UNIVERSIDAD POLITÉCNICA DE MADRID

Escuela Técnica Superior de Ingenieros de
Caminos, Canales y Puertos

**MECHANICAL PERFORMANCE OF HALF-WARM MIX
RECYCLED ASPHALT MIXTURES CONTAINING TOTAL RATES
OF RECLAIMED ASPHALT PAVEMENT FOR THEIR USE IN
ROAD PAVEMENTS**

DOCTORAL THESIS

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Bachelor's degree in Civil Engineering

M.Eng.'s degree in Construction Management

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DEDICATION

I would like to dedicate this thesis dissertation to my beloved parents and sisters for their never-ceasing help, support, mercy, strength, and encouragement to achieve this long-awaited goal. I'd like to thank for their love, for their support, patience, and, most of all, for convincing me that I could and should take this leap forward.

Finally, I would also like to thank God for providing me health, strength, and patience to make this dream come true.

“Every valley must be filled in, every mountain and hill leveled off; the winding roads must be straightened, and the rough ways made smooth.”

Luke 3:5-7

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ABSTRACT

Over the last few years, the use of half-warm mix asphalt (HWMA) mixtures that are manufactured below the boiling point of water (≤ 100 °C), and total recycled asphalt pavement contents equal to 100% RAP, represent a promising engineering solution for reducing energy consumption (i.e., fuel and gas-oil), raw materials (i.e., aggregates and binder) and greenhouse gas (GHG) emissions released into the atmosphere during the mix production and construction (compaction and laying) process in the field. Despite the technical, social, environmental, and economic advantages associated with this sustainable disruptive technical solution, there remain some concerns and questions to be answered regarding durability and long-term mechanical performance that endorse their durability and benefits as a promising technique of sustainable development.

Therefore, a lack of suitable mix design and characterization method was identified for this recent technology. To this end, three laboratory compaction test methods (Static compressive strength load NLT 162/00, Gyratory compactor (EN 12697-31:2013) and specimen preparation by impact compactor) were selected and put into assessment to define and evaluate the most suitable compaction test method for half-warm mix recycled asphalt (HWMRA) mixtures with 100% RAP. These mixtures were designed with two emulsion contents (2.5% and 3.0%, o/RAP) with a rejuvenator with a low pen. bitumen (160/220) and 50/70 pen. grade bitumen. The characterization allowed to select the most suitable compaction test method for the preparation and characterization of this technology and the target compaction energy to obtain and reproduce specimens with similar volumetric characteristics (air voids and density) to those obtained in the field after pavement construction. Posteriorly, the specimens were subjected to an accelerated curing/drying process for three days (72 h), at 50 °C, in a forced-draft convection oven before laboratory testing.

This doctoral dissertation aims to present the main results of the half-warm mix recycled asphalt (HWMRA) mixtures with total recycled asphalt pavement (RAP) contents equal to 100% using a continuous asphalt mixing plant specially designed for the production of this technology by Sacyr. To achieve this goal, a set of in-plant samples were collected to determine the reproducibility of up-scaling the laboratory mix design to an asphalt plant. Moreover, a sampling campaign was conducted to determine if the wearing course asphalt mixtures meet the minimum percentage of 98% of the benchmark density after compaction with conventional machinery.

The quality control results showed that both HWMRA mixes with 100% RAP meets the minimum moisture damage resistance value for binder and wearing course asphalt mixtures of road pavements. Also, the resistance to permanent deformation values of these mixes were found to be lower than 0.1 (mm/1000 load cycles), between 5000 and 10000 load cycles, and proportional rut depth (PRDAIR) below 5%; indirect tensile strength (ITS) values above 1.7 MPa; and similar fatigue cracking resistance law of half-warm mixes with 50/70 pen grade bitumen compared with conventional hot mix asphalt mixtures at 20 °C.

On the other hand, the self-healing ratio of half-warm mixes with three electric arc furnace steel (EAFS) slag aggregate contents was analyzed using a thermo-mechanical treatment. In other words, a recompaction-based mechanical method together with a microwave heating energy treatment were

conducted at the Technical University of Madrid - Department of Civil Engineering, Transport, and Urban Planning. The results showed that the self-healing ratio of this technology after the specimens are subjected to a vertical diametral load of 50.8 mm/min, presented a higher recovery capability of mixtures' mechanical performance properties (indirect tensile strength and stiffness modulus) by applying 50 recompaction gyrations at 80 °C.

This research has demonstrated the viability of using more competitive and sustainable engineering solutions compared to conventional hot mix asphalt mixture, such as half-warm mix recycled asphalt mixtures (HWMRA) mixes with a total recycled asphalt (RAP) content for their use in the binder and wearing course asphalt mixtures of road pavements. This technology allows the possibility of recycling mixtures with high and total RAP contents, obtaining results in terms of mechanical properties very similar to hot mixes, which makes it possible to reduce the GHG emissions, manufacturing and compaction temperatures and consumption of materials while improving the safety of the workers.

RESUMEN

En los últimos años, la tecnología de mezclas templadas recicladas fabricadas por debajo del punto ebullición del agua (≤ 100 °C), junto con tasas de reutilización de hasta un 100% de árido reciclado, representa una solución de gran potencial e interés para la reducción de consumo energético (fuel and gas-oil), materias primas (áridos y betún) y emisiones contaminantes de efecto invernadero (GEI) durante el proceso de fabricación, compactación y puesta en obra. No obstante, a pesar de las ventajas técnicas, sociales, medioambientales y económicas, el reciclado templado con emulsión es una técnica aún en desarrollo que requiere mayor estudio y experiencias que avalen su durabilidad y prestaciones para situarse como una técnica de desarrollo sostenible.

En este sentido, en el estudio de las mezclas templadas con tasa total de reutilización, se ha detectado la carencia de un procedimiento idóneo para su diseño, compactación y caracterización en laboratorio. Por ello, se han utilizado y comparado tres métodos de compactación de probetas cilíndricas utilizados en laboratorio, tales como (1) Compresión estática por doble émbolo NLT-162/00, (2) prensa giratoria (EN 12697-31:2013) y (3) probetas preparadas mediante compactador de impactos (12697-30:2012), empleando para ello, diferentes energías de compactación, dos contenidos de emulsión (2.5% and 3.0%) con un ligante con penetración relativamente alta (160/220) y otra con un ligante convencional de penetración 50/70.

Esta caracterización ha permitido determinar cuál es el sistema de compactación más idóneo, así como la energía de compactación más apropiada para obtener probetas con un nivel de huecos en mezcla y una densidad que sea más representativa de lo que se va a obtener y reproducir en el sitio de trabajo. Además, las probetas fabricadas y compactadas se someterán a un periodo de curado/secado de tres días (72 h) a 50 °C en estufa de convección forzada, antes de proceder a la realización de ensayos, con el objeto de evaluar el efecto de curado en las prestaciones mecánicas (resistencia a tracción indirecta y módulo) de mezclas con emulsión.

Esta tesis doctoral tiene como objetivo presentar los resultados de la tecnología de mezclas templadas recicladas con tasas de revalorización y reutilización del 100% y 70%, colocadas tanto en capa de rodadura como en capa intermedia, que han sido fabricadas en una planta prototipo de fabricación continua, especialmente diseñada para la producción de esta tecnología.

Para la consecución de este objetivo, se tomaron un conjunto de muestras tras la fabricación para determinar la reproducibilidad de esta tecnología en planta. Además, tras la compactación y extendido de esta tecnología, una campaña de extracción de testigos fue llevada a cabo con el objeto de verificar que se haya alcanzado un 98% de la densidad de referencia en la capa de rodadura con equipos de compactación convencionales. Los resultados del control de calidad indicaron que las mezclas templadas recicladas con altas tasas de reutilización del 100% RAP cumplen con los valores mínimos de sensibilidad al agua por encima de 85% para capas de rodadura y 80% para capas base e intermedia. Además, resistencia a la deformación permanente por debajo de 0.1 (mm/1000 ciclos de carga), entre los 5.000 y 10.000 ciclos de carga, profundidad media del surco (PRDAIR) por debajo del 5%; valores de cohesión en seco por encima

de 1.7 MPa; y la vida de fatiga fue algo similar a una mezcla convencional en caliente a una temperatura de 20 °C.

Por otro lado, se evaluó la recuperación de daño de mezclas templadas recicladas con tres tasas de escoria de horno de arco eléctrico (0%, 4% y 8% de EAFS en volumen total de la mezcla) mediante la reutilización de un tratamiento termo-mecánico, es decir, utilizando un sistema de recompactación pionero junto con un proceso de tratamiento de microondas desde el laboratorio de la Escuela de Caminos, Canales, y Puertos de la Universidad Politécnica de Madrid (UPM). Los resultados mostraron que la recuperación de daño de las mezclas templadas, tras someterse a una carga de compresión diametral vertical de 50.8 mm/min, presentaron mayores grados de recuperación en términos de resistencia a tracción indirecta (RTI) y módulo al aplicar 50 giros de recompactación, a 80 °C.

Esta investigación ha demostrado la viabilidad de unas mezclas más competitivas y ambientalmente más sostenibles que las mezclas convencionales en caliente como son las mezclas templadas recicladas a tasa total para capas de rodadura e intermedia. La tecnología de mezclas templadas nos abre la posibilidad de poder reciclar mezclas hasta alta tasa, obteniéndose resultados en cuanto a propiedades mecánicas muy similares a las mezclas en caliente, favoreciendo la disminución de emisiones, de temperaturas de fabricación, compactación y de consumo de materiales, además de mejorar la seguridad de los trabajos.

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Chapter 1

INTRODUCTION

1.1 Research backgrounds

Environmental awareness has been rapidly increasing over the last few decades because of air pollution and greenhouse gas (GHG) emissions. These facts have led to intensive efforts worldwide to diminish environmental burdens with the ratification of the Kyoto Protocol by the European Union. It commits the first industrialized nations worldwide to reducing greenhouse gas emissions released into the atmosphere and based on the scientific consensus that global warming is occurring (United Nations, 1992). The Paris agreement on climate change (better known as Accord de Paris in French), which entered into force on November 4th, 2016, was in line with the United Nations Framework Convention on Climate Change (UNFCCC) dealing with GHG emissions mitigation, adoption, and finance. This agreement aims to strengthen the ability of countries to deal with the adverse impacts of climate change, foster climate resilience and support sustainable development in parallel (Wang et al., 2018a), and limit the temperature increase by 2.7 °C, between 2030 and 2050, which means zero emissions over that period (Schleussner et al., 2016).

1.2 Problem Statement

Nowadays, the use of new energy-efficient and cleaner production technologies with high and total reclaimed asphalt pavement (RAP) contents is gaining boost because of the provision of environmental, social, technical and economic advantages over other existing asphalt paving technologies in the asphalt market. Nonetheless, the addition of high and total RAP contents into the new mixture design has been tagged by Departments of Transportation (DOTs), and research pavement community in general, as a potential issue linked to surface pavement distresses (e.g., thermal, longitudinal, transverse, and fatigue cracking). In other words, the recycled RAP mixture tends to show higher stiffness modulus and hence early fatigue cracking pavement failures because of the physical hardening and oxidative aging (i.e., due to the evaporation of the lighter fractions of the recycled asphalt) suffered by the recycled binder during its initial service life.

Therefore, it is well known that neither HWMA nor RAP may be effectively used separately. For these reasons, there remain a large number of concerns and questions that should be answered regarding the volumetric and mechanical performance properties of half-warm emulsified bitumen mixtures with high and total RAP contents. To do so, a more in-depth analysis of the fatigue cracking behaviour is therefore of paramount importance to guarantee the satisfactory mid- and long-term mechanical performance of half-

warm mix recycled mixtures and, hence, reach their widespread use in base, binder, and wearing course asphalt mixtures of road pavements/highways or in urban areas.

1.3 Overall objectives

The general objective of this dissertation is to present the main findings and results arising from an extensive laboratory research study aimed at quantifying the volumetric and mechanical performance properties, in-laboratory and in-situ, of half-warm recycled asphalt mixtures with total RAP contents (100%), and emulsified bitumen, and, after that, compared to conventional hot mix asphalt (HMA) mixture.

1.4 Particular objectives

The primary objectives that can be drawn from this research study are listed as follows:

- To collect the current the state-of-the-art review and state-of-practice of new cleaner and greener disruptive production technologies total RAP contents (100%) and emulsified bitumen used in the binder and wearing course asphalt mixtures of road pavements or urban areas.
- To select the most suitable laboratory compaction test method and mix design compaction energy that allows reproducing the volumetric characteristics (i.e., density and air voids content) and mechanical performance properties obtained from the field after pavement construction.
- To analyze the effect of laboratory-accelerated curing process on the development of the ultimate mechanical performance properties (i.e., indirect tensile strength (ITS) and stiffness modulus) of half-warm mix recycled asphalt mixtures containing a total RAP content equal to 100% and emulsified bitumen.
- Short-term mechanical performance assessment of the half-warm mix recycled asphalt mixes with 100% RAP and emulsified bitumen
- To analyze and quantify the self-healing ratio (HR) of half-warm mix recycled asphalt mixtures with electric arc furnace steel slag (EAFS) and recycled asphalt pavement (RAP) aggregates using a breakthrough thermomechanical treatment (i.e., microwave (MW) heating energy and recompaction-based mechanical treatment) for the optimization of maintenance and rehabilitation (M&R) activities of wearing course asphalt mixtures in road pavements or urban areas.
- To present the main findings, future opportunities, recommendations, and conclusions drawn from this doctoral dissertation.

1.5 Structure of the dissertation

This thesis dissertation was broken down into eight phases to meet the particular and overall objectives established in this research document.

Chapter 1. Introduction

This introductory Chapter aims to describe the research methodology and scope of the thesis document based on the problem statement and specific objectives. This chapter presents a brief justification of the interest in conducting this research while collecting the technical content of the document.

Chapter 2. Literature review

This research Chapter includes a thoroughly analysis of the scientific papers, hearings, technical reports, books, conference proceedings, working papers, and thesis dissertations, which makes it possible to achieve a better understanding of what has been done to date with reference to half-warm mix recycled asphalt (HWMRA) mixtures with high and total RAP contents equal to 100% and emulsified bitumen.

Furthermore, the technical, environmental, economic, and social advantages and drawbacks linked to this recent technology will be presented and compared with those obtained from conventional hot mix asphalt (HMA) mixtures. The issues related to the fatigue cracking, stiffness, and moisture damage will be addressed to provide higher confidence in using this technology in binder and wearing course asphalt mixtures of road pavements.

Chapter 3. Materials and test procedures

This Chapter outlines the mixture testing plan along with a preliminary laboratory research study aimed at determining the physical properties of the materials (i.e., reclaimed asphalt pavement (RAP), virgin aggregates, asphalt binder, and cationic emulsion) that were selected for producing HWMRA mixtures. In this recognition, the characterization of the materials, as well as the mixtures, was based on the European Committee for Standardization's (EN) standards and, in some cases, the Spanish Technical Specifications (NLT) developed by the Centre for Public Works Studies and Experimentation (CEDEX) for highway testing.

Chapter 4. Methodology

This research Chapter aims to shed light regarding some technical gaps and detailed mix design procedures for the half-warm mix asphalt (HWMA) mixtures' preparation and characterization in the laboratory. A summary of the testing procedures used to analyze the volumetric and mechanical performance properties of the half-warm mixes containing 100% RAP and emulsified bitumen.

The experimental methodology followed in this doctoral dissertation was broken down into six main phases. **In the first phase**, preliminary field and laboratory studies were conducted to characterize respectively the RAP that was used in the production of half-warm mix recycled asphalt mixtures (HWMRA) as well as the remaining mixture's components (i.e., bituminous emulsion and asphalt binder).

The second phase consisted in evaluating three different laboratory compaction test methods to define the most suitable compaction test method and get more consistent volumetric characteristics (e.g., air void and density) and mechanical performance properties of these mixtures in the field. The compaction test methods examined in this research study were the (1) static compressive stress load by a double-plunger action (**NLT-161/98: Standard test method for Compressive Strength of Bituminous Specimens**); (2) Marshall impactor, according to EN-12697-30:2007. **Part 30: Specimen preparation by impact compactor**; (2) and the gyratory compactor test method, according to EN-12697-31:2007. **Part 31: Gyratory Compactor**.

In the third phase, an assessment of the volumetric and mechanical performance of four emulsion contents (2.0, 2.5%, 3.0%, and 3.5% over the weight of RAP) was conducted, after which the optimum emulsion content was subjected to an accelerated curing treatment (0, 24, 48 and 72 h) to quantify whether there was improvement of the mechanical performance properties of the mixtures. Indirect tensile strength (ITS), stiffness modulus, rutting performance, and four-point bending (4PB) beam fatigue test method were evaluated in this research stage.

In the fifth phase, the quality control of the mixtures after in-plant manufacturing was evaluated and tested in the laboratory to verify the reproducibility of manufacturing these mixes in a batch plant, and also to check their compliance in terms of binder content in the final mix design, air voids, stiffness modulus, water sensitivity and rutting resistance. A set of pavement cores will be extracted after pavement construction (EN 12697-27:2017. Part 27: Sampling) and tested for stiffness modulus, indirect tensile strength (ITS), and indirect tensile fatigue test (ITFT). Finally, a comparison between the laboratory results arising from the three compaction methods (i.e., Marshall, Static load and gyratory compactor) and field performance will be conducted.

As for the sixth phase, surface friction characteristics of the binder course mixtures of the test road sections will be determined and compared with those values obtained from conventional HMA mixtures. The macrotexture will be evaluated through the spread of a modified sand patch with microspheres, according to EN 13036-1:2010. **Road and airfield surface characteristics. Part 1: Measurement of pavement surface macrotexture depth using a volumetric patch technique**. The International surface Roughness Index (IRI) will also be calculated using a high-speed profiling laser device, according to EN 13036-6:2008. **Road and airfield surface characteristics. Part 6: Measurement of transverse and longitudinal profiles in the evenness and megatexture wavelength ranges**.

Chapter 5: Results and discussions

The primary objective of this Chapter was to present the results of a new technology based on the use of half-warm mix recycled asphalt mixes containing 100% RAP and two emulsion contents (2.5% and 3.0% o/RAP): From mix design to full-scale implementation. In this context, the main contributions of this Chapter (1) were found to be the adoption of the gyratory compactor system as the most suitable method for this recent technology; (2) the use of an accelerated curing treatment allowed to improve the mixtures' mechanical performance properties in the range of curing between 48 and 72 h, at 50 °C. (3) Another bottom

line was that the HWMRA mixes with 50/70 pen. grade bitumen showed acceptable performance in terms of fatigue life. A 50/70 pen. bitumen exhibited slightly lower microtensile fatigue-strain (ϵ_6) values than the results from the 160/220 pen. bitumen, likely attributed to the effect of a softer penetration grade bitumen in the final mixture design that allowed the provision of higher ductility and flexibility of the mixture. More results and discussion of this thesis dissertation can be found in Chapter 7.

Chapter 6. Looking ahead: Self-healing analysis of half-warm mix recycled asphalt (HWMRA) mixtures containing 100% RAP

This Chapter was developed under the framework of a Spanish research project aimed at quantifying the self-healing ratio (HR) of half-warm mix recycled asphalt (HWMRA) mixtures using three electric arc furnace steel (EAFS) slag aggregates (0%, 4%, and 8% of EAFS) by volume of the mix. The steel slag was used as a replacement of recycled aggregates pavement (RAP) in the fine fraction of 0/4 mm sieve size. In this context, four emulsion contents (e.g., 2.0%, 2.5%, 3.0%, and 3.5% o/RAP) were selected and used to achieve the target air voids criterion, aiming at the target air voids content of 4-6%. The gyratory compactor was chosen for HWMRA mix' production and characterization in the laboratory by applying a mix design compaction energy of 80 gyros, at 80 °C, and following the standard compaction conditions established (0.82°, 30 rpm, 600 kPa) by the EN 12697-31:2007. Part 31: Gyratory Compactor.

Posteriorly, a thermographic analysis was conducted using a FLIR thermographic camera and an infrared temperature-measured gun, along with a microwave oven with a maximum theoretical output capacity of 1200 W and a 230 V, 50 Hz power supply. The initial mechanical performance was calculated in terms of stiffness modulus, at 20 °C, and indirect tensile strength (ITS), at 15 °C. After that, the damaged specimens were subjected to a thermomechanical treatment to determine the self-healing recovery of the mixtures using an experimental mechanical recompaction method (0, 25, and 50 gyros), together with three microwave heating temperatures (25 °C, 60 °C, and 80 °C). A re-mechanical testing phase was conducted again to quantify the self-healing ratio (HR) of the mixtures. Therefore, this study revealed that the slag mixes with 8% EAFS showed the highest self-healing ratio (1.6) while reducing the average energy consumption of 50% compared with those values obtained for the 0% EAFS mixture.

Chapter 8. Conclusions and future research studies

The main contributions and upcoming studies are presented to summarize the findings and lessons learned in this thesis dissertation.

Chapter 9. References. This chapter aims to include all the research documents reviewed to develop this thesis dissertation: hearings, conference proceedings, reports, journal articles, and doctoral dissertations.

Figure 1. Detailed flow chart of the experimental methodology followed in the thesis dissertation

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Asphalt mixtures requiring lower mixing, spreading and compacting temperatures have received considerable attention worldwide in the recent years as a way to improve environmental performance and reduce energy consumption, the extraction and exploitation of natural resources and greenhouse gas (GHG) emissions, construction and production costs. Thus, the concept of greener and cleaner paving technologies has gained momentum in the wake of the increasing global environmental awareness of the environmental damages arising from the greenhouse gas (GHG) emissions and the consumption of scarce and non-renewable resources with which the paving industry has been associated with. This fact has motivated departments of transportations (DOTs), and the pavement community in general, to investigate strategies that improve the environmental performance and reduce the costs of road pavement construction and maintenance practices by using sustainable engineering solutions.

Recycled asphalt pavement (RAP) material is also often used to mitigate the problem related to (1) the disposal of the materials removed from road pavements that have reached unacceptable service conditions and (2) the exploitation and extraction of raw materials. Additionally, considerable economic savings can be achieved as a result of the reuse of RAP into new mixtures (Kandhal PS and Mallick RB, 1997). Therefore, asphalt pavement sections requiring reconstruction or in need of a new overlay are potentially good candidates for recycling. Over the years, several recycling technologies have been developed to facilitate the use of RAP into new asphalt mixtures. Notwithstanding these efforts, there are fewer than expected sustainable technical solutions that enable the reuse of high or total RAP contents. For instance, the most common recycling techniques, such as cold mix asphalt (CMA) mixtures, have been mainly used in maintenance and rehabilitation (M&R) activities of road pavements subject to low traffic load categories. However, these asphalt mixtures tend to present some drawbacks and shortcomings associated with curing period, coating, tenderness, delayed cohesion, low early strength, and the need for a maturation process that allow them to develop the final properties (e.g., indirect tensile strength (ITS) and stiffness modulus) at the early hours after being placed in the field (Al-hdabi and Al, 2018; Bocci M et al., 2011; Graziani A et al., 2016; Swaroopa S et al., 2015).

One example of a technology that has the potential to improve pavement sustainability is the half-warm mix asphalt (HWMA). HWMA mixes are manufactured, spread, and compacted in the range values of 65-100 °C. This technology can be conceived as an essential step forward to improve road pavement sustainability by achieving energy consumption savings in the range of 25-50% compared to both hot-recycling and warm mix asphalt (WMA) technologies while reducing the exploitation and extraction of non-renewable resources (i.e., virgin aggregates and binder) and fuel source consumptions (gas-oil); (3) the amount of pollutant emissions (i.e., smoke and fumes) released into the atmosphere as a result of decreasing the heating and drying temperature of virgin aggregates; (4) less aging of the recycled RAP binder due to the adjustment of the burner flame during the mix production; (5) as well as the possibility to stretch the asphalt paving window throughout cold-weather conditions, due to a slower mix cooling rate over longer hauling distances before its placement in the field (Manolis et al., 2008; Vaitkus et al., 2009).

In this context, it has been suggested that HWMA technologies are good solutions to further increase the potential environmental and economic benefits associated with the use of RAP, as they make the compaction process easier than those with virgin asphalt binder. However, there remain some concerns and questions to be tackled and answered regarding the mid-long term mechanical performance and durability of these mixes due to (1) the unknown source and variability of RAP (Silva Hugo M R D et al., 2012), (2) the lack of a good understanding of the mixing between RAP and other mixtures components (Lo Presti D et al., 2016), and (3) the fact that the use of RAP can lead to increased stiffness, lower durability, and workability of the mixtures if proper adjustments to mix design process are not performed (Kusam et al., 2017). For instance, Zhao et al. (2013) (Zhao et al., 2013) and Lopes et al. (2014) (Lopes M et al., 2014a) showed that the addition and reuse of high RAP contents increases the resistance to permanent deformation, but it can likely lead to an increase in stiffness modulus because of the reuse of the aged recycled asphalt binder (Valdés et al., 2011; West et al., 2013), that in turn, reduces the mixture's fatigue cracking resistance (Boriack P et al., 2014; Rebbechi J and Green M, 2005).

In **Figure 2**, the average energy consumption of the conventional HMA mixture was found to be 7-8 kg of fuel/t, resulting in an average carbon dioxide emissions during the HMA mix production within the order of 20-25 kg of CO₂/t, whereas, for the HWMA 100% RAP mixes, the average energy consumption fell within the range of 2-3 kg of fuel/t, and an average amount of pollutant emissions of 5 kg CO₂/t (D'Angelo et al., 2007). However, some others researchers reported that the average energy consumption of HMA mixes was found to be 6-7 kg of fuel/t, from which 30-35% are losses, 25-30% corresponding to the heating process of virgin aggregates, and 15% belong to the evaporation of water due to the emulsion breaking (Bardesi and Soto, 2010). As a result of this, some researchers claim that the decrease in the manufacturing temperatures might lead to a significant reduction in pollutant emissions, energy consumption and hence economic costs (Coppola et al., 2016; Kristjánsdóttir et al., 2007; McDaniel et al., 2001).

1. Hot mix asphalt (HMA) mixes are fabricated and compacted in the range of 150-170 °C.
2. Warm mix asphalt (WMA) mixes are laid and compacted in the range of 105-140 °C.

3. Half-warm mix asphalt (or enrobés semi-tièdes in French) – HWMA are mixtures that are formulated either with foamed or emulsified bitumen technology, and they are fabricated, laid and compacted below the boiling point of water ($\leq 100^\circ\text{C}$), or in the workable temperature range of $100^\circ\text{C} - 65^\circ\text{C}$ (212°F to 155°F).
4. Cold mix asphalt (CMA) is spread and compacted at room temperatures, and it is formulated with bitumen emulsion content and cement.

Figure 2. Classification of asphalt mixes based on the manufacturing temperature reduction and fuel usage (D'Angelo et al., 2007)

2.2 Classification of HWMRA mixes

Though there is no general agreement nor consensus on how these mixtures should be classified, the classification accepted is based on (1) the recycled content to be reused into the new mixture design; (2) bitumen production either foamed or emulsified; (3) aggregate particle size distribution (AC D, S, PA, BBTM); (4) Mix production temperature (hot/warm/half-warm) and industrial production process using a continuous drum plant or asphalt batch plant.

- **HWMRA with total RAP contents.** They are made up of a combination of virgin aggregates (if necessary) and the respective quantity of RAP material equal to or greater than ($\geq 80\%$) RAP. Also, for the correct mix production, it is recommended that the recycled binder not enter into contact directly with the burner flame in the drum-dryer to prevent binder aging

- **HWMRA mixes with high RAP contents.** This mix is made up of an amount of RAP equal to, or higher than ($\geq 50\%$) and lower than $<80\%$.
- **HWMRA mixes with intermediate RAP contents** are made-up of a combination of virgin aggregates and RAP contents higher than $>20\%$, and lower than $<50\%$ RAP.

Another way to classify these mixes is by the particle aggregate size distribution (1) dense-graded asphalt concrete (AC16 D), or semi dense-graded (AC16 S); (2) Open-graded mix; (3) porous asphalt (PA); and (4) Beam-to-Beam Traffic Matrix (BBTM), as illustrated in **Figure 3**.

