ/m^2). Figure 3.9b shows a comparison with results calculated from the literature (Jahanbakhsh et al., 2018) presenting Jc up to the third damage and healing cycle. The comparison shows that the obtained Jc values are within the same range as those obtained from the literature (Jahanbakhsh et al., 2018), with an undamaged Jc of 0.96 kJ/m^2, and damaged and healed Jc between 0.36 and

0.54 kJ/m^2. The HI_{SCBJc} ranges from 0.27 to 0.44 (Figure 3.9c) for the damage and healing cycles applied, confirming that the healing index remains relatively constant. However, these are slightly lower than the results from the literature (Jahanbakhsh et al., 2018) (Figure 3.9d), which range from 0.38 to 0.56. The difference is explained by the different mixture composition (e.g., carbon black modified binder), size of test samples, and testing temperature differences between this research and the research reported in the literature (Jahanbakhsh et al., 2018). Moreover, these results show that the HI_{SCBJc} are nearly 20% lower than those of HI_{SCBF}. Taking into account that the Jc parameter is related with pavement cracking resistance, these results allow us to state that the HI based in maximum force may lead to overestimating the healing effect on the asphalt mixture.

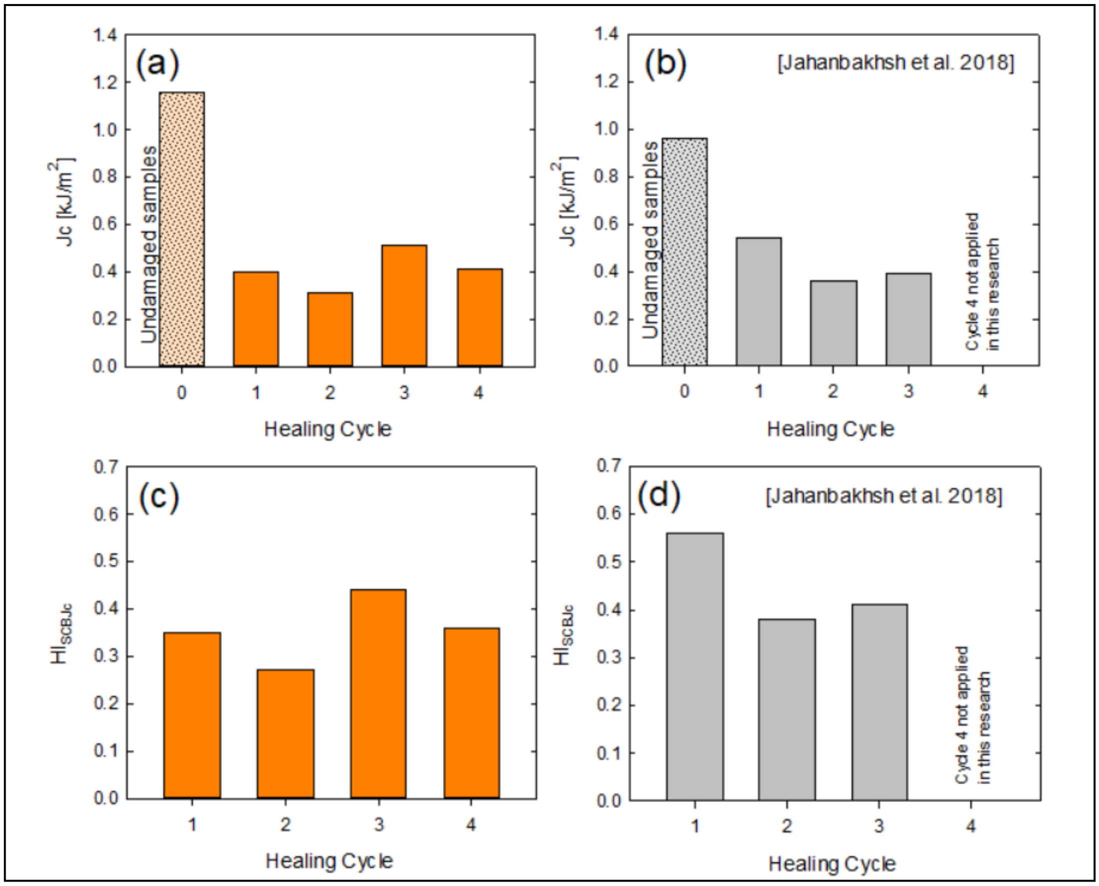

Figure 3.9 Results from semicircular bending tests: **(a)** Jc **(b)** Jc calculated from results reported in the literature **(c)** HI_{SCBJc} **(d)** HI_{SCBJc} calculated from results reported in the literature

3.5.3.3. Evolution of the fatigue life extension

As mentioned above, the purpose of using Jc to study the effects of self-healing is the correlation between this parameter and the fatigue behavior of asphalt mixtures. Using Eq. 20 and assuming that the dynamic modulus and critical strain of the asphalt layer remain relatively constant, the increase of the fatigue life is calculated from the laboratory tests as follows:

$$\left.\begin{aligned} N_{f0} &= k_{f1}(C)(C_H)(\varepsilon_t)^{k_{f2}}(E)^{k_{f3}}(J_{c0})^{k_{f4}} \\ N_{fi} &= k_{f1}(C)(C_H)(\varepsilon_t)^{k_{f2}}(E)^{k_{f3}}(J_{ci})^{k_{f4}} \end{aligned}\right\} \quad \frac{N_{fi}}{N_{f0}} = \frac{\cancel{k_{f1}}\cancel{(C)}\cancel{(C_H)}\cancel{(\varepsilon_t)^{k_{f2}}}\cancel{(E)^{k_{f3}}}(J_{ci})^{k_{f4}}}{\cancel{k_{f1}}\cancel{(C)}\cancel{(C_H)}\cancel{(\varepsilon_t)^{k_{f2}}}\cancel{(E)^{k_{f3}}}(J_{c0})^{k_{f4}}} = \left(\frac{J_{ci}}{J_{c0}}\right)^{k_{f4}} \tag{21}$$

Where, N_{f0} and N_{fi} are the allowable number of 80 kN axle-load repetitions for the undamaged pavement and the pavement after the i-th healing cycle respectively, and J_{C0} and J_{Ci} are the Jc value for the undamaged mixture and the mixture after the i-th healing cycle, respectively. Therefore, the ratio between N_{fi} and N_{f0} is the increase of fatigue life of the asphalt pavement after the i-th healing cycle estimated using Jc from laboratory results. The proposed index is called the Fatigue Life Extension Healing Index (HI_{FLE}), which is presented in Figure 3.10. For calculating this life extension, a crucial assumption is made: the applied healing technique heals uniformly for the full depth of the treated asphalt concrete layer. Thus, the healed asphalt pavement mechanical properties (e.g., Jc) are constant throughout the pavement depth.

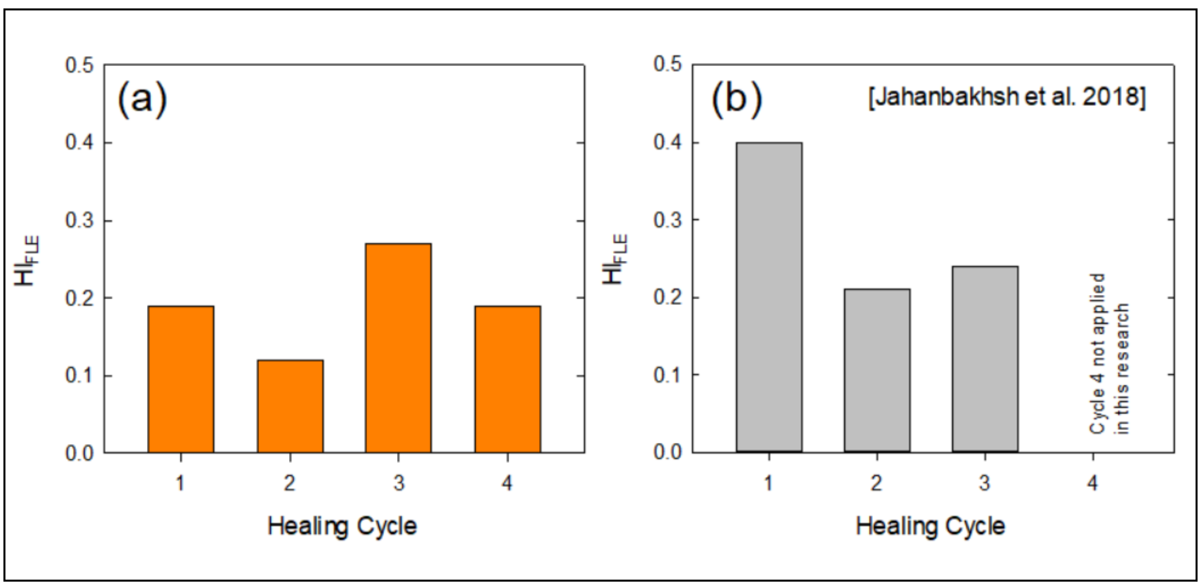

Figure 3.10 Fatigue life extension index (HI_{FLE}) of asphalt pavements versus healing cycles

Results in Figure 10 show that the calculated fatigue life extension using the test data after each healing cycle ranges from 0.19 to 0.27, which is less than one half of the healing index obtained from peak load results (HI_{SCBF}, Figure 3.8b). In addition, results show that the fatigue life of asphalt pavements increases approximately 19% after the first healing cycle, and then 12%, 27%, and 19% after the second, third, and fourth healing cycles. In other words, if the expected fatigue life of an asphalt pavement is $1x10^6$ 80 kN axle-load repetitions, the fatigue life of the asphalt pavement increases to 1.19×10^6, 1.31×10^6, 1.58×10^6, and 1.77×10^6, respectively. For comparison, the fatigue life extension was calculated from Jahanbakhsh, et al. 2018 (Jahanbakhsh et al., 2018), and included in Figure 10b showing a 40% fatigue life increase after the first healing cycle and between 21-24% for the second and third healing cycle. Conversely, the fatigue life extension observed in laboratory fatigue four-point bending tests (FFPBT) range between 20% and 60% (Liu et al., 2012; H. Wang et al., 2020; Xiang et al., 2020). The diverse laboratory testing and healing conditions applied to FFPBT explain the difference between results for instance, the researchers who adopted FFPBT applied different healing temperatures and different damage levels to asphalt specimens to estimate the fatigue life extension (Liu et al., 2012; H. Wang et al., 2020; Xiang et al., 2020). Nevertheless, the fatigue life extensions reported by authors who adopted FFPBT for testing conditions similar to the present study (asphalt mixture without additives, healing temperature of 70°C) range between 35% and 46% for the first healing cycle (Liu et al., 2012; H. Wang et al., 2020; Xiang et al., 2020), higher than those calculated using the proposed approach used in this article.

3.5.3.4. Healing indexes comparison

As previously mentioned, many researchers have used the HI_{SCBF} index to quantify the healing effect of self-healing techniques because it is a simple parameter for comparing different healing techniques. However, the use of the HI_{SCBF} index to assess the fatigue life extension of a pavement could be misleading. Figure 3.8 shows that HI_{SCBF} using the results obtained from the laboratory study fluctuate between 58%-60% for each healing cycle. Conversely, the calculated HI_{SCBJc} index ranges between 27%-44% for each healing cycle, considerably lower than the healing indexes calculated using $HI_{SCBF.}$ The difference is higher for the calculation of the fatigue life extension, which is approximately one third of the HI_{SCBF}. This difference is explained by the methodology adopted to calculate HI_{SCBF}, which is the ratio between peak loads applied to SCB samples. Because the peak force is not clearly linked with asphalt pavement fatigue performance, the current research recommends the use of the fatigue life extension ratio calculated with Eq. 21. HI_{FLE} links the damaged and healed laboratory results from SCB specimens with field performance using fracture mechanics, although these results must be confirmed with full scale testing of asphalt pavements and rigorous analytical methods (Alvaro González et al., 2012).

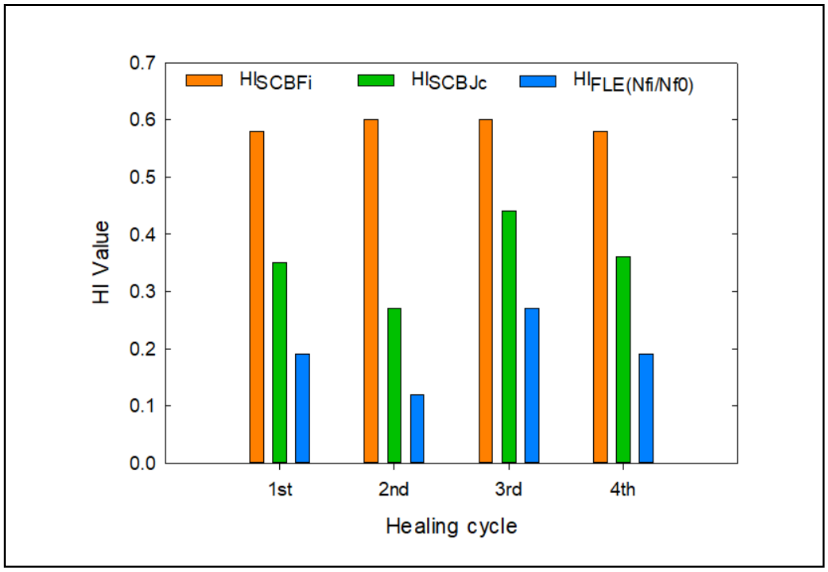

Figure 3.11 HI value comparison

3.6. Conclusions

This paper presents different alternatives from those typically used to quantify the efficiency of self-healing techniques and instead assesses pavement fatigue life of asphalt pavements with self-healing properties using analytical methods based on fracture mechanics and laboratory results. Based on the analysis and discussion of results, the following conclusions are presented:

- Several HI have been used to quantify the healing performance of self-healing techniques; however, they provide little information about the increase of the fatigue life in order to define the application frequency of self-healing maintenance techniques or to assess the increase of pavement fatigue life in the field.
- HI_{SCBF}, a common healing index calculated with the peak force in SCB tests could be misleading, since it overestimates the self-healing effectiveness. Jc is a fracture mechanics parameter related to field crack initiation and propagation in asphalt

pavements and pavement fatigue life. Hence, HI elaborated from the Jc parameter or the fatigue life extension of pavements is proposed.

- Experimental results from the current research were used to calculate Jc in asphalt mixtures healed by external microwave heating and to assess pavement fatigue life. Results indicate that the fatigue life of asphalt pavements increases 20% after the application of microwave heating.
- Overall, the SCB-Jc-fatigue proposed methodology provides a valuable tool for investigating the performance of asphalt concrete self-healing techniques through a simple laboratory experiment until self-healing field experiments are carried out.

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4. ASSESSMENT OF THE SUSTAINABILITY OF ASPHALT PAVMENT MAINTENANCE WITH MICROWAVE HEATING SELF-HEALING TECHNIQUE

A paper to be submitted to Journal of Cleaner Production

Kevork Micael Nalbandian, Manuel Carpio, Álvaro González

Abstract

Road infrastructure is of paramount importance for countries' development; however, a pavement's life cycle has high environmental, economic and social impacts. Asphalt pavement microwave heating self-healing technique (MWHST) has emerged as a sustainable maintenance alternative to traditional techniques. Research has focused mainly on its technical feasibility, but its beneficial effect on economic, environmental and social sustainability has still not been quantified. The present work addresses the way including MWHST in asphalt pavement maintenance strategies impacts on pavement sustainability through an environmental, and socio-economic impact analysis compared to traditional maintenance, on thin conventional hot mix asphalt pavement. Results show that microwave heating self-healing has the potential to substantially reduce climate change impact, raw material and energy consumption, and investment and user´s costs during pavement's life cycle, having also potential positive effect from the social perspective.

4.1. Introduction

The impact of human activities on the environment has generated great concern to the global society. In 2015, the United Nations (UN) countries reached an agreement for 2030 sustainable development goals (United Nations, 2015). Some of these goals are associated with civil infrastructure and their sustainable management, such as roads, which are of paramount importance for the transport of people and goods (Balaguera et al., 2018). For instance, in 2009 in Chile, 83% of all goods and 61% of people were transported over roads (Conicyt, 2010). Trucks carried near 61% of the weight and value of all goods shipped within the United States of America (USA) in 2018 (Statistics and Transportation, 2020) and 72% of freight transport in the European Union (EU) countries in 2011 (Balaguera et al., 2018). In international transport, these numbers decrease because road transportation is less effective for long distances and great loads, and also due to geographical restraints. However, in 2019, road transport accounted for 20% of the EU's exports and 16 % of its imports (Eurostat, 2020). Thus, road infrastructure plays a critical role in the economic and social development of any region or country. For this reason, governments spend large amounts of their budgets on the construction and maintenance of highways and roads. However, life cycle of road infrastructure has significant impacts on the environment, being responsible for between 70% and 90% of the greenhouse gas (GHG) emissions of world transport (Egis, 2010; European Commission, 2014), and the construction and maintenance of roads is responsible for more than 13% of the total emissions related to construction worldwide (Mukherjee and Cass, 2012). As a result, many construction and maintenance techniques have been developed to address this issue, for instance, the use of sustainable materials (Plati, 2019), recycling on site (González et al., 2010), long-lasting pavements, recycled and stabilised granular materials (González et al., 2018), porous concrete pavements (Elizondo-Martínez et al., 2020), and self-healing maintenance techniques (García, 2012; Tabaković and Schlangen, 2016).

Asphalt pavement self-healing techniques take advantage of the asphalt mixture ability to recover mechanical properties slowly and progressively under certain conditions (Little and Bhasin, 2007), by enhancing it in order to obtain faster healing results and achieving a greater recovery of the original properties. These alternatives have been catching the scientific community's interest for their promising results as viable alternatives to traditional pavement maintenance techniques (Nalbandian et al., 2021). Some advantages include reducing or eliminating maintenance needs, reducing the consumption of natural resources, decreasing the disruption of traffic and CO_2 emissions during maintenance, and increasing road safety (Tabaković and Schlangen, 2016), as well as reducing pavement life cycle related costs (user´s costs and agency's) (Rodríguez-Alloza et al., 2019).

The main technologies currently being developed are the use of microcapsules with rejuvenating agents or heating techniques (microwave and electromagnetic induction) (Nalbandian et al., 2021) (Fig. 4.1). The emphasis of most current research is on optimizing healing techniques' performance, but little research has been conducted to quantify their environmental benefits, or address their sustainability with a few exceptions found in the literature (Nalbandian et al. 2021).

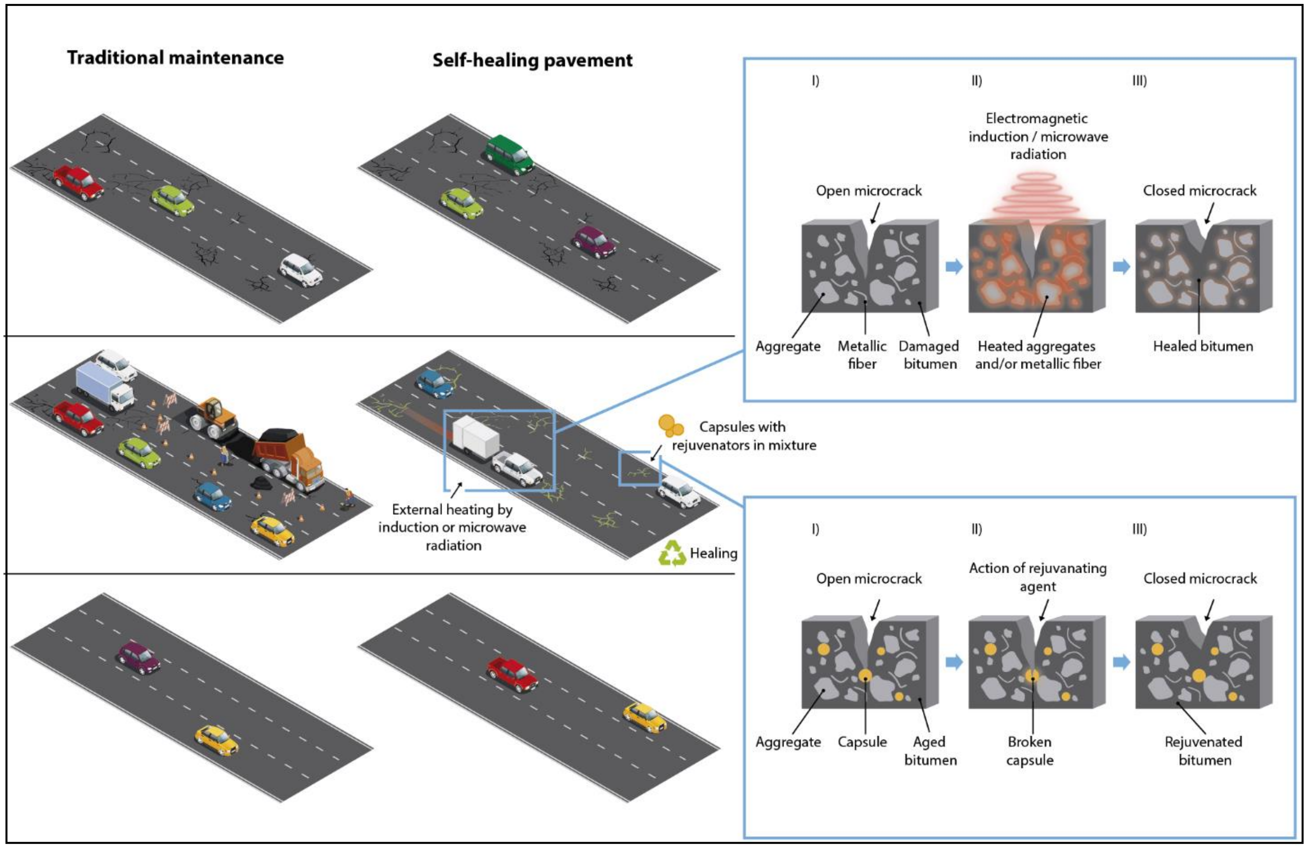

Figure 4.1 Traditional maintenance vs Self-healing pavement

Sustainability of induction-healed asphalt has been addressed by Lizasoain-Arteaga et al. (2019) from an environmental perspective through a life cycle assessment (LCA) in a steel fibre modified asphalt concrete pavement, finding that induction heating is a fast and less intensive maintenance technique that minimises traffic disruption. The authors also found that in 12 of 17 midpoint impact categories analysed, the induction heating technique outperformed traditional maintenance. As a result, positive outcomes were achieved in the three end point impact categories studied (damage to human health, damage to ecosystem diversity, and damage to resource availability). On the other hand, Rodríguez-Alloza et al.

(2019) studied the environmental and economic performance of the microwave (MW) heating self-healing technique compared to conventional maintenance techniques. Through a hybrid input–output-assisted LCA, using industry data and previous microwave hating research, the authors found that for a one-lane per direction roadway with steel slag modified asphalt mixture, a reduction of 16% GHG emissions and 32% of costs was achieved. It should be mentioned that the above referred articles, studied cases where metallic elements were included in the asphalt mixture; nevertheless, the MW heating self-healing technique can be used in traditional asphalt mixtures without metallic additives in the presence of microwave sensitive aggregates (González et al., 2019; Sun et al., 2017; Trigos et al., 2019), which has the potential to increase microwave self-healing technique benefits.

However, sustainability not only refers to environmental and economic aspects; it is also widely recognised as a more complex concept that includes social aspects as part of a three-pillar based definition (Fig. 4.2) known also as the "triple-bottom line" (Purvis et al., 2019). This concept has its origin in the most widespread definition issued in 1987 by the World Commission on Environment and Development which states that "Sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own need" (WCED, 1987). Moreover, in the context of pavements Van Dam et al., (2015) stated that sustainable "…refers to system characteristics that encompasses a pavement's ability to (1) achieve the engineering goals for which it was constructed, (2) preserve and (ideally) restore surrounding ecosystems, (3) use financial, human, and environmental resources economically, and (4) meet basic human needs such as health, safety, equity, employment, comfort, and happiness”. Despite finding examples of LCA and life cycle cost assessment (LCCA) of road infrastructure (Batouli et al., 2017; Liu et al., 2015; Yu et al., 2013), no work has been found in the literature addressing the three aspects of sustainability, proposing a MW heating self-healing maintenance strategy. Thus, this research investigates the sustainability of the inclusion of the MW heating self-healing technique as part of asphalt pavement maintenance strategies compared to traditional asphalt pavement maintenance, focusing mainly on the third point of Van Dam et al.’s definition, through the implementation of a comparative three-legged analysis that includes environmental, economic, and social sustainability for thin traditional dense hot mix asphalt (HMA) pavements.

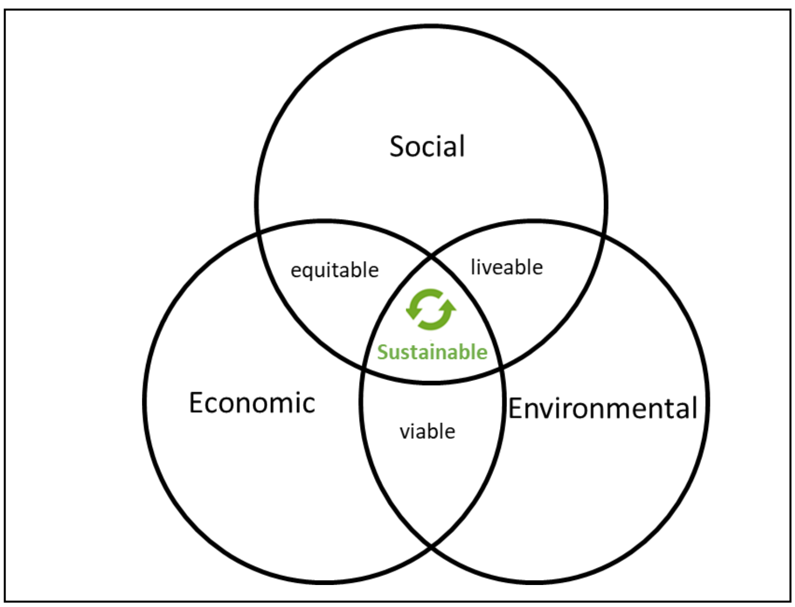

Figure 4.2 Three pillars of sustainability (adapted from (Purvis et al., 2019))

4.2. Methods and data

4.2.1. Environmental sustainability

Environmental sustainability of products or process is measured quantifying its environmental impacts. The most widespread methodology used is LCA, particularly the one established in ISO standards ISO 14040:2006 and ISO 14044:2006. This framework has been previously used in pavement LCA to assess the use of recycled materials for rehabilitating asphalt pavements (Balaguera et al., 2019; Chiu et al., 2008), to study road maintenance work, and traffic disruption emissions (Huang et al., 2009; Wang et al., 2020), and to study the influence of pavement design on emissions and energy consumption (Smith and Durham, 2016), among others. In the present work regarding sustainability, the authors also followed the recommendations of the *Pavement Life Cycle Assessment Framework* of the Federal Highway Administration (FHWA) of the U.S. Department of Transportation (Harvey et al., 2010, 2016), which presents specific recommendations for road infrastructure LCA.

The LCA method consists of four phases: (4.2.1.1) goal and scope, (4.2.1.2) life cycle inventory (LCI), (4.2.1.3) life cycle impact assessment (LCIA), and interpretation of the results (Fig. 4.3).

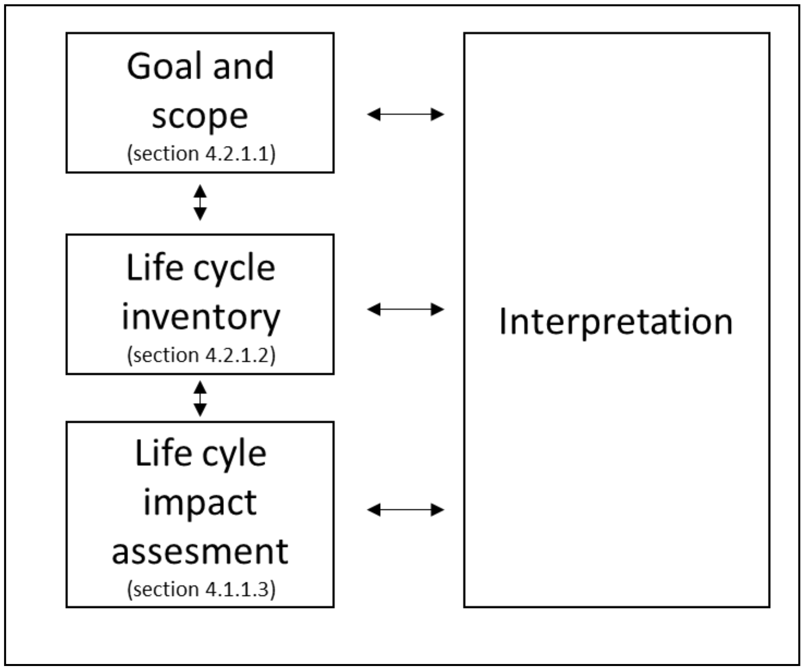

Figure 4.3 Life cycle assessment framework (adapted from ISO 14040:2006 (ISO, 2014))

4.2.1.1. Goal and scope

The goal of the present LCA study was to analyse the environmental sustainability of the microwave heating self-healing technique as part of a maintenance strategy for thin asphalt pavements, by comparing the environmental impact of maintaining a thin asphalt pavement through maintenance alternatives including MW self-healing to a traditional maintenance techniques strategy. As previously mentioned, the MW heating self-healing technique can be applied to traditional HMA pavements when microwave sensitive aggregates are utilised (González et al., 2019; Sun et al., 2017; Trigos et al., 2019). Thus, the alternatives compared in this study present the same mixture design and structure, as well as the same traffic and climatic characteristics; the only difference between the compared alternatives is the maintenance strategy configuration. Pavement’s cradle to grave life cycle includes, raw material acquisition, material production, construction, use stage, and end-of-life stage (Harvey et al., 2016) (Fig. 4.4). Because all stages but the use stage are equivalent between alternatives, analysis focused on the use stage of the pavement life cycle. The functional unit defined was 1km – 1 lane of the case study road. Considering that asphalt concrete pavements are designed for a 20-year life (Ministerio de Obras Públicas, 2017), following the recommendations of the FHWA, a period of 40 years was defined for the LCA.

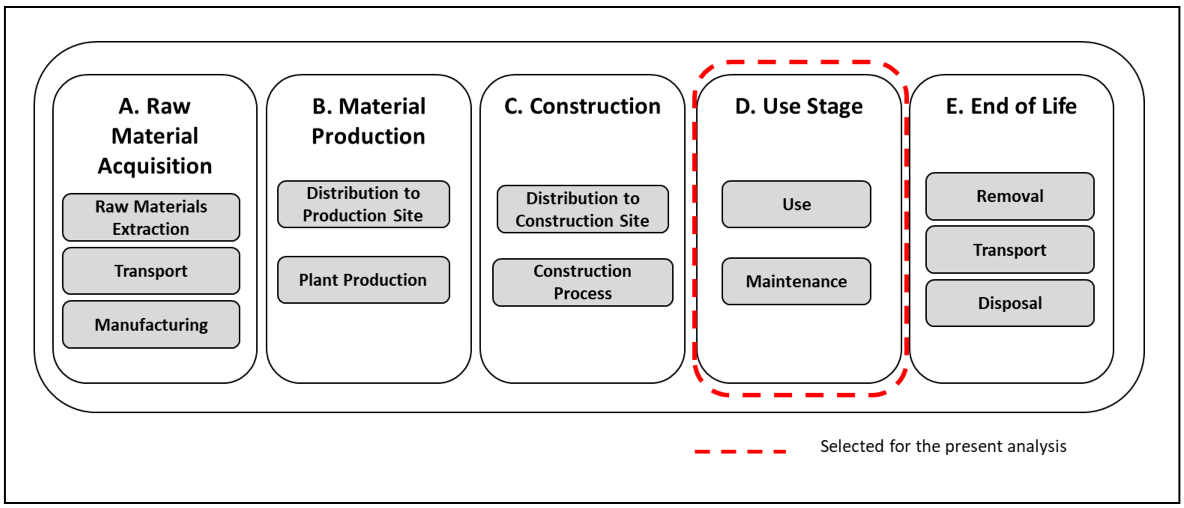

Figure 4.4 Stages of pavement life cycle (adapted from Harvey et al., 2016)

4.2.1.2. Life cycle inventory

The life cycle inventory (LCI) is the phase of the LCA in which input and output environmental flows are identified and quantified for each alternative and for each stage of the life cycle, defined in the scope of the assessment (Harvey et al., 2016). In the present work, as previously explained, the inventory corresponded to the use phase of the life cycle. As a result, the inflows and outflows corresponded to the maintenance and rehabilitation activities (raw material extraction, materials production, transport and construction) and to vehicles' propulsion (e.g., fuel and energy consumption, GHG emissions) in road maintenance work condition. Vehicles' propulsion related LCI linked to regular flow were considered equivalent for the maintenance alternatives because they supposedly have an equivalent effect on road surface condition and thus on vehicle rolling resistance and fuel consumption.

Inventory data related to maintenance and rehabilitation activities were retrieved from previous studies such as Athena Institute, (2006); Butt et al., (2012); Chehovits and Galehouse, (2010); Eurobitume, (2012); Stripple, (2001); Wang et al., (2020). Work zone congestion inventory data was obtained from simulations with the traffic microsimulation software Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks (AIMSUN)(AIMSUN, 2021). For these simulations, the hourly distribution of traffic must be defined. This distribution depends on the type and function of the road that is analysed; urban streets or highways have a different traffic intensity profile than interurban roads. In this case, as the present study was focused on rural or interurban roads based on literature examples (Caceres et al., 2012; Dunne and Ghosh, 2013; Martin, 2002), we assumed that 80% of the annual average daily traffic (AADT) occurred during day-time (8:00 to 20:00) and the remaining 20% occurred during night time (20:00 to 8:00) at a constant traffic flow intensity, resulting in the flow intensity profile shown in Figure 4.5.

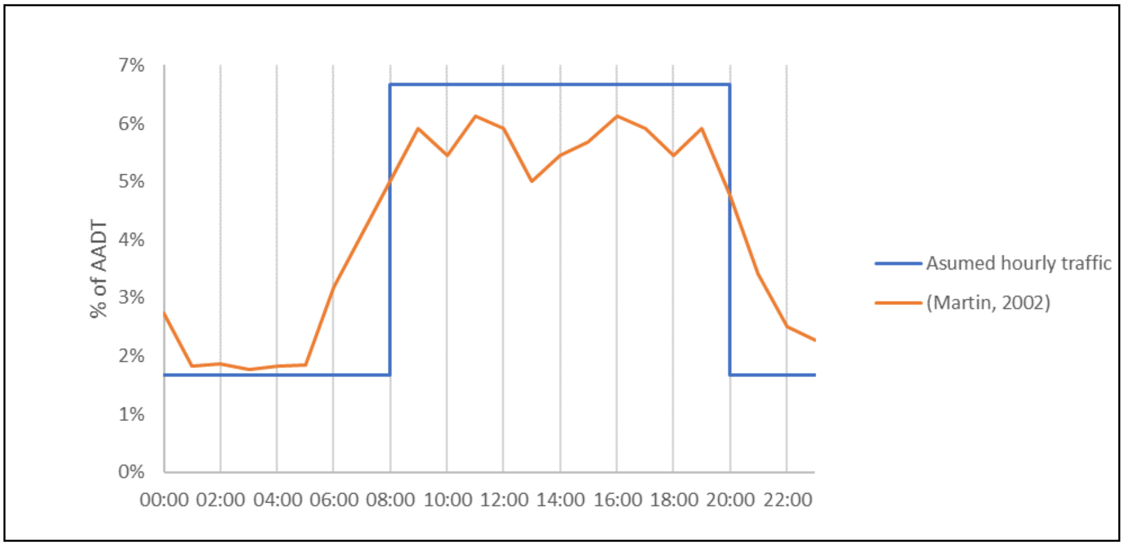

Figure 4.5 Assumed hourly traffic distribution compared to literature (Martin, 2002)

4.2.1.3. Life Cycle Impact Assessment

The life cycle impact assessment (LCIA) is the stage in which results from de LCI are translated into measures of human or environmental impact. To quantify these effects, impact categories' indicators are defined, and through characterisation models, LCI results are added up. Pavement sustainability includes multiple issues such as, GHG emissions, energy consumption, impacts on water quality, air quality, mobility, depletion of non-renewable resources, and economic development (Van Dam et al., 2015). Also, Van Dam et al. (2015) stated that a reduction of the use of virgin aggregates and asphalt binder would improve pavement sustainability. From the literature, it is clear that the main environmental impact benefits of self-healing techniques are related to GHG emissions end energy consumption due to maintenance activities and maintenance work zone congestion, as well as raw material consumption (Tabaković and Schlangen, 2016). Thus, the environmental sustainability of the inclusion of MW heating self-healing technique in asphalt pavement maintenance was assessed trough the following environmental impact categories: (i) climate change, (ii) energy and (iii) raw materials consumption (aggregates and asphaltic materials).

(i) Climate change impact was quantified through the climate change indicator (CCI) measured in CO_2 equivalent units:

$$CCI = \sum_i m_i * GWP_i \qquad (1)$$

where m_i is the mass of the *i* GHG obtained from the LCI and GWP_i is the global warming potential of i GHG in a period of 100 years.

(ii) Energy was measured in MJ and was separated as recommended by FHWA (Harvey et al., 2016) into consumed energy and feedstock energy (potential to create energy of asphaltic materials if used as fuel) (Harvey et al., 2016).

(iii) To assess materials consumption several methodologies have been proposed in the literature (Klinglmair et al., 2014); however, in the present work, materials were grouped into aggregates and asphaltic materials (asphalt binder and asphaltic emulsion), as these are the main materials used in asphalt pavement maintenance.

The impacts of maintenance and rehabilitation activities considered are shown in Table 4.1.

Table 4.1 Maintenance activities environmental impacts

Activity	Unit	Energy (MJ/unit)	Feedstock energy (MJ/unit)	CCI (g CO_2eq/unit)	Materials consumption	
					Aggregates (Kg/unit)	Asphaltic material (Kg/unit)
3cm HMA overlay	m2	46*	144***	3600*	68.4	3.6
Slurry seal	m^2	6.5*	37.4***	300*	11.44	1.56
Surface patching	m^2	9.75	37.4	450	11.44	1.56
Granular base/sub base	t	113*	-	15000*	1000	-
Rehabilitation (7cm)	m^2	125.9*	336.0***	10392.7*	599.6	8.4
Rehabilitation (10cm)	m^2	179.8[1*]	480.0***	14940*	888.0	12.0
Rehabilitation (12cm)		212.5*	576.0***	17532.7*	933.6.0	14.4
Milling	m^2	1.7**		7.45E-1**	-	-

* Calculated from (Chehovits and Galehouse, 2010), ** Calculated from (Stripple, 2001), ***(Butt et al., 2012) (40MJ/kg)

The density of the asphalt concrete pavement considered was 2.4 t/m^3 with an asphalt binder content of 5%. The assessment considered three types of rehabilitation activities: milling of the existing asphalt layer, patching of 20% of the rehabilitated area, and the production, transportation, and laying of the new asphalt concrete layer. The first, second, and third alternatives consisted of a 7, 10 and 12 cm HMA overlay respectively. The density of the slurry seal was considered 13 kg/m^2 with 12% bituminous emulsion (60% asphalt binder). Lastly, surface patching refers to a local surface treatment, which was considered similar to slurry seal, but applied only over the affected areas to treat slight surface distress.

4.2.2. Economic sustainability

As explained in Van Dam et al. (2015) sustainable pavements must use financial resources economically, thus construction or maintenance alternatives resulting in lower costs through pavement life cycle would be more sustainable.

In the present study, economic sustainability was analysed through an LCCA following the recommendations of the US FHWA (FHWA, 2002; James Walls III and Smith, 1998; Rangaraju et al., 2008; Van Dam et al., 2015). The methodology specifies that agency costs and users' costs should be taken into account throughout the entire life cycle period assessed (Fig. 4.6). In the present case, maintenance alternatives for thin asphalt pavement were compared, and only the costs associated with the use stage of the road were considered. Regarding agency costs, maintenance activities and rehabilitation investments were taken into account. As to user costs, first, work site user-delay cost should be quantified; moreover, this delay results in variation in vehicles' fuel consumption, which was also considered as part of the users' cost. During normal circulation, assuming that the maintenance alternatives have equivalent effects on pavement condition from the user's perspective, vehicle operation costs would be equivalent for all alternatives; thus, it was not necessary to calculate them. Furthermore, due to a lack of information, accident costs were not considered as well; however, in future research, it would be important to include this last element because safety is one of the presumed advantages of self-healing maintenance techniques (Tabaković and Schlangen, 2016).

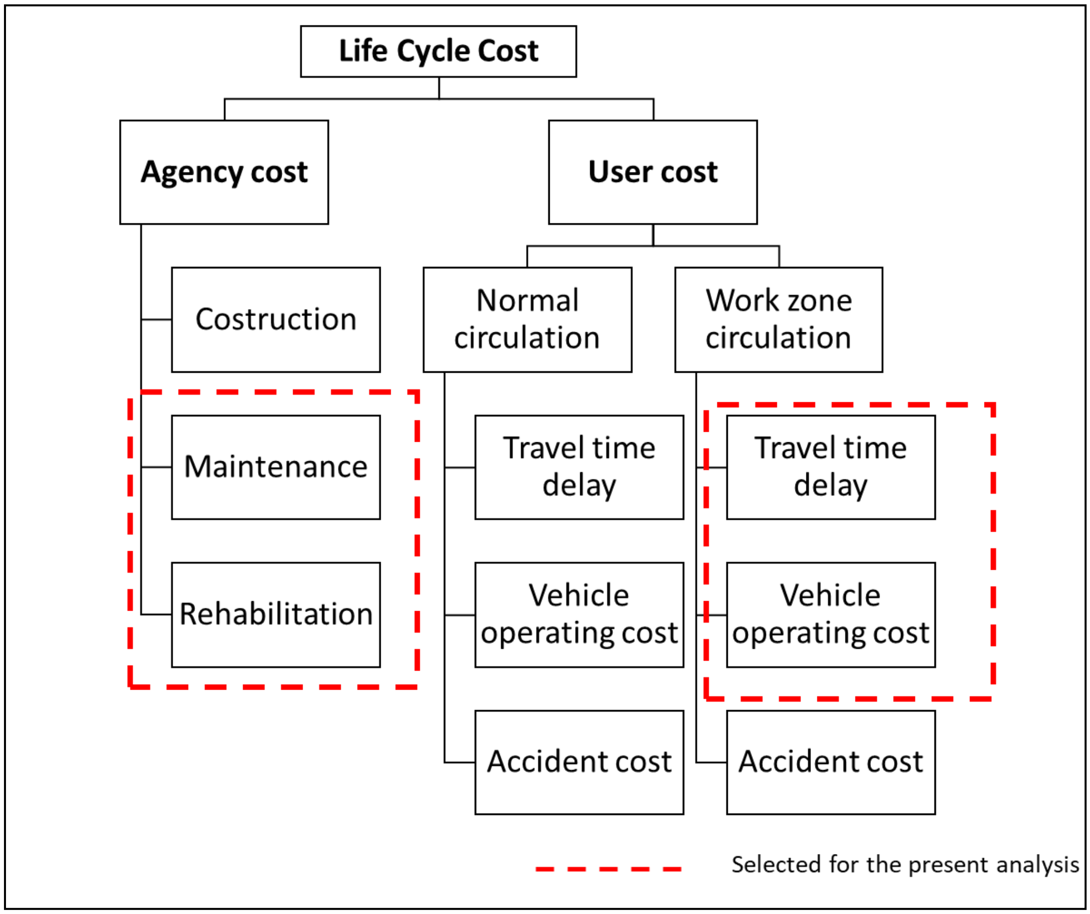

Figure 4.6 Life cycle costs (adapted from (Batouli et al., 2017))

The maintenance activity costs, fuel costs, and users' time costs were obtained from local market prices (Chile), as shown in Table 4.2. The discount rate considered was 6%, as recommended for Chilean infrastructure projects (Sistema Nacional de Inversiones, 2020) to compare alternatives through net present value (NPV). As costs are presented in 'Unidad de Fomento de Chile' (CLF by ISO 4217), which is a Chilean monetary unit that is adjusted by inflation and its value as of 23/02/2021 was 1CLF=41.5USD; no inflation rate was considered for the analysis. As in the case of environmental LCA, LCCA was performed for a period of 40 years.

Table 4.2 Costs at 2021

Concept	Unit	CLF/unit	USD/unit
HMA 3cm overlay	m^2	0.11	4.57
Slurry seal	m^2	0.08	3.32
Rehabilitation (7cm)	m^2	0.38	15.77
Rehabilitation (10cm)	m^2	0.50	20.75
Rehabilitation (12cm)	m^2	0.58	24.07
Surface patching	m^2	0.10	4.15
Milling	m^2	0.07	2.91
Traffic delay user's cost (car)	hour	0.25	10.38
Traffic delay user's cost (truck/bus)	hour	0.175	7.26
Diesel	L	1.7E-2	0.7
Gasoline	L	2.6E-2	1.08

4.2.3. Social sustainability

Social sustainability was partially studied through quantitative analysis of users costs and GHG emissions as recommended by Van Dam et al. (2015) and also through a qualitative analysis, taking into account the potential positive and negative effects of using MW-heating self-healing instead of the traditional maintenance techniques from the point of view of the main stakeholders: construction industry community, users community, neighbouring community (Almahmoud and Doloi, 2014), and governmental agency. Aspects such as contamination levels, extraction of material resources, work creation, utilisation of local labour, utilisation of innovation that produces business, proximity of local supply arrangements, lodging of complaints by the local community, and innovation improvement were taken into account (Balasbaneh and Marsono, 2020).

4.2.4. Case study

4.2.4.1. General definition

For the case study, the three thin asphalt pavement scenarios described in Tables 4.3 and 4.4 were proposed, based on data of existing roadways in the central zone of Chile (Rodríguez, 2014) and considering that pavement structures were designed for a service life of 20 years (Section 4.2.1.1). These scenarios were analysed for four different maintenance strategies, one with traditional maintenance techniques and the other including MW heating self-healing (Table 4.9). In the examples found in the literature maintenance strategies were defined arbitrarily (Lizasoain-Arteaga et al., 2019; Rodríguez-Alloza et al., 2019); however, in the present study maintenance strategies were defined using the software Highway Development and Management Model (HDM-4) (Odoki and Kerali, 2006) which simulates the evolution of pavement condition, and is a standard analytical procedure in the field of pavement management (Archondo-Callao, 2008).

Table 4.3 Proposed pavement structures for the three scenarios studied (based on Rodríguez, 2014)

		Scenario		
		A	B	C
	Section	1 lane per direction	1 lane per direction	1 lane per direction
	Lane width (m)	3.5	3.5	3.5
	Shoulder width (m)	1.5	1.5	1.5
Structure	Sub grade	CBR* 10%	CBR 10%	CBR 10%
	Subbase (CBR=40%)	20cm	30cm	30cm
	Base (CBR=80%)	20cm	20cm	30cm
	Surface layer (HMA)	5cm	5cm	7cm
	V_{max} (km/h)	90	90	90
Traffic composition	AADT**/lane	600	1200	5000
	% light vehicles	70	60	60
	% Buses	15	10	15
	% Trucks (2Ax***)	10	15	15
	%Heavy trucks (+2Ax)	5	15	10

*CBR = California Bearing Ratio ** Annual Average Daily Traffic ***Axle

Table 4.4 Vehicles characteristics adapted from (Rodríguez, 2014)

	Light vehicles	Buses	Trucks	Heavy trucks
Annual growing rate	3.0%	6.5%	2.5%	6.0%
ESAL	-	1.98	2.00	3.55

4.2.4.2. Maintenance

4.2.4.2.1. Criteria for traditional maintenance definition

In order to define the traditional maintenance activities, each scenario was modeled in the HDM-4 software and after running the model the needed maintenance activities were defined following the criteria in Table 4.5.