- **Dense- and semi dense-graded asphalt concrete mixtures (AC D or AC S).** A dense-graded mix is made-up of a combination of homogeneous aggregate particle size distribution resulting from coarse and fine particles, and, eventually, mineral filler, with dense-graded asphalt concrete gradation and bitumen emulsion used as asphalt binder and additives, **EN 13108-1:2016. Bituminous specifications. Material specifications. Asphalt Concrete.**
- **Open-graded mixtures.** These types of mixtures can be defined as the combination of homogeneous aggregates, including a low proportion of fine aggregates, mineral filler, bitumen emulsion and, in some cases, additives. These mixtures can also be classified according to their particle size distribution as follows: (1) Porous Asphalt (PA), and (2) gap-graded mixtures.
- **Porous Asphalt (PA) mixtures.** This mix is made up of a higher air voids content than conventional dense-graded mixes and interlinked together, which makes it possible to provide more suitable drainage characteristics. The structural strength of the gap-graded mixture depends on the mortar of sand, bitumen, and filler. These mixes are also made-up of aggregates corresponding to a sieve size fraction in the range of 2-6 mm, and its aggregate particle size distribution is based on **EN 13108-7:2016. Bituminous mixtures. Material specifications. Porous Asphalt.**
- **Beam-Beam Traffic Matrix (BBTM).** The gap-graded mixtures contain a small percentage of aggregate particles in the mid-size range. The aggregate grading curve is flat in the mid-size range corresponding to BBTM A and B, according to EN 13108-2:2016. Bituminous mixtures. Material specifications. Asphalt Concrete for Very Thin Layers (BBTM).

Figure 3. Four different types of half-warm mix textures for road pavements

2.3 Sustainable development

Sustainability is one of the most important social concepts used to quantify environmental, social, and economic advantages offered by today's sustainable engineering solutions. In this regard, the most well-known definition of sustainability corresponds to Brundtland definition: **“the development that meets the needs of the present without compromising the ability of the future generations to meet their own needs”** (UN Document, 1987). In this respect, developing environmentally friendly and energy-efficient asphalt paving technologies appear to be of great importance (Wang et al., 2018a); to reduce pollutant emissions and energy consumption (Alkins et al., 2012), and, in turn, to fulfill and be consistent with the social desire to use technologies that reduce, recycle and reuse (3Rs). **Figure 4** shows the triple bottom line (TBL) approach offered by using HWMA mixes.

Figure 4. Schematic representation of the 3BL approach using HWMRA mixes

2.4 Potential benefits and drawbacks

The use of half-warm mix reclaimed asphalt (HWMRA) mixtures is typically seen and conceived as a new step towards road pavement sustainability because of the provision of environmental, social, technical and economic benefits with which these mixes have been associated. In due recognition, the expected potential benefits of using these sustainable mixtures include; (1) reduced mixing and compaction temperatures at the worksite (2) the extension of the paving season window or when mixtures should be hauled long distances before their placement in the field (Brosseaud and Saint Jacques, 2008; Manolis et al., 2008; Vaitkus et al., 2009); (3) good compactibility to lower mix production temperatures (Croteau and Tessier, 2008); (4) less RAP binder ageing process due to the reduction of heating and drying temperatures; (5) lower emissions derived from the incineration of fossil fuel sources, such as carbon dioxide (CO₂), carbon monoxide (CO), oxides of nitrogen (NO_x), volatile organic compounds (VOCs) and particles (Rubio et al., 2013). With this in mind, sustainable development is met by using sustainable pavements (Maher et al., 2006). Therefore, the primary benefits associated with this technology are classified in four different categories as follows:

- **Economic** → Reduced energy consumption, fossil fuels, and funding costs
- **Environmental** → Lower pollutant emissions (CO₂, VOCs, CO, NO_x)
- **Paving** → Improved workability and compaction efficiency, longer hauling distances
- **Production** → Potential for increasing higher RAP contents

2.4.1 Economic benefits

The HWMRA mix is conceived as a new disruptive energy-efficient technology due to its ability to reduce mix production/compaction temperatures, energy consumption, and economic costs. Therefore, this technology enhances road pavement sustainability by achieving energy consumption savings of up to 50%, thereby reducing fossil-fuel consumption in about 3-4 kg/t (Bardesi and Soto, 2010; Harder et al., 2008; Miranda, 2008; Olard and Romier, 2009) in comparison with both conventional hot in-place recycling and warm mix asphalt (WMA). In this context, the decrease in manufacturing and spreading temperatures lead to a significant reduction in energy consumption and economic costs (Coppola et al., 2016; Kristjánssdóttir et al., 2007). Nonetheless, the real economic gains from the decreased energy consumption depending on the type of energy and its current cost in the asphalt paving market (Hossain et al., 2009). In this context, additional benefits can be quantified due to the decrease in production/compaction temperatures, i.e., reduced greenhouse emissions, fumes, and odors generated at the asphalt mixing plant and paving site (Rashwan, 2012).

2.4.2 Environmental benefits

The production of hot mix asphalt (HMA) mixtures raises a large number of environmental concerns as a result of polluting (CO_2 , NO_2 , and NO_x) emissions released into the atmosphere and brings up health risks by the staff responsible for the maneuvers in the asphalt batch plant. In order to overcome these issues, the adoption of the HWMA mixes, as a greener and cleaner production technology produced below the boiling point of water (100°C), provides several advantages associated with the reduction of harmful emissions and fuel consumption as a consequence of lowering mix production temperatures.

In other words, this technology allows to save energy consumption of up to 3-4 kg/t, in comparison with both hot in-place recycling and warm mix asphalt (WMA) mixtures (Bardesi and Soto, 2010; Olard and Romier, 2009; Ventura et al., 2009), while diminishing the amount of pollutant emissions released into the atmosphere in the quantitative range of 10-15 kg/ CO_2 , in comparison with hot in-place recycling and WMA mixes, by decreasing the emission of harmful emissions above 3 million/tons each year in Europe (Bardesi and Soto, 2010; Olard et al., 2009).

Gaarkeuken et al. (2016) investigated the amount of CO_2 emissions released into the atmosphere using the Low Energy Asphalt Concrete - Porous Asphalt (LEAB-PA) approach. The authors found that the average harmful emissions accounting for 1 ton of HMA LEAB-PA mix were found to be approximately 11.93 kg/ CO_2 , while, for the production of 1-ton HWMA-PA was found to be 9.26 kg/ CO_2 . Therefore, a considerable reduction of emissions and energy consumption of the HWMA-PA of 22% and 50% were obtained, respectively, in comparison with HMA-PA mix.

Rubío et al. (2013) investigated the environmental benefits linked to cleaner and greener production technology. This study aimed at measuring the amount of polluting emissions during the construction of test road sections in an asphalt batch plant. They found that the reduction at half-warm temperatures may lead to a significant decrease in terms of polluting emissions of up to 58% of CO_2 and 99.9% of sulfur dioxide (SO_2), harmful gases, volatile organic compounds (VOCs) and polycyclic aromatic hydrocarbons (PAHs).

Miranda (2008) conducted a comparison between HWMA and HMA mixes in a continuous asphalt plant. They claim that the decrease in production and compaction temperatures below 100°C might lead to a remarkable energy consumption reduction by achieving energy (fuel and gas-oil) savings of up to 50%, and hence a significant reduction in harmful emissions in about 30% CO_2 compared to traditional HMA mixes. They also reported that the average harmful emissions calculated during the HWMA mix production were about 3.81 ton of CO_2/h , while, for the conventional HMA mix, this number was 4.81 ton of CO_2/h , as illustrated in **Table 1**.

Table 1. Pollutant emissions released into the atmosphere during the mix manufacturing

Emissions released in-plant	Miranda (2008)		Rubio et al. (2013)		Limit values
	HWMA	HMA AC16 D	HWMA AC16 S	HMA AC16 S	
CO ₂ (%)	-	-	1.7	4.1	-
CO (ppm)	-	-	51	628	1445
NO _x (ppm)	3	27	17	51	300
SO ₂ (mg/m ³ N)	136 ppm	181 ppm	1.1	1025.9	850 ppm
H ₂ (ppm)	184	460	-	-	-
Particles (mgC/Nm ³)	-	-	12.9	30.9	150
TOC (mgC/Nm ³)	-	-	26.48	18.47	150
VOCs (µg/L)	-	-	<0.30	<0.67	3.5
PAHs (µg/L)	-	-	<0.059	<0.019	3.5

2.4.3 Paving/compaction benefits

Though the main driving factors for HWMA mix implementation are highly linked to its economic and environmental benefits, there are many other potential benefits expected from adopting this technology. In other words, the expected potential benefits are mainly associated with the decreasing in viscosity, longer hauling distances, quicker turnover to traffic due to a shorter cooling time, fewer restrictions in non-attainment areas, improved workability, higher compaction efficiency, lower aging and physical hardening of the recycled asphalt binder because of the lowering of mix production/compaction temperatures.

Moreover, it has been suggested that HWMA mix technologies are good solutions to further increase the potential paving benefits associated with the RAP usage, as they make the compaction process easier than those with virgin asphalt binder. This phenomenon is likely attributed to the fact that the compaction process is easier because of the reduction in binder viscosity during the mix spreading process (Zaumanis, 2010). In this line, some researchers demonstrated that the workability and compactability of the half-warm mixture remain excellent at relatively low-temperatures (≤ 80 °C) (Croteau and Tessier, 2008), which represents a specific benefit to encourage the use of these mixes in the field (Croteau and Tessier, 2008). Therefore, they can be spread and compacted in cooler thermal weather due to a slower mix cooling rate in the workable temperature range of 65-100 °C, since they can have better workability, compactability and easier handwork. Moreover, recent works have therefore focused on showing that reducing temperatures to within the warm/half-warm range and introducing RAP should not compromise the performance of the mixes in the field (Chang-fa et al., 2014; Dinis-Almeida et al., 2016; Swaroopa et al., 2015).

2.4.4 Production benefits

The half-warm mix technology enables to reduce production and compaction temperatures compared with other existing paving solutions offered by the asphalt paving market. In other words, the HWMMA mix facilitates the reduction (1) of the asphalt binders' viscosity by enabling the bonding and coating of the recycled aggregates at lower temperatures (Hill, 2011); (2) increased workability that leads to the inclusion of higher RAP contents into new mixes; lower pavement compaction energy to achieve the target benchmark density (Bonaquist, 2007); lower thermal susceptibility (Hurley and Prowell, 2006; Jamshidi et al., 2013), longer pavement service life (Rodríguez-alloza et al., 2015), and less RAP binder ageing because of the decrease in the production/compaction temperatures, enabling a less brittle and less stiff mixture, while preventing fatigue cracking issues at low thermal gradients (Chiu et al., 2008; Wagoner et al., 2005).

In this context, Chiu et al., (2008) reported a remarkably eco-burden impact reduction of 23% because of the decrease in energy consumption and asphalt binder content, required to heat and dry the virgin aggregates during mix production. Moreover, the decrease in production/compaction temperatures entails significant advantages in terms of reduction of harmful emissions, energy consumption and hence economic costs savings (Coppola et al., 2016; Kristjánsdóttir et al., 2007; McDaniel et al., 2001). The decrease in manufacturing temperature helps to place asphalt plants closer to metropolitan areas (Kristjánsdóttir et al., 2007) and prevent the shutdown of asphalt plants if they do not meet air quality standards (Hill, 2011).

2.4.5 Drawbacks

Despite the economic, environmental, and technical advantages associated with the use of half-warm mix recycling technology, there still remain some questions to be answered concerning their production, durability, quality control and long-term mechanical performance properties in the field. In this line, the typical concerns that can be drawn from the state-of-the-art review are summarized as follows:

1. The lack of a good understanding during the mixing between the RAP and other mix components (Lo Presti et al., 2016).
2. The main restriction and hindrance in the widespread use of total RAP contents of up to 100% is the uncertainty of the long-term mechanical performance and lack of a system that allows having a better selection of the materials and mix design (Zaumanis et al., 2016).
3. The often unknown-nature, stocking, and variability in the physical properties of the recycled aggregates (Bernier et al., 2012; Boriack et al., 2014).
4. The uncertainty regarding the degree of blending between RAP and virgin binder (Shirodkar et al., 2011).
5. Lack of long-term field experiences and the state-of-the-practice that allow increasing confidence in using the half-warm emulsified bitumen mixes in wearing course asphalt mixtures.

6. A further concern towards the full-scale implementation of this recent technology pertains to its manufacturing since there are no asphalt batch plants readily available for dealing with 100% RAP contents, bitumen emulsion, and at half-warm temperatures.

2.5 Mechanical performance characterization

This section aims to present a preliminary outlook of the current technical experiences (in-laboratory and in-field) of mixes containing high and total rates of recycled asphalt, and compare their mechanical performance with other existing paving solutions offered in the asphalt paving market, such as (1) durability via water sensitivity/moisture damage; (2) stiffness modulus; (3) resistance to permanent deformation; (4) resistance to fatigue cracking behavior; and (5) resistance to low temperatures.

2.5.1 Water sensitivity test

In a report submitted to the National Center for Asphalt Technology (NCAT), Kiggundu and Roberts., (1988) proposed several definitions of stripping phenomenon in asphalt mixtures from the point of view of a large number of researchers (Breakah et al., 2009; Caro et al., 2008; Petersen et al., 1982; Tunnicliff and Root., 1984). The progressive functional deterioration of a pavement mixture by the loss of the adhesive bond between the asphalt cement and the aggregate surface and the failure of the cohesive resistance within the asphalt cement principally from the action of water (Kiggundu and Roberts, 1988). Airey et al., (2008) and Capitão et al., (2012) defined the phenomenon as the loss of resistance to water action caused by the failure at the interface of binder- aggregate or the loss of cohesion in the binder-filler mastic.

Some researchers reported that mixes containing total RAP content of up to 100%, and manufactured at low temperatures, tend to develop equivalent moisture damage resistance values compared to the conventional HMA mixtures, as shown by RAP mixtures that exhibited a percentage of water sensitivity greater than 85% (Dinis-Almeida et al., 2016; Dinis-Almeida and Afonso, 2015). Other researchers have concluded that the durability assessed through the moisture damage of RAP-HWMA is quite similar to the conventional HMA mixture. Other researchers found similar outcomes for RAP mixes. For instance, Dunning and Mendenhall, (1978) and Kiggundu and Newman, (1987) claimed that the RAP mixtures tend to have better resistance to water action than those mixes containing only virgin aggregates.

Karlsson and Isacsson, (2006); Mogawer et al., (2012) reported that mixtures with a high RAP content tend to develop similar or even higher resistance to moisture damage than that of conventional mixes because the RAP aggregates are covered with a thin film of asphalt binder that impedes the water penetration in the mix. However, Li et al., (2004) examined the moisture susceptibility of mixes with up to 40% RAP and found that there was 38% of moisture damage failure rate when using the tensile strength ratio for AC mixtures. Tabakovi et al. (2010) claimed that the addition of a RAP content higher than 50% might reduce the durability of the mix. Therefore, a more in-depth analysis is necessary to evaluate the resistance to moisture damage since it can lead to surface pavement distresses and hence the reduction of the pavement service life (Boadu, 2005; Sengoz and Agar, 2007).

Additionally, the aggregate-binder adhesion will be conducted by characterizing the resistance to water action via indirect tensile strength (ITS) test, at 15 °C, according to EN 12697-12:2009. **Part 12: Determination of the water sensitivity of bituminous specimens.** The minimum resistance to moisture damage value to be met for base and binder course asphalt mixtures should be 80% and 85% for wearing course asphalt mixtures of road pavements. The specimens have to be preferably compacted with the Marshall impactor by applying 50 impact blows on each face for mixes made up of a maximum aggregate size equal to or lower than 22 mm. On the contrary, for mixes with a maximum aggregate size above 22 mm, the specimens will be compacted using a vibratory compactor for a short period of 80 ± 5 s, according to EN 12697-32:2003+A1. Test methods for hot mix asphalt. **Part 32: Laboratory compaction of bituminous mixtures by the vibratory compactor.**

2.5.2 Stiffness modulus

The elastic stiffness modulus is a measure of materials ability to distribute the traffic loading (Gómez-Meijide et al., 2015; Read., 1996), and this one displays the relationship of stress and strain or viscoelastic characteristics at a given temperature (Yan et al., 2010). The stiffness modulus of bituminous mixtures can be defined as the resistance to deformation under applied stress conditions; or the ratio of uniaxial stress and the corresponding strain, which depends on temperature, loading time, physical consistency of the bitumen (i.e. Penetration grade and softening point) and mineral skeleton; wherein the bitumen is responsible for the viscoelastic properties, whilst the skeleton mineral influences on the plastic and elastic properties of the mixture.

The stiffness modulus is a crucial factor to design flexible pavements, as it is directly linked to the bearing capacity of the material to distribute the loads and also serves as a structural strength indicator of the mixture (Pasetto and Baldo., 2011). The mixture' stiffness can be determined by a variety of laboratory testing methods such as (1) load indirect tensile test, (2) uniaxial repeated load test, (3) four-point bending beam test. However, the method used and selected to determine the stiffness modulus was based on the EN 12697-26:2012. **Test methods for hot mix asphalt. Part 26: Stiffness modulus.**

The stiffness modulus of a recycled mixture depends on the type of aggregate and its gradation, but the most significant factor is the stiffness of the recycled binder contained in the RAP (Rebbechi and Green., 2005). In this sense, some researchers claim that RAP mixes are usually stiffer and have a higher complex modulus than those which contain only virgin materials (Li et al., 2004), likely due to chemical aging and natural hardening process suffered by the asphalt binder in the RAP during its service life. On account of the increased stiffness of the binder, RAP mixes usually exhibit better (or at least equivalent) resistance to rutting than conventional mixes (Hajj et al., 2009).

Button et al., (2007) reported that mixes requiring lower manufacturing temperatures, such as HWMA and CMA, are primarily characterized by having a lower bearing capacity than that of conventional HMA mixtures, which could lead to a shorter service life under heavy traffic loads and resistance to permanent deformation issues. However, and opposite to this, Apeagyei et al., (2013) examined the influence of a high

RAP content in terms of mixture stiffness, concluding that the addition of up to 30% RAP to AC mixtures did not produce a considerable effect on it, i.e., the virgin binder's stiffness influences the stiffness of the RAP mixture.

Bardesi and Del Val (2017) published an outstanding research manuscript concerning the influence of mix design considerations on the structural pavement rehabilitation using recycling pavement techniques in 6.3 I-C contexts. They reported that it seems acceptable to assign a lower coefficient of equivalence of 0.8 for hot in-place recycling of bituminous mixtures (with a RAP content equal to or higher than 50%). In other words, the higher the RAP content, the more it further goes away from a new bituminous mixture that has a coefficient of equivalence of 1.0. Additionally, they reported that it makes sense to establish a modulation for the coefficient of equivalence based on the asphalt batch plant and its capacity for handling and processing of RAP; but it does not seem feasible to address such considerations in the mix design stage.

2.5.3 Resistance to permanent deformation

The resistance to permanent deformation is referred to as “Rutting” or “Plastic deformation”; It is defined as the progressive accumulation of tiny irrecoverable deformation strains of each layer of the pavement structure caused by repetitive shear deformation under traffic loading and at high service temperatures (Abdulshafi, 1988; Tayfur et al., 2007). Meanwhile, Whiteoak and Read, (2003) defined as the permanent deformation in the low stiffness response of the material, when the stiffness of the bitumen is less than 0.5 MPa, resulting in a crucial characteristic that affects durability and load-bearing capacity (Bernier et al., 2012).

The rutting performance of asphalt mixtures can be assessed by using different devices or methods that allow determining this feature. Therefore, the standardized wheel tracking devices include the followings methods: (1) the asphalt pavement analyzer (APA) (Malladi et al., 2015; Yang et al., 2014), (2) Hamburg wheel tracking device (HWTd) (Collins and Lai, 1992; Lu and Harvey, 2006; Luo and Yang, 2015; Shao et al., 2017), (3) wheel tracking test (small size device WTT: EN 12697-22), (4) LCPC French wheel tracking tester (large size device – FWTT: EN 12697-22, (4) Asphalt Mixture Performance Tester (AMPT) based on the Marshall flow number (Alavi et al., 2016; Azari and Mohseni, 2014), and (5) cyclic compression test or cyclic triaxial test (Goh et al., 2011; Ulloa et al., 2013).

Several studies have shown that the addition of RAP into new mixes improves the load-bearing capacity and rutting because of the physical hardening and oxidative aging suffered by the asphalt binder during its initial service life, likely caused due to the evaporation or loss of the lighter bitumen components (i.e. maltenes and saturates) (Gaarkeuken et al., 2016). For this reason, the addition of high recycled asphalt contents into new mixtures has been widely used, likely due to its high resistance to some of the most common surface pavement distresses such as rutting. Therefore, the effects of RAP mixes on rutting resistance have been reported in other studies conducted by Doyle and Howard, (2013); Lopes et al., (2014); Zhao et al., (2013), who investigated the resistance to rutting of mixtures containing high RAP contents using loaded wheel tracking test, and found that the reuse of a high RAP content increases the resistance to permanent deformation, but it can likely lead to an increase in stiffness modulus because of the reuse of the

aged recycled binder (Valdés et al., 2011). In due recognition, mixes containing RAP usually exhibit better (or at least equivalent) resistance to rutting than conventional mixes on account of the increased stiffness of the binder (Hajj et al., 2009; Silva et al., 2012).

However, and contrary to popular beliefs, some results have been rather less conclusive and contrary to the general results found by other researchers. For instance, Mogawer et al., (2012) reported that mixtures containing a high rate of RAP, and fabricated at low temperatures, showed low-rutting resistance values when using the Hamburg Wheel Tracking Device (HWTB), likely caused due to the decreasing in mixing and compaction temperatures. To further support this hypothesis, Button et al., (2007) reported that mixes fabricated at lower temperatures and emulsified bitumen are typically characterized by having a lower load-bearing capacity and rutting performance than that of conventional HMA mixtures. In this sense, a more in-depth research is, therefore, necessary to determine whether the use of half-warm mixes can be feasible, or not, for their use in base, binder or surface course asphalt mixtures subject to any heavy traffic load category and thermal zone in Spain.

2.5.4 Resistance to fatigue cracking

Fatigue cracking is one of the most common failure modes of road pavements that are caused by repeated traffic loading and the action of thermal gradients (Colombier, 1997). There are different laboratory testing methods to characterize the short- and long-term mechanical performance properties of half-warm mix recycled asphalt mixtures, according to EN 12697-24: 2007. Test methods for Hot Mix Asphalt - Part 24: Resistance to Fatigue – Annex E: Indirect tensile fatigue test and Annex D: four-point bending beam test.

Over the last few decades, the addition of recycled asphalt into new mixtures has been widely used ($\geq 30\%$), likely due to its high resistance to some of the most common surface distresses that occur in road pavements, such as rutting. However, it appears that the reuse of high RAP contents into new mixtures can lead to an increase in oxidation levels due to the hardening and the natural aging process suffered by the recycled binder during its service life. For these reasons, the aged RAP binder increases mixture stiffness (Li et al., 2004; Li and Gibson, 2016; Shah et al., 2007), which can lead to early fatigue cracking issues (Al-Qadi et al., 2012; Al-rousan et al., 2008; Daniel et al., 2010; Shah et al., 2007) and low temperature-brittleness (Terrel et al., 1992). The stiffening and aging of the recycled binder are the main reasons for the reluctance of local administrations and researchers to allow the addition of high and total RAP contents in the final mixture design (Mogawer et al., 2012; Willis et al., 2012).

These facts are likely caused by the fact that the recycled asphalt binder becomes stiffer and more brittle. It is also likely caused by the loss of visco-elastic properties and ductility suffered by the recycled binder during its service life - making it more susceptible to fatigue cracking than that of the virgin asphalt binder. These issues are in general agreement with other recent studies conducted by Shah et al., (2007) and Zaumanis et al., (2014), who claimed that RAP mixes tend to typically become less resistant to fatigue cracking behavior than conventional HMA mixes. Therefore, an increase in stiffness binder, together with the loss of ductility can be considered as detrimental to the fatigue cracking or fracture resistance of the

asphalt binder (Motamed et al., 2014). In this regard, these facts, along with some drawbacks arising from the loss of uniformity of the recycled aggregates and type of gradation may considerably affect the mechanical performance properties such as fatigue, rutting resistance and water susceptibility (Bernier et al., 2012). West et al. (2013) found that the stiffness modulus of mixes with up to 55% RAP increased by 25–60% when compared to virgin mixtures.

Nonetheless, several experimental results are somewhat less conclusive regarding their performance. For instance, Dinis-Almeida et al., (2016a) reported that mixes containing up to 100% RAP have demonstrated to exhibit better (or at least equivalent) fatigue cracking resistance when compared to conventional HMA mixes, without adversely affecting the water sensitivity. In this line, Huang et al., (2004); McDaniel et al., (2012); Tabaković et al., (2010) claimed that the reuse of RAP could lead to significant improvements in the fatigue life of mixes.

Shu et al. (2008) examined the performance of mixes containing 10, 20, and 30% RAP using various fatigue criteria. They found that the addition of RAP appeared to either increased or decreased the fatigue life of pavements. In this line, Hajj et al. (2009) reported that the inclusion of RAP could result in either poorer or better fatigue cracking resistance depending on the source of this material.

Al-Qadi et al., (2012); Huang et al., (2005a, 2004); McDaniel et al., (2012); Shu et al., (2008) and Sargious and Mushule, (1991) reported an increased fatigue life of mixtures containing up to 40–45% RAP compared to conventional HMA mixes. These results can be explained as a result of reduced tensile strains in the mixture due to increased stiffness and improved binder-aggregate adhesivity (Zaumanis et al., 2014). For instance, Huang et al., (2005) reported that the hardening and chemical aging suffered by the recycled RAP binder makes a stiff and thin layer at the interface of the RAP to reduce the stress and strain conditions, and lead to improving the mixtures' fatigue cracking resistance.

Finally, more in-depth research analysis of the fatigue behavior of foamed and emulsified mixes is therefore of critical importance to guarantee their satisfactory fatigue performance during their service life and also strengthen confidence in using these mixes containing high or total rates of RAP material.

2.5.5 Resistance to low-temperature fracture

The low-temperature fracture can be considered as one of the main concerns arising from the long-term mechanical performance of road pavement. Despite this assumption, several studies are focused on showing that the resistance to fatigue of half-warm mixes with high and total RAP contents can exhibit similar, or equivalent, fatigue cracking behavior to conventional HMA mixes, regardless of the fatigue test method used for their characterization (e.g., four-point bending (4PB) beam fatigue and indirect tensile fatigue test) and semi-circular bending (SCB) test for crack propagation.

Botella et al., (2016) presented the fatigue cracking performance results of half-warm mix recycled asphalt mixtures with high (50%) and total RAP contents (100%) using emulsified bitumen with three different penetration grade bitumen (35/50, 50/70 and 70/100 latex) at three temperatures (20 °C, 5 °C, and -5 °C).

To this end, two distinctive test methods were selected to characterize the fatigue mixture behavior in the laboratory such as (1) the semicircular bending (SCB) test or Fenix Test; and (2) cyclic uniaxial tension-compression strain sweep (EBADE). They claim that the half-warm mixes with total RAP contents (100%) appear to have similar fatigue cracking behavior and fracture energy, at different low testing temperatures (20 °C and -5 °C), in comparison with conventional HMA mixes. In other words, the HMA mixture showed a remarkable increase in the complex modulus of 35% compared to those mixes produced with 100% RAP.

Nosetti et al. (2018) assessed the effect of the recycling process and binder type on bituminous mixtures with 100% reclaimed asphalt pavement. The authors claimed that it is possible to manufacture half-warm mix recycled asphalt mixtures with similar, or equivalent, flexibility, ductility, and stiffness compared to that of the hot recycled mixture at three temperatures (20 °C, 5 °C and -5 °C).

2.6 Self-healing analysis of asphalt mixtures

2.6.1 Laboratory and field studies

The self-healing phenomenon or the capability of recovery of microdamage in bituminous mixtures dates back from the 60s (Bazin and Saunier, 1967; Raithby and Sterling, 1990). The self-healing process is defined as the recovery of material properties and decreasing in cracking of bitumen and asphalt mixes (Little et al., 1998). The self-healing is capable of counteracting the development of microdamage (Karki et al., 2014) in-situ pavements (Gallego et al., 2013). The recovery of microdamage can be divided into two phases: (i) physicochemical and (ii) mechanical way. There are two conventional heating methods used, either in-laboratory or in-situ, to speed up the self-healing (microcracks) process of bituminous mixtures, i.e., Microwave (MW) radiation and Induction heating method. Microwave radiation is a healing technique by which asphalt materials are exposed to alternating electromagnetic fields, in the order of Megahertz (Flores et al., 2018; Franesqui et al., 2017; Norambuena-contreras and Garcia, 2016), while the induction heating system consisted of mixing ferrous materials in the asphalt mixture exposed to electromagnetic fields, with frequency of Kilohertz (García et al., 2012). In other words, it induces an electrical current in the ferrous particles that increase their temperature by the Joule principle, and the heat energy diffuses into the asphalt mixture, increasing the temperature of bitumen (Schlangen and Vliet, 2011).

The self-healing process can be understood as the ability of bituminous materials to recover their initial performance properties (i.e., due to the loss of the lighter fractions of the asphalt binder during its service life) by wetting and interdiffusion between the two phases of the micro-crack (Butt et al., 2012), which occurs during rest periods (Mazzoni et al., 2016), and/or when the material is exposed to high temperatures (García, 2012; Liu et al., 2011). In fact, there are two ways of self-healing methods in bituminous mixes such as adhesive healing associated with the aggregate-bitumen interface bonding and the cohesive healing of the mastic (Little et al., 2001); whilst the external factors influencing the self-healing properties of the mixtures can be classified as follows: (1) bitumen properties such as viscoelastic properties (Kim et al., 1991), wetting (i.e., due to the bonding adhesion of two crack surfaces by surface free energy - SFE) (Ayar et al., 2016; Lytton et al., 1993), oxidative aging (Ofori-Abebresse, 2006), and diffusion and randomization of asphaltene structure (Bhasin et al., 2011; Phillips, 1998); (2) asphalt mix composition

(LEE et al., 2000); and (3) environmental conditions (e.g. temperature, loading and rest periods) (Bhasin et al., 2011; Castro and Sánchez, 2006; Tabakovic and Schlangen, 2015).

In order to address these issues, some examples of innovative self-healing techniques reported in the literature review that have the potential to speed up the recovery of macrodamage in bituminous mixtures include (but are not limited to): (i) Nanoparticles (i.e. Nanoclay and Nanorubber) (Fang et al., 2013; Qiu et al., 2009); (ii) Induction heating by electrically conductive fibers and fillers (e.g. steel wool, scrap tire wire, silicon carbide, graphite and iron filings) (García et al., 2009; Schlangen and Vliet, 2011); (iii) Microwave (MW) heating radiation energy combined with industrial by-products such as electric arc furnace steel (EAFS) slag aggregates (Ameri and Behnood, 2012a; Franesqui et al., 2017; Gallego et al., 2013; Skaf et al., 2017) and recycled asphalt pavement (RAP) (Benedetto and Calvi, 2013); and (iv) Microcapsules incorporating some healing agents (i.e. sunflower oil, and prepolymers of melamine-formaldehyde) (Al-Mansoori et al., 2017; Su and Schlangen, 2012).

2.6.2 Self-healing with EAFS aggregates

Gallego et al. (2013) assessed the technical viability of heating asphalt mixtures with microwaves energy and electromagnetic induction in the laboratory. They added 0.2% steel wool (10 mm length) by mass of the mixture to improve energy efficiency, and that this percentage was ten times less than the quantity recommended when employing electromagnetic induction for heating. Therefore, the use of microwaves, thus, appears to be a promising technique for in situ asphalt pavement heating. However, some researchers claim that there remain some in-situ limitations regarding the use of steel wool since they require a lot of time to be heated (García et al., 2013).

Gallego et al., (2017) studied the use of additives (i.e. steel wool, scrap tire wire, silicon carbide, iron filings) and electric arc-furnace slag using four different contents (2%,5%,10%,20%) to improve the capacity and ability of bituminous mixtures to be heated by microwaves (MW) radiations. They claimed that 5% of steel slag aggregates (by total weight of the mixture) represents the best alternative for self-healing of the mixtures because of technical and economic reasons. They claimed that EAFS can be regarded as the optimal component for the production of bituminous mixtures since they are susceptible to microwave heating. Asi, (2007) conducted a replacement of 30% limestone aggregates with EAFS aggregates in a bituminous mixture, thereby obtaining the highest skid resistance using the British Pendulum Tester (BTP) for EAFS mixes.

Kandhal and Hoffman (1997) evaluated the HMA mixtures containing steel slag and control aggregates (limestone) were subjected to hot-water conditioning and Lottman freeze-and-thaw to define possible issues. They found that HMA mixtures fabricated with EAFS fine aggregates showed higher Marshall stability (between 20 and 30%) than the control mixtures fabricated with limestone aggregates; whilst other researchers claim that surface course mixtures containing thermal power plant wastes exhibited inadequate performance and faster wear of the aggregates caused by traffic load conditions (Shuler, 1976; Xie et al., 2012).

Bosisio et al. (1974) found that by using a load-frequency of up to 4.5 GHz, the microwave radiations can reach up to ~ 12 cm depth in wearing course asphalt mixtures. Al-Ohaly and Terrel (1988) studied the effect of microwave heating on adhesion and moisture damage on asphalt mixtures. They found that microwave energy improves the binder-aggregate adhesion and, hence, the water sensitivity of the asphalt mixtures.

Stock et al., (1996) reported that the steel slag aggregate surfaces presented an adequate long-term skid resistance than that of 14-mm rock chippings, and at the same time exceed the behavior expectations of these aggregates with similar polished stone values (PSV). With this in mind, Fernández et al. (2013) assessed the PSV test and its relationship with petrographic parameters and surface micro-roughness in both natural and industrial by-product aggregates. They found that the PSV value of EAFS aggregates was way much higher than conventional aggregates such as quartzite gravel and diorite.

Liu et al. (2018) evaluated the heating characteristics and induced healing efficiencies of asphalt mixtures via induction and microwave heating. In this context, asphalt samples were heated by two heating methods: (1) an induction heating machine with an output power of 8.3 kW and a load frequency of 123 kHz; and (2) a microwave machine using a loading frequency of 2.45 GHz, and output power of 5 kW. They found that the heating speed by heating induction was way much higher than that of the microwave machine heating, under a similar output power and the same radiation method. However, the sufficient heating depth of microwave heating is way much higher than that of induction heating. **Figure 5** shows the microwave machine with a microwave magnetron, control panel, and metal cover. The microwave launcher radiates waves from the top of the device to heat the beam samples.

Figure 5. Microwave heating machine for porous asphalt concrete mixture slabs (Liu et al., 2018)

2.7 Surface friction characteristics

2.7.1 Macrottexture

Macrottexture is related to the large scale texture defined by the shape and size of stone particles contained on the surface course mixture (Austroads, 2011). Pavement macrottexture provides the hysteresis component of the friction and allows for the rapid drainage of water from the pavement. In addition to this primary task, higher macrottexture can provide better escape paths for water by reducing aquaplaning and thus improving adhesion friction. The surface macrottexture depth can be calculated, according to EN 13036-1:2010. Road and airfield surface characteristics. Test methods. Measurement of pavement surface macrottexture depth using a volumetric patch technique.

For this reason, the macrottexture of each sample was measured after compaction using a modified sand patch test (EN 13036-1), in which 5000 mm³ of sand were spread over the surface of the specimen with the spreading tool defined by the standard. The voids on the surface of the specimen were filled until the sand reached the peak level (Ramírez et al., 2015). **Table 2** shows how the pavement texture has been classified into three ranges based on the wavelength of its components: microtexture, macrottexture, and megattexture.

Table 2. Texture classification range

Texture classification	Relative Wavelengths
Microtexture	$\lambda < 0.5 \text{ mm}$
Macrottexture	$0.5 \text{ mm} < \lambda < 50 \text{ mm}$
Megattexture	$50 \text{ mm} < \lambda < 500 \text{ mm}$
Roughness/Smoothness	$0.5 \text{ m} < \lambda < 50 \text{ m}$

Figure 6 shows the microtexture that refers to the smallscale texture on the surface of a stone particle, which is more influenced by both characteristics of the aggregates and aggregate source, while the macrottexture depends on the large-scale texture defined by the shape and size of stone particles presented on the road surface.

Figure 6. Microtexture and surface macrottexture depth

2.8 Conclusions of the literature review

The main conclusions and findings that can be drawn from the current-state-of-the-art review and state-of-the-practice are summarized below:

- The study of the issues related to the fatigue cracking resistance of half-warm mix recycling technology with 100% RAP has not yet been thoroughly studied in the current state-of-the-art review and state-of-the-practice, and, thus, remains shrouded in uncertainty. Therefore, a more in-depth investigation is necessary to draw more consistent conclusions from the mixtures' fatigue behavior at low test temperatures (5 °C).
- It was found in the literature review that there is no general agreement concerning what the most appropriate compaction test method is, nor is there a full consensus regarding the required mix compaction energy should be used for the production and characterization of half-warm mix recycling technology with 100% RAP and emulsified bitumen.
- There still remain some technical gaps to be filled in and questions to be answered concerning whether there is a positive effect of an accelerated curing/drying treatment on the development of the mechanical performance properties (indirect tensile strength (ITS) and stiffness modulus) of half-warm emulsified mixes containing 100% recycled asphalt pavement.
- The volumetric and mechanical performance of half-warm mixes with 100% RAP and emulsified bitumen have not yet been compared with a corresponding conventional HMA mixture, after in-plant manufacturing and in-situ, in terms of fatigue resistance, rutting, indirect tensile strength, and stiffness modulus.
- No research papers are addressing the self-healing analysis of half-warm mix recycled asphalt mixtures, with electric arc furnace steel slag (EAFS) and total recycled asphalt pavement (RAP) contents, using a thermomechanical treatment (i.e., a microwave and mechanical recompaction treatment) in the laboratory. The self-healing ratio (HR) of the mechanical performance (stiffness modulus and indirect tensile strength) and energy consumed (kWh) have not been calculated for this recent technology, either.

In summary, one can say that the literature review revealed that the use of half-warm mix recycled asphalt (HWMRA) mixtures with emulsified bitumen represent a tremendous opportunity for the asphalt paving industry to reduce the costs of construction and maintenance and rehabilitation practices. Moreover, there is a consensus about the environmental, social, and economic benefits provided by this greener production technology compared with other existing paving techniques such as hot mix asphalt (HMA), warm mix asphalt (WMA) and cold mix asphalt (CMA).

Chapter 3

MATERIALS AND TEST PROCEDURES

3.1 Introduction

This Chapter outlines the mixture testing plan along with a preliminary laboratory research study aimed at determining the physical properties of the materials (i.e., reclaimed asphalt pavement (RAP), virgin aggregates, asphalt binder, and cationic emulsion) that were selected for producing HWMRA mixtures. In this recognition, the characterization of the materials, as well as the mixtures, was based on the European Committee for Standardization's (EN) standards and, in some cases, the Spanish Technical Specifications (NLT) developed by the Centre for Public Works Studies and Experimentation (CEDEX) for highway testing.

3.2 Materials

3.2.1 RAP characterization

The reclaimed asphalt pavement (RAP) material was recovered from a test road section and classified in two fractions: coarse (5/25 mm) and fine (0/5 mm). For the coarse fraction 5/25 mm (60%) the residual binder content was found to be 2.60 (% o/RAP), whereas, for the fine fraction 0/5 mm (40%), this content was 6.45 ± 0.1 (% o/RAP). As a result, the content of the aged binder in the RAP ($2.60 * 0.6 + 6.45 * 0.4$) was 4.14% over the weight of RAP. Following the dosing procedure, 2.5% o/RAP of emulsion (with 60% residual asphalt binder) was added to the RAP material ($60\% * 2.5\%$), 1.5% of residual asphalt binder is obtained and added in the aged RAP binder (4.14%o/RAP), resulting in a total residual binder content of 5.64%o/RAP for 2.5% emulsion; whilst, for 3.0% emulsion, this content was found to be 5.94%o/RAP.

In this regard, both RAP fractions (0/5 and 5/25 mm) were homogenized, quartered, treated and characterized to determine their residual binder content, through the centrifuge extractor method (EN 12697-1:2012. **Part 1: Soluble binder content**), and white and black RAP aggregate grading curves. The binder' consistency properties were determined in terms of penetration test (EN 1426:2015) and softening point temperature, by ring and ball (R&B) method, according to EN 1427:2015; where the average penetration value of the aged RAP binder was found to be 17 dmm and softening point temperature of 67.2 °C. Moreover, white and black RAP aggregate grading curves were also determined, that is, the white curves can be defined as the RAP gradation after extracting the residual aged binder while the black curves represent the RAP gradation containing the recycled asphalt binder. **Figure 7** depicts the black and white

RAP grading curves of both recycled aggregate fractions (0/5 and 5/25 mm) in which the dashed lines represent the black grading curves, while the solid continuous lines depict the white grading curves.

Figure 7. White and black grading curves for both RAP fractions

3.2.2 Bituminous emulsion characterization

In this research study, two different cationic slow-setting bitumen emulsions (C60B5) were formulated and selected, depending on the penetration grade bitumen to be used, i.e., (1) a 50/70 pen. grade with a residue bitumen content of 61.2% by total weight of the emulsion; and (2) a second bitumen emulsion made up of a rejuvenator binder, with a softer penetration bitumen of 160/220; where the bituminous emulsion meets the current specifications of the framework for specifying cationic bituminous emulsions, according to EN 13808:2013. The characterization of the bituminous emulsion consisted of the analysis of the viscosity at 25 °C, water content, the residue on sieving, the residual binder content, and penetration test of the residual binder. **Table 3** shows the general technical characteristics of the cationic bituminous emulsion used to produce both HWMRA mixtures.

Table 3. Technical characteristics of the cationic bituminous emulsions (C60B5)

Characteristics	Test Method	Unit	C60B5 160/220	C60B5 50/70
Penetration, at 25 °C (100 g, 5 s)	EN 1426:2015	0.1 dmm	183	66
Residual bitumen content (from water content)	EN 1428:2012	%	61	61.2
Water content	NLT 137	%	39	38.8
Recovered oil distillate from emulsion by distillation	EN 1431:2009	%	0	0
Saybolt-Furol Viscosity, at 25°C	EN 12846-1:2011	s	23	26
Storage stability by Sieving (0.5 mm sieve size)	EN 1429:200	%	0.01	0.01
pH	NLT 195		3.0	3.0

3.2.3 Asphalt binder characterization

A conventional dense graded asphalt concrete mixture (AC 16 D) was designed with a conventional asphalt binder of 35/50 penetration grade. The physical properties of the asphalt binder used to produce the HMA mixture are shown in **Table 4**.

Table 4. Physical properties of the virgin asphalt binder

Physical properties	Reference unit	Test method	Value
Penetration test	dmm	EN 1426	42
Softening point	°C	EN 1427	55.6
Penetration index	-	Annex A	-0.33
Relative density	g/cm ³	NLT-122	1.03

3.3 Aggregate grading curve

3.3.1 HWMRA 100% RAP mixture

The particle size distribution of the recycled material fell within the threshold sieve size values stipulated by the Art. 20 of PG-4 “In-situ recycling of asphalt mixtures with bitumen emulsion (Spanish Ministry of Public Works, 2017). The proportion of RAP aggregates, after the screening, was determined to be 40% in the fine fraction (0/5 mm) and 60% in the coarse fraction (5/25mm). This proportion was selected (1) in order to deal with a RAP content equal to 100%; (2) to ensure the mixture’ homogeneity (i.e., control mixture quality, fines particles and mastic content in the mixture design). **Table 5** and **Figure 8** show the selected recycled aggregate grading curve of the HWMRA 100% RAP mixture, as well as the

upper and lower threshold values of the RE2 particle size distribution band, where this band is selected for pavement layer thickness within the range of 6-10 cm (Spanish Ministry of Public Works, 2017). In this study, total RAP content equal to 100% means that there was no need to incorporate new virgin aggregates in the mix design, and 2.5% emulsion content is added over the weight of RAP.

Table 5. RE2 aggregate gradation band (Spanish Ministry of Public Works, 2017) and gradation curve adopted

Sieve size UNE (mm)	32	22	16	8	4	2	0.50	0.25	0.063
Upper limit	100	100	89	77	58	42	20	10	3
Lower limit	100	80	62	49	31	19	2	0	0
Grading curve	100	99.8	88.1	70.96	46.50	26.94	9.64	5.10	0.86

Figure 8. RE2 aggregate gradation sieve sizes and aggregate grading curve adopted

3.3.2 Conventional HMA mixture

The composition and aggregate grading curve of the conventional mixture fell within the threshold values of asphalt concrete (AC 16 D) mixture, as illustrated in **Table 6** and **Figure 9**.

Table 6. AC 16 D threshold limit values and selected grading curve adopted for comparison

Sieve size UNE (mm)	22.4	16	8	4	2	0.5	0.25	0.063
AC 16 D - Upper limit	100	100	74	59	46	27	20	8
AC 16 D - Lower limit	100	90	64	44	31	16	11	4
Grading curve selected	100	96.7	70.5	55	34.5	16.1	12.5	6.9

Figure 9. Aggregate grading curve of the conventional mixture selected

3.4 Testing program

The experimental testing program has been broken down into two phases: the volumetric characteristics and mechanical performance properties of the mixtures as follows:

Volumetric characteristics

- Determination of maximum density of bituminous specimens, according to EN 12697-5
- Determination of bulk density of bituminous specimens, according to EN 12697-6
- Determination of void characteristics of bituminous specimens, according to EN 12697-8
- Marshall impact compactor, according to EN 12697-30 and Marshall Test, according to EN 12697:34
- Gyratory compactor, according to EN 12697-31
- Static compression stress load by double-plunger action, according to NLT-162/00
- Determination of water sensitivity, according to EN 12697-12

Mechanical performance

- Determination of the resistance to permanent deformation, according to EN 12697-22
- Determination of the stiffness modulus, according to EN 12697-26
- Determination of the resistance to fatigue, according to EN 12697-24
- Determination of the indirect tensile fatigue test, according to EN 12697-23

The next Chapter aims to describe the performance tests, specialized equipment, and test procedure used for this study. These laboratory tests methods give information on the recycled binder's consistency properties (i.e., penetration test and softening point by R&B method), resistance to permanent deformation using the wheel tacker, stiffness modulus, in wet and in-dry indirect tensile strength (ITS), susceptibility to moisture damage and fatigue resistance using two performance criteria: (1) indirect tensile fatigue test and (2) four-point bending (4PB) beam test method. Performance results will be compared with each pavement section's field conditioning results to determine how laboratory performance tests compare with field cores.

Chapter 4

METHODOLOGY

4.1 Introduction

This research study has been broken down into six phases. **In the first phase**, preliminary laboratory studies were conducted to characterize the RAP that was used in the production of half-warm mix recycled asphalt (HWMRA) mixtures as well as the remaining mixture components such as bituminous emulsion and asphalt binder. **The second phase** consisted of comparing three different laboratory compaction test methods (i.e. Marshall Impactor, Static Compressive Load and Gyratory Compactor) in order to define the most suitable compaction test method and hence the mix design compactive effort that allows to posteriorly obtain the benchmark density in the field; where N_{design} represents the number of gyrations required to match the specimens' benchmark density with the density expected from the field. Moreover, the mix design procedure was based on the comparison of the (1) Immersion-Compression (I-C) test (NLT 162/00: Effect of Water on Compressive Strength of Compacted Bituminous Mixtures) and (2) the indirect tensile strength ratio (ITSR), according to EN 12697-12:2018: **Determination of the water sensitivity of bituminous specimens**.

In the third stage, a preliminary research study was conducted to determine the effect of five emulsion contents (0%, 2.0%, 2.5%, 3.0%, and 3.5%o/RAP) on the volumetric and mechanical performance properties of the mixtures. This characterization was conducted in terms of bulk density, by SSD conditions, air voids content, stiffness modulus at 20 °C, and indirect tensile strength at 15 °C. To do this, an average of three cylindrical specimens for each emulsion content were prepared (with a diameter of 100 mm and 63 mm in height) to determine the optimal emulsion content (OEC) that allows better optimization of the ultimate mixture design. An assessment of the effect of four accelerated curing treatments (0, 24, 48, and 72 h) on mixtures' mechanical performance (i.e., ITS and stiffness modulus) was conducted.

In the **fourth phase**, an advanced mechanical characterization was carried out based on four different behavior criteria such as stiffness modulus at 20 °C, indirect tensile strength (ITS) at 15 °C, rutting performance using the wheel tracker (50 °C and 60 °C), and fatigue cracking strength, at 20 °C, via four-point (4PB) bending beam test method. **For the fifth phase**, in-plant produced samples were collected and tested in the laboratory in order to characterize the recovered RAP binder and also to verify their compliance in terms of grading curves and binder content in the final mix design, air voids content, stiffness modulus at 20 °C, and indirect tensile strength at 15 °C. Indirect tensile strength (ITS) and stiffness modulus values were contrasted with those values obtained from the pavement cores (2.5% and 3.0% over the weight of RAP) after pavement construction. After that, a set of pavement cores were extracted from the field after pavement construction, according to EN 12697-27:2017. **Part 27: Sampling**, to verify the compliance of

the minimum percentage of 98% of the benchmark density of the laboratory specimens compacted at 70 load cycles with gyratory compactor and standard conditions (0.82°, 600 kPa, 30 rpm) by EN 12697-31.

As for the sixth phase, the surface friction characteristics were evaluated and calculated in terms of macrotexture and international roughness index (IRI). The macrotexture of the mixtures was conducted, EN 13036-1:2010. Road and airfield surface characteristics. Test methods. Measurement of pavement surface macrotexture depth using a volumetric patch technique. In turn, the surface roughness index was evaluated, according to EN 13036-6:2008. Road and airfield surface characteristics. Test methods. Measurement of transverse and longitudinal profiles in the evenness and megatexture wavelength ranges.

Figure 10-11 summarizes the main six phases followed in the experimental methodology of the Chapter.

Figure 10. Detailed flow chart of the experimental methodology

Figure 11. Graphic representation of the experimental methodology of this Chapter

4.2 Characterization of binder

4.2.1 Penetration and Softening point test

Initially, the binder' extraction and recovery tests were conducted on both coarse- and fine-aggregate RAP fractions to obtain the corresponding percentage of recycled asphalt binder, according to EN 12697-1. Part 1: Soluble binder content. To do this, the recycled asphalt was recovered using a rotary evaporator after the solvent extraction method, according to EN 12697-3:2013. **Part 3: Bitumen recovery – Rotary evaporator.** **Figure 12** shows the procedure followed for the binder' physical properties characterization (i.e., penetration test, and softening point by ring and ball (R&B) method) used in Spain.

Figure 12. Binder's physical characterization in terms of penetration and softening point

4.3 Volumetric characteristics

4.3.1 Determination of the maximum density

The mixtures' volumetric characteristics were determined in the laboratory, according to EN 12697-8:2003. Part 8: Determination of void characteristics of bituminous specimens using the bulk density, by saturated surface dry (SSD) conditions, according to EN 12697-6:2012. Part 6: Determination of bulk density of bituminous specimens, and the maximum density was obtained using a pycnometer, according to EN 12697-5:2010. Part 5: Determination of the maximum density - Procedure A: Volumetric method.

In the mathematical procedure, the maximum density of a bituminous mixture is calculated from its composition (binder content and aggregate content) and the densities of the constituent materials; whereas, for the volumetric and hydrostatic procedures, the maximum density of bituminous mixture is determined from the volume of the sample without voids and from its dry mass. In this regard, an average of three cylindrical shaped specimens was prepared and manufactured to determine the bulk density while the maximum density was calculated using two asphalt samples with the pycnometer. The maximum density was calculated according to Volumetric method as shown in Eq 4.1

$$P_{mv} = \frac{(x_{y2} - x_{y2})}{V_p(x_{y2} - x_{y2}) / P_w} \quad (4.1)$$

P_{mv} is the maximum density calculated with the volumetric method (g/cm^3); m_p is the mass of the empty pycnometer. **Figure 13** shows the maximum density test with a residual pressure of 4 kPa for 15 min.

Figure 13. Determination of maximum density using pycnometers on non-compacted specimens

4.3.2 Determination of bulk density of bituminous specimens

The bulk density of an intact compacted bituminous specimen is determined from the mass of the specimen and its volume. The mass of the specimen is obtained by weighing the dry specimen in air. The volume of the specimen is obtained from its mass in air and its mass in water. In the dry procedure, the mass in water is determined without pre-treatment. In the SSD-procedure, the specimen is first saturated with water, after which its surface is blotted dry with a towel, according to EN 12697-6, Bituminous mixtures — Test methods for hot mix asphalt — Part 6: Determination of bulk density of bituminous specimen – saturated surface dry (SSD) conditions, as illustrated in **Figure 14**.

Figure 14. Determination of bulk density by SSD conditions,: (a) Dry (no water in the sample)¹; (b) SSD water fills the HWMRA air voids; and (c) submerged in a water bath at 25 °C

¹ <https://www.pavementinteractive.org/>

The masses are calculated on an average of three specimens, and the final value of the bulk density is assumed to be the average value of the three measurements. The SSD value is calculated based on Eq. 4.2:

$$P_{b,ssd} = \frac{m_1}{m_3 - m_2} \cdot P_w \quad (4.2)$$

Where: P_{ssd} is the bulk density of bituminous specimens in g/cm^3 ; m_1 is the mass of the dry specimen in g; m_2 is the mass of specimen in water (g); m_3 is the mass of the saturated surface-dried specimen in g; P_w is the density (0.9971 g/cm^3) of the water at the test temperature g/cm^3 .

Posteriorly, the air void content of the compacted specimens was determined, according to EN 12697-8:2003. Bituminous mixtures – Test Methods for hot mix asphalts – Part 8: Determination of void characteristics of bituminous specimens. The procedure is calculated based on Eq. 4.3.

$$V_{m,ssd} (\%) = \frac{P_m - P_b}{P_m} \cdot 100 \quad (4.3)$$

Where: P_m is the maximum density in g/cm^3 (EN 12697-5:2007) and represents the mass per unit volume without air in a bituminous material at a known test temperature; P_b is the bulk density of the specimen (EN 12697-6:2007) expressed in g/cm^3 and represents the mass per unit volume, including the air voids, of a specimens at a known test temperature, following the SSD method.

4.3.3 Determination of the geometric density

This method, the simplest, determine the volume of the specimens as a function of the height and diameter measurements. The specimen's dimensions and geometry were determined by following EN 12697-29:2002 standard. **Bituminous mixtures. Test methods for hot mix asphalt. Part 29: Determination of the dimensions of a bituminous specimen.**

Though it avoids problems associated with the SSD condition, it is often inaccurate because it considers a perfectly smooth surface, thereby ignoring surface irregularities, i.e., the rough surface texture of a typical specimen. In accordance with the EN 12697-6:2012 – Annex C, the bulk density in Mg/m^3 of the specimen was firstly calculated by adopting the dimensional procedure $P_{b, \text{dim}}$, according to Eq. 4.4.

$$P_{b,dim} = \frac{(m_1)}{\left(\frac{\pi}{4} \cdot h \cdot d^2\right)} \cdot 10^3 \quad (4.4)$$

Where m_1 is the mass of the dry specimen (g), h is the height of the specimen (mm), and d is the diameter of the specimen (mm). **Figure 15** shows how the specimens' height is measured using a slide caliper, which provides an accuracy of up to 0.001. They include full-featured electronic tools, with or without IP67 protection optional output.

Figure 15. Starrett Precision measuring tools and Saw blades

4.4 Resistance to water action

The laboratory tests selected to determine the resistance to moisture damage of the mixtures were (a) EN 12697-12:2009. **Part 12: Determination of water sensitivity test of bituminous specimens**; and (b) the immersion-compression (I-C) test, according to NLT-162/00: **Standard Test Method for Effect of Water on Compressive strength of Compacted Bituminous Mixtures**.

4.4.1 Water sensitivity

The resistance to water attack of the specimens was determined, according to EN 12697-12:2009. Part 12: Water sensitivity. This test consisted in manufacturing a set of six cylindrical samples, with a diameter of 101.6 mm and 63.5 mm in height, and compacted by the gyratory compactor using two-thirds (2/3) of the benchmark compaction energy previously selected, and following the standard compaction conditions established (0.82°, 600 kPa, and 30 rpm) by the EN 12697-31:2008 standard. The specimens were classified into two subsets as follows: (1) a dry subset stored at 20 °C for 72 h, and the wet subset immersed in-water bath, at 40 °C, during the same period after a vacuum was selected using the pressure of 6.7 ± 0.3 MPa. **Figure 16** shows the in-wet and in-dry conditioning process of the laboratory samples.