Table 4.5 Pavement condition admissible limits

Concept	Maximum
Roughness (m/km)	4.5
Raveling (% of total area)	20
Potholes (°/km)	40
Rutting (mm)	10
Cracking (%)	10
Total damaged area (%)	10

The maintenance activities for this case study were limited by the authors in order to simplify the analysis to two alternatives, Slurry Seal and Thin (3cm) HMA overlay, also considering a mayor rehabilitation (milling, base patching and HMA overlay) at the end of the 20 years period for which the pavement was designed. The intervention criteria defined based on Table 4.5 limits are presented in Table 4.6.

Table 4.6 Traditional maintenance intervention criteria

Activity	Intervention criteria
Thin HMA overlay	IRI*>4.5m/km or potholing >40°/km and total damaged area>15%
Slurry seal	Raveling>20% or structural cracking>10% or total damaged area>10%

*IRI= International Roughness Index

4.2.4.2.2. Criteria for microwave heating self-healing maintenance definition

The literature shows that MW heating self-healing is effective to repair cracks. Microwaves radiation interacts with the HMA aggregates, heating them, and then this heat is transferred to the asphalt binder, lowering its viscosity and allowing it to flow and fill the cracks present in the asphalt pavement structure (Trigos et al., 2019). However, other pavement distress should be treated through complementary traditional maintenance methods. The literature (de Solminihac et al., 2018) demonstrates that the reduction of cracking in asphalt pavements would also decrease the deterioration rate of potholes or patches; however, other distress such as ravelling, rutting, shoving, polished aggregates, and roughness, should be treated by conventional methods complementing the MW heating self-healing technique. Thus, micro milling and surface patching were included as part of MW heating self-healing maintenances strategies (Table 4.7).

Table 4.7 MW heating self-healing technique complementing activities

Activity	Intervention criteria
Micro milling	IRI>4.5m/km
Surface patching	Raveling>20%

There are several critical aspects to define when applying the MW heating self-healing technique such as optimum moment, temperature and duration of the heating process. With regard to optimum moment, researchers found that to achieve the best healing effect this technique should be applied when 35% of fatigue life is achieved (Garcia et al., 2020). Healing temperature should exceed the binder's softening point temperature as many researchers have pointed out (García, 2012; Tang et al., 2016). For instance Zhu et al. (2020), affirmed that optimum temperature is between 60°C and 80°C. Some studies have been conducted to determine the heating rate of asphalt pavement when microwave radiation is applied. For instance, for an 800W heater, a heating ratio of 0.284°C/s (17°C/min) was achieved (Sun et al., 2017). On the other hand, Salski et al. (2017) for a 1000W and 2450MHz heater achieved a rate of 5.7°C/min. Assuming that in this case study would be necessary to increase the asphalt concrete temperature from 25°C to 70°C, about 2.6 min $\left(\frac{(70°C-25°C)}{17°C/min}\right)$ to 7.9 min $\left(\frac{(70°C-25°C)}{5.7°C/min}\right)$ would be needed. However, as stated by Salski et al. (2017), more powerful heating equipment with power up to 30kW currently exists, so this heating time could be considerably reduced. Taking into account heating times from the literature, 80s for reaching 80°C from 20°C (1kW and 2.45Ghz microwave source) (Wang et al., 2020), 135s for reaching 70°C from 25°C (1kW and 1Ghz microwave source)

(Zumbo et al., 2021) and 90s for reaching 70°C from 25°C (700W and 2.450GHz microwave source) (Nalbandian et al., 2021b), it was reasonable to assume a heating time of 90s.

Another critical aspect for the analysis in order to assess the environmental and socio-economic sustainability of the inclusion of MW heating self-healing technique in asphalt pavement maintenance is the determination of the MW heating effect on the pavement's life extension. For instance, the needed frequency of MW heating applications on the pavement, directly affects the amount of environmental impacts such as GHG emissions or energy consumption, and socio-economic impacts such as maintenance and user's cost. Based on Nalbandian et al.'s (2021b) results, a fatigue life extension of 20% was assumed for conventional HMA pavement. In other words, if the pavement was originally designed for rehabilitation in year 20, MW heating self-healing would increase by 20% (4 years) this period.

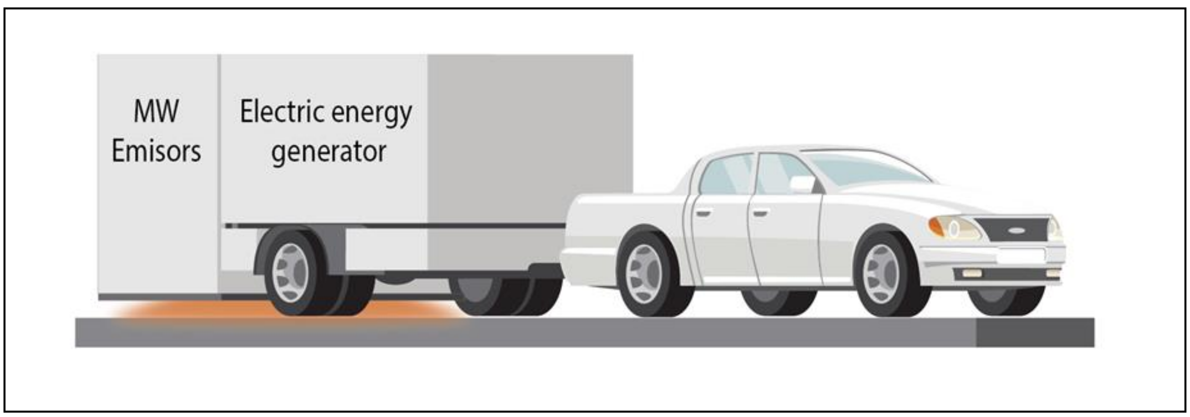

Figure 4.7 Schematic view of MW heating self-healing equipment

Regarding the MW heating self-healing technique LCIA and cost, additional assumptions were needed. First, four microwave sources (magnetrons) of 10kW each were considered to make up the heating device, so the power source of a total power of 40kW was needed. This was addressed using four 10kW diesel generators (Fig. 4.7). Then, a conventional pick-up truck with a trailer was considered to move the MW heating device as well as the generators. Because the MW heating equipment available to date are static (Fig. 4.8), a discrete advance was considered with 1.5 minute of the heating phase and then 1 minute for advancing to the next section (Fig. 4.9). Lastly, to estimate the operating costs, it was considered that three workers are needed in the field for the application of this technique. Based on the above-mentioned assumptions, using the appropriate calculations the environmental impact and unitary cost were estimated (Table 4.8).

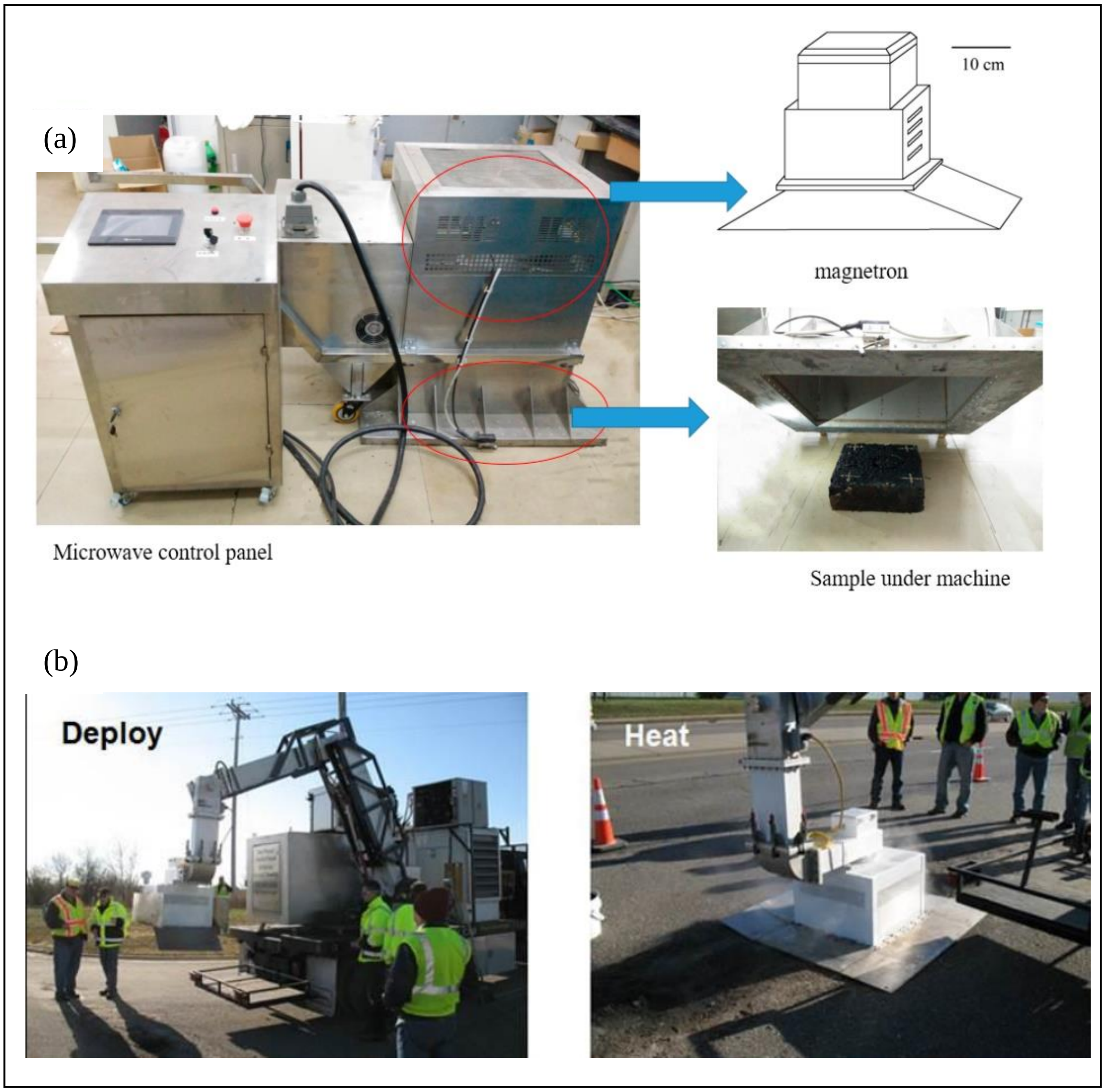

Figure 4.8 MW heating prototypes. a) (Liu et al., 2018), b) (Zanko et al., 2016)

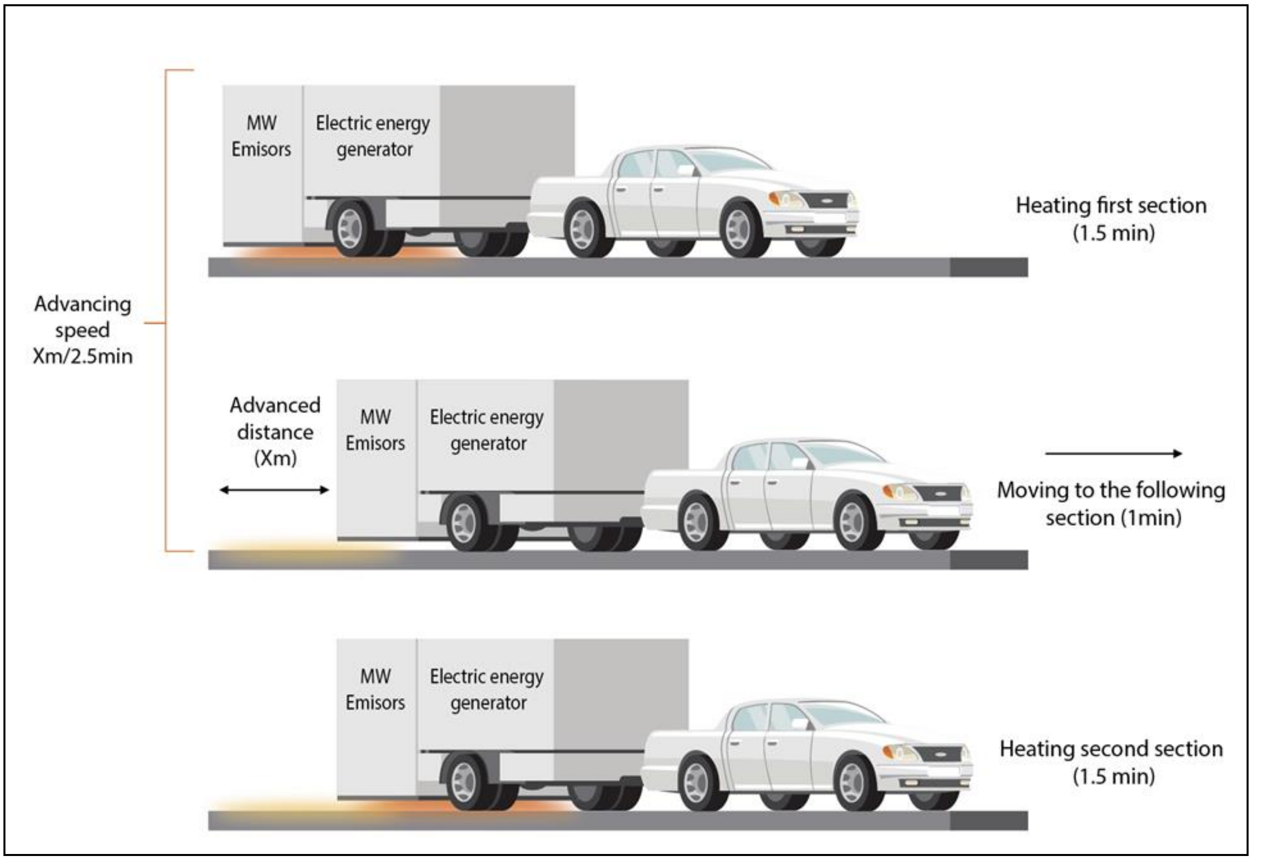

Figure 4.9 MW heating self-healing working process

Table 4.8 MW heating self-healing technique environmental impact and application cost

Concept	Unit	Amount
Energy	MJ/lane-km	6.39E+04
Feedstock energy	MJ/lane-km	-
CCI	g CO2eq/lane-km	4.62E+6
Aggregates	kg/lane-km	-
Asphaltic material	kg/lane-km	-
Cost	CLF/lane-km	99.1
Cost	USD/lane-km	4,112

The maintenance alternatives including self-healing technique were developed assuming three levels of effectiveness of the MW heating self-healing treatment. MW1 was the most optimistic alternative considering that no other maintenance activity is necessary when the self-healing technique is applied as considered by Lizasoain-Arteaga et al. (2019) and Rodríguez-Alloza et al. (2019). MW2 alternative was proposed based on the previously explained concept that MW heating needs complementary maintenance activities. Lastly, MW3 alternative was the most pessimistic alternative, proposed based on the same fundamentals as that of MW2 but considering a lower effectiveness of MW heating; thus, one MW application every five years is needed.

4.2.4.2.3. Maintenance alternatives

Based on the criteria described in the previous sections, the maintenance alternatives for the three thin asphalt pavement scenarios were defined, as presented in Table 4.9. The frequency of the application of the traditional maintenance techniques was a result of running the three scenarios' models in HDM-4 with the previously mentioned intervention criteria (Section 4.2.4.2.1 and 4.2.4.2.2), and the MW heating self-healing applications (MW in Table 4.9) were established as explained in Section 4.2.4.2.2.

Table 4.9 Maintenance alternatives for each scenario

Scenario A							
Traditional		MW1		MW 2		MW 3	
Year	Activity	Year	Activity	Year	Activity	Year	Activity
0	Construction	0	Construction	0	Construction	0	Construction
10	Slurry Seal	10	MW	10	MW	5	MW
20	Rehabilitation (7cm)	24	Rehabilitation (7cm)	13	Surface Patching	10	MW
30	Slurry Seal	34	MW	17	Surface	13	Surface Patching

					Patching		
40	Rehabilitation (7cm)			21	Surface Patching	15	MW
				24	Rehabilitation (7cm)	17	Surface Patching
				34	MW	20	MW
				37	Surface Patching	21	Surface Patching
						24	Rehabilitation (7cm)
						29	MW
						34	MW
						37	Surface Patching
						39	MW
Scenario B							
Traditional		MW 1		MW 2		MW 3	
Year	Activity	Year	Activity	Year	Activity	Year	Activity
0	Construction	0	Construction	0	Construction	0	Construction
10	Slurry Seal	10	MW	10	MW	5	MW
20	Rehabilitation (7cm)	24	Rehabilitation (7cm)	13	Surface Patching	10	MW
30	Slurry seal	34	MW	17	Surface Patching	13	Surface Patching
40	Rehabilitation (7cm)			19	Micro milling	15	MW
				21	Surface Patching	17	Surface Patching
				24	Rehabilitation (7cm)	19	Micro milling
				34	MW	20	MW
				37	Surface Patching	21	Surface Patching
						24	Rehabilitation (7cm)
						29	MW
						34	MW
						37	Surface Patching
						39	MW
Scenario C							
Traditional		MW 1		MW 2		MW 3	
Year	Activity	Year	Activity	Year	Activity	Year	Activity
0	Construction	0	Construction	0	Construction	0	Construction
10	Slurry Seal	10	MW	10	MW	5	MW
16	Slurry Seal	24	Rehabilitation (10cm)	13	Surface Patching	10	MW
20	Rehabilitation (10cm)	34	MW	17	Surface Patching + Micro milling	13	Surface Patching
30	Slurry Seal			21	Surface Patching	15	MW
36	Slurry Seal			24	Rehabilitation (10cm)	17	Surface Patching + Micro Milling
40	Rehabilitation (10cm)			34	MW	20	MW

	37	Patching	21	Surface Patching
			24	Rehabilitation (10cm)
			29	MW
			34	MW
			37	Surface Patching
			39	MW

4.2.4.2.4. Maintenance work zone congestion

For all maintenance work, it was assumed that the construction company would be able to close 500m of lane at a time. Considering a safety width of 0.5m and using the existing 1.5m shoulder on the side that is not being repaired, a total lane width of 2.3m in both directions (Fig. 4.10b) will remain for the traffic flow. Following the recommendations of the National Commission of Traffic Safety of Chile (CONASET, 2013) if a safety width of 0.5m is followed, then the work zone maximum speed is defined as 40km/h.

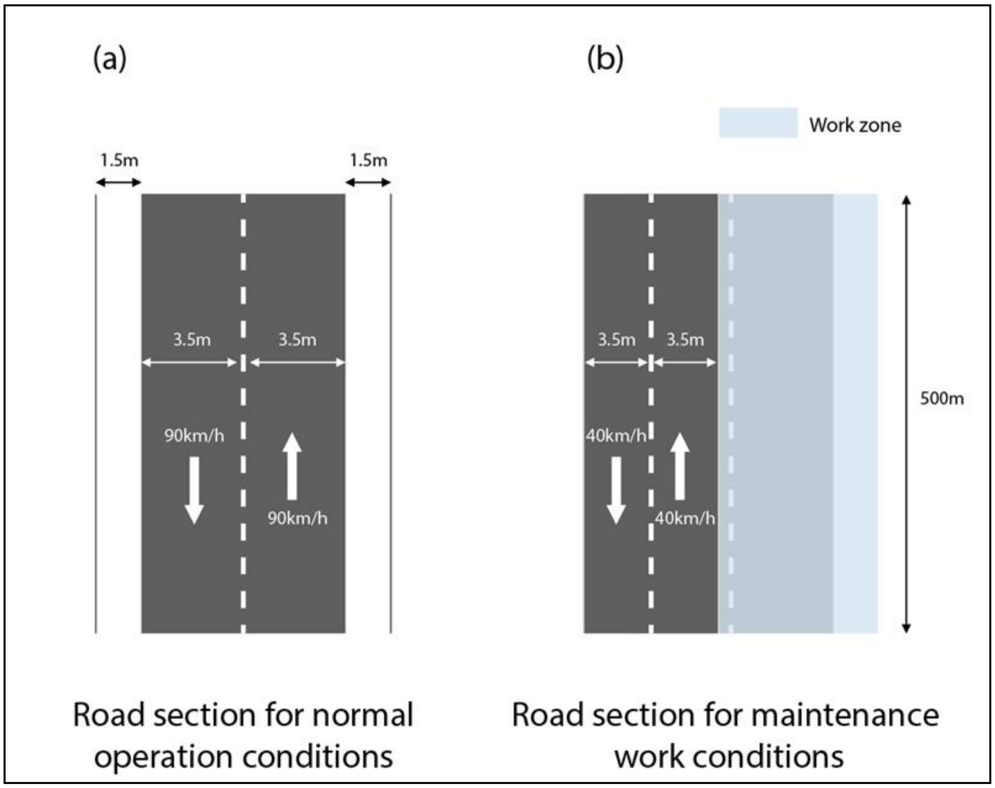

Figure 4.10 Top view of road section for (a) normal operation conditions and (b) maintenance work conditions

To calculate and evaluate vehicles' associated environmental and socio-economic impacts, it is necessary to calculate the users' delay time, and the vehicles' fuel consumption, which depend directly on the time needed to accomplish the maintenance activities. Table 4.10 shows the estimated lane closure times for each maintenance activity.

Table 4.10 Road closure time for different maintenance activities

Activity	Days/500m-lane	Nights/500m-lane
Slurry seal	2	1
Micro milling	1	0

Rehabilitation	10	9
Light patching	1	0
Microwave heating	0	3.5

4.2.5. Sensitivity analysis

A sensitivity analysis was carried out to identify the most relevant parameters of the analysis. These parameters should be optimised to improve the MW heating self-healing maintenance performance for thin asphalt pavements. The parameters modified for the sensitivity analysis related to the MW heating device were: MW heating device advancing speed (Fig. 4.9), MW heating device power, and MW heating device pick-up truck fuel consumption rate (Fig. 4.7), all of which have effects on the environmental, economic and social impact of MW heating self-healing technique application, for instance due to variations on GHG emissions, maintenance costs, road user's cost due to road work related traffic congestion. Then, regarding traditional maintenance activities, their environmental impacts and cost variations were also analysed.

MW heating device speed may vary due to a reduction in heating time, moving to the next position time, or the MW heating device heating area. Moreover, this speed must be defined by the MW heating device technician/user when applying the MW heating self-healing technique, depending on equipment characteristics, pavement susceptibility to MW, and climate conditions, among other parameters. As expressed in Section 4.3.2.2. a heating time of 1.5min and a moving to the next position time of 1min were considered (Fig. 4.9). For the sensitivity analysis, various alternatives were arbitrarily studied, such as an increment to 2min of heating time (-17% of original speed), a reduction of heating time to 1min and 0,5min (+25% and +67% of original speed respectively), and the assumption that the heating process can be continuous without stopping, thus considerably increasing the advancing speed. For instance, a heating time of 1.5min without moving to the next position time because continuous movement is achieved, results in an increase of 67% in advancing speed (Fig. 4.8). However, the power of the MW heating device, which was initially assumed to be 40kW (four MW sources of 10kW) varied from 10kW (-75%) up to 70kW (+75%). Moreover, the carrying pick-up truck (Fig.4.7) fuel consumption rate originally assumed as 5L/min (near to 15km/L at 80km/h speed) would vary from 1L/h (near to pick-up trucks idle consumption) up to 10L/h (8km/L at 80km/h speed). The base situation for this analysis, as mentioned above, considered a heating time of 1.5min, moving forward time of 1 min, MW heating device´s total power of 40kW, and MW heating device carrying pick-up truck fuel consumption of 5L/h.

The environmental impacts of traditional maintenance, can vary from region to region, depending on the technology available, construction methods, geographical conditions, and electric energy matrix composition among other parameters. Thus, it is crucial to study their variation. A review of various HMA providers' environmental product declaration (EPD), found a standard deviation of 30% in HMA CCI (Baker Rock Resources, 2019; Construcciones y Obras Llorente S.A., 2019; NCC Industry Nordic AB, 2019; Payne and Dolan Inc., 2020; Vulcan Materials Company Mountain West Division, 2019). As a result, in the present study, a range of -50% and +100% variation was considered. Lastly, regarding traditional maintenance costs, this may be the parameter that has the least uncertainties; however, a range of variation between -50% and +50% was considered in the analysis.

4.3. Results and discussion

4.3.1. Environmental life cycle assessment (LCA)

4.3.1.1. Energy consumption

The first environmental impact category selected to evaluate the impact on pavement environmental sustainability of the inclusion of MW heating self-healing technique in asphalt pavement maintenance was energy consumption. This category included the energy consumption from maintenance activities, also from the vehicles in the work zone (maintenance work conditions), and, separately, the feedstock energy in the materials used for maintenance.