Figure 16. Water sensitivity process: (a) vacuum pressure; (b) conditioning process at 15 °C; (c) and ITS in dry conditions

Following the laboratory standard, the indirect tensile strength (ITS) test was carried out (EN 12697-12:2009. **Part 12: Water Sensitivity**) to calculate the percentage of Indirect Tensile Strength Ratio (%ITSR) between the wet and dry subset (EN 12697-23:2018. Part 23: **Determination of the indirect tensile strength of bituminous specimens**). The ITS test consisted in subjecting the specimens to diametral compressive strength loads using two loading strips (with a width of 12.7 mm) at a constant deformation rate of 50 ± 2 mm/min, at 15 °C, in which this load produced tensile stress along the vertical diametral plane. This stress is what progressively fractures the cylinder and ultimately causes the splitting failure of the diametric plane **Figure 17** shows the indirect tensile strength test at 15 °C.

Figure 17. Indirect tensile strength test set-up at 15 °C

The minimum indirect tensile strength ratio (ITSR) values to be met in relation to base course asphalt mixtures and intermediate traffic load categories should be equal to or higher than 75%, whereas, for low-traffic load categories and shoulders, this percentage should be above 70%, according to the latest Spanish technical specifications required by Art. 20 of PG-4 (OC 40/2017: Recycling of pavements) (Spanish Ministry of Public Works, 2017). The indirect tensile strength (ITS) of each specimen is calculated from the peak load applied at breaking and the specimens' dimensions, following Eq. 4.5.

$$ITS = \frac{2 \cdot P}{\pi \cdot D \cdot H} \quad (4.5)$$

Where ITS= indirect tensile strength expressed in gigapascals; P = peak load expressed in kilonewtons; D= diameter of the specimen in millimeters; and H = thickness of the specimen in millimeters. Therefore, the average of the three values obtained for each of the specimens can be understood as the indirect tensile strength (ITS) of the mix. The test was run at 15°C, according to standard UNE-EN

12697-23:2018. Determination of the indirect tensile strength of bituminous specimens. On the other hand, the indirect tensile strength ratio (%), ITSR) can be defined as the relationship between in-wet and in-dry specimens to evaluate the mixtures' water sensitivity test, as shown in Equation 4.6.

$$ITSR = \frac{ITS_w}{ITS_d} \cdot 100 \quad (4.6)$$

Where: ITSR is the ratio of the indirect tensile strength (%); ITSw is the average of the indirect tensile strength value for in-wet specimens (kPa); ITSD represents the indirect tensile strength values for the dry specimens (kPa).

4.4.2 Immersion-Compression test

The immersion-compression (I-C) test was conducted, according to NLT-162/00: Effect of Water on Compressive Strength of Compacted Bituminous Mixtures. To conduct this test, an average of eight cylindrical shaped laboratory specimens was prepared with a diameter of 101.6 mm and a height of 100 mm and compacted with a static contact load pressure produced by double-plunger action. The initial pre-loading applied was approximately 1 MPa, and, hence, the load starts gradually increasing until reaching 20.7 MPa (3000 psi), maintaining the vertical contact load pressure for 2 min. The first four specimens are left at room temperatures (25 °C) for 24 h. The other subset was immersed in a water bath for 24 h, at 60 °C. Posteriorly, the specimens were placed in a water bath, at 25 °C, for 2 h. Both subsets were subjected to a simple compressive load at a constant deformation rate of 5.08 mm/min. Afterward, the percentage of retained water strength resistance is calculated between the wet and dry subsets, which makes it possible to obtain the resistance to moisture damage of the specimens. The optimal percentage should meet the minimum retained water strength requirements, depending on the levels of heavy traffic load to be supported.

4.5 Advanced mechanical characterization of the mixture

Concerning the advanced mechanical characterization of the mixtures studied, the stiffness modulus, rutting performance, and fatigue cracking resistance by four-point (4PB) flexural bending beam test method were evaluated and tested in the laboratory.

4.5.1 Stiffness modulus

The load-bearing capacity of the mixtures was assessed through the **stiffness modulus** (S_m), at 20 °C, according to EN-12697-26:2012. Bituminous mixtures - Test methods - **Part 26: Stiffness**. The stiffness modulus is defined as the relationship between applied stress and maximum measured strain response $E = \frac{\sigma}{\epsilon}$; where E is the elastic stiffness (modulus), in Megapascals (MPa); σ stress (t), and strain ϵ (t). **Figure 18** shows the test frame with loading strips and half-warm specimen ready for stiffness modulus test.

Figure 18. Stiffness modulus test, at 20 °C, of laboratory specimens

This mechanical property was computed as the average value of five indirect-tensile haversine-shaped load waveform pulses on a diametrical section with a rise time of 124 ± 3 ms, target peak horizontal deformation of $5\mu\text{m}$, loading frequency of 2.1 Hz, peak loading force of 1000 N, and Poisson's ratio (ν) of 0.35. Previously, ten load pulses were applied to set up the system in terms of loading level and frequency. Therefore, the average stiffness modulus value was validated and contrasted by turning the cylindrical specimen at an angle of $90 \pm 10^\circ$, according to their longitudinal axis on the plate. Thus, for an applied dynamic load of P in which the resulting horizontal dynamic deformations are determined, the total stiffness modulus is calculated, according to Eq. 4.7 (Modarres and Ayar, 2014):

$$S_m = \frac{P(\gamma+0.27)}{t\delta_h} \quad (4.7)$$

Where: S_m : stiffness modulus, MPa; P : Maximum dynamic load, N; γ : Poisson's ratio (0.35); t : specimen thickness, mm; δ_h : total horizontal recoverable deformation expressed in terms of mm.

4.5.2 Resistance to permanent deformation

The resistance to permanent deformation of the mixture was assessed by conducting the wheel-tracking test (WTT), at 50 °C and 60 °C, using the respective optimal emulsion content with 2.5% and 3.0% o/RAP and 50/70 pen. grade emulsified bitumen, according to EN 12697-22:2008+A1:2008. **Part 22: Wheel Tracking.** Although the wheel tracking test temperature of 50 °C is not considered in the Spanish technical specifications, this test temperature was conducted to simulate and reproduce the real thermal gradients suffered by the binder course asphalt mixture in the field.

In this context, the rutting test consisted in applying a total duration of 10.000 load cycles, at a frequency of 26.5 ± 1 load cycles/minute, procedure B, in air, using a loaded rubber wheel back and forth on the prismatic specimen with a load contact of 700 N. To this end, an average of two prismatic-shaped specimens were prepared (with a length of 400 mm, 250 in width and 60 mm in height) and compacted with a percentage of 98% of the benchmark density using the steel roller device, according to EN 12697-33:2006+A1. Part 33: Specimen prepared by roller compactor, as illustrated in **Figure 19**.

Figure 19. Specimen' preparation and compaction (a) using a roller compactor; and (b) prismatic specimen after compaction ready for rutting performance test

Posteriorly, the wheel tracking slope (WTS) has been calculated, according to Eq. 4.8:

$$WTS_{AIR} = \frac{RD_{10000} - RD_{5000}}{5} \quad (4.8)$$

Where: WTS is the curve of the wheel tracking slope, or creep slope, for 1000 number of load cycles expressed in terms of mm/1000 load cycles; RD5000 is the rut depth when applying 5000 load cycles (mm); RD10.000: is the rut depth after 10.000 load cycles (mm). **Figure 20** illustrates the resistance to permanent deformation using the wheel tracker, at 60°C, of the HWMRA 100% RAP mixtures.

Figure 20. Wheel tracking test, at 60 °C, of the HWMRA 100% RAP mixtures

4.5.3 Four-point bending (4PB) beam fatigue test

In order to complete the mechanical characterization of the mixtures studied, the four-point fatigue bending beam (4PB) test method was conducted, at 20 °C, using a loading frequency of 30 Hz, according to EN 12697-24:2012. Part 24: **Resistance to Fatigue** – Annex D. To do so, more than twelve laboratory prismatic-shaped specimens for each type of asphalt mixture were compacted with the steel roller compactor and thereafter sawed (with a length of 380 mm, 50 mm in width and 50 mm in height), for their posterior testing in the 4PB device.

Following the production/compaction process, the 4PB fatigue strength test was conducted applying harvesine-shaped load pulses in strain-fatigue control mode and with a selected loading frequency of 30 Hz. In turn, the vertical deflection at the center of the beam was measured using a Linear Variable Differential Transducer (LVDT) positioned at the bottom of the specimen. The controlled fatigue-strain amplitude levels selected for the 4PB test varied, as follows: 200-250 $\mu\text{m/m}$, 150-190 $\mu\text{m/m}$ and 100-140 $\mu\text{m/m}$; where the fatigue life should fall within the range of 10^4 and 2×10^6 load cycles. In view of that, the two parameters selected to depict the mixtures' fatigue cracking resistance were the number of load cycles to failure and the corresponding tensile fatigue-strain level (ε_t).

Moreover, the fatigue failure approach (N_f) was defined using the classical fatigue method expressed by a relationship between the tensile strain (ε_t) and the number of load cycles to failure, N_f , at which the initial stiffness modulus of the specimens measured in the load cycle number 100th is reduced to 50% of its initial beam stiffness (Dondi et al., 2013; Kim et al., 2018; Li et al., 2013). The procedure was based on Eq. 4.9:

$$\varepsilon_t = A \cdot (N_f)^B \quad (4.9)$$

Where ε_t : is the tensile strain, $\mu\varepsilon$, applied in the center of the prismatic specimens; N_f : is the number of load cycles to failure; A, B are material coefficients determined in the laboratory depending on the type of the material. **Figure 21** shows the prismatic shaped specimens conditioned at 20°C and the four-point fatigue bending (4PB) beam fatigue test method, at 20 °C, of the HWMRA 100%RAP mixtures with 2.5% and 3.0% (over the weight of RAP) emulsion and two penetration grade bitumen (50/70 and 160/220).

Figure 21. Four-point bending beam (4PB) fatigue test device

4.5.4 Indirect tensile fatigue test

Additionally, for the asphalt samples were taken after in-plant manufacturing and prepared in the laboratory by gyratory compactor method (EN 12697-31:2007. **Part 31: Gyratory compactor**), the indirect tensile fatigue test (ITFT) on cylindrical shaped specimens were conducted, at 15 °C, using a loading frequency of 10 Hz, according to EN 12697-24:2012. **Part 24. Resistance to fatigue - Annex E.** **Figure 22** displays the indirect tensile fatigue test device, at 20 °C. The test consisted in applying a repeated haversine load with 0,1 s loading time and 0,4 s rest time, through the vertical diametral plane, in which the test shall start at a loading amplitude of 250 kPa. In order to do this, an average of three cylindrical specimens was tested in the laboratory at four different strain-fatigue levels, in which the fatigue test was carried out over a dynamic tensile strain range of approximately 100 $\mu\text{m/m}$ to 400 $\mu\text{m/m}$. The failure criterion was defined as the number of load cycles at which the initial stiffness of the sample is reduced up

to 50% of its initial value or when the specimen breaks, whichever comes first. The resultant fatigue life of the tested specimens should fall within a range between 10^3 and 10^6 load cycles, and the fatigue criterion for the bituminous material shall be determined from the tested specimens according to Eq. 4.10:

$$N_f = k \left(\frac{1}{\varepsilon_0} \right)^n \quad (4.10)$$

Where: N_f is the number of load applications; k , n are material constants in the laboratory; ε_0 is the tensile strain in $\mu\text{m/m}$ at the center of the specimen.

Figure 22. Indirect tensile fatigue (ITFT) test set up

4.6 Laboratory compaction study

Nowadays, there is no general agreement concerning what the most suitable laboratory compaction method is, nor is there a full consensus regarding the mix design compaction energy that should be selected for the production and compaction of half-warm mix recycling technology with emulsified bitumen. For this reason, the compaction test method chosen should be capable of reproducing the benchmark density, air voids, and more consistent mechanical performance properties (e.g., indirect tensile strength, rutting, and stiffness modulus) when compared with those values obtained from the road worksite after pavement construction.

In this context, due to a lack of knowledge on what target air voids content should be adopted for this technology, it was decided to support and base our research study on the real-scale construction project conducted by Harmelink et al., (2007). They evaluated the in-situ air voids content in 22 real scale sections for 6 years and found that, by applying a mix design compaction effort of 75 gyrations ($V_m = 4.0\%$), the air voids criterion matches the in-situ air voids in the pavement after three years of service life. For this reason, the air voids design criterion sought for the half-warm specimens' production/ compaction in the laboratory was targeted to be in the order of 3-4%, given that if the air voids design in the mixture fall below 3%, it may lead to causing issues associated with rutting because of plastic deformation (Roberts et al., 1991). To avoid this type of failure, the target apparent density values, by SSD method, for this technology should fall within the range of between 2,311 and 2,335 g/cm³, considering a maximum specific gravity (ρ_m), by the volumetric method (EN 12697-5:2010/AC:2012: **Determination of the maximum density**), of 2.407 g/cm³, for the 2.5% o/RAP emulsion. The above-mentioned threshold density (SSD) values range shall be considered as part of the benchmark range to defining the most suitable compaction method and thus ensuring its satisfactory field performance.

Therefore, three different laboratory compaction methods were selected and put into assessment to determine and compare the corresponding volumetric, and mechanical performance properties of the half-warm emulsified mixtures. The compaction methods examined in this research study were as follows (1) the **Marshall Impactor hammer**, according to EN 12697-30:2012; (2) **Static compressive strength load**, according to NLT-161: **Simple Compressive Strength of Cylindrical Specimens**; and (3) **Superpave Gyratory Compactor (SGC)**, according to EN 12697-31:2007, as illustrated **Figure 23**. To do so, the HWMRA 100% RAP mixture production consisted in initially heating both fractions of RAP (0/5 and 5/25 mm) at 95 °C, adding 2.5% emulsified bitumen (50/70) at 65 °C, heating cylindrical molds at 80 °C, mix compaction temperature within the range of 70-80 °C, and a prefixed compaction energy depending on the compaction method to be used.

Figure 23. Compaction test methods: (a) Marshall impactor hammer; (b) Static stress load by double-plunger; and (c) gyratory compactor method

4.6.1 Marshall Impactor hammer

In this first phase, the Marshall specimens were prepared (with a diameter of 101.6 mm and a height of 63.5 ± 1.5 mm) and compacted by both the Marshall impactor (EN 12697-30:2012) and the gyratory compactor (EN 12697-31:2007) in order to determine if there was a possible correlation between the results shown by both compaction methods. To this end, the Marshall specimens were compacted by applying two different compaction energies, i.e., 75 and 100 impact-blows on each side, and 70 gyrations with the gyratory compactor, respectively. Following the compaction process, the apparent density, by SSD conditions, stiffness modulus at 20 °C, and indirect tensile strength at 15 °C, were determined and compared with those results obtained from the gyratory compactor. In this context, the average apparent density value of 75 impact-blows was found to be 2.282 g/cm³, and an average air voids content of 5.2%, while, for 100 impact blows, this number was 2.297 g/cm³ and 4.6% air voids.

On the other hand, by applying 100 impact-blows, the average stiffness modulus value of the HWMRA 100% RAP mixture was 2,473 MPa, and an average indirect tensile strength value of 1.18 MPa; whereas, for 75 impact-blows, the stiffness modulus and indirect tensile strength values were somewhat similar to those values obtained with 100 impact-blows.

Concerning the gyratory compactor test method, it was observed that, by applying a mix design compaction energy of 70 gyros and following the current laboratory standard test conditions established (0.82°, 30 rpm, and 600 kPa) by the EN 12697-31:2007 standard, the average stiffness modulus value of 3,134 MPa was obtained, and an average indirect tensile strength value of 2.02 MPa. In other words, the laboratory specimens compacted by the Marshall impactor hammer displayed a significant decrease of the stiffness modulus values of 20%, and lower indirect tensile strength, ITS in-dry, values in the range of 34-42%.

Analogous outcomes for recycled mixes compacted with the Marshall impactor were found in other laboratory studies. Hartmán et al., (2001) claim that the Marshall compactor does not have a kneading effect to re-orientate the particle size distribution, and, hence, produces lower density, increased stiffness, and mechanical properties that differ considerably from the values obtained in the field cores (Button et al., 1994; Khan et al., 1998; Mollenhauer and Wistuba, 2013; Ulmgren, 1996). For this reason, the Marshall impactor was not considered for further testing, since it delivers lower volumetric characteristics (e.g., air voids and bulk density) and mechanical performance properties (i.e., indirect tensile strength and stiffness modulus) than those obtained with the gyratory compactor.

4.6.2 Static compression load by double-plunger action

The static compression load method consists in using a higher load contact pressure to achieve the benchmark density in the field, resulting in crushing of aggregates and squeezing of the binder film and also revealing in-situ density differences in the fieldwork (Bonnot, 1997; Hartmán et al., 2001). In this research study, the static compressive stress load (NLT-161/00: **Standard Test Method for Compressive strength of Bituminous Mixtures**) was evaluated as a laboratory compaction test method to prepare half-

warm emulsified bitumen specimens (with a diameter of 101.6 mm and 100 mm in height) and characterized in terms of apparent density, indirect tensile strength and stiffness modulus.

The initial pre-loading applied was of approximately 1 MPa, and, after that, the load starts gradually increasing until reaching 21 MPa, maintaining the vertical contact load pressure during 2 min. The subset group consisted of preparing specimens, in-dry, and in-wet conditions, from which the former subset, in-dry conditions, is left at room temperatures (25 °C) for 24 h. The other subset was immersed in a water bath for 24 h, at 60 °C. Posteriorly, the specimens were placed in a water bath, at 25 °C, for 2 h. Both subsets were subjected to a simple compressive load at a constant deformation rate of 5.08 mm/min. Afterward, the percentage of retained water strength resistance is calculated between the wet and dry subsets, which makes it possible to obtain the resistance to moisture damage of the specimens. The optimal percentage should meet the minimum retained water strength requirements, depending on the levels of heavy traffic load to be supported. For instance, for intermediate traffic load categories, the minimum retained water strength percentage required for their use in base, and binder course asphalt mixtures should be above 75%; whereas, for low traffic load categories and shoulders, this percentage should be higher than 70% (Spanish Ministry of Public Works, 2001).

4.6.3 Gyrotory compaction

The gyrotory compactor was selected and evaluated to determine the volumetric and mechanical properties of the mixtures, according to EN 12697-31:2007. **Test method for hot mix asphalt. Part 31: Gyrotory Compactor.** The laboratory standard compaction conditions considered for the HWMRA mix' production and compaction in the laboratory were as follows:

1. Internal angle velocity of 0.82°;
2. Constant speed of 30 rpm;
3. Vertical consolidation pressure of 600 kPa;
4. Mix compaction temperature of 80 °C;
5. Number of compaction gyrations: variable.
6. Mold diameter: 100 mm

In this regard, this compaction test method is typically adopted as the most appropriate laboratory compaction system to successfully achieve the benchmark density, a more even homogeneous air voids distribution (Gao et al., 2015; Lo Presti D et al., 2014), more consistent engineering properties to those obtained in the field (Consuegra et al., 1989), as well as for simulating field compaction conditions because of the effect of kneading motion (Butcher M, 1998; Cross, 2003; Hartmán et al., 2001; Newcomb et al., 2007). For these reasons, the gyrotory compactor system was selected and evaluated as a benchmark test method for HWMRA mix' production and characterization in the laboratory (Asphalt Institute, 2007; Polaczyk et al., 2018).

Figure 24 shows the thermographic analysis of the half-warm specimens manufactured with total RAP contents (100%) together with the thermography of the cylindrical mold heated at 80 ± 5 °C. To do so, a FLIR C2 thermographic imaging camera (with an average temperature emissivity of 0.95, surface reflexivity temperature of 20 °C and infrared (IR) resolution of 80 x 60 pixels) and FLIR tool software were used to obtain the main parameters during the production/heating and compaction process (i.e., maximum, minimum and average temperature), wherein the central rectangular-shaped section of the cylindrical mold was recorded for ensuring the target compaction temperature (~ 80 °C). However, the actual temperature monitoring of the specimen was conducted using a thermal probe that is inserted into a hole of the mold to control that the working temperature is approximately 80 °C during the mix compaction process. The geometric density is calculated with the change of the geometric volume of the specimens, and it depends on the specimens' thickness change.

Figure 24. Gyratory compactor device set-up: (a) cylindrical mold with a diameter of 100 mm; and (b) Thermographic analysis of the specimen compacted at ~ 80 °C

4.7 Mixture design

4.7.1 HWMRA 100% RAP mixtures

Once the aggregate gradation curve, emulsion-type, and mix design compaction energy were defined, the next step was to continue the manufacturing of new cylindrical-shaped specimens to calculate the optimum emulsion content (OEC), by testing a wide range of emulsion contents, depending on the mixtures' volumetric and mechanical performance properties. The HWMRA mixtures were manufactured by heating the RAP at 95 °C, bituminous emulsion at 65 °C, mix fabrication at 95 °C, cylindrical molds at 85°C, and mix compaction temperature in the range of 70-80 °C using a prefixed compaction energy of 70 gyrations (see **Figure 25**); where the optimal mixture design consisted of defining the optimal emulsion

content to meet the minimum laboratory performance requirements regarding the ITS, at 15 °C, the stiffness modulus, at 20 °C, the water sensitivity, the rutting performance, apparent density, and the air voids content in the range of 3.0-4.0%. To do so, an average of three cylindrical specimens were prepared (with a diameter of 100 mm and 60 ± 1.5 mm in height) and tested by considering slight variations of the emulsion content to be used in the mixture design.

Figure 25. Production (weighing and mixing) and optimization process of the mixes in the laboratory

4.7.2 Effect of the curing process on the mixture' mechanical performance

Once the optimal emulsion content (2.5% o/RAP) was defined, the next step was to quantify how the laboratory-accelerated curing treatment process promotes the development of mechanical performance properties (ITS and stiffness modulus) of the emulsified mixtures. In this sense, the curing/drying treatment was conducted, as part of the optimization of the mix design, using a forced-draft convection oven, at 50 °C, at four different curing periods (0, 24, 48, and 72 h), at 24 h increments, until reaching constant weight before their testing, according to Art. 20 of PG-4: In-situ recycling of bituminous layers with bitumen emulsion (Spanish Ministry of Public Works, 2017).

4.8 HMA mixture (AC16 D) design

The Marshall design method was used to calculate the optimum binder content of the conventional HMA mixture, according to EN 12697-34:2013. **Part 34: Marshall test.** To do so, four different asphalt binder contents were selected and added into the preliminary mix design, ranging from 4.5 to 6.0%, at 0.5% increments, and, after that, the Marshall specimens were compacted with the Marshall hammer by applying 75 impact-blows on each face, at 160 °C, according to EN 12697-30:2012. **Part 30: Specimen preparation by impact compactor.** Figure 26 shows the production and compaction process of the conventional HMA mixture as follows: (a) mixing process at 165-170 °C, pouring the mix into the Marshall mold (with a diameter of 100 mm and), mix compaction at 150 °C, and cylindrical specimens after compaction.

Figure 26. Production and compaction of the conventional HMA specimens using the Marshall impactor

4.9 Description of the test road section in Lerma

A test road section with 100% RAP was built in a service road, parallel to A1 motorway, between 203 and 204 km, located in Lerma, province of Burgos, in Spain, as illustrated in **Figure 27**. The test road pavement section is now subjected to a T2 heavy traffic load category corresponding to an annual average daily traffic (AADT₀) equal to or higher than 200 and lower than 800 and with a traffic growth rate of 3.0 ± 0.5 %/year. The service road is made up of two lanes with one-way traffic on a carriageway of 10 m in width.

The rehabilitation works consisted in replacing the conventional HMA mixture with half-warm mix recycled asphalt mixtures in a total length of 400 m and 5cm in depth laid in the entire carriageway width for their use in binder course asphalt mixtures. Also, the contiguous remaining 300 m were rebuilt with an asphalt concrete mixture with a nominal maximum aggregates size (NMAS) of 16 mm (AC16 D). The slow traffic lane was built with 3.0% o/RAP emulsion, while the high-speed lane was 2.5%o/RAP emulsion content. Finally, the wearing course asphalt mixture (AC16 D) was repaved and compacted in the test road section with a length of 700 m and with a layer thickness of 40 mm. The construction process was conducted using conventional machinery typically used in the construction of real pavement sections. The paving process was performed at 100°C by using an asphalt paver to ensure a high quality of the mix spreading, a pneumatic tire road roller, along with a steel double-drum road roller. Moreover, a UM-260 INTRAME asphalt batch plant was set up and run with a maximum theoretical output capacity of 120 t/h. This batch plant was equipped with some new devices to deal with 100% RAP production, at half-warm temperatures and emulsified bitumen.

Figure 27. Arlanzón motorway location ($x=42.04466$ and $y=-3.748913306$) in Lerma Spain

Additionally, the surface friction characteristics of the binder course asphalt mixture were determined and calculated after pavement construction in terms of macrotexture and international surface roughness index (IRI) to determine the finished construction quality of the mixtures. For the IRI, this procedure was based EN 13036-6:2008. Road and airfield surface characteristics. **Test methods. Measurement of transverse and longitudinal profiles in the evenness and megatexture wavelength ranges.**

4.10 Macrotexture

On the 15th of November 2015, four months after being subjected to traffic loads, the early life skid resistance and surface macrotexture depth were determined. The macrotexture was measured with the modified sand patch arena method, in accordance with EN 13036-1:2010. **Road and airfield surface characteristics. Part 1: Measurement of pavement surface macrotexture depth using a volumetric patch technique.** Specifically, 5000 mm³ of graded sand were spread over the wearing course asphalt mixture using a spreading tool, after which the total area covered by the sand was measured. The surface macrotexture depth value is commonly accepted in terms of Mean Texture Depth (MTD) expressed in terms of mm, based on the procedure Eq. 4.8:

$$MTD = \frac{4V}{\pi D^2} \quad (4.8)$$

Where; MTD: is the mean texture depth expressed in terms of mm; V is the sample volume in mm³; D is the average diameter of the area covered by the material in mm. **Figure 28** shows the macrotexture procedure using the patch test method and the repeatability of the circular patch method used in the binder course asphalt mixtures of the urban test section.

Figure 28. Macrotexture surface depth

4.11 International surface roughness index

The International surface roughness index (IRI) of the HWMRA 100% RAP mixtures (2.5% and 3.0%o/RAP) was measured and calculated from the longitudinal profile with a high-speed profiling device “Greenwood Digital Profilometer P59”, at 60 km/h, according to EN 13036-6:2008. **Road and airfield surface characteristics. Part 6: Measurement of transverse and longitudinal profiles in the evenness and megatexture wavelength ranges.** In order to do this, a set of surface campaigns was conducted in the northbound section (with a length of 400 m and with a surface carriageway width of 7.5 m) to calculate the evolution of the surface roughness values over three years in service, i.e., from 2012 to 2014.

Chapter 5

RESULTS AND DISCUSSION

In previous Chapters, the backgrounds, experimental methodology, and test procedures resulting from three different compaction test methods, in-plant samples, and pavement cores drilled from in-situ pavement have been presented. The performance testing results and analysis will be shown in graphical form with tabulated values also provided in referenced Annexes.

5.1 Laboratory compaction study results

5.1.1 Marshall impactor hammer

Following the compaction process, the apparent density, by SSD conditions, stiffness modulus at 20 °C, and indirect tensile strength at 15 °C, were determined and compared with those results obtained from the gyratory compactor. In this context, the average apparent density value of 75 impact-blows was found to be 2.282 g/cm³, and an average air voids content of 5.2%, while, for 100 impact blows, this number was 2.297 g/cm³ and 4.6% air voids.

On the other hand, by applying 100 impact-blows, the average stiffness modulus value of the HWMRA 100% RAP mixture was 2,473 MPa, and an average indirect tensile strength value of 1.18 MPa; whereas, for 75 impact-blows, the stiffness modulus and indirect tensile strength values were somewhat similar to those values obtained with 100 impact-blows.

Concerning the gyratory compactor test method, it was observed that, by applying a mix design compaction energy of 70 gyros and following the current laboratory standard test conditions established (0.82°, 30 rpm, and 600 kPa) by the EN 12697-31:2007 standard, the average stiffness modulus value of 3,134 MPa was obtained, and an average indirect tensile strength value of 2.02 MPa. In other words, the laboratory specimens compacted by the Marshall impactor hammer displayed a significant decrease of the stiffness modulus values of 20%, and lower indirect tensile strength, ITS in-dry, values in the range of 34-42%. Analogous outcomes for recycled mixes compacted with the Marshall impactor were found in other laboratory studies. Hartman et al. (Hartmán et al., 2001) claim that the Marshall compactor does not have a kneading effect to re-orientate the particle size distribution, and, hence, produces lower density, increased stiffness, and mechanical properties that differ considerably from the values obtained in the field cores (Button et al., 1994; Khan et al., 1998; Mollenhauer and Wistuba, 2013; Ulmgren, 1996). For this reason, the Marshall impactor was not considered for further testing, since it delivers lower volumetric characteristics (e.g., air voids and bulk density) and mechanical performance properties (i.e., indirect tensile strength and stiffness modulus) than those obtained with the gyratory compactor.

5.1.2 Static load by a double plunger

Looking at the mixtures' compressive strength results, it was observed that, by applying a static compressive load of 21 MPa, the HWMRA 100% RAP mixture with 2.5% (o/RAP) emulsion showed an average apparent density, by SSD method, of 2.357 g/cm^3 , and an average air voids content of 2.08% (see **Figure 29**); whilst the average compression strength value was found to be 5.63 MPa. Despite this, it was found that the static compressive stress results were much higher than the minimum threshold values required by the Spanish technical standards, according to Art. 20 of PG-4 (Spanish Ministry of Public Works, 2001). Analogous results for the static compressive test have been found and contrasted in other laboratory studies conducted by Hartman et al. [47] and Martínez et al. [48]. They claim that the compressive system is not regarded as the most reliable laboratory compaction method since it always provides much higher density values than those obtained in the field cores. This increased density is likely caused by a higher contact load pressure applied on the cylindrical specimens, causing the crushing and breakage of aggregates as well as the squeezing of the binder, resulting in a much higher density than the obtained from the field cores (Bonnot, 1997). Moreover, since these specimens are prepared with a height of 100 mm, they cannot be reused for further mechanical testing, such as ITS, stiffness modulus.

In view of that, and based on the author's findings and laboratory results, the cylindrical specimens had to be prepared with new pre-fixed dimensions (i.e., with a height of 60 mm and with a diameter of $101.6 \pm 0.1 \text{ mm}$) and compacted with a lower static compressive pressure of 10 MPa. In other words, a 53% lower compressive stress energy was selected to obtain specimens with field-like density, and more consistent mechanical properties compared to those values achieved in the road worksite after pavement construction. **Figure 30** displays the indirect tensile strength (ITS) and retained water strength results against three emulsion contents (2.5%, 3.0%, and 3.5%o/RAP) of the half-warm mixes compacted with the static compressive load.

In summary, for 10 MPa static load, the average apparent density, by SSD, was found to be 2.289 g/cm^2 , and air voids content of 4.9%, resulting in slightly higher air voids content than those values expected from the target air voids content set in the mixture design. Thus, the average indirect tensile strength (ITS) value was found to be 1.66 MPa and an average stiffness modulus of 3,578 MPa when applying the selected static compaction pressure of 10 MPa. However, at the end of the compaction process, it was observed that this latter compaction energy caused the breakage of aggregates, showing that the static load was not the most suitable compaction method for this technology.

Therefore, based on the Spanish technical regulations (Art. 20 of PG-4: In-situ recycling of bituminous layers with emulsion), the minimum indirect tensile strength ratio (ITSR $\geq 75\%$) was successfully achieved, without any compactability issue, by applying the selected static compaction pressure of 10 MPa. These mixtures can be laid for their use in base course asphalt mixture subject to a T1 heavy traffic load category corresponding to annual average daily traffic (AADT) lower than 2000, and equal to or higher than 800 and T2 load traffic category ($800 > \text{AADT} \geq 200$), according to 6.1 IC: Pavement sections, investigation of road pavements.

Figure 29. Apparent density and air voids content versus emulsion content

Figure 30. Indirect tensile strength, at 15 °C, and retained water strength versus three emulsion contents

5.1.3 Gyrotory compactor

Figure 29 illustrates the specimens' geometric density change and air voids content curves against the number of compaction gyrations ranging from 0 to 200 gyrations. In this regard, the compaction curves showed in this **Figure** are determined using the geometric density, according to EN 12697-10:2010. **Part 10: Compactibility**, while the bulk density is calculated at the end of the compaction process, by saturated surface dry (SSD) conditions (EN 12697-6:2012. **Part 6: Determination of bulk density of bituminous specimens**). The geometric density is therefore calculated with the change of the geometric volume of the specimens, and it relies on the change of the thickness of the specimens.

Concerning the slope of the densification curve of the 100%RAP mixture (2.5%o/RAP emulsion), it can be observed in **Figure 31** that, by following the laboratory standard compaction conditions set out in EN 12697-10:2003/AC, there is a significant decrease in the air voids curve when increasing the number of load cycles derived from an initial mix densification of **13.3%** (i.e., increased from **2.040** to **2.311 g/cm³**) during the first 70 gyrations. Afterward, an aggregate–aggregate interlocking was noted in the compaction range of 70-100 gyrations, which led to an increase in density of approximately **0.61%** in 30 gyrations (i.e., from **2.311** to **2.325 g/cm³**); whereas at the end of the compaction test (i.e., 200 gyrations), the slope of densification curve becomes more stable and asymptotic thereafter, i.e., it reaches a slight increase in the geometric density of 0.77% in the last 100 gyrations applied on the specimen ($\rho_{b,dim}$ =**2.347 g/cm³** and V_m = **2.5%** air voids).

To put it in another way, by applying a mix design compaction effort of 70 gyros, the average geometric density was found to be **98.5%** of the specimen' density compacted with 200 gyrations; whereas, for 100 gyrations, this percentage was **99.1%**, according to EN 13108-20:2007. **Type Testing – Annex C.4: Degree of compaction.** In which the $\rho_{b,dim}$ can be defined as the geometric density obtained for N_i load cycle, obtained from the gyratory compactor software in terms of g/cm³; while the $\rho_{b,ben}$ can be understood as the benchmark density obtained at the end of the compaction process (N_i =200 load cycles).

Figure 31. Compaction curves based on the geometric density and air void content versus

In summary, it was found that, for 70 gyrations, the average geometric density of the HWMRA 100% RAP (2.5% o/RAP) mixture with 50/70 pen. bitumen was found to be 2.311 g/cm^3 , an average air voids content of **4.0%**; and average indirect tensile strength values of 1.7 MPa. Therefore, the gyratory compaction curve revealed that it is possible to successfully meet the target air voids criterion within the range of 3.0-4.0%.

Once the mix design compaction effort was selected as a function of the compaction gyration curves, an average of three cylindrical-shaped specimens were prepared (with a diameter of 100 mm and 60 ± 1.5 mm in height) and compacted by following the laboratory standard compaction conditions established by the EN 12697-31:2007 standard. **Table 7** provides a comparison between the volumetric and mechanical performance value results obtained from the gyratory compactor at 70 gyrations, Marshall impactor hammer at 75 and 100 impact-blows, and vertical static compressive strength load of 10 MPa, respectively.

It can be observed in this Table that, by applying a mix design compactive effort of 70 gyrations and by setting-up the gyratory compactor with an internal angle of gyration of 0.82° and vertical consolidation pressure of 600 kPa, the highest apparent density, indirect tensile strength (ITS_{in-dry}) and retained water strength values were obtained. This is likely attributed to the kneading effect of the gyratory compactor on the mixtures' internal structure that allowed the provision of higher apparent density, better rearrangement,

and interlocking of the aggregate particles contained in the specimens (Kutay et al., 2010; Masad et al., 2002; Tarefder and Ahmad, 2016) – implying that the higher the aggregate-aggregate-interlocking effect, the better the dissipation of the shear stress of the mixture (Coleri et al., 2013).

Table 7. Comparison of volumetric and mechanical properties of HWMRA 100% RAP mixtures with 2.5% emulsion and 50/70 pen. bitumen

Properties	Test method	Marshall Impactor*		Static stress load*	Gyratory compactor
Compaction energy	-	75 x 2	100 x 2	10 MPa	70 gyros
Specimens' height, (mm)	-	-	-	67.3	65.2
Apparent density, SSD, (g/cm ³)	EN 12697-6:2012	2.282	2.297	2.289	2.331
Air voids, (%)	EN 12697-8:2003	5.2	4.6	4.9	3.2
ITS, in-dry, (MPa)	EN 12697-23:2018	1.18	1.33	1.66	2.02
ITSR, (%)	EN 12697-12:2012	-	-	79	95.7

***Key:** The Marshall impactor and static stress load methods were not considered for further mechanical testing since they caused the breaking of aggregates during the mix compaction process

In this context, one can say that the gyratory compactor was the most suitable compaction test method for the production/compaction and characterization of the half-warm mix recycling technology with total RAP content (100%) and emulsified bitumen. Therefore, Marshall hammer impactor and static compressive strength load by double-plunger were not considered for further mechanical testing analysis, since they tend to induce higher mechanical impact stress load and static compressive load on the cylindrical specimens, which results in the breakage of aggregates and, hence, the weakening of the mixture' mechanical performance.

Additionally, an assessment of the volumetric and mechanical performance properties was conducted to determine the feasibility of using half-warm mix asphalt mixtures with two emulsion contents (2.5% and 3.0%) and two different penetration grade bitumens (160/220 and 50/70 dmm), as illustrated in **Table 8**. In this sense, for the HWMRA mixture with 2.5% emulsion and 50/70 and 160/ 220 pen. grade bitumen, the highest stiffness modulus values of 2988 and 2901 MPa were obtained, respectively; while, for the HWMRA mixture with 3.0% emulsion, this number was much lower than the 2.5% emulsion. Nevertheless, only 2.5% o/RAP emulsion met the required air voids content within the range of 3.0-4.0%.

Therefore, it is worth noting that the 2.5% emulsion with 50/70 pen grade bitumen meets the minimum indirect tensile strength ratio (ITSR $\geq 70\%$) stipulated for their use in low traffic load categories

and shoulders, as well as the $ITSR \geq 75\%$ for their use in base and binder course asphalt mixtures and intermediate traffic load categories, according to the latest Spanish technical regulations edition in Art. 20 of PG-4 (Spanish Ministry of Public Works, 2017). Moreover, the HWMRA mixtures meet the minimum indirect tensile strength ratio values required for hot mix asphalt mixtures for their use in base, binder ($ITSR \geq 80\%$), and wearing course asphalt mixtures ($ITSR \geq 85\%$) of road pavements, according to Art. 542 of PG-3 (Spanish Ministry of Public Works, 2015).

Table 8. Volumetric and mechanical performance properties of the mixtures compacted with 70 gyrations

Mixture properties	Test Method	HWMRA 100% RAP mixture			
		Rejuvenator binder (160/220 dmm)		Residual binder (50/70 dmm)	
Emulsion (% o/RAP)	-	2.5%	3.0%	2.5%	3.0%
Specimens's height, (mm)	-	65.0	64.9	65.5	65.4
Apparent density, SSD, (g/cm ³)	EN 12697-6	2.347	2.350	2.340	2.344
Air voids, V_m , (%)	EN 12697-8	2.98	2.47	3.08	2.49
ITSdry, 15 °C, (MPa)	EN 12697-23	2.14	2.06	1.99	1.67
ITSwet, 15 °C, (MPa)	EN 12697-23	2.05	1.91	1.91	1.57
ITSR, (%)	EN 12697-12	95.7	92.7	95.8	94
Stiffness modulus, 20 °C, (MPa)	EN 12697-26	2901	2389	2988	2560

5.2 Mix design results

Table 9 shows the volumetric and mechanical performance results of the preliminary mix design with five emulsion contents, ranging from 0 to 3.5%, of the half-warm mixes with 100% RAP. **Figure 32** displays the air voids content and apparent density values of the mixtures designed with 50/70 pen. bitumen against five different emulsion contents, ranging from 0% to 3.5%, were plotted.

Regarding the stiffness modulus values, the HWMRA 100% RAP mixture with 2.5%o/RAP showed a decrease in the stiffness of 23%, in comparison with the 0% emulsion. This result implies a positive aspect to improve the mixtures' fatigue cracking resistance in the field since it would make the mixture less stiff and less brittle by enabling higher tensile deformations before its fatigue cracking failure occurs in the field. **In Figure 33**, the 100% RAP mixture with 0% emulsion content exhibited lower indirect tensile strength (ITS) values ($1.08 < 1.5$ MPa), increased stiffness modulus, and lower moisture damage ($69\% < 75\%$) values than those minimum required by the Spanish technical specifications in Art. 20 of PG-4 (Spanish Ministry of Public Works, 2017). The decreased water susceptibility values can be partially

attributed to the loss of the adhesive bonding between aggregates and binder, i.e., due to the failure of the cohesive strength of the binder - although it is expected that such a stripping effect can be counteracted when adding the respective emulsion content to be used in the preliminary mix design (Karlsson and Isacsson, 2006; Mogawer et al., 2012).

Table 9. Volumetric and mechanical performance of the HWMRA 100% RAP mixtures

Mixture properties	Test method	Emulsion content (% o/ RAP) – 50/70				
		0%	2.0%	2.5%	3.0%	3.5%
Maximum density (g/cm ³)	EN 12697-5	2.481	2.428	2.407	2.389	2.377
Apparent density, SSD, (g/cm ³)	EN 12697-6	2.268	2.327	2.328	2.338	2.339
Air voids, V _m , (%)	EN 12697-8	8.6	4.2	3.3	2.1	1.6
ITS _{dry} , (MPa)	EN 12697-23	1.55	1.87	2.13	1.93	1.72
ITS _{wet} , (MPa)	EN 12697-23	1.08	1.82	2.08	1.89	1.69
ITSR, (%)	EN 12697-12	69.5	97.3	97.6	98.1	98.3
Stiffness modulus, (MPa)	EN 12697-26	3754	3034	2891	2861	2364

Figure 32. Volumetric characteristics (air voids and density) of the preliminary mix design

Figure 33. Stiffness modulus at 20 °C, and ITS, at 15 °C, versus emulsion content

Finally, it can be said that though the 100% RAP mixture with 0% o/RAP emulsion exhibited lower volumetric, durability, and mechanical performance (i.e., due to its low compactability), the HWMRA 100%RAP mixture with 2.5% emulsion fell within the required target air voids criterion ($V_m=3.3\%$ air voids) set out in the mixture design, average internal cohesion values (ITS in-dry) above 2.0 MPa, and moisture damage resistance values much higher than those minimum stipulated ($\geq 75\%$) by the Spanish technical regulations in Art. 20 of PG-4 (Spanish Ministry of Public Works, 2017), as well as the moisture damage value requirements (ITSR $>85\%$) set out for hot mix asphalt (HMA) mixtures, according to Art.542 of PG-3 (Spanish Ministry of Public Works, 2015).

5.3 Advanced mechanical characterization of the mixture

5.3.1 Stiffness modulus and indirect tensile strength

The load-bearing capacity of the mixtures was also evaluated through the stiffness modulus test, at 20 °C, according to EN 12697-26:2018. Part 26: Stiffness. As it can be observed in **Table 10** and **Figure 34**, the stiffness modulus values exhibited a steeper upward curve as a result of the increase in curing time, which led to a higher maximum peak stiffness modulus value of about 3462 MPa – showing a significant improvement in the average load-bearing capacity of 13% (i.e., from 24 to 72 h), which is likely attributed to the higher residual internal friction between the aggregate particles because of moisture loss by evaporation and breaking of the emulsion (Bocci M et al., 2011).

Therefore, it can be said that the use of a curing/drying treatment is assumed as a positive aspect to improve the indirect tensile strength, stiffness modulus, and resistance to permanent deformation (Wu and Li, 2017). Analogous results for mixes in need of curing process were found in other laboratory studies conducted by (Kim and Lee, 2011)(Kim and Lee, 2011)Kim and Lee, (2011), who claim that the mixtures' mechanical performance (i.e., flow number, ITS, and dynamic modulus) improves as a consequence of the increase in curing time (Gao et al., 2014; Kim et al., 2011); whilst some other authors reported that mixtures containing emulsified bitumen and fabricated at low temperatures tend to require an accelerated curing treatment to further develop the ultimate mechanical performance properties (e.g., stiffness modulus and ITS) at the early hours of being placed and compacted in the field (Bocci M et al., 2011; Godenzoni C et al., 2016; Graziani A et al., 2016). In this recognition, the increase in the stiffness modulus values of the HWMRA 100% RAP (2.5%o/RAP) mixtures confirms that these types of mixtures require a curing process to develop a higher strength capacity and internal cohesion values of the ultimate mixture performance.

Figure 34 depicts the indirect tensile strength values of the HWMRA 100% RAP (2.5%o/RAP) mixture with a 50/70 pen. bitumen against the effect of short- (0-24 h) and long-term curing treatment (48-72 h) on the mix performance. As it can be observed in this Figure, the indirect tensile strength (ITS) values remained relatively constant at the early stage of the curing treatment. However, at the end of the accelerated curing process of three days (72 h), this mixture increased its internal cohesion value by approximately 8%, i.e., the ITS values increased from 2.17 to 2.34 MPa (from 48 to 72 h). The likely explanation for this result lies in the adequate combination of the cohesive strength of the binder and adhesive interface bonding between RAP aggregates and binder. Therefore, the use of an accelerated curing treatment of three days (72 h), at 50 °C, in a forced-draft convection oven is highly recommended for half-warm mix' production and characterization in the laboratory.

Table 10. Mechanical and volumetric properties results of the mixtures after curing/drying treatment

Mixture properties	Test method	Curing time (h) – 2.5% emulsion				Δ ITS/ITSM 0-72h
		0	24	48	72	
ITS, in-dry, 15 °C, (MPa)	EN 12697-23	2.11	2.13	2.17	2.34	11%
Stiffness modulus, 20 °C, (MPa)	EN 12697-26	2891	2984	3077	3462	20%

Fig. 34. Stiffness modulus at 20 °C, and ITS, in dry, at 15 °C vs. curing time

5.3.2 Rutting test

The results obtained from this testing method are displayed in **Table 11**, and consist of the wheel tracking slope (WTS_{AIR}) computed between 5000 and 10,000 load cycles, the mean rut depth max (mm, RDAIR) and the proportional rut depth at 10,000 load cycles (% , PRDAIR). The results presented in this table show that both HWMRA mixtures display similar, or equivalent, resistance to permanent deformations to that of the HMA mixture. The wheel tracking test resulted in an average creep slope of 0.08 (mm/10³ load cycles) between 5000 and 10,000 load cycles and a mean rut depth lower than 5%. Based on these values and Spanish technical regulations in Art. 542.5.1.3: **Resistance to permanent deformation of hot mix asphalt mixtures**, the HWMRA mixtures were found to meet the minimum requirements for hot mix asphalt mixtures in binder and wearing course asphalt mixtures of road pavements or urban areas. In other words, the wheel tracking slope of the 100% RAP mixture (2.5% o/RAP), at 60°C, was found to be 0.109 (mm/10³ load cycles) and a proportional rut depth of 3.47%. Therefore, this mixture meets the maximum threshold rutting values stipulated for hot mix asphalt mixtures in the base, binder, and surface layer asphalt mixtures of road pavements subject to intermediate and low traffic load categories, and moderate thermal weather zones in Spain (Spanish Ministry of Public Works, 2015).

Table 11. Wheel tracking test results, at 50 °C and 60 °C, of the 100% RAP mixtures

Mix properties	Unit	HWMRA 100% RAP samples		
		2.5% 50 °C	2.5% 60 °C	3.0% 60 °C
Apparent density, by SSD,	g/cm ³	2.302	2.328	2.330
Deformation at 5000 load/cycles, (RDAIR)	mm	0.52	2.11	2.48
Deformation at 10.000 load/cycles, (RDAIR)	mm	0.86	2.66	3.19
Wheel tracking slope, (WTS _{AIR})	mm/10 ³	0.068	0.109	0.143
Proportional rut depth, (PRDAIR)	%	1.42	3.47	5.3

Key: *It is worth noting that though the asphalt mixture does not meet the maximum wheel tracking slope (WTS_{AIR}) value of 0.07 (mm/1000 load cycles), between 5000 and 10.000 load cycles, the asphalt mixture is allowed to extend its maximum wheel tracking slope (WTS_{AIR}) value up to 0.15 (mm/1000 load cycles) and proportional rut depth (PRDAIR) value lower than 5%, according to Art. 542.5.1.3: Resistance to permanent deformation of hot mix asphalt mixtures (Spanish Ministry of Public Works, 2015)

On the other hand, it was observed that HWMRA 100%RAP mixture with 2.5% (o/RAP) emulsion, at 50 °C, exhibited an average wheel tracking slope value of 0.068 (mm/10³ load cycles), between 5000 and 10,000 load cycles, and an average proportional rut depth (% PRD) value of 1.42%, suggesting that the wheel tracking results, in general, depend more on the test temperature than on the recycled content added, even for the HWMRA 100%RAP mixture. It is highly recommended to include these types of rutting performance requirements in the drafting of new technical guidelines for this technology.

Figure 35 shows that the slope of the 100% RAP mixture' rut depth curve (2.5% o/RAP), at 60 °C, was slightly steeper by rising sharply during the first 5,000 loading cycles and becomes more stable when applying 8,000 loading cycles with the wheel tracker. Despite this, the addition of high RAP contents in asphalt mixtures typically tends to improve the resistance to permanent deformation as a result of the physical hardening and chemical aging (i.e., because of the evaporation of the lighter oil fractions in the bitumen) suffered by the asphalt binder during its service life.

Analogous results for mixes containing high and total rates of RAP and additives have been found and contrasted by multiple authors (Apeagyei et al., 2011; J. . Doyle and Howard, 2013; Hajj EY et al., 2009; Kim et al., 2017; Topal et al., 2017; Zhao et al., 2012); whilst the results reported by other authors are rather less conclusive, in the sense that mixtures manufactured at low temperatures and emulsified bitumen are typically characterized by having a lower rutting performance than that of the conventional HMA mixtures (Button et al., 2007). It was observed that for the 3.0% (o/RAP) emulsion content, the slope of the rut depth curve was much steeper by rising rapidly during the first 3000 loading cycles and becomes more stable thereafter (i.e., for 8,000 loading cycles with the wheel tracker) – suggesting that this

content might have lower resistance to permanent deformation, regardless of the recycled RAP content added into the new mix. The likely explanation for this result lies in the effect of higher emulsion content (3.0%o/RAP) added in the mixture design that promoted the decrease in the mixture' rutting performance values.

Figure 35. Wheel tracking results of the HWMRA 100% RAP mixes with 2.5 and 3.0%o/RAP and 50/70 pen. bitumen

5.3.3 Fatigue resistance

In Figure 36, the classical mixtures' fatigue cracking resistance laws for each type of penetration grade bitumen (50/70 and 160/220) were evaluated. The determination coefficients, (R^2), fell within the range of 90-95%, indicating a right level of correlation. It was observed that for the strain-fatigue levels tested; the HWMRA mixes with 50/70 and 160/220 pen. grade bitumen showed comparable fatigue slopes - suggesting that they have an equivalent sensitivity to stress in terms of fatigue life, although a slight discrepancy can be noted at lower tensile-strain fatigue levels. In other words, the fatigue life of the HWMRA 100% RAP with 160/220 pen. grade bitumen was found to be slightly better than that of the 50/70 pen. bitumen, likely attributed to the effect of softer penetration grade bitumen in the final mixture design that promoted the extension of the mixture' fatigue resistance law.

In this context, for the HWMRA 100% RAP (2.5%) mixtures with **50/70** pen. grade bitumen, the average flexural modulus was found to be **6331 MPa** (with a standard deviation (SD) of 465 MPa and a low coefficient of variation (CV) equal to 7.5%), and strain-fatigue level, (ϵ_6), at 10^6 load cycles, of **143 $\mu\text{m/m}$** ; whereas, for 2.5% emulsion with **160/220** pen. grade bitumen, the average flexural modulus of **5936 MPa** was obtained, and an average microstrain-fatigue level of **155 $\mu\text{m/m}$** . Analogous results for 4PB fatigue

cracking and fracture properties have been found in other laboratory studies by other researchers (Botella et al., 2016; Dinis-Almeida M et al., 2016; Nosetti et al., 2018) for a WMA/ HMWA mixture with a total RAP content (100%) and emulsified bitumen.

Figure 36. Fatigue resistance laws, at 20 °C, of the HWMRA 100% RAP mixe with 2.5%o/RAP emulsion and 50/70 and 160/220 pen. grade bitumens

5.4 Conventional HMA mixture

Figure 37 illustrates the volumetric and mechanical performance values of the traditional HMA mixtures against four asphalt binder contents (4.5%, 5.0%, 5.5%, and 6.0% by weight of aggregates), at 0.5% increments. The results of each binder content were calculated: (a) maximum density (g/cm³); (b) bulk density (g/cm³); (c) air voids in the mix (Vm,%); (d) air voids in the mineral aggregate (VMA,%); (e) Marshall stability (kN); and (f) flow number expressed in terms of mm.

It can be observed in this Figure that the slope of the Marshall stability curve showed a steeper upward behavior by reaching a maximum peak value of 9 kN for the 5.5% binder content, however, this latter content exhibited a flow number of 2.6 mm; whereas, for 5.0% binder, this number was found to be 8.5 kN and 2.4 mm flow. Despite this, and based on the Spanish technical specifications, all of the bitumen contents used in the preliminary mix design were slightly lower than the minimum Marshall stability (10 kN) values suggested by other researchers (Arabani and Azarhoosh, 2012; Dhir et al., 2019; Lee et al.,

2012; Motter et al., 2015; Pasandín and Pérez, 2013; Pérez et al., 2007; Zhu et al., 2012) for T3 traffic load category ($200 > \text{AADT} \geq 50$). The likely explanation for the decreased result lies in the fact that the overdose of bitumen content added into the mixture design, which reduces the internal friction/adhesion properties between aggregates and binder and hence decreases the stability values (Ruíz, 2001).

Nevertheless, for the Marshall flow number, it was observed that 5.0% (of total weight of aggregates) was slightly lower than the minimum threshold values (2.5-3.5 mm) stipulated by the Spanish technical specifications (Spanish Ministry of Public Works, 2015) and others researchers (Behnood et al., 2015; Djakfar et al., 2015; Hou et al., 2017; Marques et al., 2014; Pasandín and Pérez, 2013; Pérez et al., 2013; Rafi et al., 2011) and that the more the bitumen content added into the preliminary mix design, the better the mixture behavior (when it is loaded during the Marshall stability test), except for 6.0% binder content. Therefore, it can be concluded that 5.5% binder content (of the total weight of aggregates) was discarded for this research study since it delivers/offers much lower mechanical performance properties in terms of rutting with the wheel tracker (EN 12697-22:2008+A1).

Figure 37. Volumetric characteristics (e.g., maximum density, bulk density, Vm, VMA) Marshall stability and flow number against four asphalt binder contents with a 50/70 pen bitumen

Once the optimum emulsion content (5.0% of the total weight of aggregates) of the conventional HMA mixtures was defined based on the average values of Marshall stability, Marshall flow, air voids, VMA and VFB, the resistance to moisture damage, or binder – aggregate adhesion, was assessed by conducting the water susceptibility test, according to EN 12697-12:2008. **Part 12: Water sensitivity.** To this end, a set of three specimens were prepared and compacted by applying 50 impact-blows on each side with the Marshall compactor hammer, according to EN 12697-30:2012. **Test methods for hot mix asphalt. Part 30: Specimen preparation by specimen compactor.** The wet and dry indirect tensile strength, ITS-dry, of 2.149 and 2.47 MPa, respectively, and the indirect tensile strength ratio (ITSR) was found to be 87%. For the ITSdry, the average specimen's height of 63.4 mm was obtained.

Posteriorly, the mixtures' mechanical performance was completed by conducting the wheel tracking test, at 60 °C, according to EN 12697-22:2012. **Part 22: Wheel tracking test.** The average wheel tracking slope (WTS_{AIR}) of the HMA mixture was found to be 0.063 (mm/ 1000 load cycles), between 5000 and 10.000 cycles, with an average rut depth (RD_{AIR}) of 3.1% and a proportional rut depth maximum (PRD_{AIR}) of 5.2%.