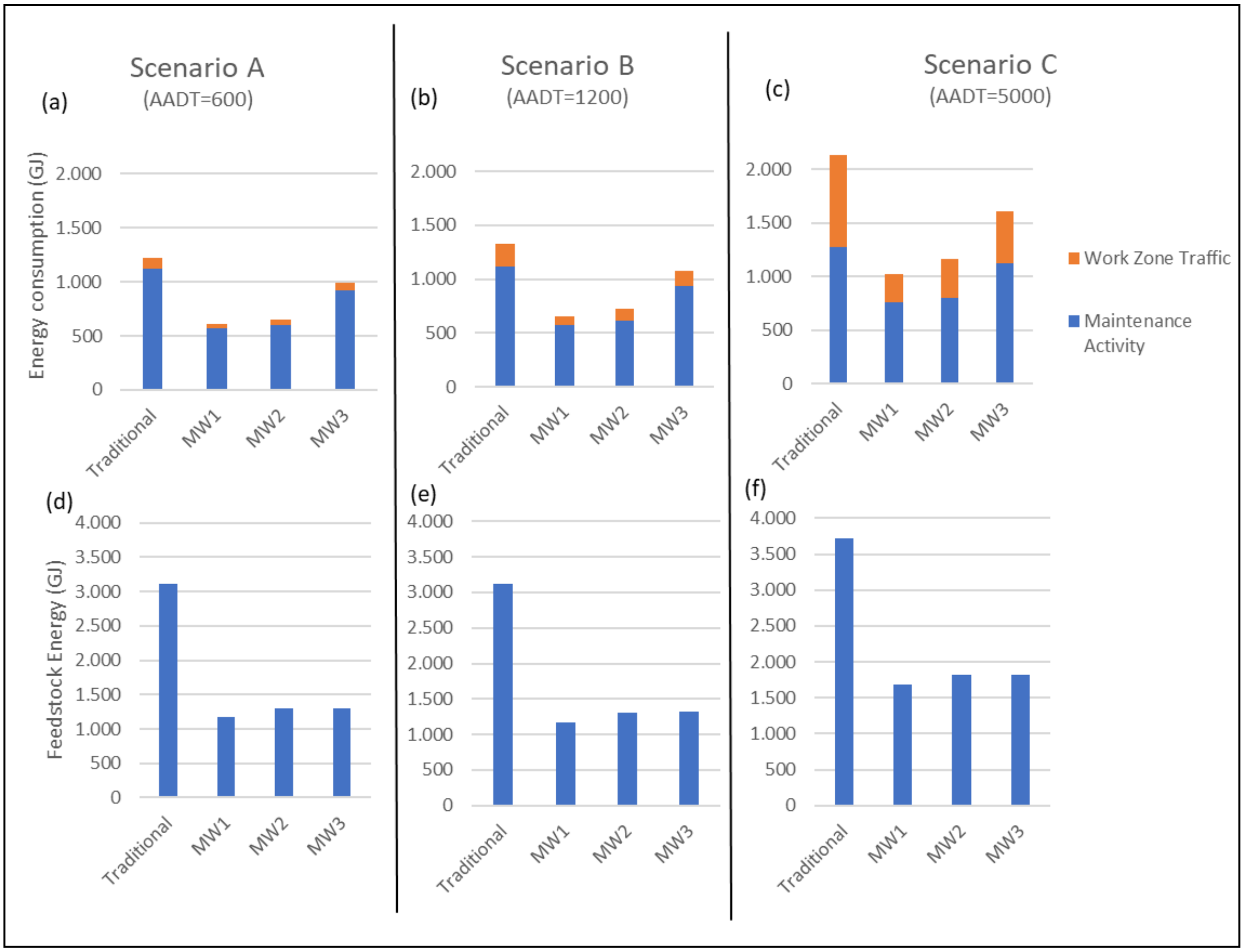

Figure 4.11 Energy consumption and feedstock energy for each maintenance alternative considering; (a) and (d) Scenario A; (b) and (e) Scenario B; (c) and (f) Scenario C

Figure 4.11a shows that for Scenario A, maximum energy consumption was achieved by the traditional maintenance alternative (1,225 GJ), followed by MW1, MW2 and MW3 (609 GJ, 645 GJ, and 989 GJ, respectively). The energy consumption for MW3 was higher than for MW1 and MW2, because this strategy doubled the MW interventions (Table 4.9). Despite being a pessimistic maintenance alternative for MW, MW3 showed a 17% reduction in energy consumption compared to the traditional maintenance alternative.

Figure 4.11a also shows that energy consumption from traffic was only between 7% and 9% of the total energy, which is explained by the low traffic level considered in Scenario A.

Figure 4.11b (Scenario B) also shows that the maximum energy consumption was achieved by the traditional maintenance alternative (1,330 GJ); MW1 and MW2 hit the mark of 653 GJ and 723 GJ, respectively, while the energy consumption for MW3 was 1,079 GJ. In this scenario, the energy consumption of vehicle flow is between 13% and 16% of the total energy, which is more significant than in Scenario A. MW1 and MW2 energy consumption was about 50% of traditional maintenance alternative, while MW3 was approximately 15% lower than traditional maintenance.

Scenario C (Figure 4.11c) shows an overall higher total energy consumption caused by the importance of the vehicles' work zone-related consumed energy due to the increment in AADT in this scenario, representing between 26% and 40% of the total consumed energy in each maintenance alternative. In this scenario, the energy consumption for the traditional maintenance alternative exceeded 2,000 GJ, while for MW1, MW2, and MW3, it was 1,023 GJ, 1,166 GJ, and 1,609 GJ, respectively (20% less than the traditional alternative), again showing the overall lower energy consumption of MW heating self-healing maintenance alternatives. In this higher traffic scenario, more traditional maintenance interventions are required; hence, the work zone congestion related energy consumption of traditional alternative was larger in proportion to the other alternatives' work zone energy thus incrementing the energy efficiency of MW heating self-healing alternatives.

Figures 4.11d to 4.11f present the feedstock energy, which was proportional to asphalt consumption, as explained in Section 4.2.1.3. A substantial difference between traditional maintenance and MW heating self-healing alternatives was observed, as shown in Figures 4.11d to 4.11f, indicating that feedstock energy for MW heating self-healing alternatives was only 38 - 49% of the traditional maintenance alternative.

Overall, in the three scenarios analysed, MW heating self-healing alternatives showed a beneficial effect on energy consumption and feedstock energy compared to traditional maintenance, although the MW heating self-healing technique should be complemented with some traditional maintenance techniques to address pavement surface distresses that are not reduced by the application of the MW heating self-healing technique. As a result, the inclusion of MW heating self-healing technique in asphalt pavement maintenance alternatives reduce the environmental impact of pavement maintenance regarding to energy consumption.

4.3.1.2. Climate change impact

The second environmental impact category selected to evaluate the impact on pavement environmental sustainability of the inclusion of MW heating self-healing technique in asphalt pavement maintenance was climate change. As explained in Section 4.2.1.3, the climate change impact of the presented alternatives was studied through the CCI in accumulated tonnes of equivalent CO_2.

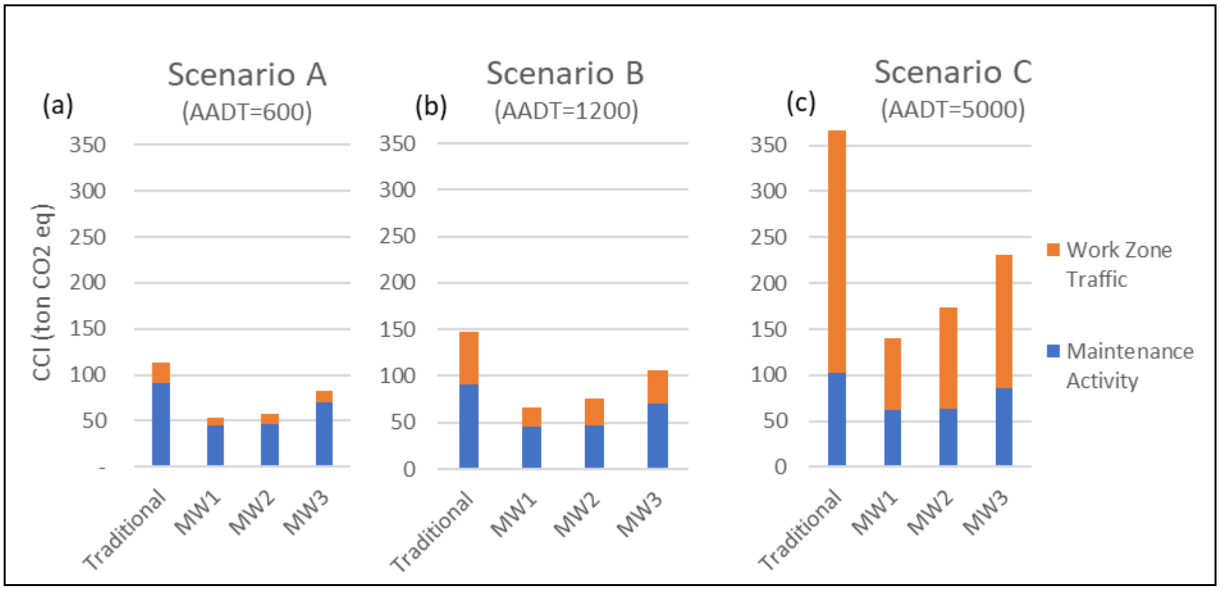

Figure 4.12 Climate change impact (CCI) for each maintenance alternative considering (a) Scenario A, (b) Scenario B, and (c) Scenario C

Figure 4.12a shows that for Scenario A, maximum CCI was also achieved by the traditional maintenance alternative (113tonnes), followed by MW3, MW2, and MW1 (83 tonnes, 57 tonnes and 53 tonnes, respectively) in descending order. MW1 and MW2 CCI represented around 50% of the traditional maintenance alternative´s CCI. Despite being a pessimist MW maintenance alternative, MW3 reduced traditional maintenance CCI by 26%. Figure 4.12a also shows that work zone traffic-produced CCI is only between 14% and 20% of the total CCI, achieving its maximum (20%) for traditional maintenance alternative, as expected due to traffic disruption associated to its maintenance techniques.

Figure 4.12b shows that for Scenario B, the maximum CCI was achieved by the traditional maintenance activity (147 tonnes) while MW1 again was less than half with 66 tonnes, also near MW2 with 76 tonnes, and finally MW3 resulted in 106 tonnes showing a reduction of

28% compared to the traditional alternative. In this scenario, the work zone traffic-related CCI represented between 31% and 38% of the total CCI for each alternative. This increment compared to Scenario A (Fig.4.12a) is explained by the increment in AADT.

Figure 4.12c shows that in Scenario C, the gap between traditional maintenance and MW heating self-healing alternatives regarding CCI was drastically increased. Traditional maintenance reached a total of 366 tonnes, while MW1, MW2 and MW3, reached 141 tonnes, 174 tonnes and 231 tonnes respectively. MW3, being the MW heating self-healing most pessimist alternative, achieved a 37% reduction in total CCI. This is explained by the increment in AADT (Table 4.3), which also resulted in an increment in the incidence of work zone traffic CCI in the total CCI, reaching values between 56% and 72% of the total CCI in each alternative.

These results are consistent with the findings of Rodríguez-Alloza et al. (2019) and Lizasoain-Arteaga et al. (2019), who indicated a 16% and 10- 25% reduction, respectively, of GHG emissions achieved during the pavement´s life cycle. However, in this current case, the reduction found was greater in all three scenarios because the microwave self-healing technique is applied to traditional asphalt mixtures without any metallic additives cancelling the increment of GHG emissions produced during pavement´s construction phase.

These results showed that, the inclusion of MW heating self-healing technique in asphalt pavement maintenance alternatives reduce the environmental impact of pavement maintenance regarding to climate change.

4.3.1.3. Materials consumption

The third environmental impact category selected to evaluate the impact on pavement environmental sustainability of the inclusion of MW heating self-healing technique in asphalt pavement maintenance was materials consumption. This environmental impact category was addressed by quantifying the amount of aggregate and asphaltic materials (asphalt binder and asphaltic emulsion) used in each alternative. As shown in Figure 4.13, this was the category in which the environmental impact reduction was more evident.

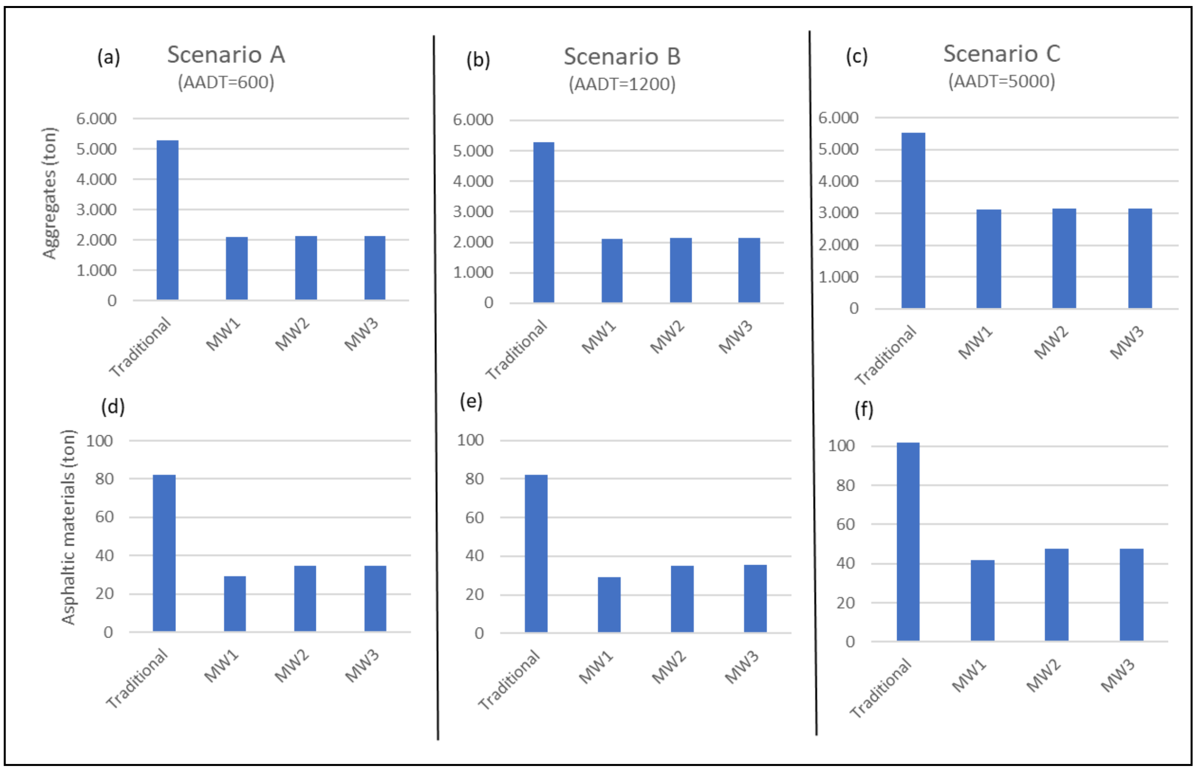

Figure 4.13 Materials consumption for each maintenance alternative considering; (a) and (d) Scenario A, (b) and (e) Scenario B, and (c) and (f) Scenario C

In Scenario A (Fig. 4.13a), the traditional maintenance alternative presented the maximum aggregate consumption with a total of 5,287 tonnes, followed by MW1, MW2 and MW3 with a total of 2,099 tonnes, 2,137 tonnes and 2,137 tonnes respectively. MW2 and MW3 had the same consumption because they imply the same traditional maintenance activities to complement MW heating self-healing; this pattern is repeated in al scenarios due to the maintenance alternatives definitions. In this case (Scenario A), a reduction of around 60% in the aggregate consumption was achieved for MW alternatives compared to traditional maintenance alternative.

Figure 4.13b (Scenario B) also shows that the maximum consumption of aggregates was achieved by the traditional maintenance alternative (5,287 tonnes, the same maintenance activities as in Scenario A), while MW1, MW2, and MW3 alternatives resulted in an aggregate consumption of 2,099 tonnes, 2,140 tonnes and 2,140 tonnes respectively. In Scenario B, a reduction of around 60% in the aggregate's consumption is obtained by MW alternatives compared to traditional maintenance.

Lastly, Figure 4.13c shows the results for Scenario C, where again traditional maintenance resulted in the maximum consumption of aggregates reaching a total of 5,526 tonnes compared to MW1 (3,108 tonnes), MW2 (3,150 tonnes), and MW3 (3,150 tonnes). In this scenario, the reduction in aggregates consumption of MW alternatives compared to traditional maintenance alternative was around 43%, less than in Scenario A and Scenario B. This is due to the increase in traditional maintenance interventions needed to complement MW heating self-healing caused by the increase in AADT.

Regarding asphaltic materials consumption, Scenario A and Scenario B presented the same results (Fig. 4.13d and Fig. 4.13e), where the traditional maintenance alternative exhibited the maximum consumption (82.3 tonnes), followed by MW2 and MW3 alternatives with 34.6 tonnes and lastly MW1 with 29.4 tonnes of asphaltic materials. Thus, these scenarios presented a 57-64% reduction in asphaltic material consumption of MW alternatives compared to traditional maintenance alternatives.

Similarly, in Scenario C (Fig. 4.13f) the traditional maintenance reached the maximum in asphaltic materials consumption with a total of 101.6 tonnes followed by MW2 and MW3 with 47.4 tonnes and MW with 42.0 tonnes. As in the case of aggregates consumption, Scenario C experienced an increment compared to the other scenarios because of the need for more maintenance interventions due to the increment in AADT. In this scenario, a 53-59% reduction in consumption of asphaltic materials was achieved by the MW alternatives compared to the traditional maintenance alternative.

These significant reductions in materials consumption were expected, as previously stated in the literature (Tabaković and Schlangen, 2016) and also considering that MW heating self-healing is a technique that does not include the use of construction materials. In MW alternatives only the complementary traditional techniques are responsible for consumption. As a result, the inclusion of MW heating self-healing technique in asphalt pavement maintenance alternatives reduce the environmental impact of pavement maintenance regarding to materials consumption.

4.3.2. Life cycle cost analysis

As explained in Section 4.2.2 economic sustainability was evaluated through a LCCA comparing the NPV of the different alternatives.

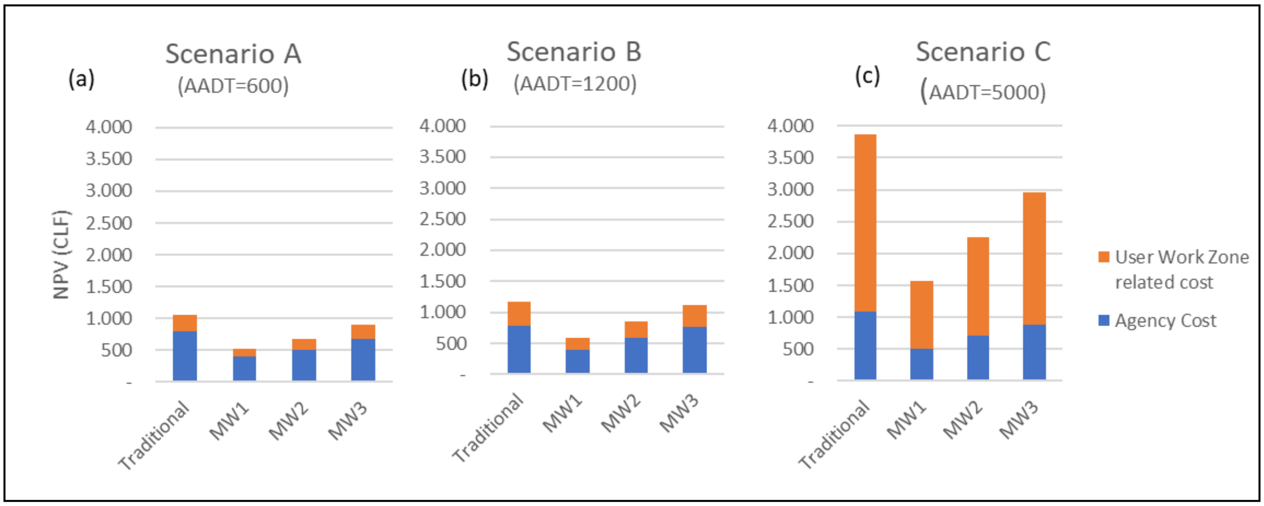

Figure 4.14 Net present value for each maintenance alternative considering (a) Scenario A, (b) Scenario B, and (c) Scenario C

Figure 4.14a shows that in Scenario A, the maximum cost was achieved by the traditional maintenance alternative (1,062CLF), followed by MW3 (906CLF), MW2 (676CLF), and MW1 (528CLF), in descending order. MW3 cost is noticeably higher than MW1 and MW2 because of more maintenance interventions (double MW heating self-healing interventions) with the resulting traffic disruption associated costs. In this scenario, the most pessimistic MW alternative, MW3, reached a 15% reduction compared to the traditional maintenance alternative cost. Figure 14a also shows that the users' work zone-related cost represented near 25% of total cost for all alternatives.

In Scenario B (Fig. 4.14b), the traditional maintenance also achieved the maximum cost through the pavement life cycle with a total NPV of 1,177CLF, followed by MW3, MW2, and MW1 with 1,116CLF, 859CLF, and 586CLF respectively. In this scenario, MW1 and MW2 alternatives presented 50% and 27% reductions, respectively, compared to the traditional maintenance alternative; however, MW3 presented only a 5% reduction. This small reduction for the most pessimist MW alternative implies that if the worst assumptions were made, in Scenario B no substantial economic advantage would be found for MW heating self-healing maintenance in comparison to traditional maintenance. Mainly, this results from the need for more traditional maintenance techniques applications to complement MW self-healing technique due to the increment in AADT, which narrows the cost gap between alternatives. Regarding the composition of the total cost, Figure 14b shows that for Scenario B, around 30% of the total cost corresponded to the users' work zone-related costs.

Lastly, in Scenario C (Fig. 4.14c), the results changed again to favour MW alternatives. The maximum cost was presented by the traditional maintenance alternative, reaching a total of 3,864CLF, followed by MW3 (2,955CLF), MW2 (2,258CLF), and MW1 (1,576CLF), in descending order. In this scenario, the most pessimistic MW alternative, MW3, presented a substantial 24% reduction in the total cost compared to the traditional maintenance alternative, while MW2, which is a reasonable alternative had a 42% reduction. This change, compared to Scenario B is mainly due to the increment in AADT of more than 400%, which results in a great increment in the users' work zone-related cost due to the presence of more vehicles consuming more fuel and more passengers losing more time.

Lastly, in Scenario C, the incidence of users' work zone-related costs in the total costs increased, reaching levels between 68% and 72%.

Rodríguez-Alloza et al. (2019) stated that self-healing roads have 32% lower costs over their life span than traditionally constructed and maintained roads. The present study shows that between 24% (Scenario C, MW3) and 64% (Scenario A, MW2) reductions in cost could be reasonably achieved depending on the scenario (traffic volume) and MW heating self-healing technique assumed performance. Being the NPV achieved through the LCCA the indicator of economic sustainability, the reduction in NPV presented by the MW maintenance alternatives in comparison to the traditional alternatives shows that these alternatives are more sustainable than traditional maintenance from the economic perspective.

However, the present study findings also show that for medium-level traffic scenarios, where several traditional maintenance interventions are needed to complement the MW heating self-healing technique in comparison to the traditional maintenance alternative, the economic benefit of this novel maintenance technique was not as evident, presenting a reduction of only 5% when the worst MW alternative was compared with the traditional alternative.

4.3.3. Social life cycle assessment

Several benefits have been identified for MW heating self-healing technique in comparison to traditional maintenance alternatives.

Quantitatively, as stated in Van Dam et al. (2015) reduction in GHG emissions or users cost lead to a more sustainable pavement from the social perspective. As shown in sections 4.3.1.2 and 4.3.2, the inclusion of MW heating self-healing technique in asphalt pavement maintenance results in GHG emissions reduction and also user costs (linked to user time and vehicle fuel consumption) reduction. As a result, incorporating MW heating self-healing technique in asphalt pavement maintenance alternatives increase pavement sustainability compared to traditional maintenance.