Therefore, based on the author's results and Spanish technical regulations in Art. 542.5.1.3: **Resistance to permanent deformation of hot mix asphalt (HMA) mixtures**, one can conclude that the HMA mix meets the minimum moisture damage requirements of HMA mixtures for their use in the binder and wearing course asphalt mixtures of road pavements, as illustrated in **Table 12**.

Table 12. Wheel tracking test results of the conventional HMA mixture

Mixture property	Test method	Sample 1	Sample 2	Value
Apparent density, SSD, (g/cm ³)	12697-6:2012	2.325	2.325	2.325
Wheel tracking slope, WTS _{AIR} , mm/10 ³ load cycles	12697-22:2012	0.059	0.067	0.063
Proportional rut depth max, PRD _{AIR} , (%)	12697-22:2012	4.8	5.5	5.2
Deformation at 10,000 cycles, Rut depth, RDA _{AIR} , (mm)	12697-22:2012	2.9	3.3	3.1

5.5 Quality control after in-plant manufacturing

In order to evaluate the technical viability of manufacturing the HWMRA mixtures in a modified asphalt batch plant, in-plant produced samples were collected (EN 12697-27: 2017. **Bituminous mixtures. Test Methods. Part 27: Sampling**) and tested in the laboratory in order to characterize the recovered RAP binder and also to verify their compliance in terms of binder content in the final mixture design, air voids content, stiffness modulus, at 20 °C, water sensitivity and resistance to permanent deformations.

The RAP binder was extracted through the rotatory evaporator (EN 12697-3:2012. Part 3: Bitumen recovery) to obtain some conclusions regarding bitumen's physical consistency properties (i.e., penetration and softening point) and chemical properties through the chromatography technique, according to ASTM D4124-09: Standard Test Method for Separation of Asphalt into Four Fractions; where SARA fractionation test consisted of determining the percentage of asphaltenes, aromatic, resins, and saturates contained in the RAP binder. **Table 13** shows the results of the physical characterization of the recovered RAP binder after in-plant mixtures manufacturing.

Table 13. Characterization of the recovered RAP binder of the in-plant samples

Properties	Test method	HWMRA 100% RAP	
		2.5% -50/70	3.0% - 50/70
Binder content, b/a, (%)	EN 12697-1:2012	6.09	5.85
Penetration, (0.1 mm)	EN 1426:2015	17	18
Softening point, R&B, (°C)	EN 1427:2015	69.2	71
ASTM D 4124:2018: Standard Test Method for Separation of Asphalt into Four Fractions			

Saturates Hydrocarbons (%)	ASTM D4124-09	12.88	10.63
Asphaltenes, (%)	ASTM D4124-09	29.90	30.17
Resin, Naphthene-aromatic, (%)	ASTM D4124-09	27.92	29.16
Aromatic-polar compounds, (%)	ASTM D4124-09	29.15	30.04
Stability Index			
Compatibility, $C > 0.5$		2.68	2.27
Colloidal Instability Index, $CII < 1$		0.79	0.74
Durability, $0.4 < CCR < 1.5$		1.18	1.41

The final binder content in the HWMRA 100 mixtures was found not to vary on a percentage greater than $\pm 0.3\%$, in relation to the content previously established in the preliminary laboratory mixture design, according to Art. 542.9.3.1 of PG-3: Manufacturing, as illustrated in **Figure 38a-b**. The binder contents in the final mixture design were found to be always above 4.5% (% b/m) of the total weight of the mixture, which is the minimum binder content required for dense-graded HMA mixtures (AC16 D), according to Spanish technical regulations in Art. 542 of PG-3 (Spanish Ministry of Public Works, 2015).

Laboratory specimens were prepared and compacted with the gyratory compactor following the same laboratory standard conditions, namely an internal angle of 0.82° , a compaction pressure of 600 kPa, and a rotation speed of 30 gyrations/minute. Posteriorly, the quality of the in-plant manufactured mixtures were evaluated in the laboratory through the following tests: (1) water sensitivity test; (2) stiffness modulus, at 20°C ; (3) resistance to permanent deformation, at 60°C , and; (4) indirect tensile strength (ITS), at 15°C ; and (5) air voids. **Figure 38c** displays the air void content of the samples. From the results presented in this figure, it can be concluded that the air voids contents targeted were successfully achieved for both HWMRA mixtures, as they were found to fall within the range of 3-6%.

The moisture damage resistance was assessed through the water sensitivity test, according to EN 12697-12:2008. **Part 12: Water sensitivity**. Thus, the samples were prepared and compacted with the gyratory compactor by applying two-thirds (2/3) of the total compaction energy used for laboratory specimen production, that is, 44 gyros for the HWMRA 100% RAP mixture. The test was carried out on six cylindrical samples divided into two subset groups: wet and dry conditions. The wet subset was submerged under a water bath at 40°C during 72 h, whereas the dry subset group was kept in dry. The samples were then subjected to a loading-controlled rate of 50 mm/min, after which the indirect tensile strength ratio (ITSR) was computed as the retained strength ratio, according to EN 12697-23:2007. **Part 23: Determination of the indirect tensile strength of bituminous specimens**.

The indirect tensile strength ratio (ITSR) of each mixture was found to be above 85% (**Figure 38d**). The average moisture damage resistance value of the 100% RAP mixture (2.5%o/RAP) was found to be 89%, while for the 3.0%o/RAP, this percentage was 94%. In particular, the high retained water strength value results of both mixtures can be attributed to the fact that RAP mixes, or recycled aggregates, are already coated with a thin film of asphalt binder, that in turn, prevents the water penetration into the particles (Karlsson and Isacson, 2006; Mogawer et al., 2012; Zaumanis et al., 2014). Therefore, both HWMRA mixtures meet the minimum percentage required for hot mix asphalt mixtures in base, binder (80%) and wearing (85%) courses of road pavements subjected to any load traffic category and thermal weather zone in Spain.

The resistance to permanent deformation of the HWMRA 100% RAP mixture with 2.5% (o/RAP) emulsion was determined, according to EN 12697-22:2012. **Part 22: Wheel tracking test.** To do this, the in-plant samples were compacted with a benchmark density value above 98% using the steel roller compactor, according to EN 12697-33:2006+A1. **Part 33: Specimen prepared by roller compactor.** The average apparent density of the finished prismatic-shaped specimens was found to be 2.329 g/cm³ and air voids content of 4.2%. Generally, the inclusion of high RAP contents enables to improve the resistance to permanent deformations because of the hardening and aging process suffered by the asphalt binder. In this consonance, similar rutting resistance results have been found and corroborated for various authors (Apeagyei AK et al., 2011; J. . Doyle and Howard, 2013; Hajj et al., 2009; West R et al., 2012).

As far as the HWMRA 100% RAP mixture samples are concerned, they showed some deformation slope values slightly above 0.10 (mm/ 1000 load cycles), between 5,000 and 10.000 load cycles, as depicted in **Figure 38e**. Despite that, they still meet the mean rut depth value of lower than 5% when applying 10,000 load cycles in the wheel tracker. In other words, the average wheel tracking slope (WTS_{AI}) of the HWMRA 100% RAP mixtures with 2.5%o/RAP and 50/70 pen. bitumen was found to be 0.12 (mm/10³ load cycles), between 5000 and 10.000 load cycles, and an average rut depth (RD_{AI}) of 4.28 mm – implying that this mixture presented a slightly lower wheel tracking slope than the maximum value (WTS=0.15 mm/10³ load cycles) established by the Spanish technical specifications, according to Art. 542.5.1.3 of PG-3: **Resistance to permanent deformation of hot mix asphalt mixtures** (Spanish Ministry of Public Works, 2015).

The mixtures' load-bearing capacity was evaluated through the stiffness modulus test, at 20°C, according to EN 12697-26:2018. **Part 26: Stiffness.** This parameter was computed as the average value of 10 indirect tensile haversine load waveform pulses, while five (5) load pulses were posteriorly applied, with a rise time of 124 ± 3 ms, to determine the stiffness modulus of the asphalt mixtures. To this end, asphalt samples of each type of asphalt mixture (100% and 70% RAP content) collected after in-plant manufacture, were prepared and compacted in the laboratory, with a diameter of 101.6 mm and a height of 60 ± 5 mm, using the same standard conditions set in the preliminary laboratory mix design. **Figure 38f** shows the stiffness modulus values obtained for each type of HWMRA mixture.

For the HWMRA 100% RAP mixture with 2.5% emulsion content, the average stiffness modulus value of 5839 MPa was obtained, whilst for the 3.0% RAP emulsion, this number was 5604 MPa (with a standard deviation of 293 MPa and a COV equal to 6.6%), where the latter mixture showed a lower bearing capacity than that of the 100% RAP mixture. Similar stiffness modulus values for cold recycled mixtures (CRM) with a total RAP content (100%) were reported in other studies conducted by other researchers (Sangiorgi et al., 2017). However, the decrease in the stiffness of the 100% RAP mixture with 3.0% emulsion can be assumed as a positive aspect to improve the mixture' fatigue cracking resistance since it would make it less stiff and brittle by enabling higher deformations before its cracking failure occurs in the field.

Figure 38. Results of the quality control tests of in-plant manufacture mixes: a) binder contents in the final mixture design of the HWMRA 100% RAP mixture with 2.5% and 3.0% emulsion content; b) binder contents in the final mixture design of the HWMRA 100% RAP mixture; c) air voids; d) retained strength ratio; e) deformation slope, and; f) stiffness modulus at 20°C.

Table 14 collates the particle size distribution of the 100% RAP mixes with 2.5% and 3.0% (o/RAP) emulsion after in-plant manufacturing; whilst **Figure 39** shows the aggregate grading curves and the upper and lower threshold values stipulated for an AC16 D mixture; where the orange solid-continuous curve represent the target grading curve after in-plant manufacturing, whilst the purple dashed lines stands for the restricted threshold values, according to Art. 542.9.3.1: **Manufacturing***.

The aggregate particle grading curves (2.5% and 3.0% o/RAP) fell within limits stipulated for an AC16 D mixture and meet the minimum threshold values established by the Spanish technical specifications. The likely explanation is attributed to the right maneuvers of screening, processing, and classification of the RAP material into two fractions (i.e., 0/5 mm and 5/25 mm) that allowed the provision of adequate volumetric and mechanical performance properties in the final mix design. However, it can be observed that for the 0.025- and 0.063-mm sieve size, the aggregate grading curves fell out of the threshold values stipulated for an AC 16 D mixture.

Table 14. Aggregate gradation composition and binder content

Sieve size – UNE (mm)	HWMRA 100% RAP		HMA AC 16 D	
	2.5% o/RAP	3.0% o/RAP	Lower limit	Upper limit
31.5	100	100	100	100
22	100	99.5	100	100
16	96.2	94.8	90	100

8	70.7	69.7	64	79
4	49.7	49.2	44	59
2	37.2	37	31	46
0.5	21.4	21.3	16	27
0.25	16.1	16	11	20
0.063	8.5	9.0	4	8
Binder content (% , b/a)	5.85 ± 0.29	6.19 ± 0.1	-	-

***Key:** The threshold dispersion limits, and/or tolerance permissible values, that should be met in relation to the particle size distribution (EN 933-2:1996: Determination of particle size distribution. Test sieves, nominal size of apertures) of the job mix formula, referred to the total mass of aggregates (including mineral filler), include the followings requirements: (a) For sieve size above 2 mm: four-percent ($\pm 4\%$); (b) For 2 mm sieve size: three-percent ($\pm 3\%$); (c) For sieve size between 2 and 0.063 mm should be equal to $\pm 2\%$, and (d) 0.063 sieve size: one-percent ($\pm 1\%$).

Figure 39. Aggregate grading curves of HWMRA mixes with 100% RAP (2.5% and 3.0% o/RAP)

Figure 40 shows the mix production, construction process, and monitoring of the HWMRA 100% RAP mixes with 2.5% and 3.0% (o/RAP) emulsion content in the test road section: (a-b) Manufacturing, at 100 °C, in a discontinuous asphalt batch plant; (c-d) mixture spreading by a Vögele asphalt paver in the range of between 80 °C and 95 °C; (e-f) mixture compaction using a vibratory steel double-drum and a pneumatic road roller in the working range of 60 -80 °C; and (g-h) final surface texture of the binder course asphalt mixture and pavement cores extraction with a rotary drill. Moreover, an infrared thermographic camera system (FlirB-360) was used to monitor the manufacturing, paving, and compaction temperatures throughout the construction process in the urban street section.

Figure 40. Manufacturing and construction process of the HWMRA100% RAP mixtures with 2.5% and 3.0% o/RAP emulsion and 50/70 pen. bitumen (Lizarraga et al., 2017)

5.6 Benchmark density after pavement construction

Once the HWMRA mixtures with 2.5% and 3.0% (over the weight of RAP) emulsion were laid and compacted, an average of sixteen (16) pavement cores of each type of mixture were extracted from the test road section in order to verify if the mixtures meet the minimum percentage of the benchmark density of the specimens compacted with the gyratory compactor at 70 gyrations (0.82°, 600 kPa and 30 rpm) in the laboratory. Thus, the bulk density of the pavement cores was calculated, according to EN 12697-6:2012. Test methods for hot mix asphalt. **Part 6: Determination of bulk density of bituminous specimens.**

This research study revealed that the pavement cores' benchmark density was successfully reached, without any compactability issue, after the first-round sampling took place in the field. In other words, the average bulk density of the 2.5%o/RAP cores was found to be 2.262 g/cm³ (with an SD of 57.8 g/cm³ and

a CV equal to 2.6%), with an average air voids content of 6.92% (with a standard deviation (SD) of 2.38% and coefficient of variation (CV) of 34.46%) and cores' height of 53.64 mm; whilst, for the 3.0%o/RAP emulsion, the average apparent density was 2.309 g/cm³ (with an SD of 59.4 g/cm³ and a CV equal to 2.57%), cores's height of 54.9 mm (with a SD 6.02 mm and a CV of 11%) and air voids content of 5.2% (with an SD of 34.5% and a CV of 2.38). In short, the benchmark density of the pavement cores with 2.5%o/RAP emulsion was fixed as 2.330 g/cm³, while, for the 3.0% emulsion, this value was 2.340 g/cm³. Therefore, the average compaction percentage of the 2.5% o/RAP cores was found to be 99.1%, while, for the 3.0% emulsion, this percentage was 97%.

Although the mixture densification for the 3.0% o/RAP was slightly lower than that of the expected density, this mixture still meets the minimum benchmark density value (97%) of hot mix asphalt mixtures for layer thickness below 60 mm, according to Spanish technical specifications in Art. 542.7.1: **Density**. **Figure 41** shows the apparent density (g/cm³) and percentage of compaction achieved by using conventional machinery, i.e., a steel double-drum roller and a pneumatic tire road roller.

Figure 41. Volumetric characteristics and mechanical properties of the pavement cores after in-situ construction

5.6.1 Mechanical performance

Figure 42 shows a comparison of three laboratory compaction test methods (Marshall with 75 and 100 impact-blows, Static compressive stress load of 10 MPa and gyratory compactor with 70 gyrations) and pavement cores (2.5% and 3.0% over the weight of RAP) in terms of mechanical performance.

Regarding the indirect tensile strength (ITS) values of the 100% RAP (2.5%, o/RAP) mixtures, the average wet and dry internal cohesion values were found to be 2.63 MPa and 2.83 MPa, respectively, and the indirect tensile strength ratio (ITSR) of 93% was obtained; whereas, for the 3.0% (o/RAP) mixture cores, the average wet and dry internal cohesion values were 1.78 MPa and 2.04 MPa, respectively, and the resulting moisture damage value was 87.3% - showing that whether the pavement cores are compacted below 97% of the benchmark density, the air voids increases and hence the indirect tensile strength is reduced. This is likely attributed to the rise of spaces without aggregate or bitumen on the plane where the break occurs, which means that there is less surface for resisting tensile stress due to traffic loading (Moreno-Navarro et al., 2014). As for the stiffness modulus value results, the average load-bearing capacity values, at 20 °C, of the 2.5% pavement cores was found to be 4577 MPa (with an SD of 1030 MPa and a CV of 22%), whilst, for the 3.0% emulsion, this content turned out to be 3431 MPa (with an SD of 1037 MPa and a CV equal to 30%).

Figure 42. Comparison of mechanical performance (ITS and stiffness modulus) of laboratory and field performance

5.6.2 Fatigue characterization

The indirect tensile fatigue test on cylindrical shaped specimens was conducted, at 20°C, using a loading frequency of 20 Hz, according to EN 12697-24:2012. **Part 24: Resistance to fatigue - Annex E.** The fatigue cracking resistance slopes of the HWMRA 100% RAP (3.0%o/RAP) and HMA mixtures, they are practically identical – suggesting that they have an equivalent sensitivity to stress in terms of fatigue life (i.e., the number of load cycles N_f linked to the mixtures' fatigue failure criterion at a given temperature, frequency, and loading). **Figure 43** collates the fatigue cracking resistance laws of the HWMRA100%RAP mixtures with two emulsion contents (2.5% and 3.0%o/RAP) and conventional HMA mixture.

On the other hand, the fatigue slope of the HWMRA (2.5%o/RAP) mixture is slightly steeper than that the rest of the mixtures studied, whereas, for the HWMRA (3.0%o/RAP) mix, it appears to have a good ability to withstand a higher number of load cycles before its fatigue cracking failure occurs. The likely explanation for this result lays in the effect of higher emulsion content in the final mixture design that promoted a higher stable behavior in terms of fatigue life (Maupin Jr et al., 2008). Thus, one can say that for the stress level tested, the fatigue performance of the HWMRA mixes (2.5% and 3.0% o/RAP) was satisfactory in comparison with conventional HMA mixes. **Table 15** shows the coefficient of determination, R^2 , stiffness modulus, and tensile strain at 10^6 load cycles (a , b , R and ϵ_0) of each type of mixture studied.

Figure 43. Fatigue cracking laws, at 20 °C of HWMRA 100% RAP mixes (2.5% and 3.0%o/RAP) and HMA mixture

Table 15. Fatigue law coefficients of HWMRA 100 (2.5 and 3.0%) and HMA cores

Mixture type	HWMRA 100 % RAP mixtures		HMA AC 16 D 50/70 dmm
	2.5% - 50/70	3.0% - 50/70	
a ($\mu\text{m/m}$)	0.0007	0.0009	0.0006
b (-)	0.159	0.177	0.149
R ²	0.7906	0.8727	0.9195
Modulus (MPa)	3284	3792	4287
ϵ_6 ($\mu\epsilon$)	63	69	75

5.7 Monitoring plan of the pavement surface characteristics

5.7.1 Macrotexture

Figure 44 shows the average surface macrotexture depth value results in the two surface friction campaigns. As can be seen in this Figure, all mixtures met the minimum values required (0.7 mm) for use in the binder and wearing courses asphalt mixture, according to the Spanish technical specifications in Art. 542.7.4: **Macrotexture**, being the HWMRA 100% RAP mixture (3.0%,o/RAP) the one that presented the highest average value (0.79 mm). However, a significant progressive reduction in the macrotexture value was found after one year and a half after the construction of the pavement section. The likely explanation for this result lay on the occlusion of the air voids as a consequence of the migration of the binder and dust existing in the mixture, as well as on the post-compaction action promoted by the vehicle traffic loads (Vaiana R et al., 2012). For the HWMRA 100%RAP mixtures (2.5% and 3.0%) reached a maximum post-peak macrotexture value and, after that, they fell again to the initial value measured in the first surface campaign.

Figure 44. Surface macrotexture depth value results in the two first surface campaigns

5.7.2 International surface roughness index

Looking at the international roughness index values, in 2014, the HWMRA (3.0%,o/RAP) mixture showed the highest average surface roughness index value of 1.115 m/km (with an SD of 0.29 m/km and a coefficient of variation (CV) equal to 26.3%), whilst, for the HWMRA (3.0%o/RAP) the average surface roughness was found to be 1.015 m/km (with an SD of 0.34 m/km and a CV equal to 34.3%). Therefore, a slight increase in roughness deterioration of the latter emulsion mixture of 10% was calculated, likely due to the vertical stress and deformation promoted by the heavy traffic loads on the low-speed lane. However, this surface deterioration is somewhat attributed to the potential construction or paving operations than of pavement wear or surface distress (i.e., rutting, transverse, reflective and longitudinal cracking) of the pavement structure (Martínez-echevarría et al., 2016; Zaumanis M and Haritonovs V, 2015). **Figure 45** illustrates how the average international surface roughness index values (m/km) of the 100% RAP mixtures (2.5% and 3.0% o/RAP) evolve by considering the traffic loading category to be supported over three years in service. This Figure also shows the error bars plotted in terms of standard deviation (SD) along with the coefficient of regression, wherein, R^2 , represents a regression model for IRI prediction values over time. This mixture still meets the requirements stipulated by the Spanish technical specifications in Art. 542.10.3: Surface Roughness.

Figure 45. International roughness index (m/km) of the 100% RAP mixtures (2.5% and 3,0% o/RAP)

Chapter 6

LOOKING AHEAD: SELF-HEALING ANALYSIS OF HWMRA MIXES CONTAINING 100% RAP

In previous Chapters, the viability and characterization of half-warm mix recycled asphalt (HWMRA) mixes were studied to contribute to the development of the current practices and research projects associated with this recent technology. Therefore, this Chapter aims to promote a new technology based on new perspectives that allow achieving a better optimization of maintenance and rehabilitation (M&R) works of road pavements. This Chapter can be read as a Foreword to the doctoral thesis adapted for upcoming research projects.

6.1 Introduction

Asphalt concrete (AC) mixtures are typically exposed to repeated heavy traffic loading cycles and thermo-mechanical surface distress that triggers the appearance of cracking. To overcome these issues and contribute to further extend the service life of road pavements, a novel thermomechanical treatment is gaining boost as an effort to put into practice more sustainable engineering solutions for in-situ asphalt mixtures heating and healing. One example of a technology that possesses the potential to enhance road pavement sustainability is the use of half-warm mix asphalt (HWMA) mixtures combined with industrial by-products (e.g., electric arc furnace slag (EAFS) and recycled asphalt pavement (RAP) contents) because of the provision of the decrease of extraction and exploitation of raw materials, lower greenhouse gas (GHG) emission, and higher sensitivity to microwave (MW) radiation energy.

Nonetheless, the microwave radiation energy is becoming as a promising heating treatment for in-situ asphalt mixtures heating due to the provision of an alternating electromagnetic field with a frequency in the order of Megahertz (Fransesqui et al., 2017; Norambuena-contreras and Garcia, 2016), which corresponds to a wavelength of 120 mm (Gallego et al., 2013). In fact, some technical and economic advantages of using microwave treatments on steel slag mixtures include: (1) a rapid and uniform heating without overheating the pavement surface (Wang et al., 2018b); (2) a 30-40% lower energy consumption compared to induction heating method; and (4) increased mixture temperature by changing the orientation of polar molecules in accordance with the applied electric field (Liu et al., 2018; Metaxas and Meredith, 1983).

In order to prove that the microwave heating method has the potential to improve the adhesive bonding of aggregate-bitumen, durability, and mechanical performance of mixtures with steel slag aggregates, some investigations have been conducted and contrasted by different researchers. For instance, (Al-Ohaly and Terrel, 1988) reported that the microwave heating treatment improves the adhesion bonding properties of asphalt and aggregates system, i.e., due to the work of adhesion that can be described as the necessary energy to break up the aggregate-binder bond at the interface (Liu et al., 2017).

In this line, Norambuena-contreras and Garcia (2016) evaluated the self-healing ratio of semi-circular test specimens using both induction and microwave heating methods. They emphasized that the microwave treatment turned out to be the most efficient solution and that the air voids content represents a crucial aspect of being considered for the self-healing recovery of the mixtures, due to an increase of internal pressure and mobility of bitumen during the heating process. For instance, Luo, (2012) reported that mixtures with lower air voids content in the mix (V_m) and fewer air voids mineral aggregates (VMA) exhibited better self-healing recovery, regardless of the bitumen-type, aging, and temperature. Nevertheless, if the optimum microwave heating time is not correctly managed, the bitumen' melting point and aging can occur, due to overheating (Norambuena-contreras and Gonzalez-torre, 2017).

Additionally, the previous advantages can be further enhanced by adding some ferrous particle aggregates into the new bituminous mixture since they have the potential to improve the adhesive bonding and cohesive strength between aggregates and binder (Al-Ohaly and Terrel, 1988), conduct more thermal energy, and accelerate the increase in mixture temperature by enabling higher absorption of microwave radiation energy (Skaf et al., 2017; Wang et al., 2016). In other words, the replacement of virgin/recycled aggregates with steel slag aggregates has been tagged as a suitable alternative, showing acceptable mechanical performance (e.g., stability, indirect tensile strength (ITS), resilient stiffness, creep modulus, cracking and permanent deformations) (Ameri et al., 2013; Ameri and Behnood, 2012b; Asi et al., 2007; Sorlini et al., 2012), while improving the susceptibility to microwave heating radiation (Gallego et al., 2013). In this regard, Gallego et al. (2017) examined the potential effect of using steel slag aggregates on bituminous mixtures using microwave radiation energy. They found that a 5% of steel slag aggregates by weight of the mixture represented the most technical and energy-efficient solution for in-situ asphalt pavement heating.

Nonetheless, the results reported by other researchers are somewhat less conclusive, in the sense that mixtures with EAF slag fine aggregates displayed lower mechanical performance (e.g., Marshall stability, resilient modulus ratio, tensile strength, and fracture energy ratio) and moisture sensitivity, likely as a result of the particle size of slag, aggregate-type, and binder selected (Hesami et al., 2014). In this consonance, some other authors asserted that the use of EAF slag fine fraction aggregates decreased the resistance to permanent deformation while increasing the binder consumption (Ameri et al., 2013; Kavussi and Qazi Zadeh, 2014). What's more, Shuler, (1976) and Xie et al., (2012) claim that mixes manufactured with thermal power plant residues showed mechanical behavior and deteriorated more rapidly under traffic loads.

Therefore, due to contradictory results concerning the slag mixtures' mechanical performance, a more in-depth research study is necessary to quantify the self-healing process of half-warm mixes with recycled and steel slag fine fraction aggregates in new bituminous mixtures for their use in wearing course asphalt mixtures. For this reason, an innovative Spanish research project conducted by the road engineering laboratory of the Technical University of Madrid (UPM) entitled: "Self-healing analysis of half-warm mix recycled asphalt (HWMRA) mixture with EAFS and RAP aggregates using a thermomechanical treatment for enhancing road pavement sustainability."

6.2 Methodology

The aim of this research study was to present and quantify the self-healing ratio of half-warm mix asphalt mixtures containing three different electric arc furnace steel (EAFS) slag aggregate contents (0%, 4% and 8% of EAFS by total volume of the mixture) used as a replacement of recycled RAP aggregates in the fine fraction 0-4 mm sieve size. In order to do this, the research methodology was broken down into **five main stages/phases**. **In the first phase**, the RAP material was characterized to determine the bitumen consistency properties (i.e., penetration grade, and softening point temperature) and black and white RAP grading curves. The steel slag aggregates were classified in five different fractions (4, 2, 0.5, 0.25, and 0.063 μm) and, after that, weighted to determine the aggregate grading curve of this material, according to **EN 12697-2:2015. Part 2: Determination of particle size distribution**.

The second stage consisted in determining the optimum emulsion content (OEC) of the half-warm mix with a total RAP content (100%) in order to achieve the required target air voids content in the range of $5 \pm 1\%$, aiming at the center of the interval of a dense-graded asphalt concrete mixture (AC16 D), according to **Art. 542.5.1.2: Air voids** (Spanish Ministry of Public Works, 2015). The EAF slag aggregate mixtures were prepared (with a diameter of 100 mm and 60 ± 5 mm in height) and then compacted using the gyratory compactor by applying a mix design compaction energy of 80 gyrations, at 80 °C, and following the standard compaction conditions ($\alpha=0.82^\circ$, 600 kPa, and 30 rpm) established by EN 12697-31:2007. **Part 31: Gyratory Compactor**. Posteriorly, the specimens were put into a forced-draft convection oven for being subjected to a specific accelerated curing/drying heating treatment for three days (72 h), at 50 °C, according to the Spanish technical specifications collected in Art. 20 of PG-4: **"In-situ recycling of bituminous mixtures with emulsion"** (Spanish Ministry of Public Works, 2017).