Qualitatively, from the perspective of the roadway surrounding community, an improvement in their life quality during maintenance is identified caused by a reduction of traffic congestion, reduction of accidents, lower noise levels, and reduced delay time in comparison to those issues during traditional maintenance. Given that MW self-healing does not need additional materials, the local community would have positive experiences with reduced noise and traffic disruptions from hauling the materials and HMA production, and the communities surrounding raw materials extraction areas would also be benefited. However, it should be mentioned that work opportunities related to maintenance activities would shrink for local workers because only a few and specialized professionals would be needed to apply MW self-healing.

From the perspective of the governmental agency, lower impacts on the local community would bring a reduction in the complaints received, as well as an increase in the satisfaction of the community with the government.

Lastly, from the point of view of the construction industry, as MW self-healing is a simpler technique compared to traditional techniques with regards to materials acquisition and personal management equipment logistics, it would result in less uncertainties thus easing risk and project management.

4.3.4. Sensitivity analysis

As the results in the previous sections have shown that the most pessimistic MW maintenance alternatives also presented clear advantages in terms of environmental impact to traditional maintenance alternatives, the MW3 alternative in Scenario B was selected for the sensitivity analysis because it was the most critical scenario in terms of total cost (Section 4.3.2). Following the criteria explained in Section 4.2.5, total consumed energy, CCI, and cost were selected as the main categories to analyse, as feedstock energy and materials consumption were the categories where MW alternatives had by far the lower impact than traditional alternatives.

4.3.4.1. Cost sensitivity analysis

Figure 4.15 shows the results of the cost sensitivity analysis in which traditional maintenance cost and MW speed, MW power, and fuel consumption of MW pick-up truck are expressed as a variation in percentage to the base situation established in Sections 4.2.2 and 4.2.4.2.2. The results showed that MW speed and traditional maintenance costs were the most critical parameters, and their variation would drastically change the results, whereas MW heating device power and pick-up truck's fuel consumption rate had negligible effects. A reduction of the heating time to 1 min (25% increase in advancing speed (Fig. 4.9)) would result in a cost reduction of 6% (from 95% to 89%), whereas achieving a continuous movement of the heating device with an advancing speed of 0.67 m/min (67% increase in advancing speed) resulted in a reduction from 95% to 83% of the traditional maintenance cost.

As expressed in Section 4.2.5 a variation on assumed traditional maintenance costs was also studied. Results showed that, if traditional maintenance costs were 10% or 20% lower than the assumed costs, an increment in the MW3 cost in comparison to traditional alternative would be experienced from 95% up to 97% and 99%, respectively.

Hence, it is important from the point of view of economic sustainability, to accurately define traditional maintenance costs and try to technically improve MW heating devices to achieve a continuous working process, reaching higher advancing speeds.

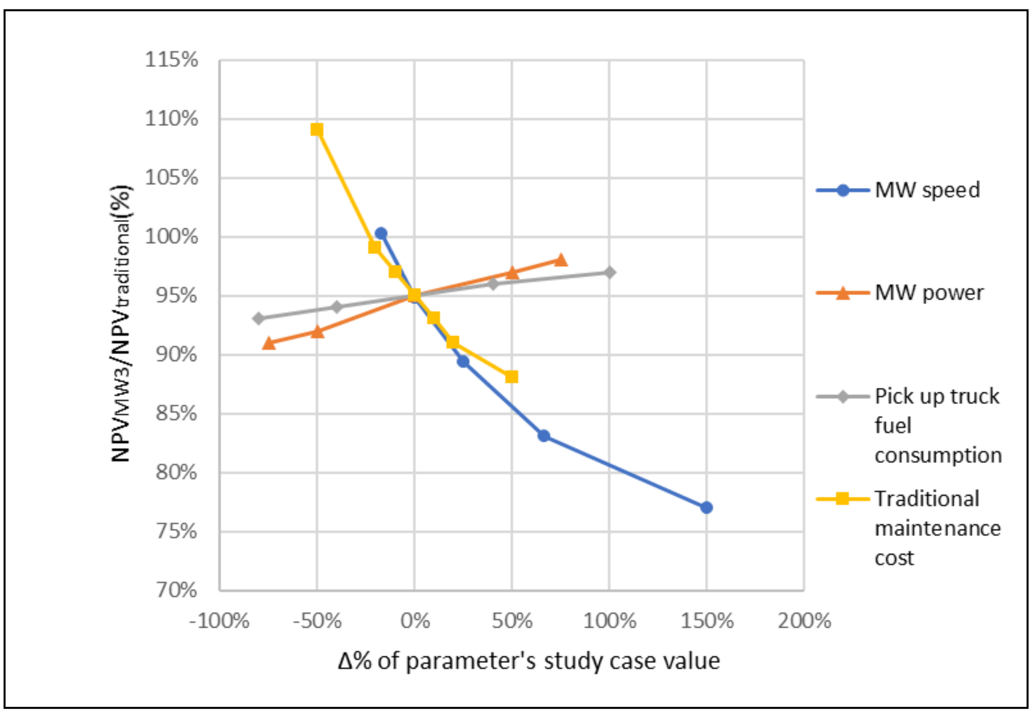

Figure 4.15 Cost sensitivity analysis

4.3.4.2. Climate change indicator sensitivity analysis

As shown in Figure 4.16, CCI is very sensitive to MW heating device speed and its power. As in the case of cost, reducing heating time to 1 min or achieving a continuous advance at a 0.67 m/min speed would allow a reduction in the CCI from 72% to 67% or 60% of the traditional maintenance CCI, respectively. However, a variation of the MW heating device power of +50% or -50% would result in an increment of up to 80% or a reduction of up to 64% of the traditional maintenance CCI; moreover, an increment of 100% of the needed power would not be enough to harm MW3 CCI-related benefit, augmenting the CCI value of MW3 alternative to 88% of traditional maintenance ICC.

The other parameter to which CCI is sensitive is traditional maintenance activities CCI. An accurate estimation of this value is needed to correctly evaluate MW heating self-healing maintenance alternative's environmental sustainability. If the CCI of the traditional maintenance techniques were 20% or 50% lower than the CCI assumed, MW3's CCI would augment from 72% to 76% or 85%, respectively, compared to traditional maintenance alternative's CCI. However, coincidentally with MW heating device power, reasonable variations in the traditional maintenance alternative's CCI would not affect the MW maintenance alternative's substantial reduction in CCI compared to the traditional maintenance alternative. Lastly, if instead of using diesel power generators or fuel propelled pick-up truck as in the studied case, solar energy-powered generators or electric engine pick-up truck were used, the performance of MW heating self-healing technology regarding CCI would be substantially improved.

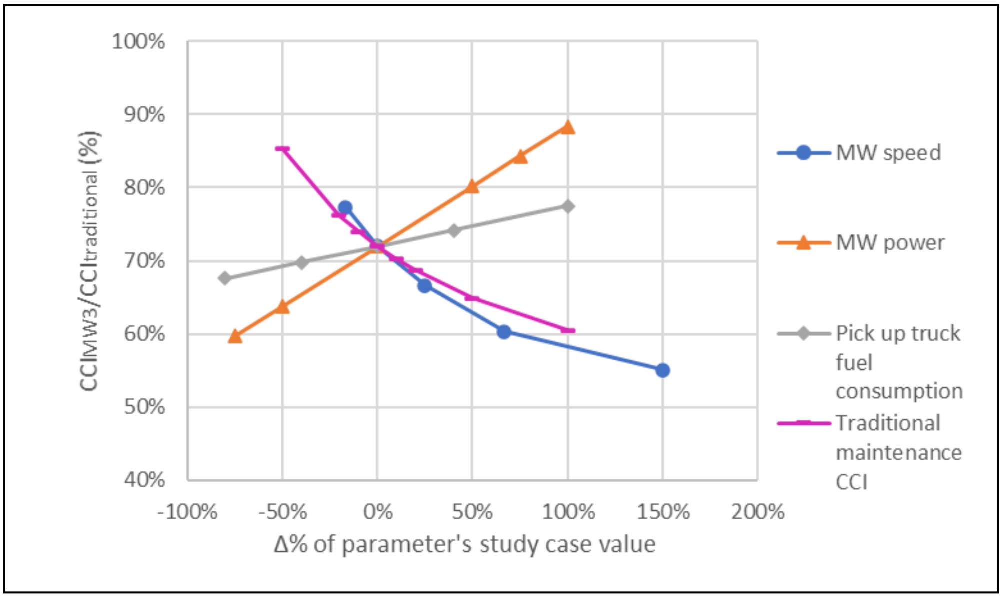

Figure 4.16 CCI sensitivity analysis

4.3.4.3. Energy sensitivity analysis

The energy case is similar to the CCI case where as shown in Figure 4.17, the parameters that have the greatest influence in energy consumption variation are MW heating device speed, its power, and traditional maintenance activities energy consumption. The difference with the CCI case is that reductions of less than 50% in traditional maintenance activities energy consumption could make more energy effective traditional maintenance than MW3 (Fig. 4.17). This would also be the case with an increase of 75% in MW heating device power, however this is unlikely to happen. On the contrary, MW heating device power reduction can be achieved by optimizing the heating device, allowing the reduction of energy consumption from 81% to 69% of traditional maintenance energy consumption with a 50% reduction of power needed.

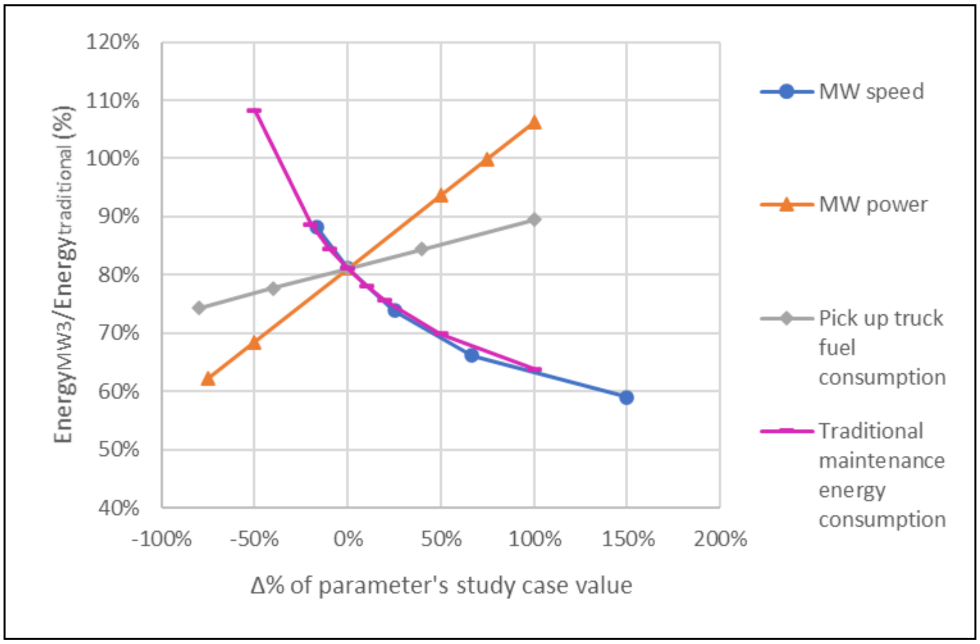

Figure 4.17 Energy consumption sensitivity analysis

4.3.4.4. Sensitivity analysis conclusion

From the sensitivity analysis of the parameters, it can be concluded that MW heating device speed and power are the main parameters to work with from the point of view of the self-healing technology. If these aspects can be optimised when making the final production devices, MW self-healing technique would undoubtedly present significant benefits from an environmental and economic perspective compared to traditional maintenance. Another factor that should be mentioned is the healing effect achieved. In the present study 20% fatigue life extension was considered (Section 4.2.4.2.2); however, if higher healing levels are achieved, resulting in a larger pavement´s life extension, fewer MW interventions and complementary traditional interventions would be necessary, thus increasing MW heating self-healing benefits. On the other hand, traditional maintenance costs and environmental impacts also have an important influence on the results achieved, but these parameters do not depend on the development of self-healing technology. However, when studying this novel technology’s sustainability, it is important to accurately define traditional maintenance economic and environmental performance to achieve trustworthy results and accurate comparisons.

4.4. Conclusions

In this study, the sustainability of the inclusion of MW heating self-healing technique in thin traditional HMA pavement maintenance strategies as an alternative to traditional maintenance was assessed through a tree-legged analysis of a 40-year analysis period that evaluated environmental, economic, and social sustainability. Based on the analysis of the results obtained and the discussion presented, the following conclusions were drawn:

- Maintenance alternatives including MW heating self-healing, present substantial reductions in the environmental sustainability indicators; energy consumption, feedstock energy, materials consumption, and CCI compared to traditional maintenance alternative during the asphalt pavement life cycle, increasing pavement sustainability. This positive environmental effect increases in large traffic scenarios.
- In the studied cases, the inclusion of MW heating self-healing technique in maintenance alternatives results in a significant reduction of the economic sustainability indicator NPV estimated through a life cycle cost compared to traditional maintenance, as a result increasing pavement economic sustainability. However, for the medium traffic level analysed (AADT=1200) the total NPV of

traditional maintenance and the most conservative MW maintenance alternative (MW3) are very similar (5% difference).

- The inclusion of MW heating self-healing technique in asphalt pavement maintenance has potential social benefits for the three main stakeholders. Noise and traffic disruption reduction improve the neighbouring community's quality of life, reduce citizen complaints, and improves the perception of road authorities.
- MW heating self-healing maintenance alternatives' economic and environmental performance depends strongly on the MW heating device's advancing speed and power. These parameters should be optimised for the mass application of this technology.
- Traditional maintenance costs and environmental impacts, which depend on local conditions, should be precisely estimated to correctly evaluate MW heating self-healing maintenance benefits in each application case.
- Overall, the inclusion of MW heating self-healing technique in the maintenance of thin HMA pavements has the potential to improve the economic, environmental, and social aspects of sustainability in comparison to traditional asphalt pavement maintenance.

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5. GENERAL CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE RESEARCH

The present work aimed to assess the sustainability of the inclusion of MW heating self-healing technique in asphalt pavement maintenance as an alternative to traditional maintenance. To achieve this objective, it was necessary to identify MW heating self-healing technique's effect on asphalt pavement fatigue life, and then carry on environmental, economic and social life cycle assessment to investigate this technique's influence on maintenance sustainability.

First, a bibliographic and bibliometric review on the state-of-the-art of the asphalt self-healing technology was conducted reaching the following findings:

- The production of documents related to self-healing has been growing since 1994. In particular, since 2015, this number has dramatically increased, reaching a peak in 2020.
- China and the USA have an outstanding performance in the production of documents followed by the Netherlands, UK, Spain, and Chile. Nevertheless, Europe is the continent with the largest number of countries active in the development of this area of knowledge.
- From 1994 to 2015, researchers were developing self-healing knowledge. However, predominantly from 2015, research themes became more specific and related to self-healing, and the healing ability of asphalt mixtures were studied as an opportunity to achieve sustainable pavements, enhancing their service life through diverse self-

healing promoting techniques such as microwave and induction heating and microcapsules.

- Numerous studies have been done to understand self-healing phenomena and to develop self-healing techniques in the laboratory. In addition, research proved that these techniques reduce the consumption of natural resources and emission of GHG among other positive effects on environmental impacts, allowing self-healing techniques to be an alternative to achieve a sustainable road infrastructure.
- Future research should deepen on the optimization of self-healing techniques, link the laboratory findings to the field behavior of asphalt concrete pavements and thus provide tools to design pavement maintenance strategies in order to conduct comprehensive LCA studies.

Following these first recommendations, the effects of the MW heating self-healing technique on pavement fatigue life extension, and the relationship between laboratory results and pavement field performance were studied. The experimental and analytical research conducted found that:

- Several HI have been used to quantify the healing performance of self-healing techniques; however, they provide little information about the increase of the fatigue life in order to define the application frequency of self-healing maintenance techniques or to assess the increase of pavement fatigue life in the field.
- HI_{SCBF}, a common healing index calculated with the peak force in SCB tests could be misleading, since it overestimates the self-healing effectiveness. Jc is a fracture mechanics parameter related to field crack initiation and propagation in asphalt

pavements and pavement fatigue life. Hence, a HI elaborated from the Jc parameter or the fatigue life extension of pavements is proposed to accurately describe the healing effect.

- A methodology to estimate pavement´s field fatigue life extension from laboratory tests Jc results is developed. Applying the proposed methodology for MW heating self-healing technique, a life extension of 20% is calculated.

Finally, from the previous results, an asphalt pavement maintenance strategy was established including MW heating self-healing technique. Thus, a three-legged (environmental, economic and social) sustainability assessment was carried out comparing MW heating self-healing maintenance alternatives to traditional asphalt pavement maintenance, reaching the following conclusions:

- Maintenance alternatives including MW heating self-healing present substantial reductions in the energy consumption, feedstock energy, materials consumption and CCI in comparison to asphalt pavement traditional maintenance alternative during pavement´s life cycle.
- In most traffic scenarios studied MW heating self-healing alternatives present an evident reduction in the life cycle cost compared to traditional maintenance.
- MW heating self-healing maintenance presents social benefits for the three main stakeholders, infrastructure users including neighboring community, construction industry and governmental agency.

- MW heating self-healing maintenance economic and environmental performance depends strongly on MW heating device's advancing speed and needed power. These parameters should be optimized for the mass application of this technology.
- Traditional maintenance cost and environmental impacts which depend on local conditions, should be precisely estimated in order to correctly evaluate MW heating self-healing maintenance benefits in each application case.

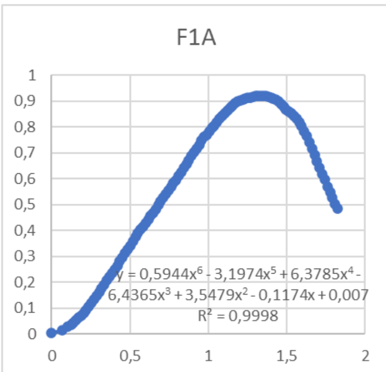
Having fulfilled the general and specific objectives of the present thesis, it can be concluded based on the previous presented results, that the hypothesis has not been refuted. Thus, MW heating self-healing technology has proven to represent a viable and more sustainable maintenance alternative for thin asphalt pavements compared to traditional maintenance techniques, improving not only the results on the environmental impact categories studied but also regarding the economic and social performance.

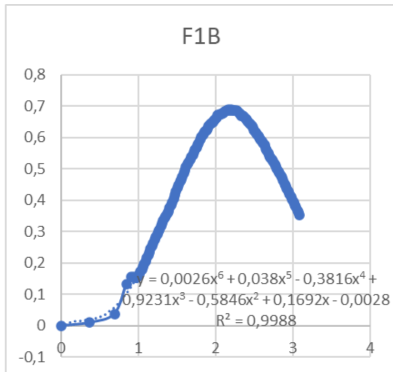
Lastly, the author suggests that future research should aim to develop in the first place efficient MW heating equipment to start field applications. Then, with field performance results more accurate life cycle assessments should be performed to quantify MW heating self-healing benefits. On the other hand, it is also recommended that researchers develop laboratory test standards to evaluate the suitability of each asphalt mixture to be treated with MW heating. In addition, it is recommended to define the optimum healing parameters (heating time, cooling time, maximum and minimum temperature, etc.), considering parameters such as, binder rheological properties, aggregates mineralogic composition, pavement density and climate conditions, among others.

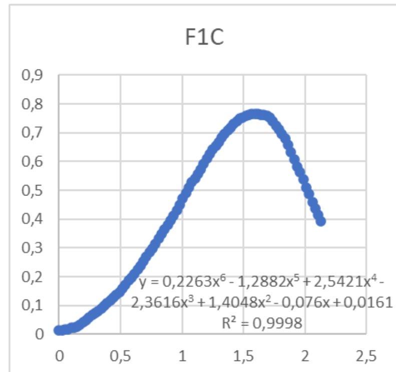
APPENDICES

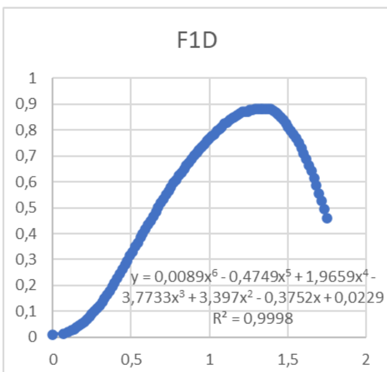
APPENDIX A: SCB TEST RESULTS (CHAPTER 3)

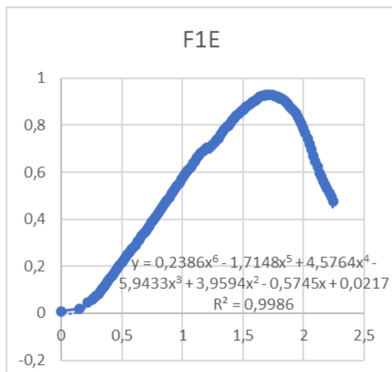
First loading cycle- load (kN) vs displacement (mm)

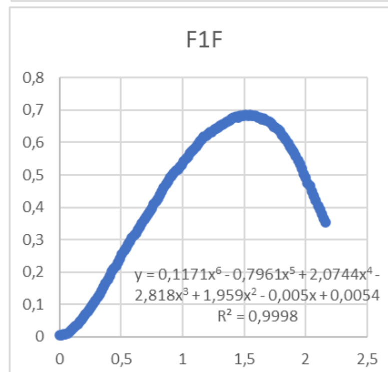


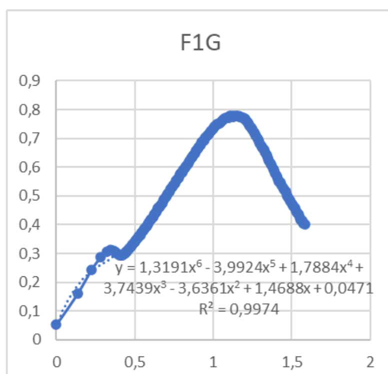


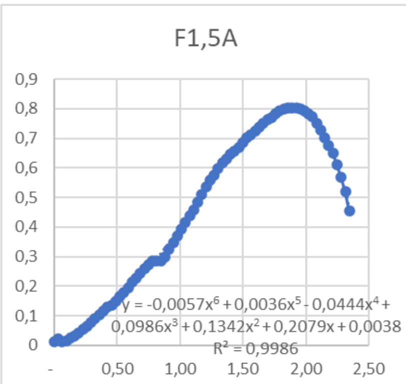


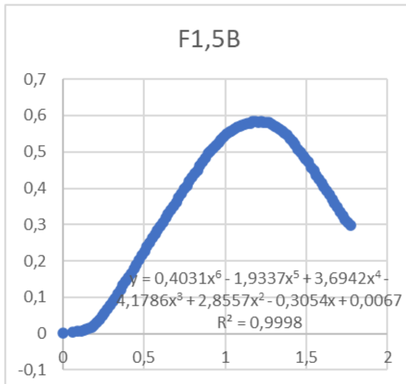


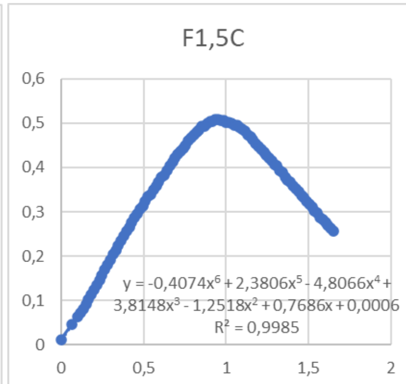


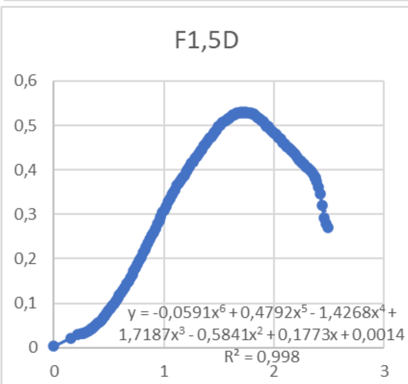


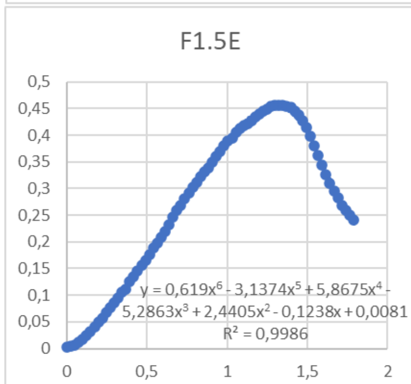


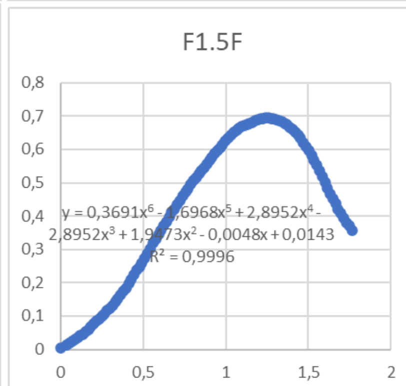

F1,5A
$y = -0,0057x^6 + 0,0036x^5 - 0,0444x^4 + 0,0986x^3 + 0,1342x^2 + 0,2079x + 0,0038$
$R^2 = 0,9986$

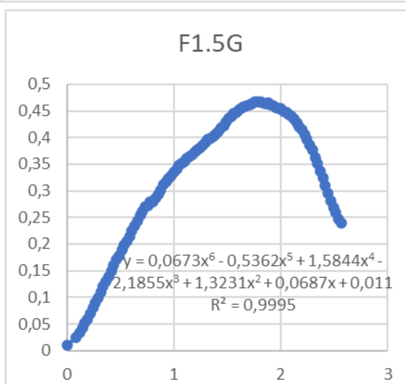

F1,5B
$y = 0,4031x^6 - 1,9337x^5 + 3,6942x^4 - 4,1786x^3 + 2,8557x^2 - 0,3054x + 0,0067$
$R^2 = 0,9998$

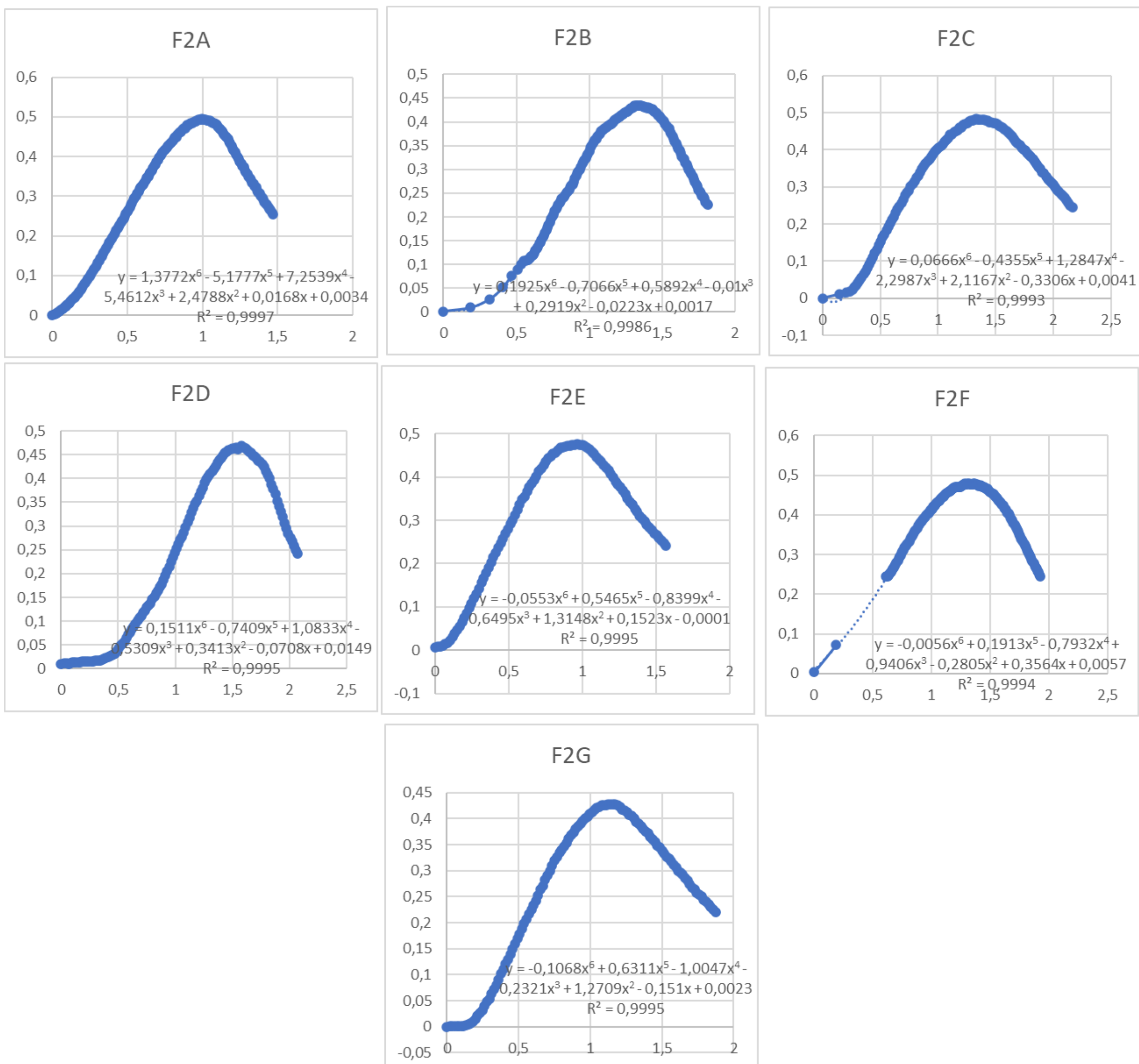

F1,5C
$y = -0,4074x^6 + 2,3806x^5 - 4,8066x^4 + 3,8148x^3 - 1,2518x^2 + 0,7686x + 0,0006$
$R^2 = 0,9985$


F1,5D
$y = -0,0591x^6 + 0,4792x^5 - 1,4268x^4 + 1,7187x^3 - 0,5841x^2 + 0,1773x + 0,0014$
$R^2 = 0,998$

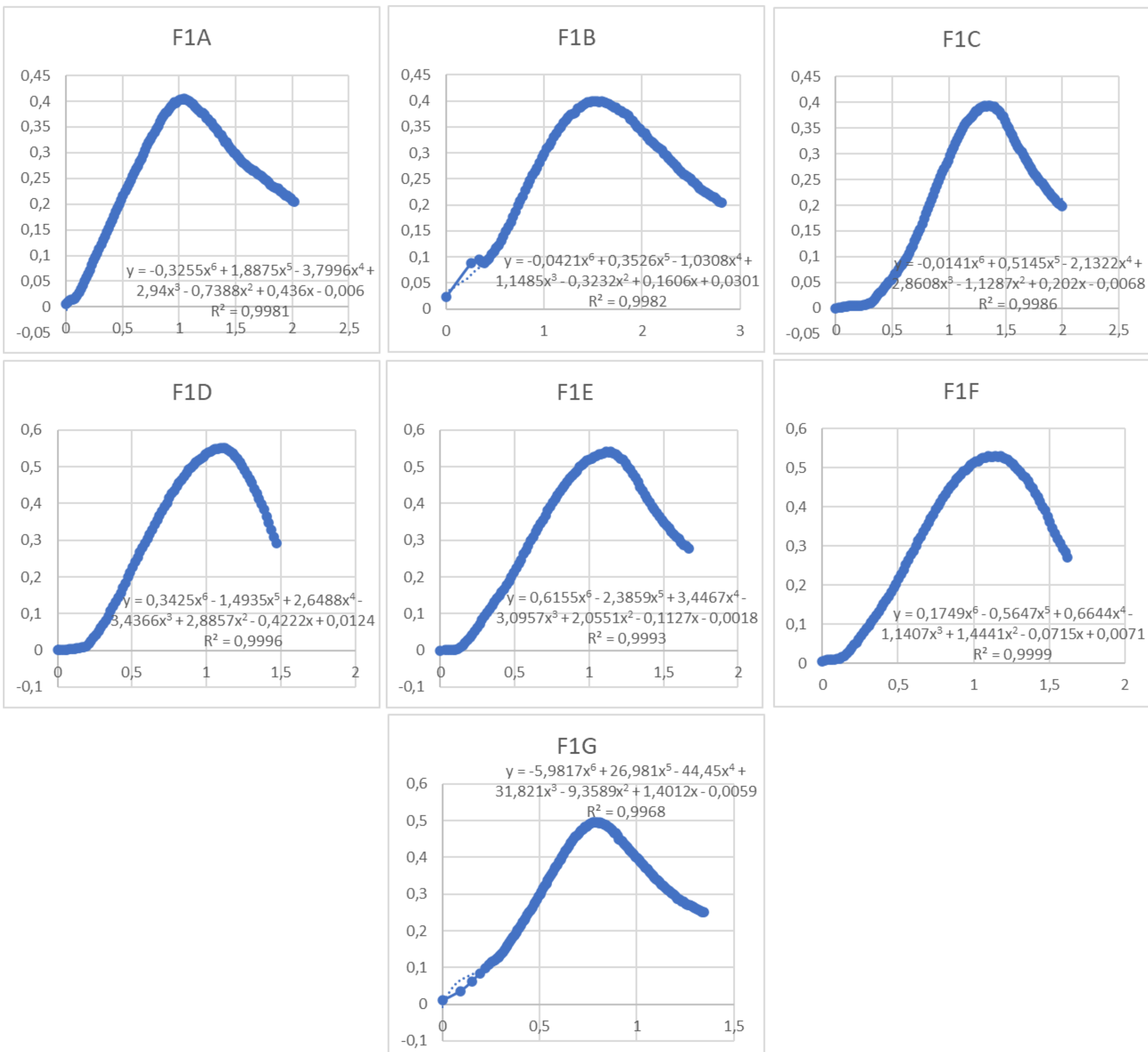

F1.5E
$y = 0,619x^6 - 3,1374x^5 + 5,8675x^4 - 5,2863x^3 + 2,4405x^2 - 0,1238x + 0,0081$
$R^2 = 0,9986$

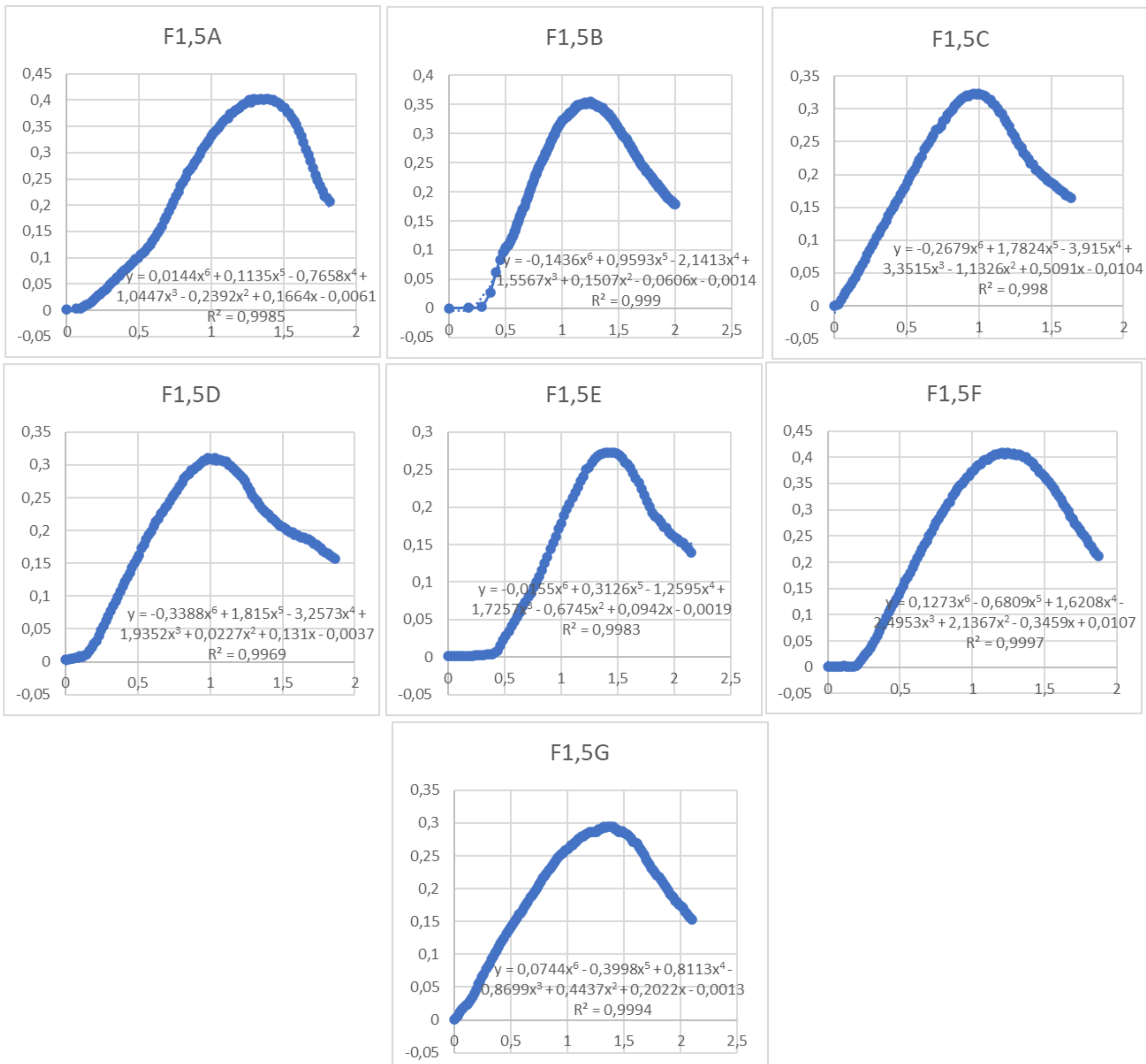

F1.5F
$R^2 = 0,9996$

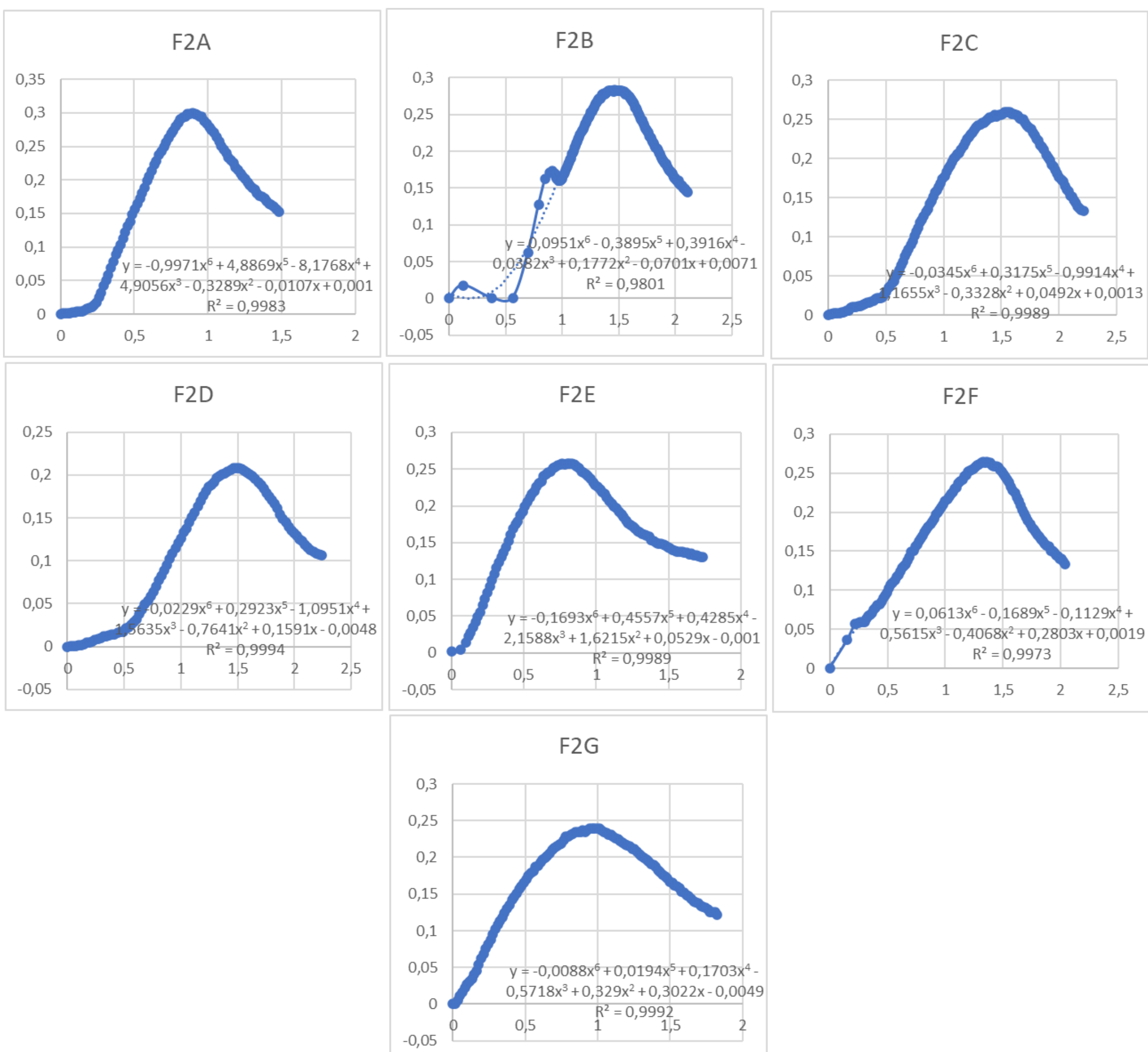

F1.5G
$y = 0,0673x^6 - 0,5362x^5 + 1,5844x^4 - 2,1855x^3 + 1,3231x^2 + 0,0687x + 0,011$
$R^2 = 0,9995$


F2A
$y = 1,3772x^6 - 5,1777x^5 + 7,2539x^4 - 5,4612x^3 + 2,4788x^2 + 0,0168x + 0,0034$
$R^2 = 0,9997$
F2B
$y = 0,1925x^6 - 0,7066x^5 + 0,5892x^4 - 0,01x^3 + 0,2919x^2 - 0,0223x + 0,0017$
$R^2 = 0,9986$
F2C
$y = 0,0666x^6 - 0,4355x^5 + 1,2847x^4 - 2,2987x^3 + 2,1167x^2 - 0,3306x + 0,0041$
$R^2 = 0,9993$
F2D
$y = 0,1511x^6 - 0,7409x^5 + 1,0833x^4 - 0,5309x^3 + 0,3413x^2 - 0,0708x + 0,0149$
$R^2 = 0,9995$
F2E
$y = -0,0553x^6 + 0,5465x^5 - 0,8399x^4 - 0,6495x^3 + 1,3148x^2 + 0,1523x - 0,0001$
$R^2 = 0,9995$
F2F
$y = -0,0056x^6 + 0,1913x^5 - 0,7932x^4 + 0,9406x^3 - 0,2805x^2 + 0,3564x + 0,0057$
$R^2 = 0,9994$
F2G
$y = -0,1068x^6 + 0,6311x^5 - 1,0047x^4 - 0,2321x^3 + 1,2709x^2 - 0,151x + 0,0023$
$R^2 = 0,9995$

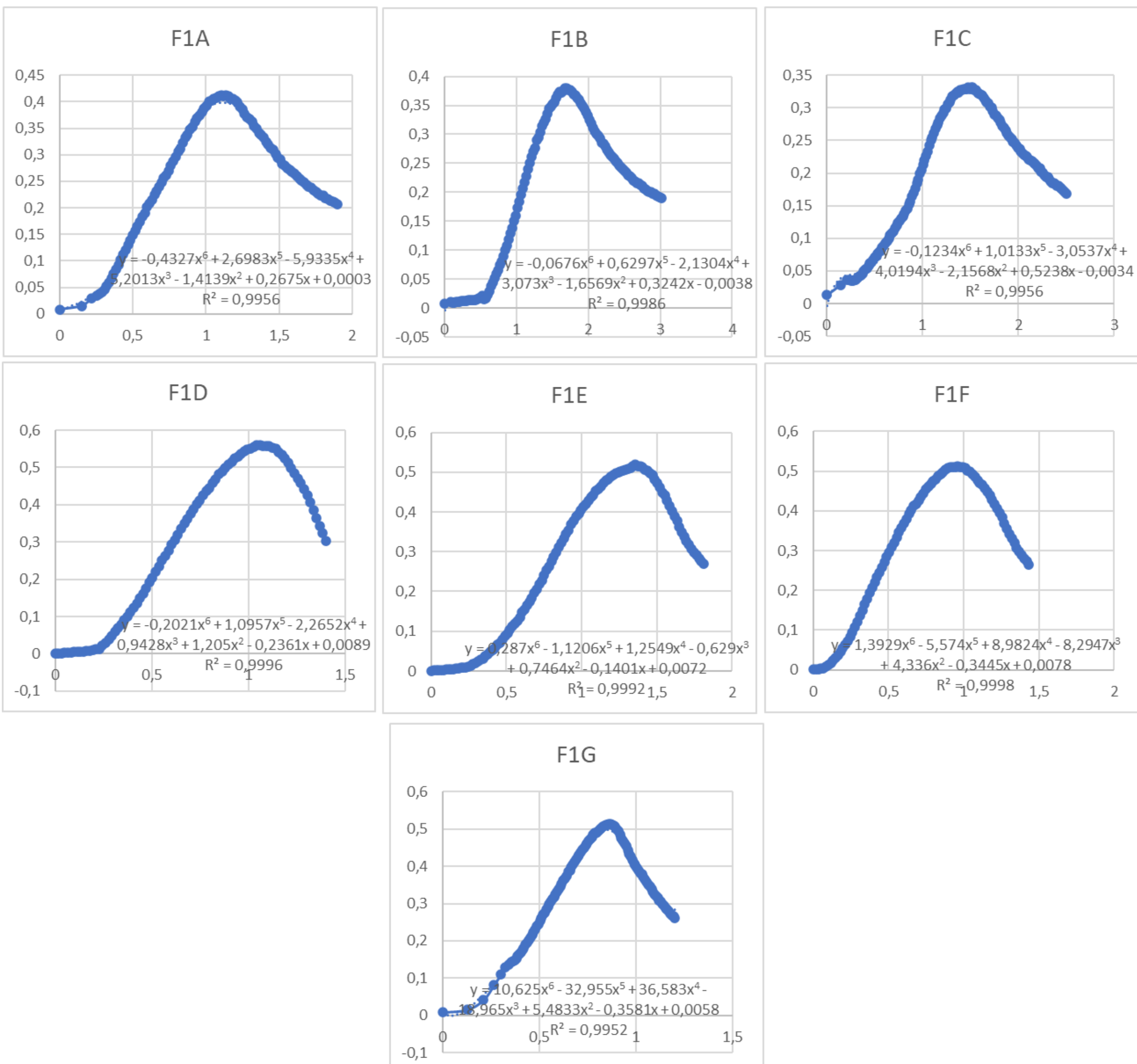
Second loading cycle- load (kN) vs displacement (mm)

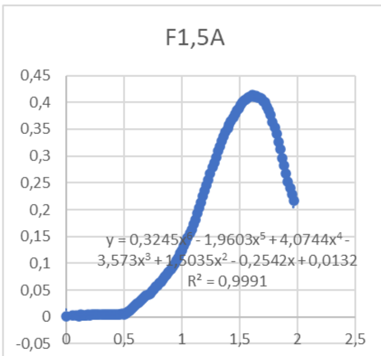


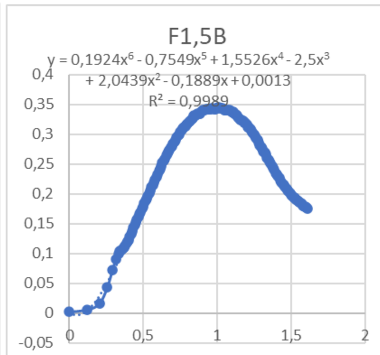

F1,5A
y = 0,0144x⁶ + 0,1135x⁵ - 0,7658x⁴ + 1,0447x³ - 0,2392x² + 0,1664x - 0,0061
R² = 0,9985
F1,5B
y = -0,1436x⁶ + 0,9593x⁵ - 2,1413x⁴ + 1,5567x³ + 0,1507x² - 0,0606x - 0,0014
R² = 0,999
F1,5C
y = -0,2679x⁶ + 1,7824x⁵ - 3,915x⁴ + 3,3515x³ - 1,1326x² + 0,5091x - 0,0104
R² = 0,998
F1,5D
y = -0,3388x⁶ + 1,815x⁵ - 3,2573x⁴ + 1,9352x³ + 0,0227x² + 0,131x - 0,0037
R² = 0,9969
F1,5E
R² = 0,9983
F1,5F
R² = 0,9997
F1,5G
y = 0,0744x⁶ - 0,3998x⁵ + 0,8113x⁴ - 0,8699x³ + 0,4437x² + 0,2022x - 0,0013
R² = 0,9994