In the third stage, a thermographic imaging analysis was conducted to define the most energy-efficient mixture solution using an electric meter with the microwave heating time process. To this end, the average energy consumption and specimens' surface and internal thermal maps of the four slag aggregate contents (0%, 2%, 4%, 6%, and 8% of EAFS by the total volume of the mixture) were computed and plotted. This thermal study was conducted using a microwave heating oven with a maximum output capacity of 1200 W and a 230 V, and 50 Hz power supply, which corresponds to an approximate wavelength of 120 mm (Gallego et al., 2013). However, for this research study, the microwave oven was set to produce 800 W, with a frequency of 2.45 GHz, to compare the results found by different researchers (Gallego et al., 2017).

The microwave thermal plots extracted from the thermographic study included: (1) Microwave surface/internal heating temperatures (°C) vs. Energy consumed during microwave heating (kWh); (2) Microwave surface/internal heating temperature (°C) vs. Microwave heating time (s). To this end, a FLIR C2 thermographic imaging camera (with an average temperature emissivity of 0.95, surface reflexivity temperature of 20 °C and infrared (IR) resolution of 80 x 60 pixels) and an infrared temperature-measured gun were used to draw some conclusions from the target internal and surface heating temperature [(e.g. Maximum, Minimum, Mean (μ), standard deviation (SD), and coefficient of variation (CV)] of the rectangular central section of the half-warm specimens. **Figure 46** shows the infrared and microwave heating temperatures in the range of 80-85 °C, which seems to be sufficient to activate the effect of self-healing on asphalt mixtures (Liu et al., 2012).

Figure 46. Thermographic and infrared temperature: (a) Infrared gun; (b) Microwave oven at 800 W; (c) specimen cut into two halves for internal temperature measuring; (d) surface temperature at above 75 °C

The fourth phase consisted of determining the initial mechanical performance of three different steel slag mixture contents (0%, 4%, and 8% EAFS). The mixtures were tested for stiffness modulus at 20 °C, and followed by the indirect tensile strength test, at 15 °C. To this end, the stiffness modulus values were calculated using a set of five stress-controlled load pulses at a loading frequency of 2.1 Hz, with a rise time of 124 ± 3 ms, and horizontal maximum peak deformation of 5 μm , according to **EN 12697-26: 2012. Part 26: Stiffness**. Subsequently, the indirect tensile strength (ITS) was conducted, at 15 °C, using a deformation load rate of 50.8 ± 2 mm/min on the vertical diametral plane, according to EN 12697-23:2008. **Part 23: Determination of the indirect tensile strength of bituminous specimens.**

Once the mixtures' mechanical performance characterization was conducted, the next step was to determine the extent to which four different slag aggregate contents impact on the mixtures' mechanical performance properties. The results were validated using the central limit theorem-based normal distribution to find out whether the mechanical performance data are normally distributed. In other words, a three-way Analysis of Variance (ANOVA) analysis was selected for the stiffness modulus since they were found to fit well within the Parametric distribution (Box, 1953; Dien, 2017); whereas, for the indirect tensile strength (ITS) values, the data suited well within the Non-parametric range by the Kruskal-Wallis distribution test (Kruskal and Wallis, 1952). Therefore, based on the **Kruskal-Wallis and Analysis of Variance (ANOVA) test**, it was found that the replacement of the **recycled aggregates with EAF slag**

fine fraction aggregates had a statistically significant effect on the initial and ultimate mechanical performance properties such as indirect tensile strength (ITS) and stiffness modulus values. After running the SPSS software, the p-values were found to be 0.003 and 0, respectively.

In the fifth phase, the self-healing ratio of the half-warm steel slag mixtures was quantified in terms of the indirect tensile strength (ITS) at 15 °C, and stiffness modulus at 20 °C. To this end, three microwave heating temperatures (25 °C, 60 °C, and 80 °C) along with three mechanical recompaction gyrations (0, 25, and 50) were used.

As for the sixth phase, the energy efficiency of the self-healing process was calculated by obtaining the self-healing recovery of the mechanical performance properties (ITS and stiffness modulus) of each type of mixture (0%,4%, and 8% EAFS) against the healing energy efficiency (kWh) depending on the number of recompaction gyrations (0,25, and 50 gyros) applied on the samples and microwave heating temperature (25 °C, 60 °C, and 80 °C). **Figure 47** illustrates the summary of the six main phases followed in the experimental methodology: (1) characterization of materials; (2) mixture design; (3) thermographic analysis; (4) initial mechanical testing phase; (5) thermomechanical treatment; and (6) Self-healing ratio.

Figure 47. Detailed flow chart of the methodology followed in this research Chapter

6.3 Test procedures

The volumetric characteristics of the mixtures were calculated using the bulk density, by saturated surface dry (SSD) conditions, according to EN 12697-6:2012. **Part 6: Determination of bulk density of bituminous specimens;** while the maximum density is measured using a pycnometer set at 4 kPa atmospheric pressure, according to EN 12697-5:2012. **Part 5: Determination of the maximum density. Procedure A: Volumetric method.** To this end, an average of two samples were taken for each emulsion content, ranging from 2.0 to 3.5% - at 0.5% increments, whilst an average of three cylindrical specimens were prepared ($\varnothing=100$ mm and $h = 60$ mm in height) and compacted with the gyratory compactor (EN 12697-31:2007) to determine the bulk density of the specimens.

To further evaluate the recovery capability of the mechanical performance properties of the steel slag mixtures, (1) the stiffness modulus, at 20 °C, and (2) the indirect tensile strength test, at 15 °C, were determined. The mixtures' load-bearing capacity was assessed through the stiffness modulus (S_m), at 20 °C, according to EN-12697-26:2012. **Part 26: Stiffness.** This property was determined by applying five indirect-tensile haversine-shaped load waveform pulses on a diametral section using the following conditions: rise time of 124 ± 3 ms; target peak horizontal deformation of $5\mu\text{m}$; loading frequency of 2.1 Hz; (4) peak loading force of 1000 N; (5) and Poisson's ratio (ν) of 0.35. In turn, ten (10) load pulses were previously applied to set up the device and system in terms of loading level and frequency. The average stiffness modulus value of the specimen was then validated and contrasted by turning it at an angle of $90 \pm 10^\circ$, according to their longitudinal axis on the plate. Thus, for an applied dynamic load of P in which the resulting horizontal dynamic deformations are determined, the average stiffness modulus is calculated from Eq. 6.1 (Modarres and Ayar, 2014):

$$S_m = \frac{P(\gamma+0.27)}{t\delta_h} \quad (6.1)$$

Where: S_m represents the stiffness modulus, MPa; P : Maximum peak dynamic load, N; γ : Poisson's ratio; t : specimen thickness, mm; δ_h : total horizontal recoverable deformation expressed in terms of mm.

The second test method used to evaluate the capability of the steel slag mixtures was the internal cohesion strength assessed through the indirect tensile strength (ITS_{dry}), at 15 °C, according to EN 12697-23:2017: Determination of the indirect tensile strength. This test consisted of subjecting the specimens to compressive loads between two loading strips (with a width of 12.7 mm) at a constant deformation speed of 50 ± 2 mm/min. This load provides tensile stress along the vertical diametral plane, which causes the splitting failure on the diametral plane. The peak compressive load was measured to calculate the indirect tensile strength of the specimens, according to Eq. 6.2:

$$ITS = \frac{2P_{max}}{\pi td} \quad (6.2)$$

Where: ITS: horizontal tensile strength expressed in gigapascals (GPa); P_{max}: represents the ultimate load required to fail specimens under diametral compression (kN); t: specimens' thickness (mm); d: specimens' diameter (mm);

Additionally, an assessment of the effect of three microwave heating treatments (25 °C, 60 °C, and 80 °C) and three recompaction gyrations (0, 25 and 50 gyrations) on three steel slag mixture contents (0%, 4% and 8% of EAFS), was conducted. To do so, an average of twenty-seven (27) cylindrical-shaped specimens were manufactured (with a diameter of 100 mm and height of 60 ± 1 mm) for each type of steel slag mixture to quantify the extent to which the self-healing phenomenon can recover the stiffness modulus and the tensile strength of the mixtures. In order to quantify the self-healing ratio of the steel slag mixtures, the stiffness modulus, and indirect tensile strength was calculated as the relationship between the initial and the ultimate strength resistance using Eq. 6.3:

$$HR = \frac{F_p}{I_p} \quad (6.3)$$

Where; I_p: is defined as the vertical load applied before subjecting to a healing treatment and recompaction test; and F_p: after being subjected to healing treatment and mechanical recompaction.

6.4 Materials

6.4.1 EAFS aggregates

In this research study, the electric arc furnace slag aggregates (EAFS) were selected, as replacement of recycled aggregates in the fine fraction of 0-4 mm, for the half-warm mix' production and characterization in the laboratory. The steel slag aggregates have a CE marking as a replacement aggregate for bituminous mixtures and surface treatments for roads, airfields, and other trafficked areas, according to EN 13043:2002+AC:2004. The specific gravity of the steel slag aggregates was found to be in the range of 3.51-3.64 g/cm³ (Al-Negheimish et al., 1997). **Table 16** exhibits the composition of the slag aggregates grading curve in this research study and aggregate particle grain curve of the mixture produced and threshold values stipulated for a dense-graded asphalt concrete mixture (AC 16 D) with a nominal maximum aggregate size (NMAS) of 16 mm, according to **Art. 542.3 of PG-3: Type and composition of**

the mixtures. The particle aggregate grading curve of the EAFS aggregates are presented in **Figure 48**, and the chemical composition of the steel slag aggregate is collated in **Table 17**.

Table 16. Particle grain size distribution and AC 16 D gradation threshold values

Sieve size (mm)	8	4	2	0.5	0.25	0.063
Passing (%)	100	96.29	49.64	15.40	9.97	5.26

Figure 48. Aggregate grading curve of the EAF slag aggregates

Table 17. Chemical composition of slag (before hydration)

Chemical composition	Value (%)
Al ₂ O ₃	8.81
CaO	24.28
Fe ₂ O ₃	40.49
MgO	3.02
MnO	4.72
SiO ₂	12.60
P ₂ O ₅	0.36
Other substances	5.72

6.4.2 RAP characterization

The recycled asphalt pavement was homogenized, treated and characterized in order to determine its residual bitumen content using rotary evaporator by the centrifuge extractor method (EN 12697-3:2013. Part 3: Bitumen recovery. Rotary evaporator), bitumen' consistency properties (softening point (°C) and penetration test) and white grading curves of the recycled RAP binder obtained from the urban test section; where these curves can be defined as the RAP gradations after the extraction of the residual aged bitumen. The physical characteristics of the recycled binder as well as the percentage contained in the recycled mixture are collated in **Table 18**. The white RAP grading curves were divided into four different fractions (12.5/20 mm, 8/12.5 mm, 4/8 mm and passing 4 mm) after extracting the aged RAP binder. The average binder content found in the RAP material was found to be approximately 4.89 %.

Table 18. Physical characterization of the aged RAP binder obtained from an urban test section

Properties	Test method	Value
Maximum density (g/cm ³)	EN 12697-6:2012	2.443
Bitumen content (%)	EN 12697-1:2012	4.89
Penetration test (0.1 dmm, 100 g, 5 s at 25 °C)	EN 1426:2015	11
Softening point (°C) R&B method	EN 1427:2015	80.3

6.4.3 Bituminous emulsion characterization

A cationic slow-setting bituminous emulsion (C67B3) with a residual asphalt binder content of 67% by weight of the emulsion was selected and used in order to guarantee (1) a thick asphalt emulsion film coating and bonding between RAP and virgin aggregates; (2) much better cohesion; (3) to provide good workability during the paving and compaction phase. The emulsion was formulated with a 50/70 pen. grade bitumen. The characterization of the emulsion consisted of analyzing the viscosity, the water content from the bituminous emulsion, the residue on sieving, residual binder content, penetration, and softening point. **Table 19** shows the general technical specifications of the bitumen emulsion used to produce HWMRA mixtures.

Table 19. Technical characteristics of a slow-setting cationic bitumen emulsion (C67 B3)

Characteristics	Unit	Test method	Standard
Particle polarity of emulsion	-	EN 1430	Positive
Determination of breaking value of cationic bituminous emulsions, mineral filler method	-	EN 13075-1	70 to 155

Water content (from bituminous emulsions). Azeotropic distillation method	% by weight	EN 1428	65-69
Residual binder and oil distillate from bitumen emulsions by distillation	% by weight	EN 1431	≥ 65
Oil distillate content by distillation	% by weight	EN 1431	≤ 2.0
Efflux time by the efflux viscometer.	s	EN 12846	40-100
Determination of residue on sieving of bituminous emulsions, and determination of storage stability by sieving	% by weight	EN 1429	≤ 0.1
Settling tendency of bituminous emulsions	% by weight	EN 12847	≤ 5
Adhesivity of bituminous emulsions by water immersion test	% by weight	EN 13614	≥ 90
Elastic recovery of modified bitumen	%	EN 13398	DV

6.5 Determining optimum emulsion content

In order to determine the optimum emulsion content (OEC) of the HWMRA 100% RAP mixtures, these mixtures were manufactured in the laboratory by heating the emulsion at 65 °C, RAP aggregates at 100 °C, slag aggregates at 100 °C, basket at 95 °C, and cylindrical molds at 100 °C, for 2 h, in a convection oven. All of these materials were posteriorly mixed in a blending basket, for 3 min, at 80 rpm, for ensuring a good coating and bonding between recycled RAP aggregates and emulsion. Moreover, an average of three cylindrical-shaped specimens were prepared (with a diameter of 100 mm and with 60 ± 1.5 mm height) for each emulsion content (2.0%, 2.5%, 3.0%, and 3.5% o/RAP) and compacted with a mix design compaction effort of 80 gyrations, at 80 °C, following the standard compaction conditions ($\alpha = 0.82^\circ$, 600 kPa and 30 rpm) established by the EN 12697-31:2007. **Part 31: Specimen preparation by the gyratory compactor**

The mixtures' volumetric characteristics were determined in terms of maximum density, bulk density, and air voids in the mix. Thus, the air void content is calculated using the bulk density of the test specimens, by saturated surface dry (SSD) conditions, according to EN 12697-6: 2009. **Part 6: Determination of bulk density of bituminous specimens**, while the maximum density of the mixture is calculated using a pycnometer based on the EN 12697-5:2009. **Part 5: Determination of the maximum density – Procedure A: Volumetric method**. Table 20 illustrates the volumetric characteristics of the preliminary mix design in terms of maximum density, bulk density, and air voids.

The emulsion content was defined based on the target air voids content ($V_m = 5.0\%$), aiming at the center of the dense-graded asphalt concrete (AC 16 D) mixture, according to Spanish technical regulations in Art. 542.5.1.2: **Air voids** (Spanish Ministry of Public Works, 2015). A 2.6% (o/RAP) was calculated by linear

interpolation with a regression coefficient (R^2) of 0.99, to achieve 5.0% air voids, at the center of the interval of 4-6% air voids. Therefore, a 2.6%o/RAP emulsion made up of a 67% of residual asphalt content ($2.6 \times 0.67 = 1.94\%$ cationic emulsion + 4.19 %RAP binder = 6.13% binder o/a) was calculated by linear interpolation with a fitted regression coefficient (R^2) of 0.99, to achieve 5.0% air voids content, at the center of the interval of 4-6%, as illustrated in **Figure 49**.

Table 20. Volumetric characteristics of the preliminary laboratory mix design

Mixture properties	Test method	Emulsion content (% o/RAP)			
		2.0%	2.5%	3.0%	3.5%
Maximum density, (g/cm ³)	EN 12697-5:2012	2419	2418	2414	2395
Apparent density, by SSD, (g/cm ³)	EN 12697-6:2012	2269	2292	2313	2339
Air voids, V_m , (%)	EN 12697-8:2003	6.1	5.2	4.2	3.3

Key: * bitumen emulsion content over recycled asphalt content (%o/RAP)

Figure 49. Determination of the optimum emulsion content aiming at the target air voids content of 5.0%

6.5.1 Compaction curves

Figure 50 shows the evolution of the geometric density (g/cm^3) curve of the 100% RAP mixtures with four emulsion contents (2.0%, 2.5%, 3%, and 3.5% o/RAP) against the number of compaction gyrations (up to 200 gyros). It can be observed in this **Figure** the average geometric density value of the 100%RAP mixture with 2.5% emulsion was found to be $2.298 \text{ g}/\text{cm}^3$ and average specimens' height of 56.82 mm, whilst, for the 3.0% emulsion, this number was $2.313 \text{ g}/\text{cm}^3$ and an average specimens' height of 56.01 mm. Therefore, for the 2.5%o/RAP emulsion and at 80 gyrations, 98.22% of the geometric density of the specimens compacted with up to 200 gyrations ($\rho_{b, \text{dim}} = 2339 \text{ g}/\text{cm}^3$) was obtained; whereas, for the 3.0%o/RAP, this percentage was found to be 97.3% ($\rho_{b, \text{dim}} = 2378 \text{ g}/\text{cm}^3$); where **Pb**, dim can be understood as the average geometric density calculated for Ni load cycles expressed in terms of g/cm^3 .

Additionally, it can be said that the gyratory compaction curves displayed a rising sharply behavior during the first 50 load cycles due to consolidation and densification process, and, thereupon, they become more asymptotic afterward, likely attributed to a greater aggregate-aggregate interlocking effect. At the end of the compaction process, the 3.0% and 3.5%o/RAP emulsion mixes showed similar, or equivalent, geometric density (g/cm^3), implying that they are comparable in terms of density.

Figure 50. Compaction curves of the HWMRA 100% RAP mixtures with four emulsion contents

6.5.2 Mixture composition

Once the target air voids design-based optimum emulsion content of the 100% RAP mixture was determined, the next step was to quantify the additional emulsion content on the EAF slag mixture design, i.e., the RAP aggregates were replaced with the corresponding percentage of steel slag aggregate in the fine fraction of 4-0 mm sieve. Due to the difference in RAP and EAFS aggregate density, it was necessary to recalculate the effective emulsion content in the final mixture design to produce a similar effective emulsion content on each type of mixture. Therefore, the absorption coefficient of RAP aggregates was 0.75, while, for the recycled aggregates, this number was found to be 3, as illustrated in Eq. 5.5:

$$\% OBC_{slag} = \% emulsion + \left[\% b_{efec} - \left(\frac{\% RAP}{100} \right) \cdot 0.75 + \left(\frac{\% Slag}{100} \right) \cdot 3 \right] \quad (5.5)$$

Where; OBC: optimum binder content in terms of percentage; % b_{efec} : effective bitumen (%); **Table 21** shows the final composition of the mixtures with five different steel slag aggregate contents (0%, 2%, 4%, 6% and 8% EAFS by the total volume of the mixture) in the fine fraction of 0-4 mm sieve, along with the corresponding emulsion content added into the mixture design. In other words, the steel slag aggregate fraction absorbs a slightly higher emulsion content in the mixture design than the recycled aggregates, due to the higher porosity of this material.

Table 21. Composition of the mixtures of the HWMRA mixtures containing EAFS aggregates

Sieve size (mm)		100% RAP (0% EAFS)		98% RAP + 2% EAFS		96% RAP + 4% EAFS		94% RAP + 6% EAFS		92% RAP + 8% EAFS	
		(%)	Mass (g)	Mass (g)		Mass (g)		Mass (g)		Mass (g)	
				RAP	EAFS	RAP	EAFS	RAP	EAFS	RAP	EAFS
20	12.5	9.3	93	93	-	93	-	93	-	93	-
12.8	8	9.8	98	98	-	98	-	98	-	98	-
8	4	30.3	303	303	-	303	-	303	-	303	-
4	2	13.8	138	123	22.5	113	37.5	138	60	88	75
2	0.5	16.2	162	159.8	3.3	155	9.9	162	13.2	148.8	19.8
0.5	0	20.6	206	203.2	4.2	198	12.6	206	16.8	189.2	25.2
Weight (g)		100	1000	980	30	960	60	940	90	920	120
*Emulsion (%)			2.6	2.7		2.8		2.9		3.0	
Weight (g)			1026	1037		1048		1059		1070	

Key: *Emulsion content added in the mixture design expressed in terms of percentage (%); **Key**:** For the 8% EAFS aggregates, a 5% of slag aggregates was selected in the range of 2-4 mm (passing 4 and retained in 2 μ m sieve) and 3% for the 0/2 mm sieve size; For the 6% EAFS, 4% of slag aggregates for the 2/4 mm sieve, and 2% for the 0/2 mm; For the 4% EAFS aggregates, 2.5% of EAFS aggregates for the 4/2 mm sieve size, and 1.5% EAFS for 0/2 mm sieve size; and For the 2% EAFS aggregates, 1.5% of EAFS aggregates was chosen for 4-2 mm sieve and 0.5% in the sieve size fraction of 0-2 mm;

6.6 Thermographic study: Microwave heating stage

The HWMRA specimens were prepared (with a diameter of 100 mm and 60 mm in height) and cut into two semi-cylindrical halves on the vertical diametral plane with an electric saw to facilitate the specimens' internal temperature measurement. To this end, a microwave heating oven with a theoretical maximum output capacity of 1200 W and a 230 V, 50 Hz power supply, was selected. However, the oven was adjusted to produce microwaves of up to 800 W, with a frequency of 2.45 GHz. Also, rectangular shaped cardboard (with a length of 200 mm, 160 mm in width, and 2.5 mm in thickness) was placed right below the cylindrical specimen to prevent heat transfer by conduction of the microwave crystal plate.

In this context, both surface and internal microwave heating temperatures were monitored using (1) a FLIR C2 thermal imaging camera to obtain the most significant data (Maximum, Minimum, Mean (μ), standard deviation (SD), and coefficient of variation CV) from the rectangular-shaped section of the cylindrical specimens. (2) A Testo 830-T1 infrared gun (with 10:1 optics, spectral range of 8-14 μ m, and infrared resolution processor of 0.1 $^{\circ}$ C for non-contact surface temperature measurements) was selected for this temperature study. **Figure 51** shows the specimen's surface heating temperature (80 $^{\circ}$ C). It was found that the specimens showed a slightly higher internal temperature than that of the surface temperature, likely caused by a higher heat-flow diffusion in the periphery of the sample, which allows achieving the required target internal heating temperature more efficiently (Gallego et al., 2017). In turn, the recycled binder can be observed that began to burn at the microwave heating temperature above 105 $^{\circ}$ C, likely caused by hot gases trapped inside the specimens that cause the specimen's swelling.

Figure 51. Thermographic imaging analysis: (a) Microwave heating oven; and (b) thermography at 80 $^{\circ}$ C

It was noted that for the 8% steel slag aggregates, the average energy consumption of 0.035 kWh was obtained; while for the 0% EAFS mixture, the energy consumed was found to be 0.079 kWh; In other words, a significant reduction in the average energy consumption of 55.7% was found. This is likely caused by the addition of ferrous particles that allowed to promote a higher susceptibility to microwave energy. In order to determine the effect of the slag aggregates on energy consumption (kWh), an assessment of five different slag aggregate compositions (0%, 2%, 4%, 6%, 8% by total volume of the mixture) and different microwave heating times (0, 30, 60, 90, 120, 150, 180, 210, 240 and 270 s) was studied in the laboratory, as illustrated in **Figure 52-53**.

Figure 52. Microwave heating analysis: Average inner heating temperature (°C) vs. heating time (s)

Figure 53. Microwave heating analysis: Average inner heating temperature (°C) vs. heating time (s)

Figure 54 and 55 show the average microwave heating surface and in binder temperature (°C) vs. energy consumed (kWh) of each type of mixture studied (0%, 2%, 4%, 6%, and 8% of EAFS). It can be observed in this Figure that the most susceptible mixture to microwave energy were those mixtures fabricated with 8% EAFS aggregates by volume of the mixture, followed by the subsequent slag aggregates content.

Figure 54. Thermographic analysis: Surface microwave heating temperature (°C) vs. energy consumed (kWh)

Figure 55. Thermographic study: Inner microwave heating temperature (°C) vs. Energy consumed (kWh)

6.7 Self-healing testing program

Once the optimum emulsion content and thermographic temperature analysis were defined, the next step was to quantify the initial mechanical performance properties of the steel slag mixtures in terms of (1) **stiffness modulus**, at 20 °C, according to **EN 12697-26:2018. Part 26: Stiffness**; and (2) **indirect tensile strength (ITS)** test, at 15 °C, according to **EN 12697-23:2018. Part 23: Determination of the indirect tensile strength of bituminous specimens**.

- **Healing stage – second stage.** Once the specimens were subjected to compressive loads at constant deformation load of 50 ± 2 mm/min, the damaged specimens were subjected to three thermomechanical treatments using a microwave oven with an output capacity of 800 W, and four microwave heating times, depending on the steel slag aggregate content added into the mixture design. Also, a novel recompaction-based technique was used to quantify the self-healing recovery of the steel slag mixtures using (1) three thermomechanical treatments (25 °C, 60 °C, and 80 °C and (2) three recompaction gyrations (0, 25, and 50 gyros).
- **Retensile break -specimen after healing.** The stiffness modulus and indirect tensile strength tests were conducted again on the cylindrical specimens, as illustrated in **Figure 56**.

Figure 56. Schematic self-healing testing program of this research Chapter

6.7.1 Stiffness modulus

In **Figure 57**, the initial and ultimate stiffness modulus values (ITSMi) of the half-warm mixes with three different EAF slag aggregate contents (0%, 4%, and 8% of EAFS) were plotted. In this context, the self-healing rate (HR) of the mixtures' stiffness modulus values was determined by considering the analysis of three heating treatments (25 °C, 60 °C, and 80 °C) combined with three mechanical recompaction gyrations (0, 25, and 50 gyros), and, hence, compared with those values obtained from initial testing for the stiffness modulus values.

The average stiffness modulus value of the 100% RAP mixtures of **6465 MPa** was obtained (with a standard deviation (SD) of **502 MPa** and a coefficient of variation (CV) of **7.4%**), whilst the load-bearing capacity of the 4%EAFS mixture was found to be **6128 MPa** (with an SD of **438 MPa** and a CV of **6.87%**) and **5556 MPa** (with an SD of **569 MPa** and a CV of **9.91%**) for the 8%EAFS mixture, respectively. Therefore, a significant decrease in the stiffness modulus values of the 4% and 8%EAFS mixtures of 5.2% and 14.1% was noted, compared with the 0% EAFS mixture, whereby the decrease in the stiffness modulus values was in the order of **337 MPa** and **909 MPa**, respectively. Other researchers reported similar results for the steel slag mixture properties. For instance, (Kavussi and Qazizadeh, 2014) agrees with the fact that the initial stiffness modulus increased by decreasing the EAF slag aggregates content in the ultimate mixture design, and that the fatigue resistance and resilient modulus were much lower than those values obtained of conventional mixes (Bagamapadde and Wahhab, 1999).

Figure 57. Initial and ultimate stiffness modulus results, at 15 °C, of the steel slag mixtures

Figure 58 plots the self-healing ratio (HR) of the steel slag mixtures against the energy consumption (kWh). Regarding the self-healing ratio of the slag mixtures with twenty-five recompaction gyrations, the 4%EAFS mixture reached the highest self-healing ratio of 1.26 (with an SD of 0.189 and a CV equal to 13.23) with an average energy consumption of 0.047 kWh; whereas, for the 8% EAFS mixture, this ratio was found to be 1.21 (with an SD of 0.065 and a CV equal to 5.657) and 0.038 kWh. Therefore, a remarkable increase in energy consumption of the 4%EAFS mixture of 23.69% (0.009 kWh) was calculated, although a higher self-healing ratio was obtained, as illustrated in **Figure 59**. In particular, the slope of the self-healing ratio curve for the 4% EAFS mixture showed a steeper upward behavior, rising sharply at 60 °C and become more stable after that, at 80 °C.

As concerns the self-healing ratio of the stiffness modulus values, it was found that, by applying a mix recompaction energy of 50 gyros at half-warm temperatures (~ 80 °C), the 8% EAFS mixture exhibited the highest self-healing ratio of 1.392 (with an SD of 0.082 and a CV equal to 6.24) and an average energy consumption of 0.038 kWh; whereas, for the 0% and 4% EAFS mixtures, these healing ratios were found to be in the order of 1.11-1.38, and 0.064 and 0.0471 kWh energy, respectively. Therefore, a significant increase in the self-healing rate of the 8%EAFS mixtures of 25% and 0.7% was obtained; whilst, in terms of energy consumed, a significant decrease in energy consumption was found to fall in the range of 0.026-0.009 kWh, i.e., there were energy savings of up to 41% to 19%, for microwave heating times of 220 s and 160 s, respectively. The likely explanation for the density result lies in the increase of the average geometric density value by approximately 4.6%, ranging from 2.230 g/cm³ to 2.332 g/cm³ when applying 50 gyrations at 80 °C, as illustrated in **Figure 60**.