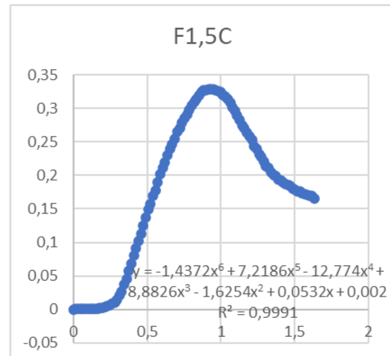

F2A
y = -0,9971x⁶ + 4,8869x⁵ - 8,1768x⁴ + 4,9056x³ - 0,3289x² - 0,0107x + 0,001
R² = 0,9983
F2B
y = 0,0951x⁶ - 0,3895x⁵ + 0,3916x⁴ - 0,0382x³ + 0,1772x² - 0,0701x + 0,0071
R² = 0,9801
F2C
y = -0,0345x⁶ + 0,3175x⁵ - 0,9914x⁴ + 1,1655x³ - 0,3328x² + 0,0492x + 0,0013
R² = 0,9989
F2D
y = 0,0229x⁶ + 0,2923x⁵ - 1,0951x⁴ + 1,3635x³ - 0,7641x² + 0,1591x - 0,0048
R² = 0,9994
F2E
y = -0,1693x⁶ + 0,4557x⁵ + 0,4285x⁴ - 2,1588x³ + 1,6215x² + 0,0529x - 0,001
R² = 0,9989
F2F
y = 0,0613x⁶ - 0,1689x⁵ - 0,1129x⁴ + 0,5615x³ - 0,4068x² + 0,2803x + 0,0019
R² = 0,9973
F2G
y = -0,0088x⁶ + 0,0194x⁵ + 0,1703x⁴ - 0,5718x³ + 0,329x² + 0,3022x - 0,0049
R² = 0,9992

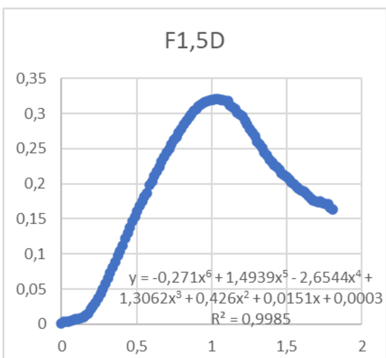
Third loading cycle- load (kN) vs displacement (mm)

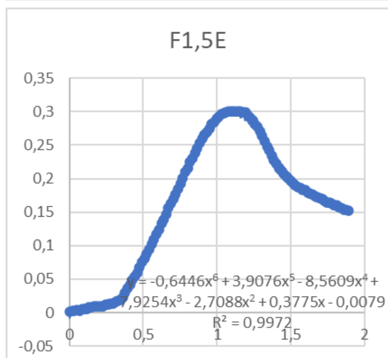


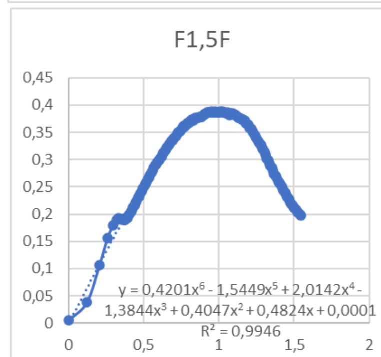

F1,5A
y = 0,3245x⁶ - 1,9603x⁵ + 4,0744x⁴ - 3,573x³ + 1,5035x² - 0,2542x + 0,0132
R² = 0,9991

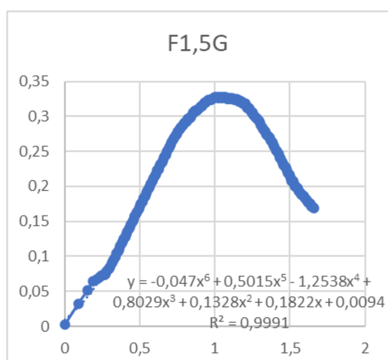

F1,5B
y = 0,1924x⁶ - 0,7549x⁵ + 1,5526x⁴ - 2,5x³ + 2,0439x² - 0,1889x + 0,0013
R² = 0,9989

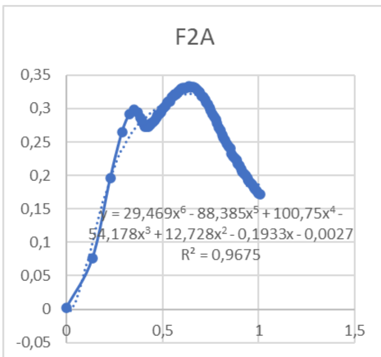

F1,5C
y = -1,4372x⁶ + 7,2186x⁵ - 12,774x⁴ + 8,8826x³ - 1,6254x² + 0,0532x + 0,002
R² = 0,9991

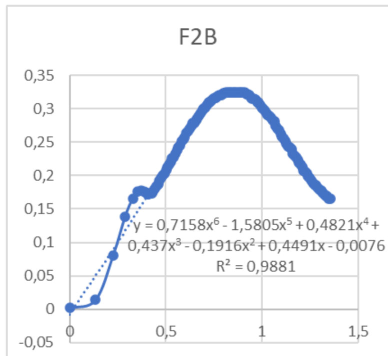

F1,5D
y = -0,271x⁶ + 1,4939x⁵ - 2,6544x⁴ + 1,3062x³ + 0,426x² + 0,0151x + 0,0003
R² = 0,9985

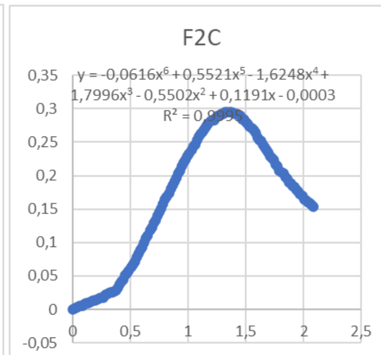

F1,5E
y = -0,6446x⁶ + 3,9076x⁵ - 8,5609x⁴ + 7,9254x³ - 2,7088x² + 0,3775x - 0,0079
R² = 0,9972

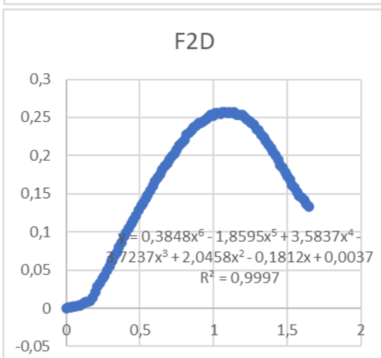

F1,5F
y = 0,4201x⁶ - 1,5449x⁵ + 2,0142x⁴ - 1,3844x³ + 0,4047x² + 0,4824x + 0,0001
R² = 0,9946

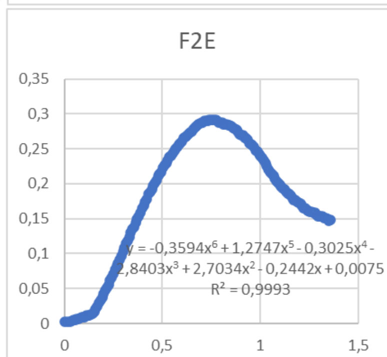

F1,5G
y = -0,047x⁶ + 0,5015x⁵ - 1,2538x⁴ + 0,8029x³ + 0,1328x² + 0,1822x + 0,0094
R² = 0,9991

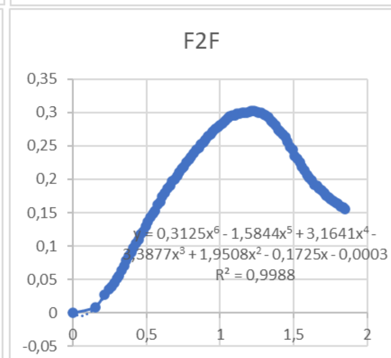

F2A
y = 29,469x⁶ - 88,385x⁵ + 100,75x⁴ -
54,178x³ + 12,728x² - 0,1933x - 0,0027
R² = 0,9675

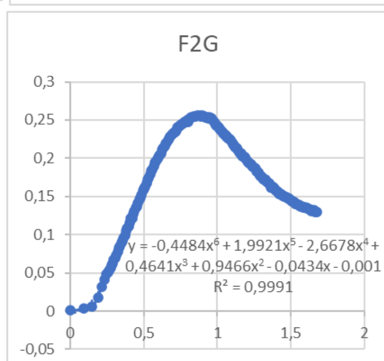

F2B
y = 0,7158x⁶ - 1,5805x⁵ + 0,4821x⁴ +
0,437x³ - 0,1916x² + 0,4491x - 0,0076
R² = 0,9881


F2C
y = -0,0616x⁶ + 0,5521x⁵ - 1,6248x⁴ +
1,7996x³ - 0,5502x² + 0,1191x - 0,0003

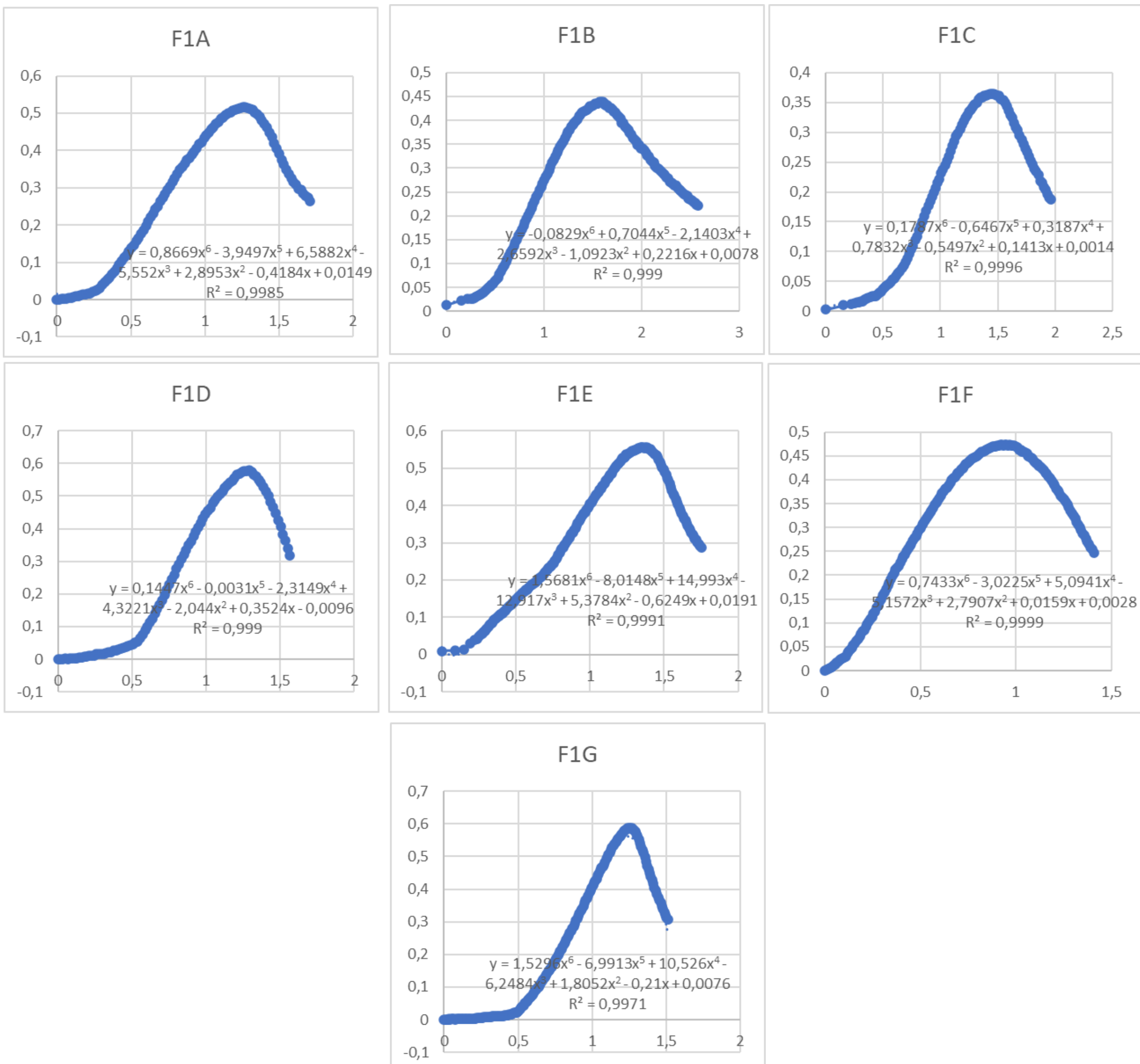

F2D
y = 0,3848x⁶ - 1,8595x⁵ + 3,5837x⁴ -
3,7237x³ + 2,0458x² - 0,1812x + 0,0037
R² = 0,9997

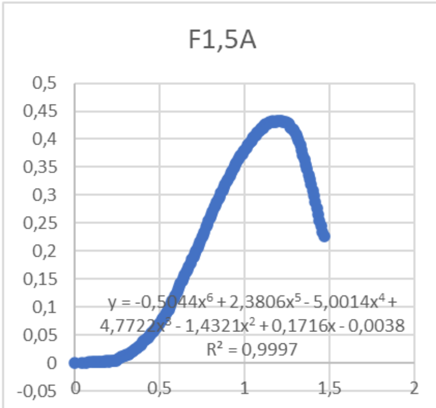

F2E
y = -0,3594x⁶ + 1,2747x⁵ - 0,3025x⁴ -
2,8403x³ + 2,7034x² - 0,2442x + 0,0075
R² = 0,9993

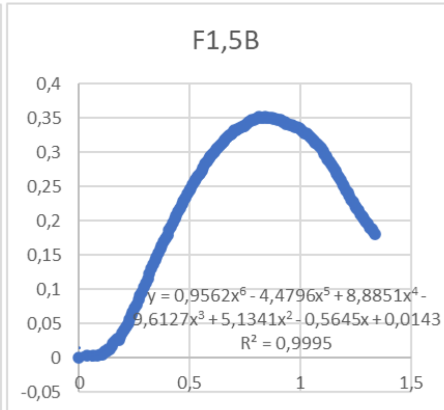

F2F
y = 0,3125x⁶ - 1,5844x⁵ + 3,1641x⁴ -
3,3877x³ + 1,9508x² - 0,1725x - 0,0003
R² = 0,9988

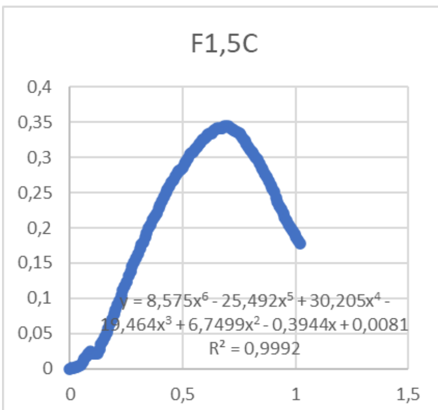

F2G
y = -0,4484x⁶ + 1,9921x⁵ - 2,6678x⁴ +
0,4641x³ + 0,9466x² - 0,0434x - 0,001
R² = 0,9991

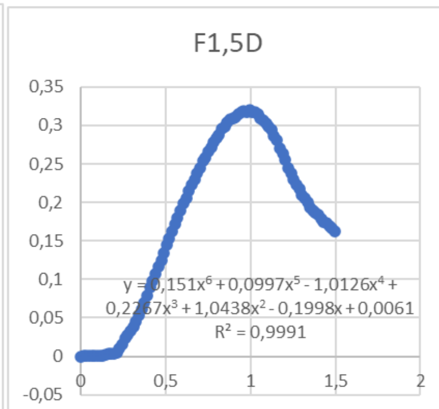
Fourth loading cycle- load (kN) vs displacement (mm)

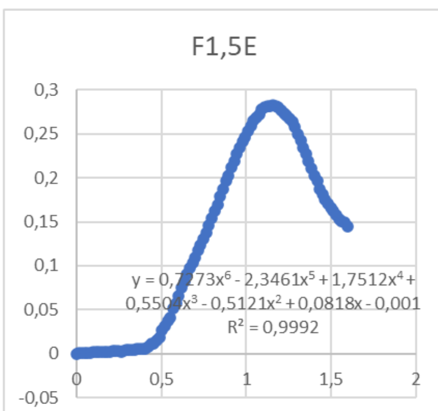


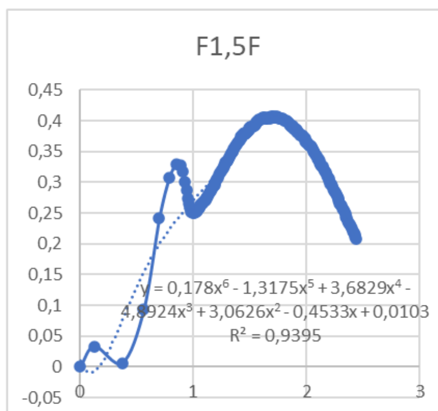

F1,5A
$y = -0,5944x^6 + 2,3806x^5 - 5,0014x^4 + 4,7722x^3 - 1,4321x^2 + 0,1716x - 0,0038$
$R^2 = 0,9997$

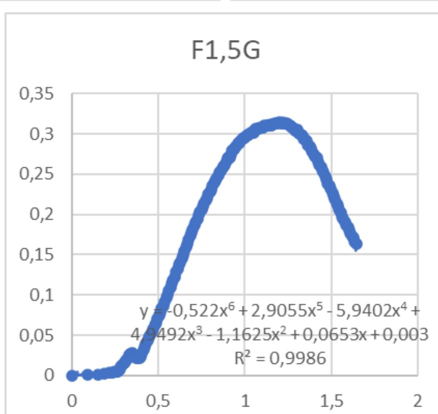

F1,5B
$y = 0,9562x^6 - 4,4796x^5 + 8,8851x^4 - 9,6127x^3 + 5,1341x^2 - 0,5645x + 0,0143$
$R^2 = 0,9995$

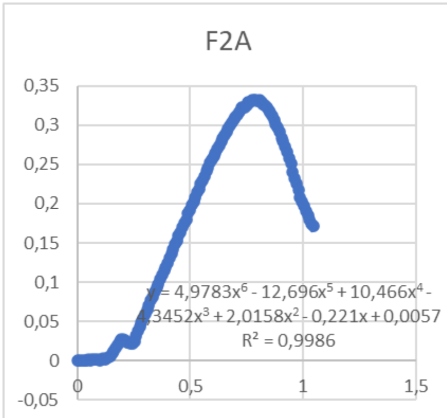

F1,5C
$y = 8,575x^6 - 25,492x^5 + 30,205x^4 - 19,464x^3 + 6,7499x^2 - 0,3944x + 0,0081$
$R^2 = 0,9992$

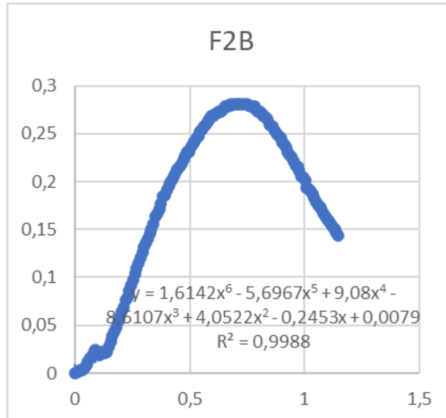

F1,5D
$y = 0,151x^6 + 0,0997x^5 - 1,0126x^4 + 0,2767x^3 + 1,0438x^2 - 0,1998x + 0,0061$
$R^2 = 0,9991$

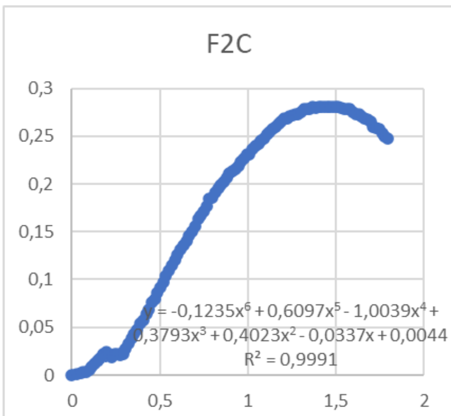

F1,5E
$y = 0,7273x^6 - 2,3461x^5 + 1,7512x^4 + 0,5505x^3 - 0,5121x^2 + 0,0818x - 0,001$
$R^2 = 0,9992$

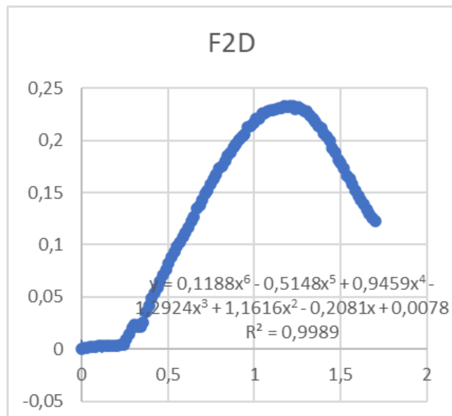

F1,5F
$y = 0,178x^6 - 1,3175x^5 + 3,6829x^4 - 4,8924x^3 + 3,0626x^2 - 0,4533x + 0,0103$
$R^2 = 0,9395$

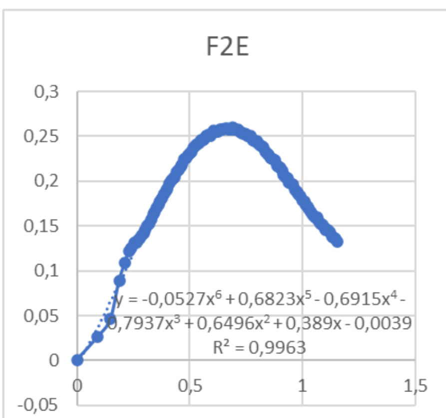

F1,5G
$y = -0,522x^6 + 2,9055x^5 - 5,9402x^4 + 4,5492x^3 - 1,1625x^2 + 0,0653x + 0,003$
$R^2 = 0,9986$

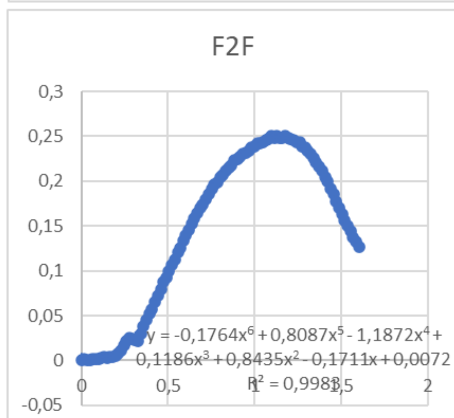

F2A
$y = 4,9783x^6 - 12,696x^5 + 10,466x^4 - 4,3452x^3 + 2,0158x^2 - 0,221x + 0,0057$
$R^2 = 0,9986$

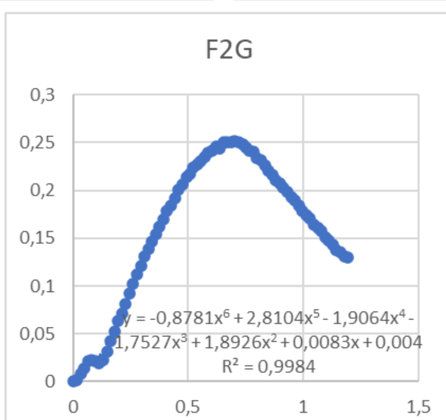

F2B
$y = 1,6142x^6 - 5,6967x^5 + 9,08x^4 - 8,6107x^3 + 4,0522x^2 - 0,2453x + 0,0079$
$R^2 = 0,9988$