However, without recompaction energy on the specimens, the self-healing ratio of the steel slag mixtures was found to fall below 0.2, regardless of the slag aggregate content added into the mixture design and microwave heating temperature. These outcomes were consistent with the self-healing result of asphalt concrete (AC) mixtures found by other researchers. They claim that the self-healing recovery of these mixtures was found to be in the range of 0.12-0.18 and that the bar error limits had followed similar trends, likely caused because of less uncertainty compared to heat specimens (Wang et al., 2018b). Therefore, it can be assumed that the optimum heating times to obtain the highest self-healing recovery levels for 4% and 8% EAFS mixtures were 160 and 130 s, respectively. **Figure 61** depicts the self-healing rate and error bars corresponding to the half-warm steel slag mixtures (0%,4% and 8% of EAFS) with three different mix recompaction energies (0, 25, and 50 gyros) and three microwave temperatures (25 °C, 60 °C, and 80 °C).

Figure 58. Self-healing rate of the stiffness modulus without using recompaction energy

Figure 59. Self-healing rate of the stiffness modulus with 25 recompaction gyrations

Figure 60. Self-healing ratio of the stiffness modulus with 50 recompaction gyrations

Figure 61. Self-healing rate of the stiffness modulus of the half-warm steel slag mixtures (0%,4% and 8% of EAFS)

6.7.2 Indirect tensile strength

The self-healing ratio of the half-warm mixes was also determined in terms of the indirect tensile strength (ITS), at 15 °C, according to **EN 12697-23:2017: Determination of the Indirect Tensile Strength of the bituminous mixtures**. Therefore, three recompaction levels (0,25, and 50 load cycles) and three microwave heating temperatures (25 °C, 60 °C, and 80 °C) were selected to quantify the indirect tensile strength of the steel slag mixtures, as illustrated in **Figure 62**.

Figure 62. Indirect tensile strength test, at 15 °C, of the steel slag mixtures

Figure 63 exhibits and compares the initial ($ITS_{initial}$) and the ultimate indirect tensile strength (ITS_{final}) value results, as well as the self-healing ratio (ITS_f/ITS_i) of the HWMRA mixtures containing three different slag aggregate contents (0%,4%,8% of the total volume of the mixture), at 4% EAFS increments, respectively; where the mixtures were tested from laboratory specimens, at three different recompaction testing levels (0,25 and 50 gyrations), at 25 gyros increments, for each type of slag aggregate content and three different microwave heating temperatures (80 °C, 60 °C, and 25 °C), with an oven output capacity of 1200 W and a 230 V, 50 Hz power supply.

For the 100% RAP mixture, the average indirect tensile strength value was found to be 2.28 MPa (with a low standard deviation (SD_{μ}) of 0.209 MPa, and a coefficient of variation (CV_{γ}) of 8.35%); whilst the ultimate internal cohesion value of 2.826 MPa was obtained (with SD of 0.307 MPa and CV equal to 10.87%). In view of that, an increase of the internal cohesion value by approximately 23.7% was observed, likely to be due to the effect of higher recompaction energy (50 gyrations) and microwave heating process.

Figure 63. Initial and ultimate indirect tensile strength value results, at 15 °C, of the steel slag mixtures

In terms of thermomechanical treatment, the cracked specimens were heated depending on the EAF slag aggregate content added into the mixture design and the target heating temperature to be achieved. For instance, for the 0%EAFS mixture, the specimens were heated for **15,130, and 220 s**; whereas, for the **4% EAFS**, the microwave heating times were **160,90, and 12 s**, and, for the **8% EAFS**, these times were **130,70 and 10 s**, respectively.

Looking at the initial internal cohesion values of the 0% EAFS mixtures with 0 recompaction gyros, the average indirect tensile strength value of the 100% RAP mixture was found to be 2.14 MPa (with a low standard deviation (SD) of 0.12 MPa, and a coefficient of variation (CV) of 5.2%); whilst, for the **4% and 8% EAFS** mixture, these values were found to fall within the range of **2.067** (with an SD of **0.148** MPa and a CV of **7.25%**) and **1.947** MPa (with an SD of **0.2** MPa and a CV of **9.87%**), respectively. Therefore, a slight decrease in the average internal cohesion values of the **4% EAFS** mixture of **3.3%** (-**0.071** MPa) was obtained; whereas, **for the 8% EAFS mixture**, this cohesion value decreased in terms of absolute value by approximately **0.191** MPa (**-8.9%**) when compared to the 0% EAFS mixture. **Figure 64** depicts the self-healing ratio of the internal cohesion (Ft/It) with 25 recompaction gyrations against the energy consumed (kWh) for each type of slag mixture.

Additionally, it was found that, by applying a mix recompaction energy of 50 gyrations at 80 °C, the average geometric density of the 0% EAFS mixture of **2.415 g/cm³** (with an SD of **22.85 g/cm³** and a CV equal to **0.95%**) was obtained, and mean specimen's height of **54.05 mm**; whilst, for the **4%EAFS** mixture, the average densification value was found to be **2.369 g/cm³** (with an SD of **43.84 g/cm³** and a CV of **1.85%** and **h= 56,44 mm**) and **2.332 g/cm³** (with a SD of **15.1 g/cm³** and a CV of **0.65%** and **h= 57.82 mm**) for the **8% EAFS**, respectively, as illustrated in **Figure 65**.

Figure 64. Self-healing rate of the indirect tensile strength of the slag mixtures

Figure 65. Self-healing rate of the indirect tensile strength of the slag mixtures using 25 recompaction gyrations

In Figure 66 the self-healing ratio (ITS_f/ITS_i) of the mixtures with three different slag aggregate contents (0%, 4%, and 8% of EAFS by volume of the mixture) against the amount of energy consumed (kWh), were depicted. In terms of energy consumption (kWh), an average linear energy consumption value of 0.008 kWh was calculated, for every 30 s, using an electric monitoring device. Thus, the specimens were heated for different microwave heating times as follows: (1) the 0% EAFS specimens were heated for 220 (85 °C), 130 (65°C) and 15 s (25 °C); (b) for the 4% EAFS mixture, the optimal microwave heating times were 160, 90 and 12 s; (3) whilst, for the 8% EAFS mixture, these times turned out to be 130, 70, and 10 s, respectively.

Therefore, it can be said that the indirect tensile strength (ITS) value was found to be highly linked to the density and air voids of the steel slag mixtures - suggesting that the lower the density (or, the higher the air voids contents), the less the indirect tensile strength and stiffness modulus. These results were consistent with those found by other researchers. For instance, Luo, (2012) claimed that mixes with lower air voids content in mix have a higher self-healing level, regardless of the type of bitumen, aging, and temperature although an asphalt mixture with higher bitumen content, a coarse gradation, and fewer air voids content has better healing capability (Ayar et al., 2016). However, and contrary to popular beliefs, the cohesion results were somewhat less conclusive in terms of resisting tensile stress loads on the specimens' vertical diametral plane. In other words, the higher the EAF slag aggregate content added into the mixture design, the less the mixtures' internal cohesion values, likely caused as a result of a weak

interaction/blending between slag aggregates (lower CaO/SiO₂) and recycled asphalt. Other researchers found similar outcomes for internal cohesion values. For instance, Hesami et al., (2014) asserted that the use of EAF slag fine/filler fractions gets worse the mechanical performance of these mixtures. **Figure 67** self-healing rate of the indirect tensile strength, at 15 °C, of each type of the slag mixture.

Figure 66. Self-healing ratio of the indirect tensile strength with 50 recompaction gyrations

Figure 67. Self-healing rate of the indirect tensile strength, at 15 °C, of each type of the mixture

6.8 Gyratory compaction curves

In **Figure 68a**, the evolution of the geometric density (g/cm^3) of the steel slag mixtures (0%, 4%, and 8% EAFS by the total volume of the mixture) against two different recompaction gyrations (25 and 50 load cycles) was plotted, respectively. The specimens were recompacted by considering the standard compaction conditions established (0.82° , 600 kPa, and 30 rpm) by the EN 12697-31:2008 standard, along with a microwave conditioning treatment at three microwave heating temperatures (80°C , 60°C , and 25°C); where the effect of the recompaction and temperature had a significant impact on the mixture densification as well as in the recovery of the mixtures' mechanical performance.

In **Figure 68b**, a significant improvement in the average geometric density value of 100% RAP mixture of 3.1% was obtained, i.e., this number increased by approximately 0.7 g/cm^3 (i.e., from 2224 to 2314 g/cm^3) due to the application of a mix recompaction effort of 50 gyros at half-warm temperatures ($\sim 80^\circ\text{C}$); whereas, **Figure 68c-d** showed the slope of the recompaction curve with 4% EAFS presented a steeper upward curve behavior in terms of densification, rising sharply during the first 20 load cycles and becomes more stable after that. In other words, an increase in the geometric density value by approximately 4.4% was obtained, likely caused by the kneading effect provided by the gyratory compactor that allowed the rearrangement of the particles in the specimen and, subsequently, the aggregate-aggregate interlocking effect that promoted the densification of the mixture and, thus, the reduction of air voids content in mix (Pérez-jiménez et al., 2014).

In particular, for the 8%EAFS mixture recompacted with 50 gyros, at 80°C , showed the highest average densification value of 2.332 g/cm^3 , i.e., a considerable increase in the geometric density value of about 4.58% was obtained, whereas, for the mixture compacted at room temperature (25°C), this percentage was practically negligible, as illustrated in **Figure 68e-f**.

Figure 68. Geometric density (g/cm^3) value results of the 0%, 4%, and 8% of EAFS mixture versus two recompaction energies (25 and 50 gyros)

Chapter 7

CONCLUSIONS AND FUTURE RESEARCH STUDIES

7.1 Laboratory compaction study

The primary objective of this study was to define the most appropriate compaction test method for the production and characterization of half-warm mix recycling technology with 100% RAP and emulsified bitumen and define the number of compaction gyrations (N_{design}) needed to match the benchmark density of the samples compacted with 70 gyrations with the field density after pavement construction. In turn, the second goal was to quantify how an accelerated curing treatment promotes the ultimate mechanical performance properties (i.e., ITS and stiffness modulus) of the half-warm mix recycled asphalt mixtures containing a RAP content equal to 100% and emulsified bitumen (2.5% o/RAP). The mixture mechanical performance was also considered for this research Chapter in terms of rutting performance, stiffness, four-point bending (4PB) beam fatigue test method. As for the HWMRA specimens' production/compaction and characterization in the preliminary mix design stage, the main findings and results that can be drawn from this phase are collated below:

- The gyratory compactor system turned out to be the most suitable compaction method for half-warm mix recycled asphalt (HWMRA) specimens' production and characterization in the laboratory. This compaction method allowed the provision of the benchmark density within the range of between 2.311 and 2.335 g/cm³, and target air voids content in the order of 3.0-4.0%. These results were obtained by applying a mix design compaction energy of 70 gyros, at 80 °C, and setting up the gyratory compactor at an internal angle of gyration of 0.82°, vertical consolidation pressure of 600 kPa, and speed of gyration of 30 rpm.

Moreover, the compaction study revealed that, for 70 gyrations, a 98.8% ($\rho_{b,\text{dim}} = 2.311 \text{ g/cm}^3$) of the ultimate geometric density of the gyratory compaction curve ($\rho_{b,\text{dim}} = 2.340 \text{ g/cm}^3$ - at 200 gyros) was obtained – thus ensuring the benchmark density and target air voids content sought for this technology;

- It is worth noting that the use of static compressive stress load by double-plunger of 21 MPa load was discarded since this method led to a much higher bulk density, indirect tensile strength, and stiffness modulus values than those expected from the road worksite after pavement construction. Moreover, it was observed that the static method caused the breakage of aggregates and binders' squeezing throughout the specimen' compaction process;

- Concerning the Marshall impactor results with 75 and 100 blows on each side, a significant decrease in the volumetric (e.g., air voids and bulk density) and mechanical performance properties (e.g., indirect tensile strength and stiffness modulus) of the recycled mixtures was obtained, compared to the results from the gyratory compactor at 70 gyrations (0.82°, 600 kPa and 30 rpm), likely as a result of the breakage of aggregates during the specimen' compaction process.
- The effect of a long-term accelerated curing treatment of three days (72 h), at 50 °C, was found to be rather positive on the development of the ultimate mixtures' mechanical performance properties. In other words, the stiffness modulus value increased by approximately 20%, i.e., ranging from 2891 (0 h) to 3462 MPa (72 h); whereas the indirect tensile strength values grew by 11% (i.e., from 2.11 to 2.34 MPa), respectively. This improvement is likely caused by the breaking and setting of emulsion, as well as for the maturation process suffered by the half-warm emulsified specimens that promoted the ultimate mixtures' mechanical performance properties in terms of load-bearing capacity and indirect tensile strength values. No longer curing treatments were required for this technology since they were found to reach a constant weight at 72 h and 50 °C.

Looking at the advanced mechanical performance characterization of the mixtures studied, the principal results and conclusions that can be drawn from this section are summarized below:

- The HWMRA 100% RAP (2.5%o/RAP) mixtures meet the minimum moisture damage resistance values for their use in intermediate and low traffic load categories of road pavements. What's more, they meet the current stringent moisture sensitivity requirements stipulated for hot mix asphalt mixtures in base, binder, and wearing course asphalt mixtures of road pavements;
- The HWMRA 100%RAP mixture with 2.5% emulsion (o/RAP) showed suitable resistance to permanent deformation at 50 °C and 60 °C. In fact, for the 2.5% emulsion and 50/70 pen. grade emulsified bitumen, the wheel tracking slope (WTSAIR) value, at 60 °C, was much lower than the maximum wheel tracking slope value (0.15 mm/10³ load cycles) required by the Spanish technical regulations for hot mix asphalt mixtures subject to intermediate and low traffic load categories of road pavements;
- For the same stress levels selected, one can say that the HWMRA mixes with 50/70 pen. grade bitumen showed similar fatigue cracking performance. However, 50/70 pen. bitumen exhibited slightly lower micro-tensile fatigue-strain (ϵ_6) values compared with the results from the 160/220 pen. grade bitumen. This is likely attributed to the effect of a softer penetration grade bitumen in the final mixture design that allowed the provision of higher mixtures' ductility and flexibility by enabling greater tensile-strain fatigue loads.

As for upcoming research lines, it is vital to keep working on the monitoring and characterization of the half-warm mix recycled asphalt mixtures, either in the laboratory or field, to encourage higher confidence in promoting the use of for maintenance and rehabilitation (M&R) activities of road pavements. To this end, a set of scheduled sampling and testing campaigns on the test road section will be scheduled to draw some conclusions regarding volumetric, mechanical performance (e.g., indirect tensile strength, stiffness modulus, and fatigue resistance), and surface friction characteristics of these mixtures in the field. In summary, these sampling campaigns allow getting more accurate data on the possible correlation between the laboratory mix design phase and field performance.

7.2 Conclusions of the manufacturing and quality control

Once the compaction test method and mixture design were defined, the next step was to evaluate the reproducibility of manufacturing half-warm mixes with 100% RAP and emulsified bitumen (2.5% and 3.0% o/RAP) in a portable modified asphalt batch plant. In order to do this, an average of sixteen (16) in-plant samples were prepared (with a diameter of 100 mm and 60 mm in height) and compacted using the gyratory compactor, at 80 °C, by applying a mix design compaction energy of 70 gyros using the laboratory standard compaction conditions (0.82°, 600 kPa and 30 rpm) established in EN 12697-31:2008 standard. After that, in-plant samples were tested for stiffness modulus at 20 °C, indirect tensile strength at 15 °C, moisture sensibility, rutting performance, and resistance to fatigue cracking to indirect tensile at 20 °C. The principal results and conclusions that can be drawn from the quality control are collated in detail as follows:

- The results obtained from the quality control campaigns showed good homogeneity and reproducibility of the HWMRA mixtures concerning grading curves and binder content and air void content, suggesting that they can be successfully reproduced in real-scale asphalt manufacturing plants.
- The HWMRA mixes (2.5% and 3.0% o/RAP) fell within the threshold values stipulated for an AC16 D mixture, and at the same time met the restricted threshold values established by the Spanish technical specifications in Art. 542.9.3.1: Fabrication of hot mix asphalt mixtures.
- The RAP material is properly pretreated, screened, and divided into, at least, two RAP fractions, i.e., fine (0/5 mm) and coarse fraction (5/25 mm). In other words, the RAP's fractionation and processing allowed to ensure (1) the required bitumen contents targeted; (2) reduce the RAP variability ($\pm 0.3\%$ o/RAP) in terms of binder content; and (2) it also allowed to guarantee the physical bitumen's consistency properties, increased mix homogeneity, and get more consistency properties in terms of aggregate grading curves and binder contents;

- Additionally, the theoretical RAP binder content of the 100% RAP mixture (2.5% o/RAP) was found to be 4.15% o/RAP and adding 60% of residual emulsion content (from the 2.5% o/RAP), the ultimate binder content, after in-plant manufacturing, of 5.7% o/RAP was obtained; whereas, for the 3.0%o/RAP emulsion, this content was found to be 6.0 %o/RAP. The likely explanation for these results lies in the good maneuvers of processing, treatment, screening, and classification of RAP materials into two RAP fractions, which allowed to ensure and achieve the required targeted binder contents in the final mixture design.
- Concerning the physical bitumen' consistency properties of the recovered RAP binder, it was found that the recycled binder exhibited a slight increase in the penetration values (dmm), though a statistical variability in terms of softening point temperature (°C) was noted, likely as a result of the aging and heterogeneity of aged RAP binder obtained from different RAP millings;
- Both HWMRA 100% RAP mixtures meet the minimum moisture damage resistance value required for in-situ recycling of bituminous layers with emulsion above 75%, likely attributed to the fact that RAP aggregates are already coated and covered with a thin film of asphalt that prevents the water penetration into the recycled particles;
- The average stiffness modulus, at 20 °C, of the HWMRA 100% RAP mixtures with 2.5% emulsion was found to be in the range of a conventional HMA mixture corresponding to 6000 MPa;
- The HWMRA 100% RAP mixture with 2.5%o/RAP showed a wheel tracking slope slightly lower than the maximum value (0.15 mm/10³ load cycles) required for hot mix asphalt mixtures in the binder and wearing course asphalt mixtures of road pavements;

7.3 Conclusions: Sampling

An average of sixteen (16) cylindrical pavement cores (with a diameter of 100 mm and a height of 55 mm) for each emulsion content (2.5% and 3.0% o/RAP) were drilled from the test road sections, and tested in the laboratory to determine apparent density, by SSD conditions, air voids content, stiffness modulus, indirect tensile strength, and moisture susceptibility. Therefore, the main results and conclusions that can be drawn from the test road section are summarized and compared in detail as follows:

- The apparent density and air voids content obtained from the field cores (2.5% and 3.0% o/RAP) exhibited slightly lower density and higher air voids content than those values obtained from the in-plant samples and; therefore, they may not exactly match the density obtained in the laboratory. The likely explanation for these results is that the contractor could have applied lower compaction energy since this mixture was going to be placed as binder course asphalt mixture;

- The average stiffness modulus value of the HWMRA 100% RAP mixtures with 2.5% and 3.0%o/RAP emulsion was found to be within the range between 4800 MPa and 3500 MPa, respectively.;
- The mixtures' fatigue cracking resistance was evaluated through the indirect tensile strength at 15 °C and loading frequency of 10 Hz. This test revealed that, for the same stress level applied, the HWMRA 100% RAP (2.5% and 3.0%o/RAP) specimens exhibited equivalent fatigue cracking slopes and similar strain-fatigue levels compared to conventional HMA mixtures. However, it was noted that the effect of higher bitumen emulsion content in the final mixture design of 3.0%, likely promoted the extension of the mixtures' fatigue life;
- Looking at the mechanical performance properties of the pavement cores, the 100% RAP mixtures (3.0% o/RAP) showed a slight decrease in terms of indirect tensile strength and stiffness modulus values, i.e., the mechanical performance reduction was found to be 13.3% for the former and 27.9% for the latter. Nonetheless, it was noted that the 3.0% mixture showed a slight increase in the mixture' fatigue cracking resistance, whereby the effect of higher emulsion content in the final mixture design likely promoted the extension of the mixtures' fatigue life.
- It was found that the HWMRA 100% RAP mixtures have not displayed significant surface distresses issues (i.e., wheel-path longitudinal cracking, transverse cracking, reflective cracking) - showing that the HWMRA mixtures should be considered as a potential solution compared with that of conventional mixes, due to the reduction of environmental and economic costs associated with maintenance and rehabilitation practices;
- Regarding the international roughness index (IRI) values, it was observed that the HWMRA 100%RAP mixes with 2.5% and 3.0%o/RAP showed satisfactory functional characteristics, i.e., the average IRI was found to be 1.011 and 1.115 m/km, respectively. Also, no significant change in surface roughness occurred during the first three years of service—suggesting that the imperfections are derived more from paving operations than a function of surface pavement wear. Moreover, no surface distresses (e.g., transverse cracking and wheel-tracking longitudinal cracking, and rutting) were observed for this technology.

In summary, HWMRA showed equivalent mechanical performance to conventional HMA mixes, as demonstrated by both the laboratory and field-stage tests, i.e., after in-plant manufacturing and field cores. In this sense, HWMRA produced with emulsion can be considered as a true environmental alternative compared to traditional mixes. Thus, a more in-depth research is being carried out to further evaluate and achieve a better understanding of the long-term mechanical performance properties of this technology.

7.4 Self-healing conclusions

The objective of this study was to present and quantify the self-healing ratio (HR) of the half-warm mix recycled asphalt (HWMRA) mixtures with three different steel slag aggregate contents (0%, 4%, and 8% of EAFS) used as a replacement of recycled asphalt pavement (RAP) in the fine fraction of 0-4 mm. For this reason, the mixtures' self-healing ratio was determined using a thermomechanical treatment, i.e., three different microwave heating temperatures (25 °C, 60 °C, and 80 °C) and three mechanical recompaction gyrations (0, 25, and 50 gyrations) for HWMRA mix' production and characterization in the laboratory. In turn, the main findings and conclusions that can be drawn from the experimental methodology of this research Chapter are summarized below:

Concerning the mixtures' mechanical performance properties, it was found that the addition of steel slag fine fraction into the new mixture design leads to a remarkable decrease in the mixtures' mechanical performance properties. In other words, the stiffness modulus values of the 8%EAFS mixture decreased by 14% ($S_m = 5569$ MPa); whereas, for the stiffness modulus value with 4% EAFS, this property dropped by 9% ($S_m = 6128$ MPa) compared to the HWMRA 100% RAP mixture (6465 MPa); likely caused by the reduced interaction between slag aggregates and bitumen emulsion.

Nevertheless, one can say that the replacement of recycled aggregates with steel slag fine fraction aggregates (0-4 mm sieve) represents a promising energy-efficient and environmental solution since it allows to speed up the heating temperature of the internal specimen while increasing the self-healing rate of the steel slag mixtures by applying a thermomechanical treatment at half-warm temperatures (80 °C) and 50 recompaction gyrations.

For the indirect strength tensile (ITS) value, the 4% EAFS mixtures showed the highest recovery capability of the healing ratio (40%), whereas, for the stiffness modulus, the average healing ratio of 68% was obtained, by applying a recompaction effort of 50 gyrations at a microwave heating temperature of 80 °C. Therefore, for the stiffness modulus values, the higher the microwave heating temperature and recompaction gyrations, the higher the recovery capability of the mixtures;

Finally, it is worth noting that there is not much difference between the self-healing ratio of the mixtures using half- (25) or total recompaction energy. In general, the mechanical performance results encourage greater confidence in promoting the revalorization of industrial by-products in new sustainable asphalt mixes, by promoting the novelty of a cutting-edge mechanical recompaction treatment, along with microwave heating energy.

7.5 Future research studies and upcoming opportunities

Since half-warm mix recycling technology with 100%RAP and emulsified bitumen is a new paving product released to the asphalt market, some specific issues should be investigated to keep improving the current state-of-the-art review and state-of-the-practice while helping in the decision-making process for the adoption of new disruptive production technologies such as half-warm mix asphalt.

1. Concerning long- term mechanical performance
 - It is recommended to keep investigating the evolution of the volumetric and long-term mechanical performance properties of half-warm mixes containing high (50-70%), and total RAP contents (100%) laid either in the urban test section or in the test road section. To this end, it is intended to conduct a set of coring and testing campaigns to draw more consistent conclusions from the stiffness modulus, internal cohesion, rutting performance, and fatigue cracking behavior. In particular, the mixtures' stiffness modulus is recommended to be tested at four different testing temperatures (5 °C, 20 °C, 30 °C, and 40 °C) to look into the evolution of the mixtures' mechanical performance as a function of the thermal season studied.
2. With regard to surface pavement friction characteristics as part of the pavement management system:
 - To analyze the evolution of the pavement surface friction characteristics of the wearing course asphalt mixtures in terms of (1) Macrotexture, according to EN 13036-1:2010: Measurement of pavement surface macrotexture depth using a volumetric patch technique; (2) Skid resistance of a pavement surface using the Dynamic Friction Tester, according to ASTM E1911-09a¹; and international surface roughness index, according to EN 13036-6:2008. Part 6: Measurement of transverse and longitudinal profiles in the evenness and megatexture wavelength ranges
3. Concerning fatigue cracking characterization of mixes with total RAP contents and at half-warm temperatures:
 - It is important to evaluate the crack propagation behavior of half-warm mixes with 100% RAP and emulsified bitumen using the semi-circular bending (SCB) test by applying a 1 mm/min constant displacement load, according to EN 12697-44:2010.

4. As for the self-healing analysis of half-warm mixes with steel slag used for replacement of recycled aggregates in the fine fraction of 0-4 mm by the total volume of the mixture.
 - It is highly recommended to prepare a new set of cylindrical specimens, with a C67B3 cationic emulsion, for being subjected to a controlled-stress fatigue load using the indirect tensile fatigue test (ITFT), at 20 °C, and loading frequency of 10 Hz (EN 12697-24:2012: Resistance to Fatigue). In order to achieve this goal, it is suggested to keep evaluating the same heating treatment temperatures (25 °C, 60 °C, and 80 °C) and mechanical recompaction-based technique (0,25, and 50 gyros) with the gyratory compactor (0.82°, 600 kPa, and 30 rpm) and, after that, quantify and compare the self-healing ratio (HR) of the steel slag mixtures with a conventional hot mix asphalt (HMA) mixture.
 - To analyze the effect of half-warm steel slag mixtures (0/4 mm) on the resistance to permanent deformation, moisture susceptibility, stiffness modulus at 5°C, 20 °C, and 30 °C, and tensile strength at 15 °C, and indirect tensile fatigue test at 20 °C. To this end, it is suggested that four number of recompaction gyrations (0,25,50, and 75 gyros) and four microwave heating treatment temperatures (25 °C, 60 °C, 80 °C, and 95 °C) can be used and evaluated for quantifying the self-healing ratio of such mixtures. In order to reliably compare the self-healing results, it is crucial to maintain the microwave output capacity of 800 W, with a frequency of 2.45 GHz.
 - Determining if the replacement of recycled aggregates with 4% and 8% of steel slag coarse fraction (4-8 mm by the total volume of the mixture) improve the mechanical performance and the self-healing ratio of the steel slag mixtures compared with the fine fraction (0/4 mm).
 - Development of a self-healing prediction model that enables to simulate the long-term field performance of HWMA mixes containing high and total RAP contents. This prediction models can help local road administrations, agencies, and decision lawmakers to choose which type of solutions may have a better field performance than conventional mixes based on the cost-effective ratio throughout their life cycle assessment.
5. Regarding the Life cycle assessment (LCA) of half-warm mix recycled asphalt (HWMRA) mixtures with 100% RAP and emulsified bitumen by conducting the life cycle assessment (LCA) based on the ISO 14040:2006: Life cycle assessment. Principle and framework and ISO 14044:2006, and life-cycle costing analysis ISO 15686-5:2017. Buildings and Constructing Assets -Life Planning. Part 5: Life-cycle costing.

Chapter 8

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