F2C
$y = -0,1235x^6 + 0,6097x^5 - 1,0039x^4 + 0,3793x^3 + 0,4023x^2 - 0,0337x + 0,0044$
$R^2 = 0,9991$

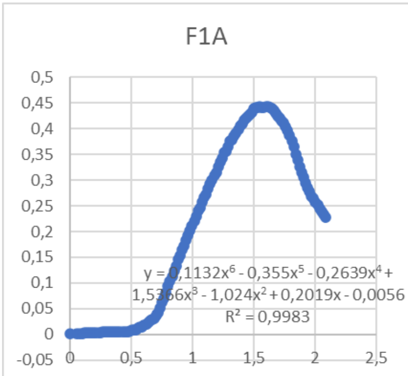

F2D
$y = 0,1188x^6 - 0,5148x^5 + 0,9459x^4 - 1,2924x^3 + 1,1616x^2 - 0,2081x + 0,0078$
$R^2 = 0,9989$

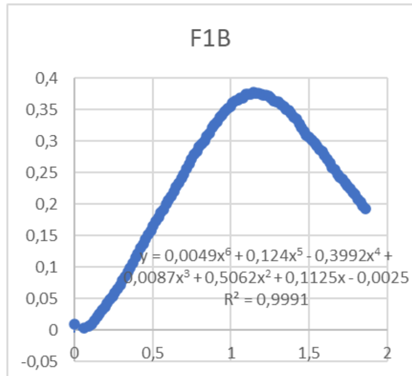

F2E
$y = -0,0527x^6 + 0,6823x^5 - 0,6915x^4 - 0,7937x^3 + 0,6496x^2 + 0,389x - 0,0039$
$R^2 = 0,9963$

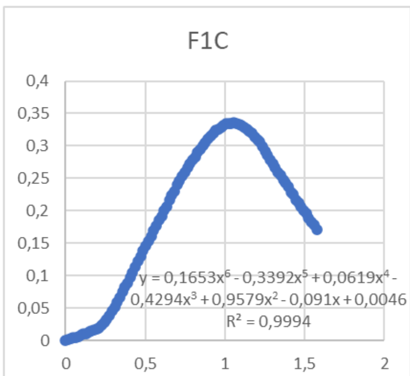

F2F
$y = -0,1764x^6 + 0,8087x^5 - 1,1872x^4 + 0,1186x^3 + 0,8435x^2 - 0,1711x + 0,0072$
$R^2 = 0,9983$

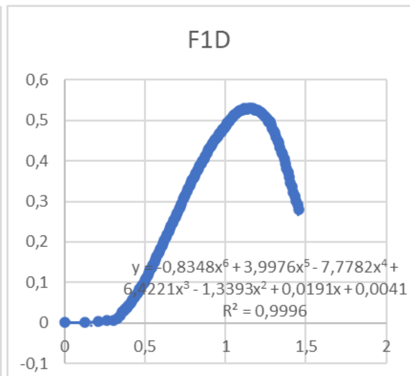

F2G
$y = -0,8781x^6 + 2,8104x^5 - 1,9064x^4 - 1,7527x^3 + 1,8926x^2 + 0,0083x + 0,004$
$R^2 = 0,9984$

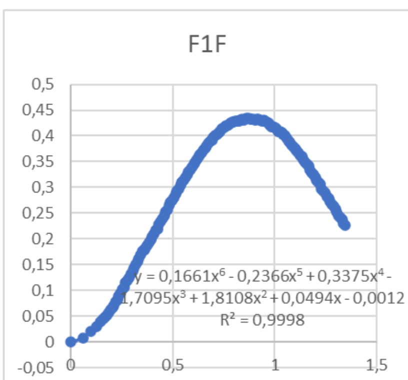
Fifth loading cycle - load (kN) vs displacement (mm)

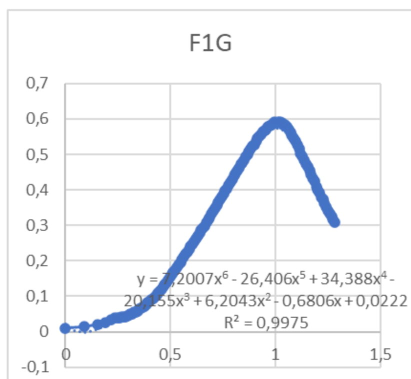


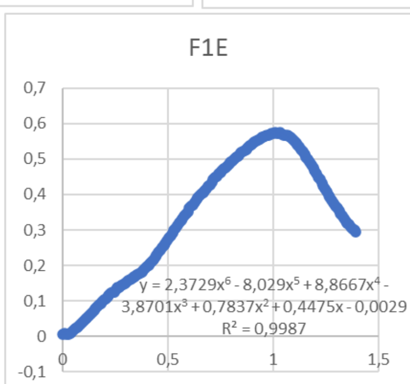


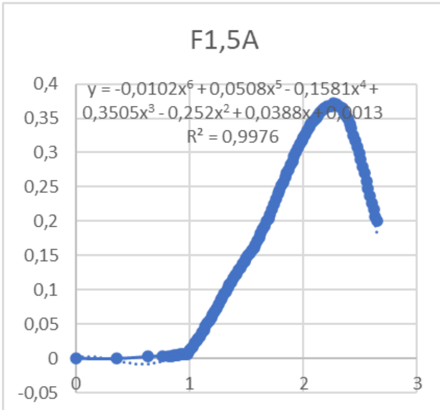


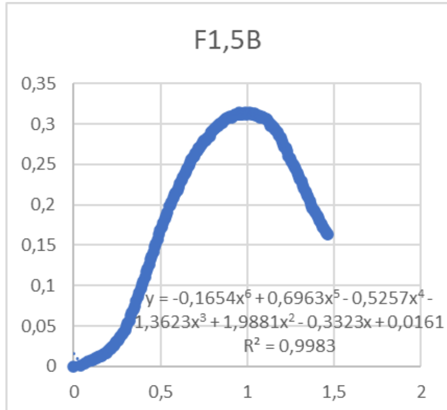


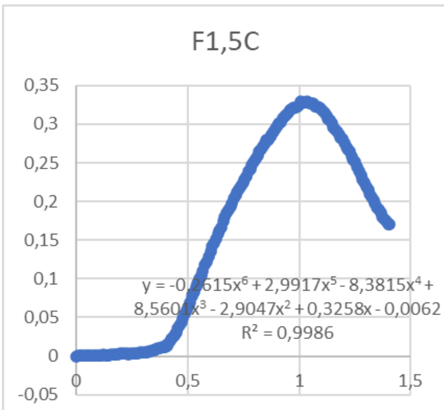


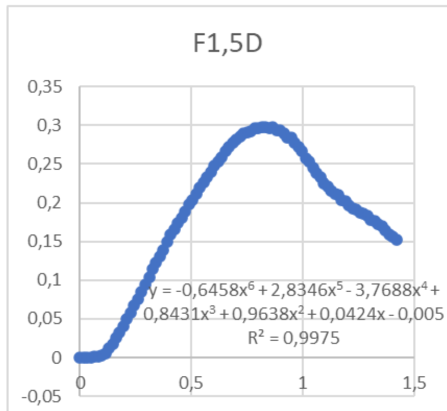


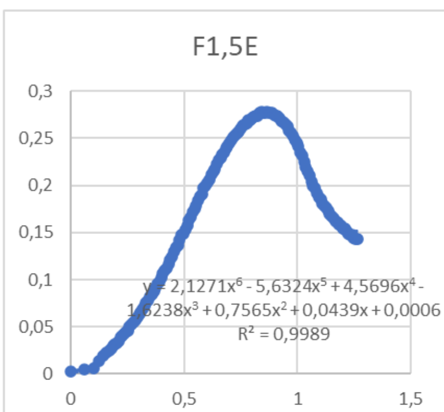


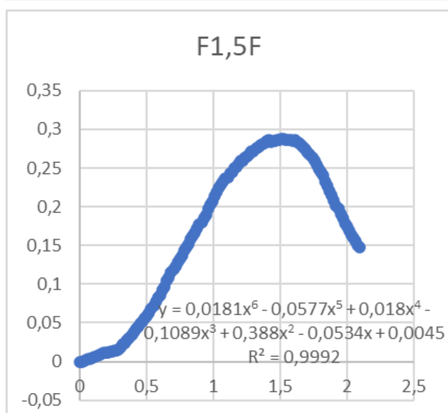

F1,5A
$y = -0,0102x^6 + 0,0508x^5 - 0,1581x^4 + 0,3505x^3 - 0,252x^2 + 0,0388x + 0,0013$
$R^2 = 0,9976$

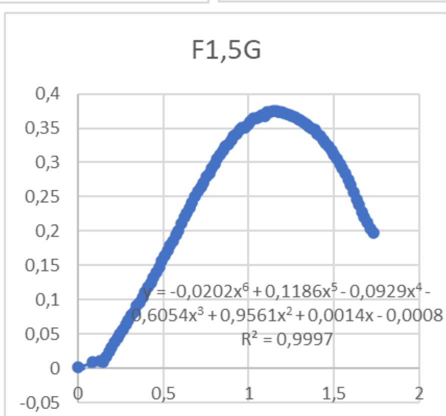

F1,5B
$y = -0,1654x^6 + 0,6963x^5 - 0,5257x^4 - 1,3623x^3 + 1,9881x^2 - 0,3323x + 0,0161$
$R^2 = 0,9983$

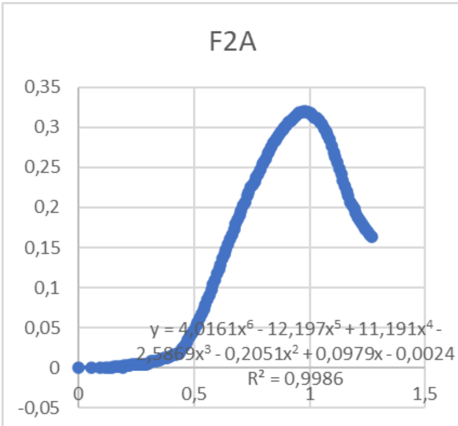

F1,5C
$y = -0,2615x^6 + 2,9917x^5 - 8,3815x^4 + 8,5601x^3 - 2,9047x^2 + 0,3258x - 0,0062$
$R^2 = 0,9986$

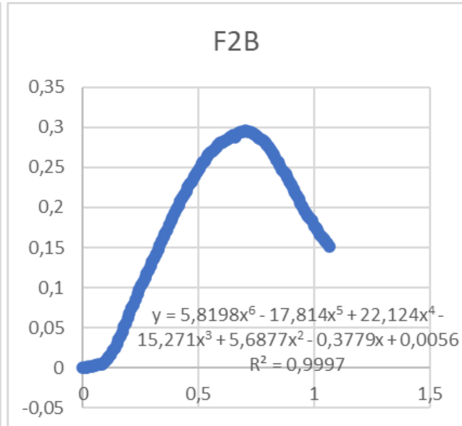

F1,5D
$y = -0,6458x^6 + 2,8346x^5 - 3,7688x^4 + 0,8431x^3 + 0,9638x^2 + 0,0424x - 0,005$
$R^2 = 0,9975$

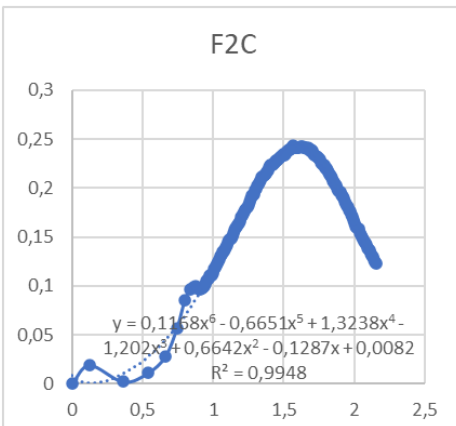

F1,5E
$y = 2,1271x^6 - 5,6324x^5 + 4,5696x^4 - 1,6238x^3 + 0,7565x^2 + 0,0439x + 0,0006$
$R^2 = 0,9989$

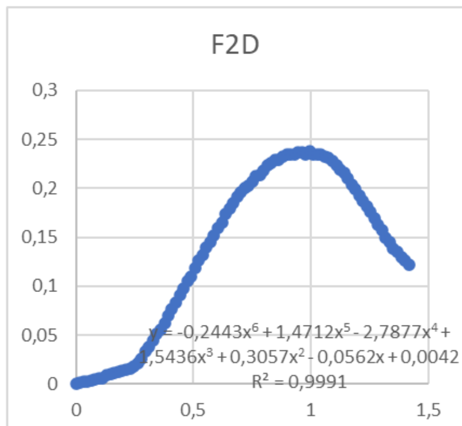

F1,5F
$y = 0,0181x^6 - 0,0577x^5 + 0,018x^4 - 0,1089x^3 + 0,388x^2 - 0,0534x + 0,0045$
$R^2 = 0,9992$

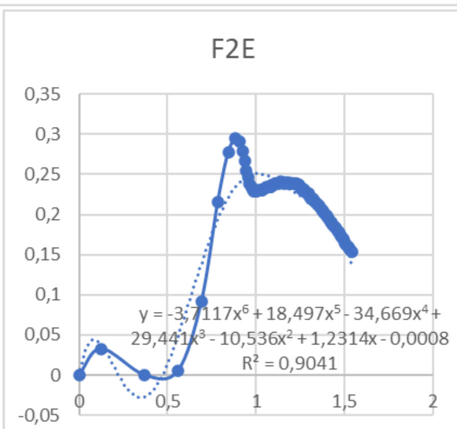

F1,5G
$y = -0,0202x^6 + 0,1186x^5 - 0,0929x^4 - 0,6054x^3 + 0,9561x^2 + 0,0014x - 0,0008$
$R^2 = 0,9997$

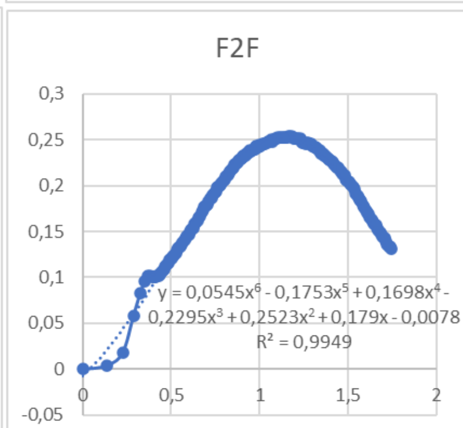

F2A
$y = 4,0161x^6 - 12,197x^5 + 11,191x^4 - 2,5869x^3 - 0,2051x^2 + 0,0979x - 0,0024$
$R^2 = 0,9986$

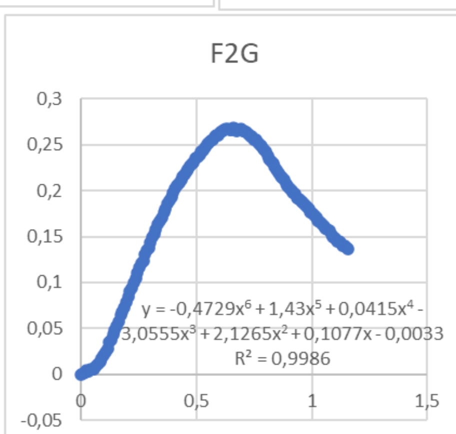

F2B
$y = 5,8198x^6 - 17,814x^5 + 22,124x^4 - 15,271x^3 + 5,6877x^2 - 0,3779x + 0,0056$
$R^2 = 0,9997$


F2C
$y = 0,1168x^6 - 0,6651x^5 + 1,3238x^4 - 1,202x^3 + 0,6642x^2 - 0,1287x + 0,0082$
$R^2 = 0,9948$


F2D
$y = -0,2443x^6 + 1,4712x^5 - 2,7877x^4 + 1,5436x^3 + 0,3057x^2 - 0,0562x + 0,0042$
$R^2 = 0,9991$

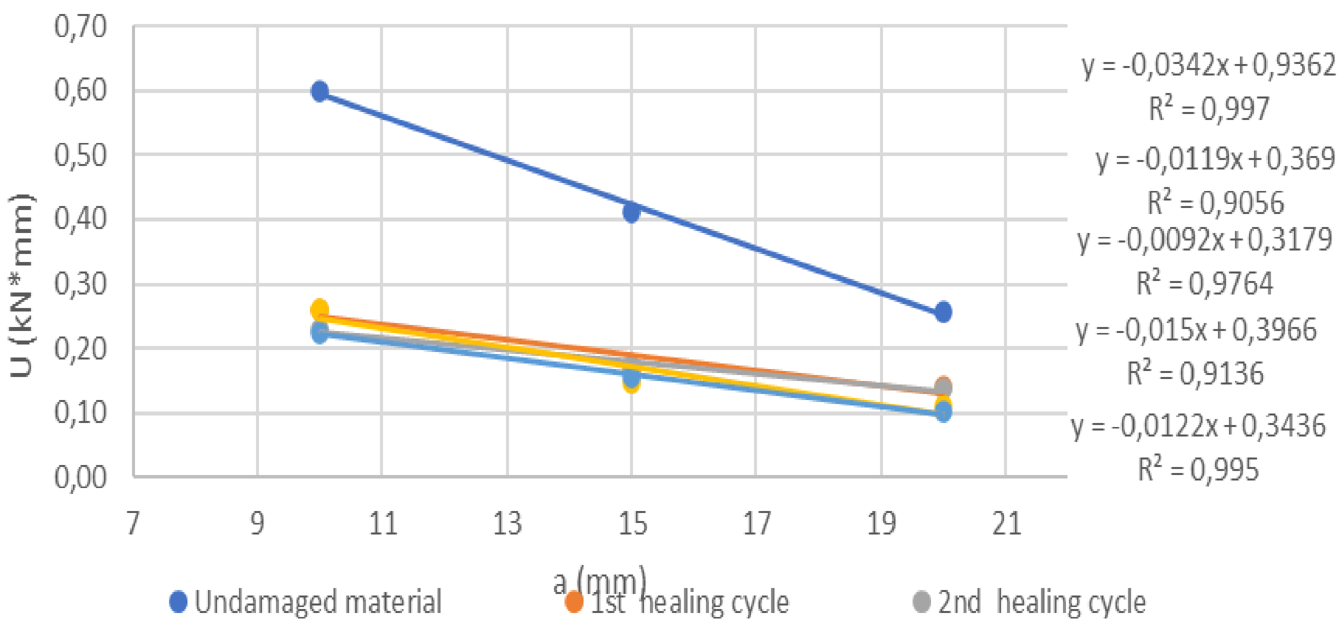

F2E
$y = -3,7117x^6 + 18,497x^5 - 34,669x^4 + 29,441x^3 - 10,536x^2 + 1,2314x - 0,0008$
$R^2 = 0,9041$


F2F
$y = 0,0545x^6 - 0,1753x^5 + 0,1698x^4 - 0,2295x^3 + 0,2523x^2 + 0,179x - 0,0078$
$R^2 = 0,9949$


F2G
$y = -0,4729x^6 + 1,43x^5 + 0,0415x^4 - 3,0555x^3 + 2,1265x^2 + 0,1077x - 0,0033$
$R^2 = 0,9986$

Jc value calculus

		Undamaged material		1st healing cycle		2nd healing cycle		3rd healing cycle		4th healing cycle	
	a (mm)	U (kN*mm)	D.est	U (kN*mm)	D.est	U (kN*mm)	D.est	U (kN*mm)	D.est	U (kN*mm)	D.est
10mm	10	0,60	0,03	0,26	0,03	0,23	0,03	0,26	0,03	0,22	0,02
15mm	15	0,41	0,09	0,17	0,05	0,17	0,03	0,15	0,03	0,16	0,05
20mm	20	0,26	0,02	0,14	0,02	0,14	0,02	0,11	0,02	0,10	0,01
B prom (mm)	29,5										
Jc(kN/mm)		1,16E-03		4,03E-04		3,11E-04		5,08E-04		4,13E-04	
Jc(kJ/m2)		**1,16**		**0,40**		**0,31**		**0,51**		**0,41**	



APPENDIX B: HDM-4 INPUT DATA (CHAPTER 4)

Climate	
Moisture Classification	Semi-arid
Mositure index	-40
Duration of dry season	7.2 months
Mean monthly precipitation	40mm
Temperature Classification	Subtropical - cool
Mean temperature	14.1°C
Avg. Temperature Range	35°C
Days T>32°C	45 days
Freeze Index	55 C-days
Percentage Of Time Driven	
on snow covered roads	0
on water covered roads	30
Calibration series for asphalt concrete	
Asphalt concrete	
Kcia	1.98
Kcpa	0.18
Kcpw	0.53
Kvi	1.00

Vehicle fleet				
	Ligth vehicles	Bus	Truck	Heavy truck
Definition				
Vehicle type	Car Medium	Bus heavy	Truck heavy	Truck Articulated
Basic Characteristics				
Physical				
Passanger Car Space Equiv	1	1.6	1.6	1.8
No of Wheels	4	10	10	18
No of Axles	2	3	3	5
Tyres				
Tyre type	Radual-ply	Bias-ply	Bias-ply	Bias-ply
Base no. Of recaps	0	1.35	1.3	1.58
Retread cost (%)	0	18	15	30
Utilisation				
Annual km (km)	19000	65000	86000	49000
Working hours (hrs)	600	1700	2050	1700
Average life (years)	6,91	8	12	9.27
Private use (%)	80	0	10	10
Passengers (persons)	2	60	2	2
Work related passangers-trips (%)	50	75	90	90

APPENDIX C: AIMSUN INPUT DATA (CHAPTER 4)

Fuel consumption model Input

	Model parameters						
Vehicle type	**Fi (ml/s)**	**C1 (ml/s)**	**C2 (ml/s)**	**F1 (l/100km)**	**F2 (l/100km)**	**Fd (ml/s)**	**Vm (km/h)**
Light vehicles	0.33	0.42	0.26	4.7	6.5	0.54	60
Bus	3	1	0.5	14	18	3.5	50
Truck	0.7	1	0.5	10	12	1	60
Heavy truck	0.7	1	0.5	10	12	1	60

Emissions model input for CO2 emissions (Panis et al 2006)

	Light vehicles	Bus	Truck	Heavy truck
Gasoline	75%	0%	0%	0%
Diesel	25%	100%	100%	100%

		Model parameters						
Vehicle type	**Fuel type**	**E0**	**f1**	**f2**	**f3**	**f4**	**f5**	**f6**
Light vehicles	Gasoline	0	0.553	0.161	-0.00289	0.266	0.511	0.183
Light vehicles	Diesel	0	0.324	0.0859	0.00496	-0.0586	0.448	0.23
Bus	Diesel	0	0.904	1.13	-0.0427	2.81	3.45	1.22
Truck	Diesel	0	1.52	1.88	-0.0695	4.71	5.88	2.09
Heavy truck	Diesel	0	1.52	1.88	-0.0695	4.71	5.88	2.09

Vehicles characteristics						
		Light vehicles	**Bus**	**Truck**	**Heavy truck**
Length (m)	*Average*	4	12	8	14
	Std. Deviation	0.5	0	2	3
	Min	3.5	12	6	13
	Max	4.5	12	10	17
Width (m)	*Average*	2	2.5	2.25	2.3
	Deviation	0	0	0.2	0.45
	Min	2	2.5	2	2
	Max	2	2.5	2.8	2.5
Max. Desirable Speed (km/h)	*Average*	110	90	85	80
	Deviation	10	10	10	10
	Min	80	70	70	70
	Max	150	100	100	80
Max. Acceleration (m/s2)	*Average*	3	1	1	1
	Deviation	0.2	0.3	0.5	0.5
	Min	2.6	0.8	0.6	0.6
	Max	3.4	1.8	1.8	1.8
Normal Deceleration (m/s2)	*Average*	4	2	3.5	1
	Deviation	0.25	1	1	0.5
	Min	3.5	1.5	2.5	0.8
	Max	4.5	4.5	4.8	1.5
Deceleration Max (m/s2)	*Average*	6	5	5	3
	Deviation	0.5	1	0.5	1
	Min	5	4	4	2
	Max	7	6	6	4